

KERN- UND TEILCHENPHYSIK

The Cluster-Jet and Gas-Jet Targets for $\overline{\text{P}}$ ANDA and MAGIX: Upgrades and Operation at COSY and MAMI

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Abstract

The cryogenic cluster-jet and gas-jet targets developed in Münster play an important role in precision experiments in particle physics due to their windowless nature. The two targets for $\overline{\text{PANDA}}$ and MAGIX share a similar design, although they are optimized for completely different experiments.

The $\overline{\text{PANDA}}$ cluster-jet target is designed for the interaction with antiprotons at the FAIR facility in Darmstadt. The interaction point will be surrounded by a spectrometer setup consisting of a solenoid magnet and several detector systems. Therefore, the target source will be installed at a distance of more than 2 m from the interaction point. However, it still achieves a target thickness of more than $2 \cdot 10^{15} \text{ atoms/cm}^2$ at the interaction point. Within this thesis, the $\overline{\text{PANDA}}$ target was operated at the COSY accelerator in Jülich. Here, a new record target thickness of $(3.14 \pm 0.17) \cdot 10^{15} \text{ atoms/cm}^2$ for the $\overline{\text{PANDA}}$ target was achieved, which was only surpassed once at the Münster prototype target with the same nozzle [Gri18]. With this target, intense measurements have been performed during three beam times at COSY with the aim to study the influence of the target in combination with a stochastic cooling on the accelerator beam and especially on its momentum spread. This thesis explores the dependence and shows how important its understanding is for the operation of the $\overline{\text{PANDA}}$ experiment at FAIR. It allows finding the best combination of target thickness and accelerator beam intensity to achieve the smallest possible momentum spread, which is important for the quality of some precision measurements at $\overline{\text{PANDA}}$. Furthermore, several upgrades of the $\overline{\text{PANDA}}$ cluster-jet target, such as a new beam dump that allows for the installation of several monitor systems, are described. One of these systems is an MCP monitor system that enables 2D online monitoring by ionizing the cluster-jet beforehand. When operated at an accelerator, the accelerator beam can ionize the cluster-jet, and thus the MCP system visualizes only the overlap region. Intense studies with this new system have also been performed at COSY. These studies focused on the dependence of the intensity of the recorded MCP images on the target thickness, the accelerator beam intensity, and the MCP voltage.

In the second part, the gas-jet target for the MAGIX experiment at the future electron accelerator MESA in Mainz is discussed. It allows for a target thickness of

more than $1 \cdot 10^{18}$ atoms/cm² at a distance of about 5 mm from the nozzle, where the interaction point with the MESA electron beam will be located. Currently, this target is already in operation at the A1 experiment at MAMI, where an optimized nozzle design proposed in [Bra19] was validated. This design showed a significant reduction of the jet divergence, leading to an increase of the target thickness and an improvement of the vacuum conditions. Furthermore, for the first time, the MAGIX target was operated with liquid argon. The detailed calculations to adapt the target for this measurement are described. Finally, for some experiments foreseen at MAGIX, other windowless target concepts like the droplet or filament targets are also beneficial. This thesis shows how such a target will increase the target thickness while reducing the gas flow rate by more than an order of magnitude. This will have a large impact on the performance of the MAGIX experiment, as it will improve the vacuum conditions and allow for higher target thicknesses.

Zusammenfassung

Die kryogenen Cluster-Jet und Gas-Jet Targets aus Münster spielen aufgrund ihres fensterlosen Designs eine wichtige Rolle in Präzisionsexperimenten in der Teilchenphysik. Obwohl sie für verschiedene Experimente vorgesehen sind, teilen sich die beiden Targets für $\overline{\text{PANDA}}$ und MAGIX ein ähnliches Konzept.

Das $\overline{\text{PANDA}}$ Cluster-Jet Target ist für die Wechselwirkung mit Antiprotonen an der FAIR-Beschleunigeranlage in Darmstadt konzipiert. Der Interaktionspunkt dort ist von einem Spektrometer umgeben, das aus einem Solenoiden und mehreren Detektorsystemen besteht. Daher wird das Target in einem Abstand von mehr als 2 m zum Interaktionspunkt installiert. Trotz des großen Abstands erreicht es am Interaktionspunkt immer noch eine Targetdichte von mehr als $2 \cdot 10^{15}$ Atome/cm². Im Rahmen dieser Arbeit wurde das $\overline{\text{PANDA}}$ -Target am COSY-Beschleuniger in Jülich betrieben. Dabei wurde eine neue Rekord-Targetdichte von $(3.14 \pm 0.17) \cdot 10^{15}$ Atome/cm² für das $\overline{\text{PANDA}}$ -Target erreicht, die nur einmal mit der gleichen Düse am Münsteraner Prototyp-Target übertroffen wurde [Gri18]. Mit diesem Target wurden intensive Messungen während dreier Strahlzeiten durchgeführt, um den Einfluss des Targets in Kombination mit einer stochastischen Kühlung auf den Beschleunigerstrahl und insbesondere auf seine Impulsbreite zu untersuchen. In dieser Arbeit wird diese Abhängigkeit bestimmt und gezeigt, wie wichtig es ist, sie für den Betrieb des $\overline{\text{PANDA}}$ -Experiments an FAIR zu kennen. Diese Kenntnis ermöglicht es, die beste Kombination aus Targetdichte und Beschleunigerstrahlintensität zu finden, um die kleinste mögliche Impulsbreite zu erreichen, die für die Qualität einiger Präzisionsmessungen bei $\overline{\text{PANDA}}$ wichtig ist. Darüber hinaus werden verschiedene Upgrades des $\overline{\text{PANDA}}$ Cluster-Jet Targets wie ein neuer Beam Dump beschrieben, der die Installation mehrerer Monitorsysteme ermöglicht. Eines dieser Systeme ist ein MCP-Monitorssystem, das eine 2D-Online-Visualisierung durch Ionisierung des Cluster-Jets vor dem MCP ermöglicht. Bei Betrieb an einem Beschleuniger kann der Beschleunigerstrahl den Cluster-Jet ionisieren und das MCP-System visualisiert nur die Überschneidung von Cluster-Jet und Beschleunigerstrahl. Detaillierte Studien mit diesem neuen System wurden ebenfalls am COSY durchgeführt. Diese konzentrierten sich auf die Abhängigkeit der

Intensität der aufgenommenen MCP-Bilder von der Targetdichte, der Intensität des Beschleunigerstrahls und der MCP-Spannung.

Im zweiten Teil dieser Arbeit wird das Gas-Jet Target für das MAGIX-Experiment am zukünftigen Elektronenbeschleuniger MESA in Mainz beschrieben. Dieses Target ermöglicht eine Targetdichte von mehr als $1 \cdot 10^{18}$ Atome/cm² in einem Abstand von etwa 5 mm von der Düse, in dem sich der Interaktionspunkt mit dem Elektronenstrahl von MESA befinden wird. Dieses Target ist bereits am A1-Experiment am MAMI in Betrieb, wo ein in [Bra19] optimiertes Düsendesign geprüft wurde, welches eine signifikante Reduktion der Jet-Divergenz zeigte. Dies führte zu einer Erhöhung der Targetdichte und einer Verbesserung der Vakuumbedingungen. Darüber hinaus wurde das Target erstmals mit flüssigem Argon betrieben, wofür detaillierte Berechnungen zur Anpassung des Targets nötig waren. Schließlich sind für einige Experimente, die bei MAGIX geplant sind, auch andere fensterlose Targetkonzepte wie das Droplet- oder Filament-Target eine Option. Diese Arbeit zeigt, wie ein solches Target die Targetdichte erhöhen und den Gasfluss um mehr als eine Größenordnung reduzieren wird. Dies wird sich erheblich auf die Leistung des MAGIX-Experiments auswirken, da es die Vakuumbedingungen verbessern und höhere Targetdichten ermöglichen wird.

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Introduction

Particle physicists all over the world aim for a deep understanding of the fundamental forces and particles in nature by an interplay of theory and experiments. This is demonstrated by the search for the Higgs boson, which was already theoretically described and predicted in 1964 [EB64, GHK64, Hig64], but it took until 2012 for its first discovery to be announced by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC) at CERN [Aad⁺12, Cha⁺12]. With this discovery, the standard model of particle physics, in its current state, which will be described in chapter 1, was completed. However, despite the success of the standard model, the improved precision in theory and experiments has also unveiled discrepancies. A prominent example here is the deviation of the anomalous magnetic moment of the muon measured by the $g_\mu - 2$ collaboration [Agu⁺24] from the theoretical prediction [Aoy⁺20]. Within this thesis, two experiments are covered that aim to contribute to the understanding of the fundamental forces. The $\overline{\text{P}}\text{ANDA}$ experiment will mainly focus on the strong interaction by, e.g., charmonium spectroscopy and the search for exotic states like glueballs or tetraquarks. The MAGIX experiment will focus on high precision electron scattering experiments to contribute to, e.g., the proton radius puzzle and the search for new physics beyond the standard model. Both experiments are located at future accelerator facilities, the FAIR facility in Darmstadt and the MESA accelerator in Mainz, respectively, and are designed as fixed-target experiments. The operation of these two targets, the $\overline{\text{P}}\text{ANDA}$ cluster-jet target and the MAGIX gas-jet target, is the topic of this thesis. Furthermore, upgrades of both targets will also be discussed.

The $\overline{\text{P}}\text{ANDA}$ experiment at the FAIR facility in Darmstadt will mainly study proton-antiproton collisions. The necessary accelerator infrastructure for the antiproton beam and the $\overline{\text{P}}\text{ANDA}$ experiment, along with its physics program and experimental setup, will be discussed in chapter 2. A crucial system of this experiment is the state-of-the-art $\overline{\text{P}}\text{ANDA}$ cluster-jet target that will provide a hydrogen cluster-jet for the interaction with the antiproton beam. It can deliver a target thickness of more than $2 \cdot 10^{15}$ atoms/cm² [Gri18] at a distance of more than 2m from the nozzle. Within this thesis, some parts of this target system were upgraded. This includes the design of a new beam dump system, which - in contrast to the old beam dump - is able to

house monitor systems. For the first time, this allows the inclusion of an MCP monitor system for a 2D online monitoring of the cluster-jet. Furthermore, a new electron gun was designed to provide the required ionization of the cluster-jet for visualization with the MCP. Additionally, a new setup for the time-of-flight measurements with the MCP and the electron gun was designed and finally realized within [Sch24, Ves24]. These upgrades also required an update of the EPICS slow control system. The target and all its upgrades are described in detail in chapter 3.

Except for the mentioned upgrades, the $\bar{\text{P}}\text{ANDA}$ cluster-jet target is already complete and was therefore installed at the COSY facility in Jülich to operate it under realistic conditions. The COoler SYnchrotron (COSY) is the ideal accelerator for these studies due to the similar conditions compared to the FAIR facility. The energy range at COSY overlaps with the range foreseen for $\bar{\text{P}}\text{ANDA}$, and additionally, also a barrier bucket cavity and the stochastic cooling intended for FAIR are installed at COSY. Some important aspects on accelerator theory, the facility of COSY, and the installation of the $\bar{\text{P}}\text{ANDA}$ cluster-jet target at COSY are thus presented in chapter 4.

The experimental studies with the $\bar{\text{P}}\text{ANDA}$ target at COSY focused on the operation of the target in combination with the stochastic cooling and barrier bucket cavity, and the resulting effect of the beam-target interaction on the accelerator beam, especially on the momentum spread. Furthermore, a detailed analysis of the performance of the new MCP monitor system for the new beam dump system is also presented. These measurements and their analyses are described in chapter 5.

The second part of this thesis is based on the future MAGIX experiment at the energy-recovery linac MESA in Mainz. This low energy electron accelerator, with its high beam intensity, enables high precision experiments and the search for dark matter candidates. The MESA accelerator and the MAGIX experiment are described in detail in chapter 6. MAGIX will also use a jet target. Due to the very small distance of about 5 mm between the nozzle and the interaction point, a gas-jet target was designed [Gri⁺18] that achieves a target thickness of more than $1 \cdot 10^{18}$ atoms/cm². This target was installed at the existing A1 experiment at the MAMI facility in Mainz, and within [Bra19], the performance of this target operated with hydrogen at the A1 experiment was studied. Via numerical simulations, an optimized nozzle design was proposed that will reduce the divergence of the jet. The setup at the A1 experiment and the operation of the target with this new nozzle are presented in chapter 7. Additionally, the first operation with liquid argon and the needed adaptations of the target, especially the nozzle geometry, are described. At the end, two alternative target concepts, the droplet target and the filament target, and their possible impact on the MAGIX experiment are discussed.

Chapter 1

The Standard Model of Particle Physics

Within this thesis the $\overline{\text{PANDA}}$ and MAGIX experiments play an important role. They are both particle accelerator experiments that focus on the understanding of fundamental interactions. Therefore, a description of the underlying theoretical framework is provided. This chapter will give an overview of the standard model of particle physics that describes the fundamental particles and their interactions.

The standard model of particle physics divides the fundamental particles into fermions and bosons (see figure 1.1). The fermions are characterized by a half-integer spin. They are the building blocks of matter and are divided into quarks and leptons. In total, three generations of quarks exist. The lightest, the up and down quarks (u, d), form the first generation and make up the protons ($|\text{uud}\rangle$) and neutrons ($|\text{udd}\rangle$). The other generations are built by the heavier quarks, the charm and strange quark (c, s), and the top and bottom quark (t, b). The leptons are also grouped into three generations. These are the electron, muon, and tauon, each with a corresponding neutrino. For each fermion a corresponding antiparticle exists with the same mass and opposite charge.

The gauge bosons have an integer spin and mediate the interactions between the fermions. The photon is the mediator of the electromagnetic interaction that can couple to all particles with an electromagnetic charge, e.g., the electron or the quarks. More details on the electromagnetic interaction are given in section 1.2. The gluon mediates the strong interaction and couples to the color charge of the quarks, but contrary to the photon, the gluon also carries a charge and an anticharge, so that also a gluon-gluon coupling is possible. The theory of the strong interaction is described in more detail in section 1.1. The weak interaction couples to all fermions and is mediated by three gauge bosons, the Z^0 and the $W^\pm$ bosons. In contrast to the massless gluons and the photon, the Z^0 and $W^\pm$ bosons are massive with masses of

$m_Z = (91.188 \pm 0.002) \text{ GeV}/c^2$ and $m_W = (80.369 \pm 0.012) \text{ GeV}/c^2$ [Nav⁺24]. This can be explained by the spontaneous symmetry breaking in the electroweak theory, which is a unification of the electromagnetic and weak interaction. This symmetry breaking leads to the Higgs field and the Higgs boson. The gauge bosons of the weak interaction couple to the Higgs field and thus gain mass [Pov⁺13]. The Higgs boson was the latest addition to the standard model and was discovered in 2012 by the ATLAS and CMS collaborations at the LHC [Aad⁺12, Cha⁺12].

Quarks				mass	
	$2.16(7) \frac{\text{MeV}}{c^2}$ u +2/3 1/2	$1.273(5) \frac{\text{GeV}}{c^2}$ c +2/3 1/2	$172.6(3) \frac{\text{GeV}}{c^2}$ t +2/3 1/2	$0 \frac{\text{eV}}{c^2}$ g 0 1	$125.20(11) \frac{\text{GeV}}{c^2}$ H 0 1
	$4.70(7) \frac{\text{MeV}}{c^2}$ d -1/3 1/2	$93.5(8) \frac{\text{MeV}}{c^2}$ s -1/3 1/2	$4.183(7) \frac{\text{GeV}}{c^2}$ b -1/3 1/2	$< 10^{-18} \frac{\text{eV}}{c^2}$ γ 0 1	charge spin
	$0.511 \frac{\text{MeV}}{c^2}^*$ e -1 1/2	$105.66 \frac{\text{MeV}}{c^2}^{**}$ μ -1 1/2	$1776.93(9) \frac{\text{MeV}}{c^2}$ τ -1 1/2	$91.188(2) \frac{\text{GeV}}{c^2}$ Z^0 0 1	
	$< 0.8 \frac{\text{eV}}{c^2}$ ν_e 0 1/2	$< 0.19 \frac{\text{MeV}}{c^2}$ ν_μ 0 1/2	$< 18.2 \frac{\text{MeV}}{c^2}$ ν_τ 0 1/2	$80.369(14) \frac{\text{GeV}}{c^2}$ $W^\pm$ ± 1 1	Gauge Bosons

* $m(e) = 0.510\,998\,950\,00(15) \text{ MeV}/c^2$
 ** $m(\mu) = 105.658\,375\,5(23) \text{ MeV}/c^2$

Figure 1.1: The standard model of particle physics divides the fundamental particles into fermions and bosons. The fermions consist of the quarks (green) that form hadrons and the leptons (blue) which are each grouped into three generations, arranged in the first three columns of the model. The interaction between these fermions is mediated by the gauge bosons (magenta). The gluon g mediates the strong interaction, the photon γ the electromagnetic interaction, and the Z^0 and $W^\pm$ bosons the weak interaction. The Higgs boson H is responsible for the mass of the particles. The mass, charge, and spin of the particles are given in the figure [Nav⁺24].

1.1 Quantum Chromodynamics (QCD)

The Quantum ChromoDynamics (QCD) describes the interaction between quarks and gluons mediated by the strong force and thus explains how protons and neutrons, for example, are formed. This interaction couples to a charge with three charge states [Gre64, HN65]. This is called the color charge with the colors red, green, and blue and corresponding anticharges. It is described by a non-Abelian gauge theory with local $SU(3)$ color symmetry. The QCD Lagrangian is given by [AH12, Nav⁺24]

$$\mathcal{L}_{\text{QCD}} = \sum_f \bar{q}_f^a (i\gamma^\mu D_\mu^{ab} - m_f \delta^{ab}) q_f^b - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu}, \quad (1.1)$$

where it is summed over repeated indices. The sum index denotes to the six quark flavors ($f = u, d, s, c, b, t$), q_f^a are the quark-field spinors with the color index $a = 1, 2, 3$, and m_f is the quark mass. The covariant derivative is defined as

$$D_\mu^{ab} = \partial_\mu \delta^{ab} + ig_s \frac{1}{2} \lambda_c^{ab} A_\mu^c \quad (1.2)$$

and the gluonic field tensors are given by

$$F_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f^{abc} A_\mu^b A_\nu^c \quad (1.3)$$

with the QCD coupling constant g_s . The eight generators λ_c^{ab} of the $SU(3)$ group are connected to the structure constants f^{abc} via

$$[\lambda_a, \lambda_b] = i f^{abc} \lambda_c. \quad (1.4)$$

The coupling constant can also be expressed as

$$\alpha_s = \frac{g_s^2}{4\pi}. \quad (1.5)$$

Using the QCD framework with a proper renormalization, the coupling constant turns out to be dependent on the momentum transfer Q as

$$\alpha_s(Q) = \frac{4\pi}{\beta_0 \ln(Q^2/\Lambda_{\text{QCD}}^2)} \quad (1.6)$$

with the 1-loop result $\beta_0 = 11 - \frac{2}{3}n_f$, the number of quark flavors n_f [Nav⁺24] and the QCD scale $\Lambda_{\text{QCD}} \approx 250 \text{ MeV}/c$. Consequently, perturbation theory can only be applied for $\alpha_s \ll 1$ and thus for $Q^2 \gg \Lambda_{\text{QCD}}^2$ [Pov⁺13]. This region, where the coupling

becomes weak, is also known as asymptotic freedom as the quarks can be assumed as quasi-free particles [Nav⁺24]. In contrast, the coupling becomes strong for small momentum transfers, which leads to the confinement of quarks, so that quarks cannot be observed as free particles but only in color-neutral states. This is also expressed by the potential

$$V(r) = -\frac{4}{3} \frac{\alpha_s(r) \hbar c}{r} + kr \quad (1.7)$$

that includes a Coulomb-like term and a linear term. The linear term leads to an increasing energy when increasing the distance between two quarks. Instead of separating them completely the required energy becomes so large, that instead a new quark-antiquark pair is created [Pov⁺13].

Hadrons

Due to the confinement, quarks cannot be observed as free particles, instead they are bound in color-neutral states called hadrons. The QCD predicts several classes of hadrons. The most prominent examples of hadrons are protons and neutrons that belong to the baryons. These consist of three quarks, or three antiquarks in the case of antibaryons, like the proton consisting of two up- and one down quark. The three quarks together carry all three color charges and the baryons are thus color-neutral. Besides the lightest baryons, the proton and the neutron, there are also heavier baryons that either include heavier quarks like the Λ^0 that consists of an up, a down, and a strange quark, or excited baryons like the Δ^+ resonance that has the same quark content as the proton but with a total spin of 3/2 instead of 1/2 [Nav⁺24].

The other conventional class of hadrons are the mesons that consist of a quark-antiquark pair that carries a charge and the corresponding anticharge. Prominent examples are the pions, e.g., the π^+ that consists of an up- and an antidown quark. Additionally, heavier mesons exist that include heavier quarks like kaons that have a strange (anti-)quark or the charmonia that consist of a charm-anticharm pair [Nav⁺24].

Besides these conventional hadrons, also exotic hadrons are predicted and searched for in multiple experiments. These include bound states of gluons, called glueballs, which are possible due to the self-interaction of gluons. Furthermore, hybrid mesons with an excited gluon are predicted, as well as tetraquarks with two quarks and two antiquarks, where several candidates were already found [Nav⁺24]. Additionally, pentaquarks with four quarks and an antiquark are possible with the first candidate observed by the LHCb collaboration [Aai⁺15].

1.2 Quantum Electrodynamics (QED)

The electromagnetic interaction is theoretically described by Quantum ElectroDynamics (QED). This is a gauge theory with local $U(1)$ symmetry. The QED Lagrangian is given by [Mün19, PS95]

$$\mathcal{L}_{\text{QED}} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (1.8)$$

with the spinors ψ of the fermions and their mass m . The covariant derivative is defined as

$$D_\mu = \partial_\mu + iqA_\mu \quad (1.9)$$

with the electromagnetic vector potential A_μ , which is connected to the field tensor

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu. \quad (1.10)$$

This Lagrangian is invariant under the transformation

$$\psi(x) \rightarrow e^{iq\alpha(x)}\psi(x) \quad (1.11)$$

$$A_\mu(x) \rightarrow A_\mu(x) + \partial_\mu\alpha(x) \quad (1.12)$$

where the transformation parameter $\alpha(x)$ is a function of x and thus describes a local transformation [Mün19]. Contrary to the QCD, the QED can be described perturbatively with the coupling constant $\alpha_{em} \approx 1/137$. This makes predictions for the electromagnetic interaction very precise and allows for a comparison with experimental data [Mün19]. This enables precision tests of the standard model like the measurement of the anomalous magnetic moment of the muon [Agu⁺24] and its comparison to standard model predictions [Aoy⁺20]. QED is also an important tool to calculate radiative corrections that are needed for the interpretation of experimental data, e.g., in electron-proton scattering, which will be discussed in the following.

1.3 Elastic Electron-Proton Scattering

Within the physics program of MAGIX, the elastic electron-proton scattering plays an important role in the measurement of the proton radius. Such measurements were also performed within this thesis at the A1 experiment, and thus the cross section of this process will be discussed, followed by a description of radiative corrections. Within this section, natural units are used, i.e., $\hbar = c = 1$.

The measurements described in section 7.2 are performed at a fixed-target experiment. Therefore, an incoming electron with four-momentum vector $k = (E, \vec{k})$ scatters on a target proton at rest with the proton four-momentum $p = (m_p, \vec{0})$ to a final state with four-momentum $k' = (E', \vec{k}')$. This process is shown in figure 1.2.

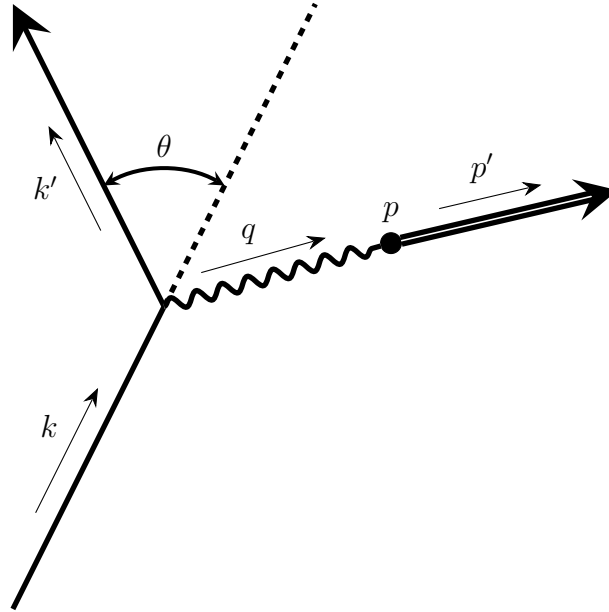


Figure 1.2: Elastic electron-proton scattering with an incoming electron (k) and a proton at rest (p) that scatters to a final state with four-momenta k' and p' via a virtual photon with four-momentum transfer q . The angle between the incoming and outgoing electron is the scattering angle θ (figure from [Bra19], based on [Ber10]).

Conservation of the total four-momentum under the assumption of a highly relativistic electron ($E \approx |\vec{k}|$, $E \gg m_e$) leads to the relation

$$q^2 = (k - k')^2 = -4EE' \sin^2(\theta/2) < 0, \quad (1.13)$$

where θ is the scattering angle. This value is always negative and thus the positive quantity $Q^2 = -q^2$ is introduced. Furthermore, energy and momentum conservation also lead to the relation

$$E' = \frac{E}{1 + \frac{2E}{m_p} \sin^2(\theta/2)} \quad (1.14)$$

for the energy of the scattered electron [Pov⁺13].

The cross section of the elastic electron-proton scattering can be approximated from QED in the lowest order by the amplitude [Pun⁺15]

$$i\mathcal{M} = -\frac{ig_{\mu\nu}}{q^2} \ell^\nu \mathcal{J}^\mu \quad (1.15)$$

with the leptonic current

$$\ell^\nu = ie\bar{u}(k')\gamma^\nu u(k) \quad (1.16)$$

and the hadronic current

$$\mathcal{J}^\mu = -ie\bar{v}(p') \left[\gamma^\mu F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2m_p} \kappa_p F_2(Q^2) \right] v(p) \quad (1.17)$$

with the anomalous magnetic moment $\kappa_p \approx 2.7928$ [Nav⁺24] of the proton in units of the nuclear magneton $\mu_N = e\hbar/(2m_p)$ and the Dirac and Pauli form factors F_1 and F_2 that describe the structure of the proton. From this amplitude, the differential elastic electron-proton cross section in the lab frame can be calculated as

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_{\text{Mott}} [F_1^2 + \tau(\kappa_p F_2)^2 + 2\tau(F_1 + \kappa_p F_2)^2 \tan^2(\theta/2)] \quad (1.18)$$

with $\tau = Q^2/(4m_p^2)$ [Pun⁺15] and the Mott cross section

$$\left(\frac{d\sigma}{d\Omega} \right)_{\text{Mott}} = \frac{4Z^2 Z'^2 \alpha_{em}^2 E'^2}{Q^4} \frac{E'}{E} (1 - \beta^2 \sin^2(\theta/2)) \quad (1.19)$$

with the charges $Z^2 = Z'^2 = 1$ of the electron and proton, the fine-structure constant α_{em} , and the electron velocity $\beta = v/c$ [Pov⁺13]. By using the Sachs form factors

$$G_E(Q^2) = F_1(Q^2) - \tau \kappa_p F_2(Q^2) \quad (1.20)$$

$$G_M(Q^2) = F_1(Q^2) + \kappa_p F_2(Q^2) \quad (1.21)$$

the cross section can be simplified to

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \left(\frac{\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)}{\epsilon(1 + \tau)} \right) \quad (1.22)$$

with

$$\epsilon = \frac{1}{1 + 2(1 + \tau) \tan^2(\theta/2)} \quad (1.23)$$

being the polarization of the virtual photon [Pun⁺15]. These form factors are normalized by $G_E(0) = 1$ and $G_M(0) = \kappa_p$. In the Breit frame ($\vec{p} = -\vec{p}'$, $q = (0, \vec{q})$),

the Sachs form factors can be interpreted as the Fourier transform of the charge and magnetization distribution of the proton [Ber10]. By expanding the Fourier transform

$$\begin{aligned}
 G(Q^2)/G(0) &= \int \rho(r) e^{-i\vec{q}\cdot\vec{r}} d^3r = 4\pi \int_0^\infty r^2 \rho(r) \frac{\sin(|\vec{q}|r)}{|\vec{q}|r} dr \\
 &= 4\pi \int_0^\infty r^2 \rho(r) \left(1 - \frac{(|\vec{q}|r)^2}{6} + \frac{(|\vec{q}|r)^4}{120} \mp \dots \right) dr \\
 &= 1 - \frac{Q^2}{6} \langle r^2 \rangle + \frac{Q^4}{120} \langle r^4 \rangle \mp \mathcal{O}(Q^6)
 \end{aligned} \tag{1.24}$$

into a power series, the proton charge radius or magnetic radius

$$\langle r_{E,M}^2 \rangle = - \frac{6}{G_{E,M}(0)} \left. \frac{dG_{E,M}}{dQ^2} \right|_{Q^2=0} \tag{1.25}$$

can be extracted from the slope of the form factor at $Q^2 = 0$ [Ber10, Sic18]. Thus, the form factor needs to be precisely known at $Q^2 = 0$. However, $Q^2 = 0$ corresponds to no scattering and the cross section cannot be measured here. Instead, the cross section is determined for the smallest possible momentum transfer and then extrapolated. This is especially challenging for the magnetic form factor as its contribution decreases with $\tau \propto Q^2$.

1.3.1 Radiative Corrections

The previously discussed cross section of the elastic electron-proton scattering is calculated in first order Born approximation. However, in the analysis of the experimental data also higher orders need to be considered. These radiative corrections result in leading order in a correction of the cross section given by

$$\left(\frac{d\sigma}{d\Omega} \right)_1 = \left(\frac{d\sigma}{d\Omega} \right)_0 (1 + \delta) \tag{1.26}$$

where the contributions to the correction factor δ are discussed in the following [Ber10].

These corrections include processes with an additional virtual photon (see figure 1.3) and with an additional real photon (see figure 1.4). The vacuum polarization shown in graph (a1) in figure 1.3 leads to [Van⁺00]

$$\delta_{\text{vac}} = \frac{\alpha_{em}}{\pi} \frac{2}{3} \left[\left(v^2 - \frac{8}{3} \right) + v \frac{3 - v^2}{2} \ln \left(\frac{v + 1}{v - 1} \right) \right] \tag{1.27}$$

with $v^2 = 1 + 4m_l^2/Q^2$ and the mass m_l of the particle inside the loop. Graph (a2) leads to an electron vertex correction [Van⁺00]

$$\delta_{\text{vertex}} = \frac{\alpha_{em}}{\pi} \left[\frac{3}{2} \ln \left(\frac{Q^2}{m_e^2} \right) - 2 - \frac{1}{2} \ln^2 \left(\frac{Q^2}{m_e^2} \right) + \frac{\pi^2}{6} \right]. \quad (1.28)$$

Furthermore, graphs (b1) and (b2) in figure 1.4 lead to the real photon emission correction [Van⁺00]

$$\delta_R = \frac{\alpha_{em}}{\pi} \left[\ln \left(\frac{(\Delta E_s)^2}{E \cdot E'} \right) \left[\ln \left(\frac{Q^2}{m_e^2} \right) - 1 \right] - \frac{1}{2} \ln^2 \eta + \frac{1}{2} \ln^2 \left(\frac{Q^2}{m^2} \right) - \frac{\pi^2}{3} + \text{Sp}(\cos^2(\theta/2)) \right] \quad (1.29)$$

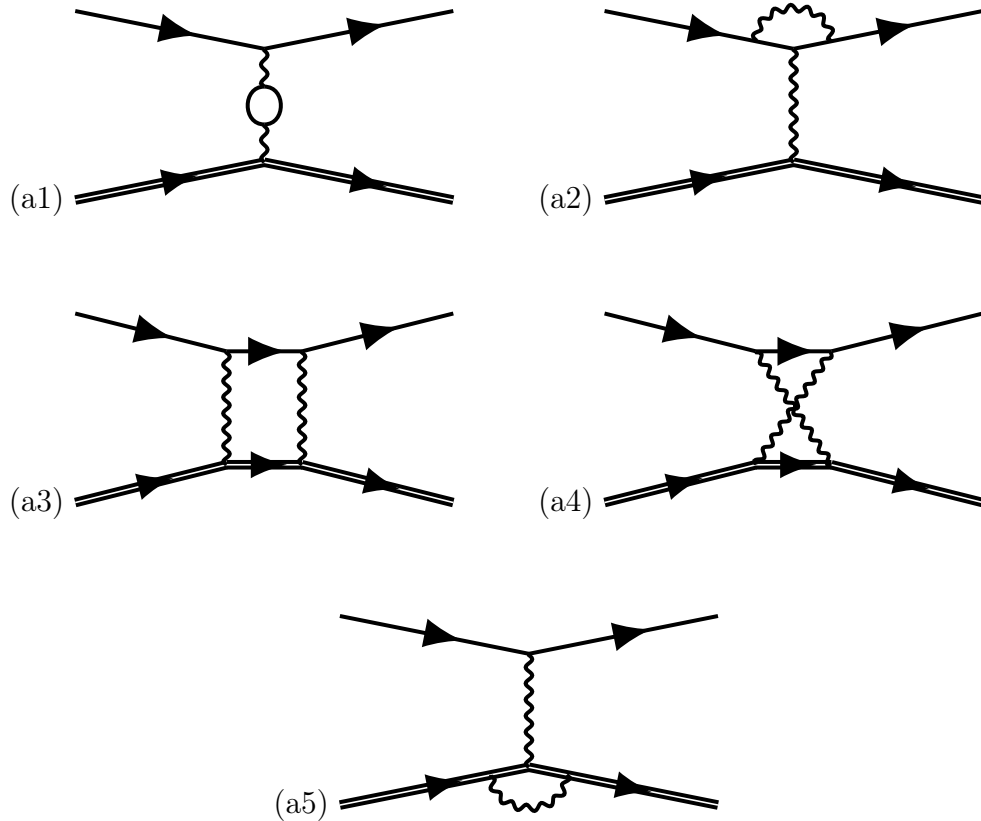


Figure 1.3: Feynman graphs for next to leading order corrections including a virtual photon. The shown effects are vacuum polarization (a1), vertex correction (a2 and a5), and the exchange of two virtual photons (a3 and a4) (figure from [Bra19], based on [Ber10], edited).

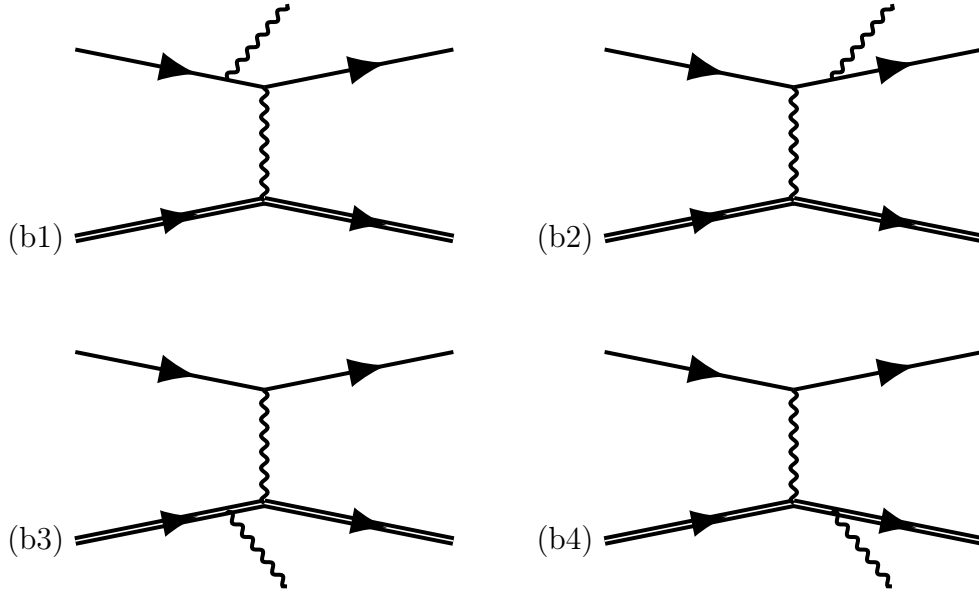


Figure 1.4: Feynman graphs for next to leading order corrections including a radiated real photon radiated off the electron (b1 and b2) or the proton (b3 and b4) (figure from [Bra19], based on [Ber10], edited).

with $\eta = E/E'$, $\Delta E_s = \eta \cdot \Delta E'$, the energy E' of the scattered electron without emission of a photon, and the cut-off energy $\Delta E'$ for the radiative tail, which is the maximum energy difference allowed to the energy E' . The Spence function is defined as [Van⁺00]

$$\text{Sp}(x) = - \int_0^x \frac{\ln(1-t)}{t} dt. \quad (1.30)$$

Due to the internal structure of the protons the corrections on the proton side (a3, a4, b3, b4) are more complex. They can be divided into a part proportional to Z (δ_1) and to Z^2 (δ_2). Contributions that are structure dependent can be neglected in case of the experiments presented here [Ber10]. The corrections are given by [MT00, Van⁺00]

$$\delta_1 = \frac{2\alpha_{em}}{\pi} \left[\ln \left(\frac{4(\Delta E_s)^2}{Q^2 x} \right) \ln \eta + \text{Sp} \left(1 - \frac{\eta}{x} \right) - \text{Sp} \left(1 - \frac{1}{\eta x} \right) \right] \quad (1.31)$$

and

$$\begin{aligned} \delta_2 = \frac{\alpha_{em}}{\pi} & \left[\ln \left(\frac{4(\Delta E_s)^2}{m_p^2} \right) \left(\frac{E'_p}{|\vec{p}'|} \ln x - 1 \right) + 1 \right. \\ & + \frac{E'_p}{|\vec{p}'|} \left(-\frac{1}{2} \ln^2 x - \ln x \ln \left(\frac{\rho^2}{m_p^2} \right) + \ln x \right. \\ & \left. \left. - \text{Sp} \left(1 - \frac{1}{x^2} \right) + 2 \text{Sp} \left(-\frac{1}{x} \right) + \frac{\pi^2}{6} \right) \right] \end{aligned} \quad (1.32)$$

with

$$x = \frac{(Q + \rho)^2}{4m_p^2} \quad \text{and} \quad \rho^2 = Q^2 + 4m_p^2. \quad (1.33)$$

A more precise correction is given when exponentiating these corrections leading to

$$\left(\frac{d\sigma}{d\Omega} \right)_1 = \left(\frac{d\sigma}{d\Omega} \right)_0 e^{\delta_{\text{vac}} + \delta_{\text{vertex}} + \delta_R + \delta_1 + \delta_2}, \quad (1.34)$$

which is thus included in the simulation framework used for the analysis of the data from the A1 experiment in section 7.2 [Ber10].

Not fully included are the effects of Coulomb distortion and two photon exchange. The latter is relevant mainly at larger Q^2 and is neglected here. The Coulomb distortion is the scattering via multiple soft photons. This effect can be described by [Tsa61]

$$\delta = Z\alpha_{em}\pi \frac{\sin(\theta/2) - \sin^2(\theta/2)}{\cos^2(\theta/2)}. \quad (1.35)$$

It is corrected for in the analysis by an additional factor of $(1 + \delta)$ to the theoretical cross section in equation 1.22 [Ber10].

Chapter 2

The $\overline{\text{P}}$ ANDA Experiment at FAIR

There are still open questions in the standard model of particle physics as, e.g., the existence of predicted exotic states like glueballs or tetraquarks. To answer these questions new facilities with unique properties like higher precision and higher interaction rate are needed. One of these is currently under construction as an extension of the existing facility of the GSI Helmholtzzentrum für Schwerionenforschung GmbH in Darmstadt, Germany. This new facility is called Facility for Antiproton and Ion Research (FAIR) and will enable a wide range of new experiments, including the $\overline{\text{P}}$ ANDA experiment. This chapter provides an overview of the accelerator facility of GSI and FAIR, and the $\overline{\text{P}}$ ANDA experiment with the $\overline{\text{P}}$ ANDA cluster-jet target that is the main focus of this work.

2.1 The Facility for Antiproton and Ion Research (FAIR)

The accelerator complex of GSI and FAIR in figure 2.1 will deliver high quality beams of all species of ions and antiprotons for several experiments. Therefore, all the existing systems have to be upgraded and new state-of-the-art accelerators and storage rings are under construction. All ions up to uranium can be accelerated with the existing GSI-UNIversal Linear ACcelerator (UNILAC) up to energies of 1.4 MeV/u and beam currents of up to 15 emA for U^{28+} ions [Bar⁺22]. Although the UNILAC is able to pre-accelerate all ions from protons to uranium, it is not designed to reach the necessary intensity of a proton beam needed for FAIR's antiproton program. These intense proton beams will be delivered by the new p-LINAC that is designed for the pre-acceleration of protons with a final energy of 68 MeV and a beam current of 70 mA [Bro⁺15, Spi⁺18].

After leaving the UNILAC or p-LINAC, the ions are guided into the existing SIS18 synchrotron with a circumference of 216 m. Its name originates from the maximum

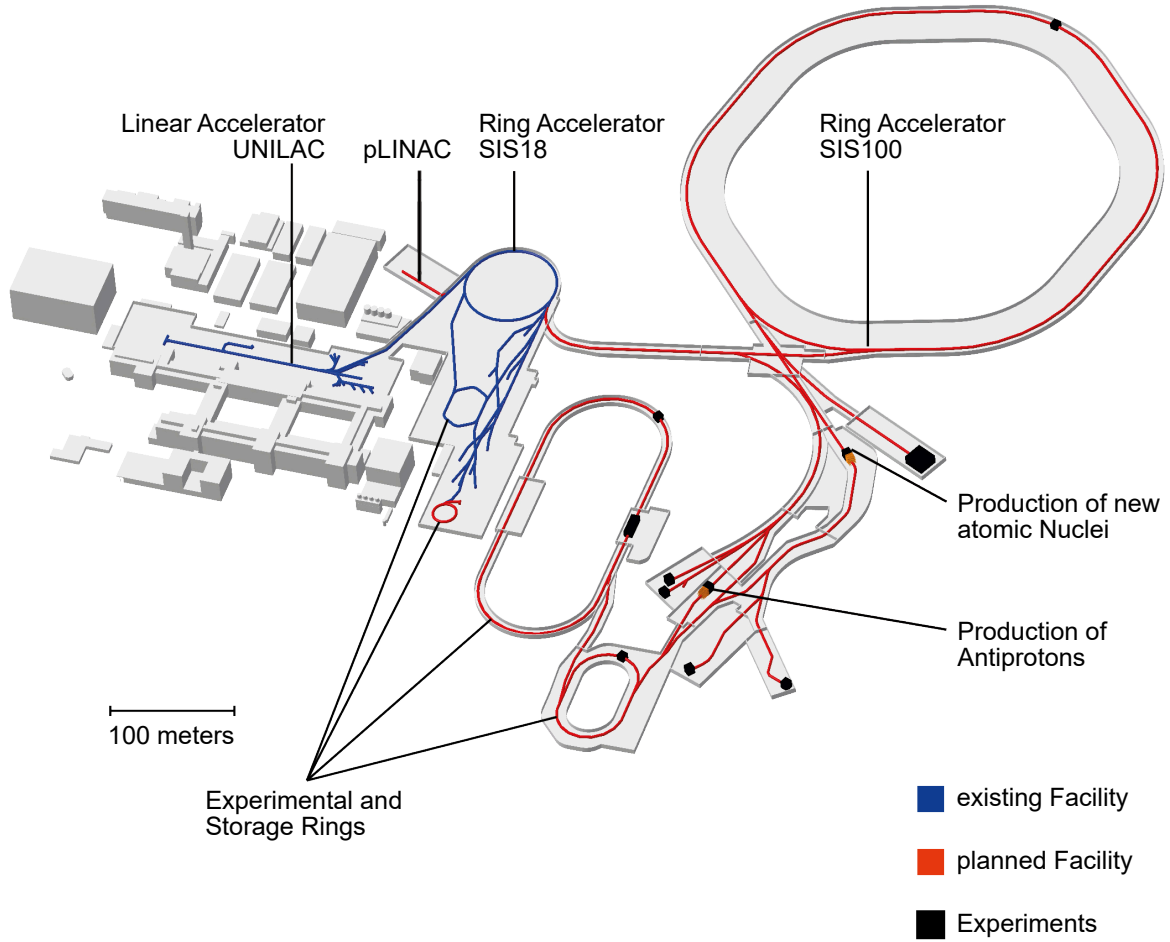


Figure 2.1: Schematic overview of the existing GSI complex (red) and the future FAIR facility (blue). The $\bar{\text{P}}\text{ANDA}$ experiment is located at the HESR (copyright by GSI/FAIR, edited).

magnetic rigidity of 18.5 Tm that allows for energies of up to 200 MeV/u for U^{28+} ions and 4.7 GeV for protons. Between the end of 2016 and mid 2018, the SIS18 was shut down for an upgrade of the building and infrastructure for the high intensities that will be reached at FAIR [Ond⁺19]. Afterwards, the particles can be guided into the existing Experimental Storage Ring (ESR) of the GSI facility [Fra87] or into the SIS100 at the new FAIR facility.

The superconducting SIS100 synchrotron will be the main accelerator of the FAIR facility that will deliver high intensity beams of all ions from protons to Uranium [Spi⁺20]. The ring will have a circumference of 1100 m [Spi⁺23] and the superconducting magnets will achieve a maximum magnetic rigidity of 100 Tm [FKK08]. This will allow for beam energies of up to 29 GeV for protons or 2.7 GeV/u to 10 GeV/u for Uranium depending on the charge state (U^{28+} to U^{92+}) [Spi⁺20].

Following the SIS100, the particles are guided through different beam lines towards the different experiments at FAIR, which are grouped into four experimental pillars [Dur⁺19]:

- The APPA (Atomic, Plasma Physics, and Applications) pillar consists of several collaborations that share experimental installations like the APPA cave. The atomic part of APPA is separated into the collaborations of SPARC (Stored Particles Atomic physics Research Collaboration) and FLAIR (Facility for Low-energy Antiproton and Ion Research). SPARC will study, e.g., atomic matter in extreme electromagnetic fields and ultrafast electromagnetic interactions to test the non-perturbative bound-state QED. The focus of FLAIR is the study of antihydrogen and antiprotonic atoms, e.g., for checks of the CPT invariance. The research in plasma physics is covered by the HEDgeHOB and WDM collaborations, which focus on matter under extreme conditions in unexplored regions of the phase diagram. Further research topics are biophysics and materials science that is addressed by the BIOMAT collaboration. Here, topics like radiotherapy with high-energy ions or the radiation hardness of materials under extreme radiation conditions are studied [Stö⁺15].
- The CBM (Compressed Baryonic Matter) collaboration will focus on heavy-ion collisions at high energies to study the phase diagram of nuclear matter. This experiment is complementary to the experiments at LHC and RHIC, since CBM will explore the phase diagram at high baryon chemical potentials and lower temperatures in a fixed-target experiment, a region where the core of neutron stars and binary neutron star mergers can be found [Aga23].
- The NUSTAR (NUclear STructure, Astrophysics, and Reactions) collaboration will use radioactive ion beams to study questions regarding nuclear structure and astrophysics. Therefore, FAIR's Super-FRS, a superconducting fragment separator, will be used to get beams of heavy, exotic nuclei without charge-state ambiguities, which are then guided to different experimental areas. Here, studies on, e.g., the dependence of the nuclear-force on proton-neutron ratios or the limits of existence of exotic nuclei will be performed [Nil15].
- The $\bar{\text{P}}\text{ANDA}$ (antiProton ANnihilation at DArmstadt) experiment will analyze antiproton-proton and antiproton-nucleus reactions to study the nucleon structure, strangeness physics, charmonia and exotics, and hadrons in nuclei [Bar⁺21]. Since $\bar{\text{P}}\text{ANDA}$ is the main topic of this thesis, more information follow in section 2.4.

2.2 Antiproton Production and the HESR

For the rich experimental program of $\overline{\text{PANDA}}$ mainly collisions of antiprotons and protons will be analyzed. The needed antiprotons will be produced by bombarding a solid target with a high-energy proton beam from the SIS100. The antiprotons are then produced via $p\bar{p}$ pair creation during the interaction of a high-energy proton with a target nucleon:

$$p + p \rightarrow p + p + p + \bar{p} . \quad (2.1)$$

Therefore, the kinetic energy of the beam proton in the laboratory system has to fulfill $E_{\text{kin}} \geq 6m_p c^2 \approx 5.6 \text{ GeV}$. At FAIR, the maximum proton beam energy of the SIS100 (29 GeV) will be used for the antiproton production and $2.5 \cdot 10^{13}$ protons will hit the target every 10 s in a 50 ns bunch. Created antiprotons with about 3 GeV in an 80 mrad cone will be collected by a magnetic horn [Kni⁺12]. Simulations show, that with an 11 cm long copper or nickel target a maximum yield of $2 \cdot 10^{-5}$ antiprotons per primary proton is expected in the antiproton separator acceptance leading to the production of $5 \cdot 10^8$ antiprotons every 10 s [Dol⁺11].

Afterwards, the antiprotons are guided into the Collector Ring (CR), where they are cooled and accumulated. The longitudinal and transversal cooling is performed by a stochastic cooling that reduces the emittance by a factor of nearly 50 and the momentum spread (2σ) from $\Delta p/p = 3\%$ at injection to 0.1% at extraction after rebunching. This is achieved by additionally using a low quadrupole ramping to increase the cooling performance, so that it fits into the acceptance of 0.12% of the cooling system at the following High Energy Storage Ring (HESR). The rebunching is necessary because of the barrier bucket system at the HESR that will be used to compensate energy losses induced by the target system. Additionally, the CR is also foreseen for collecting and cooling of radioactive ion beams coming from the Super-FRS [Dol⁺15]. There is an additional ring around the CR, called Recycled Experimental Storage Ring (RESR) where the pre-cooled antiprotons from the CR can be accumulated before injecting them into the HESR, which will increase the maximum number of stored antiprotons in the HESR [Gut06].

The $\overline{\text{PANDA}}$ experiment will be located at the HESR, which is shown in figure 2.2. It will have a circumference of 574 m with two straight sections of 132 m each. Here, the antiprotons from the CR or RESR will be injected with a momentum of 3.8 GeV/c. They are then accelerated or decelerated to momenta between 1.5 GeV/c and 15 GeV/c by an RF cavity that will also be operated as barrier bucket cavity to compensate for energy loss due to beam-target interaction. This corresponds to a maximum revolution frequency of 0.522 MHz. Additionally, the HESR is equipped with a stochastic cooling

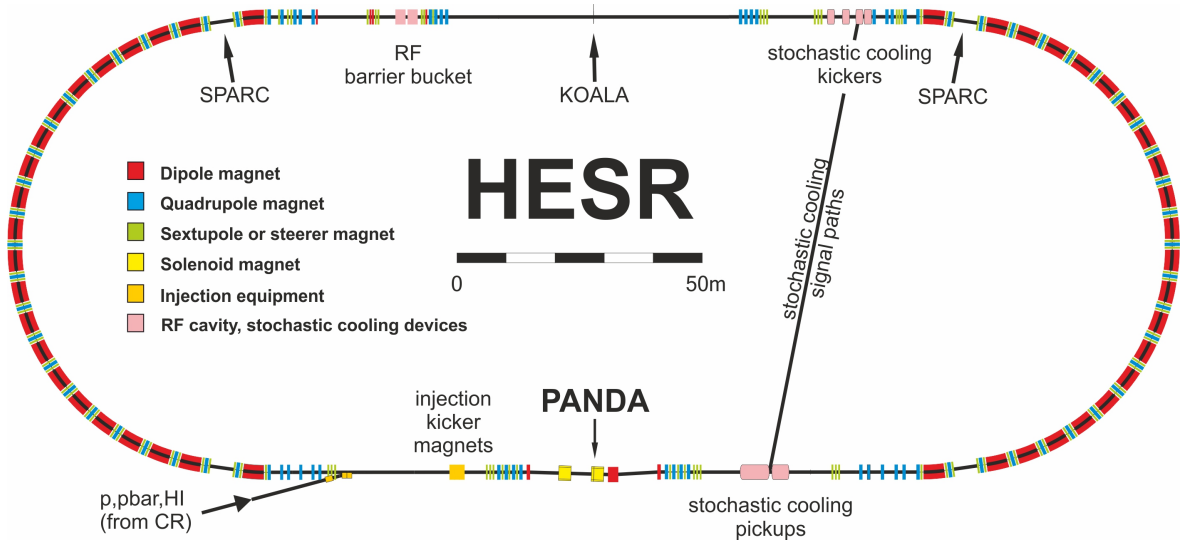


Figure 2.2: Schematic overview of the High Energy Storage Ring. The antiprotons are injected from the CR (or RESR) from the bottom left and are then accelerated or decelerated by the RF at the upper straight section, that also operates as barrier bucket cavity. Additionally, there are pickups and kickers of the stochastic cooling on opposite sides of the HESR. The PANDA experiment will be located at the lower straight section. On the other side, there will be the KOALA experiment (copyright by PANDA).

system with the kicker and pickup tanks located in the two straight sections. More on the stochastic cooling system is discussed in section 4.2. The magnetic lattice of the HESR is built up by 48 dipoles, 112 quadrupoles, 48 sextupoles, and two additional dipoles following the PANDA experiment to bend the beam back onto the desired orbit after it was deflected in the dipole of the PANDA forward spectrometer (see section 2.4). All these systems will allow the HESR to operate in two different modes, the High Resolution (HR) and the High Luminosity (HL) mode [Gut06]. Their properties are summarized in table 2.1.

Table 2.1: Properties of the High Resolution (HR) and the High Luminosity (HL) mode at the HESR [Gut06, PAN12a, Sto⁺06].

		HR	HL
stored Antiprotons		$1 \cdot 10^{10}$	$1 \cdot 10^{11}$
Luminosity	$[\text{cm}^{-2} \text{s}^{-1}]$	$2 \cdot 10^{31}$	$2 \cdot 10^{32}$
Momentum Range	$[\text{GeV}/c]$	$1.5 - 8.9$	$1.5 - 15$
Frequency Range	$[\text{MHz}]$	$0.442 - 0.520$	$0.442 - 0.522$
Momentum Spread σ_p/p		$4 \cdot 10^{-5}$	$1 \cdot 10^{-4}$
required Target Thickness	$[\text{atoms}/\text{cm}^2]$	$4.5 \cdot 10^{15}$	$4.5 \cdot 10^{15}$

There are several experiments foreseen for the HESR. Two of them are connected to the $\overline{\text{PANDA}}$ experiment. One is the $\overline{\text{PANDA}}$ experiment itself, which is described in more detail in sections 2.3 and 2.4. The other one is the KOALA experiment, which will be located at the opposite straight section of the HESR. KOALA (Key experiment fOr the $\overline{\text{PANDA}}$ Luminosity determinAtion) aims to measure the elastic pp and $p\bar{p}$ cross section precisely in a range of $0.0008 (\text{GeV}/c)^2$ to $0.1 (\text{GeV}/c)^2$ of the momentum transfer $|t|$ [Hu⁺14, Zho⁺21]. This is an important input for the luminosity determination at $\overline{\text{PANDA}}$, since the luminosity detector will measure the elastic $p\bar{p}$ scattering under very forward angles and needs a precise knowledge of the cross section to determine the luminosity [PAN18d].

2.3 The Physics Program of $\overline{\text{PANDA}}$

The $\overline{\text{PANDA}}$ experiment makes use of the unique HESR antiproton beam with its high precision and intensity. Furthermore, the momentum range of $1.5 \text{ GeV}/c$ to $15 \text{ GeV}/c$ allows for a wide range of physics topics to be studied including the production of charmonia and baryons with charm and strange content [PAN09a]. Using $p\bar{p}$ annihilation also has the advantage of not being restricted to the quantum numbers $J^{PC} = 1^{--}$ like in electron-positron annihilation so that also states with other quantum numbers can be generated in direct formation and not only by a suppressed production with other recoil particles. Additionally, baryons with strange and charm content can be produced pairwise in two-body reactions ($p\bar{p} \rightarrow B_1 \bar{B}_2$). Especially for multi-strange hyperons, other reactions would require the corresponding number of kaons to ensure strangeness conservation, while at $\overline{\text{PANDA}}$ these hyperons can also be produced pairwise in two-body reactions leading to much cleaner detection. At last, the annihilation is also a very gluon-rich process that favors the formation of states with gluonic content like glueballs or hybrids. All these aspects result in the very broad physics program of the $\overline{\text{PANDA}}$ experiment that can be divided into four pillars: nucleon structure, strangeness physics, charmonia and exotics, and hadrons in nuclei [Bar⁺21].

Nucleon Structure

While QCD can be treated perturbatively at high energies, the running coupling α_s gets larger for small energies so that a perturbative prediction is not possible (see section 1.1). This makes predictions in the regime of lower energies, where hadrons form, very challenging. To gain a deeper insight into the strong interaction in this region, the nucleon structure needs to be determined more precisely. This includes

parton distributions and electromagnetic form factors. At $\overline{\text{PANDA}}$ the electromagnetic form factors can be accessed in the time-like region ($q^2 > 0$) by studying, e.g., the reactions $p\bar{p} \rightarrow e^+e^-$ or $p\bar{p} \rightarrow \mu^+\mu^-$ for $q^2 > 4m_p^2$ or $p\bar{p} \rightarrow e^+e^-\pi^0$ for $0 < q^2 < 4m_p^2$. Furthermore, $\overline{\text{PANDA}}$ can also access the inner structure of the nucleon on the partonic level. It can, e.g., study the πN Transition Distribution Amplitudes (TDA) in reactions like $p\bar{p} \rightarrow \gamma\pi^0 \rightarrow e^+e^-\pi^0$ or $p\bar{p} \rightarrow J/\psi \pi^0 \rightarrow e^+e^-\pi^0$ or the Generalized Distribution Amplitudes (GDA) by hard exclusive reactions like $p\bar{p} \rightarrow \gamma\gamma$ or $p\bar{p} \rightarrow \gamma M$ with M being a pseudo-scalar or vector meson like π^0 , η , ρ^0 , or ϕ [Bar⁺21].

Strangeness Physics

This pillar of the $\overline{\text{PANDA}}$ physics program focuses on experiments with hyperons, which are baryons with at least one strange quark. The pair-wise production of hyperons is the cleanest way to provide experimental data for the development of phenomenological models that will help the theory to improve their understanding of QCD in the non-perturbative regime. Furthermore, spin observables are accessible in hyperon decays which can be used to study CP violation and to search for physics beyond the standard model. Additionally, the understanding of hyperon production reactions like $p\bar{p} \rightarrow Y\bar{Y}$ is also an important input for the fourth pillar, Hadrons in Nuclei [Bar⁺21].

Charmonia and Exotics

The third topic of the $\overline{\text{PANDA}}$ experimental program is the study of charmonia and charmonium-like states. This region is explored by many experiments like, e.g., the BESIII experiment that produces charmonia in electron-positron annihilation via the reaction $p\bar{p} \rightarrow \gamma^* \rightarrow c\bar{c}$ [Yua21]. The direct formation in such an e^+e^- collider is limited to $J^{PC} = 1^{--}$ due to the virtual photon. Other states can only be accessed by higher order processes like two-photon production. In contrast to that, $p\bar{p}$ annihilation can form any $c\bar{c}$ state in direct formation because the annihilation can also happen via more than one gluon or by intermediate $q\bar{q}$ pairs [BC05].

Besides the conventional $c\bar{c}$ states, the QCD allows also for other color-neutral states called exotics (see section 1.1). $\overline{\text{PANDA}}$ will be able to explore light exotics like glueballs or hybrids and charmonium-like exotics like tetraquarks. In the light exotic sector, e.g., the reaction $p\bar{p} \rightarrow \phi\bar{\phi}$ is of interest for searching tensor glueballs since the OZI rule suppresses the production via intermediate $q\bar{q}$ states, while an intermediate glueball is allowed. Further studies will concentrate on the molecular

resolution. In $\overline{\text{PANDA}}$ the line shape is proposed to be measured by an energy scan, using the cooled antiproton beam with its very small energy spread, that is smaller than the width of this state. The antiproton energy will be varied starting below the threshold of the direct formation $p\bar{p} \rightarrow \chi_{c1}(3872)$. The $\chi_{c1}(3872)$ is then identified by its decays $\chi_{c1}(3872) \rightarrow J/\psi \rho^0 \rightarrow e^+e^- \pi^+ \pi^-$ or $\chi_{c1}(3872) \rightarrow J/\psi \rho^0 \rightarrow \mu^+ \mu^- \pi^+ \pi^-$. The measured rate as function of the center-of-mass energy is then given by the convolution of the particle's line shape and the antiproton beam profile (energy spread) as visualized in figure 2.4. Due to the possibility of $\chi_{c1}(3872)$ production in direct formation, $\overline{\text{PANDA}}$ is able to measure the line shape with a precision that allows, e.g., to distinguish between a bound and a virtual state [Bar⁺19]. Thus, the resolution of the line shape is only limited by the energy spread and its precision and not by the detector resolution for the reconstruction. This planned energy scan program is one of the motivations of studying the influence of target thickness and accelerator beam intensity on the beam energy spread within this thesis (see chapter 5).

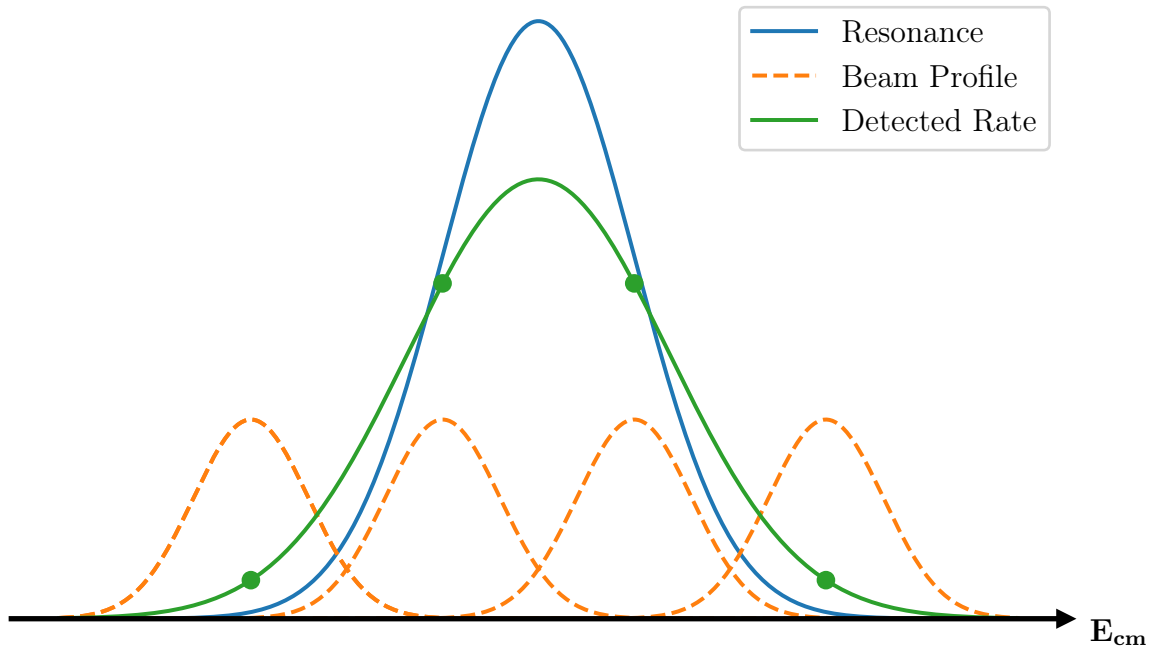


Figure 2.4: Visualization of the energy scan over a narrow resonance to study its line shape. The center-of-mass energy is varied over the resonance region by changing the energy of the antiprotons. The measured rate is then given as convolution of the antiproton beam profile (energy spread) and the line shape of the resonance. With this method, the detector is only used to identify the resonance via its decay, but one is not limited by the detector resolution in the reconstruction of the resonance line shape (based on [Bar⁺19]).

Hadrons in Nuclei

The fourth pillar of $\bar{\text{PANDA}}$ will study hadrons within nuclei. This is possible by creating particles close to the production threshold so that they are slow and get influenced by the mean field of the nuclear potential. By colliding antiprotons on nuclear targets one can implant antibaryons and mesons into the nuclear potential to study effects on their masses and decay widths. Furthermore, also studies on hypernuclei, which are nuclei with at least one hyperon inside, are possible. This can answer questions on the hyperon-nucleon and hyperon-hyperon interaction that could reduce the cooling of neutron stars [Bar⁺21].

2.4 The Experimental Setup of $\bar{\text{PANDA}}$

The broad physics program described in the previous section requires a complex detector setup, that is able to identify and reconstruct all the produced particles or their decay products with high precision. This will be done with the $\bar{\text{PANDA}}$ experiment which is a fixed-target setup. Here, antiprotons from the HESR will collide with, e.g., protons from a cluster-jet or pellet target operating with hydrogen. Due to this fixed-target setup, the reactions will have a forward boost, so that for optimal detection efficiency a close-to- 4π setup around the interaction point and a dedicated detector system in forward direction are necessary. These are called Target Spectrometer (TS) and Forward Spectrometer (FS). The target spectrometer is divided into three systems, with the barrel part covering the region of $22^\circ < \theta < 140^\circ$. The forward endcap extends this into the forward region up to 5° in the vertical plane and 10° in the horizontal plane, while the backward endcap is located in the region with $145^\circ < \theta < 170^\circ$. The forward spectrometer will then cover the gap in the forward region with an acceptance of $\pm 5^\circ$ in the vertical plane and $\pm 10^\circ$ in the horizontal plane [PAN12c]. Both systems include different detector systems for tracking, calorimetry, and particle identification as can be seen in figure 2.5.

The Target Spectrometer

The target spectrometer is built within a **Solenoid** magnet with a maximum field strength of 2 T and a uniformity within the region of the tracking detectors of $\pm 2\%$. The superconducting solenoid coil will be made of aluminum stabilized Rutherford cables with a total length of 1.6 km. It will force charged particles on a curved track. By reconstructing these tracks with the tracking detectors, the momentum of charged particles can be determined [PAN09b].

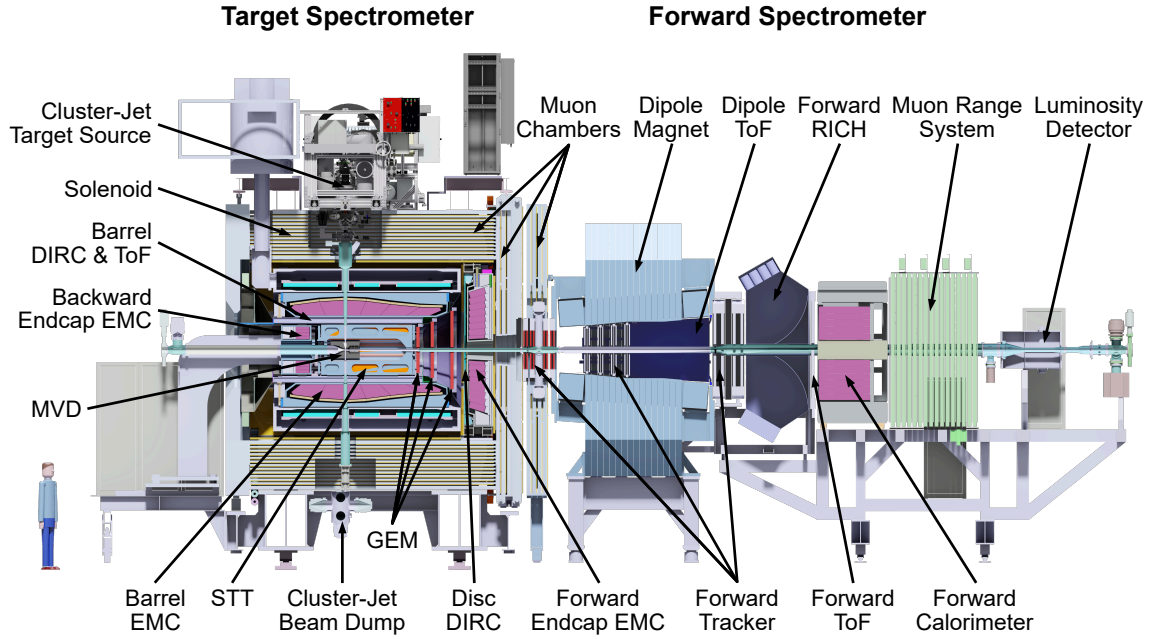


Figure 2.5: CAD drawing of the $\bar{\text{P}}\text{ANDA}$ detector setup that can be divided into the close-to- 4π Target Spectrometer (TS) and the Forward Spectrometer (FS). Both parts consist of a magnet and detectors for tracking, calorimetry, and particle identification. Furthermore, the target spectrometer also houses the target system with the cluster-jet target source as day-1 target mounted on top of the solenoid and the beam dump underneath the solenoid. In the forward spectrometer, there is the additional luminosity detector that will measure the absolute luminosity by studying the elastic $p\bar{p}$ scattering (created by D. Bonaventura, University of Münster, edited).

There is a vertical hole inside this solenoid to integrate the target system, which is either a **Cluster-Jet Target** as foreseen for the day-1 setup or a **Pellet Target**. Both targets will have a source mounted on top of the solenoid, which creates either a homogenous cluster-jet or a pulsed beam of frozen pellets with a diameter of about $20\,\mu\text{m}$. The cluster-jet or the pellet beam will then traverse through a vertical beam pipe down to the interaction point (IP). After the interaction, the beam will be removed from the vacuum system in a beam dump located underneath the solenoid [PAN12a]. More details on the $\bar{\text{P}}\text{ANDA}$ cluster-jet target, the beam dump system, and the beam dump upgrade developed within this thesis are given in chapter 3.

Directly around the interaction point, the **Micro Vertex Detector** (MVD) will be located. This is the innermost detector that is responsible for tracking charged particles directly around the vertex and for the precise measurement of primary and secondary vertices of short-lived particles. Therefore, it needs a high spatial resolution but low material budget. Furthermore, it must be capable of the high rates that can be

expected close to the interaction point. The design of the MVD foresees a barrel part around the IP consisting of four layers and a forward part with six disc layers. The inner layers will be equipped with silicon hybrid pixel sensors, while the outer layers will use double-sided silicon micro-strip detectors [PAN11].

The **Straw Tube Tracker** (STT) will surround the MVD and is also responsible for charged particle tracking for momentum reconstruction. The STT will consist of more than 4500 straws with a diameter of 10 mm. These are made of Mylar foil with a conductive inner layer as cathode and a single anode wire in its center. The straws are filled with a mixture of argon and CO_2 . Charged particles produce electrons and ions when traversing through the gas volume, which are separated by an electric field between the cathode and anode. The drift time of the electrons to the anode is then used to determine the position of the particle in the straw. Furthermore, also the energy loss can be measured, which can be used for particle identification. The straws are arranged into two semi-cylinders around the MVD with a gap of 42 mm between them to allow for space for the vertical target pipe. While the inner and outer layers are parallel to the beam pipe, there is a block of four double-layers that are skewed alternately by $\pm 2.9^\circ$ to improve the geometrical efficiency and the spatial resolution [PAN12c].

Since the STT does not cover the forward region with $\theta < 22^\circ$, an additional tracking system has to be integrated into the forward region of the target spectrometer. This gap is filled by three **Gas Electron Multiplier** (GEM) stations in a distance of 1.1 m, 1.4 m, and 1.9 m to the interaction point, which are capable of the high particle flux of up to $3 \cdot 10^4 \text{ cm}^{-2} \text{ s}^{-1}$ that is expected in the forward region around the beam pipe with a diameter of 5 cm at this point [PAN12c, PAN22].

Surrounding the inner tracking detectors, there are several detector systems for Particle Identification (PID) in the barrel and forward part of the target spectrometer. The **Barrel DIRC** and **Forward Endcap Disc DIRC** are both detector systems using the Detection of Internally Reflected Cherenkov light (DIRC). Both detectors are made of fused silica radiators. In case of the Barrel DIRC, they are shaped as bars, while in the Disc DIRC they are divided into quadrants. Charged particles that are faster than the speed of light in the medium will create Cherenkov light under the Cherenkov angle $\cos \theta_C = 1/(\beta n(\lambda))$ that is depending on the particle type and its momentum. The created light is guided through the fused silica due to total internal reflection to the end of the bars or quadrants where the light expands into an expansion volume that transforms the angle into a position that can be measured by MicroChannel Plate PhotoMultiplier Tubes (MCP-PMTs). By this, the DIRC detectors provide a clear π/K separation [PAN17, PAN19].

Since the DIRC principle only works for particles with a velocity larger than the speed of light, an additional PID system is needed in the barrel part of the target spectrometer. Therefore, the **Barrel Time-of-Flight** (ToF) system will be used, since particles with lower momenta can be identified by their different velocities. It consists of one layer divided into 16 segments made out of scintillator tiles modules and Silicon PhotoMultipliers (SiPMs) that allow for a timing resolution below 100 ps. As there is only one layer with high time resolution, the absolute time-of-flight cannot be measured. Instead, the relative timestamps of hits in the ToF detector are detected and sorted. After reconstructing the events with the help of the other detection systems, the most common start time can be reconstructed. In this way, the PID information can be extracted to allow for π/K separation below 1 GeV/c [PAN18a].

All the detectors described so far are surrounded by an **ElectroMagnetic Calorimeter** (EMC) consisting of a backward endcap, a barrel, and a forward endcap that will measure the energy of charged and neutral particles. Therefore, in total more than 15 500 PWO crystals are needed, which will be operated at a temperature of -25°C to increase the light output. This detector will allow for an energy resolution of 2 % for 1 GeV/c photons and a high count rate capability [PAN08, PAN20b].

The outermost detector of the target spectrometer is the **Muon System**. This is designed as a range system with alternating layers of absorber and detector planes to separate primary muons from pions and secondary decay muons. Therefore, the aluminum Mini Drift Tubes (MDT) will be mounted into the iron of the solenoid yoke and the downstream door of the yoke. In the barrel part, 13 detection layers with a thickness of 3 cm will be mounted with 3 cm of iron in between. Due to the higher energies in the forward region, there will be 6 cm iron between the six layers in the downstream door. Additionally, a removable muon filter is foreseen for the gap between target and forward spectrometer with four additional 6 cm thick iron layers and MDTs in between [PAN12b].

The Forward Spectrometer

The forward spectrometer includes similar systems as the target spectrometer to do tracking, calorimetry, and PID. Therefore, it also has a magnet system to curve the particle's trajectory according to their momentum. In the forward spectrometer, this is done by the **Dipole Magnet** with a magnetic rigidity of 2 Tm. This magnet also deflects the antiproton beam, making it part of the HESR magnetic lattice, which necessitates ramping during acceleration [PAN09b].

Similar to the target spectrometer, also the first detection system in the forward spectrometer is a tracking system. The **Forward Tracker** (FT) is divided into six tracking stations, which are grouped in pairs in front of the dipole, within the dipole, and behind the dipole. Each of these stations consists of four double-layers of straw tubes, where the outer layers are placed vertically and the layers in the center are inclined by $\pm 5^\circ$. In total more than 12 000 straw tubes will be mounted [PAN18c]. The FT stations 5 and 6 behind the dipole might instead be built using the former Outer Tracker of LHCb [GSI23].

Behind the Forward Tracker, another PID system using the emission of Cherenkov light will be installed. In the forward spectrometer a **Ring Imaging CHerenkov** (RICH) detector made of aerogel blocks with different refractive indices will be used. The emitted Cherenkov light will be reflected by mirrors onto photomultiplier tubes [PAN22].

Additionally, also time-of flight detectors will be used in the forward spectrometer. Following the Forward RICH detector, the **Forward Time-of-Flight** (ToF) wall will be installed in a distance of 7.5 m behind the interaction point. It will have a width of 5.6 m and a height of 1.4 m and consists of 66 scintillation counters. Particles with low momentum will not hit the Forward ToF due to their strong deflection in the dipole magnet. Therefore, the **Dipole ToF** system also consisting of scintillation counters is foreseen to be placed at both sides of the dipole magnet to detect low momentum particles with both charges [PAN18b].

A **Forward EMC** is foreseen with shashlyk-type modules with an energy resolution of $4\%/\sqrt{E/\text{GeV}}$. The modules are made of thin lead absorbers and plastic scintillators in between [PAN20b, PAN22]. This is followed by a **Muon Range System** with 15 layers of iron with a thickness of 6 cm and mini drift tubes in between, similar to the muon chambers in the target spectrometer [PAN22].

The **Luminosity Detector** is located at the most downstream part of $\bar{\text{PANDA}}$, at a distance of about 11 m from the interaction point. It aims to measure the absolute time-integrated luminosity with a precision of 5 % or better and the relative change between physics runs with a resolution better than 1 %. Therefore, it will measure the elastic $p\bar{p}$ scattering at forward angles of 3 mrad to 8 mrad with four planes of cooled high voltage monolithic active pixel sensors (HV-MAPS) [PAN18d].

Chapter 3

The $\overline{\text{P}}\text{ANDA}$ Cluster-Jet Target

The internal targets for the $\overline{\text{P}}\text{ANDA}$ experiment are a central component of the setup. Foreseen are a cluster-jet target, a pellet target, and also solid targets for the hypernuclear experiments. In this chapter the requirements for the internal targets are discussed. Afterwards, the $\overline{\text{P}}\text{ANDA}$ cluster-jet target as the main topic of this thesis is described with its source, the target beam line, and the beam dump. The update of the beam dump system that was developed during this thesis and the EPICS slow control system that had to be upgraded for the new components of the updated beam dump are presented in the last sections of this chapter.

3.1 Requirements for the internal $\overline{\text{P}}\text{ANDA}$ Targets

Most experiments in the $\overline{\text{P}}\text{ANDA}$ physics program base on the annihilation of antiprotons with protons and thus need a pure proton target, so that hydrogen is the mostly used element for the $\overline{\text{P}}\text{ANDA}$ targets. But also deuterium can be used as effective neutron target. Both will be realized by a cluster-jet target or a pellet target, which both have the advantage of being windowless in contrast to conventional cell targets [PAN12a]. On the other hand, the production of antiprotons is limited to $2 \cdot 10^7 \text{ s}^{-1}$ [Kni⁺12] so that the unwanted scattering by residual gas should be reduced as good as possible. Here, cluster-jet and pellet targets are ideal candidates since they show no strong divergence like a gas-jet target, so that not too much gas is distributed into the beam line [PAN12a].

The needed target thickness of such a target can be calculated from the maximal desired luminosity of $2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ [Gut06]. The luminosity can be calculated as

$$L = \dot{N}_{\overline{p}} \cdot n_T \quad (3.1)$$

with the areal target density (target thickness) n_T and the number of antiprotons per second

$$\dot{N}_{\bar{p}} = N_{\bar{p}} \cdot f \quad (3.2)$$

given by the total number of stored antiprotons $N_{\bar{p}}$ in the HESR and their revolution frequency f [Pov⁺13] so that the required target thickness is given as

$$n_T = \frac{L_{\max}}{N_{\bar{p}} \cdot f} . \quad (3.3)$$

With a maximal luminosity of $L_{\max} = 2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, $N_{\bar{p}} = 2 \cdot 10^{11}$ stored antiprotons in the HESR in the high luminosity mode, and a minimum frequency of $f = 443 \text{ kHz}$ at $1.5 \text{ GeV}/c$, the maximal required target thickness is $4.5 \cdot 10^{15} \text{ atoms/cm}^2$ [PAN12a].

Furthermore, it will be advantageous to be able to reduce the target density when a smaller luminosity is needed. This is easily possible with the $\bar{\text{PANDA}}$ cluster-jet target over at least two orders of magnitude by changing the operating parameters. Another advantage of the cluster-jet target is the continuous time structure that ensures a constant event rate and thus minimizes the dead time of the detectors. On the other hand, for short-lived particles a precise knowledge of the vertex point might be necessary. Here, a granular target like the pellet target in combination with a pellet tracking system has its advantages. Therefore, $\bar{\text{PANDA}}$ decided to have both types of windowless targets that can be exchanged when needed.

In a pellet target [Eks02] a cryogenic liquid (e.g., hydrogen) leaves a nozzle under typically low pressures to ensure that the liquid stream breaks up into small droplets which then freeze out to pellets within the vacuum of the target system. To make the droplets as regular as possible, the nozzle is excited by a piezoelectric element. This ensures a periodic production of droplets with the same size [PAN12a]. Such a target is currently developed at the University of Münster with droplet sizes in the range of $10 \mu\text{m}$ to $20 \mu\text{m}$. The main challenge here is the small nozzle size of about $10 \mu\text{m}$, but first successful long term measurements showed that this is solvable [Fro23, Man24].

3.2 The $\bar{\text{PANDA}}$ Cluster-Jet Target Source

The working principle of a cluster-jet target differs from a pellet target. While in both targets a cryogenic fluid (e.g., hydrogen or deuterium) is used, the fluid will leave the target under higher pressure and through a different nozzle design, so that at the end a supersonic jet of hydrogen clusters forms. The design of the final $\bar{\text{PANDA}}$ target source [Ves⁺23] is shown in figure 3.1 and described in the following.

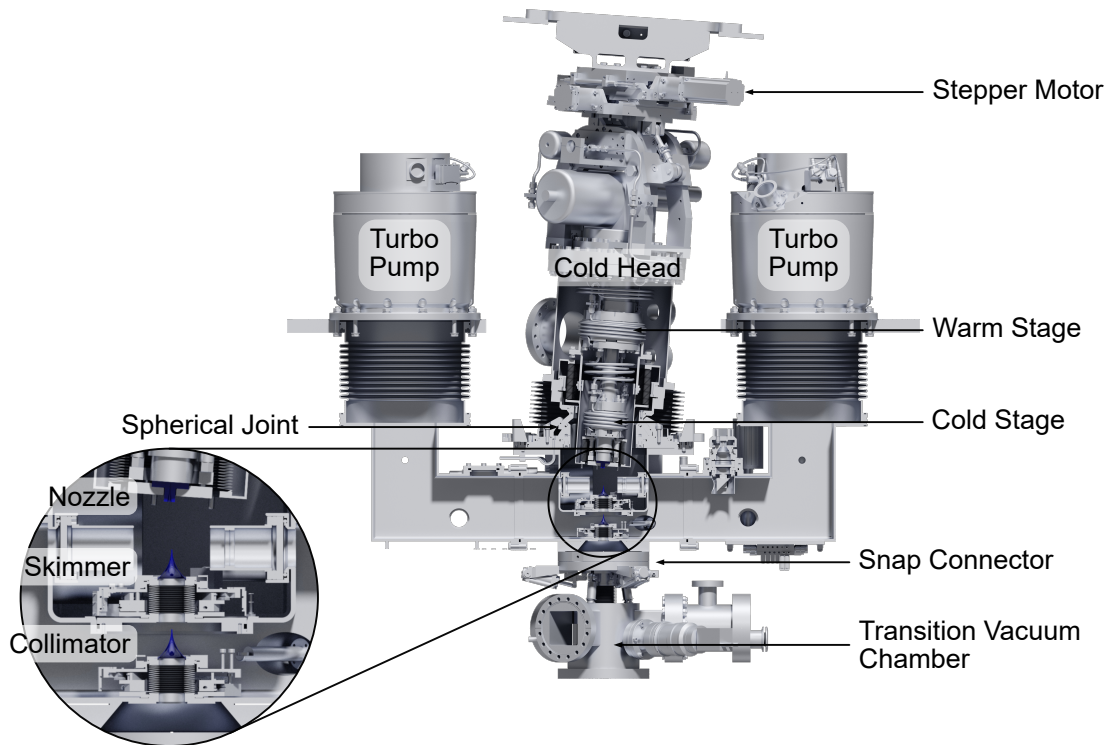


Figure 3.1: CAD drawing of the $\overline{\text{PANDA}}$ cluster-jet target source. The gas enters the target and is then cooled within the copper pipe windings around the warm and cold stage of the cold head. The gas leaves the target through a convergent-divergent de Laval nozzle into the first vacuum stage, called skimmer chamber. A cluster-jet forms in the outlet of the nozzle that can be separated from residual gas and shaped into a rectangular shape by two conical orifices called skimmer and collimator. The gas that remains in the skimmer and collimator chamber is pumped away by a powerful pumping station and turbomolecular pumps. To extract the densest part of the cluster-jet, the target source can be tilted by a system consisting of a spherical joint and two stepper motors (created by D. Bonaventura, University of Münster, edited).

3.2.1 The Gas System

The gas system of the $\overline{\text{PANDA}}$ cluster-jet target is responsible to cool down the hydrogen gas, to regulate the pressure, and to finally lead the cryogenic fluid to the nozzle. Since typical operating parameters are temperatures down to 20 K and pressures up to 20 bar, the used hydrogen gas has to be very pure, as any impurity could freeze inside the gas system, especially inside the nozzle. Therefore, commercially available hydrogen gas with a purity of 5.0 (99.999%) is used. This purity is still not sufficient so that a hydrogen purifier (PS7-PD1-08-2 from SAES Pure Gas) is used

to reach a purity of 9.0. This is achieved by guiding the gas through a palladium membrane. By heating this membrane to a temperature of 400°C the palladium lattice widens, so that only hydrogen can diffuse through the membrane. The hydrogen molecules are absorbed onto the palladium surface and dissociate into two atoms. These lose their electrons to the membrane and diffuse through before recombining with the electrons on the other side of the membrane. Impurities cannot pass the membrane and are instead purged out of the purifier cell through the bleed gas line with some hydrogen [SAE18].

Before entering the target source, the purified gas flows through a mass flow meter SLA5860 and a pressure controller SLA5820 from Brooks instruments [Het17]. The gas is then guided into the target where it is cooled down by a two-stage cold head COOLPOWER 10 MD and a compressor COOLPAK 6000 MD from Leybold using the Gifford-McMahon process [Gif66, Umr16]. Copper pipe windings are welded onto the two stages of the cold head, that are called warm and cold stage, to optimize the heat conduction between the gas inside the pipes and the cold head. To decouple the two stages and the outer walls from the cold head, pipes of stainless steel with lower heat conductivity are used in these parts. Since the cooling power cannot be regulated, two heating cartridges with 100 W are mounted at the warm stage and two cartridges with 50 W at the cold stage, where one of them is always mounted as backup. In combination with two temperature diodes (Lakeshore DT 670) at the cold stage and one at the warm stage, the temperature of both stages can be regulated separately with the help of a temperature controller (Lakeshore model 336).

Afterwards, the fluid leaves the target source through a convergent-divergent nozzle with stagnation conditions of up to 20 bar and down to 20 K. From the inlet of the nozzle an additional pipe also goes back around the two stages of the cold head to the outside of the target. At its end, a pneumatic valve can be used to protect the target from overpressure by opening it shortly. Furthermore, also a capacitive manometer (ABB Baratron 266 GST with ATEX certification) [Het17] is mounted in this gas line to monitor the absolute gas pressure.

3.2.2 The Cluster Production and Nozzle Design

The cryogenic fluid leaves the target source through a convergent-divergent de Laval nozzle as shown in figure 3.2. Within the 1 mm long inlet with an opening angle of 90° the fluid is accelerated to the speed of sound that is reached at the narrowest point with a diameter of $28\mu\text{m}$ in case of the $\bar{\text{P}}\text{ANDA}$ nozzle. Further acceleration towards supersonic velocities happens within the divergent outlet. This outlet is divided into

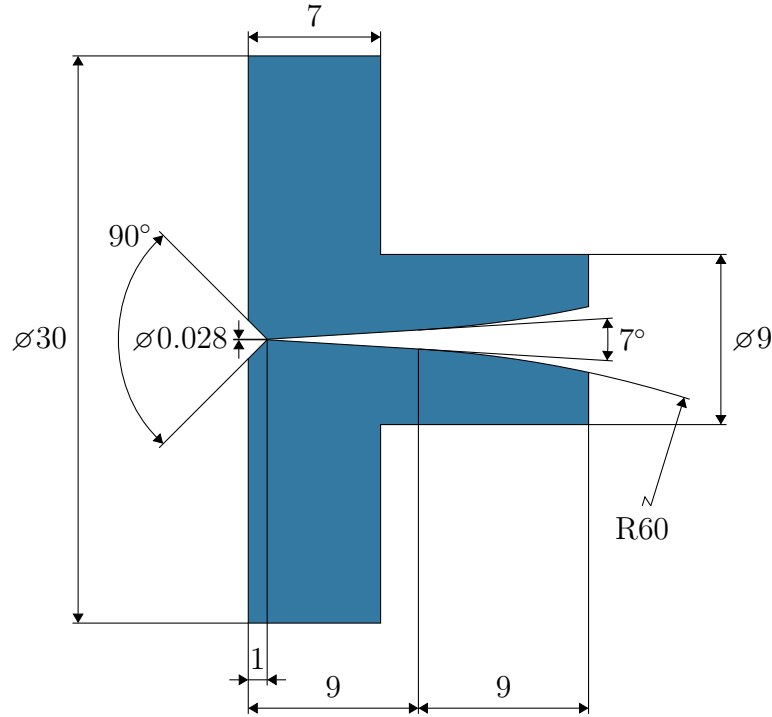


Figure 3.2: Technical drawing of a cut through the de Laval nozzle of the $\bar{\text{PANDA}}$ cluster-jet target (all dimensions in mm). The nozzle has a convergent inlet with a length of 1 mm and an opening angle of 90° that ends in the narrowest point with a diameter of $28\text{ }\mu\text{m}$. The 17 mm long outlet first diverges linearly for 8 mm with an opening angle of 7° before the divergence then increases with a curvature radius of 60 mm.

two parts. The first 8 mm long part diverges linearly with an opening angle of 7° . On the last 9 mm the outlet diverges more than linearly with a curvature radius of 60 mm.

The cluster production process within the outlet differs depending on the thermodynamic phase of the fluid in front of the nozzle. In case of a gas, the fluid is accelerated during the adiabatic expansion while also losing temperature. On a microscopic scale, this leads to smaller relative velocities of the molecules so that three-body collisions get more probable. In these collisions two molecules form a condensation nucleus via van der Waals forces and the third molecule conserves the momentum and energy. From there on, the nucleus will grow and a cluster will form. This process is limited to the region of the nozzle outlet, as only here the density is high enough for three-body collisions [Pau00]. This process is visualized on the left side of figure 3.3.

When the fluid is in the liquid phase, which is needed for the highest densities aimed for with the $\bar{\text{PANDA}}$ cluster-jet target, the cluster production process differs. Here, the production via three-body collisions is not relevant anymore, instead clusters with

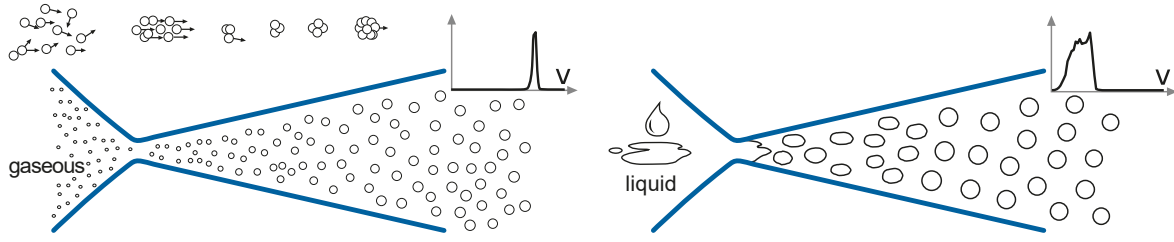


Figure 3.3: Depending on the thermodynamic phase of the cryogenic fluid in front of the nozzle, the cluster production process differs. For gaseous hydrogen clusters are formed due to three-body collisions that get more probable when the relative velocities of the molecules get smaller during the adiabatic expansion. With a liquid, larger clusters are formed by an atomization process (figure from [VFK22]).

a size of up to $10\,\mu\text{m}$ [Eic⁺23, Eic23] can form via an atomization process, which is shown on the right side of figure 3.3 [Mie55, Ves24, VFK22].

An important quantity of the cluster-jet is the velocity v of the clusters after the expansion into the vacuum, which depends on the cluster production process. It can be calculated for stagnation conditions in the gaseous regime assuming an ideal gas by

$$v = \sqrt{\frac{2\kappa}{\kappa - 1} \frac{RT_0}{M}} \quad (3.4)$$

with the heat capacity ratio κ , the universal gas constant R , the temperature T_0 in front of the nozzle, and the molar mass M . For a liquid, these calculations can be performed numerically for a van der Waals gas taking into account the nozzle shape in a quasi-one dimensional model [Täs⁺13, Täs12]. Besides the lower velocities in the liquid regime also the velocity distribution is much broader (as depicted in figure 3.3). This was used to measure the vapor pressure curve of hydrogen and their extension into the supercritical regime, the Widom line [Fis21, Ves24, VFK22].

Furthermore, also the volume gas flow rate at normal conditions q_V ($T_N = 293.15\,\text{K}$, $p_N = 1.013\,25\,\text{bar}$) through the nozzle can be calculated as

$$q_V = A^* \frac{p_0}{\sqrt{MT_0}} \frac{T_N}{p_N} \left(\frac{2}{\kappa + 1} \right)^{\frac{\kappa+1}{2(\kappa-1)}} \sqrt{\kappa R} \quad (3.5)$$

with the cross-sectional area A^* of the nozzle at its narrowest part and the stagnation conditions p_0 and T_0 in front of the nozzle [Täs12]. This equation is regularly used for the Münster cluster-jet targets to monitor the nozzle diameter by measuring temperature T_0 , pressure p_0 , and the volume gas flow rate q_V to make sure that the diameter does not change due to a blockage inside the nozzle.

3.2.3 The Skimmer and Collimator Chamber

After leaving the nozzle, a part of the cluster-jet is extracted by two conical orifices, called skimmer and collimator (see figure 3.1). The skimmer is mounted in the skimmer chamber (see figure 3.4) directly underneath the nozzle at a distance of 55 mm from the nozzle outlet and has a circular opening with a diameter of 500 μm . It separates

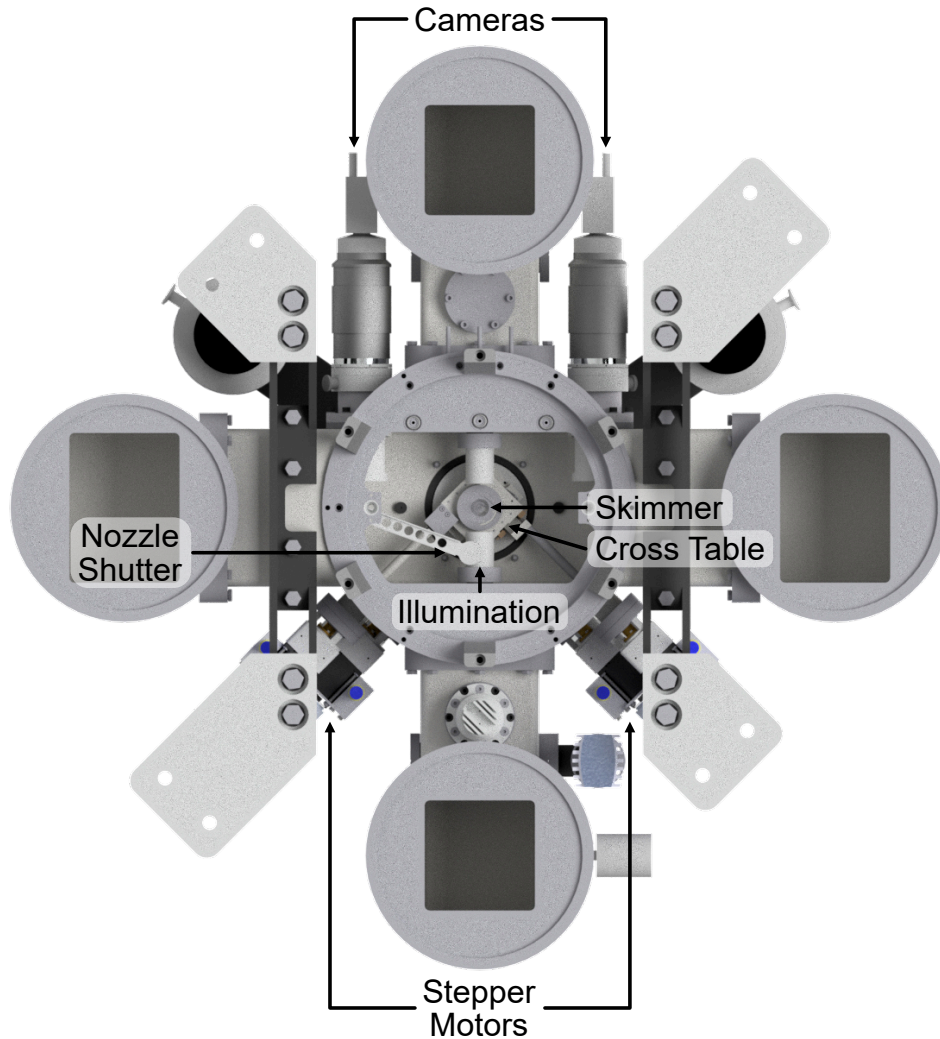


Figure 3.4: CAD drawing of the skimmer chamber of the $\overline{\text{PANDA}}$ cluster-jet target. The skimmer is mounted in the center on a cross table that can be moved by two stepper motors. Using an LED matrix as light source, the cluster-jet can be illuminated and then monitored by the two cameras on the opposite side. Via two mirrors, they see the jet under an angle of 90° with respect to each other. The cluster-jet can be stopped from entering the skimmer and the following vacuum chambers by a pneumatic nozzle shutter that can be moved between the nozzle and the skimmer (created by D. Bonaventura, University of Münster, edited).

a part of the cluster-jet from residual gas. While the residual gas remains in the skimmer chamber, the extracted cluster-jet enters the collimator chamber where the collimator is mounted at a distance of 119 mm from the nozzle outlet. This orifice has a rectangular opening with a size of $221\text{ }\mu\text{m} \times 780\text{ }\mu\text{m}$. It shapes the extracted cluster-jet into a rectangular form to maximize the beam-target overlap at the interaction point (see section 3.3) while minimizing the gas load that does not interact with the accelerator beam. Both conical orifices are mounted on cross tables that can be moved by two stepper motors (Nanotec ST5709M2608) each, which are equipped with optical absolute encoders. The orifices can be moved independently in a range of $\pm 2.5\text{ mm}$ [Het17]. A pneumatic nozzle shutter between nozzle and skimmer (see figure 3.4) can be used to block the beam so that it cannot enter the following collimator chamber. This is used to turn the cluster-jet on or off within less than a second.

Since the cluster-jet of the $\bar{\text{P}}\text{ANDA}$ target develops core beams with a higher density, it is beneficial to align these core beams with skimmer and collimator to achieve the highest thicknesses. This is done by tilting the whole target source around the narrowest point of the nozzle as rotation point. The tilting system (see figure 3.1) with a range of $\pm 2.5^\circ$ consists of a spherical joint, two stepper motors (Nanotec ST5914D4208), and two potentiometers (WayCon LZW1) as absolute encoder [Het17, Zan12].

The skimmer chamber is also equipped with an optical monitor system [Gri14] as shown in figure 3.4 that can take live pictures of the cluster-jet from two directions by using two cameras and a LED matrix as light source. This makes it possible to have a live monitoring of the cluster-jet so that the result of the adjustment with the nozzle tilting system and the skimmer can be controlled. Another optical monitor system is mounted in the transition vacuum chamber, which is described in the next section. More details on these systems can be found in section 3.6.1.

3.2.4 The Vacuum System

The vacuum system of the cluster-jet source can be divided into three sections that are visualized in figure 3.5: skimmer chamber, collimator chamber, and insulation vacuum chamber. These chambers are equipped with several pumping systems, which are described within this section. The complete vacuum system of the $\bar{\text{P}}\text{ANDA}$ target source is also shown in figure 3.6.

Within the skimmer chamber, the gas load of typically up to $6\text{ l}_\text{n}/\text{min}$ leaves the nozzle and enters the vacuum system. Only a small part of this gas leaves this chamber as cluster-jet through the skimmer. The residual gas is pumped away by the powerful

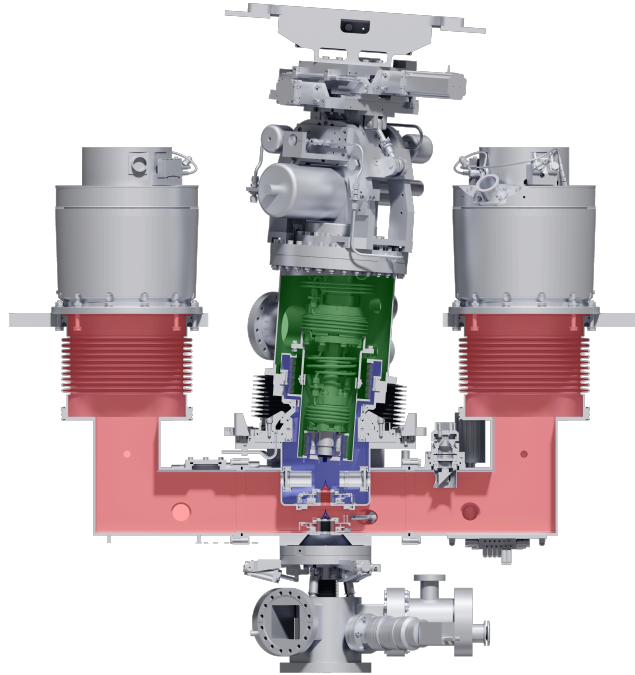


Figure 3.5: CAD drawing of the $\bar{\text{PANDA}}$ cluster-jet target source with the three different vacuum chambers marked in different colors. The skimmer chamber, that is directly attached to the pumping station, is shown in blue. The collimator chamber (red) is evacuated by two turbomolecular pumps, that use the skimmer chamber as fore vacuum. At the insulation vacuum chamber (green) one turbomolecular pump is installed that pumps directly into the collimator chamber (created by D. Bonaventura, University of Münster, edited).

pumping station that is shown in figure 3.7 is used. A symmetrical connection of this pumping station to the target from two sides ensures that no pressure gradient forms in the chamber which could deflect the cluster-jet. The pumping station consists of two Leybold SOGEVAC SV300B rotary vane pumps with ATEX certification and a nominal pumping speed of $280 \text{ m}^3/\text{h}$ [Ley21b] each that are mounted in parallel. These fore pumps are followed by two roots pumps in series. First an air-cooled RUVAC WS 2001 with a nominal pumping speed of $2050 \text{ m}^3/\text{h}$ is mounted. This is followed by a RUVAC WH 7000 with a pumping speed of $7000 \text{ m}^3/\text{h}$ [Ley21c].

Another part of the cluster-jet will be separated by the collimator and stays inside the collimator chamber. This chamber is evacuated by two turbomolecular pumps Turbovac MAG W 2200 iPL from Leybold with a nominal pumping speed for hydrogen of $17501/\text{s}$ each [Ley21a], which are installed on two opposite sides of the collimator

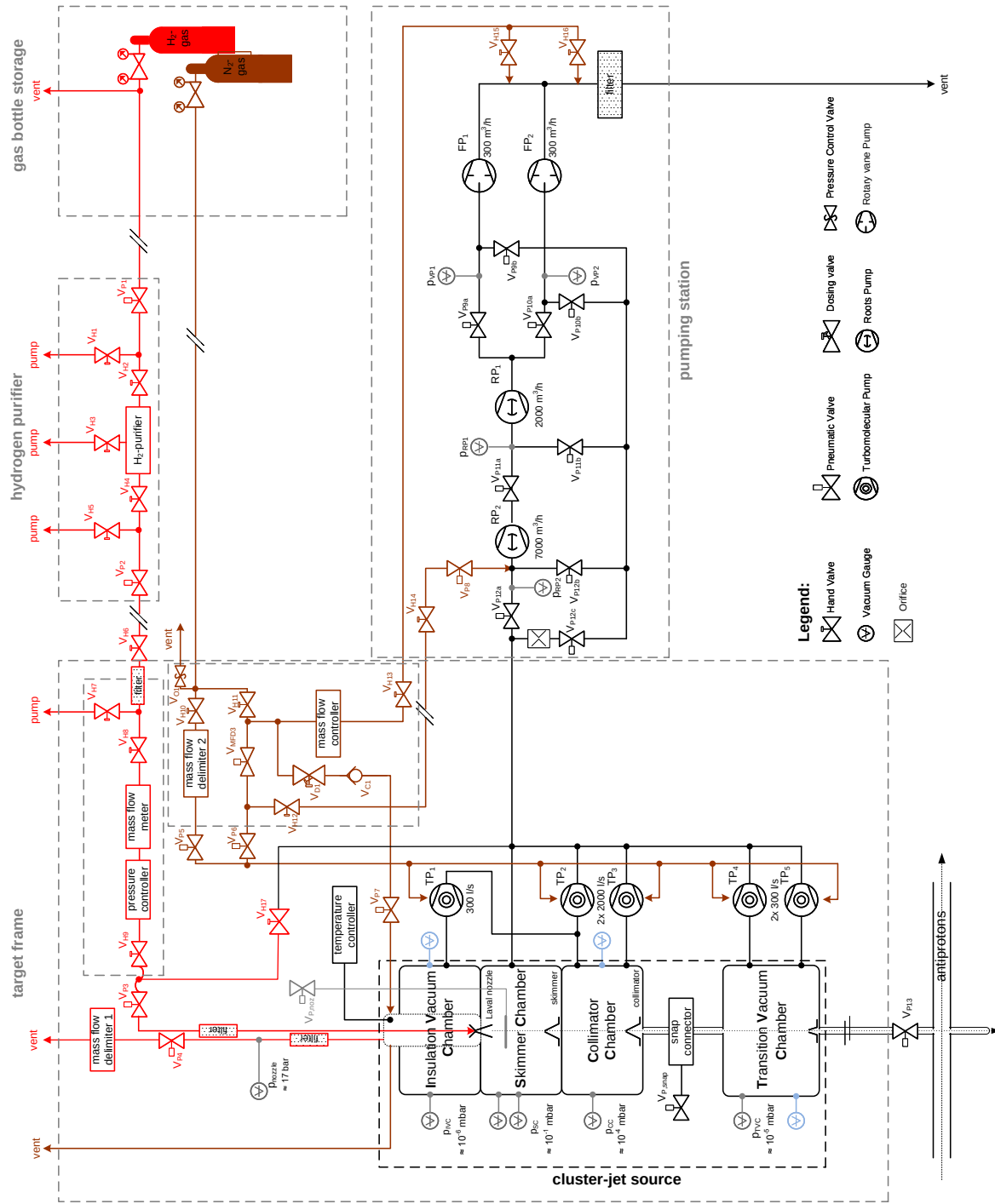


Figure 3.6: The vacuum system of the $\bar{\text{P}}\text{ANDA}$ target source consisting of the pumping station, the hydrogen and nitrogen supply, and the cluster-jet target source (original created by A. Hergemöller [Her13] and B. Hetz [Het17], University of Münster, edited).

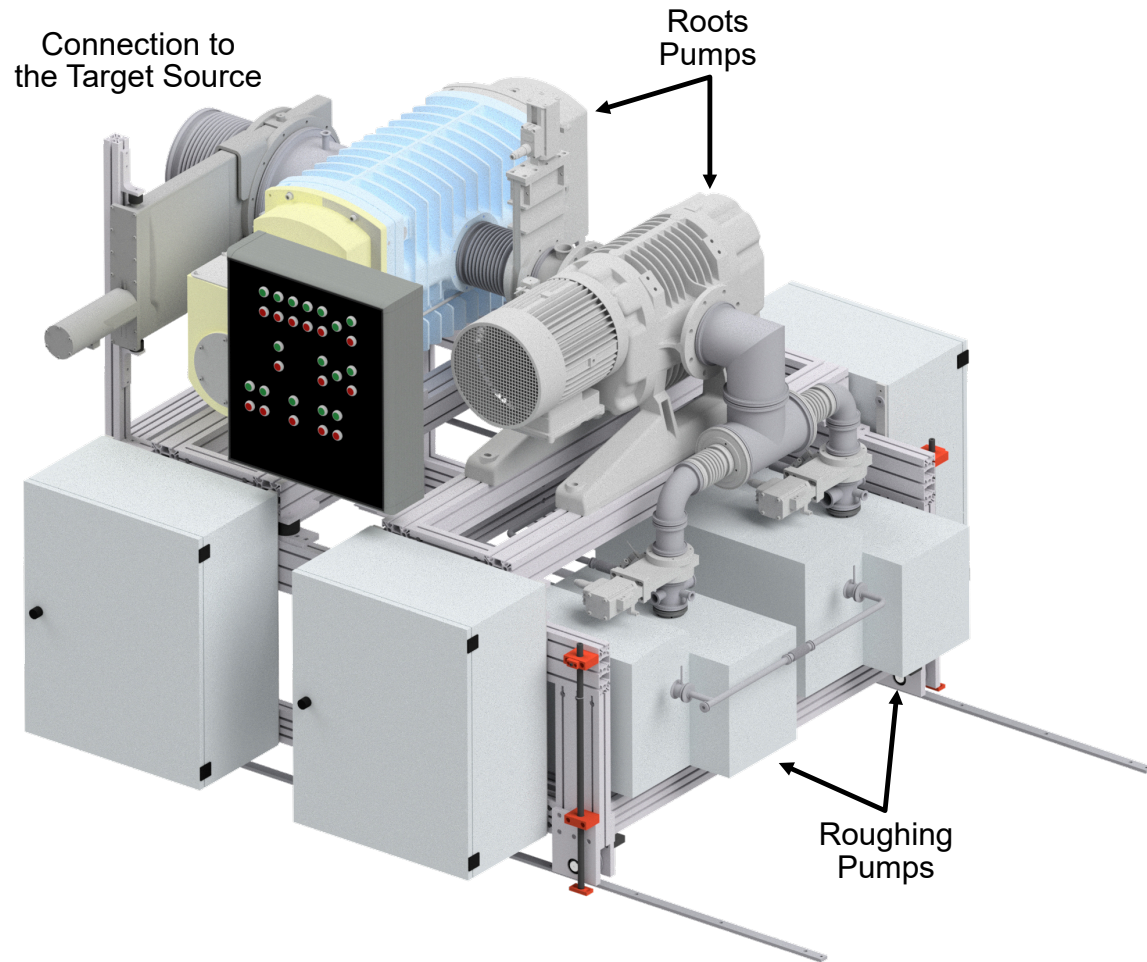


Figure 3.7: CAD drawing of the pumping station of the $\bar{\text{PANDA}}$ cluster-jet target source. It is equipped with two roughing pumps that are mounted in parallel, followed by two roots pumps. These are connected to the skimmer chamber of the target source (created by D. Bonaventura, University of Münster, edited).

chamber. They are equipped with the integrated frequency converters MAG.DRIVE iM and pump directly into the skimmer chamber.

To insulate the cold head from the outside, it is surrounded by the insulation vacuum chamber. Here, no direct gas load is expected, so that it is evacuated by only one turbomolecular pump of type Turbovac SL 300 with a pumping speed of 190 l/s for hydrogen [Oer25]. This is powered by the frequency converter TURBO.DRIVE TD 400 in combination with the power supply TURBO.POWER 300.

The pressure inside all vacuum chambers is monitored by vacuum gauges. At each fore-pump a Leybold CERAVAC CTR 100 1000 Torr is mounted, that covers a range of four orders of magnitude up to 1000 Torr or 1333 mbar, followed by a CTR 100

100 Torr at the first roots pump and a CTR 100 10 Torr at the second roots pump. The skimmer and collimator chamber are equipped with two gauges each to cover the whole expected pressure range. The skimmer chamber has a CTR 100 1000 Torr to monitor the target during evacuation and ventilation and a CTR 100 1 Torr for typical operation. At the collimator chamber a CTR 100 10 Torr and a Leybold IONIVAC ITR 200 S are mounted that allows to monitor the pressures down to the ultra-high vacuum regime. At the insulation chamber another ITR 200 S is installed.

3.3 The $\bar{\text{PANDA}}$ Cluster-Jet Target Beam Line

After leaving the $\bar{\text{PANDA}}$ cluster-jet target source, the cluster-jet enters the Transition Vacuum Chamber (TVC). Since this will be located already within the $\bar{\text{PANDA}}$ solenoid magnet, it will be difficult to access the connection flange. Therefore, the connection is done by an in-house developed snap connector operated with pressurized air. The TVC is equipped with two turbomolecular pumps of type Leybold TURBOVAC TMP 361 powered by the two frequency converters of type Leybold Turbo.Drive TD20 that pump into the collimator chamber. The pressure in the TVC is monitored by a Leybold IONIVAC ITR 200 S pressure gauge. This chamber is used as last pumping stage before the cluster-jet enters the actual beam line, so that this chamber is needed to reduce the flow of residual gas from the source down to the interaction point. Additionally, the TVC is equipped with another optical monitor system (see section 3.6.1), this time working with a laser instead of an LED matrix due to the smaller areal density of the jet after skimmer and collimator. This optical monitor system can be used to monitor the effect of the whole adjustment process including nozzle tilting, skimmer, and collimator (see section 3.6.1).

The interaction point is located 2.25 m underneath the nozzle. It is connected with a beam pipe that narrows down from a diameter of 90 mm to 20 mm at the interaction point. From there, another beam pipe, that again starts with a diameter of 20 mm, leads to the beam dump at a distance of more than 5 m from the nozzle. Directly in front of the beam dump, the installation of the pellet tracking system is foreseen, that can monitor and track the pellets with several layers of fast line scan cameras and several lasers. Together with a similar system at the pellet target source, it can precisely determine the vertex point [PAN12a, Pys⁺14]. The precise knowledge of the primary vertex can be very important for the reconstruction of reactions that have displaced vertices and neutral particles involved. One example here is the reaction $p\bar{p} \rightarrow \psi(3770) \rightarrow D^+D^-$ where the $D^\pm$ meson decays involve, e.g., neutral kaons and pions [Nav⁺24, Nor⁺06].

In the current setup, that is installed at the COoler SYnchrotron (COSY) at the Forschungszentrum Jülich, the pellet tracking system is not available and instead an Absolute thickness Monitor System (AMS) as shown in figure 3.8 is installed [Köh10]. This system consists of two 1 mm rods that can be moved by two motors from two directions through the cluster-jet. Clusters hitting the rods break up, so that a pressure increase can be measured by the installed pressure gauge ITR 200 S. This pressure increase is directly proportional to the target thickness. A detailed description of the working principle can be found in section 3.6.2. In the final setup at $\bar{\text{PANDA}}$, there is no space for this system at the target beam line. Therefore, an alternative location in a new beam dump system was found. The design of the new beam dump and the integration of a new AMS is presented in section 3.5.

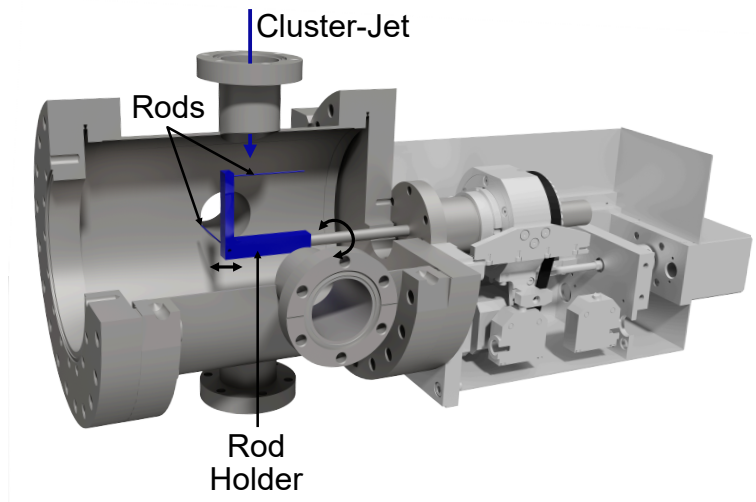


Figure 3.8: CAD drawing of the Absolute thickness Monitor System (AMS). The cluster-jet enters the chamber from the top, where it can then hit one of the two rods of the AMS. The lower rod can be moved linearly by one motor through the cluster-jet, while a second motor can rotate the rod holder and by this moves the upper rod through the cluster-jet in the other direction. When the clusters hit the rods, they break up resulting in a pressure increase that can be measured as function of the rod position (created by D. Bonaventura, University of Münster, edited).

3.4 The $\bar{\text{PANDA}}$ Cluster-Jet Target Beam Dump

Below the $\bar{\text{PANDA}}$ solenoid magnet a beam dump will be installed at a distance of more than 5 m from the nozzle [Het17] that pumps away the cluster-jet and minimizes the backflow of residual gas into the target beam line and the interaction point. In the following, the beam dump is described, which was installed at COSY together with the

cluster-jet target source, and which was used there during all beam times presented within this thesis. On the other hand, a new beam dump was designed that will replace the old beam dump. This update of the beam dump is presented in section 3.5.

The old beam dump as shown in figure 3.9 was formerly used for the JETSET experiment at the LEAR antiproton ring at CERN [And⁺89]. It has a three-stage design with each beam dump stage being equipped with two turbomolecular pumps at two opposite sides. The two pumps at the first stage are of type Varian Turbo-V 551 Navigator with a pumping speed of 510 l/s each, while the other four pumps on the sides are Varian Turbo-V 1001 Navigator with a pumping speed of 900 l/s each [PAN12a]. At the end, a Leybold TURBOVAC MAG W 1300 iPL with a pumping speed of 1130 l/s for hydrogen is mounted [Ley21a]. The cluster-jet enters the beam dump 78 mm off-axis for hydrogen is mounted [Ley21a]. The cluster-jet enters the beam dump 78 mm off-

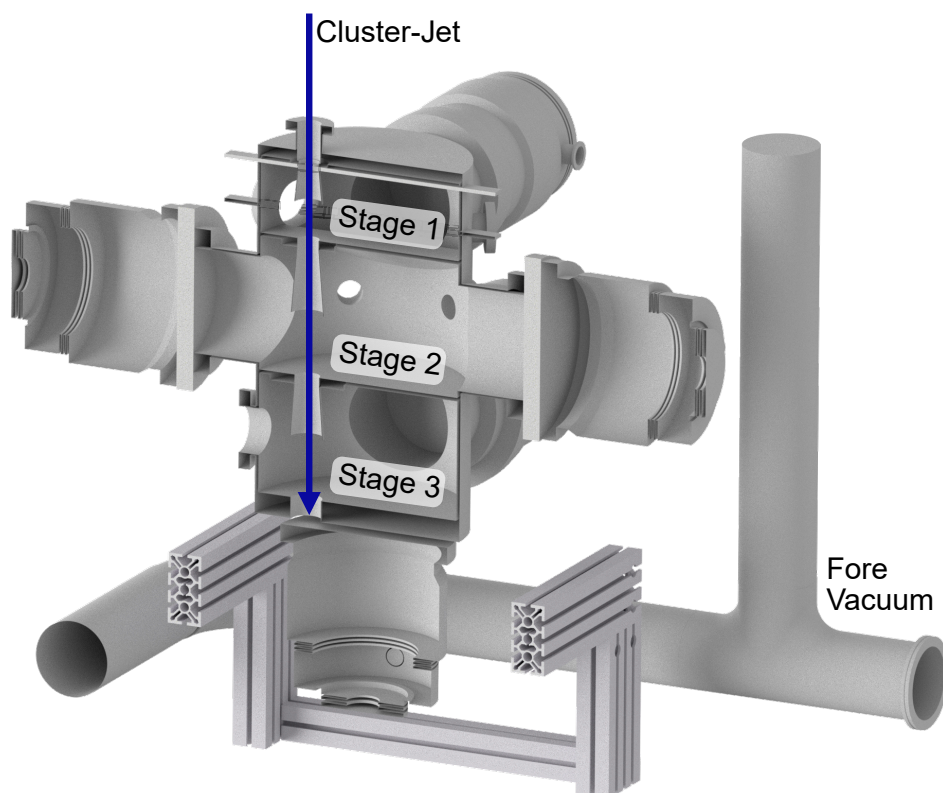


Figure 3.9: CAD drawing of the old beam dump of the $\bar{\text{PANDA}}$ cluster-jet target. It consists of three stages, each equipped with two turbomolecular pumps. At the end of the last stage, an additional pump is mounted. The cluster-jet enters the beam dump 78 mm off-axis through a conical pipe, which is also mounted between the stages. Finally, the jet hits the blades of the last turbo pump. All the pumps are connected to the same fore vacuum line (created by D. Bonaventura, University of Münster, edited).

axis and thus does not hit this last turbomolecular pump at the center but directly on its blades, so that a large part of the cluster-jet is directly pumped away. The fore vacuum for all these pumps is created by a rotary vane pump (Leybold TRIVAC D 65 B). Between the stages and also at the entrance into the first stage, conical pipes are mounted on the holes, which reduce the backflow of gas. All stages are equipped with pressure gauges of type Leybold Ionivac ITR 90 or ITR 200 S, while the fore vacuum is monitored by a Leybold CERAVAC CTR 100 1000 Torr.

3.5 Update of the Beam Dump System

The old beam dump as described before was used for several years at COSY and fulfills its requirements regarding the vacuum conditions, but it allows no implementation of any monitor system. Later at $\bar{\text{P}}\text{ANDA}$ there is no space between the TVC and the beam dump which makes the adjustment of the whole cluster-jet into the beam dump very challenging as this can only be done by monitoring the pressures in the beam dump. Therefore, it was decided to design a new beam dump as part of this thesis that allows implementing several monitor systems. This new beam dump is shown in figure 3.10.

The overall design of this beam dump is quite similar. It still has three stages equipped with two turbomolecular pumps each and an additional pump at the end. The fore vacuum will be created by a dedicated pumping station that will be described in section 3.5.5. This time, the chambers are built symmetrically, so that the cluster enters the beam dump in the middle of the chamber. To still guarantee that the clusters hit the last pump at its blades, this pump is mounted via a special, asymmetric flange. The stages are also separated by orifices, but the conical tubes are not included. Instead, the design of the orifices was optimized for the expected rectangular cluster-jet. The orifices have a rectangular shape where the length of the short side can be reduced and also the position of the orifice can be adjusted. This simplifies the whole adjustment, as it is possible to correct for a small misalignment by adjusting the orifices. More details on the beam dump orifice system are given in section 3.5.1.

The three stages now have four instead of only two CF160 flanges with two of them being occupied by the turbomolecular pumps. The others can be used for monitor systems, vacuum gauges, and other instruments. It is foreseen to install an absolute thickness monitor system into the second stage, which is discussed in section 3.5.2. This tool is of utmost importance as it is the only tool that allows for absolute determination of the target thickness. This shows the great advantage of the new beam dump, as there was no space for such a tool with the previous setup. Additionally, also an MCP

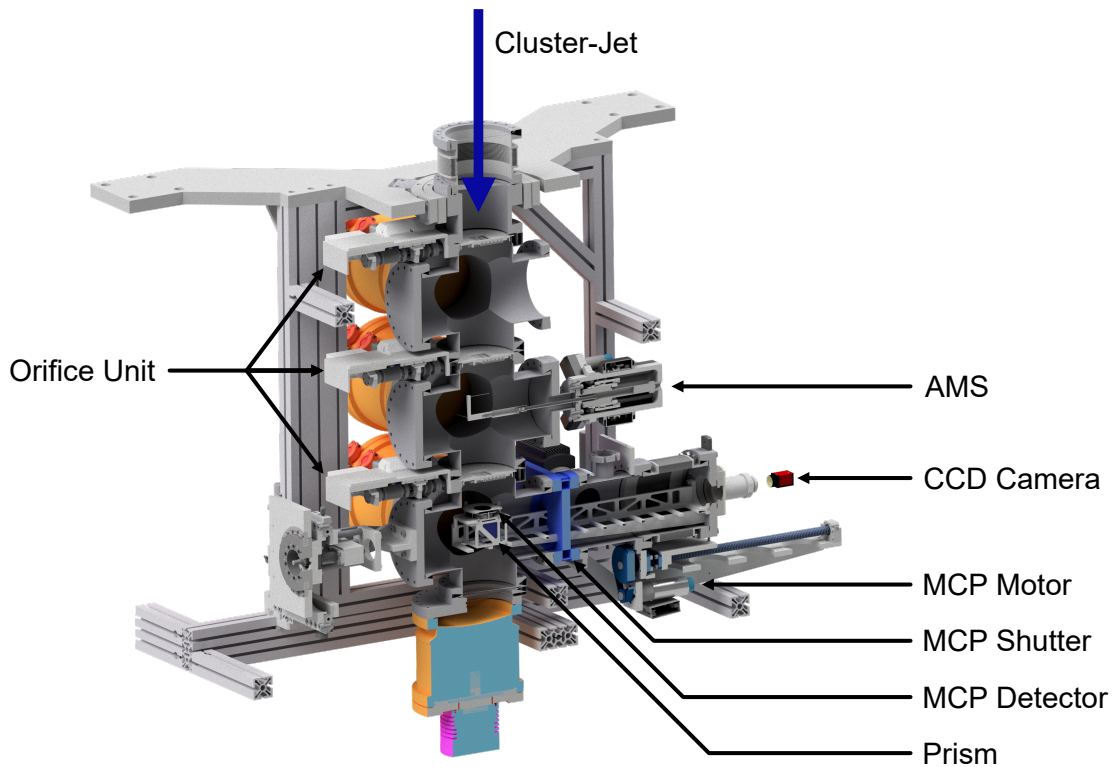


Figure 3.10: CAD drawing of the new $\bar{\text{P}}\text{ANDA}$ beam dump. Each of the three vacuum stages is equipped with two turbomolecular pumps on the sides and an additional pump is mounted at the end of the last beam dump stage. Between the stages and on top of the first stage new adjustable orifice systems are located. In the second stage, the integration of a new AMS system is planned, and the third stage will be equipped with the removable MCP system consisting of a MultiChannel Plate (MCP) detector, a prism, and a CCD camera. This system can be removed from the beam dump by a motor and can be separated from the beam dump by a shutter (created by D. Bonaventura, University of Münster, edited).

monitor system installed into the third beam dump stage is foreseen. This system is described in section 3.5.3. It allows live monitoring of the ionized cluster-jet. The clusters can be ionized by either the accelerator beam or an electron gun. Therefore, the electron gun that is described in section 3.5.4 was developed and can be installed into the first beam dump stage or even at some point at the target source depending on the application.

3.5.1 The Beam Dump Orifice System

The three stages of the new beam dump are separated by two beam dump orifice systems as shown in figure 3.11, while an additional third system is located at the

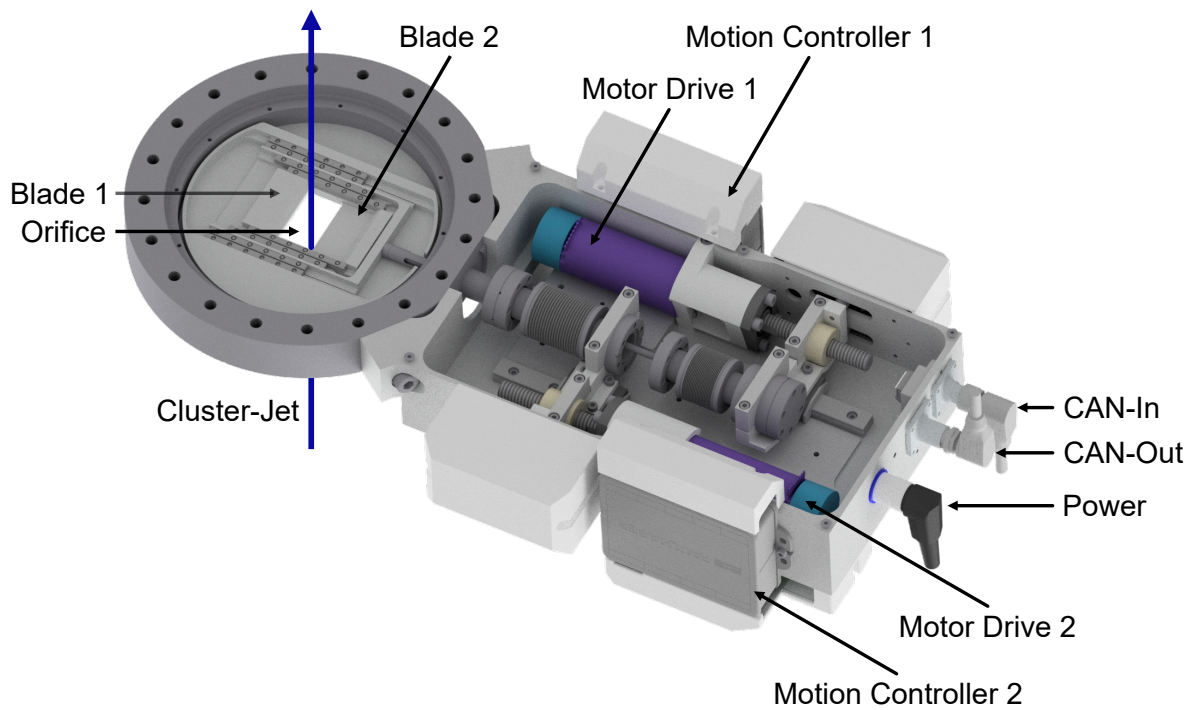


Figure 3.11: CAD drawing of the orifice system for the new $\bar{\text{PANDA}}$ target beam dump. The orifice opening can be moved and varied in size in one direction by two motor drives that move the two blades of the orifice system. The motors are operated by two motion controllers. The communication with the orifice system is foreseen via CAN bus, that allows to daisy-chain the two controllers but also multiple orifice systems and other systems (created by D. Bonaventura, University of Münster, edited).

entrance of the beam dump. These systems were designed with the goal to reduce the backflow of gas from one stage to the other. Therefore, the orifices should be as small as possible and since the cluster-jet is of rectangular shape, the orifices should also be rectangular. A photograph of an assembled system is given in figure 3.12.

Via two movable metal blades it is possible to change the width and position of the orifice in one direction, so that the opening can be reduced from $40 \text{ mm} \times 40 \text{ mm}$ to $20 \text{ mm} \times 40 \text{ mm}$. The position of the orifice can be adjusted by $\pm 10 \text{ mm}$ in the same direction where also the width is adjustable. This allows on the one hand to reduce the backflow and on the other hand adjusting the position simplifies the alignment of the whole target system. Here, it must be noted that due to the limited space inside the flange, the maximum width of 40 mm is only possible when the orifice is exactly in the center, while the maximum displacement is only allowed with the minimum width of 20 mm . If this is not considered, parts of the orifice system can collide. This is solved by integrating these dynamic limits into the slow control system [Ded24].

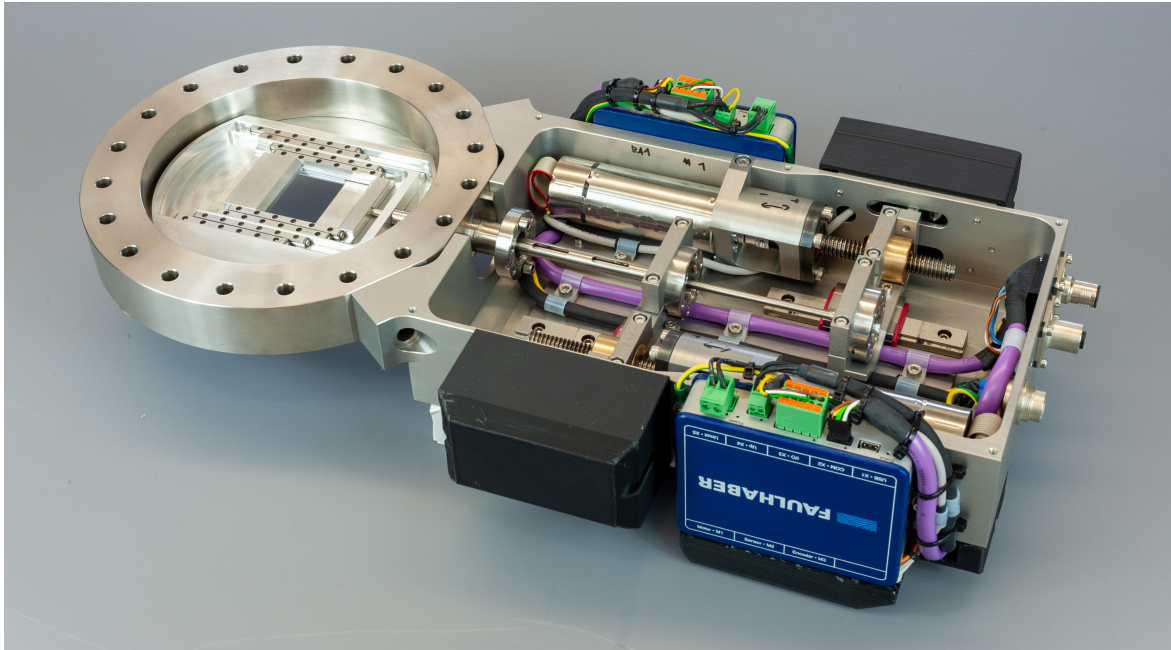


Figure 3.12: Photograph of an assembled orifice system for the new $\bar{\text{P}}\text{ANDA}$ target beam dump (picture taken by D. Bonaventura, University of Münster). For better illustration the bellows and the cover of the metal body are not installed.

The motorization of the system is done by two Faulhaber Brushless DC-Servomotors Series 3268 048 BX4 each equipped with Faulhaber Motion Controller Series 5005 S CO. The motion controllers can be controlled remotely via a CAN bus connection that allows to daisy-chain up to 128 Faulhaber motion controllers. Therefore, the two motion controllers of each orifice system are daisy-chained internally and connected to the input (CAN-In) and output (CAN-Out) so that further systems can be added to the same CAN network. The final CAN-Out is then connected to a $120\,\Omega$ terminator. More details on the remote communication with the orifice system and its integration into the slow control system are given in section 3.7.3.

3.5.2 The new Absolute Thickness Monitor System

Another system that will be implemented into the new beam dump is a new version of the AMS which is shown in figure 3.13. This will replace the old system that was described in section 3.5.2 as there is no space to include this outside of the beam dump. The new AMS will be powered by the same motor drives and motion controllers as used for the beam dump orifice system. This makes the implementation into the slow control easier and allows daisy-chaining all the motors in the CAN network. Like the old system, also the new AMS has two rods that will be moved through the cluster-jet,

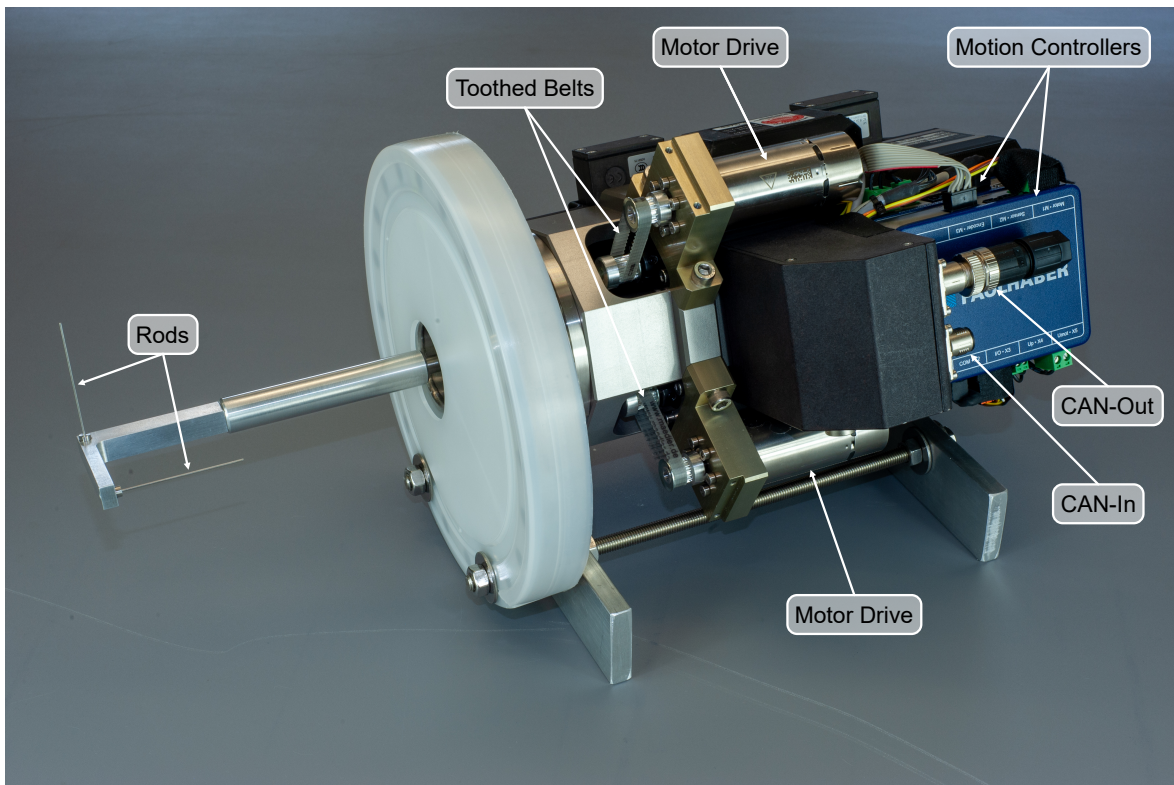


Figure 3.13: Photograph of the assembled absolute thickness monitor system for the new PANDA target beam dump (picture taken by D. Bonaventura, University of Münster). The rods can be rotated or moved linearly by the two motor drives via the toothed belts. The control of the motors is done with two motion controllers that can be connected to a CAN network via the CAN-In and CAN-out plug. The latter is here terminated by a $120\,\Omega$ terminator. The covers around the toothed belts were removed for this picture.

one by moving the rod holder linearly, the other by rotating the holder. Here, minimal step sizes of $1\,\mu\text{m}$ respectively 0.1° are possible. The working principle of the absolute thickness monitor system and the analysis of the recorded profiles are described in more detail in section 3.6.2.

3.5.3 The removable MCP Monitor System

While the AMS described before is able to measure the cluster-jet profile and thus can be used to check the result of the adjustment, it is not perfectly suited as monitor during the adjustment process since a single measurement takes some minutes. Therefore, the idea came up to include another monitor system, which is able to support the adjustment process with live monitoring of the cluster-jet. Here, an MicroChannel Plate (MCP) detector system was chosen that can visualize an ionized cluster beam.

The necessary ionization can either be done by an electron gun (see section 3.5.4), which allows monitoring the whole cluster-jet, or by an accelerator beam, which then makes only the overlap region between the cluster-jet and accelerator beam visible. This principle was already proven in [Kho⁺14] and since then regularly used at the Münster prototype target [Gri18, Köh15, Ves20]. For the new $\bar{\text{PANDA}}$ beam dump, the old MCP system of the prototype has been tested in cooperation with S. Vestrick, and it was shown that such a system can visualize the cluster-jet with the opportunity to extract even the cluster-jet thickness after a proper calibration. Furthermore, it is also possible to measure the velocity of the clusters by using a pulsed electron gun and a time-of-flight measurement [Ves20]. Before, the measurements of the velocity distribution, which is crucial for the determination of the absolute thickness with the AMS, were performed with a channeltron [Täs12]. Therefore, one always had to replace the MCP system by the channeltron so that the operation of the cluster-jet beam dump had to be interrupted. This would not be possible at $\bar{\text{PANDA}}$ so that one detection system covering both tasks is very beneficial.

The MCP monitor system as shown in figure 3.14 consists of two MCPs in a Chevron stack and a phosphor screen, where the cluster-jet gets visible. By means of a prism one can look at this screen from the side with a CCD camera. More information on how the visualization and the velocity measurements work is given in section 3.6.3.

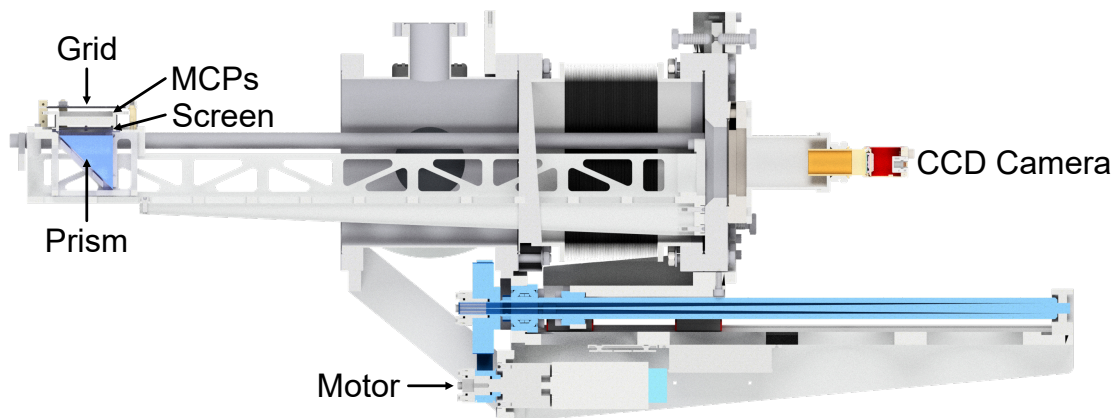


Figure 3.14: CAD drawing of the new removable MCP system. The MCP detector, consisting of two MCPs in Chevron assembly and a phosphor screen, is mounted on an arm that can be moved out of the chamber by means of a powerful motor. In front of the MCP, a grounded grid is mounted, and below it, a prism is used as mirror so that the image can be recorded by a camera from the side (created by D. Bonaventura, University of Münster, edited).

The measurements with the MCP requires the MCP detector to be placed into the cluster-jet so that it would block the path of the clusters into the last turbomolecular pump. Therefore, the MCP system is mounted on a movable arm. By means of a powerful motor of type Faulhaber Brushless DC-Servomotor Series 4490 X048 B the whole system can be moved to the side, where a shutter can separate the chamber with the MCP from the beam dump. This chamber is evacuated by a separate turbomolecular pump of type Leybold Turbovac 90i that also uses the beam dump pumping station, which will be discussed in section 3.5.5, for the fore vacuum.

Measurements with the new MCP monitor system were already performed at COSY with an interim setup where the MCP was mounted on a fixed arm into the old beam dump by replacing one of the turbomolecular pumps. These measurements are presented in section 5.6.

3.5.4 The new Electron Gun for the $\bar{\text{PANDA}}$ Target

The MCP monitor system needs the cluster-jet to be ionized. This can be done by the accelerator beam, but that would only ionize the overlap region and not the whole cluster-jet. Therefore, also an electron gun is foreseen for the ionization. Such an electron gun was already designed and built at the institute for nuclear physics at the University of Münster and was successfully used [Köh15, Täs12]. This electron gun is able to ionize the whole cluster-jet, and it also has the possibility to be pulsed, which is a necessary feature for velocity measurements via the time-of-flight method. Due to the success of the measurements it was decided to design a new electron gun with a very similar design, but to take a closer look into its exact geometry [Hum21].

The design of the electron gun foresees a filament from a halogen lamp as electron source, an acceleration electrode behind the filament, and an extraction orifice in electron beam direction. The acceleration electrode lies on a negative potential of, e.g., -150 V while the extraction orifice is grounded for continuous operation. For a pulsed operation, the extraction orifice can be set to a more negative potential of, e.g., -170 V to block the electron beam. It can then be grounded for a short period of time of, e.g., $20\text{ }\mu\text{s}$ to allow an electron pulse to pass the extraction orifice.

The optimization of the electron gun design was mainly focussing on the geometry of the acceleration electrode and the extraction orifice. Therefore, simulations in two steps have been performed. The first was the simulation of the electric field, which was then used in a second step to calculate the trajectories of the electrons. These simulations have been performed together with N. Humberg [Hum21].

The simulations of the electric field $\vec{E}$ need to solve the first Maxwell equation

$$\text{div} \vec{E}(\vec{r}) = \frac{\rho(\vec{r})}{\varepsilon_0} \quad (3.6)$$

with the charge density ρ and the vacuum permittivity ε_0 . By using the definition of the electric field as

$$\vec{E} = -\vec{\nabla} \phi \quad (3.7)$$

the Poisson equation

$$\Delta \phi(\vec{r}) = -\frac{\rho(\vec{r})}{\varepsilon_0} \quad (3.8)$$

follows [Nol16] that can be solved for the electric potential $\phi(\vec{r})$. One can then also use that the electric field will be simulated within the vacuum so that no free charges are present and thus $\rho(\vec{r}) = 0$ which then leads to Laplace's equation

$$\Delta \phi(\vec{r}) = 0 . \quad (3.9)$$

Due to the complex geometry of the electron gun, this equation has to be solved numerically, which was done in [Hum21] with the software package OpenFOAM [Ope25] that offers the solver *electrostaticFOAM* for the simulation of electrostatic problems. Here, Laplace's equation is solved in its integral form

$$\oint_{\partial V} \vec{\nabla} \phi(\vec{r}) \, d\vec{A} = 0 \quad (3.10)$$

via the finite volume method.

The second step of the simulations is the calculation of the electron trajectories. The equation of motion for a charge carrier with charge q in an electric field can be derived from the force

$$\vec{F} = q\vec{E}(\vec{r}) = -q\vec{\nabla} \phi(\vec{r}) , \quad (3.11)$$

which leads with $\vec{F} = m\vec{a}$ to the equation of motion

$$\frac{d^2}{dt^2} \vec{r} = -\frac{q}{m} \vec{\nabla} \phi(\vec{r}) . \quad (3.12)$$

This second order differential equation can be converted into two coupled first order differential equations by introducing the velocity $\vec{v} = \frac{d\vec{r}}{dt}$ giving

$$\frac{d}{dt} \begin{pmatrix} \vec{r} \\ \vec{v} \end{pmatrix} = \begin{pmatrix} \vec{v} \\ -\frac{q}{m} \vec{\nabla} \phi(\vec{r}) \end{pmatrix} , \quad (3.13)$$

which are then solved by the Runge-Kutta algorithm of fourth order [Hum21].

These simulations have been performed for different electrode geometries and distances between the acceleration electrode and the extraction orifice. The geometry that was found to give the best results is shown in the left of figure 3.15 while the electric potential and some resulting electron trajectories for this geometry are shown in the right of figure 3.15. Here, electrons were created inside the cylindrical volume of a filament with a radius of 0.5 mm and a length of 4 mm. The best geometry was chosen due to its homogeneity of the electron beam and its low divergence which showed a slope of (25.8 ± 0.7) mm/m, i.e., a half opening angle of $(1.48 \pm 0.05)^\circ$. More details on these simulations can be found in [Hum21].

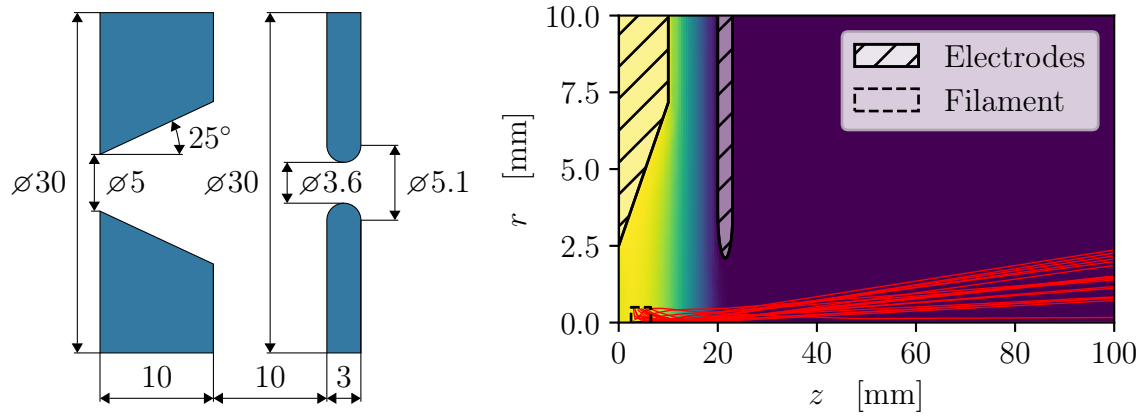


Figure 3.15: Left: Technical drawing of a cut through the best design of the acceleration electrode (left blue structure) and the extraction orifice (right blue structure) according to [Hum21]. The geometry is cylindrically symmetric, and all dimensions are given in mm. Right: Simulation of the electric field ϕ (yellow: -150 V, purple: 0 V) and electron trajectories in the electron gun [Hum21]. The shaded, hatched areas with a solid frame show the acceleration electrode and the extraction orifice while the dashed framed area is the area of the filament, where electrons are randomly created. To visualize the three-dimensional trajectories $r = \sqrt{x^2 + y^2}$ is defined.

Following these numerical studies, the new electron gun was designed in a modular way, that allows for an easy exchange of the filament or of one of the electrodes. A CAD drawing of the final design is shown in the left of figure 3.16. The base of the electron gun is a CF40 19-pin vacuum feedthrough. All other components of the electron gun are mounted directly into this feedthrough to ensure the insulation between the electrodes and the outer housing. The filament is extracted from a halogen lamp (10 W, 12 V), where the glass body was removed. It is important that the filament is oriented such that its symmetry axis coincides with the symmetry axis of the electron gun and the flight direction of the electrons, because that reduces the size of the resulting electron

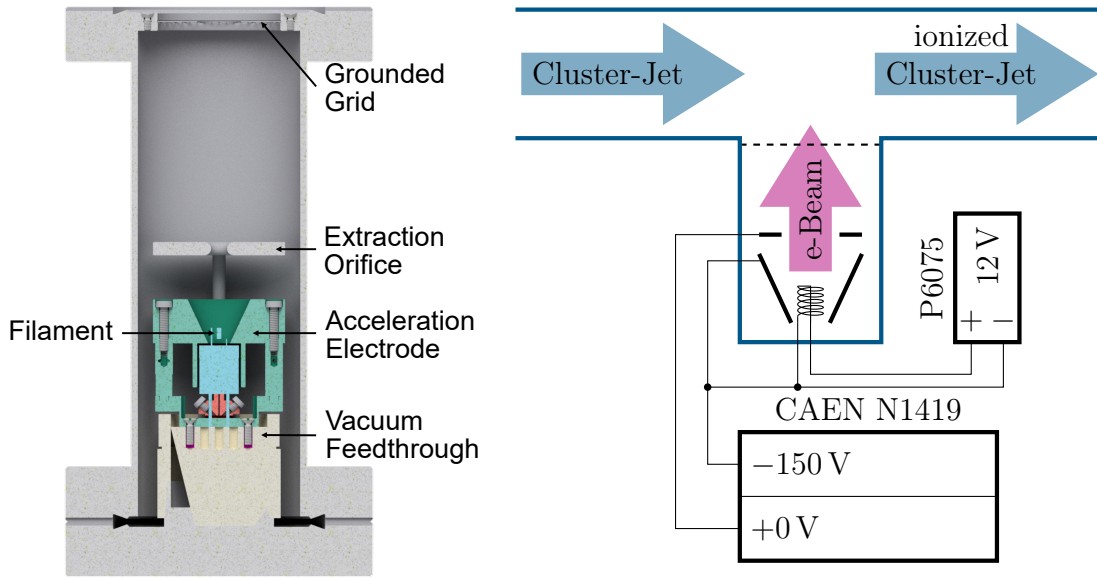


Figure 3.16: Left: CAD drawing of the new electron gun for the $\bar{\text{P}}\text{ANDA}$ target. The filament and the electrodes are directly mounted into a CF40 vacuum feedthrough. The electron gun ends with a grounded grid (created by D. Bonaventura, University of Münster, edited). Right: Sketch of the cabling of the electron gun.

beam. It is then mounted into four pins of the feedthrough, two pins are connected to each side of the filament. The acceleration electrode and the extraction orifice are also mounted each by two screws into two pins of the feedthrough.

After finishing the design of the electron gun, it was built in the institute's mechanical workshop. First tests were performed together with M. Scharpey [Sch22]. The electron gun was installed at the beam line of the Münster prototype target. The filament was powered with up to 12 V by a PeakTech P6075 power supply, while the acceleration electrode and the extraction orifice were powered by two channels of a CAEN N1419 HV power supply. Both devices were integrated into the local EPICS slow control system, which is described in section 3.7. To ensure that the electrons can be accelerated, the negative pin of the filament was connected to the potential of the acceleration orifice while the extraction orifice was grounded. The cabling of the electron gun is shown on the right of figure 3.16. The performance of the electron gun was then tested by measuring its beam current. Therefore, a blank flange was installed at the opposite side of the beam line so that the electron beam hits this flange. Furthermore, the flange was insulated from the whole target system via a ceramic vacuum tube and connected to a high precision ampere meter. These measurements were performed with the old and the new electron gun and the results for a filament voltage of 9 V are shown in

figure 3.17. This demonstrates that the new electron gun shows a significant better performance resulting from the optimized geometry. However, it should be noted that the old gun uses a different filament which has already been operated for some time and could be degraded. Nevertheless, this measurement shows, that the new electron gun fulfills the requirements for the planned measurements at the $\bar{\text{P}}\text{ANDA}$ target. More details on the performance tests can be found in [Sch22].

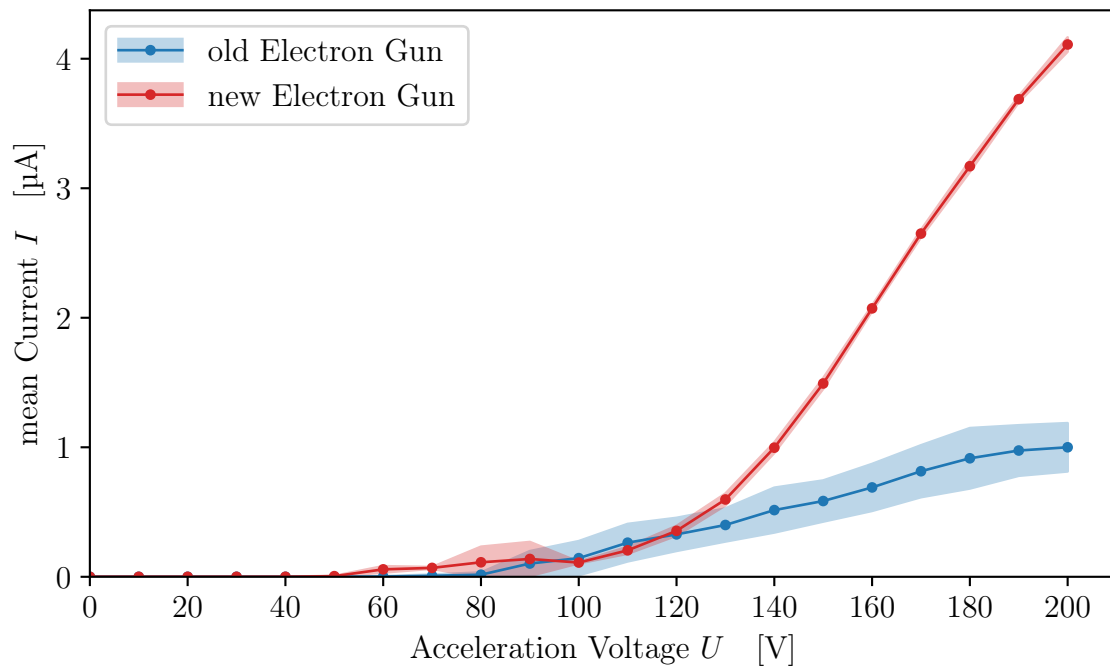


Figure 3.17: Comparison of the beam current of the old and the new electron gun for different acceleration voltages and a filament voltage of 9 V. The current was measured at a blank flange on the opposite side of the electron gun that was insulated by a ceramic vacuum tube. These measurements were performed in [Sch22].

3.5.5 Mechanical Installation and Pumping Station

The whole beam dump as shown in figure 3.18 is planned to be mounted underneath the $\bar{\text{P}}\text{ANDA}$ solenoid magnet. Therefore, four mounting points around the hole in the solenoid will establish the connection between the solenoid and the beam dump. These will carry the whole load of the beam dump system and also allow for translational alignment of the beam dump system with the target source and the beam line. The connection to the target beam line is created by a similar snap connector as used at the target source. This is necessary as this flange will not be accessible. Instead, the

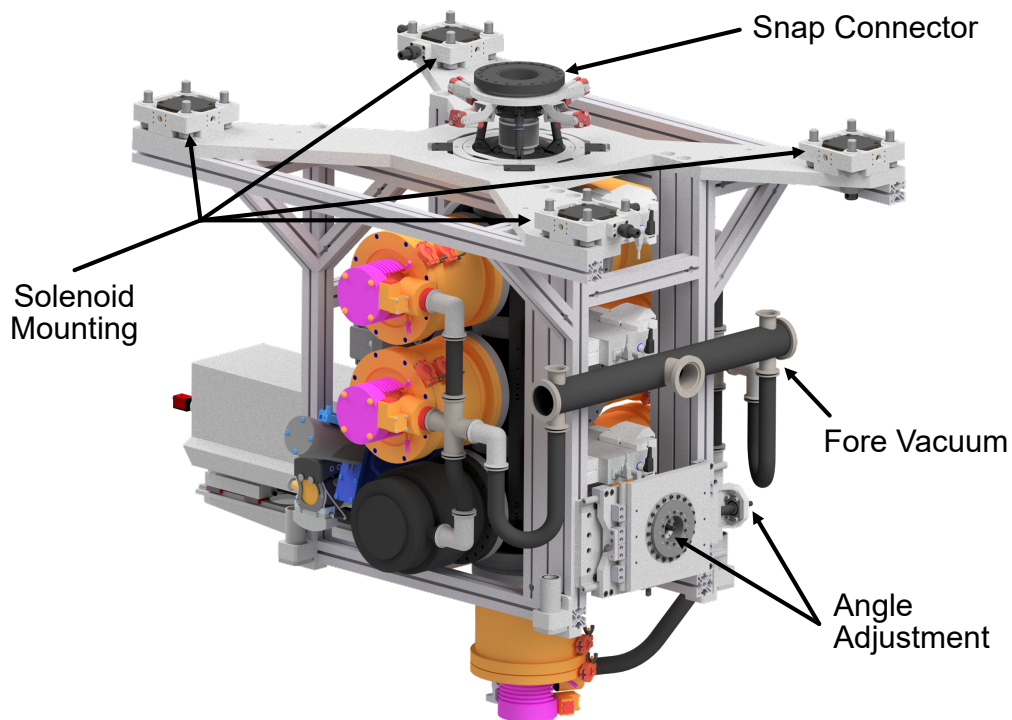


Figure 3.18: CAD drawing of the whole beam dump system. It will be installed underneath the $\bar{\text{P}}\text{ANDA}$ solenoid magnet at four mounting points. The beam dump is connected to the target beam line via a snap connector that establishes the connection by the use of pressurized air without the need of direct access to it. A final adjustment of the angle of the whole beam dump system can be done in two axes by the adjustment unit that is connected to the third beam dump stage (created by D. Bonaventura, University of Münster, edited).

flanges of the target beam line and the beam dump will be connected by four clamps of the snap connector with pressurized air. Once they are tightened no pressurized air is needed to hold the connection.

The large distance between the beam dump and the nozzle requires a precise adjustment of the beam dump. Therefore, the three beam dump stages can be tilted with respect to the Kanya frame they are mounted in. This is done by a special alignment unit that is connected to the third beam dump stage. By means of two screws the angle of the beam dump can be adjusted in two axes.

The seven turbomolecular pumps at the three beam sump stages are connected to one common fore vacuum line. An additional fore vacuum line is needed for the turbomolecular pump at the MCP chamber behind the shutter so that the MCP chamber and the beam dump can be evacuated separately. These fore vacuum lines are then connected to a new pumping station that consists of a Leybold TRIVAC D

65 B rotary vane pump and a Leybold RUVAC WSU 501 roots pump as shown in figure 3.19. Shutters and valves allow evacuating both vacuum systems separately or at once. More details on the design of the beam dump pumping station can be found in [Ves24]. The whole vacuum system of the new $\bar{\text{P}}\text{ANDA}$ beam dump system can be seen in figure 3.20.

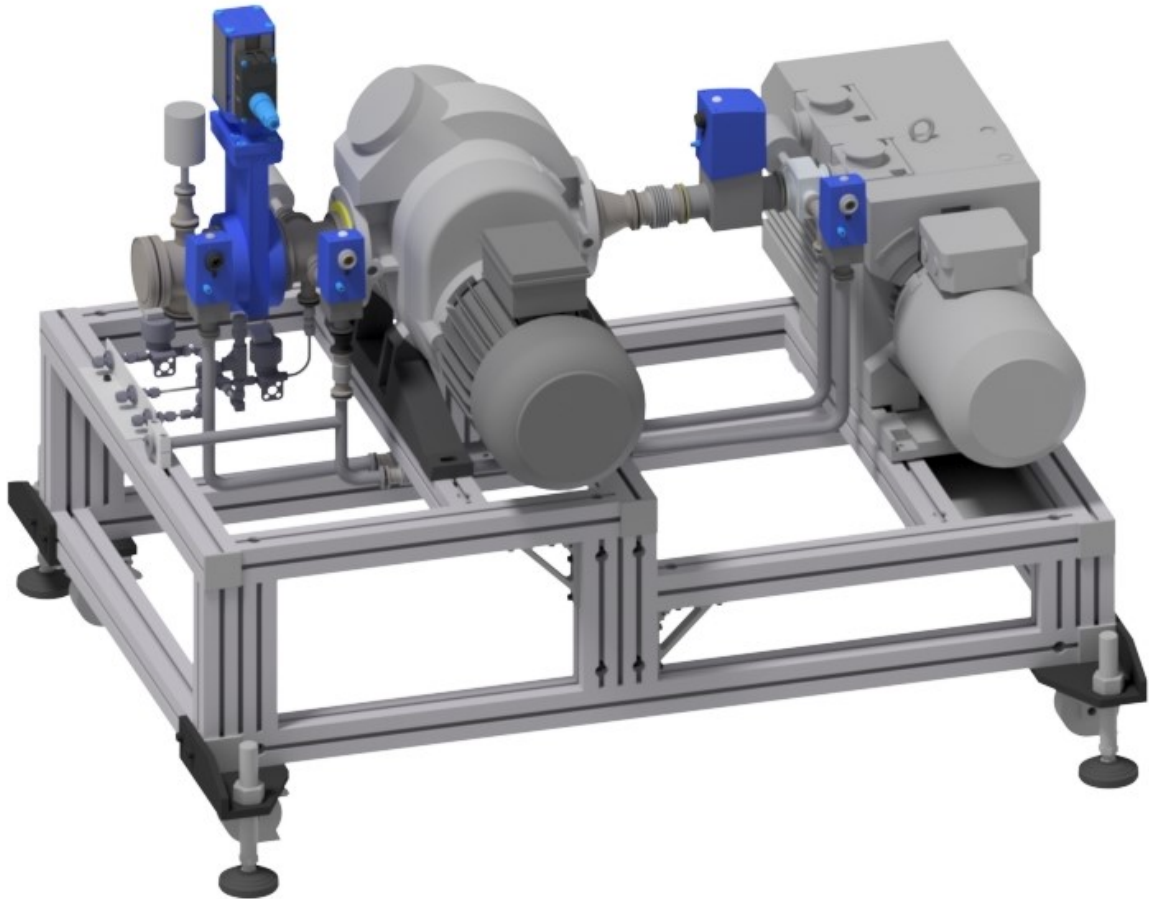


Figure 3.19: CAD drawing of the pumping station for the new $\bar{\text{P}}\text{ANDA}$ beam dump. The vacuum is established by a Leybold TRIVAC D 65 B rotary vane pump (right) and a Leybold RUVAC WSU 501 roots pump (left) (created by F. Rummler, University of Münster, edited).

3.6 Monitor Systems for the $\bar{\text{P}}\text{ANDA}$ Cluster-Jet Target

The $\bar{\text{P}}\text{ANDA}$ cluster-jet target will be equipped with several monitor systems that were already mentioned in the previous sections. These systems will allow, e.g., monitoring the cluster-jet during the adjustment over the whole range from the source down to the

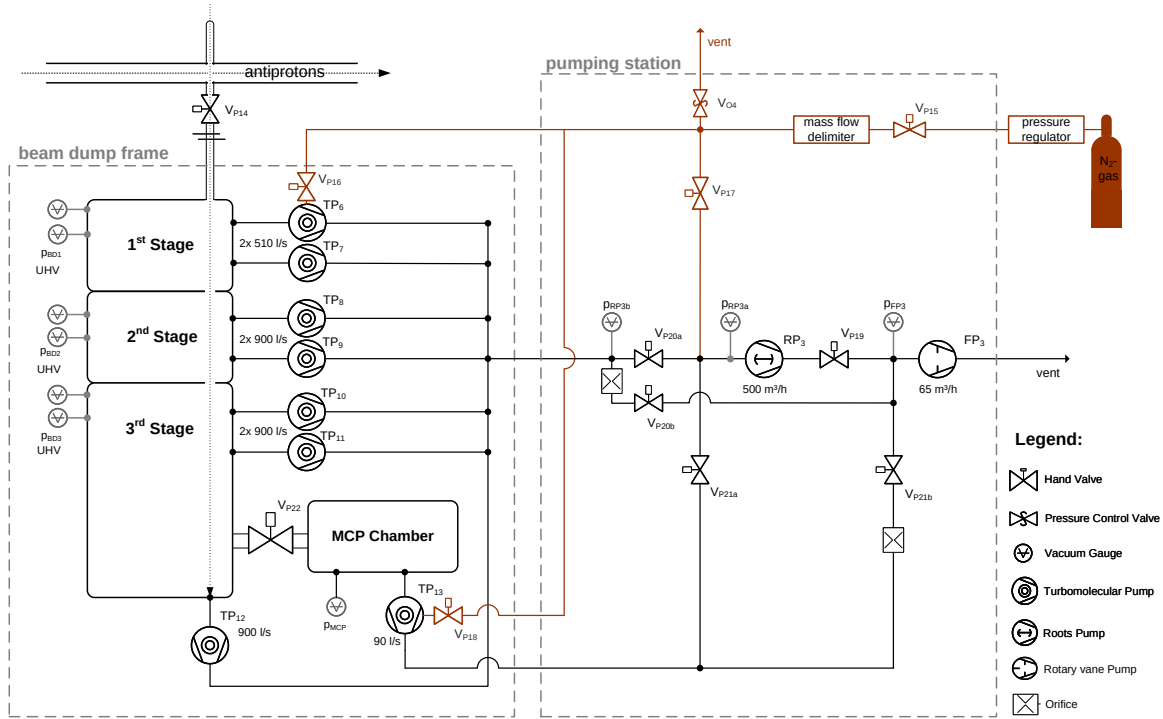


Figure 3.20: The vacuum system of the new $\bar{\text{PANDA}}$ target beam dump (left, this thesis) and the beam dump pumping station (right, [Ves24]). The turbomolecular pumps listed here are those suggested in [PAN12a] and are still subject to change. This is a continuation of figure 3.6 (created with S. Vestrick, University of Münster).

beam dump or measuring its absolute target thickness. In the following, the working principle of the optical monitor systems, the absolute thickness monitor system, and the MCP monitor system is described in more detail.

3.6.1 The Optical Monitor System

Two optical monitor systems will be installed at the $\bar{\text{PANDA}}$ cluster-jet target. The first will be located at the skimmer chamber, where it monitors the cluster beam before entering the skimmer, while the second system is located at the TVC to monitor the jet after passing the skimmer and the collimator. Each of these systems consists of two CCD cameras (pco.pixelfly usb) that look at the jet under an angle of 90° with respect to each other. In between, the jet is illuminated by a light source. In case of the optical monitor system at the skimmer chamber, this is an LED matrix in combination with a diffuser, while the system at the TVC uses a laser diode due to the smaller areal density of the jet behind the collimator [Het17]. Figure 3.21 shows example images taken by the four different cameras.

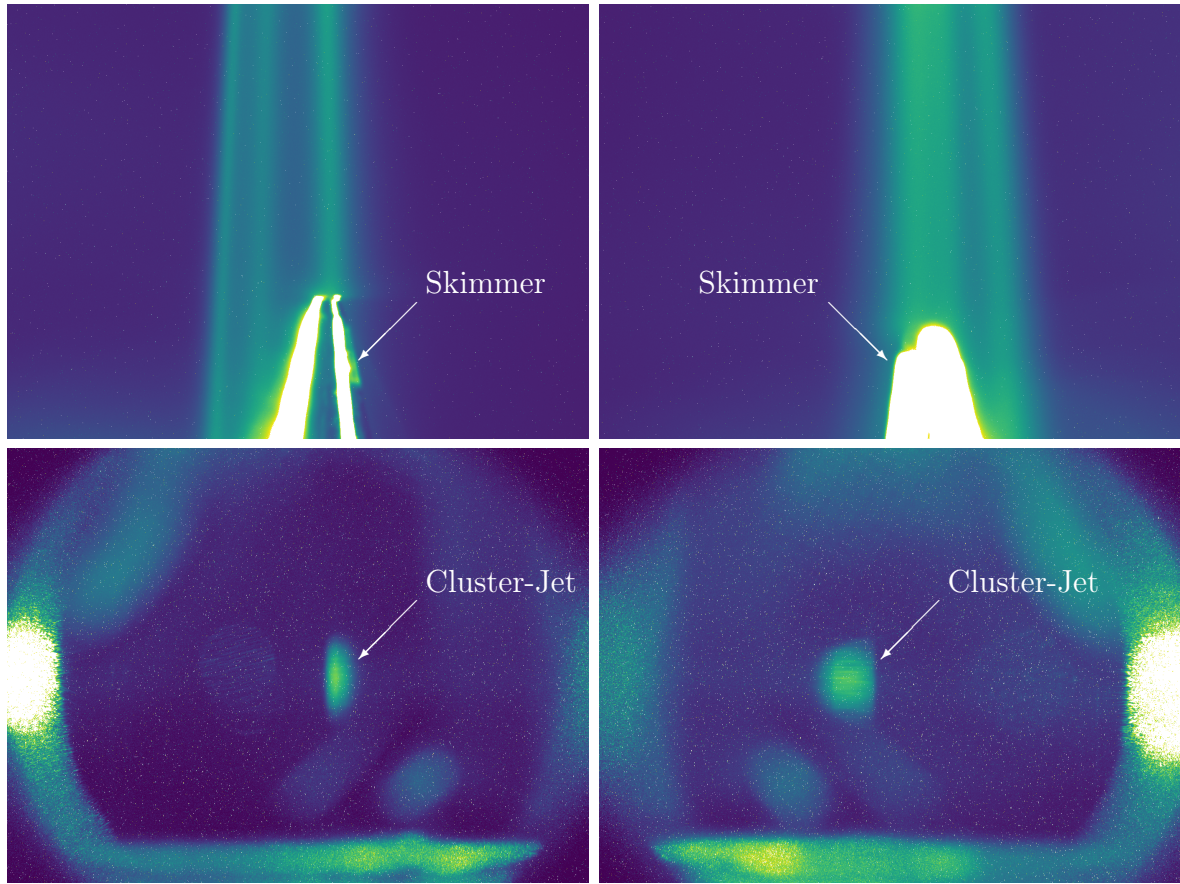


Figure 3.21: Images taken by the optical monitor systems in the skimmer (top) and transition vacuum chamber (bottom) with the target being operated at 24.5 K and 18 bar. The pictures on the left are taken by cameras mounted in accelerator beam direction, while the cameras on the right are mounted perpendicular to it. The formation of core beams is clearly visible in the skimmer chamber. For better contrast, the pictures from the TVC are scaled logarithmically, and the exposure time of the TVC cameras is longer. In this case, the exposure times are 2 s in the skimmer chamber and 10 s in the TVC.

In the images in the skimmer chamber one can clearly see the core beams that form when operating the target in the liquid region. These core beams have the highest density and therefore, the optical monitor system is crucial to monitor whether a core beam hits the skimmer while adjusting the nozzle tilting system. The challenge here is to find the maxima in the two images that belong to the same core beam. The images from the TVC show the rectangular cluster-jet from both sides. This can be used to verify, if skimmer and collimator are well aligned as otherwise the beam spot would be narrower. Furthermore, after proper calibration the location of the jet can be compared with the center of the chamber and also a density could be extracted from the intensity of the beam spot as shown in [Klo18].

3.6.2 Absolute Thickness Monitoring with the AMS

The Absolute thickness Monitor System (AMS) is commonly used in cluster-jet targets. Such a system is installed at the Münster prototype target and above the beam dump of the $\bar{\text{PANDA}}$ target at COSY. In the future, the new AMS based on Faulhaber motors will be installed into the second stage of the new beam dump. All these systems have the same working principle. Two rods are scanning from two directions through the cluster-jet. Clusters hitting the rods will break up and cause a pressure increase. From this pressure increase, the absolute target thickness can be extracted. In the following the theoretical background of the AMS is described which is based on [Her13, Köh15].

The pressure in the chamber is given by the flow q_{pV} and the pumping speed S at this chamber as

$$p = \frac{q_{pV}}{S} = \frac{q_m RT}{SM}, \quad (3.14)$$

which can also be expressed by using the ideal gas law as function of the mass flow $q_m = \dot{m}$ with the universal gas constant R , the temperature $T \approx 293.15 \text{ K}$ of the gas after hitting the rods and the walls of the chamber, and the molar mass M of the gas. In case of the AMS, q_m is the mass flow that hits the rod and thus stays in the chamber and creates a pressure increase. The mass flow hitting the rod depends on the position of the rod within the cluster-jet that is propagating in y -direction. This can be described by an integral over the rod area as

$$q_m(x) = v \int_{-\infty}^{\infty} \int_{x-d/2}^{x+d/2} \rho(x', z') dx' dz' \quad (3.15)$$

with the rod position x , the rod diameter d , the cluster velocity v , and the volume mass density ρ of the cluster-jet. With defining

$$\rho(x', z') = \rho_0 \cdot \tilde{\rho}(x', z') \quad (3.16)$$

the resulting pressure curve [Her13, Köh15] for a scan with the AMS can be derived by using equations 3.14, 3.15, and 3.16 and is given by

$$p(x) = p_{0,a} \int_{-\infty}^{\infty} \int_{x-d/2}^{x+d/2} \tilde{\rho}(x', z') dx' dz' + p_{\text{back}} \quad (3.17)$$

with

$$p_{0,a} = \rho_0 \frac{vRT}{SM} \quad (3.18)$$

and p_{back} being the pressure of the residual gas in the chamber. Due to the integral, the scaling factor $p_{0,a}$ has the dimension of a pressure per area and cannot be interpreted as the pressure increase.

The actual pressure profile $p(x)$ now depends on the shape of the cluster-jet, which is given by the opening of the collimator. Here, mainly two shapes are commonly used. A rectangular collimator is mounted into the $\overline{\text{PANDA}}$ cluster-jet target [Her13] while the Münster prototype target uses a circular target [Köh15]. Both shapes are discussed in the following with the assumption of a homogeneous cluster-jet that is smeared out at its edges.

Rectangular Collimator

For the rectangular collimator the homogeneous cluster-jet is described by a two-dimensional rectangular function

$$f(x, z) = f_x(x) \cdot f_z(z) \quad (3.19)$$

with

$$f_x(x) = \begin{cases} 1 & \text{for } |x - x_0| \leq b_x/2 \\ 0 & \text{else} \end{cases} \quad \text{and} \quad f_z(z) = \begin{cases} 1 & \text{for } |z - z_0| \leq b_z/2 \\ 0 & \text{else} \end{cases}, \quad (3.20)$$

where b_x , b_z , x_0 , and z_0 are the widths and center positions of the cluster-jet at the AMS in x - and z -direction. This perfectly rectangular shape is smeared out, which is described by a convolution with the normalized two-dimensional Gaussian function

$$g(x, z) = g(x) \cdot g(z) \quad (3.21)$$

with

$$g(x) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{x^2}{2\sigma^2}\right). \quad (3.22)$$

The normalized density function is then given by

$$\begin{aligned} \tilde{\rho}(x, z) &= f(x, z) * g(x, z) \\ &= f_x(x) * g(x) \cdot f_z(z) * g(z) \\ &= \tilde{\rho}_x(x) \cdot \tilde{\rho}_z(z) \end{aligned} \quad (3.23)$$

with

$$\begin{aligned}\tilde{\rho}_x(x) &= \int_{-\infty}^{\infty} f_x(t) \cdot g(x-t) dt \\ &= \frac{1}{2} \left[\operatorname{erf} \left(\frac{x-x_0+b_x/2}{s} \right) - \operatorname{erf} \left(\frac{x-x_0-b_x/2}{s} \right) \right]\end{aligned}\quad (3.24)$$

and similarly

$$\tilde{\rho}_z(z) = \frac{1}{2} \left[\operatorname{erf} \left(\frac{z-z_0+b_z/2}{s} \right) - \operatorname{erf} \left(\frac{z-z_0-b_z/2}{s} \right) \right] \quad (3.25)$$

where the smearing parameter $s = \sqrt{2}\sigma$ is introduced [Her13]. The function in equation 3.23 is normalized in a way that for $s \rightarrow 0$ its maximum is 1, but since this is normally not the case, the maximum volume density in the center of the cluster-jet is according to equation 3.16 given by

$$\rho_{\max} = \rho_0 \cdot \tilde{\rho}(x_0, z_0) . \quad (3.26)$$

The density function can then be plugged into equation 3.17 leading to the pressure curve of the AMS for a rectangular collimator [Her13]

$$\begin{aligned}p(x) &= p_{0,a} \int_{x-d/2}^{x+d/2} \tilde{\rho}_x(x') dx' \int_{-\infty}^{\infty} \tilde{\rho}_z(z') dz' + p_{\text{back}} \\ &= p_{0,a} b_z \int_{x-d/2}^{x+d/2} \tilde{\rho}_x(x') dx' + p_{\text{back}} ,\end{aligned}\quad (3.27)$$

where the second integral was solved by using Fubini's law [Zei13]:

$$\begin{aligned}\int_{-\infty}^{\infty} \tilde{\rho}_z(z') dz' &= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_z(t) \cdot g(z'-t) dt dz' \\ &= \int_{-\infty}^{\infty} f_z(t) \int_{-\infty}^{\infty} g(z'-t) dz' dt \\ &= \int_{-\infty}^{\infty} f_z(t) dt = b_z .\end{aligned}\quad (3.28)$$

The other integral cannot be solved analytically. Analogously, the pressure curve $p(z)$ for the other rod can be derived.

The volume mass density ρ can be used to calculate the atomic density ρ_H for hydrogen as

$$\rho_H(x, z) = 2\rho(x, z) \frac{N_A}{M_{H_2}} \quad (3.29)$$

with the Avogadro constant N_A and the molar mass M_{H_2} of hydrogen. The factor 2 is the number of atoms in a hydrogen molecule. Thus, the maximum density for the rectangular collimator is

$$\begin{aligned} \rho_{H,\max} &= 2\rho_0 \frac{N_A}{M_{H_2}} \tilde{\rho}(x_0, z_0) \\ &= 2p_{0,a} \frac{SN_A}{vRT} \operatorname{erf}\left(\frac{b_x}{2s}\right) \operatorname{erf}\left(\frac{b_z}{2s}\right) \end{aligned} \quad (3.30)$$

where equations 3.18, 3.23, and 3.26 were used. The maximum areal density or target thickness in the center of the cluster-jet is calculated by integrating equation 3.29 in accelerator beam direction [Her13]:

$$n_T = \int_{-\infty}^{\infty} \rho_H(x_0, z) dz = 2p_{0,a} \frac{SN_A}{vRT} b_z \operatorname{erf}\left(\frac{b_x}{2s}\right). \quad (3.31)$$

Circular Collimator

For the circular collimator similar calculations have been performed in [Köh15]. Here, the density function is given by

$$\tilde{\rho}(x, z) = \frac{1}{2} \left(\operatorname{erf}\left(\frac{r(x, z) + R}{s}\right) - \operatorname{erf}\left(\frac{r(x, z) - R}{s}\right) \right) \quad (3.32)$$

with

$$r(x, z) = \sqrt{(x - x_0)^2 + (z - z_0)^2}, \quad (3.33)$$

the cluster-jet radius R , the smearing parameter s , and the center position (x_0, z_0) of the cluster-jet. Plugging this equation into the pressure profile in equation 3.17 leads to a two-dimensional integral that cannot be solved analytically but only numerically which makes a fit with this function slower than for the rectangular collimator, where only a one-dimensional integral has to be solved numerically. The atomic target density for this collimator shape is

$$\rho_{H,\max} = 2p_{0,a} \frac{SN_A}{vRT} \operatorname{erf}\left(\frac{R}{s}\right) \quad (3.34)$$

and the target thickness is given by

$$n_T = 2p_{0,a} \frac{SN_A}{vRT} \cdot 2R. \quad (3.35)$$

GUI for Pressure Profile Fitting

The target thickness is extracted from the measured pressure profiles with the AMS by fitting the expected pressure curve to the data. Afterwards, the target thickness can be calculated from the fit parameters, the pumping speed, and the cluster velocity. Since this is a regular task, the graphical user interface shown in figure 3.22 was developed during the course of this thesis that performs all these steps. First, one loads the profile data for either one or both directions. These are displayed in the plot windows on the

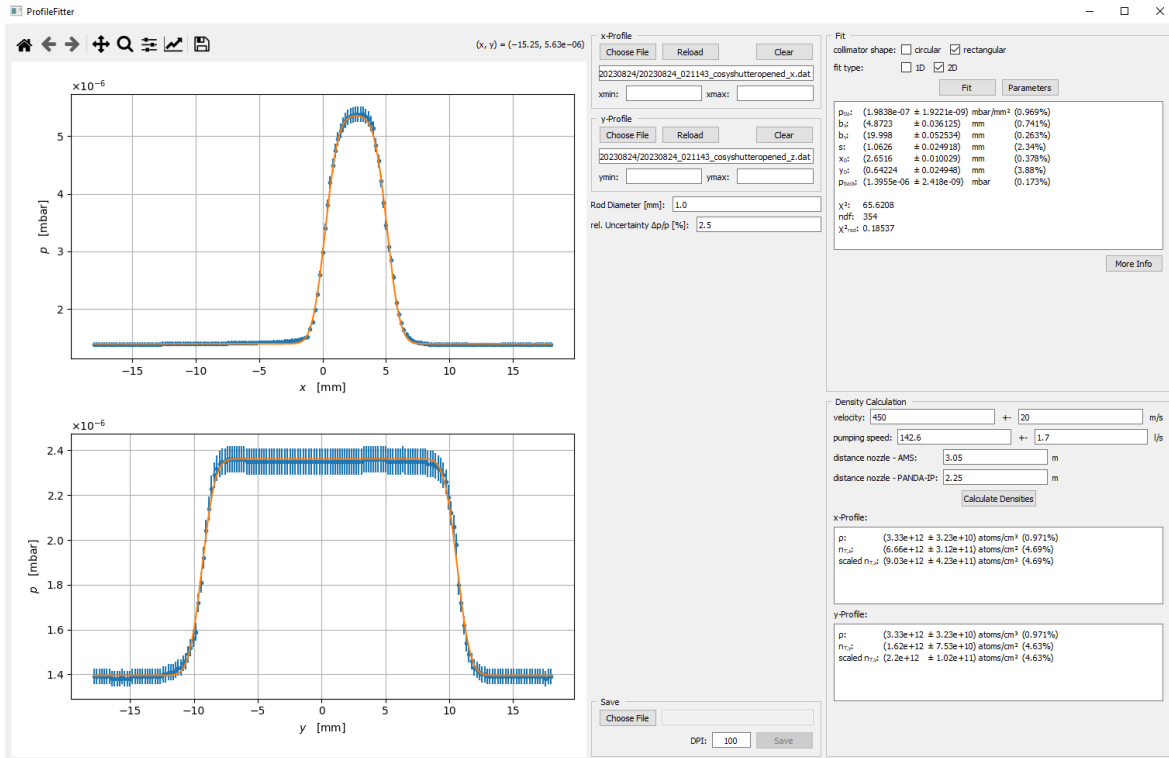


Figure 3.22: Screenshot of the graphical user interface for the fitting of the pressure profiles measured with the AMS. The data files can be loaded in the center where also the data range can be restricted, the rod diameter can be changed and the uncertainty of the pressure measurements can be selected. The uncertainty is typically given as 2.5 % reproducibility [Köh15]. The data of both profiles is plotted on the left. On the top right, the settings for the fit can be chosen with the fit results following in the text field below. In the bottom right, the volume density and target thickness calculation is displayed.

left. Here, it is also possible to restrict the data region used for a fit and to change the diameter of the rod and the uncertainty of the pressure measurements. Here, a default value of 2.5 % reproducibility is chosen [Köh15]. Afterwards, one can select the shape of the collimator and when both profiles were loaded, one can also decide whether both profiles are fitted separately (1D) or a global fit (2D) is performed where both profiles share parameters like the scaling parameter $p_{0,a}$, the constant background p_{back} , or in case of the circular collimator also the radius R .

The result of the fit is displayed in the text box on the upper right, which includes the parameters, their uncertainties, and the reduced χ^2 value. More information about the convergence of the fit and the covariance matrix is displayed in a separate window when pressing *More Info*. The last step is calculating the volume density and target thickness. Therefore, the pumping speed, the cluster velocity, and their uncertainties need to be given. These values are stored for the next usage of the program. Afterwards, the results are displayed, including uncertainties, which are calculated with considering the correlation of all fit parameters. The target thickness is also scaled by the intercept theorem to the interaction point, which requires knowledge of the distances between nozzle and AMS, and nozzle and interaction point. As default value for the rectangular collimator, the distance of nozzle to AMS is set to 3.05 m, which corresponds to the location of the AMS at the setup at COSY. For the circular collimator the distance of 2.1 m of the AMS at the Münster prototype target is used. The distance between nozzle and interaction point is set to the $\bar{\text{P}}\text{ANDA}$ value of 2.25 m. Finally, the plot including the fit curves can also be saved.

The complete program was written in Python and is divided into two parts. The first file contains all important functions for fitting with the *iminuit* package [Dem⁺22] and plotting so that these can be imported as a module into other python scripts that, e.g., automatize the fitting procedure for many profiles. The second file contains the graphical user interface that was written with the help of the *PyQt5* package [Riv25]. Here, all functions of the first module are included and used.

3.6.3 Beam Visualization and Velocity Measurements with an MCP

An MCP monitor system as foreseen for the $\bar{\text{P}}\text{ANDA}$ target beam dump (see section 3.5.3) can be used for two purposes. Its main use will be the two-dimensional visualization of the cluster-jet. Compared to other monitor systems, the MCP in combination with a camera has the advantage that pictures can be taken within some seconds. Thus, it can be assumed as a live monitoring system in contrast to the AMS

that takes some minutes for a single scan. The exact exposure time needed depends on the gain of the MCP system, the density of the jet, and the ionization by the electron gun or the accelerator beam. The second use is the measurement of the cluster velocity with a Time-of-Flight (ToF) setup. In the following both applications are described in more detail.

2D Visualization with an MCP Detector

The MCP detector systems used for the visualization of cluster-jet target beams [Kho⁺14, Köh15, Ves20] are stacks of two MicroChannel Plates (MCP) in a chevron assembly as shown in figure 3.23. Charged clusters are accelerated between the grounded grid in front of the MCP that has a center-to-center distance of 2.7 mm and a width of 0.2 mm and the surface of the first MCP that lies on a negative potential of, e.g., -1500 V. When the clusters enter a channel of the MCP and hit its wall, they create free electrons that are accelerated into the channels by a field gradient. This gradient is created by the negative potential on the surface of the first MCP and by grounding the back of the second MCP. During this acceleration they will hit the channel walls several times leading to an electron avalanche. This magnification is

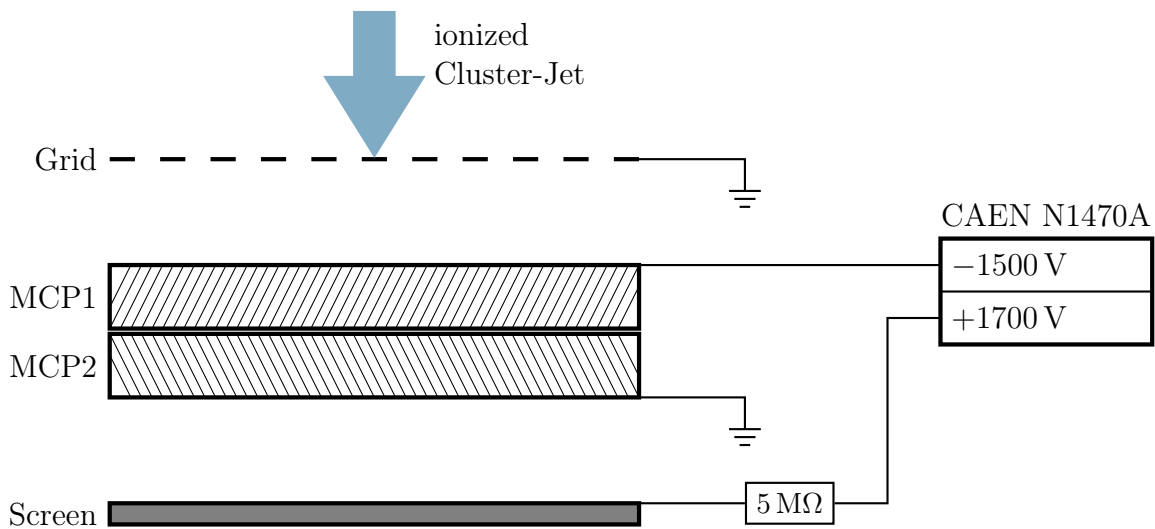


Figure 3.23: Sketch of the MCP setup for 2D cluster beam visualization. The ionized clusters are accelerated between the grounded grid and the negative potential on the surface of the first MCP. The clusters then hit electrons out of the MCP that are accelerated into the channels by the field gradient. Within the channels an electron avalanche is produced that gets finally accelerated onto the phosphor screen, which then emits light that can be detected by a CCD camera.

increased by the second MCP, where the channels are tilted to the other side, so that no electron or ion can fly straight through a channel without hitting its walls. The gain of such an MCP assembly depends on several aspects like the ratio $\alpha = L/d$ of channel length L and diameter d . This ratio is often in the range of 40 to 60. Also the supplied voltage plays an important role, as the gain shows a close to exponential behavior for the voltage [Ham21]. To make the created electrons visible, the MCP assembly is followed by a phosphor screen. The screen is connected to a positive potential of, e.g., 1700 V to accelerate the electrons onto it. This causes the phosphor to emit light that can be detected by a CCD camera with exposure times of some seconds. The specifications of the circular MCP detector (DV5615P by TOPAG Lasertechnik GmbH) that will be used for the $\bar{\text{P}}\text{ANDA}$ target beam dump are given in table 3.1. This new MCP detector was taken into operation at the Münster prototype target within [Obs23].

Table 3.1: Specifications of the MCP detector system that will be used for the $\bar{\text{P}}\text{ANDA}$ target beam dump consisting of two MCPs in chevron assembly and a phosphor screen.

TOPAG DV5615P	
Assembly type	Chevron
Diameter of Active Area	50 mm
Channel Diameter	15 μm
Outer Detector Diameter	< 82 mm
Detector Height	< 18 mm
min. Gain	10^7
Phosphor Screen	P43
Resistance	50 M Ω to 200 M Ω
Supply Voltage	< 2200 V

Cluster Velocity Measurement with a ToF Setup

The described MCP system can also be used for a Time-of-Flight (ToF) setup as shown in figure 3.24. Here, the clusters are ionized by the electron gun that was described in section 3.5.4 in a pulsed operation mode. Therefore, the extraction orifice lies on a more negative potential than the acceleration orifice so that electrons cannot pass it. Only for a short moment, the potential of the extraction orifice is set to ground by means of a HV switch that is triggered by a pulse generator leading to a short electron pulse in the order of 20 μs . This results in a short pulse of ionized clusters that will create a signal at the MCP as mentioned before. For this measurement, the

phosphor screen is not connected to a high voltage source but instead the electrons hitting the screen create a signal that can be measured by using a high pass filter, a preamplifier, and an amplifier. The created signal is then the stop signal, while the pulse that triggers the HV switch for the electron gun is the start signal.

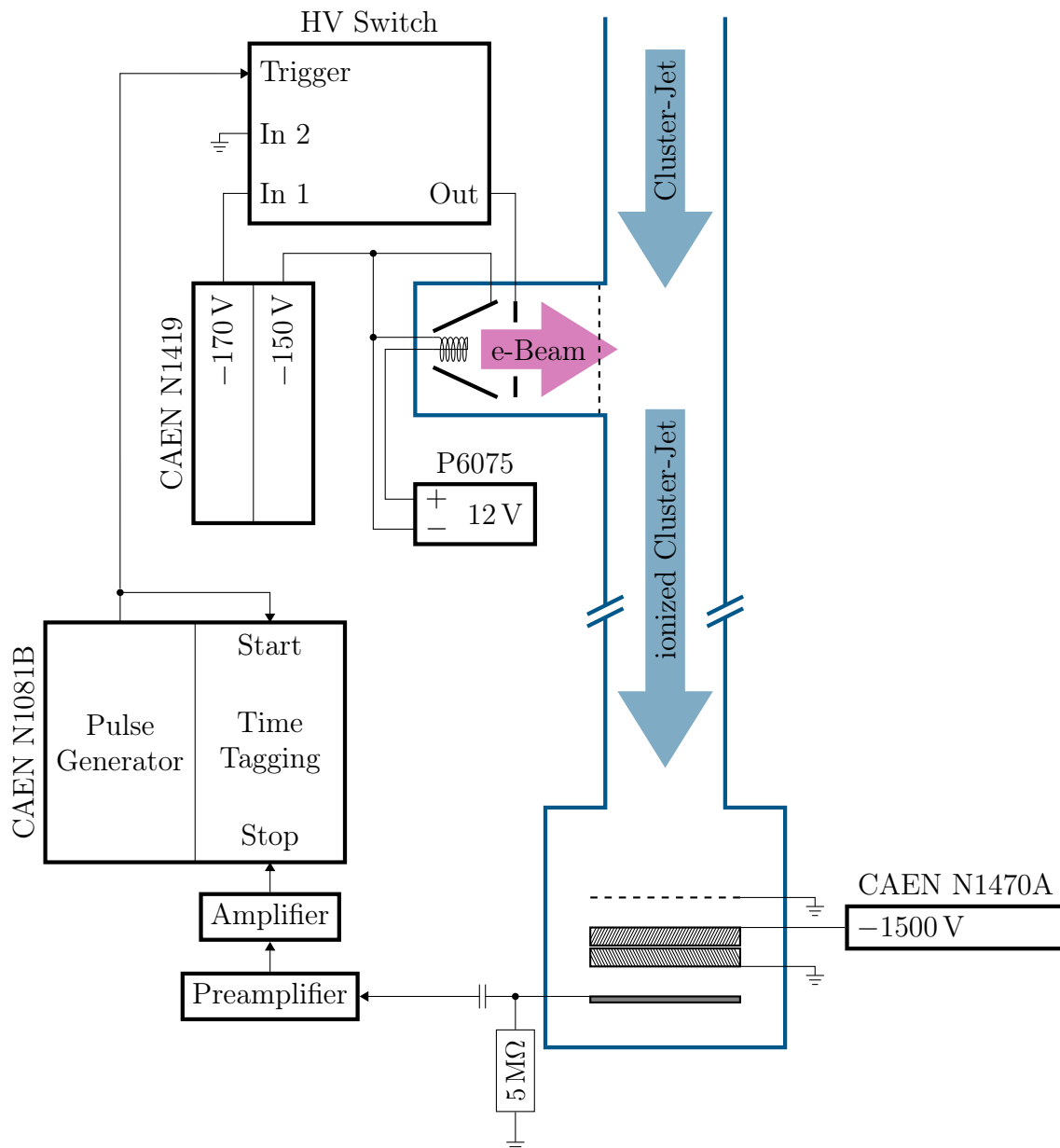


Figure 3.24: ToF Setup for the $\bar{\text{PANDA}}$ cluster-jet target. The cluster beam is ionized by a pulsed electron gun. The ionized clusters then create an electron avalanche in the MCP which can be detected as signal at the phosphor screen. The trigger signal for the electron gun as start signal and the detected signal as stop signal are then fed into a logic unit for the time-of-flight measurement.

These measurements have been routinely used at the Münster prototype target to determine the cluster velocity [Täs⁺13], which is calculated from the flight time and the length of the flight path. It requires a proper calibration to determine, e.g., the time offset due to the electronics. This is done by using a calibration source that emits a gamma signal ($t = 0$) as well as different hydrogen ions (H^+ , H_2^+ , H_3^+) [Sch24, Täs12]. Within this thesis a new setup for the electronics was designed that will allow for higher rates and a more compact setup with fewer devices. The filament of the electron gun is powered by a PeakTech P6075 linear power supply with two channels, while the acceleration electrode and the extraction orifice are powered by a CAEN N1419 4-channel HV power supply. These two devices allow operating up to two electron guns which might be necessary for the $\bar{\text{P}}\text{ANDA}$ setup. For the beam visualization an electron gun in the first stage of the new beam dump is foreseen so that the ionized clusters cannot be deflected by the magnetic field of the $\bar{\text{P}}\text{ANDA}$ solenoid. Additionally, for the ToF measurements the distance between the electron gun and the MCP might be too small, so that a second electron gun should be installed at the source. The MCP and for the beam visualization also the phosphor screen will be connected to a CAEN N1470A two-channel HV power supply. All power supplies are remotely controllable so that they can be integrated into the local EPICS slow control. The CAEN modules have the additional advantage that they can be daisy-chained which allows scaling the number of these modules easily.

In the old setup a microcontroller was used for the time measurement [Täs12] that did not allow for more than one stop signal for each start signal. Therefore, the signal rate had to be chosen so low, that not more than one event per start pulse is expected, as otherwise only the fastest cluster would be measured. For the new setup, it was chosen to use the CAEN N1081B four-fold programmable logic unit. This allows to detect multiple events per start pulse and has also the possibility to replace other devices that were used before. Its second main function will be to also create the start signals needed by the HV switch via its pulse generator function. Furthermore, it makes the use of a discriminator for the stop signals redundant as the inputs of the logic unit have an integrated programmable discriminator. Parts of this new setup have been successfully taken into operation in cooperation with M. Scharpey, where a record rate of more than 90 Hz was reached while the old setup delivered a rate in the order of 1 Hz [Sch22]. This shows the great potential of this new setup to make the measurements much faster. Further developments like the design of a new HV switch and its operation together with the power supply have been performed in [Sch24]. Furthermore, the integration of the new hardware into the local EPICS slow control is described in section 3.7.2.

3.7 The $\overline{\text{PANDA}}$ Target Slow Control System

All subdetectors of the $\overline{\text{PANDA}}$ experiment including the target will be controlled by a common Detector Control System (DCS). The requirements for this system reflect the way $\overline{\text{PANDA}}$ is designed and how $\overline{\text{PANDA}}$ will be constructed [PAN20a]:

- Since $\overline{\text{PANDA}}$ will consist of several subsystems that will be included in stages, the control system should be **scalable** and **distributed** so that the subsystems can be operated autonomously if necessary during, e.g., commissioning.
- Nevertheless, the systems should be **consistent** so that the whole experiment can be controlled from a single application.
- Furthermore, the system needs to be highly **available** to minimize downtimes and **efficient** for operators.
- It needs to be able to **communicate** with other systems within $\overline{\text{PANDA}}$ or even within FAIR, like the HESR.
- The DCS should provide an **intuitive** and **user-friendly** interface for operators that also raise alarms in case of failures of any system.
- Finally, it should be **sustainable**, which, e.g., means that it should be based on common hardware and software or industrial standards.

Therefore, $\overline{\text{PANDA}}$ decided to use the EPICS framework that is described in more detail in the following with a focus on the implementation of the local $\overline{\text{PANDA}}$ target slow control.

Experimental Physics and Industrial Control System

The Experimental Physics and Industrial Control System (EPICS) framework was developed by a collaboration of the Argonne National Laboratory, the Los Alamos National Laboratory, and other DOE national laboratories and is available under the EPICS Open license [EPI25]. This framework allows the creation of a network with servers and clients (see figure 3.25). Common tasks for the servers are providing access to data or reading data from hardware or writing into it. On the other hand, the clients are responsible, e.g., to display data by graphical user interfaces (GUIs) or to store and manipulate the data. To allow the system to be scalable and distributed, a large number of servers and clients can be connected to one network [EPI19].

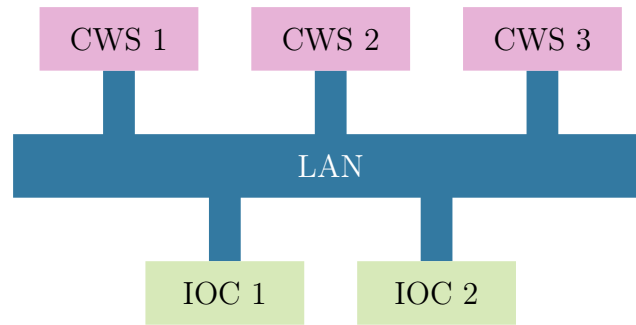


Figure 3.25: Schematic view of the EPICS framework consisting of servers (IOCs) and clients (CWSs). The Input Output Controllers (IOCs) are connected to the Client Work Stations (CWSs) via a Local Area Network (LAN). The IOCs read or write data from or to the hardware. The CWSs can be used to, e.g., display or archive data [EPI19].

The Input/Output Controller (IOC) takes the role as server in the EPICS framework that can run on various machines like desktop computers but also on, e.g., Raspberry Pis. On the other hand, the Client Work Stations (CWS) run various client applications. The connection between the IOCs and the CWSs is established by a Local Area Network (LAN) via Ethernet or wireless communication. The different services communicate either via the Channel Access (CA) or the pvAccess (PVA) protocol. Since the protocol and also the data structure is the same for all services, the communication is transparent [EPI19].

The IOC as main part of the EPICS framework consists of a database where several records of different types are defined. These can be records for, e.g., analog input (ai) or output (ao), booleans (bi, bo) or for calculations (calc, calcout). Each record consists of several Process Variables (PV) where record properties like its value, the corresponding unit, alarm limits, or the scan rate are stored. The records can be linked to each other so that a change in one record can trigger a change in another one. This makes EPICS a programming tool for large detector control systems. Via a device support it can be defined how the data is retrieved or manipulated. Furthermore, device drivers allow accessing also external devices [EPI19]. In the following, the IOC of the local $\bar{\text{P}}\text{ANDA}$ cluster-jet target slow control and some CWSs that are used are described.

3.7.1 The local EPICS Slow Control

For the $\bar{\text{P}}\text{ANDA}$ cluster-jet target an EPICS slow control system is foreseen that uses a CompactRIO cRIO-9039 from National Instruments as main component for analog and digital input and output, but also for communication via RS232 or RS485. This final $\bar{\text{P}}\text{ANDA}$ target slow control will be programmed by a group from NCBJ, National

Centre for Nuclear Research in Warsaw [PAN12a]. While this final slow control system is not yet finalized a local slow control system was set up by B. Hetz that is based on the former slow control system of the Münster prototype target and also includes a CompactRIO of type cRIO-9074 [Het17]. This system does not use EPICS in its complete form but only pushes the data into the EPICS framework while all the slow control programming is done in a separate C# program. During this thesis, the slow control of the $\bar{\text{P}}\text{ANDA}$ cluster-jet target was completely renewed so that it is now a pure EPICS slow control system. In contrast to the final slow control, this system runs on a desktop computer and not on the CompactRIO, while the CompactRIO is only used as separate IOC for analog and digital signals. This new setup was inspired by the new slow control system at the prototype target that was developed by B. Hetz in the meantime.

The new slow control system is a basic EPICS installation with several additional modules. The most important module developed at the Paul Scherrer Institute (PSI) in Villigen, Switzerland, is the *StreamDevice* module [Zim18]. While all the communication via RS232, USB, or Ethernet was programmed in the old external program, this can now be done by using this module in the IOC. This makes the implementation of new devices much easier and faster. Due to this change, the communication with all devices had to be implemented into the new system. Some of them are also used at the Münster prototype target and thus easy to implement, others had to be incorporated from scratch like the new power supplies for the MCP detector system and the new electron gun as described in section 3.7.2.

A further improvement is the use of the module *pyDevSup* [Dav19] that allows to write device support in Python which creates new opportunities. Unfortunately, this module is not yet available for Windows systems like the server computer the slow control is running on. Therefore, a modified version had to be used that was developed by P. Heesterman [Hee25]. Furthermore, this module also requires on Windows machines to build EPICS, all modules, and the IOC with dynamic libraries (DLL) which was not the case before. This package allows writing complex device supports in Python for the Faulhaber motors used in the $\bar{\text{P}}\text{ANDA}$ beam dump (see section 3.7.3) and for the logic modules of the ToF setup (see section 3.7.2).

Control System Studio

Besides the IOC, the local $\bar{\text{P}}\text{ANDA}$ target slow control also uses several CWSs for archiving, as alarm system, and for the graphical user interface. These tools are part of Control System Studio (CSS), a collection of various tools [KC18] that allow alarm

handling, data archiving, and the creation of operator interfaces. CSS is built in Java and uses the Eclipse environment. In the future, an upgrade on the newer CS-Studio Phoebus software is planned that no longer uses Eclipse.

For the $\overline{\text{PANDA}}$ target, CSS is used for data archiving and alarm handling as described in the next subsections. The other main task is to create and run user interfaces. These are called OPIs (OPerator Interfaces). For this purpose, CSS comes with the tool BOY (Best OPI, Yet) that allows creating an interface by using several widgets to display text, numbers, but also to visualize data in plots. These widgets can be connected to PVs of the IOC so that not only the data value but, e.g., also its alarm state can be displayed in real time. This toolkit was used in [Het17] to create the interface for the $\overline{\text{PANDA}}$ cluster-jet target, which was complemented with some new interfaces during this thesis and within [Ded24, Sch22, Sch24].

The Archive Engine BEAUTY

A slow control system like described before allows for controlling and monitoring an experimental setup. Very important for later understanding of the system is also to archive the data. Therefore, different CWSs are available in the EPICS community that can be used for this task. At the Münster prototype target, the EPICS Archiver Appliance [BS24] in a preconfigured version [Lee22] is used that comes with a handy web interface. This system is only available for Linux systems and is therefore running on a separate Linux server. This option is not available for the $\overline{\text{PANDA}}$ target that is currently located at the COoler SYnchrotron (COSY). Therefore, the archiver engine BEAUTY (Best Ever Archive Toolset, Yet) [KC18] is used here. This comes as part of CSS and uses a Relational Database (RDB) like MySQL as storage. The PV data and also the configuration of the archiver are stored in this database. The configuration can be exported as an XML file, where changes can be made before importing it again to the database [KC18]. The data can be accessed via SQL programming, which can also be used within other languages like Python for direct analysis. Furthermore, the archived data can be visualized in the Data Browser of CSS.

The Alarm System BEAST

Another tool that is part of CSS is the alarm system BEAST (Best Ever Alarm System Toolkit). The configuration of this system is very similar to BEAUTY. It also uses a MySQL database for configuration, which can be exported into an XML file for modifications. Furthermore, it makes use of the alarm limits of the records in EPICS. Scalar records have four alarm limits, two lower (LOW, LOLO) and two upper limits

(HIGH, HIHI) that can be set. Similar values can also be set for boolean or string records. Additionally, for every alarm limit a severity can be set (LSV, LLSV, HSV, HHSV) to one of four values: NO_ALARM, MINOR, MAJOR, or INVALID. Once the value of a record reaches one of these alarm thresholds, the state of the record changes to the corresponding severity. BEAST detects this changed state and raises an alarm. The alarm can be displayed in CSS but can also be sent by email or through messengers like Mattermost. Both channels are used for the $\bar{\text{PANDA}}$ cluster-jet target slow control.

3.7.2 Implementation of the MCP Monitor System

The MCP monitor system requires several devices to be included into the local EPICS slow control. These are the power supplies for the MCP and the electron gun and the logic module for the ToF setup. The filament power supply (PeakTech P6075) allows communication via USB to set voltage and current for its two channels. During this thesis, this device was implemented into the slow control using the *StreamDevice* module, so that all setpoints can be set remotely and the actual values can be read out. Furthermore, it allows turning the power supply on or off and to activate the modes of parallel or serial operation of the two channels to increase the maximum voltage or current. The graphical user interface was programmed with BOY as an OPI, which is shown in figure 3.26.

The acceleration electrode and the extraction orifice as well as the MCP assembly and the phosphor screen will be powered by multichannel NIM modules of the CAEN N14xx series [CAE21]. Together with M. Scharpey [Sch22] the communication with these devices was realized. The modules allow a daisy chain via RS485 of up to 32 modules so that only one device needs to be connected to the computer by USB, RS232, or RS485 [CAE21]. Therefore, the implementation into the slow control was designed in a way that modules can be easily replaced or added. More information on this topic is given in [Sch22].

The last device for the MCP monitor system is the four-fold programmable logic unit CAEN N1081B [CAE22] that was already commissioned in [Sch22] without being part of the slow control system by using its web interface. The challenge of implementing this module into EPICS is the way it communicates. The communication takes place via a JSON based web socket. Fortunately, a Python SDK [NI25] is available that could be used to write a device support with the *pyDevSup* module. More details on this are given in [Sch24].

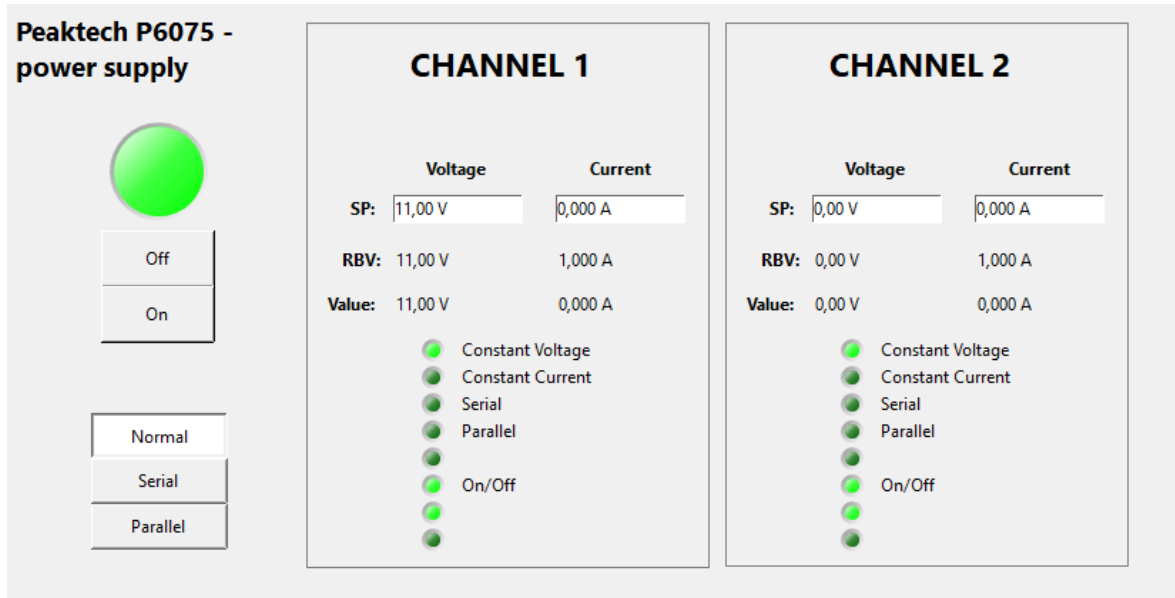


Figure 3.26: Screenshot of the graphical user interface for the PeakTech P6075 power supply. The channels can be switched on and off, the operation mode can be changed from independent operation of both channels (normal) to serial or parallel mode. Furthermore, the current and voltage can be set and read out for both channels. Some status LEDs show the current status of the channels. The unlabeled LEDs are not relevant for the user.

3.7.3 Implementation of Faulhaber Motors

The beam dump orifice system (see section 3.5.1), the new AMS (section 3.5.2), and the MCP monitor system (section 3.5.3) will all make use of Faulhaber motors that have to be implemented into the local EPICS slow control system, which was done in cooperation with L. Deda [Ded24].

The communication with the motors can be established via the Faulhaber Motion Controller Series MC 5005 S CO, which has a CANopen interface [Fau23] that is in compliance with standards CiA 301 and CiA 402 [Fau24]. This allows a standardized integration into the slow control system that can be also used for other Faulhaber motors, but also for different motors with the same standards. The implementation into EPICS was realized by using the *pyDevSup* package as the CANopen protocol can be easily implemented in Python. During the programming of the Python device support, the goal was that the motors are integrated into EPICS in the most general way, so that this Python support module can be used for any motor. All application specific programming was transferred into separate files. Finally, the motors of the beam dump orifice system and the AMS were successfully taken into operation with the slow control system. Furthermore, these motors were also used as a replacement of

the skimmer and collimator motors at the Münster prototype target. Here, the Python device support was easily used, which shows the advantage of the general approach for the programming. Several graphical user interfaces were created to monitor the single motors and systems with several motors, like the beam dump orifice system. The GUI to monitor every motor separately is shown in figure 3.27. More details on the implementation of the Faulhaber motors into the EPICS slow control system, the created GUIs, and the operation of the motors can be found in [Ded24].

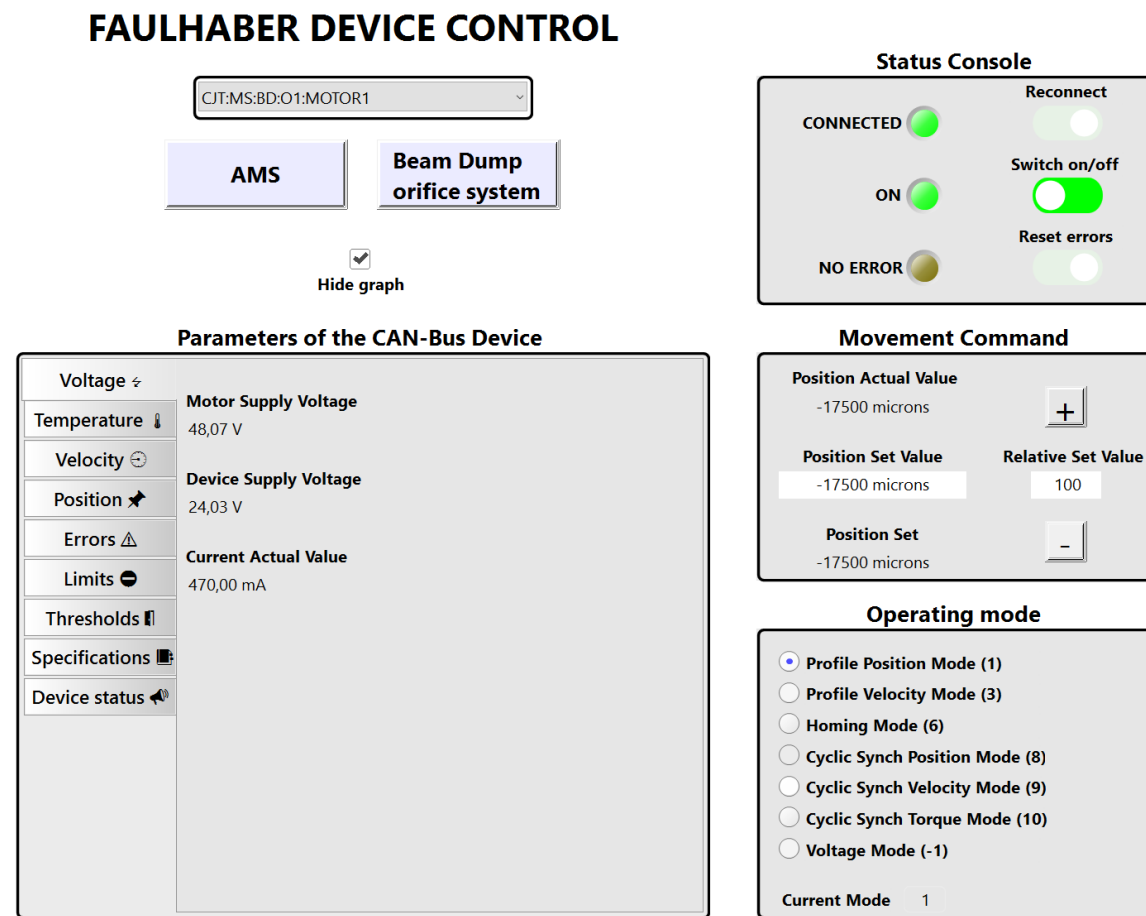


Figure 3.27: Screenshot of a part of the graphical user interface for the Faulhaber motors [Ded24]. The GUI allows control of all connected Faulhaber motors via the drop-down menu on the top. Different parameters like the position, the velocity, the current, or the temperature can be read out and partly set. Several status indicators are also displayed. Not visible on this screenshot is an additional plot window on the right, which shows some important live values (created by L. Deda, University of Münster, edited).

Chapter 4

Accelerator Physics and the Cooler Synchrotron COSY

Many experiments in the field of particle physics require the acceleration of particles to high energies by particle accelerators. While there are many types, this chapter concentrates on the synchrotron, as the relevant accelerators for this part of the thesis are the COoler SYnchrotron (COSY) at the Forschungszentrum Jülich and the High Energy Storage Ring (HESR) at the FAIR facility which are both synchrotrons. An overview of the working principle of a synchrotron is given, before going into details like beam dynamics, focusing, and beam cooling. In the second part of this chapter, COSY is introduced and some of its components which are important for this thesis are described.

4.1 Theory of Accelerator Physics

The history of particle accelerators is long, starting with the development of the first linear ion accelerator by R. Wideröe in 1928 [Wid28] that reached energies of 50 keV [Hin08]. The first circular accelerator, the cyclotron, was developed by E. O. Lawrence in 1930 [LE30] and realized by him and M. S. Livingston two years later [LL32]. This allowed the acceleration of protons up to 1.25 MeV [Hin08]. Both types, linear and circular accelerators, have been improved since then and several new variations and concepts have been developed for different particle types and energies. The synchrotron is one of these variations and is used for the acceleration of electrons, protons, and heavy ions to the highest energies [Wie15].

All these accelerators make use of electromagnetic fields to accelerate and to deflect charged particles by the Lorentz force [Hin08]

$$\vec{F} = q \left(\vec{E} + \vec{v} \times \vec{B} \right) \quad (4.1)$$

where $\vec{E}$ and $\vec{B}$ are the electric and magnetic field, respectively, q is the charge of the particle, and $\vec{v}$ is the velocity of the particle. In circular accelerators, this force is, e.g., used to force the particles on a circular orbit by a magnetic field. In this case, the Lorentz force works as centripetal force

$$F = \frac{\gamma m v^2}{R} = q v B \quad (4.2)$$

with the radius of curvature

$$R = \frac{\gamma m v}{q B} = \frac{p}{q B} \quad (4.3)$$

where γ is the relativistic Lorentz factor and p is the particle momentum [Hin08].

4.1.1 Synchrotron

Synchrotrons like COSY or the HESR are circular accelerators that use magnetic fields to force particles during the acceleration on an orbit with constant radius. According to equation 4.3 this requires to ramp the magnetic field proportional to the particle's momentum during acceleration [Wie15]. The deflection of the particles is done by several dipole magnets which allows having straight sections in between them. These sections can be used to place one or more Radio Frequency (RF) cavities for the acceleration. Within cavities standing electromagnetic waves with a longitudinal electric field component are generated that can accelerate or decelerate charged particles depending on the time they arrive [Hin08]. To accelerate particles after every circulation of the synchrotron, the frequency of this standing wave has to be synchronized with the revolution frequency of the particles. The RF frequency

$$f_{\text{RF}} = h f_{\text{rev}} \quad (4.4)$$

must be an integer multiple of the revolution frequency f_{rev} , where h is the harmonic number. Using equation 4.3 and neglecting straight sections, the revolution frequency [Hin08] is given by

$$f_{\text{rev}} = \frac{v}{2\pi R} = \frac{q B}{2\pi \gamma m} . \quad (4.5)$$

This makes it necessary, that also the RF frequency has to be changed during the acceleration to keep the synchronization with the revolution frequency. Only, for highly relativistic particles, the revolution frequency is nearly constant, so that for electrons no frequency modulation is needed when they are injected with energies of 10 MeV to 20 MeV [Wie15].

4.1.2 Beam Dynamics

The orbit of a particle within a circular accelerator like a synchrotron is determined by the optical lattice of the accelerator, i.e., by the magnetic components like dipoles or quadrupoles. In a linear approximation, with the assumption of a monoenergetic beam, the motion of the particles can be described by Hill's equation

$$x''(s) + k(s)x(s) = 0, \quad (4.6)$$

where $k(s)$ describes the quadrupole component of the magnetic field at the position s along the particle's trajectory [Wil96].

The solution of this equation is an oscillation, called betatron oscillation, described by

$$x(s) = \sqrt{\epsilon} \sqrt{\beta(s)} \cos(\psi(s) + \phi) \quad (4.7)$$

with the emittance ϵ and the phase ϕ as integration constants, the beta function $\beta(s)$, and the phase function $\psi(s)$. The solution for $\beta(s)$ and

$$\psi(s) = \int_0^s \frac{ds'}{\beta(s')} \quad (4.8)$$

are very complex and can only be solved numerically [Wil96]. This can be done with programs like MAD-X as used in [Eic23]. The betatron oscillations of all particles that will have different phases create a broadened beam with its envelope described by [Wil96]

$$E(s) = \sqrt{\epsilon \beta(s)}. \quad (4.9)$$

The solution of Hill's equation (equation 4.7) describes an ellipse in the x - x' plane, where $x' \approx \Delta p_x/p$ is the deviation from the nominal direction (z-direction) or angular deviation, that is given by

$$\gamma(s)x^2(s) + 2\alpha(s)x(s)x'(s) + \beta(s)x'^2(s) = \epsilon \quad (4.10)$$

with

$$\alpha(s) = -\frac{\beta'(s)}{2} \quad (4.11)$$

and

$$\gamma(s) = \frac{1 + \alpha^2(s)}{\beta(s)}. \quad (4.12)$$

This ellipse is called Courant-Snyder invariant and has an area of $\pi\epsilon$ [Wie15], which, according to Liouville's theorem, is constant for canonical equations of motions, such as the one for particle accelerators, when assuming a constant momentum (no acceleration). Thus, the emittance of the beam is conserved, while the orientation of the phase ellipse can change depending on the optical elements of the accelerator [Wil96]. The non-constant parameters $\alpha(s)$, $\beta(s)$, $\gamma(s)$, and $\psi(s)$ are called lattice or Twiss functions.

So far, a possible momentum deviation was neglected. But not all particles within an accelerator will have exactly the desired momentum. In a circular accelerator, a particle with momentum deviation will be deflected slightly differently in the bending magnets, which leads to a deviation in space after the magnet. This phenomenon is called dispersion. It can be described by adding a term for momentum dispersion into equation 4.6 and using the curvature radius R of the magnet instead of the quadrupole strength k :

$$x'' + \frac{1}{R^2}x = \frac{1}{R} \frac{\Delta p}{p}, \quad (4.13)$$

where $\Delta p/p$ is the relative momentum deviation. The dispersion function $D(s)$ is then the solution for $\Delta p/p = 1$ [Wil96]. The dispersion has an impact on the frequency of the circulating particles inside a synchrotron. In section 4.1.3, the concept of phase focusing is introduced, which relies on the fact that the revolution frequency ω depends on the particle momentum. This is expressed as

$$\frac{\Delta\omega}{\omega_0} = \eta \frac{\Delta p}{p_0} \quad (4.14)$$

with the phase slip factor η , and ω_0 and p_0 being the nominal frequency and nominal momentum of the particle [Hin08].

The relative deviation of the frequency $\omega = 2\pi v/C$ can be expressed as

$$\frac{\Delta\omega}{\omega_0} = \frac{\Delta v}{v_0} - \frac{\Delta C}{C_0} \quad (4.15)$$

by separating it into the deviation of the velocity Δv and the deviation of the orbit length ΔC [Hin08]. Using the relativistic momentum $p = \gamma m v$ the relative velocity deviation is

$$\frac{\Delta v}{v_0} = \frac{1}{\gamma^2} \frac{\Delta p}{p_0} \quad (4.16)$$

so that it can be transformed into a momentum deviation [Hin08]. The deviation of the orbit length can also be expressed as a function of the relative momentum deviation,

because via the dispersion a momentum change causes a change of the orbit length. Therefore, the orbit change can be expressed as

$$\frac{\Delta C}{C_0} = \alpha_p \frac{\Delta p}{p_0} \quad (4.17)$$

with the momentum compaction factor

$$\alpha_p = \frac{1}{C_0} \oint \frac{D(s)}{R(s)} ds \quad (4.18)$$

that is given by an integral over the ratio of dispersion $D(s)$ and the local curvature radius $R(s)$ [Wil96]. The phase slip factor η can then be expressed as

$$\eta = \frac{1}{\gamma^2} - \alpha_p = \frac{1}{\gamma^2} - \frac{1}{\gamma_{tr}^2} \quad (4.19)$$

with $\alpha_p = 1/\gamma_{tr}^2$. For small energies ($\gamma < \gamma_{tr}$) the phase slip factor is positive, meaning that particles with higher energy arrive earlier, while for high energies, more energetic particles will arrive later due to the longer orbit. This means that during the acceleration in a synchrotron, the transition energy ($\gamma = \gamma_{tr}$) needs to be crossed to get higher energies [Hin08].

4.1.3 Beam Focusing

The described working principle of a synchrotron only works if the particles have exactly the correct momentum and do not have even a small deviation from the desired orbit. Otherwise, the beam can get broad or particles are even lost. To avoid this, different focusing elements are used for transversal and phase (longitudinal) focusing.

Transversal Focusing

The transversal focusing aims to focus the beam in the horizontal and vertical plane. While according to Liouville's theorem, the area of the phase ellipse described before cannot be changed by conservative forces, the orientation of the ellipse can be varied. This can be used to make the beam thinner at one position, although this means according to equation 4.10, that the transversal momentum at this point can get higher to conserve the emittance. For synchrotrons there are two options, weak and strong

focusing. Weak focusing is used in constant gradient (CG) synchrotrons, which have the dipole magnets with field gradients such that $0 < n < 1$. Here,

$$n = -\frac{\partial B(r)}{\partial r} \frac{r}{B(r)} \quad (4.20)$$

is the field index. This means, that the strength of the magnetic field reduces to the outside, but it reduces less than the centripetal force that is needed to hold a particle on a constant radius more outside, so that a particle with a too large radius will be forced to a more inner orbit and vice versa. Due to the small field index the resulting focusing is weak and leads to betatron oscillations with large amplitudes [Hin08].

In an alternating gradient synchrotron, instead of weak focusing dipole magnets, strong focusing is done. The idea is, that the combination of a focusing and defocusing element in the right distance can have a net focusing effect. This can be done either by dipole magnets which have alternatively very large ($n \gg 1$) and very small ($n \ll 0$) field indices or by quadrupole magnets. The latter is used at COSY and will also be used at the HESR. Quadrupole magnets are focusing in one plane and defocusing in the other. By combining two of them appropriately they have a strong focusing effect [Hin08].

Phase Focusing

Particles cannot only have a deviation in the transversal plane, but also in the longitudinal plane, i.e., in the phase or energy. Particles that have an energy deviation would gather a phase shift so that the synchronization conditions in a synchrotron are not fulfilled anymore and particles can get lost. To avoid this, phase focusing can be used. The acceleration in the RF cavities is mediated by a standing wave with the energy gain per circulation

$$\Delta E = qU_0 \sin \Phi \quad (4.21)$$

depending on the phase Φ [Hin08]. While the maximum of the energy gain is at $\Phi = \pi/2$, using this phase would lead to an instability. Particles that have an energy deviation would have a phase shift leading to a lower energy gain. This means, that particles with too high energy would get a smaller energy gain in the next turn, which reduces the deviation. But the same also holds for particles with too small energy, so that their energy deviation increases further.

To avoid this instability, the phase Φ_S of the synchronous particle is shifted to the rising or falling edge of the potential. The side depends on the phase slip factor η . For $\eta > 0$, particles with higher energy will arrive earlier and gather a negative phase

deviation with respect to the synchronous particle. To reduce their energy deviation, the energy gain should be smaller for smaller phase values. Therefore, particles with $\eta > 0$ are accelerated at the rising edge. For $\eta < 0$ the opposite is true, so that particles are accelerated at the falling edge [Hin08].

This phase focusing allows particles to be accelerated under stable conditions even when they have small deviations in phase or energy. They will undergo oscillations, called synchrotron oscillations, like visualized in figure 4.1 on a constant orbit in the Φ - ΔE phase diagram. However, if the deviations in energy and phase are too large, the particles are outside the stable region and will get lost. The bound of this region is called separatrix, while the stable region inside is also called bucket. Both are shown in red in figure 4.1 [Hin08]. The minimum and maximum phase of this separatrix can be calculated theoretically. One phase boundary is given by the phase on the other side of the potential's maximum, that has the same potential value

$$\sin \Phi_S = \sin \Phi_1 \quad (4.22)$$

which is fulfilled for

$$\Phi_1 = \pi - \Phi_S . \quad (4.23)$$

Until this point, particles with too small energy will still gain more energy than the synchronous particle, so that the energy deviation will decrease. The limit on the other side is given by the point where the total change of the energy deviation between the phase limits Φ_1 and Φ_2 is zero. This can be formulated by an integral over the energy gain as [Hin97]

$$\int_{\Phi_1}^{\Phi_2} (\sin \Phi - \sin \Phi_S) d\Phi = 0 . \quad (4.24)$$

These limits are the maximum phase deviation, that is possible for a stable particle. Such a particle will undergo anticlockwise (for $\eta > 0$) synchrotron oscillations around the synchronous particle on the separatrix as shown in figure 4.1 by the red curves. Larger deviations will lead to steadily growing deviations, as can be seen by the gray lines outside the separatrix. The large energy deviation will then cause them to be lost due to their different deflection in the dipole magnets of a synchrotron.

When operating a synchrotron with $\eta < 0$ the synchronous particle needs to lie on the falling edge of the potential. During the acceleration in a synchrotron, the sign of η typically changes. This requires a phase jump during the acceleration. The change of the sign also mirrors the fish-like separatrix and the oscillations will now go clock-wise around the synchronous particle as can be seen in the left plot of figure 4.2. When

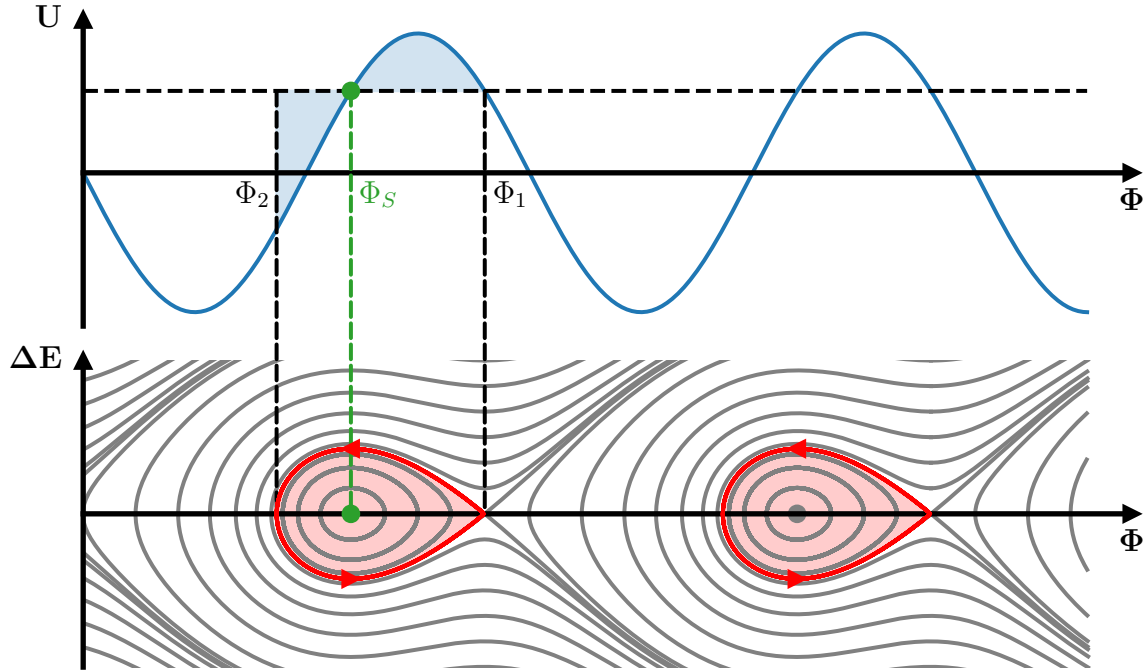


Figure 4.1: Phase focusing during acceleration by the potential of an RF cavity (upper plot) for $\eta > 0$. Particles with a too high energy ($\Delta E > 0$) than the synchronous particle (green) will arrive with a phase $\Phi < \Phi_S$ and thus get a lower energy gain, so that the energy deviation will get reduced. This results in a stable region called bucket between the phase limits Φ_1 and Φ_2 , where particles will undergo anticlockwise synchrotron oscillations around the synchronous particle (green). The motion in the phase space is shown in the lower plot. Particles outside the separatrix will get lost. The blue area shows the integral of equation 4.24 for the phase limit Φ_2 .

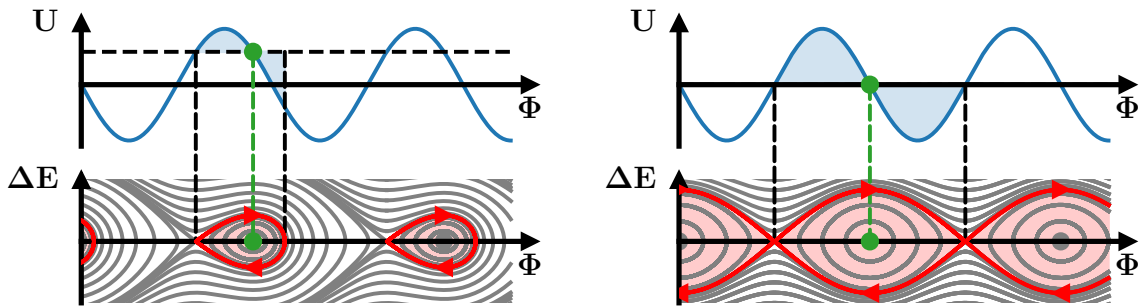


Figure 4.2: Phase focusing for $\eta < 0$ during acceleration (left) and without acceleration (right). The shape of the separatrix is mirrored compared to $\eta > 0$ and the synchrotron oscillations are now clock-wise around the synchronous particle (green). Without acceleration, the bucket gets wider and symmetric.

no acceleration is needed like in storage rings, the RF can still be applied, but the synchronous particle would be placed on the point of the edge, where the energy gain is zero. The resulting separatrix is seen in the right plot of figure 4.2. Here, one can also see, that during the acceleration the bucket is rather small, when the synchronous phase is close to the maximum. This results in a bunched beam, so that only a small part of the beam line is filled with particles. When using phase focusing without acceleration, the bucket spans the whole phase region. While the beam is still bunched due to the smaller phase space at the bucket limits, the bunches are larger and the particles are more evenly distributed over the beam line.

To get a nearly homogenous particle distribution in the beam line, a barrier bucket potential instead of a simple sinusoidal potential can be used. This potential is shown in figure 4.3 and has a broad region without energy gain around the synchronous particle. Particles in this region see no electric field and behave like free particles. Only at the edges, so when they gather a too strong phase deviation, they will see a potential wall that will focus it back into the center of the phase region. The separatrix as shown in figure 4.3 has now a more rectangular shape, which results in a more homogeneously filled beam line, with only small parts at the edges that are filled with fewer particles.

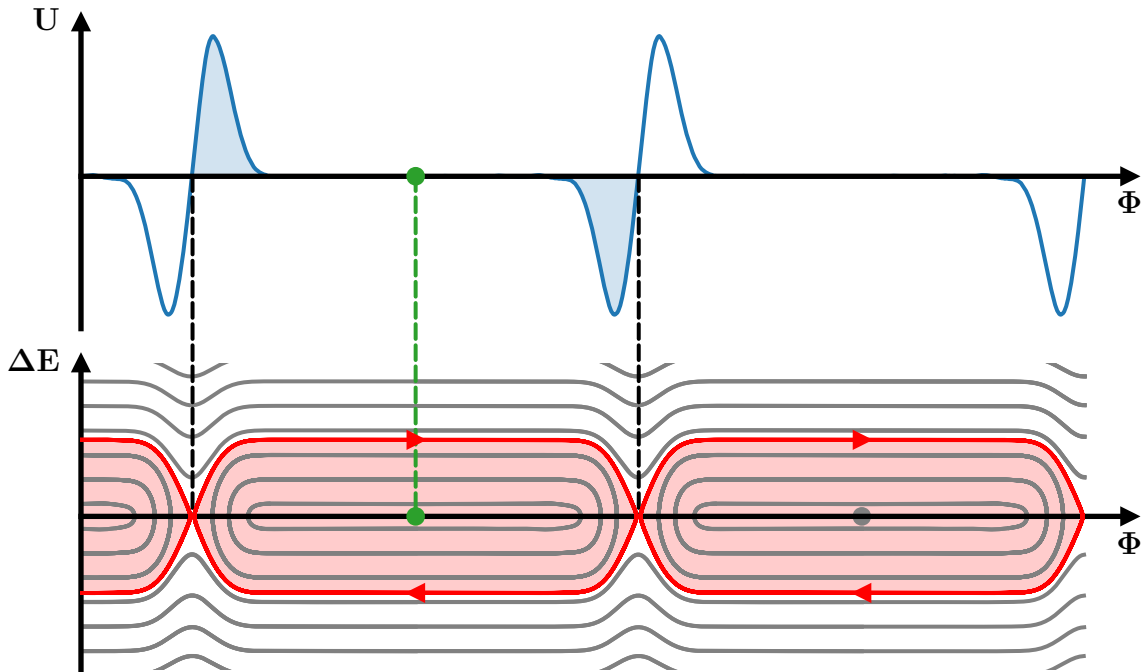


Figure 4.3: Barrier bucket potential (top) with resulting phase motion (bottom) for $\eta < 0$. The separatrix (red line) is now more rectangular, so that the beam line is filled more homogeneously with particles.

4.1.4 Beam Cooling

Within a beam, not all particles will have exactly the same momentum, instead the beam will show a momentum distribution. The relative width σ_p of these distributions can be connected to a temperature

$$\frac{k_B T_x}{2} = \frac{\sigma_{p,x}^2}{2m} \quad (4.25)$$

for the horizontal direction x (analogously for the vertical direction y) with the Boltzmann constant k_b and

$$\frac{k_B T_l}{2} = \frac{\sigma_{p,l}^2}{2m\gamma^2} \quad (4.26)$$

for the longitudinal direction, where the factor $1/\gamma^2$ results from the transformation into the center-of-mass system [Hin08]. Due to this definition, beam cooling is the reduction of the temperature or of the momentum spread. The limiting factor here is the Liouville theorem, that states that the phase space volume is constant when electrostatic or magnetic fields are used to manipulate the beam, so that, e.g., the beam size can be reduced by quadrupole magnets but this results in an increase of the momentum spread or vice versa. But nevertheless, there are also possibilities to reduce the emittance of a beam and by this reducing the beam size and momentum spread. For ion, proton, and antiproton beams, this can be done by adiabatic damping, laser cooling, electron cooling, or stochastic cooling.

Adiabatic Damping

During the acceleration of a beam the effect of adiabatic damping causes a reduction of the emittance. This effect results from the theorem of Liouville, which states that the phase space volume is constant when electrostatic or magnetic fields are applied [Hin08]:

$$\Delta x \Delta p_x = \text{const.} \quad (4.27)$$

This has the consequence that the emittance

$$\epsilon_x = \Delta x \frac{\Delta p_x}{p} = \frac{\text{const.}}{p} \quad (4.28)$$

reduces with increasing momentum. In this way, the emittance in the transversal direction is reduced during acceleration without changing the phase space volume or violating Liouville's theorem. Therefore, adiabatic damping is no cooling method in the classical sense, but has a similar effect [Hin08].

Laser Cooling

To overcome the limitation of Liouville's theorem, non-conservative forces can be used. One possibility is the laser cooling. Here, lasers are used to excite a beam particle to a higher energy level by absorbing a photon and taking its momentum. The atoms de-excite by emitting a fluorescence photon. The emission direction is isotropic leading to a net momentum gain for a laser in beam direction and vice versa. The wavelength of the laser needs to match the Doppler shifted transition energy leading to wavelengths of

$$\lambda_{\pm} = \frac{\lambda_0}{\gamma(1 \pm \beta)} \quad (4.29)$$

for a laser in accelerator beam direction (+) or vice versa (-). Here, λ_0 corresponds to the wavelength that corresponds to the transition energy in the center-of-mass system of the beam. By applying one laser on the low energy side in accelerator direction ($\lambda > \lambda_+$), particles with too low momentum are excited and gain momentum. A second laser on the high energy side in opposite direction ($\lambda < \lambda_-$) reduces the momentum of particles with too high momentum. This results in a reduction of the momentum spread [Sch⁺90].

For high energy beams, the wavelength of the laser in beam direction becomes very small due to the Doppler shift. Instead, the laser cooling is done by one laser in opposite direction to the beam in combination with an RF cavity like for phase focusing. Particles with too high momentum get an energy loss by the laser system, while particles with too low momentum will get an energy gain due to the electric field of the RF cavity. Such a system is foreseen for the SIS100 at FAIR [Win⁺15].

Electron Cooling

Another possibility of beam cooling is the electron cooler. Here, a cold electron beam with the same velocity as the ion beam is injected by toroidal magnetic fields into the ion beam. Electrons and ions then scatter so that the temperatures of both beams equalize. After a certain distance the electron beam is then extracted again. To achieve the same velocities for electrons (v_e) and ions (v), the momenta $p = \gamma m v$ or energies $E = \gamma m c^2$ have to fulfil

$$\frac{p_e}{p} = \frac{E_e}{E} = \frac{m_e}{m} \quad (4.30)$$

where $v_e = v$ and $\gamma_e = \gamma$ was used. Therefore, the electron beam needs roughly 2000 times less energy than the proton or antiproton beam [Hin08], so that, e.g., the 2 MeV electron cooler at COSY is capable to cool proton beams with energies of up to 4 GeV [Boc⁺12].

Stochastic Cooling

Stochastic cooling reduces the emittance of the beam and by this it seems to violate the theorem of Liouville. This can be overcome because the phase space is occupied by single particles with space between them. If it is possible to get information on the single particle's position in the phase space, one can rearrange them by moving particles into empty space in the phase space. By this, the particles can be arranged into a smaller area in the phase space, so that the emittance is reduced. This is the basic idea of stochastic cooling [Möh⁺80].

Therefore, a pickup and a kicker are used to measure the beam deviation and to manipulate the beam. The pickup measures the deviation x of a test particle from the reference orbit and sends this information to the kicker, where the deviation is corrected. Both the pickup and the kicker consist of electrodes on opposite sides of the beam, where a signal can be induced by charged particles. More details on the exact settings of the kicker and the pickup for transversal and longitudinal cooling will be given later and are not important for the general considerations in the following.

Due to the finite length of the kicker and the pickup, not only the signal of one particle will be used to correct the test particle, but also signals from other particles within the bandwidth W of the stochastic cooling system. The particles around the test particle within this bandwidth are summarized as slice s of the beam, with s' being the slice s without the test particle. The correction that the test particle receives is given by [Möh13]

$$\Delta x = \underbrace{-\lambda x}_{\text{coherent}} - \underbrace{\sum_{s'} \lambda_i x_i}_{\text{incoherent}} \quad (4.31)$$

with the coherent term as the direct reaction to the deviation of the particle, and the incoherent term as the result of the other particles in the slice. The quantities λ and λ_i describe the strength of the correction. The coherent term will cause the cooling of the beam, while the incoherent term will cause heating. By assuming $\lambda_i = \lambda$ for all particles and by using the average deviation

$$\langle x \rangle_s = \frac{1}{N_s} \sum_s x_i \quad (4.32)$$

of the sample with the number of particles N_s in the sample, the correction is given by

$$\Delta x = -\frac{g}{N_s} x - g \langle x \rangle_{s'} \quad (4.33)$$

with $g = \lambda N_s$ as the gain factor, describing the fraction of the deviation that is corrected per turn [Möh13]. Neglecting the incoherent term, this would result in an exponential damping with a cooling rate of

$$\frac{1}{\tau} = \frac{2W}{N}, \quad (4.34)$$

where the number of particles in the sample

$$N_s = \frac{N}{2WT_{\text{rev}}} \quad (4.35)$$

was expressed by the bandwidth W of the system, the total number of particles in the beam N , and the revolution time T_{rev} . Furthermore, $g = 1$ was assumed, so that this rate can be interpreted as upper limit for the cooling rate, which overestimates the cooling of real systems by only a factor of 2 [Möh13]. Important to note here is, that the cooling bases on the mean deviation of the sample, that is given by

$$\langle x \rangle_s = \langle x \rangle \pm \frac{\sigma_x}{\sqrt{N_s}} \quad (4.36)$$

so that even if the whole beam has a mean deviation of zero, the mean deviation of the sample can be non-zero, when the number of particles in this sample is not too large, meaning that the bandwidth should not be too large compared to the revolution time of the particles [Möh13].

So far, the deviation of a single test particle x was considered, but since later not the single particle is of interest, but the spread of the whole beam, we will now concentrate on the cooling rate for the variance x^2 . Therefore, one can reformulate equation 4.33 for the variance as

$$\Delta(x^2) = -2x \frac{g}{N_s} \sum_s x_i + \left(\frac{g}{N_s} \sum_s x_i \right)^2 \quad (4.37)$$

leading to a cooling rate of

$$\frac{1}{\tau_{x^2}} = \frac{2W}{N} (2g - g^2) \quad (4.38)$$

where the first term proportional to $2g$ represents the cooling while the second term causes the heating with $-g^2$. The cooling rate for x would then just be given as $1/\tau = 1/(2\tau_{x^2})$. This would lead to an optimum gain of $g = 1$, while for $g = 2$ the cooling rate would be zero [Möh13].

The calculations so far assume a random sample s , but once this sample was corrected, it cannot be assumed as random anymore. The stochastic cooling would only correct it until the mean deviation of this sample is zero. To get a new random sample, the particles need to mix on the way from kicker to pickup. Due to their

momentum spread, this will happen anyway for $\eta \neq 0$ since particles with different momenta will arrive at different times at the pickup. The mixing is described by the factor $M \geq 1$ that is the number of turns a particle needs to move from one sample to another. On the other hand, also unwanted mixing between pickup and kicker can happen, that causes the test particle to get the wrong correction in the kicker. This unwanted mixing is similarly described by the factor $\tilde{M}$. Finally, the signal can also have additional noise, which is described by the signal-to-noise ratio U . In total, this leads to the cooling rate

$$\frac{1}{\tau_{x^2}} = \frac{2W}{N} \left(2g \left(1 - \tilde{M}^{-2} \right) - g^2 (M + U) \right) \quad (4.39)$$

for the variance of the beam's deviation, so that the maximum cooling would be achieved for $M = 1$ and $\tilde{M} \rightarrow \infty$. This would require a complex lattice design, so that a good compromise needs to be found. The result will be that on the one hand the sample will not be completely re-randomized within one turn ($M > 1$), but on the other hand the unwanted mixing is also reduced (increased $\tilde{M}$) [Möh13]. All considerations in this section have been done for an arbitrary deviation x . This can be a deviation from the reference orbit in the transversal direction, but also a phase deviation in longitudinal direction.

So far, the cooling was described in the time domain, but to better understand the cooling methods, also the frequency domain is relevant and especially the Schottky spectra that are measured by the pickups. These signals originate from the Schottky noise observed by W. Schottky [Sch18]. A charged particle passing the pickup will induce a current every turn, which is assumed as a delta function. The broadening due to the finite length of the pickup is neglected here. A series expansion of the signal of one particle is therefore given as

$$I_L(t) = ef_0 + 2ef_0 \sum_{n=1}^{\infty} \cos(n\omega_0 t) \quad (4.40)$$

with the particle's charge e and the revolution frequency $\omega_0 = 2\pi f_0$ [Möh⁺80]. This signal and its Fourier transform is shown in the upper part of figure 4.4. This is the longitudinal signal which is extracted as sum signal from the pickup. For a transversal pickup, a differential signal from opposite electrodes is used instead, that is sensitive to the transversal deviation from the reference orbit. The signal still consists of delta functions, but these are now modulated by the betatron oscillation with frequency $Q\omega_0$ and amplitude A . Q is also called tune and describes the number of betatron oscillations

per revolution. In the following, $q = (Q \bmod 1)$ will be used as the fractional part of Q . The expanded signal is then given by [Möh⁺80]

$$I_T(t) = Aef_0 \left[\sum_{n=0}^{\infty} \cos((n+q)\omega_0 t) + \sum_{n=1}^{\infty} \cos((n-q)\omega_0 t) \right], \quad (4.41)$$

which is shown together with its Fourier transform in the lower part of figure 4.4.

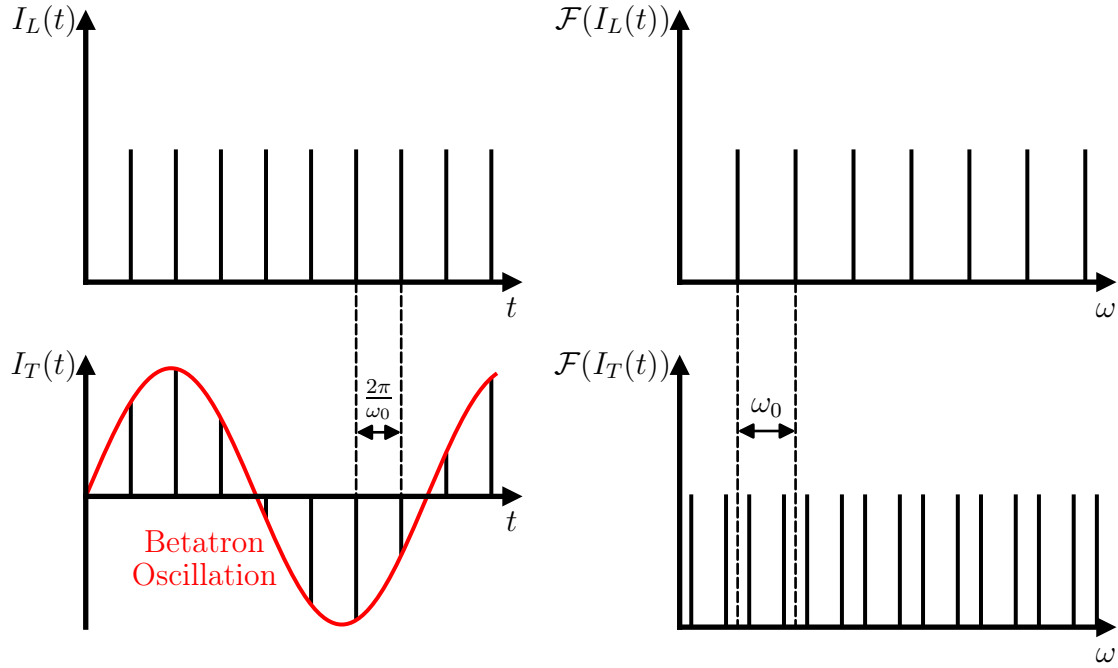


Figure 4.4: Longitudinal (top) and transversal (bottom) signal for a single particle. On the left, the signal in the time domain is shown, whereas the right shows their Fourier transform. While the Fourier transform of the longitudinal signal shows delta peaks at the revolution frequency ω_0 and its higher harmonics, the transversal signal shows two peaks next to the harmonics due to the overlap of the particles revolution and the betatron oscillation (based on [Möh⁺80]).

If now not only one particle with frequency ω_0 is present, but there is another particle with slightly different frequency $\omega_1 = \omega_0 + \Delta\omega$, the longitudinal signal and its Fourier transform will be as shown in figure 4.5.

For a beam consisting of many particles, this results in so called Schottky bands. Assuming a rectangular frequency distribution with a width of $\Delta\omega$, the Schottky band at the n -th harmonic has a width of $n\Delta\omega$. The spectral power density within these bands are then given by

$$\left(\frac{dI^2}{d\omega} \right)_n = \frac{Ne^2 f_0}{\pi} \frac{\omega_0}{n\Delta\omega}. \quad (4.42)$$

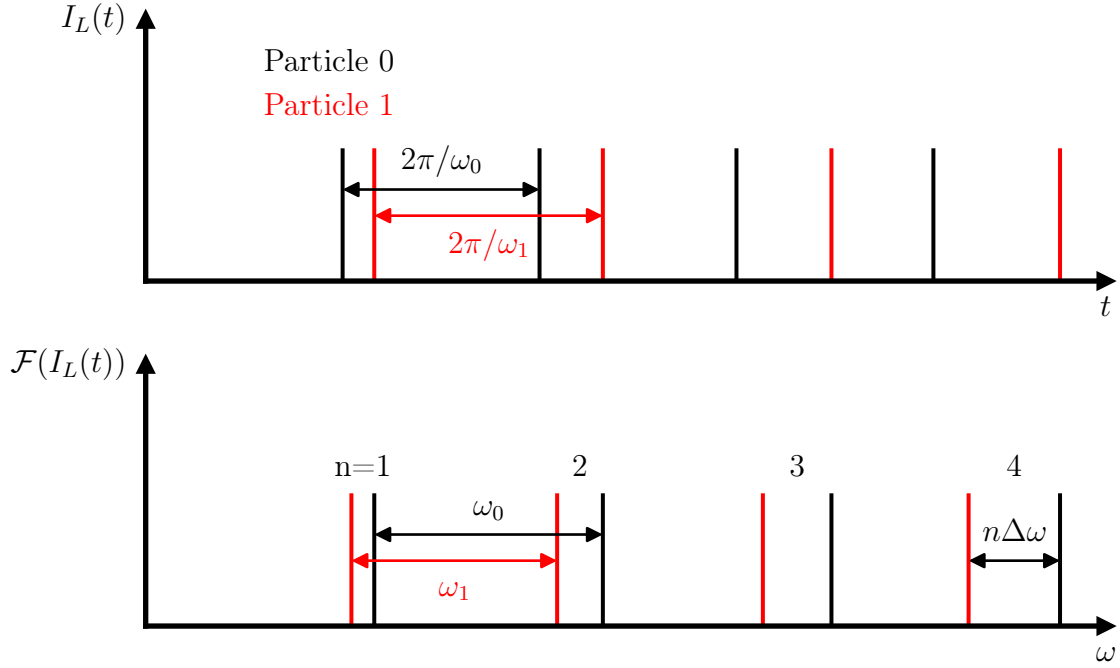


Figure 4.5: Schottky signal of two particles with different frequencies in the time (top) and frequency domain (bottom). The width of the frequency distribution is proportional to the harmonic number (based on [Möh13]).

Thus for higher harmonics, the Schottky bands get broader and the power density decreases as it is shown in figure 4.6. At some point the bands start to overlap, leading to a constant power density (sum of overlapping bands) of

$$\left(\frac{dI^2}{d\omega}\right)_{\min} = \frac{Ne^2 f_0}{\pi} \quad (4.43)$$

at high harmonics. Similarly, also the bands in the transversal spectrum get broadened [Möh13].

After the basics of stochastic cooling in the time and frequency domain has been discussed, in the following some cooling methods are presented. The first to consider is the **betatron cooling**. Particles will get a correction

$$\Delta x = 0 \quad (4.44)$$

$$\Delta(\beta x') = -g \langle x \rangle_s \quad (4.45)$$

that only changes x' , the deviation in the angle. This correction is proportional to the deviation in position $\langle x \rangle_s$ at the pickup of the test sample. By placing the kicker in the correct distance ($\pi/2$ of the betatron oscillation), this deviation can transform

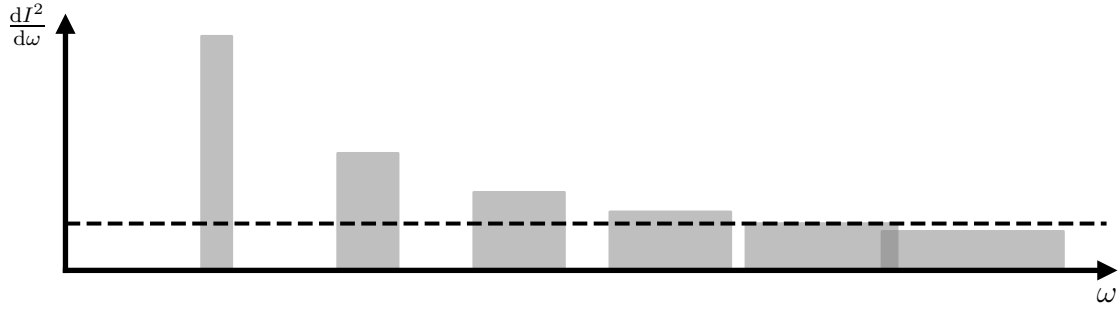


Figure 4.6: Schottky bands for a rectangular Schottky signal. At some point, the bands start to overlap. Due to the overlap, the total power density (sum of overlapping bands) has a limit that is shown by the dashed line (based on [Möh13]).

completely to an angular deviation, so that the deviation could be corrected completely. If it has not transformed completely, it needs more turns to get corrected, but the beam is still cooled. The cooling rate for $\sqrt{\epsilon}$ which is proportional to the beam envelope is given by

$$\frac{1}{\tau} = \frac{W}{2N} \left[2g_{\beta}(1 - \tilde{M}^{-2}) \sin(\Delta\psi) - g_{\beta}^2(M + U) \right] \quad (4.46)$$

with $\psi = \int \beta^{-1}(s) ds$ as the phase of the betatron oscillation and $g_{\beta} = g\sqrt{\beta_{PU}/\beta_K}$ as the gain factor scaled with the beam envelope ratio at kicker and pickup [Möh13].

The **Palmer method** is used for momentum cooling. Therefore, a horizontal pickup in differential mode [SKM16] is used within a section with high dispersion and small betatron oscillation amplitude. Thus, the displacement is dominated by the momentum ($x = D \langle \delta p/p \rangle_s$). The correction is then given by

$$\Delta x = -g (D \langle \delta p/p \rangle_s + x_n) , \quad (4.47)$$

where x_n is a noise related term [Möh13]. This correction is applied to the momentum by a kicker in sum mode by using the electronic setup in figure 4.7 [SKM16]. When x not only depends on the momentum deviation via dispersion, but also the betatron oscillation has a contribution, the Palmer method can also work for transversal and longitudinal cooling, this method is called **Hereward cooling** [Möh13].

Another method, that is more often used, is the **notch filter method**. In contrast to the setup of the Palmer method, now a sum signal is measured at the pickup. It is then also pre-amplified and a variable delay is used for phase matching. Afterwards, the signal is differentiated by means of a 90° phase shifter before it is then fed into the notch filter. In the notch filter, the signal is divided into two signal lines with



Figure 4.7: Schematic drawing of the electronic setup for the Palmer method. The differential signal from the pickup will be used, as it contains the information of the transversal deviation, which is proportional to the longitudinal deviation when the pickup is placed in a section with high dispersion. This signal is pre-amplified and delayed to match the phase at the kicker. Afterwards, it is amplified and fed as sum signal into the kicker, so that the momentum is corrected here (based on [SKM16]).

one being delayed. This delay is exactly the time a particle with nominal momentum needs for one revolution. The resulting signals are then subtracted, amplified, and fed into the kicker as shown in figure 4.8. Due to the notch filter, particles will see the correction twice but with different sign, once in the first pass of the kicker and once after another circulation. Thus, particles with nominal momentum will see in total no correction at the kicker, because the two signal lines will cancel each other out. On the other hand, particles with a momentum deviation will be accelerated or decelerated leading to a cooling of the beam. Since the signal of the pickup is used twice, also the effect of unwanted mixing is larger due to the long distance between the pickup and the second pass of the kicker. Therefore, this method is suitable if the Schottky bands are well separated, so for an already quite small momentum spread, so that a pre-cooling with a different method might be necessary. On the other hand, this method has the

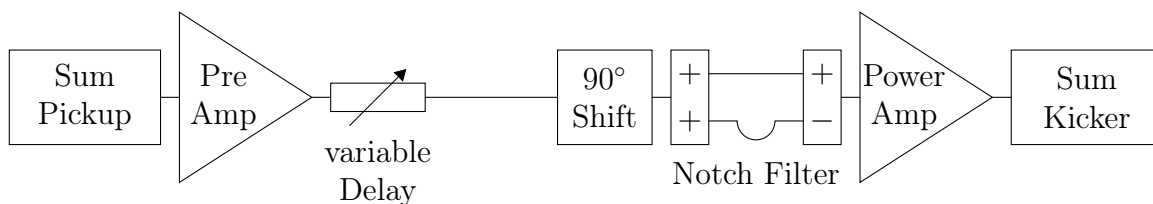


Figure 4.8: Schematic drawing of the electronic setup for the notch filter method. The sum signal from the pickup is pre-amplified and delayed to match the phase at the kicker. Afterwards, it is differentiated by a 90° phase shifter and fed into the notch filter. Here, the signal is divided into two signal lines with one being delayed by the revolution time. The resulting signals are then subtracted, amplified and fed into the kicker. Particles with nominal momentum will see no correction at the kicker, while particles with momentum deviation will be accelerated or decelerated leading to a cooling of the beam (based on [SKM16]).

advantage that the center frequency of the filter can be adjusted and can deviate from the revolution frequency, allowing the stochastic cooling to cool towards a different frequency. This can be used to optimize the cooling when the beam is heated and loses energy due to a target [SKM16].

A method, that can be used for pre-cooling before the usage of the notch filter method, is the **Time-of-Flight (ToF) method**. The setup shown in figure 4.9 is very similar to the notch filter method. Again, the signal is differentiated by a 90° phase shifter so that the signal is zero at the moment when the particle is inside the pickup. By matching the phase via the variable delay, the signal is then fed into the kicker, so that a particle with nominal momentum will arrive at the kicker at the same time, where the signal is zero. A particle with too low or too high momentum will see a correction. This can be realized using the same setup as for the notch filter method by opening the path of the delayed signal in the filter. For the correct sign an additional 180° phase shifter must be used. This method has a larger cooling acceptance and can be used for pre-cooling, before then switching to the faster notch filter method [SKM16].

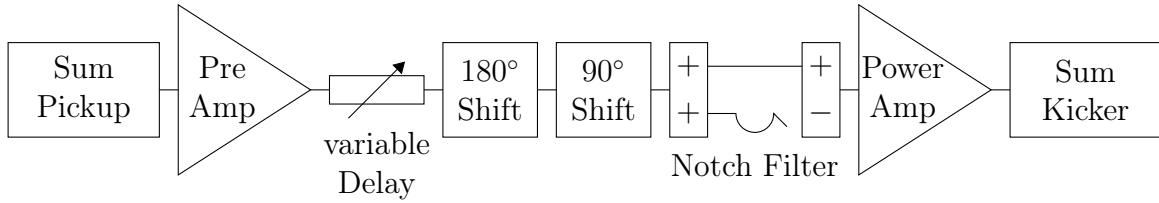


Figure 4.9: Schematic drawing of the electronic setup for the Time-of-Flight (ToF) method. The sum signal from the pickup is pre-amplified and delayed to match the phase at the kicker. Afterwards, it is differentiated by a 90° phase shifter and fed into an amplifier and the kicker through the notch filter with open delay line. An additional 180° phase shifter is used to get the correct sign for the correction (based on [SKM16]).

Beam Heating by a Target

Beam particles that interact with a target will lose energy and undergo small angle scattering due to the Coulomb interaction with target atoms. This results in an increase of the beam emittance over time that is given by

$$\frac{d\epsilon}{dt} = \frac{f_0}{2} \left(\beta_T \theta_{\max}^2 + \frac{D^2}{\beta_T} \delta_{\text{loss}}^2 + \beta_T D'^2 \delta_{\text{loss}}^2 \right) \quad (4.48)$$

with the beta function β_T at the target, the position dispersion D , the angular dispersion D' , the mean square scattering angle $\theta_{\max}$ for a single transversal of the

target, and the mean square momentum deviation δ_{loss}^2 for one target transversal. This equation makes clear, that the emittance growth has two dispersion dependent terms, that can be reduced by placing a target in a non-dispersive section of a synchrotron as it is foreseen for $\overline{\text{P}}\text{ANDA}$ at FAIR [SKM16].

4.2 The Cooler Synchrotron COSY

The COoler SYnchrotron (COSY) as shown in figure 4.10 is a synchrotron and storage ring at the Forschungszentrum Jülich that was officially inaugurated in April 1993 [Mai97a] and operated until the end of 2023. The synchrotron was designed to accelerate protons and deuterons up to a momentum of 3.7 GeV/c [Wil17]. Therefore, negatively charged hydrogen or deuterium ions are produced in the unpolarized or polarized source [Bai⁺17] and then guided into the isochronous injector cyclotron JULIC where protons are accelerated to 295 MeV/c and deuterons to 539 MeV/c [Wil17]. These are then extracted from the cyclotron, guided through the injection beam line, and injected into the COSY ring within one of the COSY dipole magnets. Within the beam line at this dipole, a carbon stripper foil is placed at the side so that the injected ions lose their electrons and are then stored in COSY as protons or deuterons. They are then orbiting in the ring on a trajectory that also passes the same dipole magnet, but due to the changed charge, they are now deflected into the other direction, so that they stay inside the ring. Furthermore, the orbit is chosen in a way, that the beam particles do not hit the stripper foil again.

The COSY ring itself has a racetrack shape with a total circumference of 184 m with two straight sections of 40 m each [Mai97a]. In the two arcs, in total 24 dipole magnets in a six-fold symmetry are used to deflect the beam [Mai97b]. The transversal strong focussing is performed with 56 quadrupole magnets, 24 of them are placed in the arcs, where always two of them (focussing and defocusing) are paired with two dipoles ensuring the symmetry. On each straight section, the quadrupoles are installed in families of four [Wag⁺21]. Furthermore, 18 sextupoles are installed for chromatic correction and 40 steerer magnets are used for horizontal and transversal orbit correction [Mai97b], which is monitored by 31 Beam Position Monitors (BPM) [Wag⁺21]. Additionally, there are two cavities installed, an RF cavity for acceleration and a barrier bucket cavity for energy loss compensation due to the targets of the internal experiments [Wil17]. Between the first and second beam time analyzed within this thesis, the RF cavity was replaced by the new cavity for the HESR.

Furthermore, COSY is equipped with two different cooling techniques that give it its name. There are two electron cooling systems. Originally, the 100 keV electron cooler

was installed for cooling at injection energy up to a momentum of 645 MeV/c [Bec⁺96]. Later, a 2 MeV electron cooler was installed, that is capable to cool beams with higher momentum even beyond the momentum range of COSY [Kam⁺14, Nie⁺19]. COSY also has two stochastic cooling systems. While the kicker of the old stochastic cooling system was removed to allow for the installation of the new HESR cavity, the pickup tank is left and can still be used for the measurement of Schottky spectra. Instead,

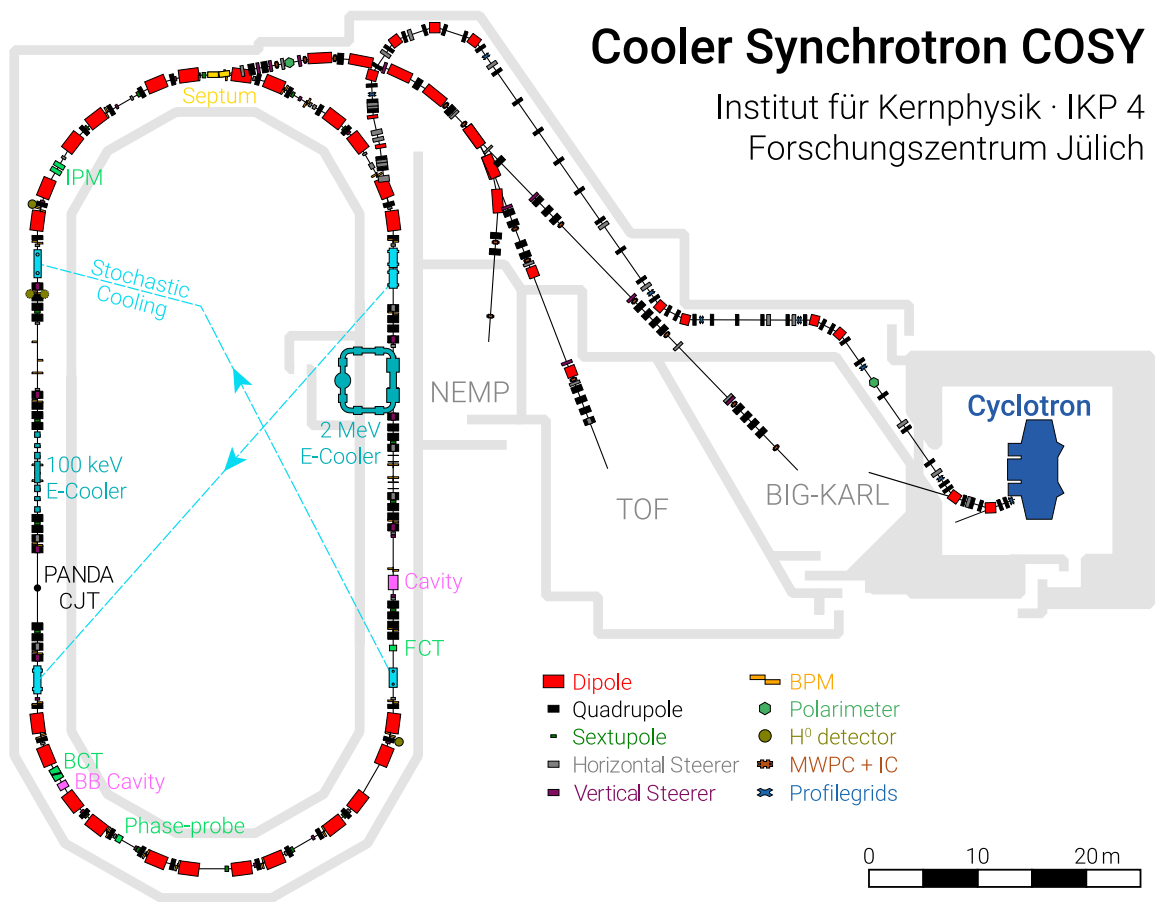


Figure 4.10: Plan of the COoler SYnchrotron (COSY) with the different devices like magnets (dipoles, quadrupoles, sextupoles, steerers), cavities, electron and stochastic cooling, and several diagnostic devices. Polarized or unpolarized H⁻ or D⁻ ions are pre-accelerated in the cyclotron JULIC. They are then traveling through the injection beam line into the COSY ring. During injection, they pass a carbon foil to strip the electrons from the ions. The protons or deuterons are accelerated in the COSY ring to momenta of up to 3.7 GeV/c. These ions are then either used in internal experiments or they can be extracted and guided towards the external experimental halls NEMP, TOF, or BIG-KARL. The PANDA cluster-jet target was installed at the former WASA experimental area in one of the straight sections of COSY (copyright by IKP/FZ Jülich, edited).

one pickup and one kicker tank of the new stochastic cooling for the HESR has been installed at COSY and commissioned in 2017 [Sta⁺18]. The innermost part of these tanks are ring slot couplers. These are octagonal rings made of an aluminum alloy, which are equipped with 8 electrodes in an octagonal arrangement [Sta⁺07]. 16 of the ring slot couplers are then stacked as shown in figure 4.11 and four stacks are mounted into each tank. Figure 4.12 shows a pickup tank during installation, with the inner structures, including the ring slot couplers, still protruding from the outer tank. This setup allows for transversal and also longitudinal cooling with the same system, where the latter is performed with the ToF cooling method or with filter cooling. The stochastic cooling was successfully operated over the past years together with the $\bar{\text{P}}\text{ANDA}$ cluster-jet target proving its capabilities for the HESR [Sta⁺23]. Detailed analyses on the usage of the stochastic cooling in presence of the $\bar{\text{P}}\text{ANDA}$ cluster-jet target are part of this thesis and are presented in chapter 5. Due to the two cooling methods, COSY is ideally suited for internal experiments using targets like cluster-jet or pellet targets, because it allows compensating the beam heating induced by the target. Therefore, internal fixed-target experiments like COSY-11 [Bra⁺96, Dom⁺97], ANKE [Bar⁺01], or WASA [Ada⁺04] have been routinely performed at COSY. On the

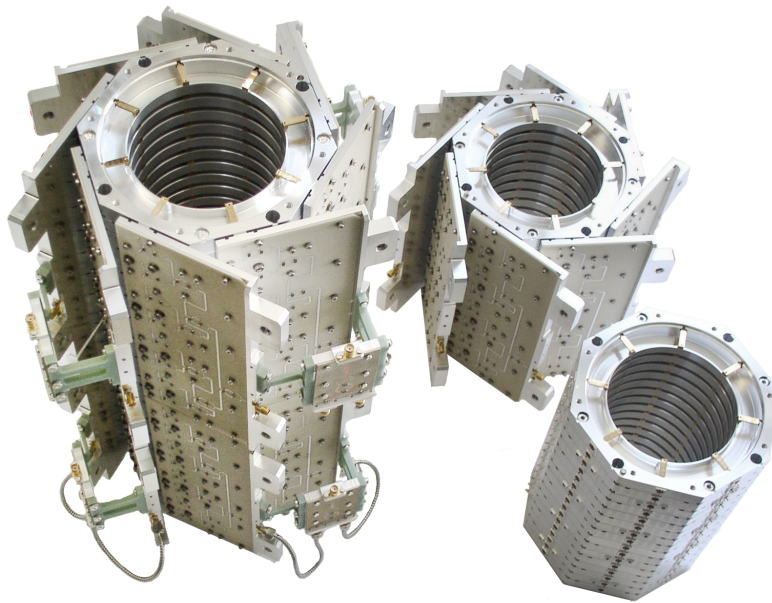


Figure 4.11: Stacks of ring slot couplers for the HESR stochastic cooling. On the right ring-slot couplers are stacked with and without the combiner boards, while on the left two of these stacks are mounted on top of each other (picture provided by R. Stassen, IKP/FZ Jülich).

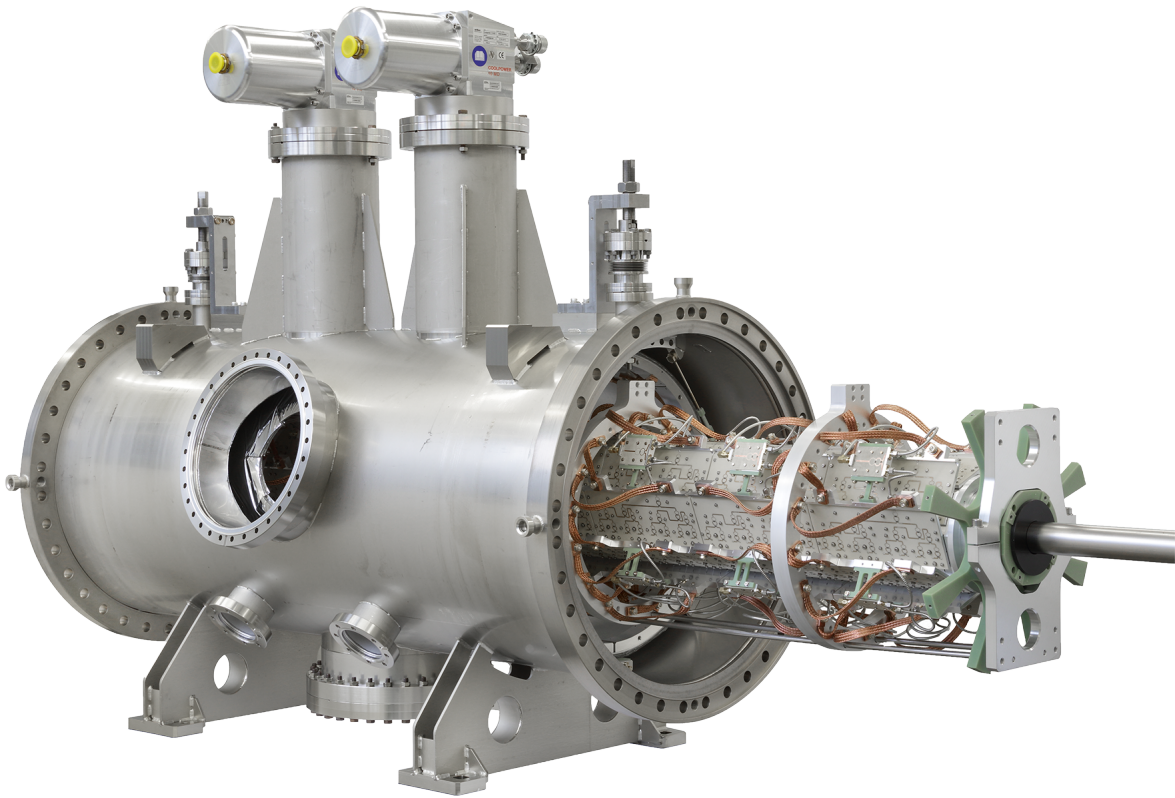


Figure 4.12: Pickup tank of the HESR stochastic cooling. The inner structure including the ring slot coupler stacks are visible outside the tank because the picture was taken during the installation. Afterwards, they were moved into the tank and the tank was closed. (picture provided by R. Stassen, IKP/FZ Jülich).

other hand, the beam can also be extracted and guided to the external experimental halls by means of an electrostatic and a magnetic septum [Mai97b].

There are also several diagnostic systems installed in the COSY ring, where only some will be mentioned here, since they are of importance for this thesis. The pickup tanks of the stochastic cooling have already been mentioned above. These are used to measure the Schottky spectra, thereby determining the momentum distribution of the COSY beam. It was seen in [Eic20] that measuring the Schottky spectra with the same pickup and in the same frequency regime as used for the stochastic cooling, a strong signal suppression is visible, that creates an artificial jump in the momentum spread when turning the stochastic cooling off. Therefore, the pickup of the old COSY stochastic cooling system was used during this thesis for all measurements, since this works at lower frequencies. Furthermore, the beam current is measured at COSY using a Beam Current Transformer (BCT) [Val⁺16] that uses the magnetic field created around a charged beam [For20]. The last diagnostic tool to mention is the Ionization Profile

Monitor (IPM), that allows to measure the transversal dimensions of the COSY beam. The COSY beam ionizes the residual gas in the beam line, the ions are then accelerated by an electric field towards an MCP stack followed by a luminescent screen and a CCD camera. This setup is used twice, for the horizontal and vertical directions [Böh⁺10]. According to equation 4.9, the width of the beam at any position s in the beam line can then be calculated as

$$w(s) = \sqrt{\frac{\beta(s)}{\beta_{\text{IPM}}}} w_{\text{IPM}} \quad (4.49)$$

with the beta function β_{IPM} at the IPM and $\beta(s)$ at the position of interest. Here, it was assumed that the width is only given by the betatron oscillation while the effect of dispersion and momentum spread can be neglected.

4.2.1 The $\overline{\text{PANDA}}$ Cluster-Jet Target at COSY

The $\overline{\text{PANDA}}$ cluster-jet target was installed at COSY in summer 2018 [Klo20] at the location of the former WASA experiment as shown in figure 4.13. Here, the WASA central detector was removed for further usage at the fragment separator FRS at GSI [Sai⁺23] leaving enough space for the installation of the $\overline{\text{PANDA}}$ cluster-jet target. The cluster-jet target source and its pumping station are installed on the concrete ceiling of the COSY tunnel. This allows having a distance between nozzle and accelerator beam line of 2.25 m so that an operation of the target in $\overline{\text{PANDA}}$ geometry is possible. Below the beam line, the space is more limited, so that the old beam dump is installed closer to the beam line than foreseen for $\overline{\text{PANDA}}$. Furthermore, the removal of the WASA central detector gives space for the installation of several systems for detailed studies of the target properties. Directly under the TVC, a second chamber called TVC 2 was installed by B. Hetz to investigate the influence of an additional pumping stage below the source on the vacuum conditions at the interaction point. Furthermore, the large scattering chamber allows the installation of pressure gauges and a large turbomolecular pump, which enables more precise studies on the vacuum system, that can give predictions for the situation later at $\overline{\text{PANDA}}$ [Klo20, Man24, Wei23]. Finally, between the scattering chamber and the beam dump an absolute thickness monitor system could be installed, that overcomes the absence of any monitor system in the old $\overline{\text{PANDA}}$ target beam dump. While the central detector was removed and created space for these systems, the WASA forward detector is still in place and operational. It was routinely used to monitor if the beam hits the target by analyzing its rates. For this purpose, only the Forward Range Hodoscope (FRH) consisting of multiple layers of plastic scintillators was used.

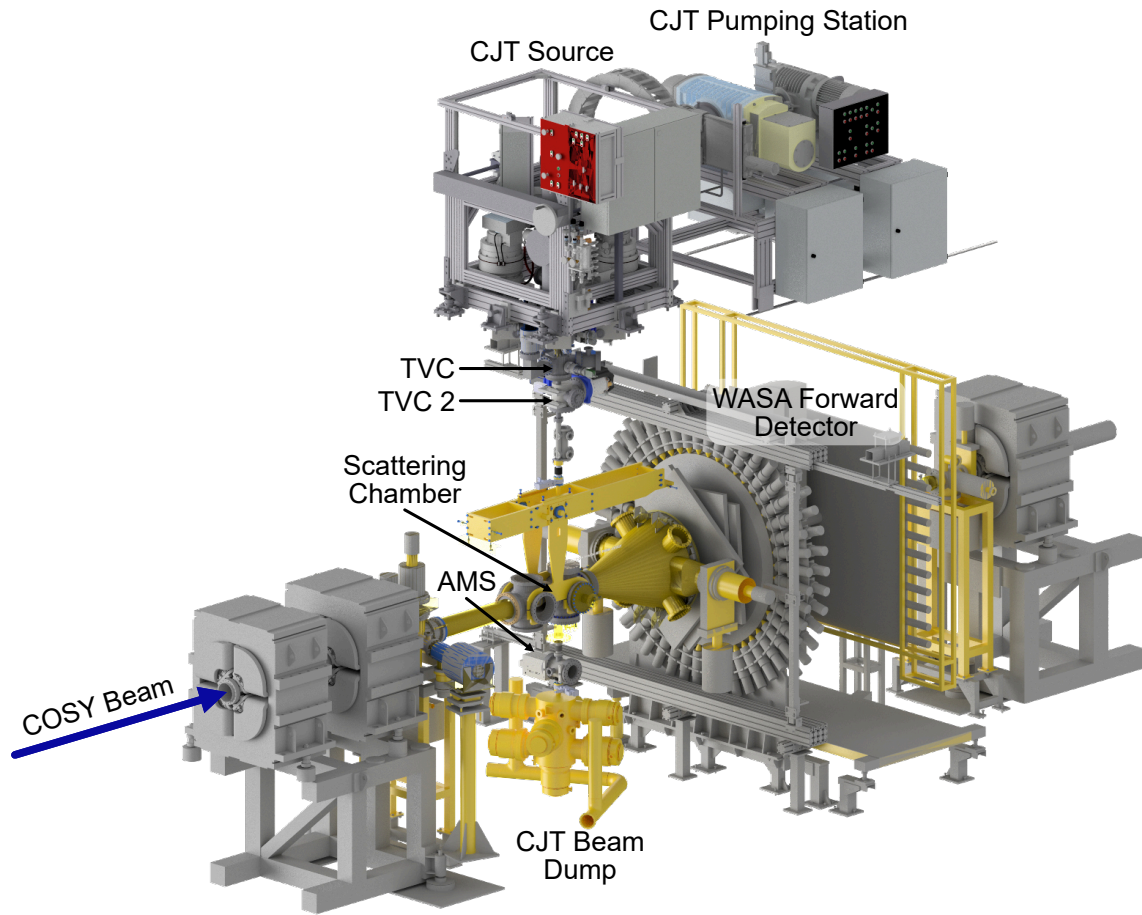


Figure 4.13: CAD drawing of the $\bar{\text{P}}\text{ANDA}$ cluster-jet target setup at the former WASA experimental area at COSY. The cluster-jet target source and its pumping station are placed on the concrete ceiling of the COSY tunnel. The cluster-jet then leaves the target vertically and crosses the TVC and an additional second TVC, that was inserted to study the influence of an additional pumping stage by B. Hetz. The jet then passes the scattering chamber in a distance of 2.25 m as also foreseen for the interaction point at $\bar{\text{P}}\text{ANDA}$. Due to the limited space below the beam line, the distance to the old beam dump is smaller. Additionally, an older version of the AMS system could be installed in front of the beam dump to overcome the absence of monitor systems in the old beam dump. The large scattering chamber also allows the installation of pressure gauges and a large turbomolecular pump to achieve a defined pumping speed at this chamber without the need to use the cryo pumps of COSY. Downstream of the scattering chamber, the former WASA forward detector is installed, which was used during the beam times analyzed in this thesis (created by D. Bonaventura, University of Münster, edited).

Chapter 5

Beam-Target Interaction at COSY

The installation of the $\bar{\text{P}}\text{ANDA}$ cluster-jet target at COSY offers the unique opportunity to operate it already under realistic conditions at an accelerator. In particular, the presence of the HESR stochastic cooling and a barrier bucket cavity enable studies of great importance for the $\bar{\text{P}}\text{ANDA}$ experiment. Therefore, in total three beam times in 2021, 2022, and 2023 were planned and carried out in the course of this thesis and the results are presented in this chapter. The program of these beam times differs only slightly and in total three main topics were addressed:

- Beam quality measurements were carried out, where the focus was on the influence of the $\bar{\text{P}}\text{ANDA}$ cluster-jet target in combination with the stochastic cooling on the COSY beam. Therefore, the reached momentum spread and beam size were measured for different target settings and COSY beam intensities. This was the main focus of these beam times and thus performed in all three of them.
- Stability measurements were performed that used very long cycle times of 30 min to study the stability of quantities like the momentum spread or the mean momentum. These measurements were performed in the beam times in 2022 and 2023.
- Energy loss measurements were carried out to study the energy loss of a coasting beam in the presence of the $\bar{\text{P}}\text{ANDA}$ cluster-jet target. From the energy loss the target thickness can be determined, and the results can be compared to the measurements with the AMS. These measurements were performed for every target setting of the two previous measurements.
- Measurements with the MCP monitor system were performed to prove the working principle and show the dependence of the image intensity on the accelerator beam intensity, the target thickness, and the MCP supply voltage. These measurements were only performed in the beam time in 2023.

All the mentioned measurements took place at COSY with an unpolarized proton beam with a momentum of 3 GeV/c. Additionally, several other measurements were performed that are needed to analyze the data and to understand the results of these beam times. These are measurements like regular scans with the AMS to determine the target thickness and its variation over time and the measurement of the phase slip factor η . Further measurements like studies on the vacuum conditions [Klo20, Wei23] or measurements for MAD-X simulations [Eic23] are summarized in other theses and are not discussed here.

5.1 Target Thickness Determination

The target thickness was regularly monitored during all measurements with the target. Therefore, the accelerator was stopped between the COSY cycles and several scans with the AMS were performed. For measurements with the target operating in the liquid regime these scans were repeated more often because of the larger fluctuations of the target. The profiles were then fitted by the function described in equations 3.24 and 3.27 to extract the target thickness in the center of the cluster-jet. Therefore, only the profile perpendicular to the beam direction was used, and the target thickness was determined with equation 3.31. This requires the knowledge of the cluster velocity and the pumping speed at the AMS chamber. The velocity can be extracted by simulations that were performed within [Täs12] for the same nozzle as used at the $\bar{\text{P}}\text{ANDA}$ target during the analyzed beam times. The pumping speed was measured by inducing a small gas flow rate of up to 3 ml_n/min into the vacuum chamber of the AMS. The resulting pressure

$$p = \frac{q_p V}{S} + p_0 \quad (5.1)$$

in the chamber is then given as a function of the gas flow rate $q_p V$ and the pumping speed S . Furthermore, a background pressure p_0 is added to the pressure that is caused by the residual gas in the chamber. The pumping speed is then extracted from the slope of a linear fit. The measurement was performed twice in 2021 and 2023 and the results are shown in figure 5.1. These data points are in good agreement, although the vacuum conditions changed slightly between the two measurements. In 2021 one vacuum pump in the third beam dump stage was not functional and sealed with a blank flange, a turbo pump in the first beam dump stage was replaced by a different type before the 2023 beam time, and one pump in the second beam dump stage was replaced by the MCP monitor system. All these changes had no significant impact on the pumping speed at the AMS chamber because of the small conductance between the

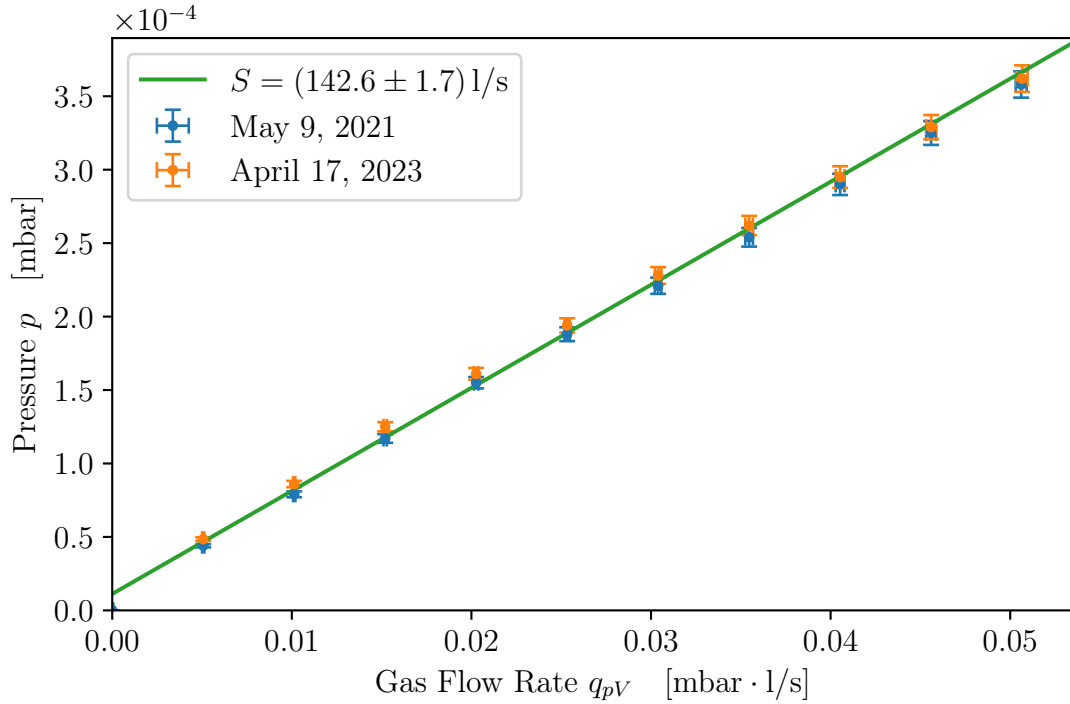


Figure 5.1: The pumping speed of the AMS chamber was determined by measuring the pressure in the AMS chamber for different gas flow rates q_{pV} into the chamber that were regulated by a mass flow controller. The measurement was performed once in 2021 and once in 2023 with slightly different vacuum configurations.

AMS chamber and the beam dump. Therefore, the measurements in 2021 and 2023 were combined into one fit that resulted in a pumping speed of $S = (142.6 \pm 1.7) \text{ l/s}$.

With this pumping speed and the simulated cluster velocity, the target profiles recorded with the AMS can be analyzed. During these beam times hundreds of AMS scans were performed which are not all shown here, but the resulting target thicknesses are summarized in sections 5.3, 5.4, and 5.6 of the corresponding measurements. As an example, the profile with the highest achieved target thickness is shown in the following. This was recorded at target conditions of 23 K and 18 bar (setpoints) during the first beam time in 2021. The velocity of $(278 \pm 15) \text{ m/s}$ was calculated for the actual pressure and temperature measured by the baratron and the temperature diode at the cold stage $((23.4 \pm 0.1) \text{ K}, (18.1 \pm 0.1) \text{ bar})$. Afterwards, the pressure profiles from the AMS can be analyzed. Therefore, a combined fit to both profiles is performed but also the narrower x-profile is fitted separately. For these two fits only a part of the x-profile data was used to avoid the influence of the asymmetric shape on one edge of the profile and to be able to describe the pressure increase more precisely since this is the quantity that will define the target thickness. The fit results are shown in figure

5.2 where also a separate fit for the z-profile is included for comparison, which is not used for the further analysis. It can be seen, that the combined fit overestimates the x-profile while the separate fit for the x-profile describes the data and especially the pressure increase well. The reason for this discrepancy is that the two profiles cannot be taken at the same time and the target conditions can change slightly between the two measurements. Therefore, in the following only the fit to the x-profile is used to determine the target thickness. For the data shown in figure 5.2 the target thickness was determined to be $(3.14 \pm 0.17) \cdot 10^{15} \text{ atoms/cm}^2$. This marks a new record target thickness for the $\bar{\text{P}}\text{ANDA}$ cluster-jet target that was only surpassed by a measurement at the Münster prototype target with the same nozzle but with a circular collimator [Gri18]. Unfortunately, this high target thickness of more than $2 \cdot 10^{15} \text{ atoms/cm}^2$ was only achieved over a time period of two hours, where the COSY accelerator was not able to provide a beam due to issues with the cyclotron, so that this high thickness will not appear in the data in the following sections. Nevertheless, at these conditions

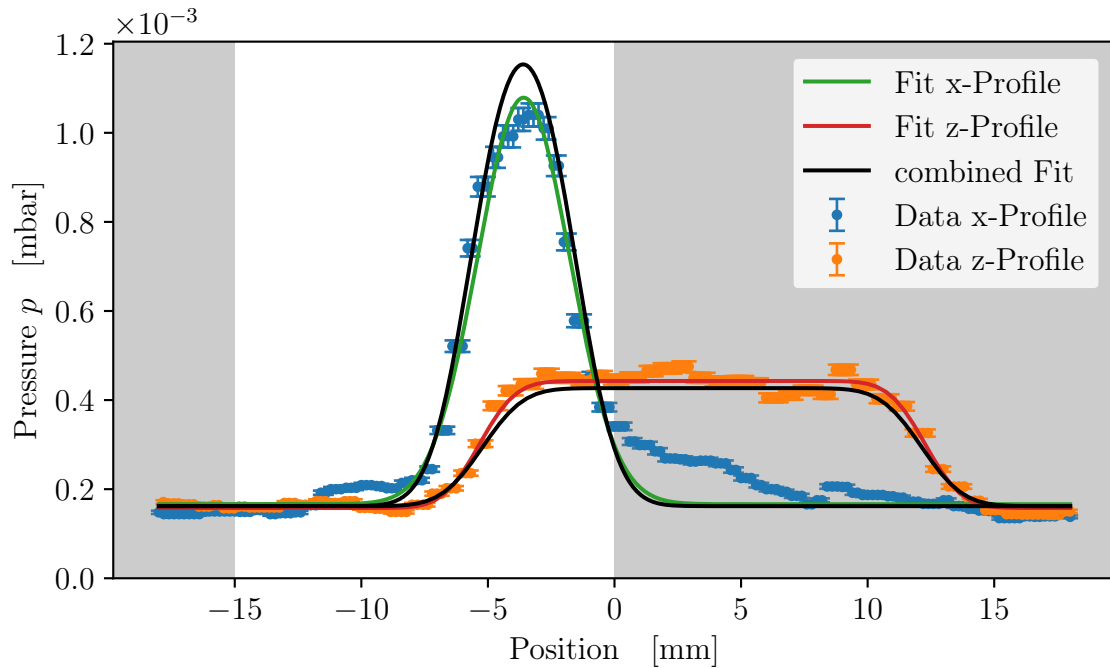


Figure 5.2: The target profile recorded with the AMS in May 2021 at operating conditions of 23 K and 18 bar. The two profiles were fitted separately (green and red) and a combined fit (black) was performed with the functions described in section 3.6.2. The gray area shows the data of the x-profile that was not included into the fits to avoid the influence of the asymmetric shape. The data of the broader z-profile was completely used. The single fit for the z-profile is shown only for comparison and not used in the analysis.

of 23 K and 18 bar the target thickness was constantly more than $1 \cdot 10^{15}$ atoms/cm² over a time period of more than 9 hours leading to the highest target thickness during the measurements described in the following sections.

Additionally, the target thickness can also be determined by studying the energy loss of a coasting beam [Ste⁺08] without using any cooling or phase focussing method. These analyses will be presented in section 5.5.

5.2 Phase Slip Factor Determination

Many measurements performed at COSY require the analysis of Schottky spectra. These give the distribution of the revolution frequency of all beam particles, which is correlated to the momentum distribution of the beam via the phase slip factor according to equation 4.14. Therefore, the momentum compaction factor α_p as defined in equation 4.17 has to be determined. This is possible via complex simulations like in MAD-X where it is calculated as the integral over the dispersion (see equation 4.18), but it can also be measured directly. When assuming that the orbit change is dominated by the effect of the dipoles, it can be measured by varying the magnetic field of the dipoles. From equation 4.3 for the deflection radius of a charged particle in a magnetic field of a dipole follows that increasing the momentum by a factor has the same effect as decreasing the magnetic field by the same factor. Thus, the relative change of the momentum

$$\frac{\Delta p}{p_0} = -\frac{\Delta B}{B_0} \quad (5.2)$$

can be replaced by the change of the magnetic field strength. Furthermore, the orbit change can be measured as change of the revolution frequency as

$$\frac{\Delta C}{C_0} = -\frac{\Delta f}{f_0} . \quad (5.3)$$

When combining this with equation 4.17, the momentum compaction factor can be defined as

$$\alpha_p = \frac{\Delta f/f_0}{\Delta B/B_0} . \quad (5.4)$$

Hence, the magnetic field was changed slightly while the resulting frequency shift was monitored with the recorded Schottky spectra. At COSY two possibilities for the measurement of the magnetic field are available. The first one is monitoring the current through the dipoles and assuming $\Delta I/I_0 = \Delta B/B_0$. This method was performed during all beam times, but large deviations compared to the η value determined by MAD-X were observed, because the dipole magnets were operated close to saturation

so that the magnetic field does not increase linearly with the current. Hence, the second method was used where the magnetic field was directly measured by means of an NMR probe PT2026 from Metrolab Technology. In this method, the NMR frequency, which is proportional to the magnetic field, is measured in a 25th dipole that is identical to the other dipoles but not part of the lattice. Since all 25 dipoles are connected in series, the magnetic field in this 25th dipole is equal to the magnetic fields in the other dipoles. In the end, the momentum compaction factor

$$\alpha_p = \frac{(\Delta f/f_0)_{\text{Schottky}}}{(\Delta f/f_0)_{\text{NMR}}} \quad (5.5)$$

is determined as function of the shifts of the revolution frequency in the Schottky spectra and of the NMR frequency. During the measurements, the magnetic field was increased linearly as shown in the NMR measurement in figure 5.3. The slope was determined by a linear fit to the data points in the linear part (green area) with some significant outliers being excluded. Furthermore, the constant region (red area) after the linear increase is used to determine f_0 ($\Delta f/f_0 = 0$). The same procedure was

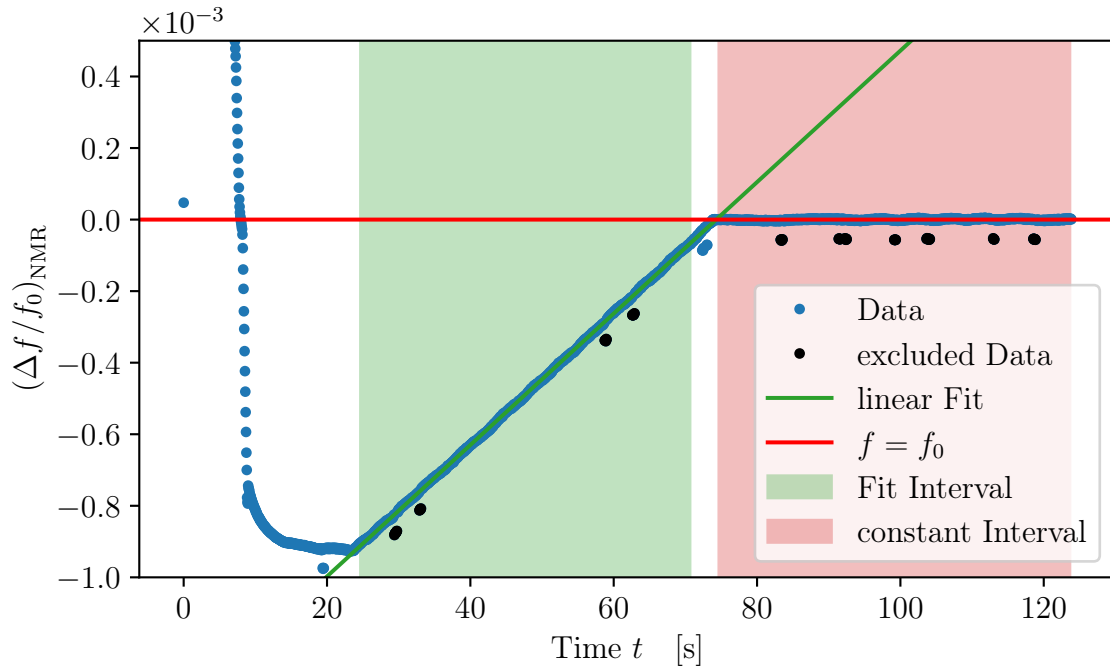


Figure 5.3: Measurement of the NMR frequency in the 25th dipole during the η measurement. The slope was determined by a linear fit to the data in the green area, with the outliers (black points) being excluded. The constant frequency f_0 is calculated as the mean of the data in the red area. Again, significant outliers are excluded.

performed for the Schottky spectra as shown in figure 5.4. Here, the shift of the mean of the Schottky spectrum is analyzed. The absolute time shown in these two plots has an unknown offset, so that the slope is used for the determination of the momentum compaction factor:

$$\alpha_p = \frac{\left(\frac{1}{f_0} \frac{df}{dt}\right)_{\text{Schottky}}}{\left(\frac{1}{f_0} \frac{df}{dt}\right)_{\text{NMR}}} . \quad (5.6)$$

This measurement was repeated several times in the beam times in 2022 and 2023 leading to an averaged value of $\alpha_p = 0.1854 \pm 0.0013$ and $\eta = -0.0963 \pm 0.0013$. This value is used for the analysis of all Schottky spectra in the following analyses.

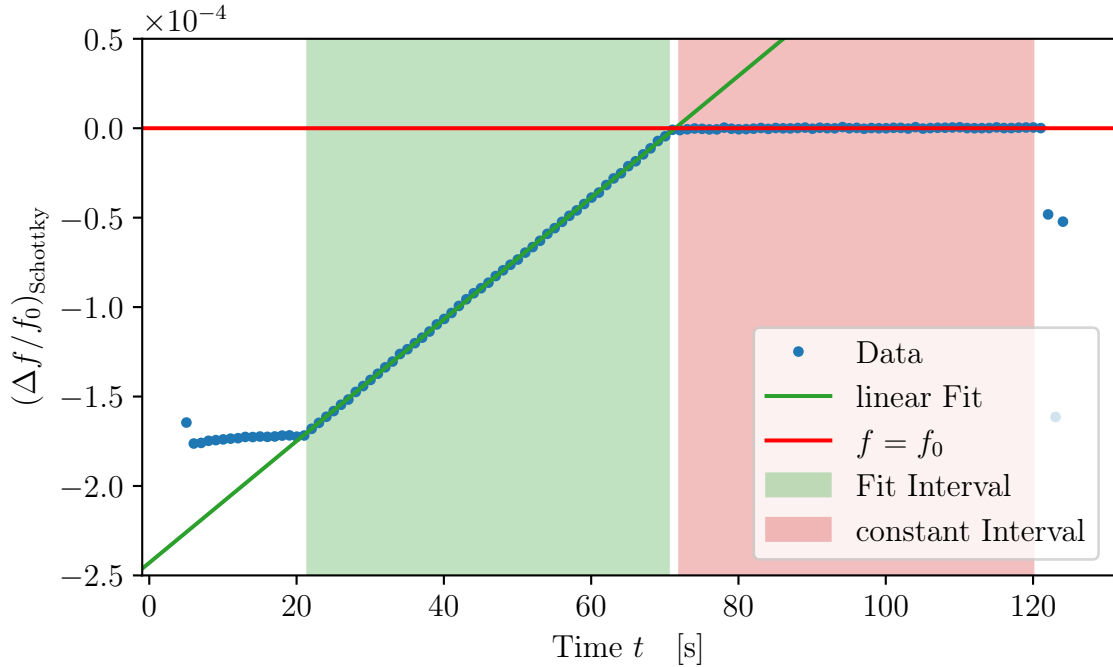


Figure 5.4: Measurement of the mean Schottky frequency during variation of the magnetic field in the dipoles. The slope was determined by a linear fit to the data in the green area. The constant frequency f_0 is calculated as the mean of the data in the red area.

5.3 Beam Quality Measurements

The beam quality measurements were the main focus in all three beam times. Here, the influence of the $\bar{\text{P}}\text{ANDA}$ cluster-jet target in combination with the stochastic cooling on the COSY beam was studied. Therefore, the achieved momentum spread and beam size

were measured for different target settings (see figure 5.5) and COSY beam intensities. The COSY beam intensity was set to three different values of about $2 \cdot 10^9$, $5 \cdot 10^9$, and $1.5 \cdot 10^{10}$ stored protons in the COSY ring that will be referred to as low, medium, and high intensity. Unfortunately, the highest intensity was not always reachable, so that in the first part in May of the 2021 beam time only the low and medium intensity was used. Hence, some additional days of beam time in June 2021 were made possible where only the high intensity was used, except for one setting with medium intensity to have some overlap. These two parts are comparable, since no major changes to the COSY settings have been done. In the 2022 beam time, due to limited time and the smaller amount of data with high intensity from the first beam time, only data with high and medium intensity was taken, while in the 2023 beam times all intensities were used. For all these measurements, different target conditions were chosen, ranging from a target thickness of 10^{13} atoms/cm² in the gaseous regime up to 10^{15} atoms/cm² in the liquid regime. Unfortunately this very high thickness was only available in the 2021

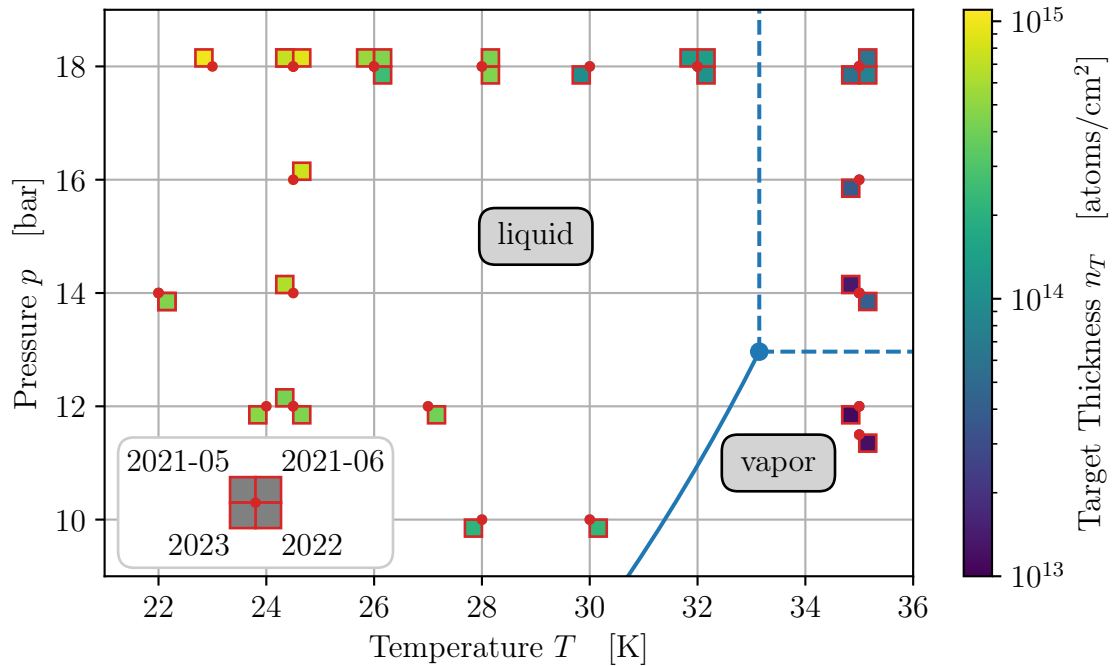


Figure 5.5: Target settings (red dots) used during the beam quality measurements in the phase diagram of hydrogen. The solid blue line shows the vapor pressure curve [LM25], while the dashed lines mark the region of supercritical hydrogen. The color code shows the achieved mean target thickness during the measurements, while the up to four quadrants around a red dot describe the different beam times. Here, the beam time in 2021 was divided into two parts, the first part took place in May and the second part in June.

beam time, while in the beam times 2022 and 2023 a maximum target thickness of roughly $5 \cdot 10^{14}$ atoms/cm² was available. In figure 5.5, all the different target settings for the beam quality measurements with the resulting target thickness are summarized in the hydrogen phase diagram, where the up to four quadrants represent the three beam times, with the red dot showing the corresponding target condition and the color visualizing the achieved target thickness.

5.3.1 COSY Cycle Sequence

As mentioned before, the COSY beam was set to three different intensities for the beam quality measurements, but also other important settings need to be discussed here. During all beam times, COSY has been operated in a supercycle mode. Each supercycle consists of four cycles. The first one is a very short cycle, which is used to ramp the dipoles once. Otherwise, the dipole fields are slightly different during the first cycle due to hysteresis effects, which would result in a smaller accelerator beam intensity. For two of the other three cycles, four steerer magnets around the target area were used to create a bump parallel to the nominal orbit at the target. By this, during the second cycle, the COSY beam was guided around the left side of the target in a distance of 8 mm to the reference orbit. The third cycle was without a bump, so that the COSY beam hits the target centrally, while the fourth cycle uses an 8 mm bump to the right. This sequence was used in all beam times to study the influence of the target and the residual gas on the beam quality. Also the sequence of each individual cycle is similar in all beam times with the exact timing shown in table 5.1. The cycles start with the injection and acceleration of the protons by the RF cavity. Afterwards, the RF cavity is turned off and the barrier bucket cavity is turned on. This

Table 5.1: The sequence of a COSY cycle for the different beam times. The times are given in seconds after the start of the cycle.

	2021	2022	2023
Barrier Bucket on	7.5	17	7.2
RF off	7.5	19	7.2
stoch. Cooling on	10	20	10
Target on	20	30	20
Target off	270	300	300
stoch. Cooling off	280	320	320
Barrier Bucket off	298	330	330
End of Cycle	300	330	330

is followed by starting the stochastic cooling and after some time of pre-cooling, the target is turned on by means of the nozzle shutter. At the end of the cycle, the target is turned off, followed by turning off the stochastic cooling, and at the end the barrier bucket is turned off and the protons are dumped. The sequences are quite similar, and especially the time between starting the stochastic cooling and turning on the target was kept constant at 10 s to get comparable results. The main difference is the longer time for the acceleration in 2022, that has no effect on this analysis as only the data during operation of the stochastic cooling is studied. The typical development of a recorded Schottky spectrum during a cycle from the 2021 beam time is shown in figure 5.6, where one can clearly see, that the spectrum gets narrower when the stochastic cooling is enabled. Besides the main peak, on the right also a smaller peak can be seen that shifts further to the right over time. This side peak is important for the following sections. This Schottky spectrum and all following were recorded with the old Schottky pickup at the 750th harmonic and the frequency is divided by the harmonic number to get the revolution frequency shown in the plots.

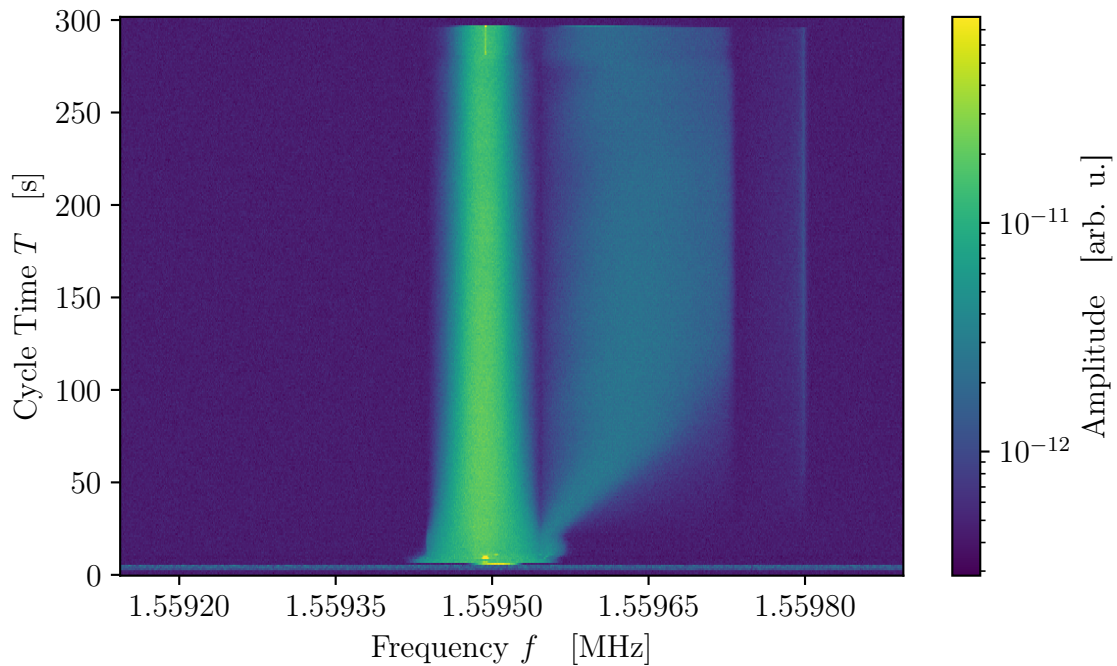


Figure 5.6: Waterfall plot of a Schottky spectrum recorded during a COSY cycle in May 2021 at target conditions of 23 K and 18 bar with a target thickness of $(1.00 \pm 0.44) \cdot 10^{15}$ atoms/cm² and medium COSY intensity.

5.3.2 Barrier Bucket Edge Determination

To study the beam quality, the main goal is to analyze Schottky spectra that were recorded with the pickup tank of the old stochastic cooling system. The Schottky spectra during the cycles show a large peak with a slightly asymmetric shape. Additionally, for high target thickness and high beam current, a second, smaller peak can occur on the right side of the main peak at higher frequencies. This corresponds to particles that cannot be held inside the bucket of the barrier bucket cavity. The following analyses will concentrate only on the particles inside the bucket. Therefore, the position of the bucket edge needs to be determined. All Schottky spectra of a cycle as shown in figure 5.6 are summed leading to the spectrum shown in figure 5.7. Here, all local minima are searched for, where a local minimum is defined as a data point with a smaller value than all of its five neighbors on both sides. For the further analysis only minima on the right of the global maximum and with a value smaller than 20 % of the maximum are considered, all others are rejected. The found minima are marked in

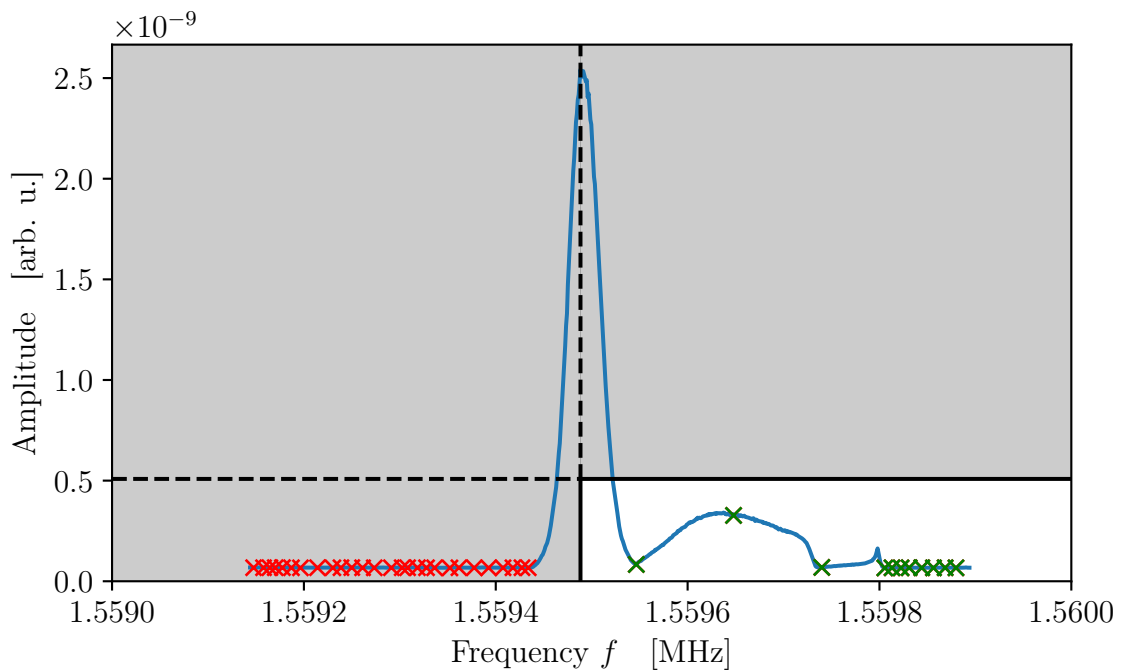


Figure 5.7: Sum of all Schottky spectra within a COSY cycle in May 2021 with a target thickness of $(1.00 \pm 0.44) \cdot 10^{15}$ atoms/cm² at target conditions of 23 K and 18 bar and medium COSY intensity. All local minima - defined as data points with a value that is smaller than the 5 neighbors on both sides - are marked by crosses. Only minima on the right of the maximum (vertical line), and with a value smaller than 20 % of the maximum (horizontal line) are considered and are shown as green crosses, all others are marked red.

figure 5.7 as green crosses, while the rejected ones are marked red. Here, the minimum between main and side peak but also many others are found.

All the found valid minima of all cycles are filled into a histogram separately for every beam time as shown in figure 5.8. A very narrow peak is visible that shows that in most spectra the same data point is found as minimum between main and side peak. The position of this peak is determined for every beam time separately and used as barrier bucket edge. These bucket edge positions are summarized in table 5.2.

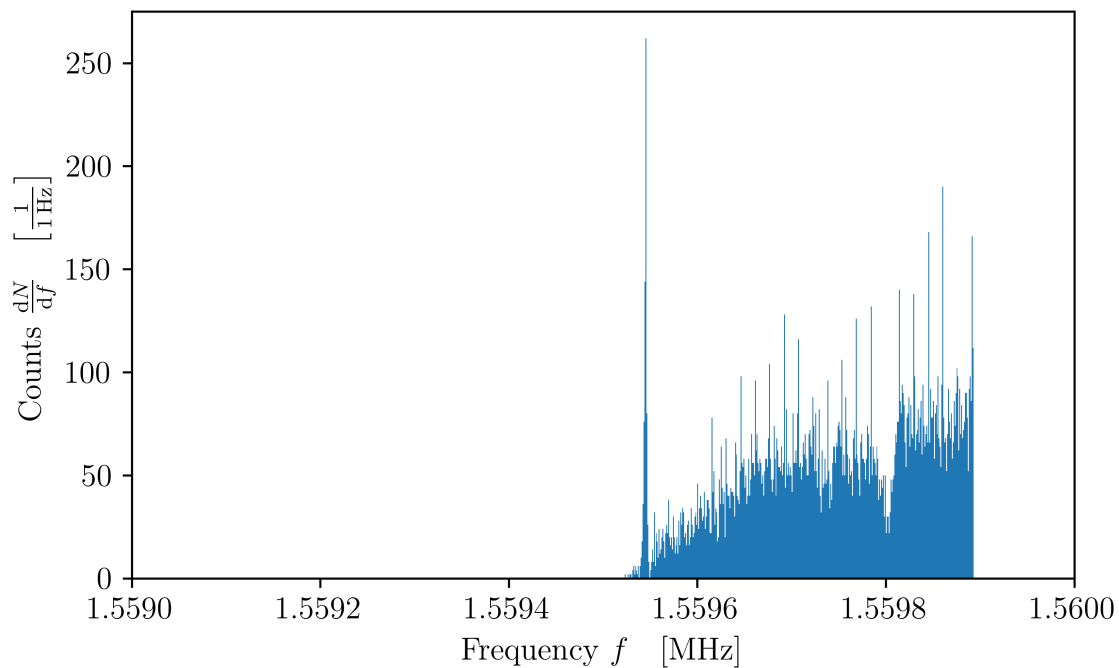


Figure 5.8: Histogram of all valid minima in the Schottky spectra for the beam time in May 2021. The maximum is located at 1.559 546 MHz and is used as barrier bucket edge for this beam time.

Table 5.2: Position of the barrier bucket edge for the different beam times.

Barrier Bucket Edge	
2021-05	1.559 546 MHz
2021-06	1.559 548 MHz
2022	1.559 544 MHz
2023	1.559 533 MHz

5.3.3 Analysis of Schottky Spectra

The determined barrier bucket edge is used to analyze the Schottky spectra, which are described in the following. The analysis procedure is visualized in figure 5.9. The side peaks at higher frequencies that occur in Schottky spectra, when a large target thickness, a high intensity, or both are used, are neglected for the following analysis. This is because later at the HESR, a higher bucket potential and also a larger bucket due to the smaller revolution frequency will be used. For this reason, it is expected that the barrier bucket cavity will be able to hold the particles inside the bucket and therefore the analysis here only concentrates on the main peak. To extract the mean of this main peak and its standard deviation, some analysis steps have to be performed as demonstrated in figure 5.9.

First, the data is fitted with the asymmetric Gaussian function

$$g(f) = A \exp \left(-\frac{(f - f_0)^2}{2\sigma(f)^2} \right) + c \quad (5.7)$$

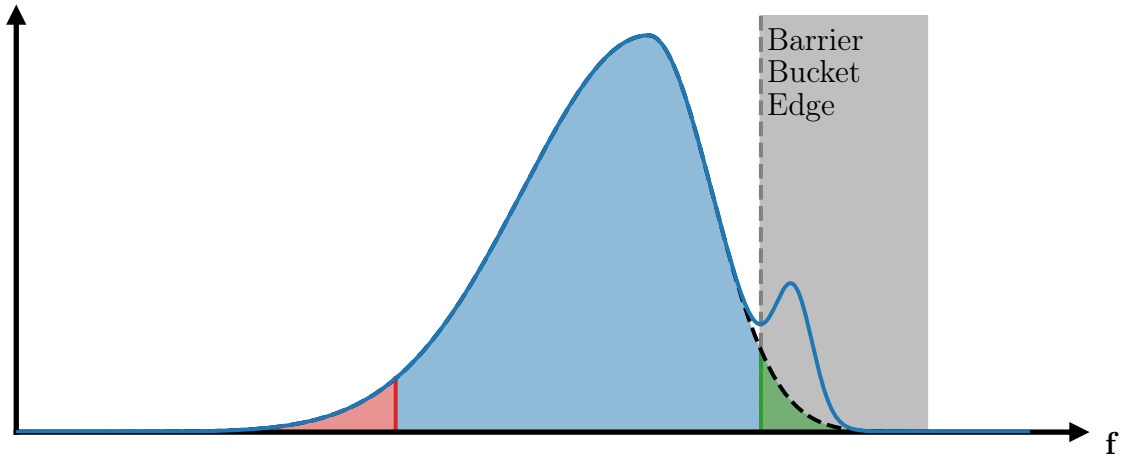


Figure 5.9: Demonstration of the Schottky spectrum analysis. A double peak structure can occur due to particles that cannot be held inside the barrier bucket potential. Therefore, only the main peak inside the bucket is analyzed. The data is fitted by an asymmetric Gaussian function. For this fit, the data outside the bucket is excluded (gray area). The mean and standard deviation of the data is then determined in three parts. The central part (blue) is analyzed via a sum of all data points. This area is limited on the left side by the 3σ -interval, and the right border is the smaller value of either 3σ or the edge of the barrier bucket. The two areas left and right of the central (red and green) are then added to the mean and standard deviation of the central part by an integral over the fit function so that the side peak is excluded from the analyses. For visualization purposes, in this figure a 2σ -interval is used, instead of the 3σ -interval used in the analysis.

with

$$\sigma(f) = \begin{cases} \sigma_l & \text{for } f < f_0 \\ \sigma_r & \text{for } f \geq f_0 \end{cases}, \quad (5.8)$$

the center frequency f_0 , and the additional constant c for the background. For this fit, the data on the right side of the barrier bucket edge is neglected except of a part at the very end of the spectrum that helps to determine the background. Based on this fit, the data is then divided into three parts as shown in figure 5.9. The left part (red) is the complete range with $f < f_l = f_0 - 3\sigma_l$, which is the complete range on the left of the 3σ -interval. The right part (green) is the complete range with $f > f_r = \min(f_{\text{BB}}, f_0 + 3\sigma_r)$, where f_{BB} is the barrier bucket edge, so that here the limit is either the bucket edge or the 3σ -interval depending on what is closer to f_0 . Everything in between is the central part (blue) that includes the largest part of the data. The mean and variance of the central part is then determined by a simple sum of all data points, but this has to be corrected for the contributions in the outer parts. Therefore, the mean revolution frequency is calculated as

$$\bar{f} = \frac{1}{n} \left(\sum_{i,\text{central}} f_i \cdot (S(f_i) - c) + \frac{1}{\Delta f} \int_{-\infty}^{f_l} f \cdot (g(f) - c) df + \frac{1}{\Delta f} \int_{f_r}^{\infty} f \cdot (g(f) - c) df \right), \quad (5.9)$$

where f_i is a data point of the spectrum with the corresponding signal height $S(f_i)$, c is the background from the fit function, and $\Delta f = f_{i+1} - f_i$ is the frequency resolution of the recorded spectrum. Similarly, the variance is given as

$$\sigma_f^2 = \frac{1}{n} \left(\sum_{i,\text{central}} (f_i - \bar{f})^2 \cdot (S(f_i) - c) + \frac{1}{\Delta f} \int_{-\infty}^{f_l} (f - \bar{f})^2 \cdot (g(f) - c) df + \frac{1}{\Delta f} \int_{f_r}^{\infty} (f - \bar{f})^2 \cdot (g(f) - c) df \right). \quad (5.10)$$

The normalization for both quantities is determined by

$$n = \sum_{i,\text{central}} (S(f_i) - c) + \frac{1}{\Delta f} \int_{-\infty}^{f_l} (g(f) - c) df + \frac{1}{\Delta f} \int_{f_r}^{\infty} (g(f) - c) df. \quad (5.11)$$

Figure 5.10 shows two examples of Schottky spectra both recorded during the first beam time in May 2021. The first one is recorded at a large target thickness of $(1.00 \pm 0.44) \cdot 10^{15}$ atoms/cm² with the target operating at 23 K and 18 bar and with medium COSY intensity. A large side peak is visible that corresponds to

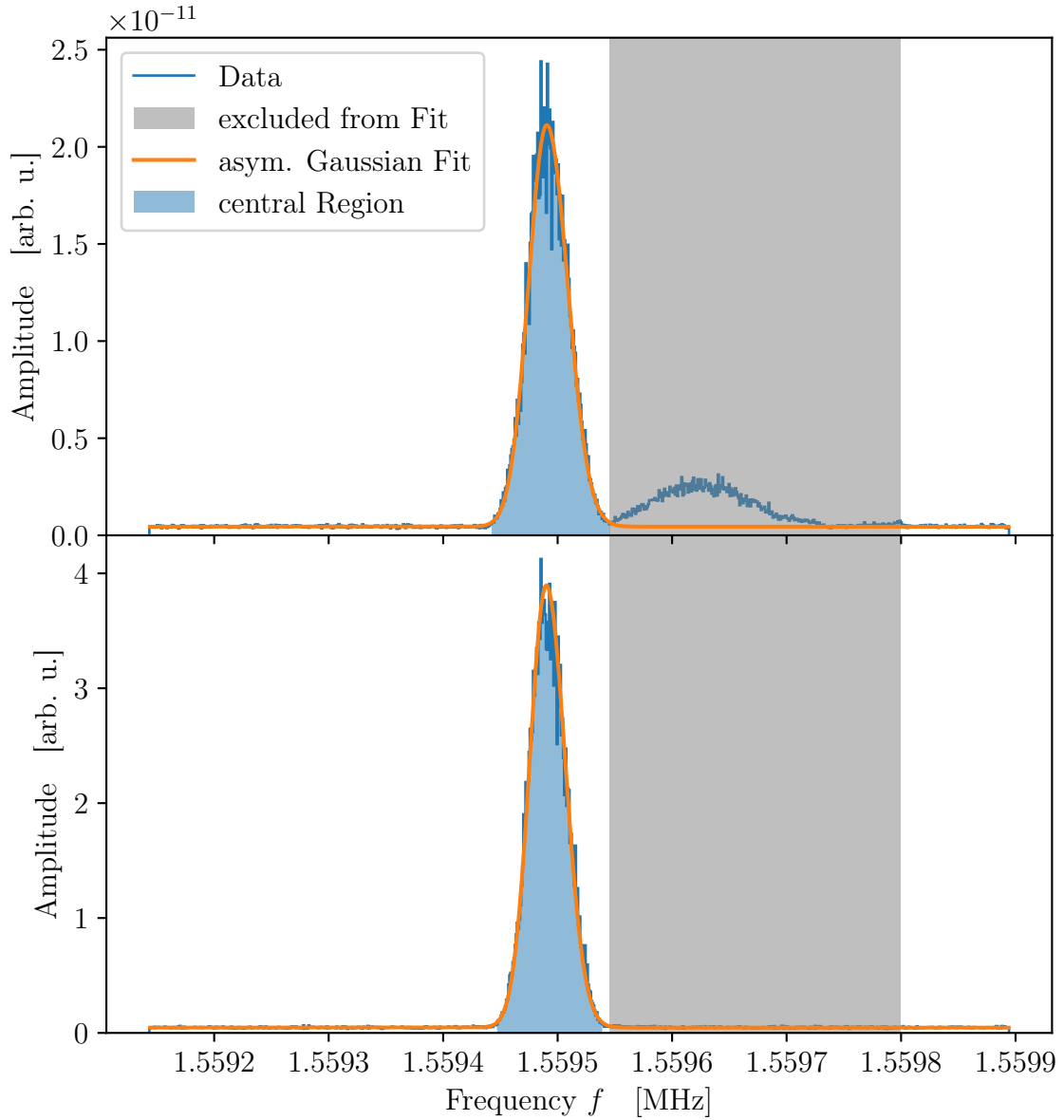


Figure 5.10: Example of a Schottky spectrum after roughly 80 s of the cycle with a target thickness of $(1.00 \pm 0.44) \cdot 10^{15}$ atoms/cm² at 23 K and 18 bar (top) and with a target thickness of $(1.32 \pm 0.05) \cdot 10^{14}$ atoms/cm² at 32 K and 18 bar, both with medium COSY intensity. Besides the main peak a strong side peak is visible in the upper spectrum. The data is fitted with an asymmetric Gaussian function, where the data in the gray area, which starts at the barrier bucket edge, is excluded.

particles outside the bucket. At large target thicknesses and high beam intensities, these particles cannot be cooled back into the bucket by the stochastic cooling. On the other hand, the second spectrum was recorded with a target thickness of $(1.32 \pm 0.05) \cdot 10^{14}$ atoms/cm² at 32 K and 18 bar and medium COSY intensity. No side peak is visible in this case. These two spectra show the two extrema of Schottky spectra that were recorded during the beam times. In both cases, the method for extraction of the features of the main peak works well. Even if in some cases the tip of the peak is not perfectly described, the mean and standard deviation are still well determined as here the sum of the data points is used. The fit only has to describe the tails sufficiently well which is mostly the case once the stochastic cooling was turned on. Only shortly after injection into COSY, the spectra have a very different shape that is difficult to describe, but these data points are not used for the analysis as the focus is on the performance of the stochastic cooling.

The Schottky spectra are recorded approximately every second and by analyzing all of them the evolution of the frequency spread can be extracted which can be converted into the momentum spread by using equation 4.14. This is shown in figure 5.11 for the two different target settings that were already discussed before, so with a target thickness of $(1.00 \pm 0.44) \cdot 10^{15}$ atoms/cm² at 23 K and 18 bar on the left and $(1.32 \pm 0.05) \cdot 10^{14}$ atoms/cm² at 32 K and 18 bar on the right. The strong fluctuations at the beginning are caused by the very different shape of the Schottky spectra that makes the analysis unstable. Once the particles are injected, accelerated, and the barrier bucket and the stochastic cooling are turned on, the shape gets more regular and therefore the extracted momentum spread is more accurate. At the beginning, the momentum spread is reduced significantly by the stochastic cooling, and it takes about 80 s after turning on the stochastic cooling to get close to an equilibrium. The reached momentum spread in the equilibrium is then extracted as the mean of all data points in the time period between 240 s and 270 s for the 2021 and 2023 beam times and between 250 s and 280 s for the 2022 beam time due to the longer time before the stochastic cooling is started here, so that the time between this interval and the onset of the stochastic cooling is the same for all settings. The extracted momentum spread and its standard deviation as uncertainty are then used for the further analysis, which studies the dependence of the momentum spread on the target thickness and the COSY intensity.

Like the momentum spread, for every setting also the target thickness and the beam current needs to be determined. The target thickness is measured via the AMS several times before the start of the measurements with a setting, between the supercycles, and after the measurements. All these measurements are analyzed as described in section

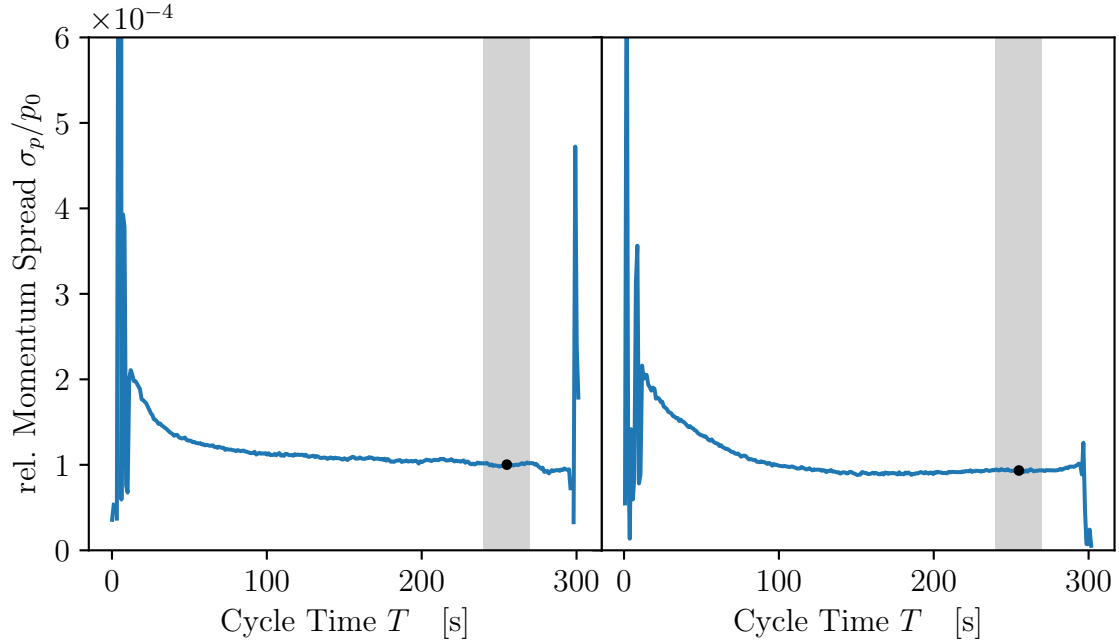


Figure 5.11: Evolution of the relative momentum spread within a cycle for a target thickness of $(1.00 \pm 0.44) \cdot 10^{15} \text{ atoms/cm}^2$ at 23 K and 18 bar (left) and a target thickness of $(1.32 \pm 0.05) \cdot 10^{14} \text{ atoms/cm}^2$ at 32 K and 18 bar (right) with medium COSY intensity. In the beginning of the cycle the momentum spread has a large variation as here the Schottky spectra have a different shape that makes the analysis unstable. After roughly 100 s the spread does not change significantly anymore. The equilibrium value is then extracted in the gray area by calculating the mean of all data points in this range.

5.1 and the variance-weighted mean and standard deviation of all these measurements is calculated. The beam current is regularly measured by the beam current transformer during the cycles and can be averaged in the same time interval as the momentum spread. The resulting momentum spread as function of the target thickness and the number of stored particles at COSY are plotted separately for all beam times in figures A.1, A.2, and A.3 in the appendix. They are also summarized in figure 5.12 with a proper scaling which is explained later.

When comparing these three figures, one can see that the momentum spread increases as expected when the target thickness or the beam intensity is increased. Furthermore, it is noticeable that the reached momentum spread of the different beam times are not comparable probably due to slightly different settings in the COSY lattice and also due to some hardware changes at the stochastic cooling system. To describe the dependence of the momentum spread on the target thickness and the beam intensity

more quantitatively, a fit function is used that is a product of two functions, one depending on the target thickness and the other on the beam intensity. While at the first glance, a linear function seems to be sufficient to describe the data, the momentum spread in the equilibrium for the HESR stochastic cooling system is expected to follow [Gut06, Hin06, SKM16]

$$\left(\frac{\Delta p}{p_0}\right)_{eq} \propto (n_T N_p)^{1/3}. \quad (5.12)$$

In this analysis, a more general function will be used. Therefore, the dependence on the target thickness n_T and the beam intensity N_p will be described as independent power laws with additional constant offsets A_1 and A_2 as

$$\left(\frac{\Delta p}{p_0}\right)_{eq} \propto (M_1 \cdot n_T^{p_1} + A_1) \cdot (M_2 \cdot N_p^{p_2} + A_2) \quad (5.13)$$

with the exponents p_1 and p_2 and the proportionality constants M_1 and M_2 . The need of the constant offsets can already be seen from the data in the figures A.1, A.2, and A.3 in the appendix and in figure 5.12 where the momentum spread is not zero for zero target thickness, which can be explained by other heating effects like intrabeam scattering [Hin06, SKM16]. This dependence is slightly restructured leading to the fit function

$$g(n_T, N_p) = a \cdot \left(m_1 \cdot \frac{n_T^{p_1} - s_1}{s_1} + 1\right) \left(m_2 \cdot \frac{N_p^{p_2} - s_2}{s_2} + 1\right), \quad (5.14)$$

where m_1 and m_2 are slope parameters that can be derived from M_1 , M_2 , A_1 , and A_2 . Additionally, the constant offsets are summarized into the parameter a as otherwise a correlation would occur. The additional parameters s_1 and s_2 are fixed scaling parameters that are set to $s_1 = (1 \cdot 10^{14} \text{ atoms/cm}^2)^{p_1}$ and $s_2 = (5 \cdot 10^9)^{p_2}$ to reduce the correlation of the fit parameters and to reduce the value of the other parameters by several orders of magnitude which makes the fit procedure more robust for numerical uncertainties.

With this function a combined, global fit to the data points of all three beam times is performed that minimizes

$$\chi^2 = \sum_{bt,i} \frac{(s_{bt} \cdot g(n_{T,i}, N_{p,i}) - y_i)^2}{(\Delta y_i)^2 + (s_{bt} \cdot g_{n_T}(n_{T,i}, N_{p,i}) \Delta n_{T,i})^2 + (s_{bt} \cdot g_{N_p}(n_{T,i}, N_{p,i}) \Delta N_{p,i})^2} \quad (5.15)$$

with the uncertainties Δy_i in the relative momentum spread, $\Delta n_{T,i}$ in the target thickness, and $\Delta N_{p,i}$ in the number of stored particles. The uncertainties in n_T and N_p are used as weighting by converting it into an additional uncertainty in the momentum spread by using the derivatives $g_{n_T} = \partial g / \partial n_T$ and $g_{N_p} = \partial g / \partial N_p$ and adding all these

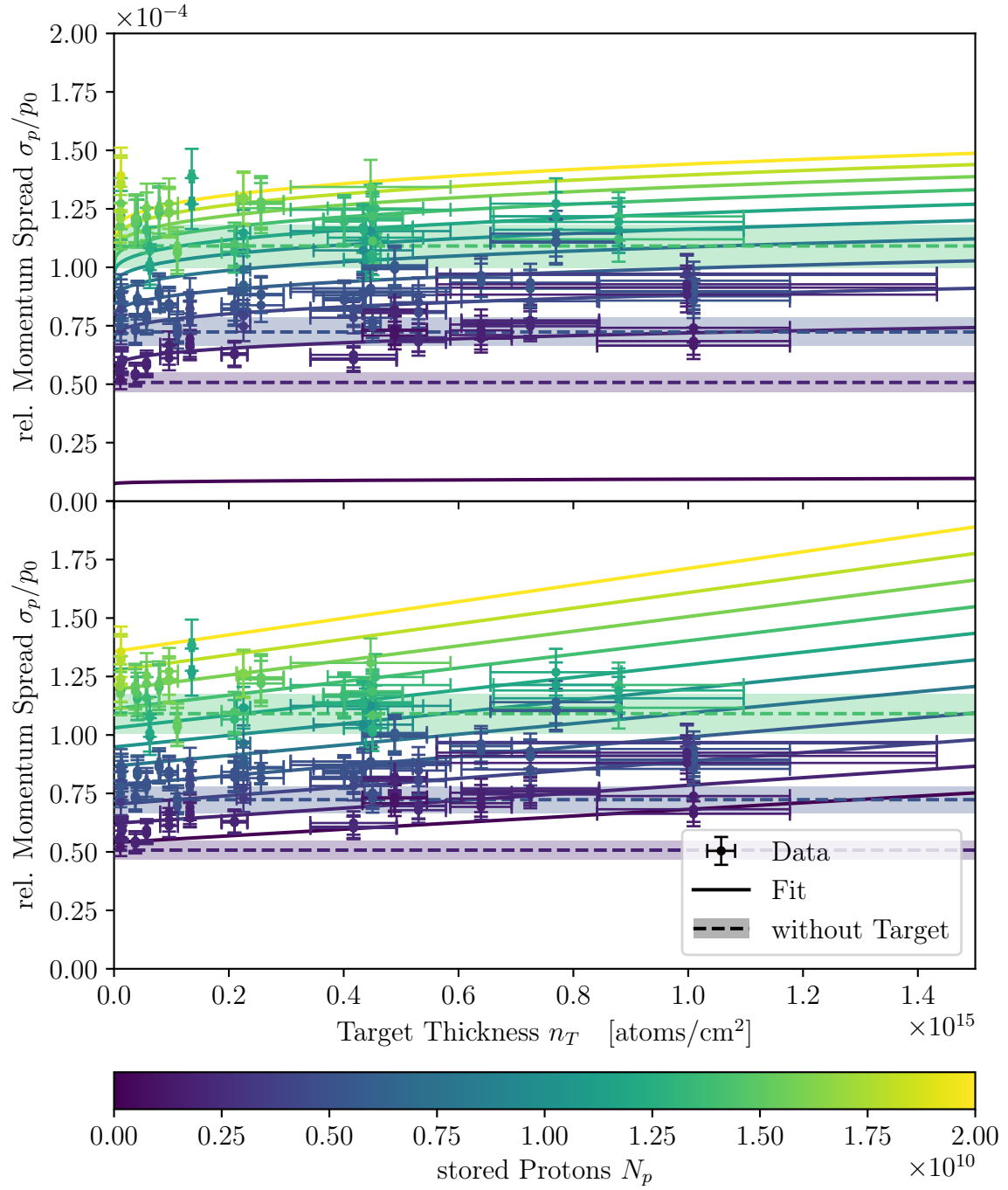


Figure 5.12: Dependence of the relative momentum spread on the target thickness for all beam times with a fit considering $p_1 = p_2 = 1/3$ (top) and $p_1 = p_2 = 1$ (bottom). The data is scaled with $1/s_{bt}$ that is determined via the fit. The colored, solid lines show the fit for different numbers of stored protons from 0 to $2 \cdot 10^{10}$ in steps of $2 \cdot 10^9$. Additional data taken without target is added as horizontal, dashed lines. The additional uncertainty (see equation 5.16) is determined by demanding $\chi^2_{red} = 1$, and it is included in all vertical error bars and error bands.

uncertainties in quadrature. Furthermore, a scaling parameter s_{bt} is introduced, that is used to scale the data points of the different beam times so that they can be fitted together. The parameter s_{bt} for the 2023 beam time is set to $s_{2023} = 1$ to have the last beam time when the best values for the momentum spread has been reached as reference, while s_{2021} and s_{2022} are free fit parameters. Since for every setting, the gain and delay of the stochastic cooling had to be adjusted to reach the optimum equilibrium value. This introduces an uncertainty that cannot be quantified. Therefore, Δy_i is modified as

$$(\Delta y_i)^2 \rightarrow (\Delta y_i)^2 + (k \cdot y_i)^2 \quad (5.16)$$

so that an additional uncertainty proportional to the momentum spread is added to the uncertainty Δy_i of the momentum spread within the equilibrium interval. The constant k was then determined as the value that results in a fit with $\chi^2_{\text{red}} = 1$. To achieve a stable fit result, the parameters p_1 and p_2 are fixed. In the upper plot in figure 5.12 the fit result for the expected power law with $p_1 = p_2 = 1/3$ is shown with the data of all beam times scaled with $1/s_{\text{bt}}$. The additional uncertainty in the momentum spread is also added to the error bar. Furthermore, cycles without a target have been performed during the 2023 beam time, that are not included into the fit but added to the plot as horizontal lines symbolizing the optimum without target. The uncertainty for the adjustment was added to the error bands.

While the dependence is expected to follow $p_1 = p_2 = 1/3$, also a fit with $p_1 = p_2 = 1$ is performed and these are compared. The resulting fit parameters and the additional scaling factor k for the uncertainty of the momentum spread are shown in table 5.3, while the fit is also shown in the lower plot of figure 5.12. The parameters are very similar for both fits. Only m_1 and m_2 change significantly when p_1 and p_2 are changed. Also the scaling factor k for the momentum spread uncertainty deviates by less than 5 %, so that one can argue that both fits can describe the data similarly well. For a

Table 5.3: Fit results for the relative momentum spread as function of the target thickness and the number of stored particles.

	$p_1 = p_2 = 1/3$	$p_1 = p_2 = 1$
a	$(8.3 \pm 0.1) \cdot 10^{-5}$	$(7.64 \pm 0.09) \cdot 10^{-5}$
m_1	0.116 ± 0.015	0.026 ± 0.003
m_2	0.90 ± 0.03	0.274 ± 0.009
s_{2021}	1.135 ± 0.020	1.138 ± 0.020
s_{2022}	1.33 ± 0.03	1.37 ± 0.03
k	0.083	0.077

better distinction between the two models, the uncertainty coming from the manual adjustment of the stochastic cooling and the uncertainty in the target thickness would need to be reduced. The latter is especially important for settings with large density where the target is more unstable. Here, a more stable operation would be needed which is expected, i.e., when the target is operated for longer time periods. This was not possible at COSY due to limited access during beam times.

5.3.4 Consequences for the Operation at $\overline{\text{PANDA}}$

The aforementioned analyses showed that the achieved relative momentum spread for all measurements was below $2 \cdot 10^{-4}$ which is still a factor of 2 larger than the value required for the high luminosity mode at the HESR and a factor 4 above the value for the high resolution mode, but these values cannot be compared directly. There are several differences in the operation at COSY and later at the HESR. First of all, only a part of the stochastic cooling system that is foreseen for the HESR was operated at COSY so that the cooling power was reduced. Furthermore, the beam parameters differ, especially the revolution frequency and the phase slip factor η . Also, a barrier bucket cavity with higher potential will be used that should reduce the number of particles outside the bucket. Due to all these aspects, it is very challenging to make a prediction for the momentum spread at the HESR based on the measurements at COSY. Nevertheless, the relative values of the momentum spread for different settings are comparable and give a good impression of the dependence of the momentum spread on the target thickness and the beam intensity and its consequences for the operation at the HESR.

For some measurements at $\overline{\text{PANDA}}$ the resolution directly depends on the momentum spread of the HESR beam. This is especially the case for the energy scans that were described in section 2.3 which are a major motivation for this thesis. As seen before, the achievable momentum spread depends on the beam intensity and the target thickness as this causes a beam heating that needs to be compensated by the stochastic cooling. From the function determined by the fit to the data in the previous section, one can now determine the optimum target thickness and beam intensity for a given luminosity. Therefore, the number of stored particles N_p is replaced in the fit function in equation 5.14 by the luminosity

$$L = n_T N_p f_0 \quad (5.17)$$

leading to

$$g(n_T, L) = a \cdot \left(m_1 \cdot \frac{n_T^{p_1} - s_1}{s_1} + 1 \right) \left(m_2 \cdot \frac{\left(\frac{L}{n_T f_0} \right)^{p_2} - s_2}{s_2} + 1 \right). \quad (5.18)$$

The optimal target thickness can now be determined by solving

$$\frac{\partial g(n_T, L)}{\partial n_T} \stackrel{!}{=} 0 \quad (5.19)$$

with

$$\begin{aligned} \frac{\partial g(n_T, L)}{\partial n_T} = & \frac{a m_1 (1 - m_2)}{s_1} p_1 n_T^{p_1-1} - \frac{a m_2 (1 - m_1)}{s_2} \frac{p_2}{n_T} \left(\frac{L}{n_T f_0} \right)^{p_2} \\ & - \frac{a m_1 m_2}{s_1 s_2} (p_2 - p_1) \left(\frac{L}{n_T f_0} \right)^{p_2} n_T^{p_1-1}. \end{aligned} \quad (5.20)$$

This cannot be solved analytically for $n_{T,\text{opt}}(L)$, but instead the inverse function

$$L(n_{T,\text{opt}}) = f_0 \left(\frac{\frac{m_1(1-m_2)}{s_1} p_1 n_{T,\text{opt}}^{p_1+p_2}}{\frac{m_1 m_2}{s_1 s_2} (p_2 - p_1) n_{T,\text{opt}}^{p_1} + \frac{m_2(1-m_1)}{s_2} p_2} \right)^{1/p_2} \quad (5.21)$$

can be determined and with equation 5.17

$$N_{p,\text{opt}}(n_{T,\text{opt}}) = \left(\frac{\frac{m_1(1-m_2)}{s_1} p_1 n_{T,\text{opt}}^{p_1}}{\frac{m_1 m_2}{s_1 s_2} (p_2 - p_1) n_{T,\text{opt}}^{p_1} + \frac{m_2(1-m_1)}{s_2} p_2} \right)^{1/p_2} \quad (5.22)$$

follows. This relation shows how the number of stored particles should be changed when the target thickness is changed. When this condition is not fulfilled, the same luminosity could be reached with a different combination of target thickness and beam intensity that would lead to a smaller momentum spread. In the case of $p_1 = p_2 = p$, N_p and n_T would scale linearly as

$$N_{p,\text{opt}}(n_{T,\text{opt}}) = \left(\frac{m_1(1-m_2)s_2}{m_2(1-m_1)s_1} \right)^{1/p} n_{T,\text{opt}}. \quad (5.23)$$

In this case, for doubling the luminosity, not only the beam intensity or only the target thickness should be doubled, but both quantities should be increased by a factor of $\sqrt{2}$.

These consequences are visualized in the following for $p_1 = p_2 = 1/3$ compared to $p_1 = p_2 = 1$. Figure 5.13 shows the resulting relative momentum spread for several

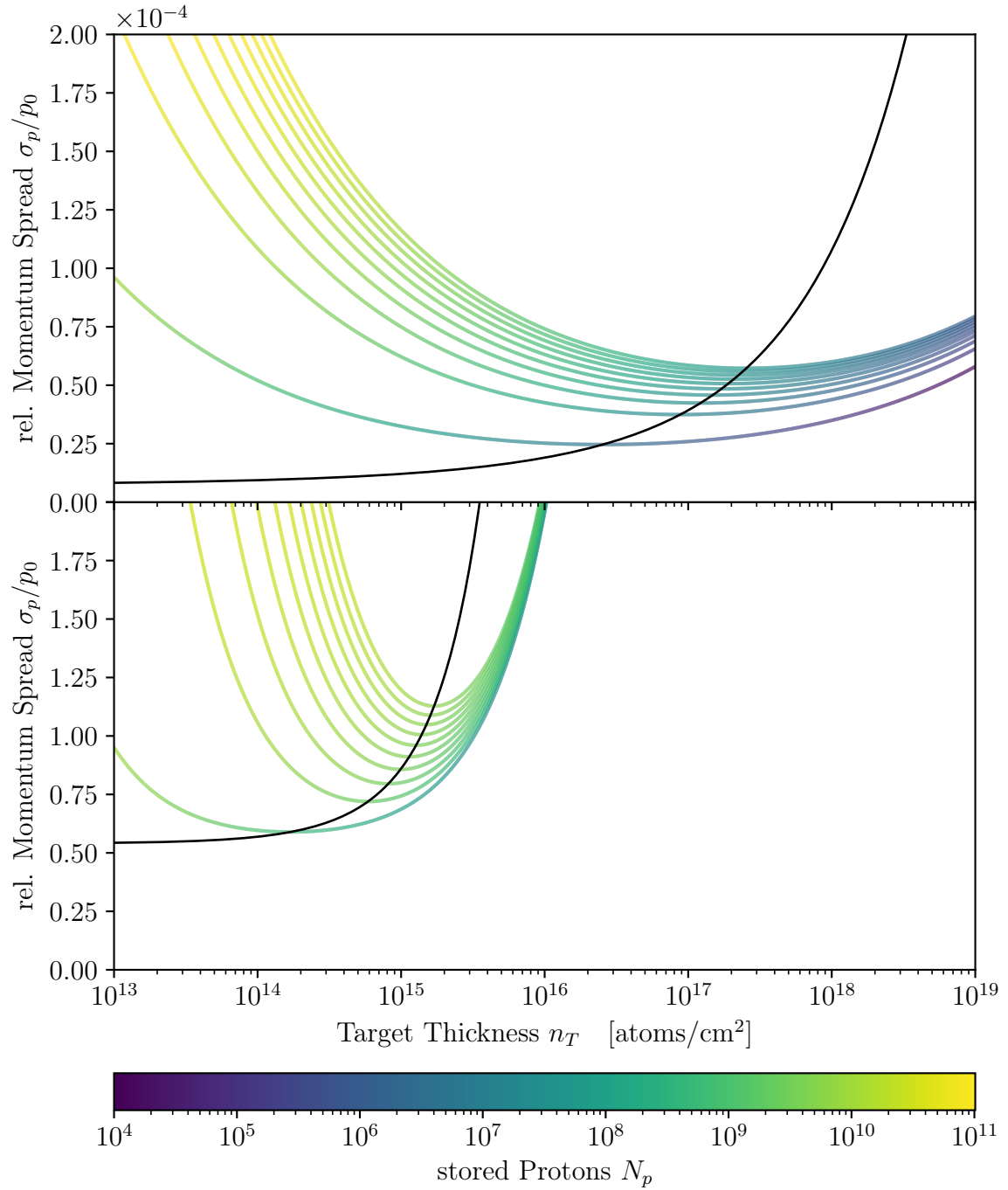


Figure 5.13: Dependence of the momentum spread on target thickness and beam intensity for several fixed luminosities according to the fit results with $p_1 = p_2 = 1/3$ (top) and $p_1 = p_2 = 1$ (bottom). The colored lines correspond to values of $n_T \cdot N_p$ between $1 \cdot 10^{23} \text{ cm}^{-2}$ and $1 \cdot 10^{25} \text{ cm}^{-2}$. The minima reflect the optimum combination of target thickness and beam intensity and are all lying on the black line that is determined analytically as $g(n_{T,\text{opt}}, N_{p,\text{opt}})$ by using equations 5.14 and 5.23.

fixed luminosities that can be reached with different combinations of target thickness and beam intensity. The curve of each constant luminosity shows a minimum which corresponds to the optimum combination that should be used for the operation at COSY in order to minimize the relative momentum spread. Figure 5.14 visualizes the resulting correlation of target thickness and beam intensity that leads to the smallest momentum spread for a given constant luminosity. As mentioned above, this dependence is linear for $p_1 = p_2$, but the slope depends on all the fit parameters. As long as the target thickness and beam intensity are within the range that are possible with the $\overline{\text{PANDA}}$ cluster-jet target and the accelerator, this combination should be chosen. When, e.g., the maximum target thickness is reached, to further increase the luminosity only the beam intensity can be increased, although this means, that the momentum spread increases faster than when staying in the optimum. This is demonstrated in figure 5.15. How fast this point is reached, heavily depends on the fit parameters and the exponents p_1 and p_2 . For $p_1 = p_2 = 1/3$, the momentum spread is strongly dominated by the dependence on the beam intensity. The highest target

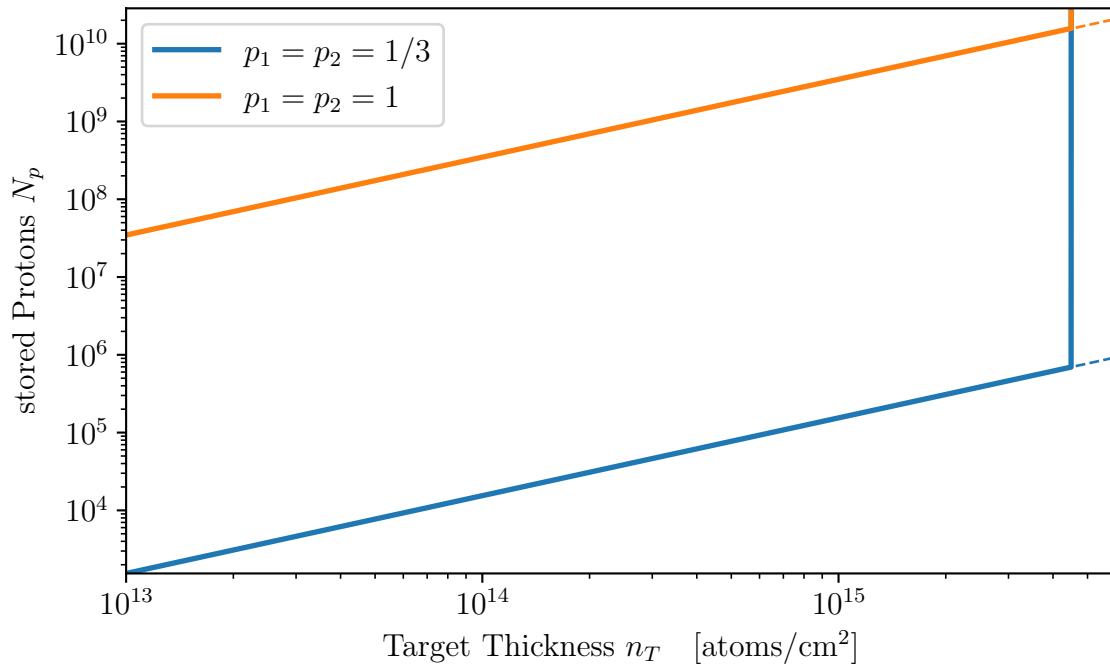


Figure 5.14: Optimum combinations of target thickness and beam intensity for the fits with $p_1 = p_2 = 1/3$ and $p_1 = p_2 = 1$. Once, the maximum target thickness is reached, only the other value can be changed (vertical line) leading to a deviation from the optimum combination (dashed line). Here, a maximum target thickness of $4.5 \cdot 10^{15}$ atoms/cm² is assumed, which corresponds to the value required by the $\overline{\text{PANDA}}$ experiment.

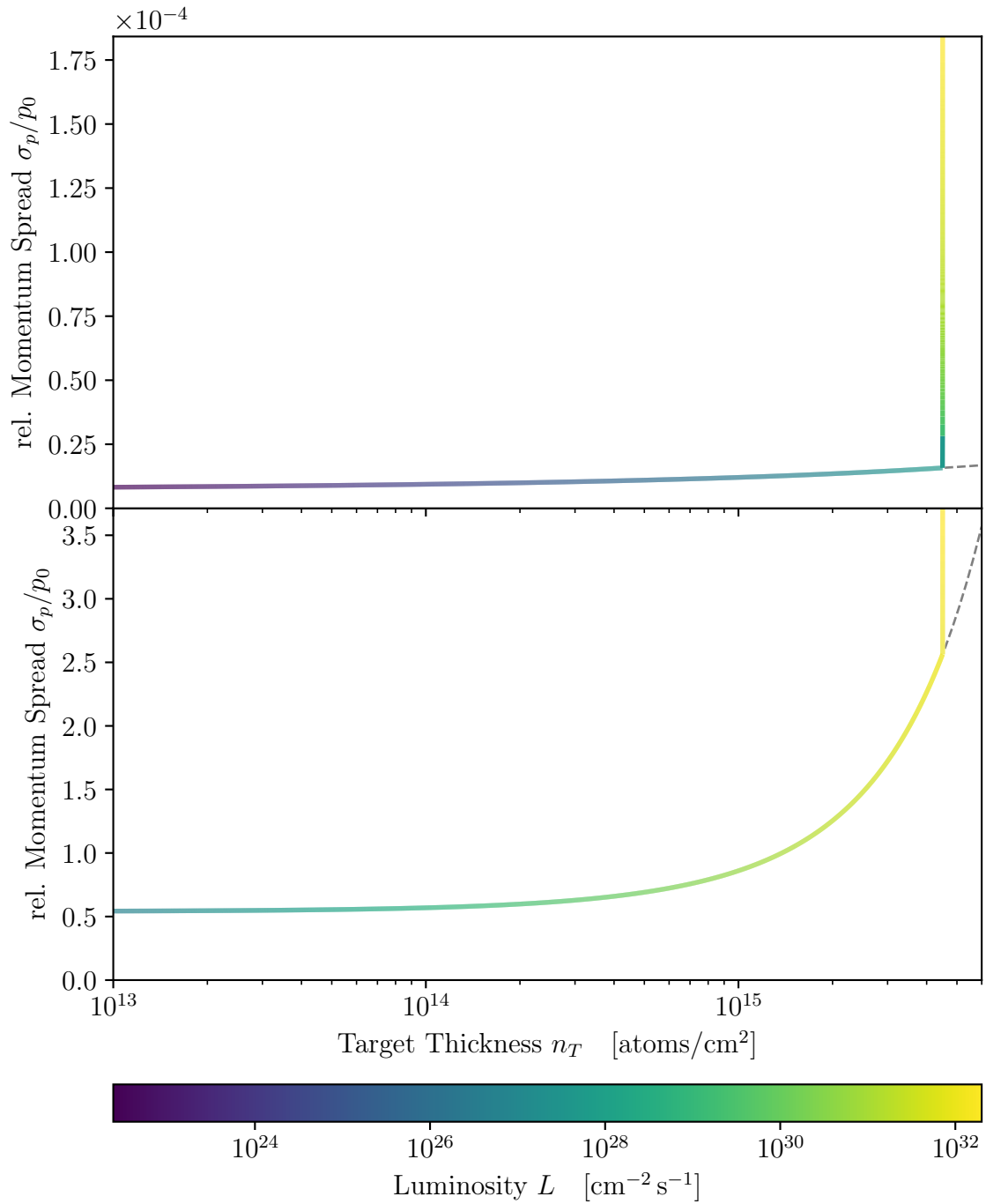


Figure 5.15: Resulting relative momentum spread for the optimum combination of target thickness and beam intensity for the fits with $p_1 = p_2 = 1/3$ (top) and $p_1 = p_2 = 1$ (bottom). Once, the maximum target thickness (or maximum beam intensity) is reached, only the other value can be changed (vertical line) leading to a faster increase of the momentum spread compared to the optimum combination (dashed gray line).

thickness, which was assumed to be the design value of $4.5 \cdot 10^{15}$ atoms/cm², would deliver the optimum momentum spread when combining it with a beam intensity of less than 10^6 stored protons at COSY, which is a very small number. In this case, to reach useful luminosities, the target should always be operated with the maximum target thickness while the beam intensity can be chosen to get the desired luminosity. When instead the exponents are set to $p_1 = p_2 = 1$, the momentum spread still depends strongly on the beam intensity, but the target thickness has a larger influence. Here, at the maximum target thickness, already a number of stored particles of nearly $2 \cdot 10^{10}$ should be chosen, which is already a quite large intensity that was not always possible during the beam times at COSY.

Therefore, at $\bar{\text{PANDA}}$ this measurement should be repeated with high precision and with the best possible stability of target and accelerator to determine the fit parameters precisely which will then help to determine the best operation point for the experiment.

Another important aspect for the planned line scan measurements at $\bar{\text{PANDA}}$ is the variation of the momentum spread from cycle to cycle as a result of the target thickness variation and the variation of the beam intensity. The variation of the target thickness strongly depends on the operating conditions, while it is typically in the order of 5 % to 10 %, it can also be much smaller for very small densities when the target is in the gaseous regime, but when getting to a target thickness of $1 \cdot 10^{15}$ atoms/cm² it can also go to 50 %. As examples, the resulting momentum spread variations for the two target settings at 23 K and 18 bar with a target thickness of $(1.00 \pm 0.44) \cdot 10^{15}$ atoms/cm² and at 32 K and 18 bar with a target thickness of $(1.32 \pm 0.05) \cdot 10^{14}$ atoms/cm² are calculated. Using Gaussian error propagation for the fit function in equation 5.14 the resulting variation of the momentum spread is given as

$$\left(\frac{\Delta g}{g} \right)_{n_T} = \frac{1}{g} \frac{\partial g}{\partial n_T} \Delta n_T = \frac{m_1 s_1^{-1} p_1 n_T^{p_1-1} \Delta n_T}{m_1 s_1^{-1} (n_T^{p_1} - s_1) + 1} . \quad (5.24)$$

The results for the fits with the different exponents are summarized in table 5.4. It can be followed, that even when the target is more unstable at highest target thickness, the resulting variation of the momentum spread is significantly lower. And at a more moderate target thickness, this variation can be even neglected. Furthermore, even the variation of the momentum spread of up to 9 % is still quite small as the momentum spread can be measured during the cycle. This allows for a correction in the analysis of the line scan measurements that reduces the additional uncertainty coming from this variation, although this makes the analysis more complex.

While the variation of the beam intensity at the HESR is not yet predictable, the change of the beam intensity during a cycle can be used to calculate the variation of

Table 5.4: Resulting variation of the relative momentum spread as result of the variation of the target thickness for two different settings and for the different fits.

Target Conditions	Momentum Spread Variation $(\Delta g/g)_{n_T}$	
	$p_1 = p_2 = 1/3$	$p_1 = p_2 = 1$
23 K, 18 bar (1.00 ± 0.44) $\cdot 10^{15}$ atoms/cm ²	(3.2 ± 0.4) %	(9.0 ± 0.8) %
32 K, 18 bar (1.32 ± 0.05) $\cdot 10^{14}$ atoms/cm ²	(0.135 ± 0.017) %	(0.107 ± 0.012) %

the momentum spread due to the beam loss. Assuming that the beam loss results only from hadronic processes, the number of stored particles after passing the target once can be calculated as

$$N_{p,1} = N_{p,0} \cdot e^{-\sigma_{\text{had}} n_T} \quad (5.25)$$

from the initial proton number $N_{p,0}$ and the hadronic cross section σ_{had} . For multiple passages through the target, the target thickness in the previous equation needs to be replaced by $n \cdot n_T$ with n being the number of passages. Within a cycle time T , the number of passages can be calculated as $n = f_0 \cdot T$ with the revolution frequency f_0 , so that the number of stored particles after a cycle is given by

$$N_p(T) = N_{p,0} e^{-\sigma_{\text{had}} n_T f_0 T} . \quad (5.26)$$

When the beam intensity reduces during a cycle, the stochastic cooling would need to be readjusted to follow the course of equation 5.14. As this is typically not done during a cycle, the momentum spread will instead decrease linearly according to [SKM16]. When assuming that the cooling is adjusted to the initial intensity, it then falls linearly with the same slope that the fit function in equation 5.14 has at this initial intensity. Thus, the momentum spread follows

$$f(n_T, N_p) = m(N_p - N_{p,0}) + g(n_T, N_{p,0}) \quad (5.27)$$

with the slope

$$m = \left. \frac{\partial g}{\partial N_p} \right|_{N_p=N_{p,0}} = a \left(m_1 \frac{n_T^{p_1} - s_1}{s_1} + 1 \right) \frac{m_2 p_2}{s_2} N_{p,0}^{p_2-1} . \quad (5.28)$$

The resulting variation can then be calculated as

$$\begin{aligned} \left(\frac{\Delta f}{f} \right)_{N_p} &= \frac{f(n_T, N_p(T)) - f(n_T, N_{p,0})}{f(n_T, N_{p,0})} = \frac{m(N_p(T) - N_{p,0})}{g(n_T, N_{p,0})} \\ &= \frac{m_2 s_2^{-1} p_2 N_{p,0}^{p_2-1}}{m_2 s_2^{-1} (N_{p,0}^{p_2} - s_2) + 1} (N_p(T) - N_{p,0}) . \end{aligned} \quad (5.29)$$

Compared to the variation in equation 5.24, this value will always be negative due to the continuous beam loss, while the target thickness can change in all directions. The resulting variation of the momentum spread due to the beam loss is given in table 5.5 for an assumed target thickness of $1 \cdot 10^{15}$ atoms/cm² and $1 \cdot 10^{14}$ atoms/cm², and an initial number of stored protons of $1 \cdot 10^{10}$ and $1 \cdot 10^9$. These numbers were calculated assuming a total hadronic cross section for p $\bar{p}$ reactions of roughly 100 mb [Nav⁺24], a cycle time of 30 min, and a revolution frequency of 0.522 MHz corresponding to the maximum frequency at the HESR [Gut06]. The resulting variations are in the same order of magnitude as the variation due to the target thickness, although a maximum variation of the target thickness of nearly 50 % was assumed there. Furthermore, here only beam losses due to hadronic interactions are considered. This shows that even a large variation in the target thickness will not solely dominate the variation of the momentum spread. Additionally, the variations due to beam loss and target thickness variations are still quite low and can be corrected for in the analysis, where the actual momentum spread can be measured during the cycle.

Table 5.5: Resulting variation of the relative momentum spread as result of the beam loss due to hadronic interaction with $\sigma_{\text{had}} = 100$ mb [Nav⁺24] for two different settings and for the different fits.

n_T [atoms/cm ²]	N_p — $N_p(T)$	Momentum Spread Variation $(\Delta f/f)_{N_p}$	
		$p_1 = p_2 = 1/3$	$p_1 = p_2 = 1$
10^{15}	$10^{10} \xrightarrow{-9.0\%} 9.10 \cdot 10^9$	$(-2.75 \pm 0.07) \%$	$(-3.9 \pm 0.1) \%$
	$10^9 \xrightarrow{-9.0\%} 9.10 \cdot 10^8$	$(-2.51 \pm 0.12) \%$	$(-0.63 \pm 0.03) \%$
10^{14}	$10^{10} \xrightarrow{-0.9\%} 9.91 \cdot 10^9$	$(-0.287 \pm 0.007) \%$	$(-0.40 \pm 0.01) \%$
	$10^9 \xrightarrow{-0.9\%} 9.91 \cdot 10^8$	$(-0.262 \pm 0.013) \%$	$(-0.066 \pm 0.003) \%$

5.3.5 Measurements on the left and right of the Target

Besides the cycles where the beam hits the target in the center, every supercycle also included a cycle with a chicane on the left side and one cycle with a chicane on the right

side of the target to study the influence of the residual gas. The data together with the fit for $p_1 = p_2 = 1/3$ are shown in figure 5.16 and the fit results are summarized in table 5.6 and compared to the results for the cycles with the beam in the center of the target.

Table 5.6: Fit results for the relative momentum spread as function of the target thickness and the number of stored particles for $p_1 = p_2 = 1/3$.

	Left	Center	Right
a	$(8.5 \pm 0.1) \cdot 10^{-5}$	$(8.3 \pm 0.1) \cdot 10^{-5}$	$(8.2 \pm 0.1) \cdot 10^{-5}$
m_1	0.115 ± 0.015	0.116 ± 0.015	0.091 ± 0.015
m_2	0.97 ± 0.03	0.90 ± 0.03	0.94 ± 0.03
s_{2021}	1.162 ± 0.020	1.135 ± 0.020	1.074 ± 0.019
s_{2022}	1.36 ± 0.03	1.33 ± 0.03	1.29 ± 0.03
k	0.080	0.083	0.084

The resulting fit parameters for all three cycle types (left/center/right) are very similar and nearly agree within their uncertainty. Nevertheless, there is a trend visible especially in the scaling parameter a . The overall scaling would have been expected to be the largest for the cycles with the beam on target, as here the beam sees the highest target thickness. But contrary the data shows, that the reached momentum spread is slightly larger for the cycles on the left of the target. Also on the right, the momentum spread is only slightly smaller. There are several reasons, that could lead to this behavior. First of all, the COSY beam pipe is quite small so that it is very challenging to have a perfect chicane around the target. This means, that even the beam on the right and left might see some part of the target in addition to the residual gas. Furthermore, the stochastic cooling is adjusted for the conditions in the center and not for the smaller target thickness on the left or right so that the momentum spread should still be smaller but not in the optimum. Finally, there is also a reason for the difference between the cycles on the left and right. Particles that lose energy will have a more inner orbit due to the stronger deflection in the dipole magnets. At COSY, the inner side corresponds to the right-hand side in beam direction. Thus, particles that lose energy while being on a chicane on the right close to the inner wall of the beam pipe come even closer to this wall and can be easily lost. Losing such particles with high momentum deviation also reduces the momentum spread, so that it has a similar effect like beam cooling. For particles on a chicane on the left side close to the outer wall, particles that lose energy will be on an orbit closer to the target and thus lose even more energy, leading to a beam heating.

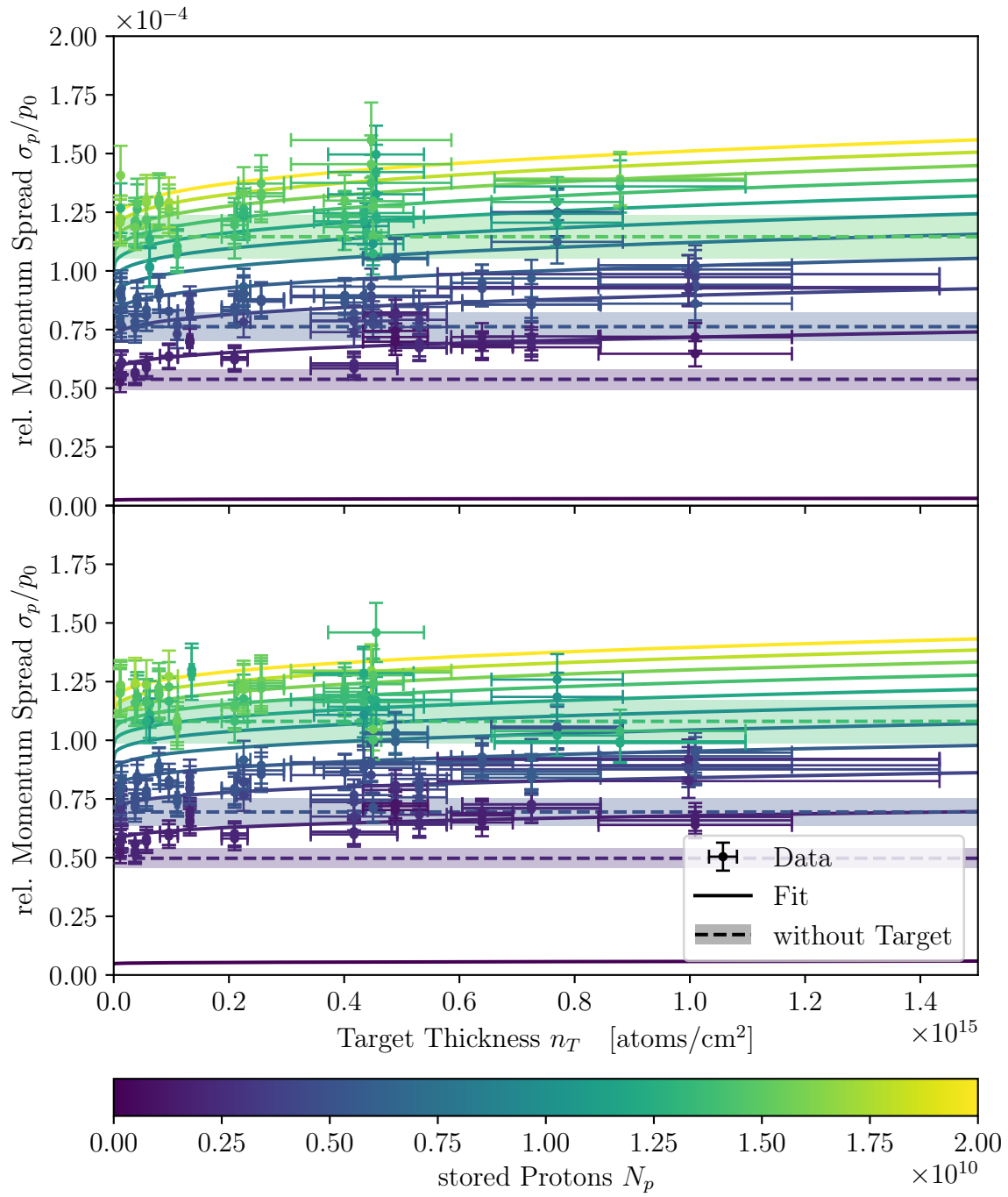


Figure 5.16: Dependence of the relative momentum spread on the target thickness for all beam times with the beam on the left (top) and right (bottom) side of the target and with a fit with $p_1 = p_2 = 1/3$. The data is scaled with $1/s_{bt}$ that is determined via the fit. The colored, solid lines show the fit for different numbers of stored protons from 0 to $2 \cdot 10^{10}$ in steps of $2 \cdot 10^9$. Additional data taken without target is added as horizontal, dashed lines. The additional uncertainty reflecting the adjustment of the stochastic cooling is included in all vertical error bars and error bands.

5.3.6 Analysis of IPM Profiles

Like the previous analysis of the momentum spread in the equilibrium as result of the longitudinal cooling, also the transversal cooling can be studied by evaluating the IPM profiles. These are analyzed directly in the dedicated LabVIEW slow control of the IPM, that fits a Gaussian function to both profiles and extracts its widths multiple times during a cycle. In figure 5.17 the evolution of the beam width at the IPM is shown for the same cycles as in figure 5.11. Here, already from these two cycles it can be clearly seen, that the dependence on the target thickness seems to be much larger than for the momentum spread, as in the first of the two plots the beam width even increases after pre-cooling once the target is turned on. Again, the value in the equilibrium is extracted in the same time interval as for the momentum spread.

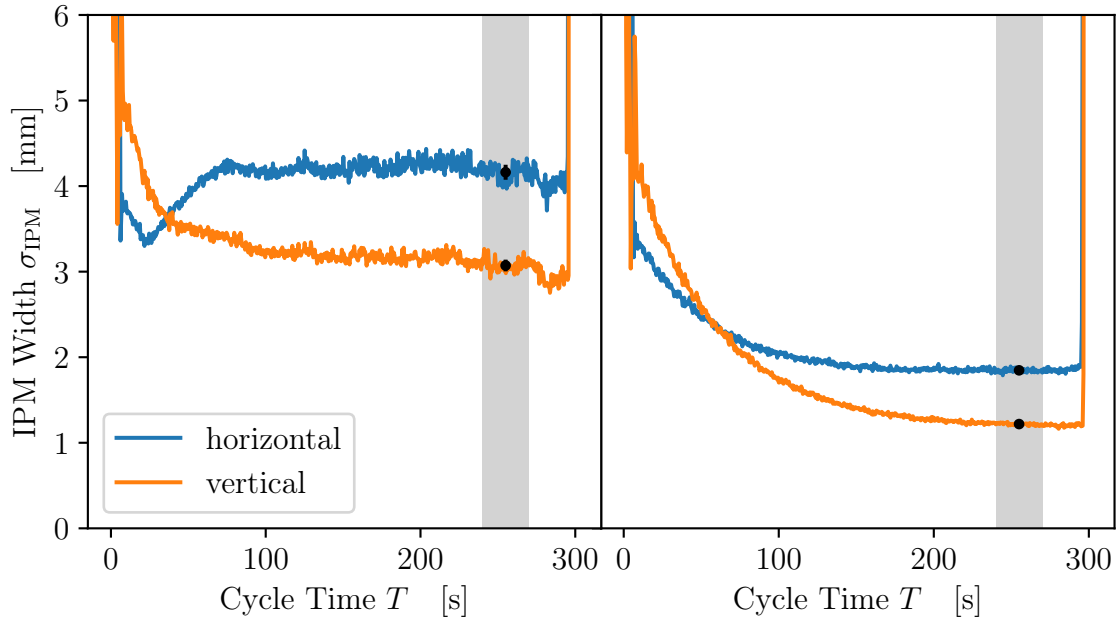


Figure 5.17: Evolution of the beam width at the IPM within a cycle for a target thickness of $(1.00 \pm 0.44) \cdot 10^{15}$ atoms/cm² at 23 K and 18 bar (left) and a target thickness of $(1.32 \pm 0.05) \cdot 10^{14}$ atoms/cm² at 32 K and 18 bar (right) with medium COSY intensity. The equilibrium value is then extracted in the gray area by calculating the mean of all data points in this range. The shown data is from the same cycles as in figure 5.11.

After extracting the width of the horizontal and vertical beam profile at the IPM, it can be scaled down to the width at the target by using equation 4.49. Therefore, the β -function at the IPM and at the target needs to be known which can be extracted from the COSY MAD-X model. The horizontal and vertical β -function at every position

s inside the COSY ring is shown in figure 5.18 for the 2021 beam time. The values differ slightly for the different beam times and its values at the IPM and the target are summarized in table 5.7.

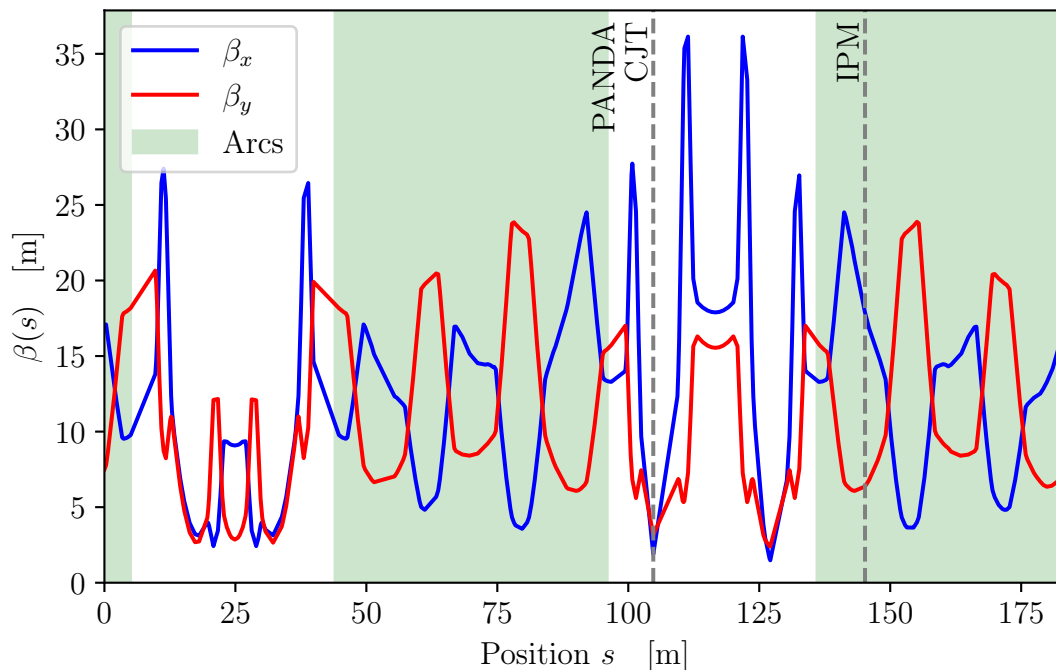


Figure 5.18: β -function for the 2021 beam time as function of the position in the COSY ring where $s = 0$ is the position of the injection from the cyclotron into the COSY ring. The $\overline{\text{PANDA}}$ Cluster-Jet Target (CJT) is installed at the location of the former WASA experiment. Here, a small value of the β -function is required to focus the beam on the target. Additionally, also the dispersion at this point is small.

Table 5.7: Values of the horizontal and vertical β -function at the IPM and the target location. These are used to scale the width of the beam measured at the IPM down to the width at the target.

	IPM		Target	
	β_x [m]	β_y [m]	β_x [m]	β_y [m]
2021	17.88	6.37	1.88	3.15
2022	19.48	5.18	1.87	3.02
2023	17.41	5.81	1.95	3.08

Afterwards, the same fit as for the momentum spread can be applied to the data as shown in figure 5.19. According to [Gut06, Hin06] the emittance in the equilibrium is expected to be linearly dependent on the target thickness and the beam intensity, so

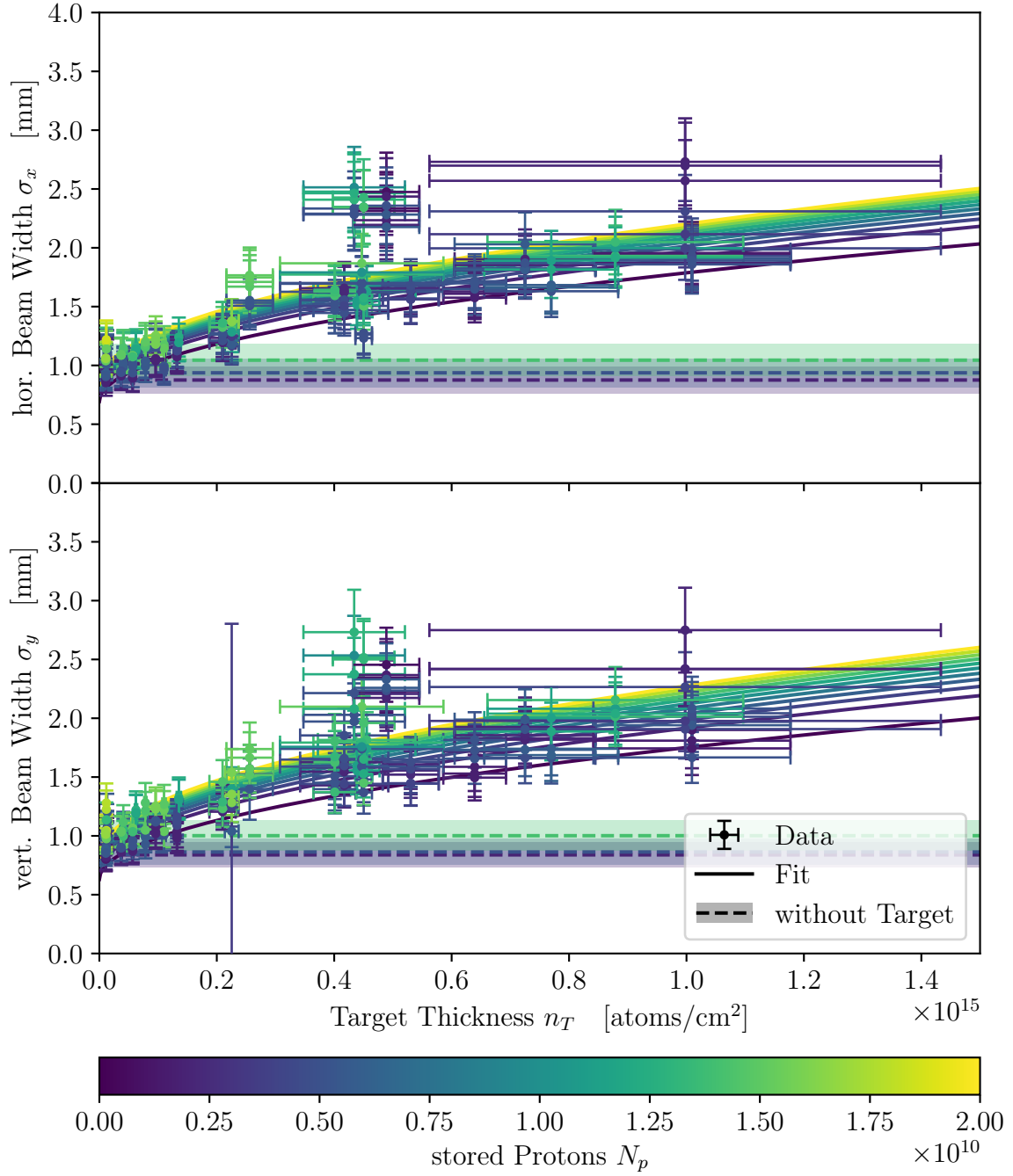


Figure 5.19: Dependence of the horizontal (top) and vertical (bottom) beam width at the target location on the target thickness for all beam times with a fit with $p_1 = p_2 = 1/2$. The data is scaled with $1/s_{bt}$ that was determined via the fit. The colored, solid lines show the fit for different numbers of stored protons from 0 to $2 \cdot 10^{10}$ in steps of $2 \cdot 10^9$. Additional data taken without target is added as horizontal, dashed lines. The additional uncertainty reflecting the adjustment of the stochastic cooling is included in all vertical error bars and error bands.

that following equation 4.9 a fit with $p_1 = p_2 = 1/2$ is favored. Additionally, again a linear fit is performed for comparison shown in figure A.4. The fit parameters are summarized in table 5.8. When comparing these parameters with the results from the fit of the momentum spread, there are some key differences. The parameters m_1 and m_2 describe how strong the momentum spread or the beam width depend on the target thickness or the beam intensity. While for the momentum spread, the dependence on the beam intensity was stronger, now the beam width has a larger dependence on the target thickness. Furthermore, while the momentum spread in the 2021 and 2022 beam times had to be scaled down ($s_{2021}, s_{2022} > 1$) to the data of the 2023 beam time, now the 2023 beam time shows the largest beam width ($s_{2021}, s_{2022} < 1$), which shows that by changing the beam optics it is possible to reduce one quantity, but this can increase others. The additional uncertainty introduced to reflect the adjustment of the stochastic cooling is also larger for the measured beam width at the IPM. This shows that the beam width is more sensitive to the exact adjustment of the stochastic cooling and the whole accelerator lattice. Fortunately, the beam width is the less important quantity for the quality of the data taken by $\overline{\text{P}}\text{ANDA}$, as long as it is still smaller than the target.

Table 5.8: Fit results for the horizontal and vertical beam width measured at the IPM and scaled down to the target position as function of the target thickness and the number of stored particles.

		$p_1 = p_2 = 1/2$	$p_1 = p_2 = 1$
horizontal	a	1.16 ± 0.03	1.098 ± 0.019
	m_1	0.333 ± 0.018	0.129 ± 0.008
	m_2	0.10 ± 0.03	0.052 ± 0.011
	s_{2021}	0.526 ± 0.016	0.502 ± 0.015
	s_{2022}	0.666 ± 0.018	0.672 ± 0.017
	k	0.130	0.118
vertical	a	1.13 ± 0.03	1.065 ± 0.019
	m_1	0.360 ± 0.018	0.141 ± 0.008
	m_2	0.13 ± 0.03	0.059 ± 0.011
	s_{2021}	0.79 ± 0.03	0.75 ± 0.03
	s_{2022}	0.88 ± 0.03	0.89 ± 0.03
	k	0.126	0.119

5.4 Stability Measurements

While the main focus of the measurement campaign were the beam quality measurements described before, during the night shifts in the 2022 and 2023 beam times also longer cycles were used to study the beam stability. Therefore, the COSY cycles were extended to roughly 30 min, which is similar to the intended cycle length for the operation of the HESR [Gut06]. The exact cycle sequences are shown in table 5.9. COSY was operated in a supercycle mode with the COSY beam once hitting the target and passing it on the right and left side. Furthermore, the target was again operated with different settings that are summarized in figure 5.20. Additionally, also the COSY beam intensity was varied. Here, only the highest and medium intensity was used due to the limited time and long duration of the supercycles.

During these measurements again Schottky spectra have been recorded with the aim to study the stability of the mean frequency when operating the $\bar{\text{P}}\text{ANDA}$ cluster-jet target in combination with the stochastic cooling system. The analysis of the Schottky

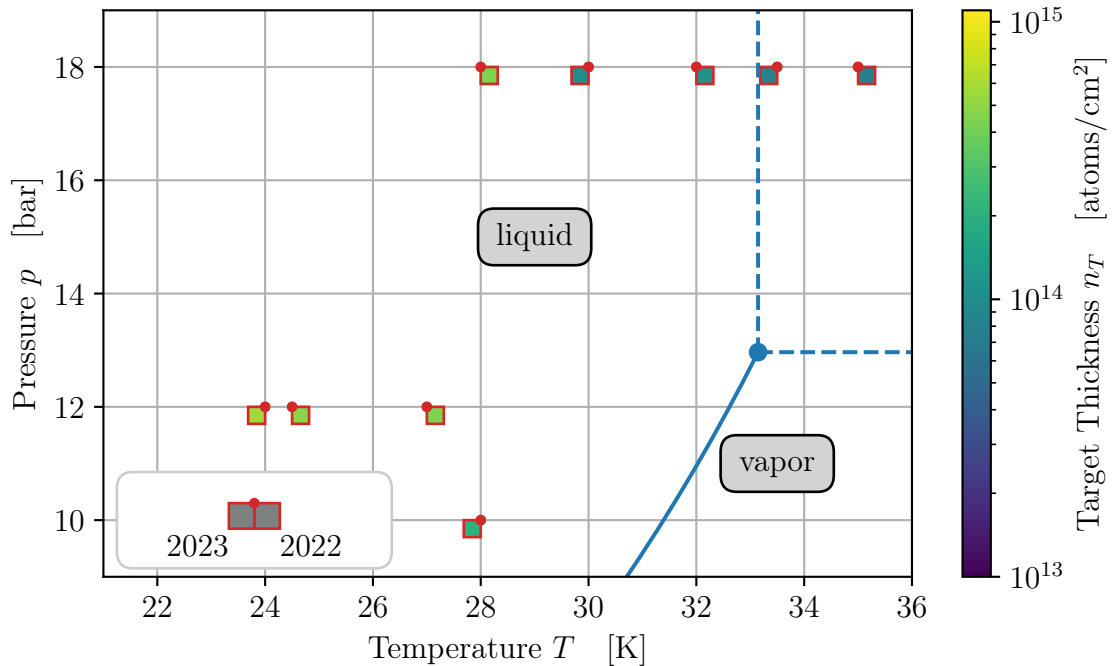


Figure 5.20: Target settings (red dots) used during the beam stability measurements in the phase diagram of hydrogen. The solid blue line shows the vapor pressure curve [LM25], while the dashed lines mark the region of supercritical hydrogen. The color code shows the achieved mean target thickness during the measurements, while the up to two quadrants around a red dot describe the different beam times.

Table 5.9: The sequence of a long COSY cycle for the different beam times. The times are given in seconds after the start of the cycle.

	2022	2023
Barrier Bucket on	17	7.2
RF off	19	7.2
stoch. Cooling on	20	10
Target on	30	20 ¹
Target off	1800	1800
stoch. Cooling off	1810	1820
Barrier Bucket off	1830	1830
End of Cycle	1830	1830

¹ For the target operating with a target thickness of $(5.6 \pm 1.0) \cdot 10^{14}$ atoms/cm² at 24 K and 12 bar, the target was turned on after 300 s to allow for a longer pre-cooling.

spectra is identical to the analysis described in section 5.3, so that the side peaks are again neglected here when calculating the mean frequency according to equation 5.9. Figure 5.21 shows the evolution of the mean frequency $\bar{f}$ during a COSY cycle for the 2022 beam time with a target thickness of $(4.4 \pm 0.3) \cdot 10^{14}$ atoms/cm² at 28 K and 18 bar. For the further analysis, only values between 300 s and 1800 s after the beginning of the cycle are used to allow the equilibrium to be reached first. Within this interval the nominal frequency f_0 is calculated as average of all mean frequencies $\bar{f}$ of the Schottky spectra. Afterwards, the relative deviation from this value

$$\delta f = \bar{f} - f_0 \quad (5.30)$$

is calculated and its standard deviation $\sigma_{\delta f}$ is calculated. Figure 5.21 shows a histogram that was filled with the relative frequency deviation $\delta f/f_0$. A Gaussian with its mean at zero and standard deviation of $\sigma_{\delta f}/f_0$ is added, which shows that the underlying histogram is well described but slightly asymmetric. The quantity $\sigma_{\delta f}$ is a measure for the stability of the mean frequency during the cycle and can be converted into the stability of the mean momentum by using equation 4.14 leading to

$$\frac{\sigma_{\delta p}}{p_0} = \frac{1}{\eta} \frac{\sigma_{\delta f}}{f_0}. \quad (5.31)$$

This relative momentum stability is measured for every cycle and is shown in the upper plot of figure 5.22 for different target thicknesses and beam intensities. It is clearly visible, that the stability is reduced when the target gets denser and also when the

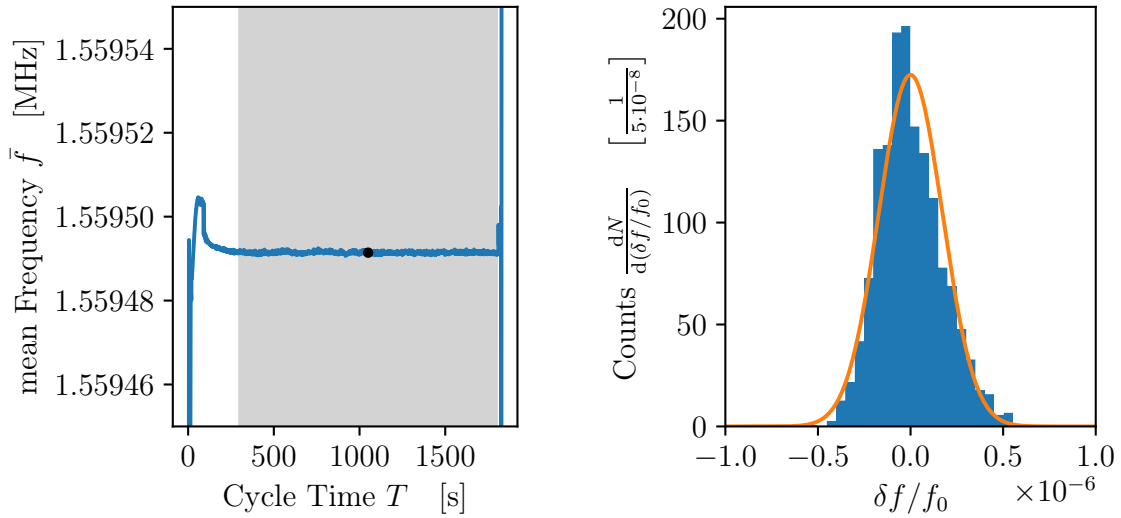


Figure 5.21: Left: Evolution of the mean frequency of the measured Schottky spectra during a COSY cycle for the 2022 beam time. Right: Histogram of the relative deviation of the mean frequency from the nominal frequency f_0 during this cycle. The orange line shows a Gaussian with its center at zero and with a standard deviation equal to the one of the histogram. The Gaussian was scaled to match the integral of the histogram. This data was recorded with the target operating at 28 K and 18 bar with a target thickness of $(4.4 \pm 0.3) \cdot 10^{14}$ atoms/cm².

beam intensity is increased. Here, it must be noted, that the beam intensity itself drops significantly during the cycles and therefore the number of stored protons shown in this plot is the number of protons at the time in the cycle when the target was turned on. The relative loss of beam particles during the cycles is visualized in the lower plot in figure 5.22. For the highest target thickness nearly all particles are lost at the end of the cycle. This loss can also be a reason for the increase of the stability as the stochastic cooling can push the beam to a smaller frequency when it does not have to fight the momentum loss of too many particles. This would lead to a change of the mean momentum during the cycles and thus a larger standard deviation. Nevertheless, the mean stability still reaches a value below 10^{-5} for all settings that will ensure high resolution measurements later at $\overline{\text{PANDA}}$, although it does not yet reach the expected value of 10^{-6} that is foreseen for the HESR [Bar⁺19]. Especially when the stronger barrier bucket potential in combination with the complete stochastic cooling system will be able to reduce the beam loss during the cycles, the stability should also be enhanced.

The strong loss of beam particles when operating the target at a high target thickness also opens up the possibility of studying the momentum spread dependence again, as

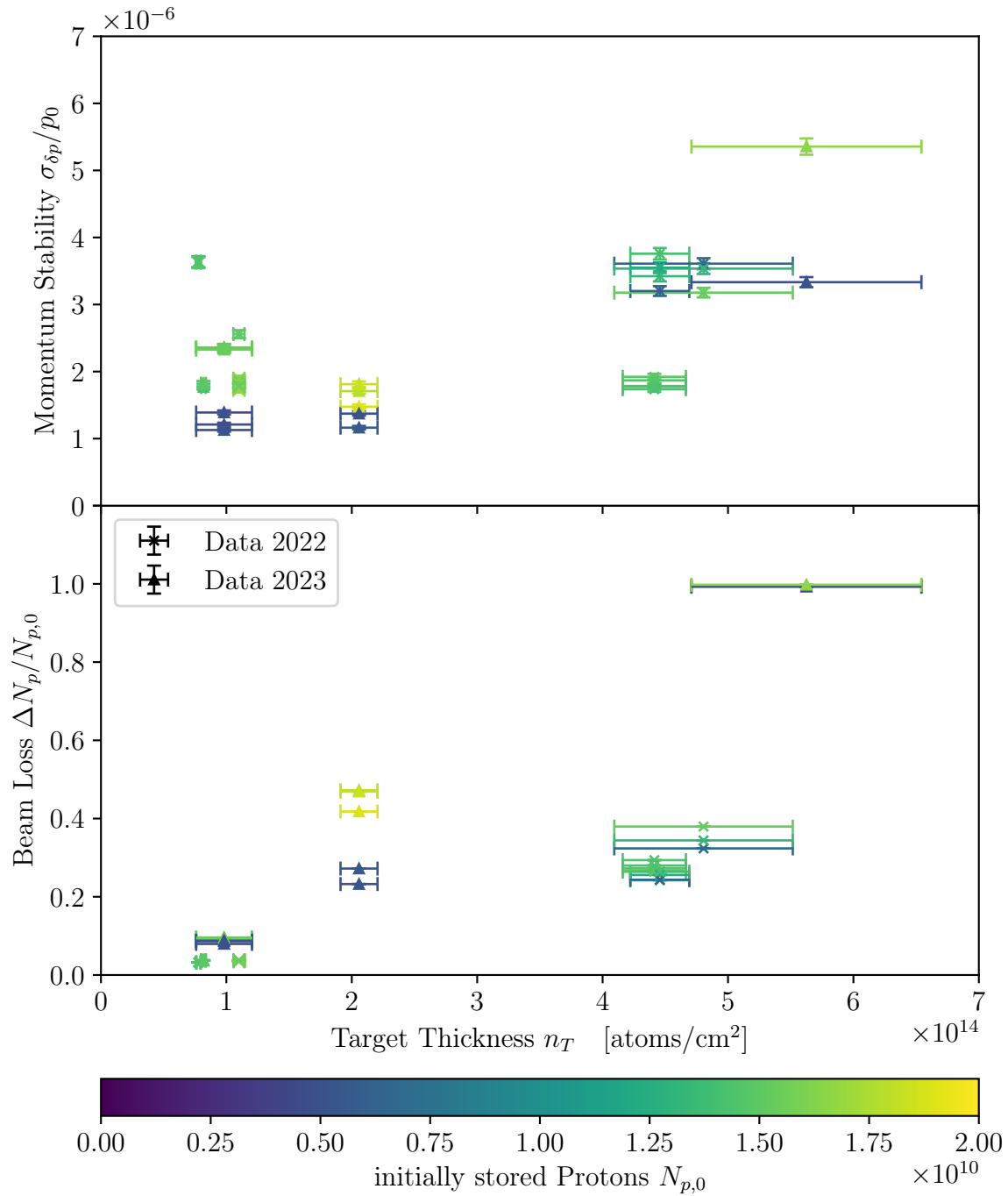


Figure 5.22: Relative stability of the mean momentum (top) during the long COSY cycles in the 2022 and 2023 beam times for different target settings and COSY intensities. The number of initially stored protons $N_{p,0}$ is measured when the target is turned on. The beam intensity decreases significantly during cycles with large target thickness. The relative beam loss is described in the lower figure.

already performed in section 5.3 during the beam quality measurements. The change of the beam intensity during the cycle should also result in a change in the momentum spread. Hence, the data in the 300 s to 1800 s interval is divided into 30 s intervals, and for each interval, the momentum spread and beam intensity are determined as the mean value, resulting in the data plotted in figure 5.23. This should be compatible with the fit function determined in section 5.3. However, while there the stochastic cooling was adjusted for every setting, this was not possible during the cycle, and thus the cooling is only optimized for the beam intensity $N_{p,0}$ at the beginning of the cycle. Therefore, for a constant target thickness and constant stochastic cooling setting, the data should now depend linearly on the beam intensity [SKM16]. The data will thus be described by

$$f(n_T, N_p) = m(N_p - N_{p,0}) + s \cdot s_{bt} \cdot g(n_T, N_p) , \quad (5.32)$$

where m is a variable slope and s is a scaling factor that scales the result of the fit function from section 5.3 for the initial intensity ($s_{bt} \cdot g(n_T, N_p)$), and thus reflects the

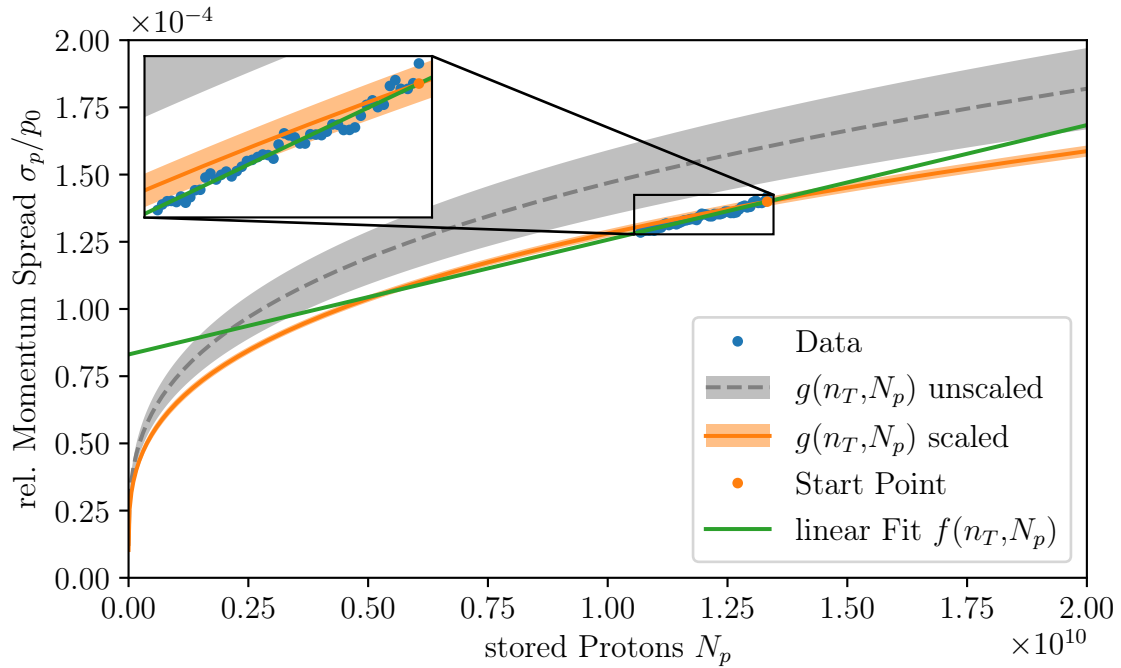


Figure 5.23: Fit function from section 5.3 scaled to the momentum spread as function of the stored particles during a long COSY cycle in the 2022 beam time with a target thickness of $(4.4 \pm 0.3) \cdot 10^{14}$ atoms/cm² at 28 K and 18 bar. The gray error band shows the additional error that was introduced to reflect the manual adjustment of the stochastic cooling, while the orange error includes the uncertainty of the fit parameters and the target thickness.

uncertainty of the manual adjustment. This function is fitted to the data as shown in figure 5.23. The gray curve shows the fit function from section 5.3 for the model with $p_1 = p_2 = 1/3$ for the fixed target thickness of $(4.4 \pm 0.3) \cdot 10^{14}$ atoms/cm² at 28 K and 18 bar. The error band includes only the additional uncertainty for the manual adjustment. It is expected that this function needs to be scaled to the data in the range of this error band. The scaled function is shown in orange, where the error band now only includes the uncertainty of the fit parameters and the target thickness. The value of this function at the initial intensity $N_{p,0}$ is shown as an orange point. This is the starting point for the linear fit (green) according to equation 5.14. Figure 5.23 clearly shows that the data is better described by the linear fit compared to the scaled function. This cannot only be seen in the cycle presented here, but in all cycles the data is described better or at least equally well by the linear fit, and thus it supports the theoretical prediction that the momentum spread depends linearly on the number of stored particles, when the stochastic cooling is not readjusted.

The upper plot in figure 5.24 shows the resulting scaling parameters, which should scatter around a factor of 1 with a standard deviation that is equal to the additional uncertainty for the manual adjustment. This uncertainty is shown as gray error band. As expected, the determined scaling factors vary around this band. Furthermore, the slope of the linear function can be studied. Assuming that the stochastic cooling was optimally adjusted for the initial beam intensity, the slope at this point should be equal to the slope of the scaled function $g(n_T, N_p)$, as it was determined by optimizing the cooling for every setting. Once the beam intensity decreases during the long cycles, the setting of the stochastic cooling is not optimal anymore, and thus the linear curve should always be above the optimal function. Therefore, the linear curve should be a tangent to the scaled function at the initial intensity. This means that at the initial intensity, the slopes of both functions should be equal. Hence, the lower plot in figure 5.24 shows the ratio

$$R = \frac{m}{s \cdot s_{bt} \cdot g_{N_p}(n_T, N_{p,0})} \quad (5.33)$$

of the slope of the linear fit and the slope of the scaled function at the initial intensity, where $g_{N_p} = \partial g / \partial N_p$ is the derivative of the function $g(n_T, N_p)$ with respect to the accelerator beam intensity. As expected this ratio is around 1 for all settings, with deviations of less than a factor of 2. These deviations show, that the adjustment of the stochastic cooling was close the optimum for the initial intensity, but still not perfect. But when comparing the curves in figure 5.23, it is clear that there are only small differences in the momentum spread and thus the optimization of the cooling is challenging leading to these small deviations.

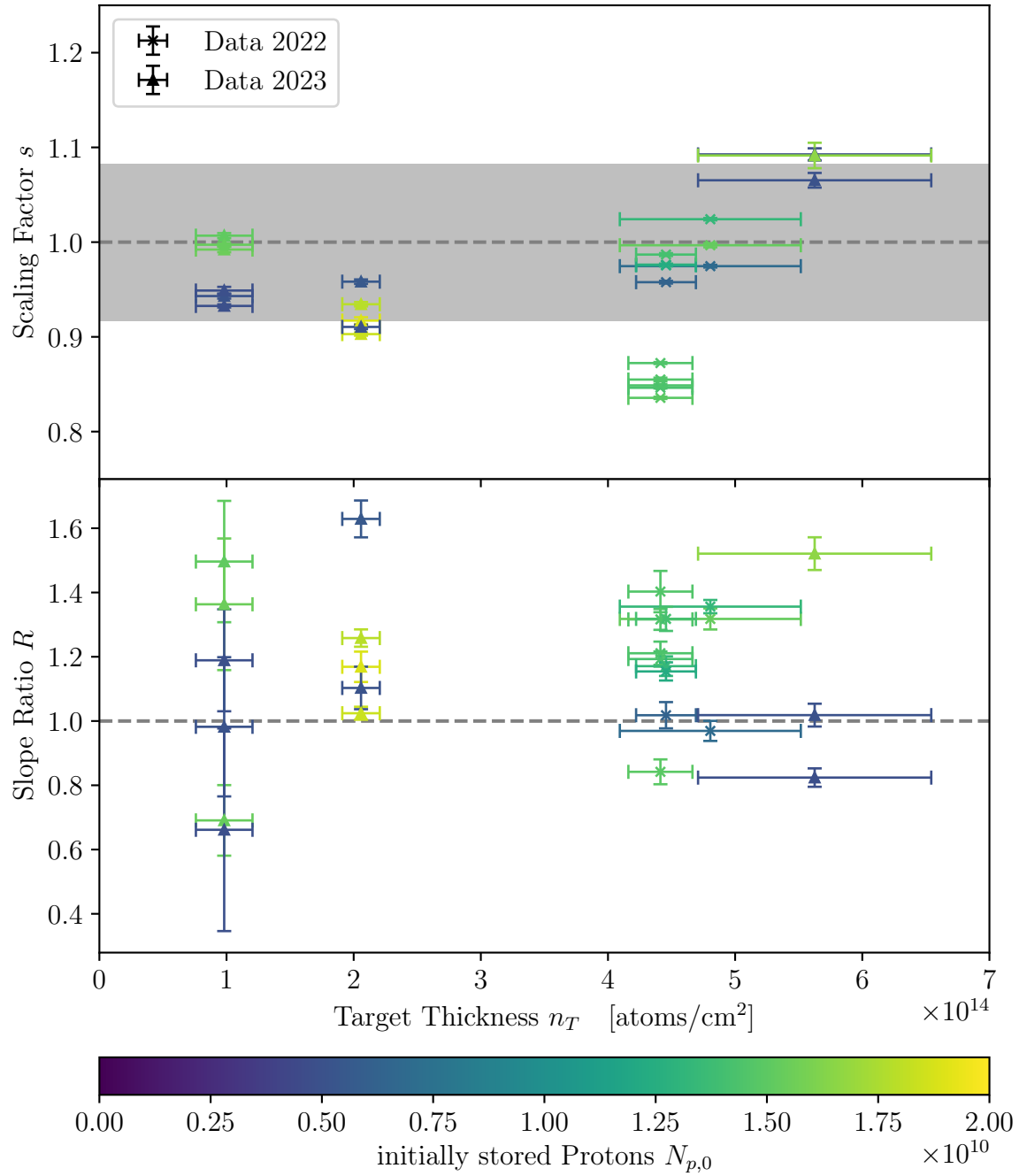


Figure 5.24: Scaling factor s (top) and slope ratio R (bottom) for the fits of the momentum spread as function of the stored particles during the long COSY cycles in the 2022 and 2023 beam times for different target settings and initial COSY intensities. The expected values of 1 are shown as dashed lines. The error band in the upper plot corresponds to the additional uncertainty that was introduced to reflect the manual adjustment of the stochastic cooling. In this plot, only cycles with a beam loss of at least 5 % are shown as otherwise the slope cannot be determined precisely.

5.5 Energy Loss Measurements

For every target setting used in the beam quality and beam stability studies, also energy loss measurements were performed that are used to determine the total target thickness including the residual gas contribution. In these measurements, the same sequence as in the beam quality studies were used but without the barrier bucket cavity and the stochastic cooling. This will result in an energy loss due to beam-target interaction that is not compensated by any system, and which is therefore a measure of the target thickness. By additionally using the chicane around the target also the thickness of the cluster-jet and the residual gas effect can be separated. Therefore, the same cycles as in the beam stability measurements were used and for most settings two supercycles were performed.

Beam particles that pass the target interact with the target atoms and lose energy. For a 3 GeV/c proton beam, the energy loss in hydrogen is given by $dE/dx = -4.112 \text{ MeV cm}^2 \text{ g}^{-1}$ [Ber⁺98], which then corresponds to a change of the frequency in the Schottky spectra. The target thickness can be determined by the relation [Ste⁺08]

$$n_T = \frac{1 + \gamma}{\gamma \eta} \frac{1}{m(dE/dx)} \frac{T_0}{f_0^2} \frac{df}{dt} \quad (5.34)$$

with the Lorentz factor $\gamma = 3.350$, the measured phase slip factor $\eta = -0.0963 \pm 0.0013$, the mass $m = 1.674 \cdot 10^{-27} \text{ kg}$ of a hydrogen atom [LM25], the nominal revolution frequency $f_0 = 1.559496 \text{ MHz}$ extracted from the MAD-X model, the kinetic energy $T_0 = 2.205 \text{ GeV}$, and the change of the revolution frequency over time df/dt . This frequency change is determined via the Schottky spectra. Without the use of cooling and phase focusing methods, no side peaks will occur so that the mean frequency can be extracted by a Gaussian fit that was already performed within the COSY slow control during data taking. The evolution of this mean frequency for a cycle with the beam in the center of the target at target conditions of 24.5 K, 12 bar, and a target thickness of $n_T^{\text{AMS}} = (3.9 \pm 0.9) \cdot 10^{14} \text{ atoms/cm}^2$ is shown in figure 5.25, which results in $df/dt = (0.6742 \pm 0.0015) \text{ Hz}$ and thus a total target thickness of $n_{T,\text{tot}}^{\Delta E} = (1.198 \pm 0.017) \cdot 10^{15} \text{ atoms/cm}^2$ that includes the residual gas background.

The resulting target thickness for all settings is shown in the upper plot of figure 5.26 compared to the target thickness measured by the AMS. The target thickness extracted from the energy loss measurements was calculated as difference of the total target thickness of cycles in the center and cycles on the right and left. The results agree well although they show some variations. There are several reasons for that. The measurements with the AMS are performed before and after the energy

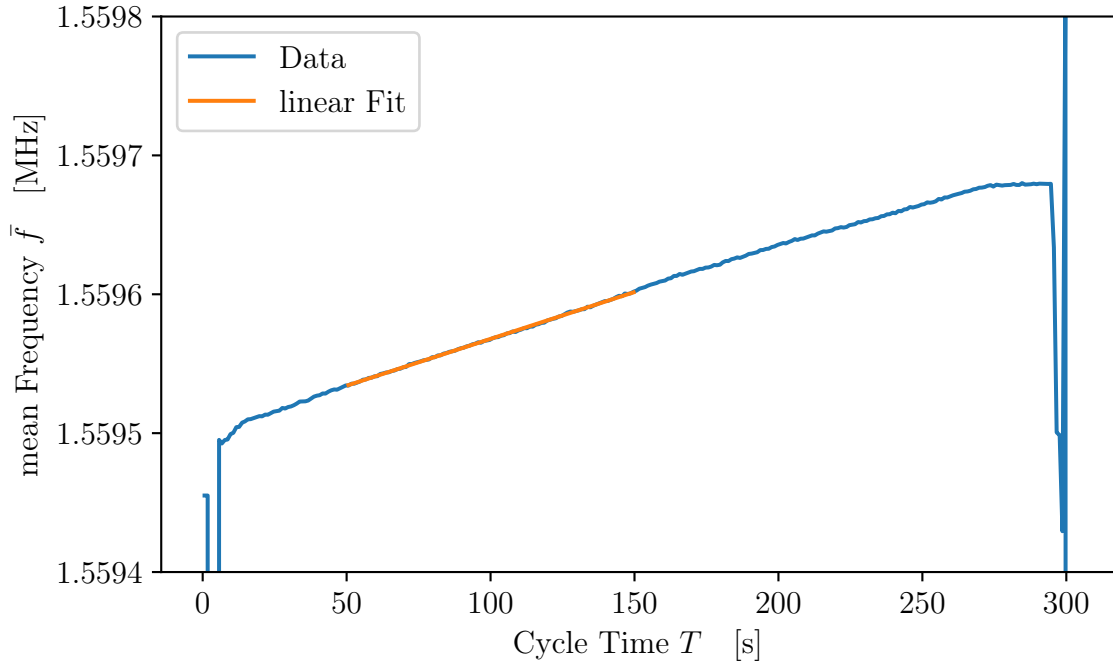


Figure 5.25: Evolution of the mean frequency of the measured Schottky spectra during a COSY cycle with the beam in the center of the target. The data was recorded with the target operating at 24.5 K and 12 bar with a target thickness of $n_T^{\text{AMS}} = (3.9 \pm 0.9) \cdot 10^{14} \text{ atoms/cm}^2$. The slope $df/dt = (0.6742 \pm 0.0015) \text{ Hz}$ was determined via a linear fit in the range from 50 s to 150 s after the beginning of the cycle to avoid nonlinear effects at the beginning shortly after turning on the target and at the end once first particles reach the end of the COSY acceptance. This corresponds to a total target thickness of $n_{T,\text{tot}}^{\Delta E} = (1.198 \pm 0.017) \cdot 10^{15} \text{ atoms/cm}^2$ including the residual gas background.

loss measurements, the exact target thickness at the moment of the cycle cannot be determined. Therefore, the target thickness can differ, especially when operating with large target thickness where the target operation is more unstable. Furthermore, it was already seen before, that the cycles with the chicane on the sides of the target are challenging and thus some overlap with the target is still possible. Finally, also the beam might not be perfectly aligned to the cluster-jet, although this was checked before the beginning of the measurements with each setting by performing a sweep and looking at the measured rate at the WASA forward detector. Nevertheless, these energy loss studies support the correctness of the AMS measurements that are used in the previous sections.

These measurements can also be used to determine the contribution of the residual gas. The lower plot in Figure 5.26 shows the ratio of the target thickness $n_{T,\text{back}}^{\Delta E}$ on

the side of the cluster-jet divided by the target thickness $n_T^{\Delta E}$ of the cluster-jet only. This shows that integrated over the whole COSY ring the residual gas contribution is in the same order as the contribution of the cluster-jet and can be even larger. To

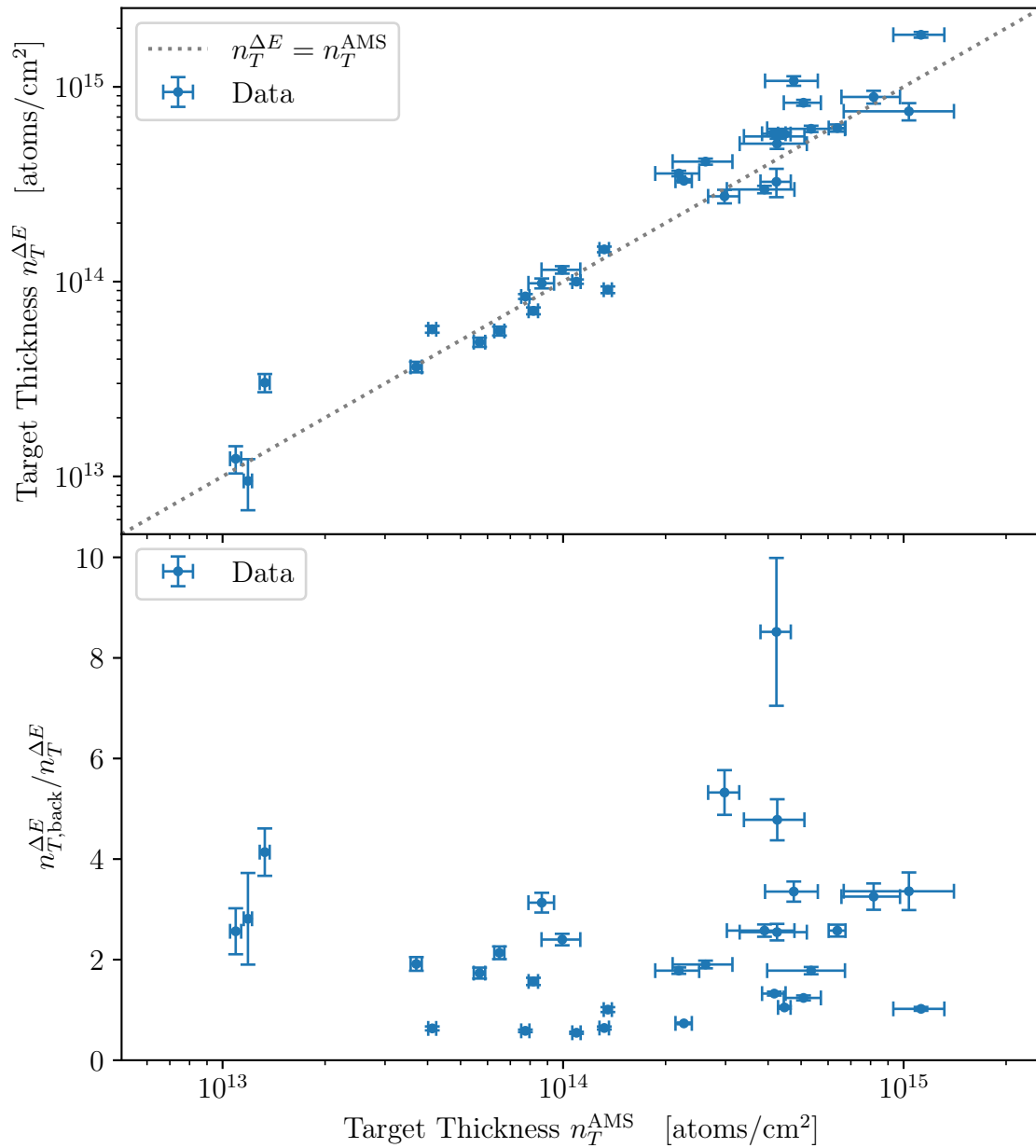


Figure 5.26: Top: Target thickness measured via the AMS and the energy loss for different target settings. The latter was measured as difference of the cycles in the center and on the sides. The dashed line shows the expected correlation for a perfect agreement. Bottom: Ratio of background target thickness to cluster-jet target thickness for different target settings. Both were measured using the energy loss method. The background was measured with the cycles on the sides of the target.

check the validity of this method, the contribution of the residual gas can also be estimated via the measured vacuum pressures around the ring. The target thickness can be calculated as

$$n_T = 2 \frac{p}{k_b T} \cdot C \quad (5.35)$$

with the pressure p , the Boltzmann constant k_b , the temperature $T \approx 293.15$ K, and the orbit length $C = 183.47$ m extracted from the MAD-X model. According to this equation, a pressure of $1.1 \cdot 10^{-6}$ mbar would be required to reach a target thickness of $1 \cdot 10^{15}$ atoms/cm² which is in the order of the measured averaged pressure in the whole COSY ring. This shows that the residual gas cannot be neglected. This is also a reason, why no significant difference in the beam quality measurements was found when comparing cycles with the beam in the center of the target and on the sides. Furthermore, the residual gas can also negatively impact the data taken later at $\overline{\text{PANDA}}$ as it can lead to a fast beam loss and thus a reduced luminosity. Therefore, the origin of the residual gas was studied in [Klo20] and [Wei23] and the results show that the main source of residual gas is the evaporation of the clusters on their way through the vacuum. This knowledge can then be used to reduce the amount of the residual gas in the vacuum system by, e.g., the installation of a cryogenic pump into the HESR beam line close to the $\overline{\text{PANDA}}$ experiment [Man24].

5.6 Measurements with the MCP Monitor System

The third big topic that is addressed with the $\overline{\text{PANDA}}$ cluster-jet target at COSY are measurements with the new MCP monitor system. Due to shortages of available beam times and due to the end of COSY operation in the end of 2023, these measurements had to be performed in the 2023 beam time although the new beam dump and the new MCP system described in section 3.5 was not yet available. Instead, a simplified version of the MCP monitor system was included into the old beam dump. The movable arm that shall allow the removal of the MCP system was replaced by a fixed arm that was installed into the second stage of the old beam dump where a turbomolecular pump was removed to make a flange at that stage available. This reduces the efficiency of the beam dump as the cluster-jet cannot directly enter the last beam dump stage anymore. But since previous studies have shown, that the backflow of gas from the beam dump is not the main source of residual gas in the interaction chamber compared to the evaporation of clusters on their way through the vacuum [Klo20, Wei23], this installation has no significant impact on the quality of the other measurements that

are discussed in the previous sections. Furthermore, the new electron gun (see section 3.5.4) was installed slightly above the interaction point.

With the MCP system, several studies have been performed. The first commissioning at COSY is described in detail in [Obs23]. Here, some more sources of ionization were discovered that would result in lower quality of the planned measurements. These originate from different pressure gauges in the beam dump and also between beam dump and interaction point. Therefore, the gauges were turned off during measurements with the MCP system. Afterwards, a clear image of the cluster-jet is found with ionization by the electron gun but also by the COSY beam [Obs23].

The first measurements performed with the COSY beam during the beam times are scans over the target. Here, the four steerer magnets that were also used to create the chicane around the target for the previous measurements were used. But instead of creating a chicane with fixed amplitude, the deflection was changed constantly resulting in a sweep over the target. An amplitude of ± 7 mm was chosen with a sweep duration of 60 s leading to a speed of 0.23 mm/s. Without operating the electron gun, the MCP system should then show only the overlap region of cluster-jet and accelerator beam and thus should also detect the sweep. Some images taken during this sweep are shown in figure 5.27. These are recorded with an Allied Vision Mako G-125B PoE CCD camera with a Tamron 35-HB objective. The camera allows for a resolution of 1292×964 pixels and can record 12 bit images leading to intensity values between 0 and $2^{12} - 1$. For a better contrast, the color scale is reduced by 3 bit to a range of 0 to $2^9 - 1$. The exposure time for this series is 1 s so that every second a picture is taken. The images clearly show that only the overlap region of cluster-jet and accelerator beam is illuminated. At the beginning, when the beam is deflected too far to the top of the image, nothing can be seen. Afterwards, the beam slowly moves from top to bottom and illuminates larger parts of the jet, before it then leaves the target region resulting in a dark image. In these and all following images, the horizontal axis corresponds to the z-axis as this is the direction of the accelerator beam. The vertical axis is the x-axis in the COSY frame.

The previous images have proven the functionality of the MCP system and the possibility to visualize the overlap of cluster-jet and accelerator beam. Afterwards, intense studies on the dependence of the intensity of these pictures on the target thickness and the beam intensity were performed that aim to clarify if such a system is capable to work as an online luminosity monitor. The different target settings used are summarized in figure 5.28. In total four settings were selected with one being repeated on a second day with a slightly different target thickness. The thickness was

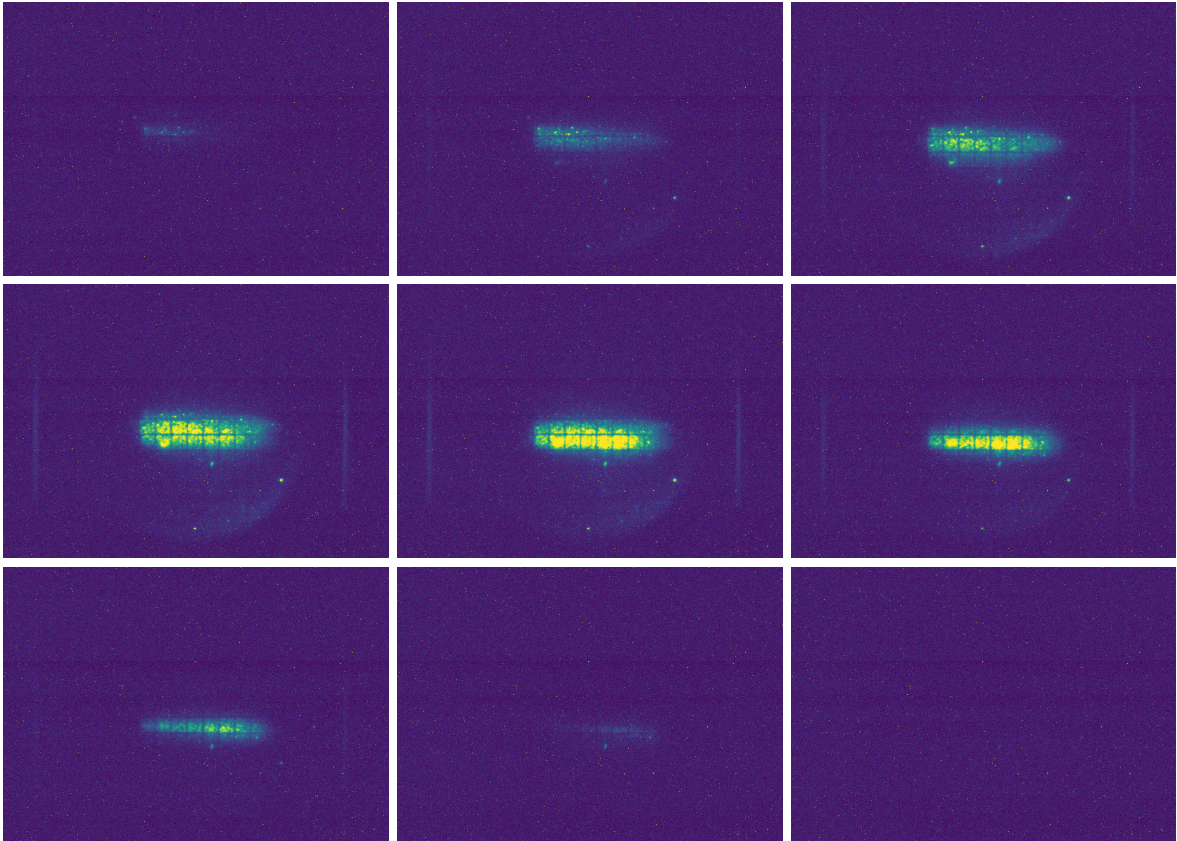


Figure 5.27: Series of images taken during a sweep over the target with the COSY beam from top to bottom. The range of the color map was reduced to a maximum of $2^9 - 1$ for a better contrast. The time between the images shown is 5 s and the images are ordered from left to right and then from top to bottom.

measured several times during data acquisition with one setting using the AMS, so that an average value can be calculated.

During data acquisition, only the smallest number of parameters possible were changed. This includes the target settings and the beam intensity, but due to the significantly lower intensity at lower luminosity, the voltage on the MCP also had to be changed, and the exposure time was varied as well in the range of 1 s to 40 s. Fortunately, the exposure time t_{exp} will affect the intensity linearly [Sch24, Ves20] as long as the images are not saturated, so that the data will be normalized by $1/t_{\text{exp}}$ to make images with different exposure times comparable. On the other hand, the MCP voltages, will significantly influence the intensity and therefore every target setting was recorded with different MCP voltages so that an overlap is achieved between the settings. This was limited towards high voltages by the maximum voltage possible before creating an electrical breakdown, that causes a rapid increase of the current

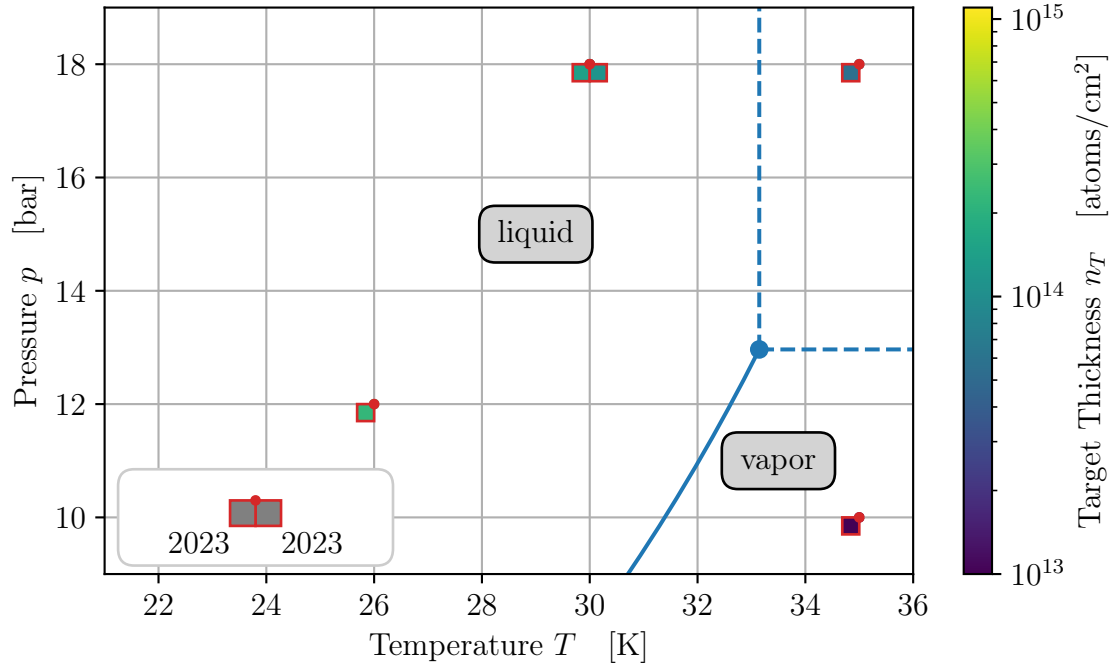


Figure 5.28: Target settings (red dots) used during the MCP measurements in the phase diagram of hydrogen. The solid blue line shows the vapor pressure curve [LM25], while the dashed lines mark the region of supercritical hydrogen. The color code shows the achieved mean target thickness during the measurements, while the up to two quadrants around a red dot always describe data during the 2023 beam time, but with one setting performed twice on different days with slightly different target thickness.

through the MCP and would damage the MCP. On the other side, the voltage was limited by the sensitivity of the camera as for too small voltages no signal could be detected. In total, the voltage at the MCP was varied from 1260 V to 1800 V. For all recorded images the voltage at the phosphor screen was fixed to $U_{\text{screen}} = 1700$ V and the gain of the camera was set to 15.

5.6.1 Calibration and Grid Recognition

Before analyzing the images, some preparatory studies must be performed, to analyze the correct part of the images and to calibrate them. The first step is to find the active area of the MCP or the phosphor screen which is visualized in figure 5.29. For this purpose, an image is used where the MCP was illuminated through a vacuum window with a flashlight. The screen can be seen on this image as mat circular area. To automatically detect this area, first the Canny edge detection algorithm [Can86] to detect the edges in this image is applied. These edges are then used for the Hough circle

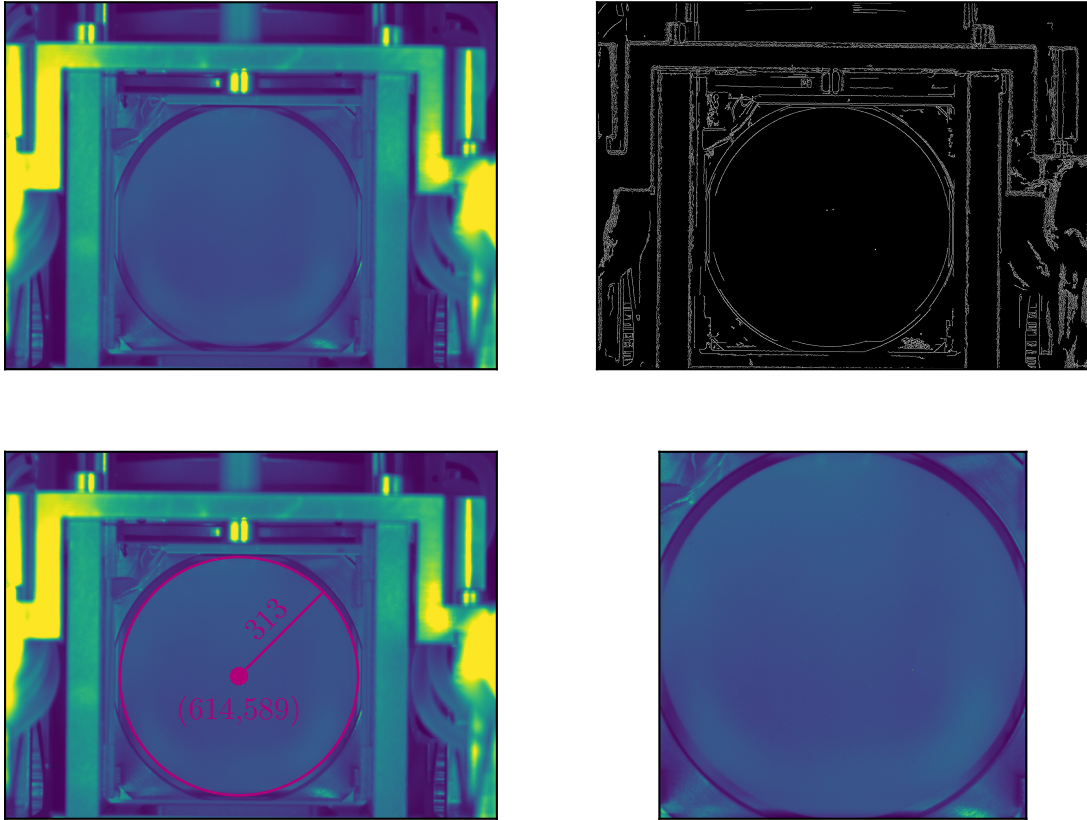


Figure 5.29: Automatic detection of the active area of the MCP. The image was taken by illuminating it with a flashlight. Top left: Original image. Top right: Image after applying the Canny edge detection algorithm that shows the detected edges. Bottom left: Best circle detected by the Hough circle transformation. Bottom right: Zoom into the detected circle that will later be used for the analysis.

transformation [Hou62] that searches for potential circles and returns their center and radius. The circle with the highest probability is selected as active area of the screen and describes it well. Later, all images are cut to the area around the center of this circle with an edge length of twice the radius as it is shown in the last image in figure 5.29. This area is then used for the analysis of the intensity.

The next steps in the preparation will use the grid that is installed in front of the MCP. The part of the cluster-jet that will hit this grid, will create a shadow on the MCP image as already visible in figure 5.27. The first task here is to determine if the camera is tilted and to correct for it if needed as it was only adjusted by eye during the installation of the MCP monitor system. Therefore, the MCP is now powered and the cluster-jet is ionized by the electron gun. Then, a small part of the image around the beam spot is selected as shown in figure 5.30. Again, the Canny edge detection

algorithm is used, followed by a Hough line transformation to detect the lines of the grid. The Hough transformation then directly returns the angle of the lines towards the vertical axis. Due to the rectangular shape of the cluster-jet, mostly horizontal lines are detected and here not more than three can be found due to the width of the jet. Thus, the best three lines are selected and also shown on the right in figure 5.30. This algorithm is not very robust due to the small substructures the images have in the signal region. Therefore, lines with a deviation of more than 1° to the horizontal (90°) or vertical line (0°) are neglected and shown in the image by the dashed line. This procedure is repeated for five sample images, where in total 9 lines within the allowed deviation are detected. These have a mean deviation of 0.06° with a standard deviation of 0.24° so that the image is already perfectly aligned within the resolution and no further correction is needed.

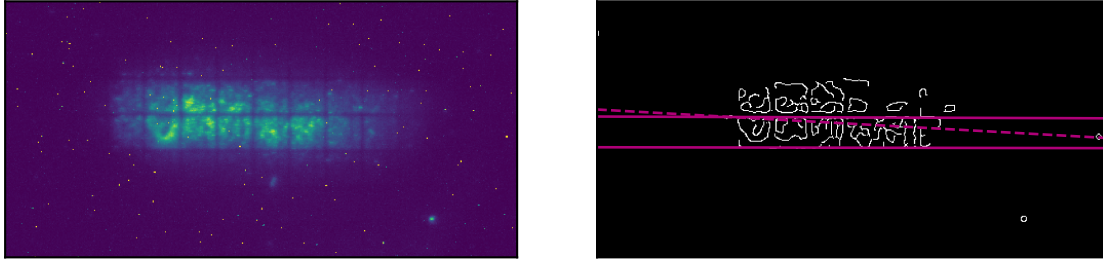


Figure 5.30: Left: Image used to detect the angle of the grid. Right: Via the Canny edge detection and Hough transformation algorithm detected lines of the grid. The found angles are 90.2° , 90.1° , and 93.2° with a resolution of 0.1° for the Hough transformation. The dashed line shows the line with the angle of 93.2° that was neglected due to the deviation of more than 1° .

This is followed by the final calibration of the images that aims to extract a conversion factor from pixels into mm. For this purpose, the grid is used again. The center-to-center distance is known to be 2.7 mm. To determine the distance in pixels a Fast Fourier Transform (FFT) is used as shown in figure 5.31. For a better contrast of the maxima the logarithm of the amplitude is used. This is then projected onto both axes where not the whole FFT is used but only the central 11 bins leading to

$$P_x(k_x) = \sum_{i=-5}^5 \ln(|\mathcal{F}(k_x, i \cdot \Delta k_z)|) \quad (5.36)$$

for the projection onto the vertical axis with the Fourier transform $\mathcal{F}(k_x, k_z)$ and the resolution Δk_z in horizontal direction. The same is done for the horizontal axis. These projections show clear maxima that are expected to be at the spatial frequency

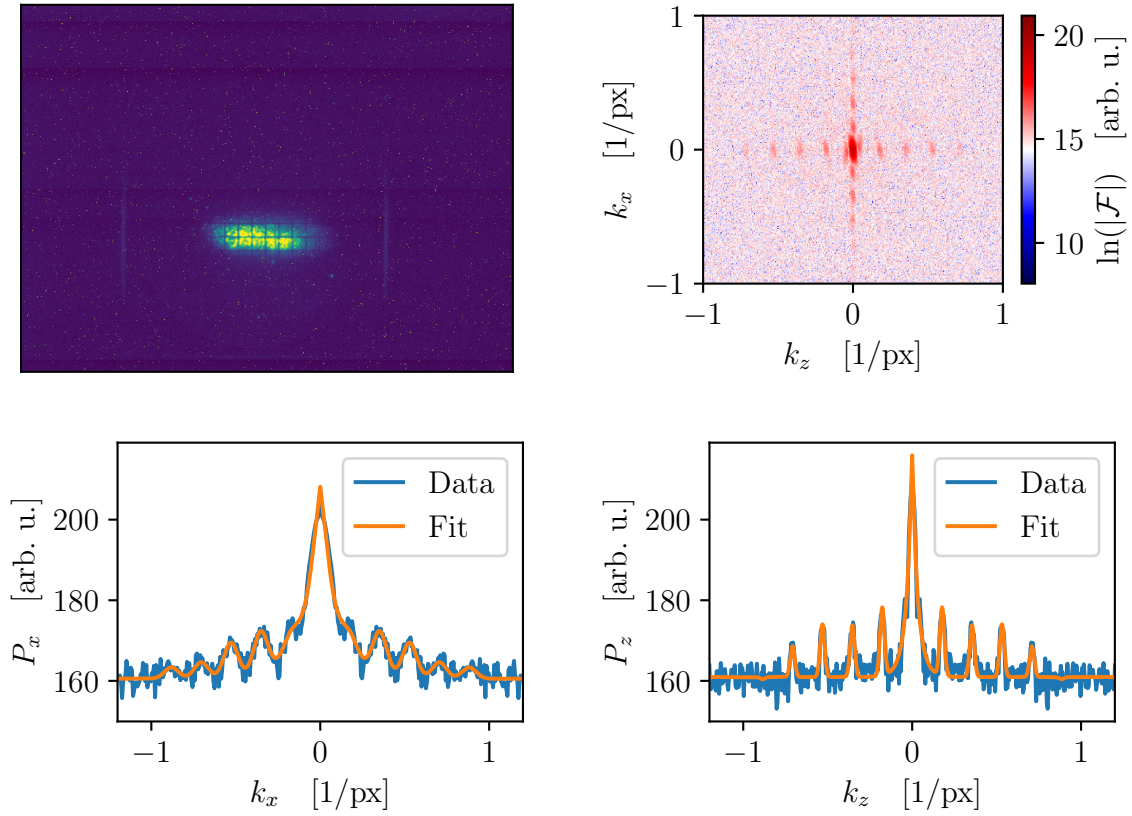


Figure 5.31: Top left: Image used for the calibration. The color scale is reduced to a maximum of $2^{10} - 1$ instead of $2^{12} - 1$ for a better contrast. Top right: Central part of the Fourier transform of this image. For a better contrast of the higher order maxima, the logarithm of the amplitude is shown. Bottom left: Projection of the Fourier transform onto the vertical axis. Therefore, only the central 11 bins are used. The fit gives a grid frequency of $k_{0,x} = (0.1762 \pm 0.0008) \text{ px}^{-1}$. Bottom right: Projection of the Fourier transform onto the horizontal axis. The fit gives a grid frequency of $k_{0,z} = (0.1771 \pm 0.0003) \text{ px}^{-1}$.

corresponding to the periodicity of the grid and at higher harmonics. Therefore, the projections are fitted with a sum of multiple Gaussian functions with their center being multiples of the spatial frequency of the grid. Additionally, a function for the background is added, which was found to be well described by an exponential that decreases towards both sides with an additional constant. Thus, the fit function is given by

$$f(k_x) = \sum_{i=0}^N a_i \cdot \left(\exp \left(-\frac{(k_x - i \cdot k_{0,x})^2}{2\sigma^2} \right) + \exp \left(-\frac{(k_x + i \cdot k_{0,x})^2}{2\sigma^2} \right) \right) + a \cdot \exp(-b|k_x|) + c \quad (5.37)$$

where a , b , and c describe the background, a_i is the amplitude of the i -th harmonic, $k_{0,x}$ is the spatial frequency of the grid in x -direction, σ is the width of all Gaussian functions, and $N = 5$ is the number of harmonics that are used. This method is repeated with five different images and at the end the grid frequency in both dimensions are averaged leading to $\bar{k}_{0,x} = (0.1761 \pm 0.0012) \text{ px}^{-1}$ and $\bar{k}_{0,z} = (0.1772 \pm 0.0009) \text{ px}^{-1}$. The conversion factors are then given as

$$C_{x/z} = 2.7 \text{ mm} \frac{\bar{k}_{0,x/z}}{2\pi} \quad (5.38)$$

leading to $C_x = (0.0757 \pm 0.0006) \text{ mm/px}$ and $C_z = (0.0761 \pm 0.0004) \text{ mm/px}$. These values match within their uncertainties. Small deviations would show that the normal on the surface of the MCP system does not coincide with the view axis of the camera. Nevertheless, the pixels are converted in the analysis into a length for both dimensions separately.

After this step, the distance between the grid bars is known, but their absolute position is still missing. This is necessary because the parts of the images where the grid is located need to be masked out to prevent the grid from influencing the analysis. Again, an MCP image of the cluster-jet is used and a projection of a small part is calculated. For the horizontal profile a projection of the image between the two horizontal lines in figure 5.32 is used, and the same is done for the vertical profile between the vertical lines. The resulting profiles show some minima that correspond to the positions of the grid. Afterwards, a peak finder is used and to make this robust

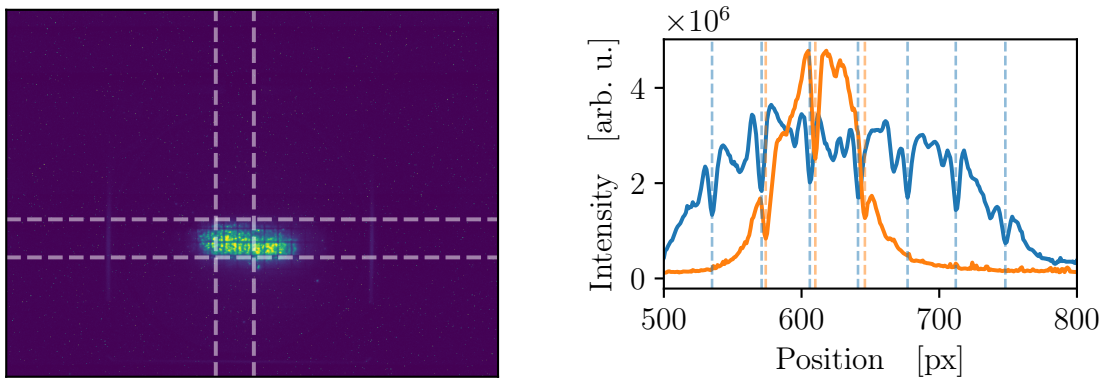


Figure 5.32: Determination of the absolute grid position. Left: A small area of an MCP image is used to make a projection onto the horizontal and vertical axis. The used areas are indicated by the dashed lines. Right: Horizontal (blue) and vertical (orange) projections of the image with found minima indicated by the dashed lines.

a minimum distance between two peaks of 25 px is required that is still significantly below the grid distance of $d_x = (35.7 \pm 0.3)$ px and $d_z = (35.47 \pm 0.17)$ px determined via the Fourier transform before. The found minima are shown on the right of figure 5.32. Due to the rectangular shape of the cluster-jet, the horizontal profile will have six to eight minima while for the vertical not more than three minima are found, sometimes even only one. To increase the statistics four different images are used. Afterwards, the position where the first grid bar would be located is determined by

$$x_0 = x_{min} \bmod d_x \quad (5.39)$$

for every found minimum and the same also for the vertical profile. The mean of these values are calculated leading to $\bar{x}_0 = (3.4 \pm 0.4)$ px and $\bar{z}_0 = (3.1 \pm 0.4)$ px. With these values the grid can now be described as shown in figure 5.33. The indicated grid in the central figures there perfectly represents the center of the grid bars. The shown mask on these images is only one pixel wide, so that still some part of the shadow is visible. The grid bars itself have a width of 0.2 mm which would correspond to a width

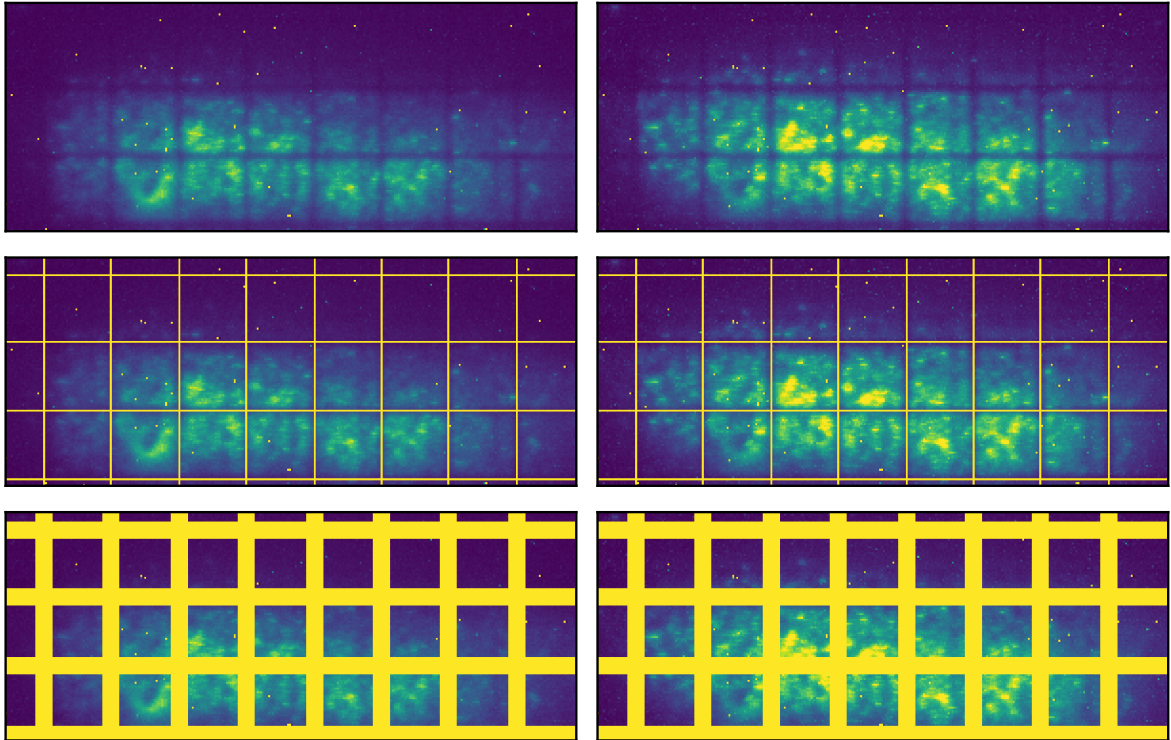


Figure 5.33: Top: Two sample images with a zoom to the spot of the cluster-jet. Center: The same images with the found grid indicated with a width of one pixel. Bottom: Final mask with a width of 9 px that will be used for the following analysis.

of $w_x = (2.642 \pm 0.018)$ px and $w_z = (2.627 \pm 0.012)$ px in the images. On the images these bars additionally smear out, so that a width of 9 px is used for the mask in the following analysis as demonstrated in the lower images in figure 5.33.

5.6.2 Analysis of the Images

After these preparatory steps, the analysis of all recorded images can be performed with the aim to extract the intensity. For this purpose, the background of the images is subtracted. Therefore, background images were recorded for every combination of MCP voltage and exposure time. The subtraction then reduces some effects of noisy pixels or other substructures in the images that originate from the camera, the MCP, or some components in between. The resulting image (see figure 5.34) still shows some substructures, but the background noise is strongly reduced. Furthermore, these structures are only visible due to the increased contrast by setting the maximum of the color scale to $2^9 - 1$ instead of $2^{12} - 1$, which makes the signal of the cluster-jet being oversaturated.

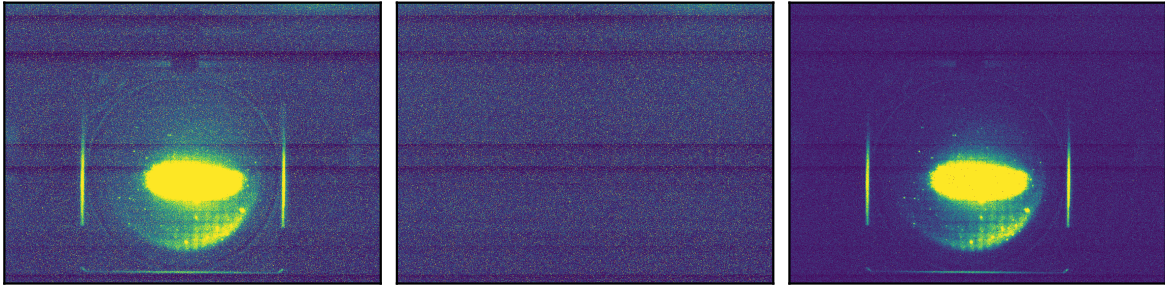


Figure 5.34: Left: Original image with a lot of noise and structures. Center: Background image that is subtracted from the original image recorded with the same MCP and camera settings. Right: Resulting image after the subtraction. The color scale is reduced to a maximum of $2^9 - 1$ instead of $2^{12} - 1$ for a better contrast.

Afterwards, only a part of these background subtracted images are used. Everything that is not within a circle with 85 % of the radius of the active area that was previously found in section 5.6.1 will be neglected. The same holds for the lower and upper 30 % of the images, because there are large parts without signal due to the rectangular shape. Furthermore, on the lower right of the images small reflections are visible like in figure 5.34. The origin of this light source was not found and could not be reduced, therefore a part in the lower right is also removed. Finally, the grid is removed by using the previously determined mask. The remaining part of the image is shown in figure 5.35.

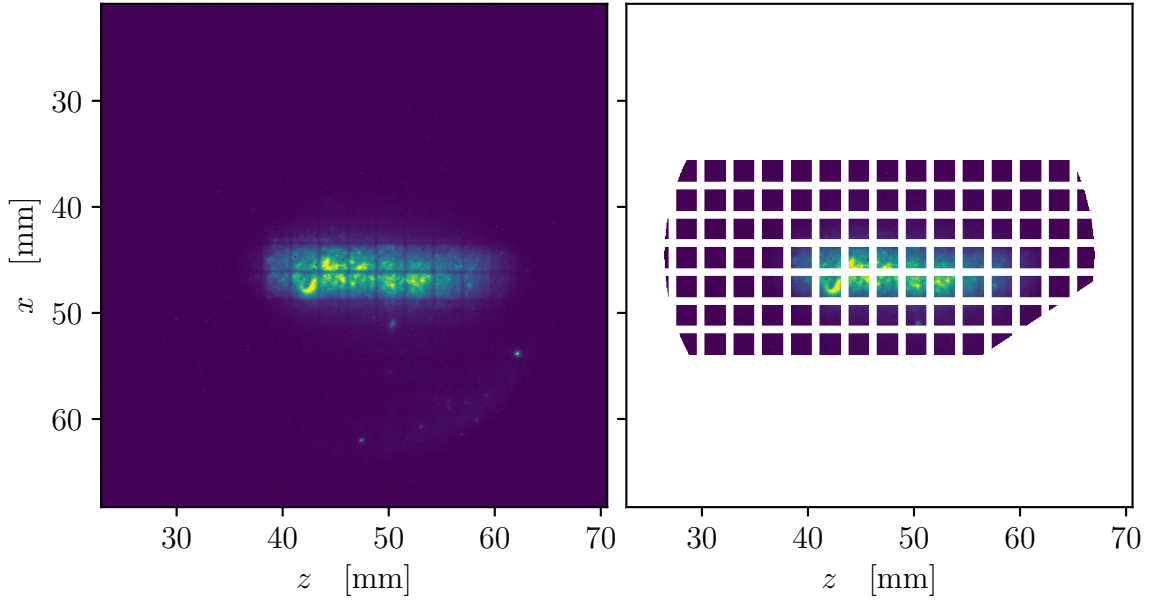


Figure 5.35: Left: Zoom into the original image that is used for the further analysis. Right: Areas that are not used for the analysis are removed, indicated by the white space. This includes everything outside a circle with 85 % of the radius of the active area, the upper and lower 30 % of the image where no part of the cluster-jet will be located due to its rectangular shape, and the lower right part where reflections are visible. The grid is also removed by the mask.

For the extraction of the intensity, the projections of the remaining image onto both axes are made and need to be fitted. As a simple model function, again a homogeneous rectangular jet is considered like for the AMS. This leads to the function

$$I(x, z) = I_0 \cdot \tilde{I}_x(x) \cdot \tilde{I}_z(z) \quad (5.40)$$

with

$$\tilde{I}_x(x) = \frac{1}{2 \operatorname{erf}(b_x/(2s))} \left(\operatorname{erf}\left(\frac{x - x_0 + b_x/2}{s}\right) - \operatorname{erf}\left(\frac{x - x_0 - b_x/2}{s}\right) \right), \quad (5.41)$$

where here the normalization was chosen such that I_0 is the maximum of $I(x, y)$. Furthermore, b_x is the width of the profile, x_0 is its center, and s is a smearing parameter which is the same for $\tilde{I}_x$ and $\tilde{I}_z$. While this is a continuous function, the image is discrete, so that the function must be binned to the pixel size. This is done

by calculating the mean of equation 5.40 for each pixel with size $\Delta x \times \Delta z$ leading to the binned intensity function

$$I_b(x, z) = \frac{I_0}{\Delta x \Delta z} \int_{x-\Delta x/2}^{x+\Delta x/2} \tilde{I}_x(x') dx' \int_{z-\Delta z/2}^{z+\Delta z/2} \tilde{I}_z(z') dz' \quad (5.42)$$

with the integral over the one-dimensional intensity function

$$\int_{x-\Delta x/2}^{x+\Delta x/2} \tilde{I}_x(x') dx' = \frac{1}{2s \operatorname{erf}(b_x/(2s))} (\operatorname{Erf}(u_{x,2}) - \operatorname{Erf}(u_{x,1}) - \operatorname{Erf}(v_{x,2}) + \operatorname{Erf}(v_{x,1})) , \quad (5.43)$$

the integral of the error function

$$\operatorname{Erf}(x) = \int \operatorname{erf}(x) dx = x \operatorname{erf}(x) + \frac{1}{\sqrt{\pi}} \exp(-x^2) + C , \quad (5.44)$$

and

$$u_{x,1} = \frac{x - \Delta x/2 - x_0 + b_x/2}{s} \quad (5.45)$$

$$u_{x,2} = \frac{x + \Delta x/2 - x_0 + b_x/2}{s} \quad (5.46)$$

$$v_{x,1} = \frac{x - \Delta x/2 - x_0 - b_x/2}{s} \quad (5.47)$$

$$v_{x,2} = \frac{x + \Delta x/2 - x_0 - b_x/2}{s} . \quad (5.48)$$

Furthermore, an additional constant background c will be added to equation 5.42. This two-dimensional function is then multiplied by the mask $m(x, z)$ that has the value 1 at every point that is not masked out and 0 everywhere else. This product is then projected onto the vertical axis by summing over all N_z pixels in the horizontal direction leading to

$$f_x(x) = \sum_{i=1}^{N_z} (I_b(x, z_i) + c) \cdot m(x, z_i) . \quad (5.49)$$

The same can also be done for the other axis to get $f_z(z)$.

These two functions can be fitted simultaneously to both projections of the image with shared parameters like the maximum intensity I_0 or the smearing parameter s . This fit is shown in figure 5.36 together with single fits that are performed separately for both profiles. The single fits have the disadvantage of not taking into account the grid bar parallel to the projection axis as no information of the shape of the jet in the

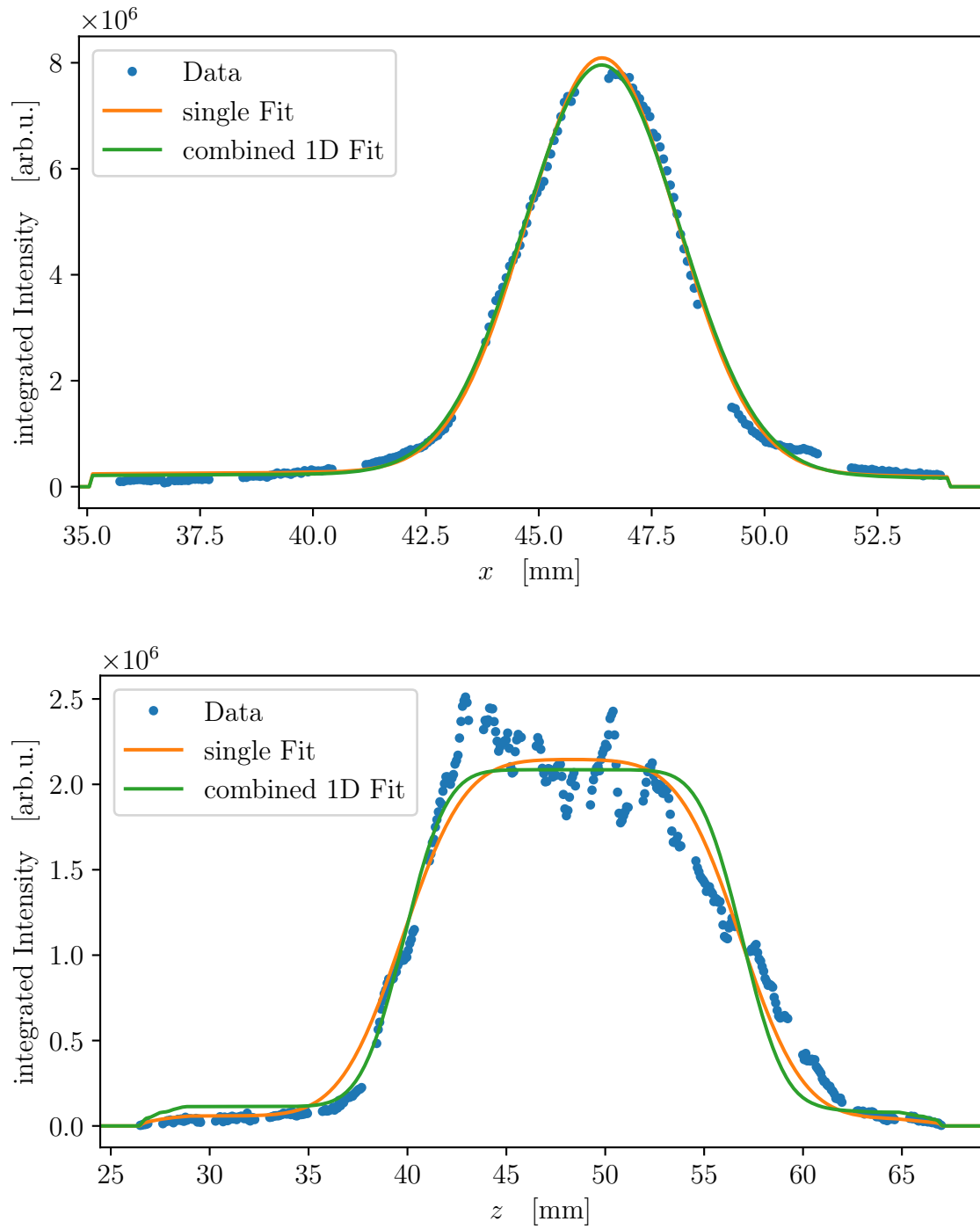


Figure 5.36: Projection of the masked image from figure 5.35 onto the vertical (top) and horizontal (bottom) axis with a combined fit according to equation 5.49 that takes the grid bars in all directions into account. The single fits can only consider the bars perpendicular to the projection axis, which is why the combined fits are used in the analysis.

other direction is available in that case. Therefore, this second method is not used in the following analysis and was just applied as comparison with the combined fit. As a proper uncertainty estimation is difficult for the intensity values of the images, a constant uncertainty for each pixel is assumed that leads to $\chi_{\text{red}}^2 = 1$ for the fit.

From these fits, the maximum intensity of the projection onto the vertical axis is calculated as

$$I_{\text{proj}} = I_0 \cdot b_z / C_z \quad (5.50)$$

which is the maximum intensity that would be achieved when no grid would be present and no mask would be used and is therefore larger than the profiles shown in figure 5.36. The factor b_z / C_z is the width of the profile in pixels and needs to be used here to compare it with the data as this was calculated as sum and not as an integral.

All the resulting intensities are divided by the exposure times due to their linear dependence confirmed in previous studies [Sch24, Ves20]. Furthermore, the intensity is also normalized by the cluster velocity as it is expected that the intensity does not directly depend on the density of the jet but on the gas flow rate onto the MCP and this scales with ρ/v as also shown in [Ves20]. The velocity was extracted from a simulation performed in [Täs⁺13, Täs12].

5.6.3 Intensity Dependence Studies

In the following the dependence of the previously extracted intensities from the MCP images on the MCP voltage and the luminosity will be studied. The normalized intensities are plotted in figure 5.37 as a function of the MCP voltage. The color scale visualizes the product of the accelerator beam intensity N_p and the target thickness n_T , which is proportional to the luminosity. The data for a constant luminosity shows a clear trend regarding the dependence on the MCP voltage. It increases nearly linearly in this logarithmic plot which corresponds to an exponential increase in the intensity. The dependence on the luminosity is not that clear. The data shows an increase of the intensity with larger luminosity, but it is not a steady increase. Sometimes a smaller luminosity can even result in a larger intensity. This is caused by different target settings, which would corresponds to different cluster size distributions and for different cluster sizes the ionization and detection efficiency can change. Therefore, in the following the dependence on target thickness and beam intensity will be analyzed separately.

The complex problem of studying the intensity dependence on three quantities, the MCP voltage U_{MCP} , the target thickness n_T , and the number of stored protons N_p , will be solved by performing a fit with a function depending on all three quantities. For this

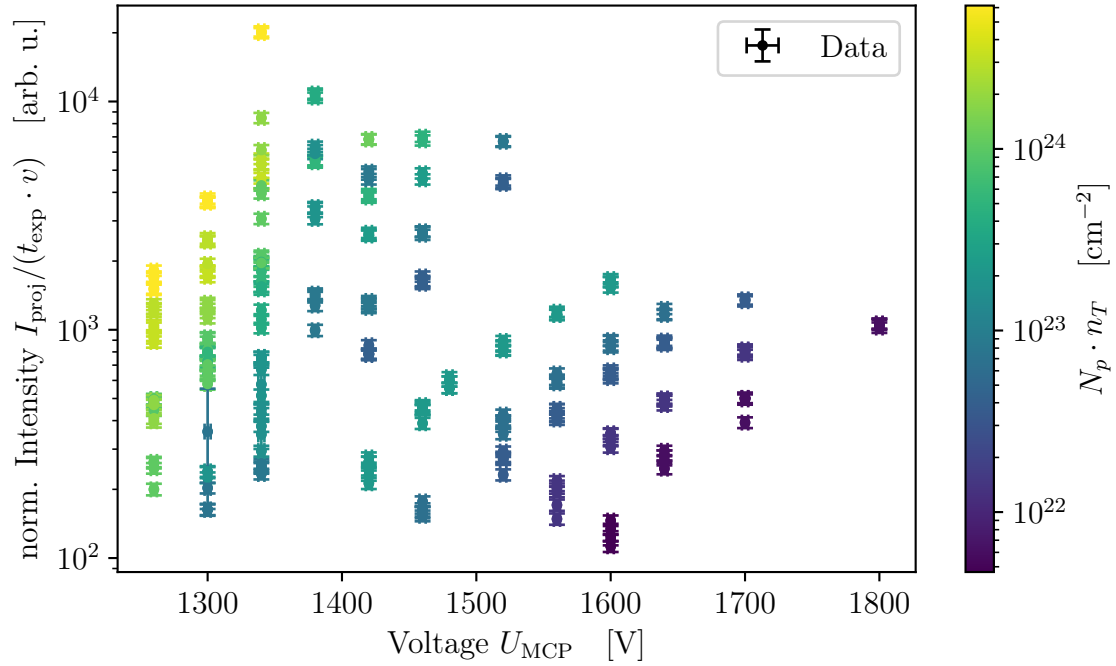


Figure 5.37: Dependence of the intensity on the MCP voltage for different target thicknesses and beam intensities which are combined as $N_p \cdot n_T$ on the color scale. While the intensity is increasing with the voltage for constant luminosity, no clear trend can be seen for the luminosity.

function, some assumptions can be made that will simplify finding a suitable function. First of all, the dependence on the MCP voltage will be modeled as an exponential function as this was already seen in the data and is also expected for the gain of an MCP [Ham21] and the exponential behavior has also been confirmed in other studies with the same MCP [Obs23, Sch24]. The dependence on the target thickness on the other hand is not that clear. Studies on the target thickness dependence has already been performed at the Münster prototype target with different MCPs, resulting in a $\sqrt{n_T}$ dependence [Ves20] or a linear behavior [Obs23]. Therefore, in the following a more general power law will be used that allows for both solutions. Furthermore, as there are no studies on the beam intensity dependence yet, also a power law for the beam intensity will be used. The following analysis will use $\ln(I_{\text{proj}}/(t_{\text{exp}} \cdot v))$ as data as this will result in a linear function in a logarithmic or double logarithmic plot. Therefore, the most general function that can be used is then given by

$$f(n_T, N_p, U_{\text{MCP}}) = \left[\ln(a_1) + b_1 \ln\left(\frac{n_T}{s_1}\right) \right] \cdot \left[\ln(a_2) + b_2 \ln\left(\frac{N_p}{s_2}\right) \right] \cdot [\ln(a_3) + c(U_{\text{MCP}} - s_3)] \quad (5.51)$$

with the constants a_1 , a_2 , and a_3 and the slope parameters b_1 , b_2 , and c . This function can be reduced to

$$f(n_T, N_p, U_{\text{MCP}}) = A \left[1 + B_1 \ln \left(\frac{n_T}{s_1} \right) \right] \cdot \left[1 + B_2 \ln \left(\frac{N_p}{s_2} \right) \right] \cdot [1 + C(U_{\text{MCP}} - s_3)] \quad (5.52)$$

to avoid correlations in the parameters when using this function for a fit. Here, the parameter A summarizes the parameters a_1 , a_2 , and a_3 and B_1 , B_2 , and C are the converted slope parameters b_1 , b_2 , and c . The scaling parameters $s_1 = 1 \cdot 10^{14}$ atoms/cm², $s_2 = 1 \cdot 10^{10}$, and $s_3 = 1400$ V are fixed parameters that shall reduce the large values of target thickness and beam intensity to smaller numbers to improve the fit stability and shall also reduce the correlations of some parameters. The four remaining parameters are determined by a fit that minimizes

$$\chi^2 = \sum_i \frac{(f(\vec{x}_i) - y_i)^2}{(\Delta y_i)^2 + (f_{n_T}(\vec{x}_i) \Delta n_{T,i})^2 + (f_{N_p}(\vec{x}_i) \Delta N_{p,i})^2 + (f_{U_{\text{MCP}}}(\vec{x}_i) \Delta U_{\text{MCP},i})^2} \quad (5.53)$$

with the data $y_i = \ln(I_{\text{proj},i}/(t_{\text{exp},i} \cdot v_i))$ and $\vec{x}_i = (n_{T,i}, N_{p,i}, U_{\text{MCP},i})$, and the partial derivatives $f_{n_T} = \partial f / \partial n_T$, $f_{N_p} = \partial f / \partial N_p$, and $f_{U_{\text{MCP}}} = \partial f / \partial U_{\text{MCP}}$.

The results of this fit are shown in the following figures. Since this four-dimensional function cannot be easily plotted, the intensity is always shown as function of two of the dependencies while the third one is grouped into subsets with similar values and every subplot shows one of these subsets. In figures 5.38 and 5.39 the dependence on the target thickness and MCP voltage is shown for $N_p = (2.4 \pm 0.3) \cdot 10^{10}$, $N_p = (8.0 \pm 0.9) \cdot 10^9$, $N_p = (4.5 \pm 0.8) \cdot 10^9$, $N_p = (1.65 \pm 0.11) \cdot 10^9$, and $N_p = (8.6 \pm 0.3) \cdot 10^8$ stored protons, while figures 5.40 and 5.41 show the dependence on the beam intensity and MCP voltage for target thicknesses of $n_T = (2.3 \pm 0.4) \cdot 10^{14}$ atoms/cm² with the target operating at 26 K and 12 bar, $n_T = (1.3 \pm 0.3) \cdot 10^{14}$ atoms/cm² at 30 K and 18 bar, $n_T = (5.55 \pm 0.17) \cdot 10^{13}$ atoms/cm² at 35 K and 18 bar, and $n_T = (8.3 \pm 0.4) \cdot 10^{12}$ atoms/cm² at 35 K and 10 bar. The fit results in a reduced chi-square of $\chi_{\text{red}}^2 = 4.63$, which shows that the fit describes the data already quite well, although the fit is quite complex. Nevertheless, the data shows some deviations, especially when looking at the dependence on the MCP voltage which is visible in figure 5.39. Here, the data is not perfectly linear for constant target thickness but flattens slightly at higher intensities. This saturation effect is expected for the gain of an MCP system, especially for a stack of multiple MCPs like the chevron assembly used here [Ham21] and can be confirmed with this data.

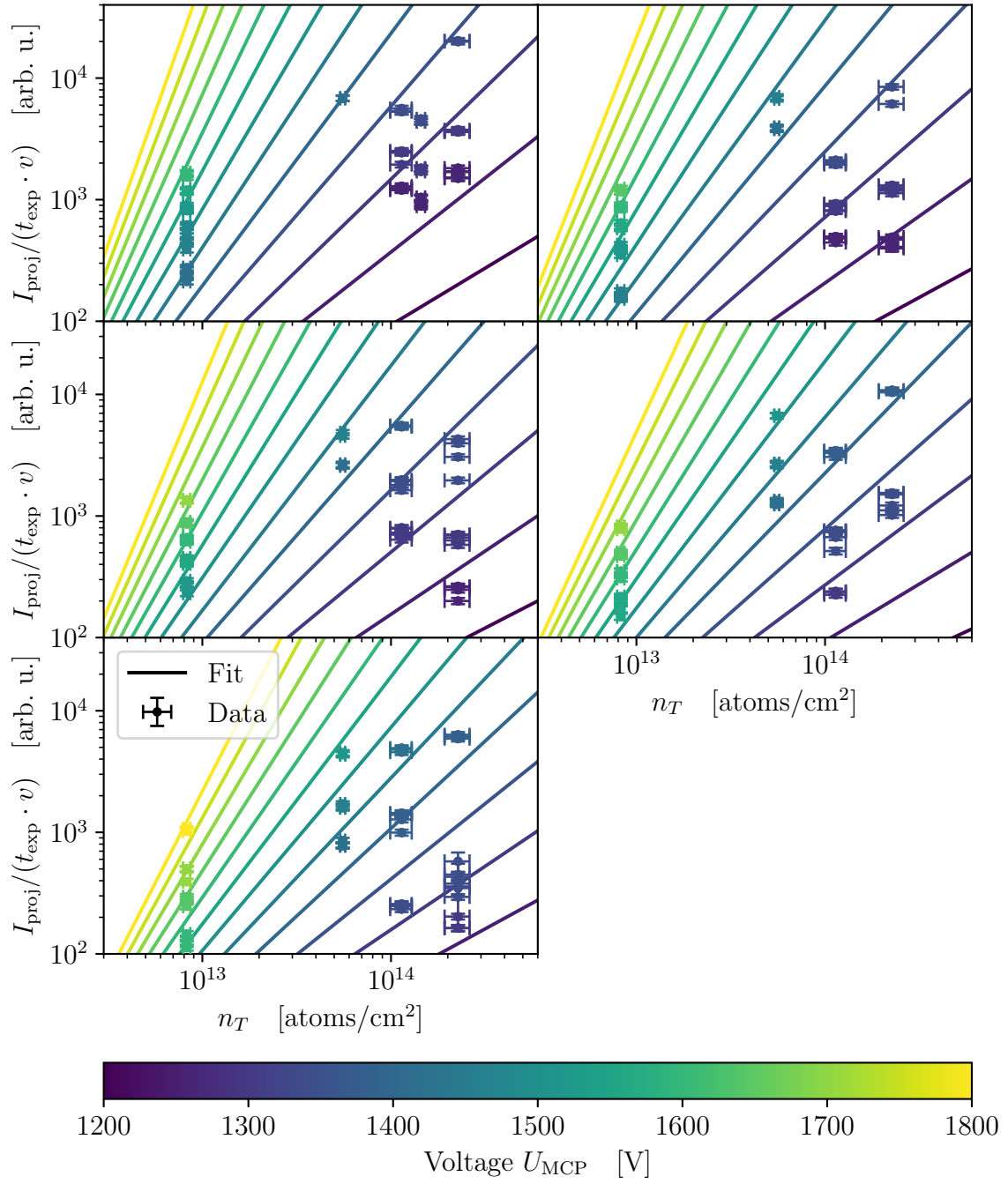


Figure 5.38: Dependence of the intensity on the target thickness and MCP voltage for different groups of beam intensities. The numbers of stored protons are $N_p = (2.4 \pm 0.3) \cdot 10^{10}$ (top left), $N_p = (8.0 \pm 0.9) \cdot 10^9$ (top right), $N_p = (4.5 \pm 0.8) \cdot 10^9$ (center left), $N_p = (1.65 \pm 0.11) \cdot 10^9$ (center right), and $N_p = (8.6 \pm 0.3) \cdot 10^8$ (bottom left). The fit is performed with the data of all subplots simultaneously. The colored lines show the fit function for the beam intensity of the group and cover the range from 1200 V to 1800 V in steps of 50 V.

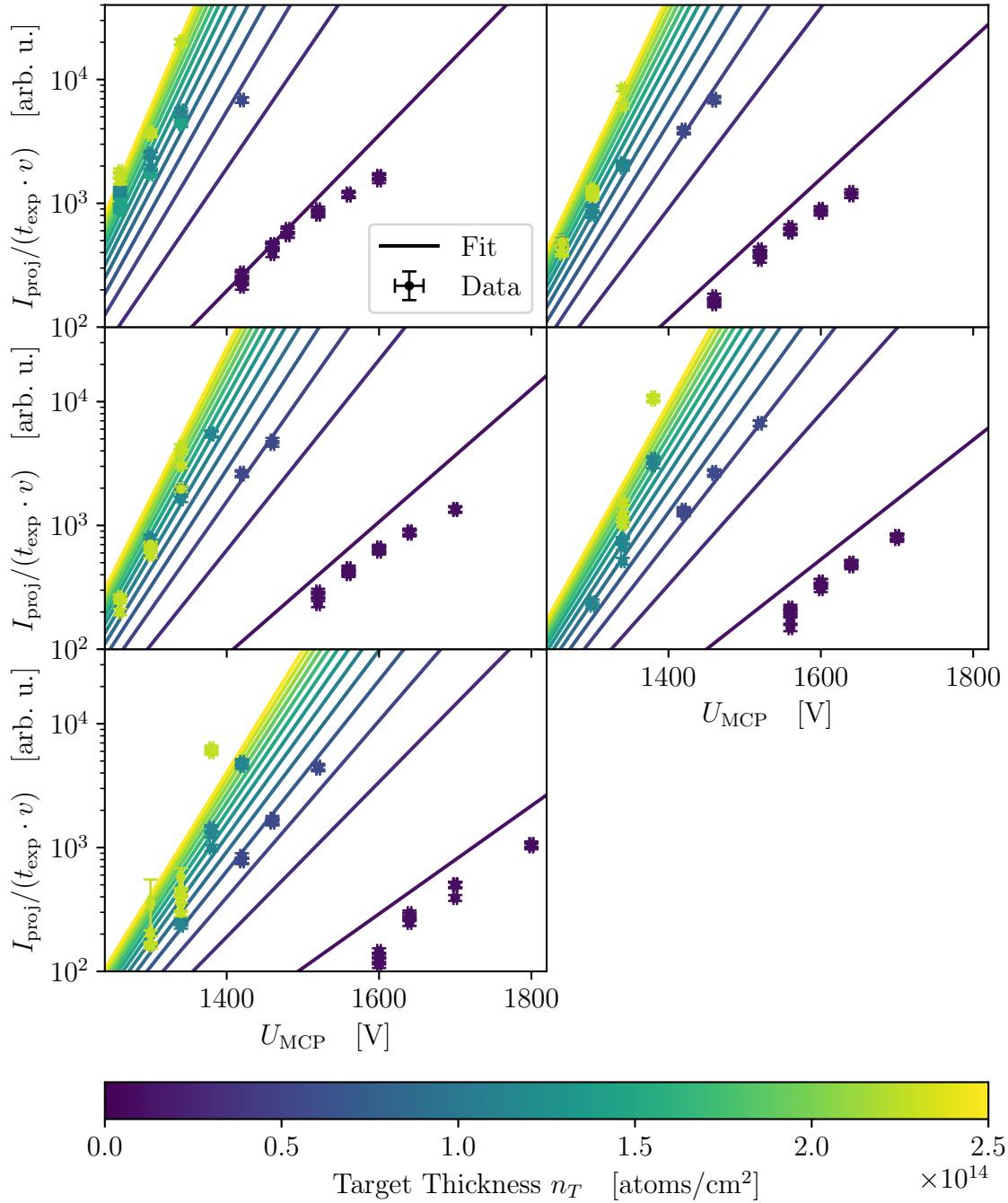


Figure 5.39: Dependence of the intensity on the MCP voltage and target thickness for different groups of beam intensities. The numbers of stored protons are $N_p = (2.4 \pm 0.3) \cdot 10^{10}$ (top left), $N_p = (8.0 \pm 0.9) \cdot 10^9$ (top right), $N_p = (4.5 \pm 0.8) \cdot 10^9$ (center left), $N_p = (1.65 \pm 0.11) \cdot 10^9$ (center right), and $N_p = (8.6 \pm 0.3) \cdot 10^8$ (bottom left). The fit is performed with the data of all subplots simultaneously. The colored lines show the fit function for the beam intensity of the group and cover the range from $1 \cdot 10^{13}$ atoms/cm² to $2.5 \cdot 10^{14}$ atoms/cm² in steps of $2 \cdot 10^{13}$ atoms/cm².

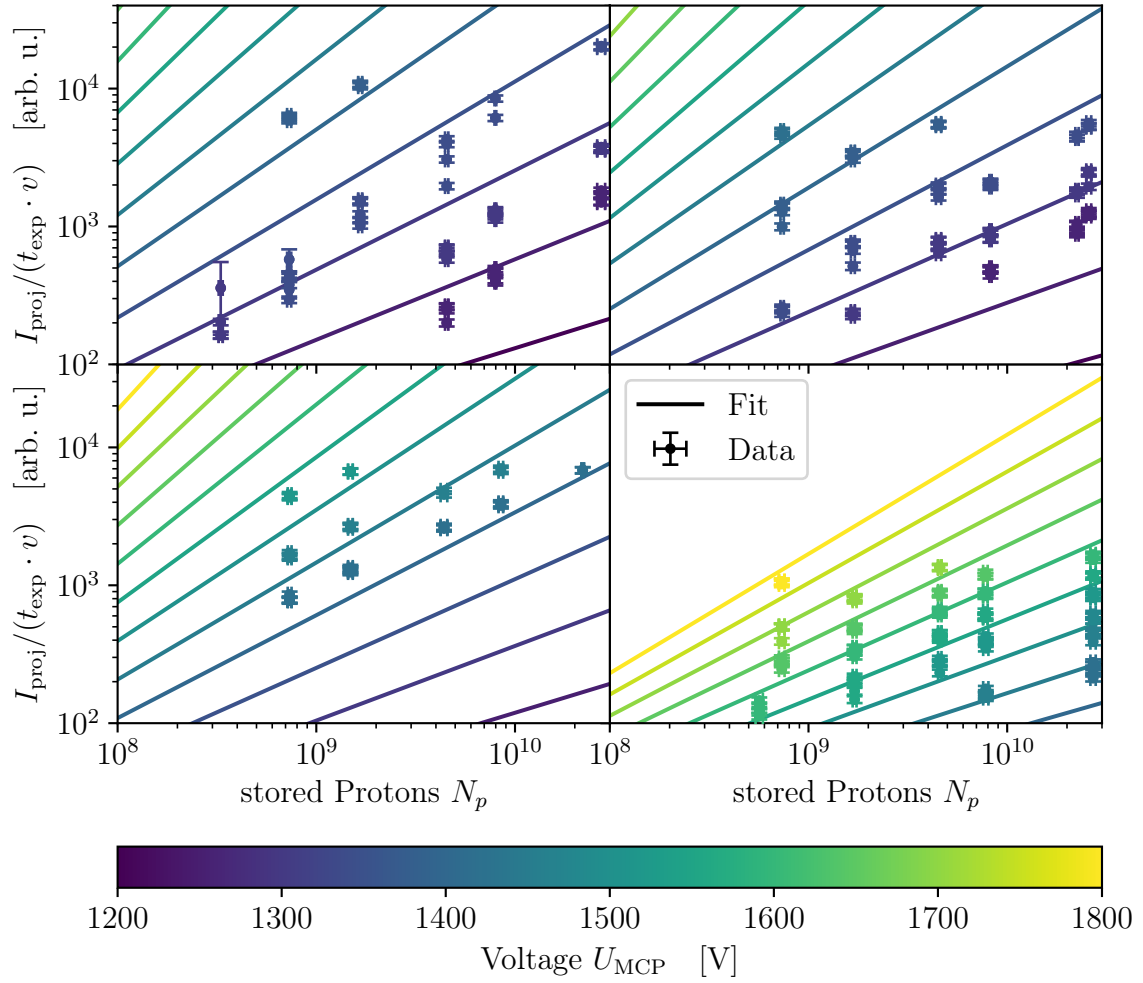


Figure 5.40: Dependence of the intensity on the beam intensity and MCP voltage for different groups of target thicknesses. The target thicknesses are $n_T = (2.3 \pm 0.4) \cdot 10^{14}$ atoms/cm² at 26 K and 12 bar (top left), $n_T = (1.3 \pm 0.3) \cdot 10^{14}$ atoms/cm² at 30 K and 18 bar (top right), $n_T = (5.55 \pm 0.17) \cdot 10^{13}$ atoms/cm² at 35 K and 18 bar (bottom left), and $n_T = (8.3 \pm 0.4) \cdot 10^{12}$ atoms/cm² at 35 K and 10 bar (bottom right). The fit is performed with the data of all subplots simultaneously. The colored lines show the fit function for the target thickness of the group and cover the range from 1200 V to 1800 V in steps of 50 V.

Figure 5.41 shows additional data points that were taken using the electron gun. The electron gun was operated with a filament voltage of 11.5 V and an acceleration voltage of 200 V. These data points show an intensity that is significantly lower than the one achieved with even the smallest COSY beam intensity of $(8.6 \pm 0.3) \cdot 10^8$ stored protons.

The fit parameters are summarized in table 5.10 and can be used to study the power law dependence on the target thickness in more detail and compare it with the results

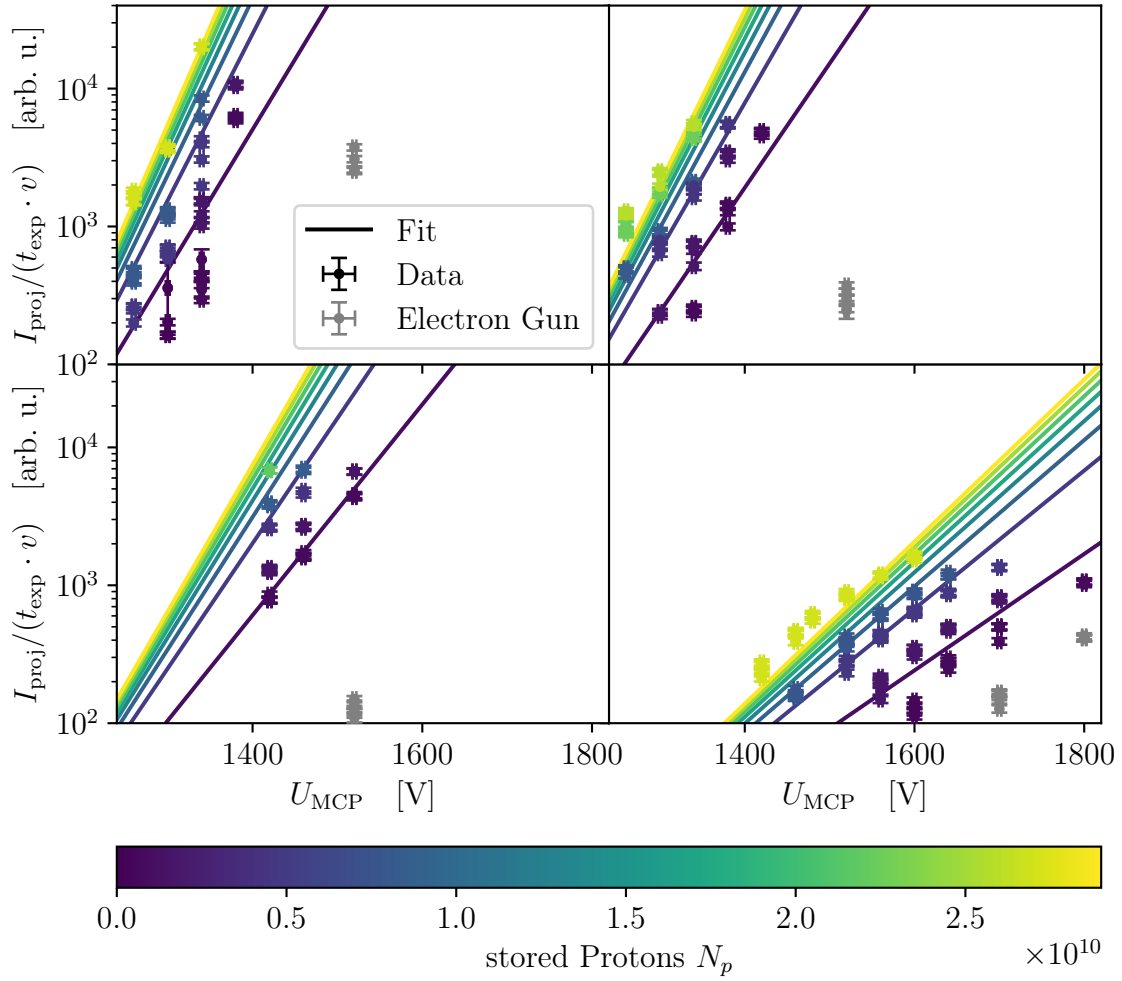


Figure 5.41: Dependence of the intensity on the MCP voltage and beam intensity for different groups of target thicknesses. The target thicknesses are $n_T = (2.3 \pm 0.4) \cdot 10^{14}$ atoms/cm² at 26 K and 12 bar (top left), $n_T = (1.3 \pm 0.3) \cdot 10^{14}$ atoms/cm² at 30 K and 18 bar (top right), $n_T = (5.55 \pm 0.17) \cdot 10^{13}$ atoms/cm² at 35 K and 18 bar (bottom left), and $n_T = (8.3 \pm 0.4) \cdot 10^{12}$ atoms/cm² at 35 K and 10 bar (bottom right). The fit is performed with the data of all subplots simultaneously. The colored lines show the fit function for the target thickness of the group and cover the range from $1 \cdot 10^9$ protons to $2.9 \cdot 10^{10}$ protons in steps of $4 \cdot 10^9$ protons. Additionally, data taken with the electron gun instead of the COSY beam is shown as gray data points.

in [Ves20] where a power law with an exponent of 1/2 was found and with the exponent of 1 in [Obs23]. Therefore, the intensity can be written as

$$\frac{I_{\text{proj}}}{t_{\text{exp}} \cdot v}(n_T, N_p, U_{\text{MCP}}) = a_{n_T}(N_p, U_{\text{MCP}}) \cdot n_T^{p_{n_T}(N_p, U_{\text{MCP}})} \stackrel{!}{=} e^{f(n_T, N_p, U_{\text{MCP}})} \quad (5.54)$$

and the exponent can then be determined by comparing this with equation 5.49 as

$$p_{n_T}(N_p, U_{\text{MCP}}) = A \cdot B_1 \cdot \left[1 + B_2 \ln \left(\frac{N_p}{s_2} \right) \right] \cdot [1 + C(U_{\text{MCP}} - s_3)] . \quad (5.55)$$

Similarly, the exponent for the beam intensity can be calculated as

$$p_{N_T}(n_T, U_{\text{MCP}}) = A \cdot B_2 \cdot \left[1 + B_1 \ln \left(\frac{n_T}{s_1} \right) \right] \cdot [1 + C(U_{\text{MCP}} - s_3)] . \quad (5.56)$$

The resulting exponent for the target thickness is shown in the upper plot in figure 5.42 and compared to the two hypotheses from [Ves20] and [Obs23]. It starts in the order of 1 for lower MCP voltages and then increases to roughly 4. With this, it is significantly larger than the exponent of 0.5 proposed in [Ves20], although it must be noted, that the old electron gun and a different MCP with completely different operation parameters have been used there. The MCP was operated there with a voltage of 3000 V and a voltage of 2200 V was applied to the phosphor screen. On the other hand, the studies in [Obs23] were performed with the same MCP as used within this work at operating parameters of 1450 V at the MCP and 2200 V at the phosphor screen. However, the old electron gun was also used there, which corresponds to much lower beam intensities as shown in figure 5.41, and thus explains the differences in these studies.

Table 5.10: Fit results for the MCP intensity dependence.

A	9.25 ± 0.03
B_1	0.206 ± 0.001
B_2	0.092 ± 0.001
C	$(2.75 \pm 0.03) \cdot 10^{-3} \text{ V}^{-1}$

For the exponent of the accelerator beam intensity dependence the same analysis is performed and shown in the lower plot in figure 5.42. There are no other studies to compare with but also the comparison with the exponent of the target thickness delivers some important aspects. First of all, it is smaller for the beam intensity by roughly a factor of two. This already explains why the intensity of the MCP images as function of the luminosity shows no clear trend and instead target thickness and beam intensity have to be considered separately. There are at least two possible reasons for this behavior. First, a larger target thickness also corresponds to a larger gas flow rate onto the MCP and thus a larger gas density around the MCP, which can increase the gain of the MCP and by this the impact of the target thickness is enhanced.

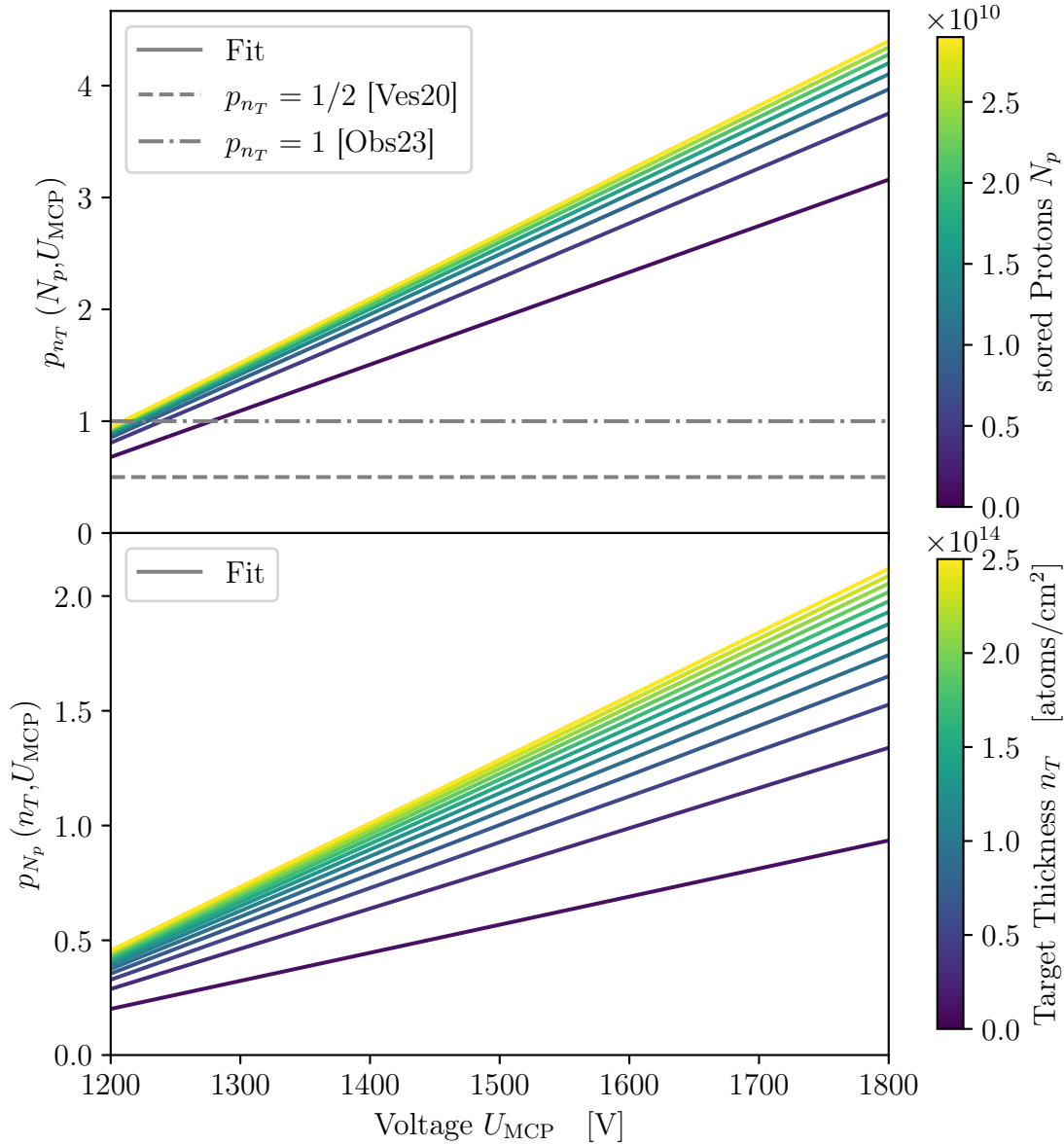


Figure 5.42: Top: Exponent of the target thickness dependence as a function of the MCP voltage for different accelerator beam intensities according to equation 5.55. The colored lines cover the range from $1 \cdot 10^9$ protons to $2.9 \cdot 10^{10}$ protons in steps of $4 \cdot 10^9$ protons. The gray lines show the found exponents in [Ves20] and [Obs23]. In [Ves20] a different MCP was used together with an old electron gun, while in [Obs23] the same MCP as in this work was used but also with the old electron gun. Bottom: Exponent of the accelerator beam intensity dependence as a function of the MCP voltage for different target thicknesses according to equation 5.56. The colored lines cover the range from $1 \cdot 10^{13}$ atoms/cm² to $2.5 \cdot 10^{14}$ atoms/cm² in steps of $2 \cdot 10^{13}$ atoms/cm².

Furthermore, a larger target thickness also corresponds to target settings more in the liquid regime where also larger cluster sizes are expected [Eic23, Köh15, Man19]. These can result in a different detection efficiency of the MCP and thus a different intensity.

The performed studies with the MCP monitor system show its great potential for the cluster-jet monitoring. The sweep measurements have proven the working principle and also show that a live monitoring of the vertex region is possible with a time resolution of 1 s. This simplifies the adjustment of the whole target system as the exact position can now be monitored by the MCP system instead of taking profiles with the AMS, which takes some minutes instead of a second. Furthermore, the study of the intensity dependence shows that the MCP monitor system cannot be used as a direct luminosity monitor as there was no clear trend visible. But if either the target thickness or the beam intensity is known, the luminosity could be determined from the intensity. For high precision a proper calibration as performed during this thesis would be required, and it would probably require regular checks to take into account that the MCP might wear over time. Thus, this system will not be able to take over the task of the luminosity monitor, but it can be used to get a rough live monitoring of the luminosity and to realize relative changes nearly immediately.

5.6.4 Stability of the MCP System

The beam time also allowed for a stability test of the MCP system. The intensity studies shown before were recorded during two days and a total of about 15 h with continuous operation. Further operation time was needed for the commissioning of the MCP system at COSY, for measurements like the sweeps, and during target adjustment. While the MCP showed no degradation after these measurements, at the end of the beam time the phosphor screen was damaged, and the phosphor was missing in the center, where the cluster-jet hits the MCP which can be clearly seen in figure 5.43. This happened, although no voltage was applied after completing the MCP studies and is probably caused by chemical degrading due to the exposure with atomic hydrogen ionized by the accelerator beam [Ves24]. Following this observation, studies with alternative scintillating screens were performed showing the potential of a YAG:Ce screen that is more chemical resistant [Sch24, Ves24].

When this type of scintillating screen proves to be long time stable, the MCP system will be an ideal monitoring tool for the $\bar{\text{P}}\text{ANDA}$ cluster-jet target with different tasks. Its most important feature for the operation of the target will be the opportunity of online monitoring of the cluster-jet when operating it in combination with an electron gun or the online monitoring of the overlap between cluster-jet and accelerator

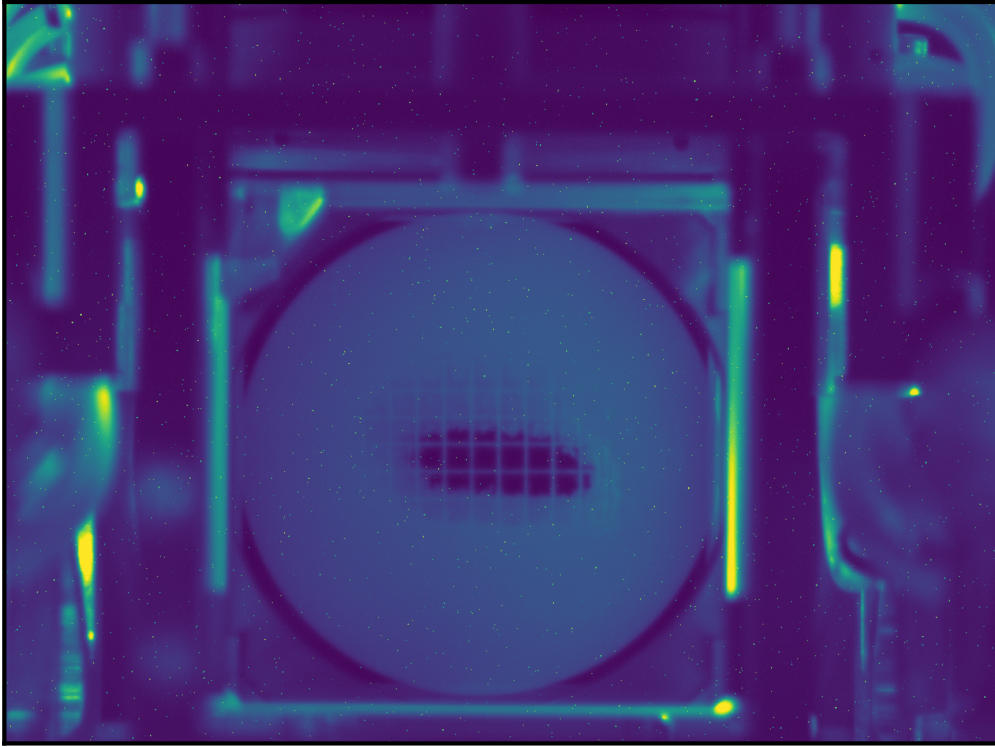


Figure 5.43: Image of the damaged phosphor screen. The region where the cluster-jet hits the target is not covered by phosphor anymore. Only the outer region and small parts behind the grid are still intact.

beam. The latter simultaneously also allows for an online monitoring of the luminosity, although this needs a proper calibration and will not be able to replace the luminosity monitor of the $\overline{\text{P}}\text{ANDA}$ detector. Furthermore, it also allows for cluster velocity measurements by operating it with a pulsed electron gun [Sch24, Ves24] which is necessary to precisely determine the target thickness using the AMS.

Chapter 6

The MAGIX Experiment at MESA

At the Johannes Gutenberg University in Mainz the new Mainz Energy-recovering Superconducting Accelerator (MESA) is currently in the final installation phase. It will use the unique design of an energy recovery linac to provide a high intensity electron beam for the three experiments P2, DarkMESA, and MAGIX that aim for high precision scattering experiments and dark matter searches [Sch⁺24]. The MESA accelerator and the MAGIX experiment with its physics program, its experimental setup, and with its dedicated jet target are described in the following sections.

6.1 The Mainz Energy-Recovering Superconducting Accelerator (MESA)

The MESA accelerator will deliver electron beams in two different operation modes. In the Extracted Beam (EB) mode, polarized electrons with an energy up to 155 MeV and a beam current of 0.15 mA will be delivered for the P2 experiment and the beam dump experiment DarkMESA. The MAINz Gas Injection target eXperiment (MAGIX) will use the Energy Recovery Linac (ERL) mode with unpolarized electrons with energies up to 105 MeV and a beam current of 1 mA. In a later upgrade even up to 10 mA will be available [Hug⁺20]. The whole MESA facility including the different experiments is shown in Figure 6.1. It will partly use existing halls of the MAINz MICROtron (MAMI) facility that were previously used by the A4 experiment.

The electrons will be produced by two photoemission electron sources [DAP22]. The first one will be the polarized Small Thermalized Electron source At Mainz (STEAM) made of GaAs [FA18] providing an extraction energy of 100 keV [Hug⁺20] and beam currents of 150 μ A up to 1 mA [DAP22]. For larger beam currents of up to 10 mA as foreseen for the MAGIX experiment [Hug⁺20] a second source called MESA-Injector Source Two (MIST) will be used [DAP22]. This source will be made of a more robust

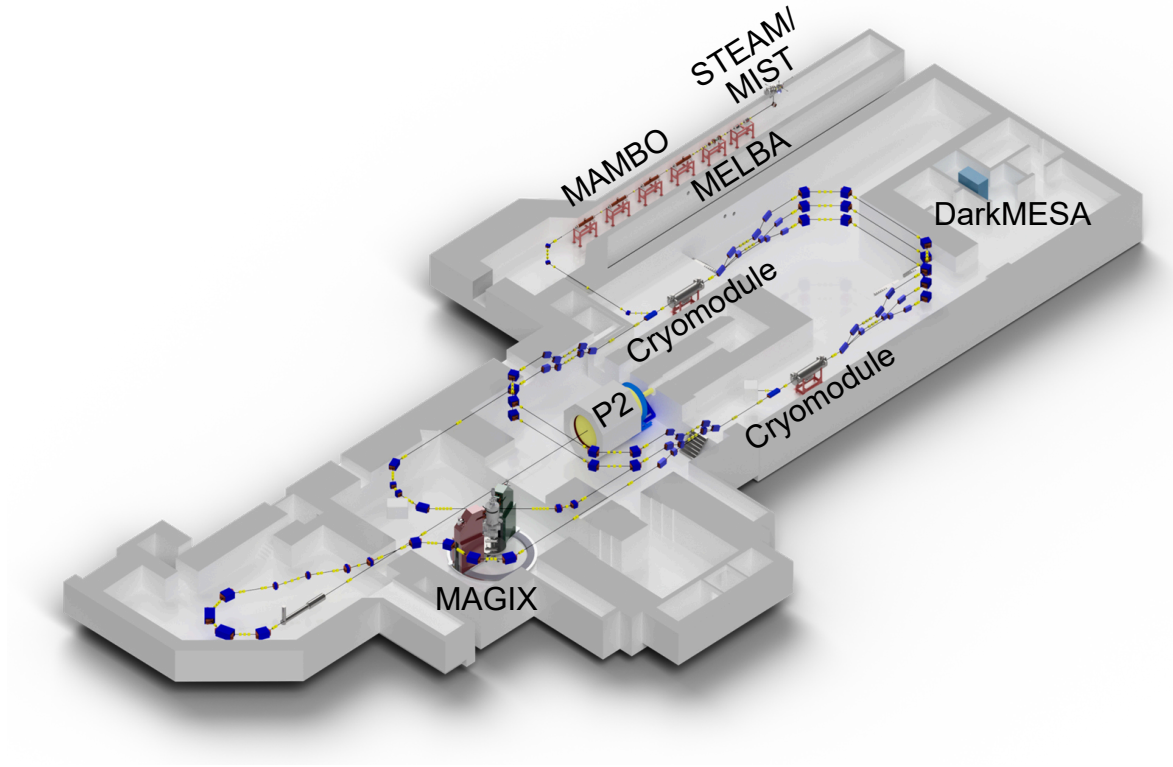


Figure 6.1: Floor plan of the MESA facility with the polarized Small Thermalized Electron source At Mainz (STEAM), the unpolarized MESA-Injector Source Two (MIST), and the MESA Low-energy Beam Apparatus (MELBA). The electrons are then accelerated in the MilliAMpere BOoster (MAMBO) to an energy of 5 MeV before entering the main accelerator. Here, they are accelerated within the superconducting cavities of two cryomodules to their final energies of up to 155 MeV in the Extracted Beam (EB) mode or 105 MeV in the Energy Recovering Linac (ERL) mode. The beam is then guided to the P2 experiment (EB) or towards the MAGIX experiment (ERL). After passing the MAGIX experiment, the electron beam is reinjected with a phase shift of 180° leading to the deceleration of the beam and energy recovery in the cavities. Behind the beam dump of the P2 experiment the beam dump experiment DarkMESA is located (copyright by the MESA group, JGU Mainz, edited).

material like, e.g., K_2CsSb . The electrons from these two sources are then guided into the MESA Low-energy Beam Apparatus (MELBA) that includes systems for spin manipulation and a polarimeter. It also adjusts the longitudinal phase space of the electron beam to the acceptance of the following acceleration section by using a chopper and a buncher [FAM21].

After longitudinal phase matching, the electrons enter the MilliAMpere BOoster (MAMBO) which is a normal-conducting injector linac operating at a frequency of 1.3 GHz [Hei23]. It will be divided into four cavities with the first one being a β -

graded cavity that reflects the velocity change during acceleration. The second cavity works at a fixed value of $\beta = 0.977$, and the other two at $\beta = 1$ [HH17]. Finally, an energy of 5 MeV will be reached. Afterwards, the beam is guided into the main accelerator via a 180° arc [Hug⁺20].

The main accelerator is a recirculating linac with two cryomodules on each side of the ring. Each cryomodule consists of two superconducting RF cavities operating at a frequency of 1.3 GHz [Hug⁺20] and accelerates the electrons by 25 MeV during each pass [Ste⁺20]. In the EB mode, the electrons will circulate three times through the MESA main lattice resulting in a maximal energy of 155 MeV. Afterwards, the particles will be extracted and guided to the P2 experiment and are finally dumped into the dedicated P2 beam dump. In the ERL mode, only two circulations are foreseen with a final energy of up to 105 MeV. Subsequently, the electron beam is guided towards the MAGIX experiment with its windowless jet target. The part of the beam that did not interact with the target is guided back into the main lattice and injected here with a phase shift of 180° . When passing the cavities, the electrons will now lose energy that will be used for the acceleration of the next electron bunches. After two circulations, the electrons are finally dumped with an energy of only 5 MeV. This energy-efficient operation mode allows reaching beam currents of more than 1 mA [Sch⁺24].

The MESA accelerator will deliver electrons for three different experiments. The P2 experiment will study scattering of a polarized electron beam on a liquid hydrogen target. With a high precision spectrometer, measurements on the parity-violating asymmetry are possible giving access to the weak charge of the proton, which is connected to the weak mixing angle at energies below the Z pole. This will provide a precision test of the standard model of particle physics as potential dark matter candidates can influence the weak mixing angle at low energies [Bec⁺18, Sch⁺24].

After passing the P2 experiment, the electrons will be dumped into a dedicated beam dump. Within this beam dump potential light dark matter candidates like the dark photon can be produced, e.g., in a bremsstrahlung-like process $eZ \rightarrow eZ\gamma'$. Therefore, behind the beam dump, shielded by several concrete walls, the beam dump experiment DarkMESA will be located. This setup aims to detect scattering events with dark matter particles that were produced via the dark photon decay $\gamma' \rightarrow \chi\bar{\chi}$ [Plu⁺24].

The third experiment is the MAGIX experiment that will use the ERL mode of the MESA accelerator. It will focus on precision studies on nuclear structure, few-body physics, astrophysical processes, and dark sector searches [Sch⁺24]. More details on the MAGIX physics program, its experimental setup, and the MAGIX jet target will be given in the following sections.

6.2 The Physics Program of MAGIX

The MAGIX experiment is a high precision spectrometer setup, which will be used for electron scattering experiments on different target nuclei. Together with the low energy MESA beam with its high intensity, it is able to study a broad range of physics topics that require high precision and high luminosity. The main physics topics addressed by MAGIX are discussed in the following.

Nuclear Structure

A major pillar in the MAGIX physics program are the measurements on the nuclear structure. One of the main studies will be on the structure of the proton. By using an electron beam, one can access the electric and magnetic form factors as described in section 1.3. This allows for the extraction of the charge and magnetic radius of the proton [Sch⁺24]. Especially, the charge radius and the resulting proton radius puzzle got large attention over the last 15 years.

Different methods can be used to extract this radius. Besides the elastic electron-proton scattering experiments, also spectroscopy of hydrogen can be used. The finite size of the proton has an influence on the Lamb shift, which is the difference between the 2S and 2P energy levels, due to the non-zero probability of the electron to be within the proton, especially for the S-orbitals. As the Lamb shift is dominated by radiative effects, a precise theoretical calculations of these effects are needed to extract the proton radius. In 2010 a new publication showed first results on measurements with muonic hydrogen. Due to the larger muon mass, the Bohr radius is reduced by a factor of 200 compared to the electron making the muon more sensitive to the proton size. These measurements resulted in a value of $(0.841\,84 \pm 0.000\,67)$ fm [Poh⁺10]. This value is in strong disagreement with the publication of the most precise electron-proton scattering data recorded at the A1 experiment in Mainz published at the same time, citing a value of (0.879 ± 0.008) fm [Ber⁺10]. This discrepancy became popular as the proton radius puzzle [BP14]. Many other experiments tried to solve this leading to different results (see figure 6.2). While the CODATA'14 cited a value of (0.8751 ± 0.0061) fm [MNT15] reflecting the electric results [Nav⁺24], a new spectroscopy measurement on muonic hydrogen [Ant⁺13] confirmed the smaller radius. Also more precise spectroscopy results on conventional hydrogen atoms became available with some confirming the small radius [Bey⁺17, Bez⁺19] and some the larger radius [Fle⁺18]. Finally, also a first measurement from electron-proton scattering by the PRad collaboration with a proton radius of (0.831 ± 0.014) fm [Xio⁺19] supports the

smaller radius, although it has a rather large uncertainty. These results finally ended up in the value of (0.8409 ± 0.0004) fm [Nav⁺24] cited by the Particle Data Group [Nav⁺24], that reflects the latest measurements on all three methods [Bez⁺19, Fle⁺18, Xio⁺19]. This value deviates by 5.6 standard deviations from the CODATA'14 value. All the mentioned results are summarized in figure 6.2.

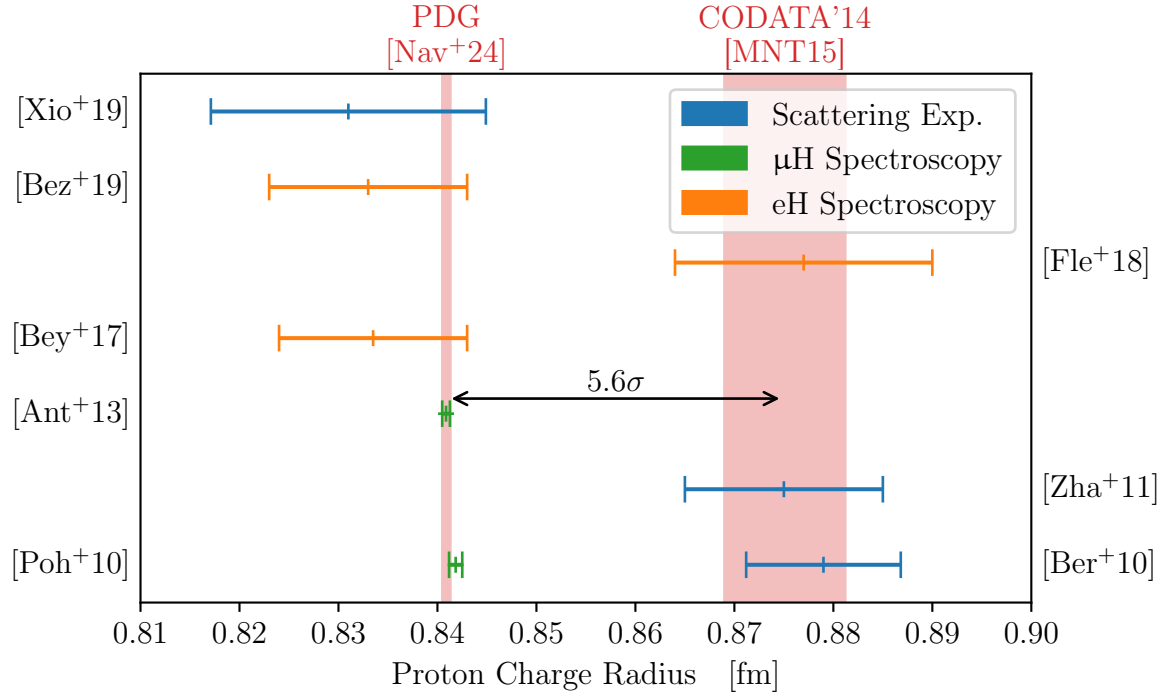


Figure 6.2: Illustration of the proton radius puzzle with results from different measurement techniques. Originally, measurements using electron-proton scattering [Ber⁺10, Zha⁺11], which are summarized in the CODATA'14 value [MNT15], deviate significantly from spectroscopy results on muonic hydrogen [Ant⁺13, Poh⁺10]. With newer spectroscopy results on conventional hydrogen [Bey⁺17, Bez⁺19, Fle⁺18] and a new scattering result [Xio⁺19], the Particle Data Group (PDG) now cites a value of (0.8409 ± 0.0004) fm [Nav⁺24], which deviates by 5.6σ from the CODATA'14 value.

To clarify the situation on the proton radius puzzle, MAGIX aims to take new data on this topic. Therefore, the low energy MESA beam and the high precision MAGIX setup are ideal as data at very low momentum transfer Q^2 is needed for a precise extrapolation towards $Q^2 = 0$. MAGIX aims to measure down to $Q^2 = 10^{-5} \text{ GeV}^2/\text{c}^2$. Furthermore, MAGIX will also address the less popular magnetic form factor and will be able to increase its precision by an order of magnitude [Sch⁺24].

Few-Body Physics

The studies on few-body physics aim to measure reactions that can be compared to theory calculations using effective field theories. This includes reactions like the inclusive ${}^4\text{He}(e, e')X$ reaction, where three-nucleon-forces plays a significant role according to theory predictions. Also exclusive reactions, where a fragment is knocked out of a nucleus, will be studied by using a recoil detector. Furthermore, also studies on the Hoyle state are foreseen, which is the 0^+ excited state of ${}^{12}\text{C}$. This state is important in the astrophysical triple- α process. The results can be compared to predictions describing the Hoyle state as triple- α system [Sch⁺24].

Astrophysical Reactions

MAGIX will be able to study multiple reactions of astrophysical interest. Most prominent example is the ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ reaction that is important for the nucleosynthesis in stars in the helium burning process and for theoretical description of the ${}^{12}\text{C}/{}^{16}\text{O}$ ratio in the universe [Sch⁺24]. For such a reaction the α -nucleus needs to tunnel through the Coulomb potential of the ${}^{12}\text{C}$ nucleus. While the probability for this process increases with the energy, the energy distribution of the α -particles is given by a Boltzmann distribution decreasing with energy. The biggest overlap of these two functions is given around the Gamow window. The α -capture process of ${}^{12}\text{C}$ is part of the stellar helium burning and starts at temperatures of $2 \cdot 10^8$ K which corresponds to a Gamow energy of roughly 300 keV [Lun22]. Therefore, the cross section of the ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ reaction needs to be precisely known at this energy. Due to the strong decrease of the cross section towards lower energies, this is very challenging, and no data is available below 0.9 MeV [Lun22].

At MAGIX, the time-reversed process will be studied via the electrodisintegration reaction ${}^{16}\text{O}(e, e'\alpha){}^{12}\text{C}$, which can be related to the ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ reaction by extrapolating from the virtual photon result to a real photon [FDM19]. In this process that is shown in figure 6.3, the reaction takes place via a virtual photon that is induced by the electrons from the MESA beam. This has the advantage, that the cross section is larger by roughly a factor of 50 [Lun22]. Thus, MAGIX will be able to reduce the uncertainties of the cross section in the region above 0.9 MeV compared to previous measurements. In a second phase, it will also significantly reduce the gap between this energy and the Gamow window, thereby allowing for a more precise extrapolation of the cross section at the Gamow peak [Lun22].

Further interesting reactions that can be covered by MAGIX are processes like ${}^{24}\text{Mg}(\alpha, \gamma){}^{28}\text{Si}$ and ${}^{24}\text{Mg}(\gamma, \alpha){}^{20}\text{Ne}$ in the silicon burning phase, the ${}^{15}\text{N}(p, \gamma){}^{16}\text{O}$

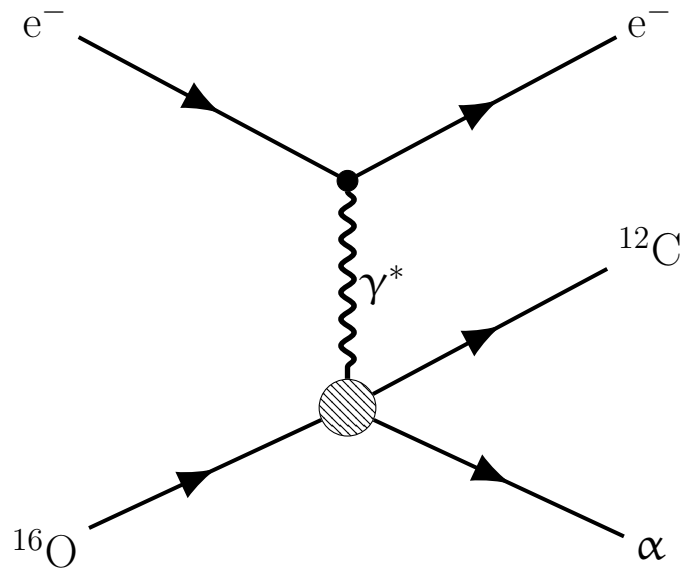


Figure 6.3: At MAGIX, the process $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ will be studied via the time-reversed electrodisintegration reaction $^{16}\text{O}(e, e'\alpha)^{12}\text{C}$. The reaction takes place via a virtual photon and the scattered electron as well as the recoil α -particle are detected by the MAGIX setup (figure from [Bra19]).

reaction in the CNO cycle, and the $d(p, \gamma)^3\text{He}$ reaction in the hydrogen burning phase. Also neutron capture reactions are possible, although these need a dedicated neutron detector [Sch⁺24].

Light Dark Matter Searches

Like the DarkMESA experiment, also MAGIX will search for light dark matter particles like the dark photon. When they couple weakly to standard model matter, dark photons can be produced in a bremsstrahlung-like process in an electron-proton scattering event. These dark photons can then decay into either two standard model particles like an electron-positron pair or, if kinematically allowed, into two dark matter particles as shown in figure 6.4. The decay into an electron-positron pair can be detected with the spectrometer setup of MAGIX and is therefore called visible decay. By detecting both particles, the invariant mass of the dark photon candidate can be reconstructed. The decay into two dark matter particles is also called invisible decay, because the dark matter particles cannot be detected in this case. Therefore, the scattered beam electron and the recoil proton need to be detected. The missing mass of the event can then be used to search for a dark photon candidate [Sch⁺24].

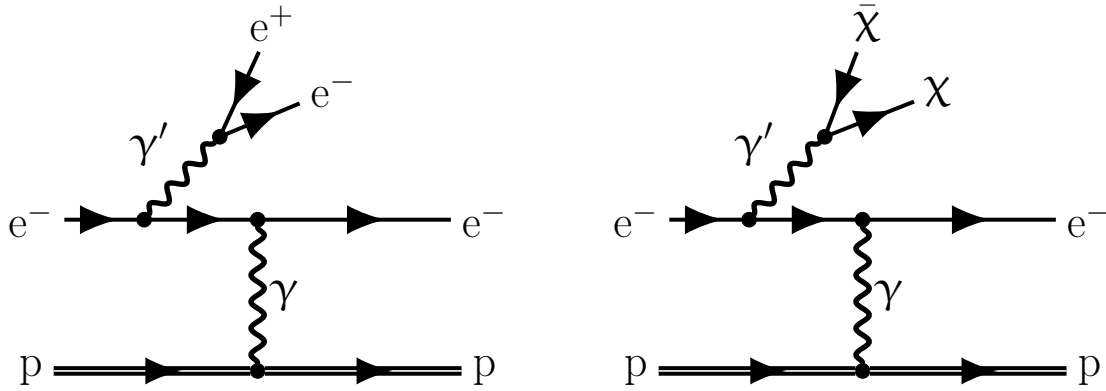


Figure 6.4: Production of a dark photon (γ') in a bremsstrahlung-like process. It can decay into an electron-positron pair (left, visible decay) or into two dark matter particles ($\chi, \bar{\chi}$) (right, invisible decay) (figure from [Bra19], edited).

6.3 The Experimental Setup of MAGIX

In the center of the MAGIX experiment, the electron beam from MESA will collide with target nuclei. Here, a cryogenic jet target will be used that will be described in more detail in section 6.4. Electrons that interact with this target in the center of a cylindrical scattering chamber can be detected in two identical spectrometers on both sides of the beam line as shown in figure 6.5 [Sch⁺24]. The spectrometers consist of a quadrupole at its entrance followed by two dipole magnets. This magnet configuration focuses the scattered electrons onto a focal plane according to their momentum so that the momentum can be measured by a very precise position measurement at the focal plane. The spectrometers will be rotatable around the scattering chamber covering a range of 15° to 165° [Lun22] and will be connected directly to the scattering chamber without vacuum windows. This enables together with the windowless jet target the broad range of the MAGIX physics program [Sch⁺24].

The focal plane has a size of $650 \times 140 \text{ mm}^2$ that will be covered by a GEM-based Time Projection Chamber (TPC) with up to four stacks of GEMs. With this, MAGIX aims for a momentum resolution of $\delta p/p = 10^{-4}$, which corresponds to a position resolution of $100 \mu\text{m}$ at the focal plane. Furthermore, the scattering angle at the vertex point will be determined with a resolution $\delta\theta < 1 \text{ mrad}$ [Cai⁺20].

Underneath the TPC, the MAGIX trigger and veto system will be located. It will consist of several layers. The first two layers are equipped with 22 plastic scintillators each, functioning as trigger layers. This is followed by multiple layers of lead absorbers. At the end, again two layers of plastic scintillators are used as veto layers with a lead absorber layer in between. Electrons are expected to give a signal in the first two layers before being absorbed in the lead absorbers. Cosmic muons, on the other hand,

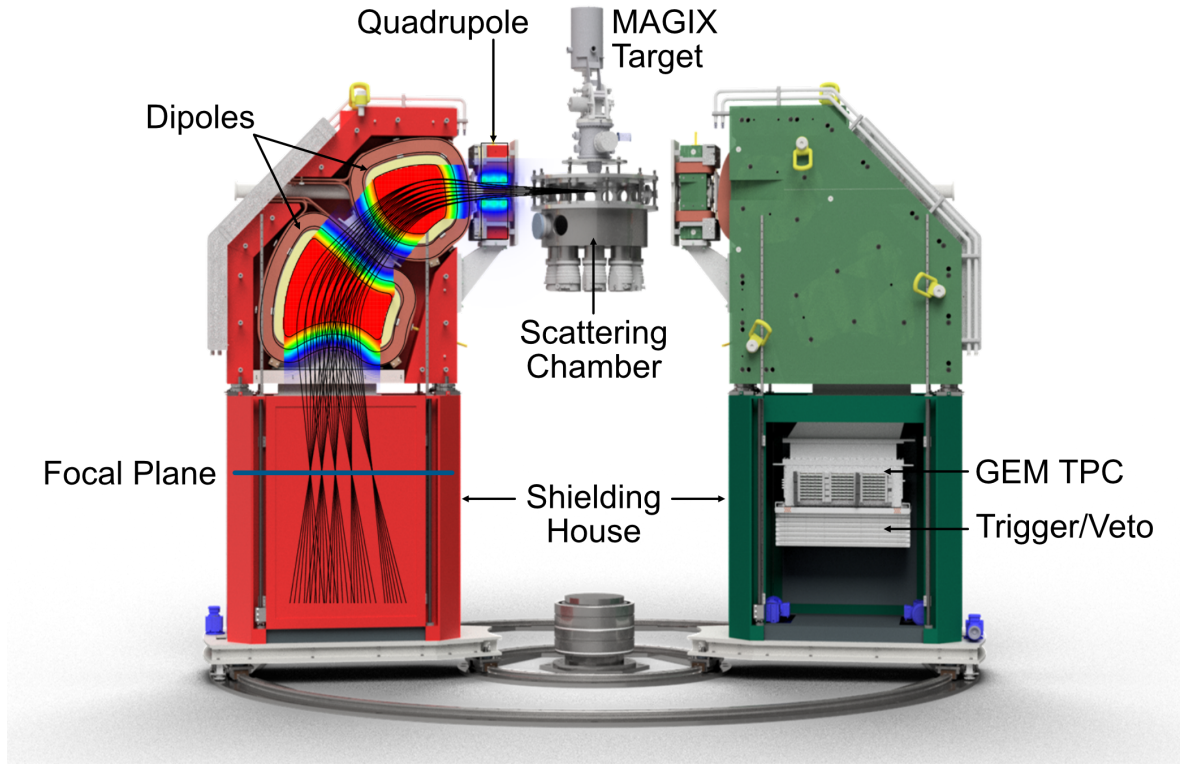


Figure 6.5: Drawing of the two-spectrometer setup of the MAGIX experiment. Both spectrometers use a quadrupole and two dipole magnets to focus the scattered electrons according to the momentum onto a focal plane. The magnetic field map of the dipoles and some trajectories are shown in the left spectrometer. At the focal plane, the position of the electrons is measured by a GEM-based Time Projection Chamber (TPC). Below the TPC a trigger and veto system is installed consisting of several layers of scintillators and lead absorbers. The MAGIX jet target is installed in the center of the setup on top of the scattering chamber. This chamber is equipped with several turbomolecular pumps. And directly below, roots pumps will be mounted for ideal pumping of the injected target gas (copyright by MAGIX, edited).

can penetrate through the absorbers and will also give a signal in the veto layers. On the other hand, signals from neutrons can lead to signals in any scintillator layer but without a correlation in time, as they can enter the detector from the side [Chr23].

Within the scattering chamber, the installation of an array of silicon strip detectors is foreseen at a distance of about 30 cm from the interaction point. This detector aims to measure low energy recoil particles, like the α -particle of the $^{16}\text{O}(e, e'\alpha)^{12}\text{C}$ reaction [Lun22]. Furthermore, for measurements as close to the Gamow peak as possible, this reaction also requires measuring under very forward angles that are not covered by the MAGIX spectrometers. Therefore, a zero degree tagger will be installed. It will use the

first MESA dipole magnet after the MAGIX setup to separate inelastically scattered electrons from the beam and guide them to a detector system [Lun22].

6.4 The MAGIX Jet Target

The MAGIX target is a cryogenic jet target that can be operated with various fluids as cluster-jet or gas-jet target depending on the used fluid and the operation conditions. To achieve the design luminosity of $10^{35} \text{ cm}^{-2} \text{ s}^{-1}$ for the operation with hydrogen at the maximum beam current of 10 mA, the target needs to achieve a target thickness of $1.6 \cdot 10^{18} \text{ atoms/cm}^2$, but it is designed to achieve even higher values up to $5 \cdot 10^{18} \text{ atoms/cm}^2$ [Gri⁺18].

The target setup shown in figure 6.6 is similar to the design of the $\bar{\text{P}}\text{ANDA}$ cluster-jet target but simplified and optimized for the MAGIX experiment. The desired operation conditions for the operation with hydrogen with a gas flow rate of up to $40 \text{ l}_n/\text{min}$ at a temperature of 40 K require a proper pre-cooling of the gas. This is enabled by a booster stage that can be filled with liquid nitrogen. This stage is surrounded by an insulation vacuum system. Inside the booster stage windings made of copper pipes are installed. The gas enters the booster and while passing the copper windings it gets cooled. Afterwards, it is guided into the main part of the source. There it is cooled down to the final temperature by passing copper windings around the warm and the cold stage of a two-stage cold head. The transfer part between the two stages are made out of stainless steel pipes to reduce the heat conduct between the stages. Furthermore, the cold head is also surrounded by a separate insulation vacuum system to minimize the heat conduct to the outside. To monitor and regulate the temperatures, temperature diodes and heating cartridges are installed at both stages. Finally, the gas leaves the target through a convergent-divergent de Laval nozzle [Gri⁺18, Gri18]. When operating the target close to the vapor pressure curve or in the liquid phase of the fluid, the target will create a cluster-jet according to the mechanisms described in section 3.2.2. This has the advantage of a more directed beam, smaller gas velocities, and thus a higher target thickness. If the target is operated more in the gaseous phase, e.g., when using helium or when a large hydrogen flow is applied without using the booster stage, the target will create a supersonic gas-jet which will have a larger divergence when entering the vacuum system. To achieve the high target thickness needed by the MAGIX experiment, the interaction point will be located directly below the nozzle in a distance of about 5 mm. About 10 mm below the nozzle a conical catcher will be installed that is connected to a powerful pumping station. With this setup, a

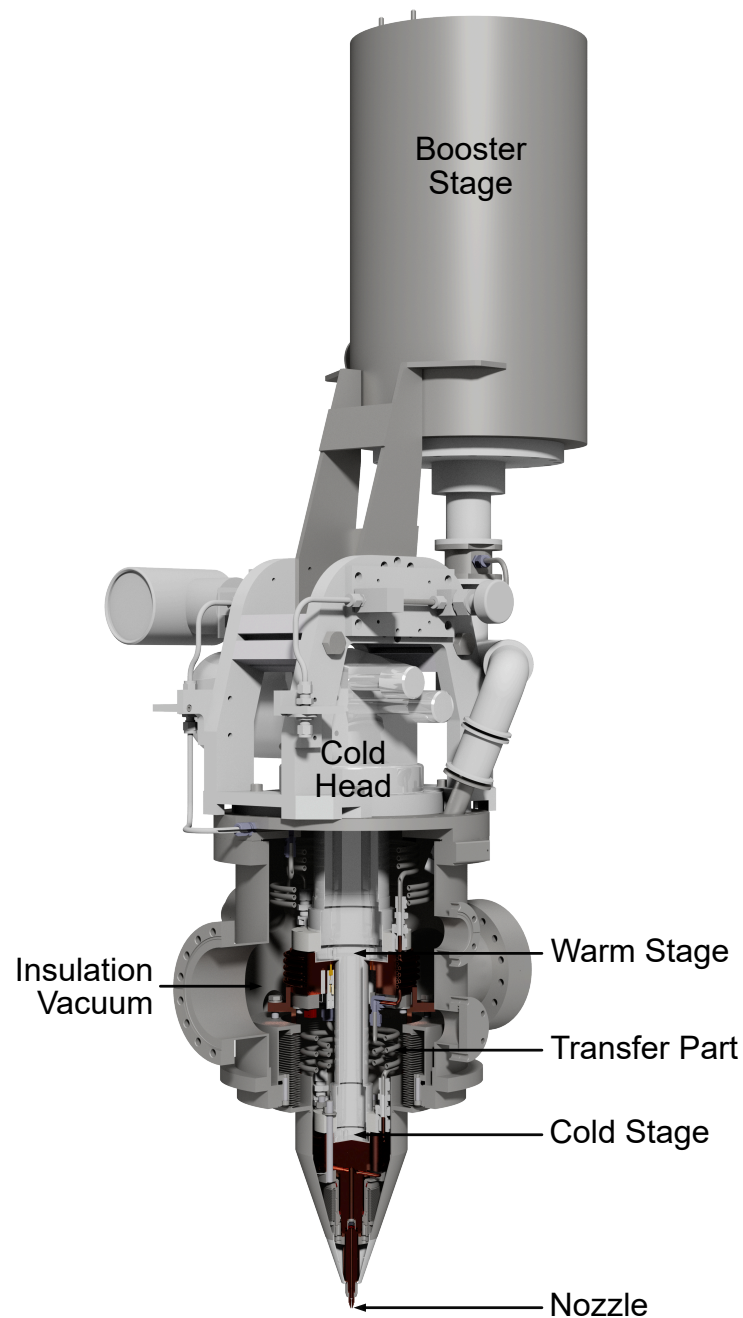


Figure 6.6: CAD drawing of the MAGIX jet target. The gas first enters the booster stage, which can be filled with liquid nitrogen for pre-cooling. Afterwards, it enters the main source, where it is cooled down within the copper windings around the warm and the cold stage of a two-stage cold head. Between these two parts, the transfer part is made out of stainless steel to minimize the heat contact between the two stages. Furthermore, the booster stage and the cold head are surrounded by two separate insulation vacuum systems. The gas finally leaves the target through a convergent-divergent de Laval nozzle (created by D. Bonaventura, University of Münster, edited).

large amount of the gas is directly pumped away and only a small amount stays in the scattering chamber [Sch⁺21].

The shape of the de Laval nozzle used at the MAGIX target differs significantly from the one used at the $\bar{\text{P}}\text{ANDA}$ cluster-jet target. Different geometries used at MAGIX are shown in figure 6.7. While the inlet of the nozzles are similar to the CERN nozzle used at $\bar{\text{P}}\text{ANDA}$, the outlet is significantly shorter with a length of roughly 10 mm. Also the outlet geometry differs. Originally, a linear divergence was used with a narrowest inner diameter of $d_{\min} = 500 \mu\text{m}$ and an outlet diameter of $d_o = 1 \text{ mm}$ [Gri⁺18]. This geometry showed a large divergence of the jet entering the vacuum of the scattering chamber. Within [Bra19] it was shown using Computational Fluid Dynamics (CFD) simulations that this can be significantly reduced by reducing the narrowest inner diameter, increasing the outlet diameter, and by using a slightly different geometry. Therefore, a cup-shaped nozzle was proposed that diverges the strongest at the narrowest point. The divergence then decreases until, after 7 mm, the

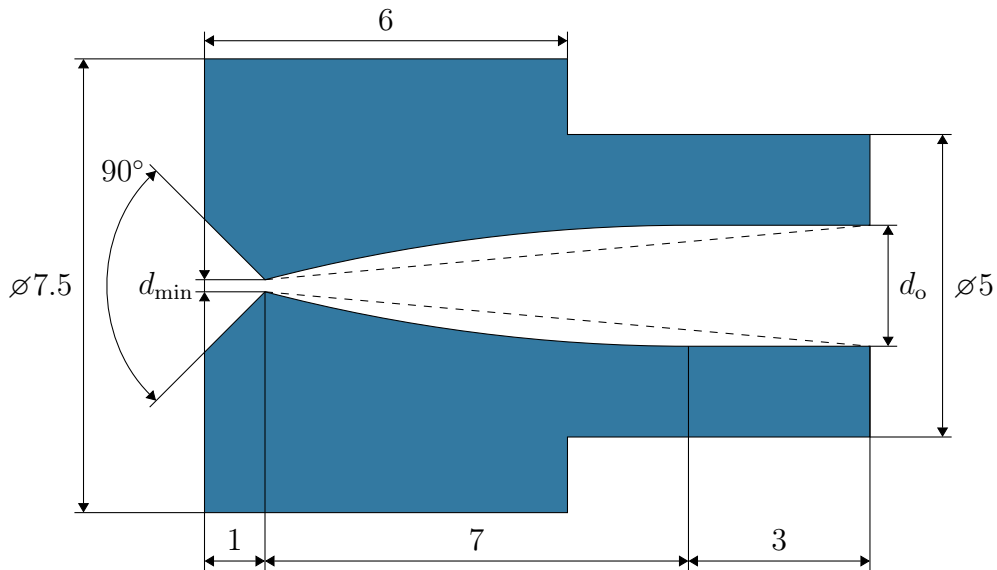


Figure 6.7: General design of the nozzles for the MAGIX jet target. All nozzles have a linear convergent inlet with a length of 1 mm and an outlet with a length of 10 mm. The outlet geometry differs. Originally, a linear divergence (dashed lines) was used with a narrowest inner diameter of $d_{\min} = 500 \mu\text{m}$ and an outlet diameter of $d_o = 1 \text{ mm}$. Within [Bra19] a new geometry with a cup-shaped outlet was proposed based on Computational Fluid Dynamics (CFD) simulations. These simulations suggest that this nozzle type with a narrowest inner diameter of $d_{\min} = 200 \mu\text{m}$ and an outlet diameter of $d_o = 2 \text{ mm}$ will reduce the divergence of the jet by a factor of 2. For the argon experiments presented in section 7.3, the same nozzle with a narrowest inner diameter of $d_{\min} = 120 \mu\text{m}$ was used.

diameter remains constant. The last 3 mm have a constant diameter. This new design with a narrowest inner diameter of $d_{\min} = 200 \mu\text{m}$ and an outlet of $d_o = 2 \text{ mm}$ showed the best performance. Simulations showed that this nozzle can reduce the divergence by a factor of 2, which corresponds in an increase of the target thickness by the same factor [Bra19]. Therefore, within this thesis this new nozzle is tested at the MAGIX target during a beam time at the A1 experiment at MAMI. The results will be discussed in section 7.2. Furthermore, for the first operation of the MAGIX target with argon a new nozzle was designed. It also has the cup-shape geometry, but with a narrowest inner diameter of $120 \mu\text{m}$ and again an outlet diameter of 2 mm. More details on the design of this nozzle and the first operation of the MAGIX target with argon will be given in section 7.3.

This target has already proven its performance during first beam times at the A1 experiment at MAMI and showed its potential for the use at the MAGIX experiment. Nevertheless, for some cases also other target concepts that reach similar or even higher target thickness with a smaller gas flow rate can be an alternative. This would lead to a significant improvement of the residual gas situation in the scattering chamber. These concepts are presented in section 7.4.

Chapter 7

Operation of the MAGIX Jet Target at MAMI

While the MESA facility and the MAGIX experiment are currently in the final installation phase, the MAGIX jet target could already be operated at the A1 three-spectrometer experiment at the MAInz MIcrotron (MAMI). This chapter will provide an overview of the setup at MAMI and some results are shown. This includes measurements using the new nozzle geometry proposed within [Bra19], the preparation for the first operation of the MAGIX target with argon, and calculations for a potential use of a droplet or filament target at the MAGIX experiment.

7.1 The MAGIX Setup at MAMI

In August 2017, the MAGIX jet target was successfully installed at the A1 hall of MAMI to perform first measurements with the MAGIX target [Gri⁺18] operating with hydrogen on, e.g., the performance of the jet target [Bra19, Sch⁺21] and the proton radius [Wan⁺22].

7.1.1 The Mainz Microtron (MAMI)

The MAMI facility [Her⁺76] is an electron accelerator with different accelerator stages shown in figure 7.1. The electrons are produced in either an unpolarized or a polarized source. For unpolarized electron beams, a thermionic source is used that can deliver beam currents up to 100 μA [Ber10]. The polarized source uses the photoelectron emission from a GaAsP cathode by using circular polarized laser light [Aul⁺97]. With this source similar currents are possible, but to ensure a reasonable lifetime, the current is typically limited to 20 μA [Sch12]. These electrons are then accelerated in a linear accelerator consisting of three cavities [Eut⁺88] to an energy of 3.97 MeV [Jan06].

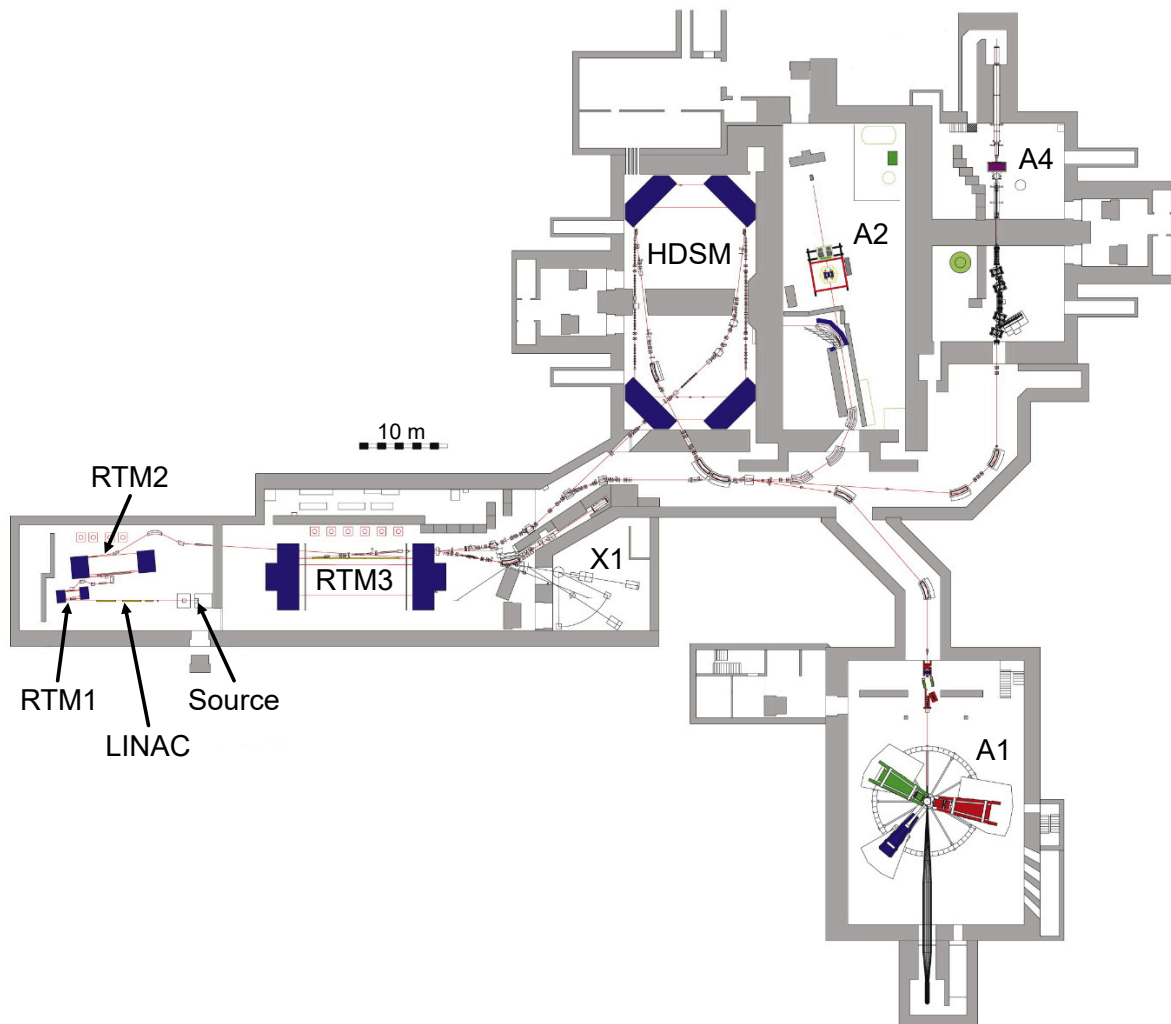


Figure 7.1: Floor plan of the MAINZ MICROTRON (MAMI) with its three RaceTrack Microtrons (RTMs). After leaving RTM3, the electrons can be guided to the different experiments (X1, A1, A2) or into the Harmonic Double-Sided Microtron (HDSM). In the bottom right, the A1 hall is located with the three-spectrometer setup, where the experiments shown in this chapter were carried out. The A4 experiment on the top right is discontinued, and its hall is used for the new MESA facility (figure from [Kai⁺08], edited).

The linear accelerator is used as injector for the first of three RaceTrack Microtrons (RTMs). In an RTM, two 180° bending magnets are used to hold the electron on a racetrack with larger radius for higher energies. On one straight section, a normal conducting linear accelerator operating at a frequency of 2.4495 GHz is located that is passed by all electrons, while on the second straight section, electrons with different energies have different orbits. Within the first microtron, the RTM1, electrons will reach an energy of 14.86 MeV after 18 circulations. The electrons are then extracted and guided into the RTM2 as next acceleration stage. Here, the electrons will reach

an energy of 180 MeV after 51 circulations. These two stages together with the linear accelerator are also called MAMI-A. MAMI-A works as an injector for MAMI-B, which consists of the third RTM (RTM3). Within this microtron, the electrons gain an energy of 7.5 MeV per circulation. They can be extracted after every second circulation with a maximum of 90 turns so that the electrons can leave the RTM3 with energies in the range of 195 MeV to 855 MeV and an energy spread of only 13 keV. This beam can then be directed to the experiments of X1, A1, and A2 [Jan06]. The former A4 experiment [Bau12] is discontinued, and its hall is now used for the MESA facility and the MAGIX and P2 experiments.

To achieve even higher energies, a third stage called MAMI-C was realized. But while the magnets of the first three RTMs had to be enlarged for every stage starting with 4 t of iron for RTM1, 90 t for RTM2, and 900 t for RTM3 [Jan06], the dipole magnets of a fourth RTM would even weigh 2200 t each. Therefore, instead of an RTM a Harmonic Double-Sided Microtron (HDSM) was installed. The HDSM uses four 90° bending magnets with a weight of 1000 t each that allow to place a linear accelerator on two of the four straight sections. One of the linear accelerators is operated at 4.8990 GHz, the double frequency of the RTMs. This allows for a smaller power consumption for the same energy. For more stable beam dynamics, the second linear accelerator is operated at the MAMI frequency of 2.4495 GHz [Kai⁺08]. After a maximum of 43 turns, the electrons can be extracted with energies up to 1.6 GeV in steps of roughly 15 MeV and with an energy spread of only 110 keV [Hei⁺10, Jan06].

7.1.2 The A1 Experiment

The main detectors of the A1 experiment are the three high-precision spectrometers called A (red), B (blue), and C (green) as shown on the photograph in figure 7.2 that can be moved around the interaction point to access different scattering angles. All three spectrometers have a similar setup, which is shown for spectrometer A on the right of figure 7.2 with a magnet configuration that focuses the scattered electrons onto an approximately 2 m long focal plane depending on their momentum. By this, the momentum and scattering angle θ can be determined by a very precise position measurement at the focal plane. For this purpose, each spectrometer is equipped with two Vertical Drift Chambers (VDCs). The first one is positioned exactly at the focal plane, the second one in a distance of 20 cm to the first one. Each VDC has two planes of wires, called x- and s-plane. The x-plane consists of wires perpendicular to the long side of the focal plane. Due to the focal plane length of about 2 m, instead of very long

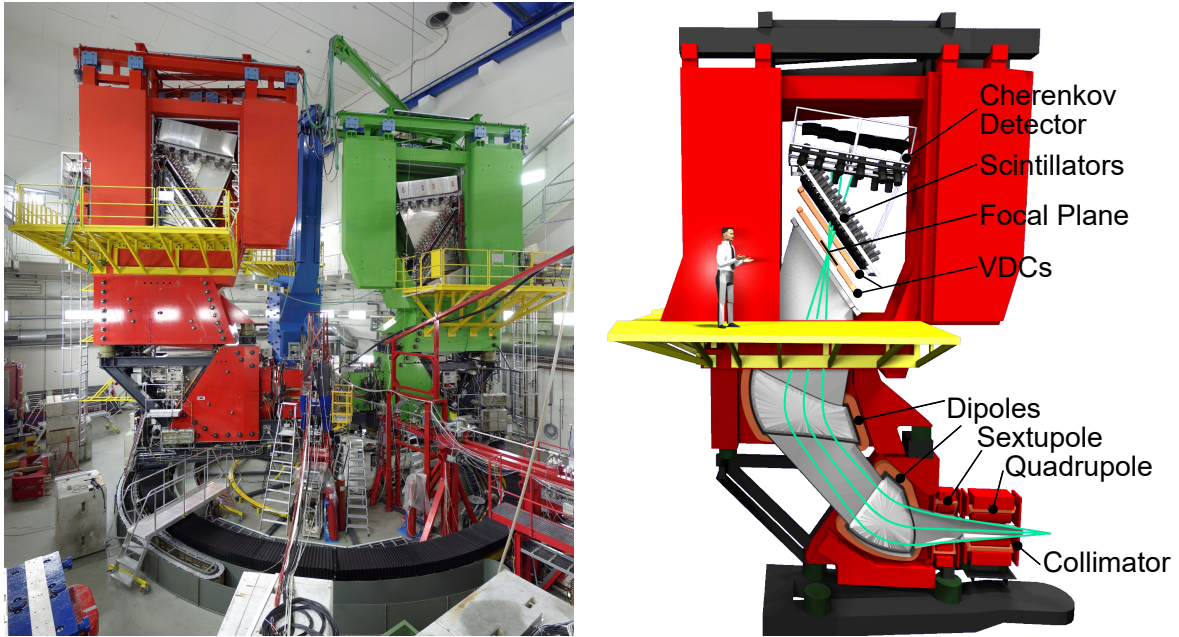


Figure 7.2: Left: Photograph of the A1 experimental hall at MAMI with the three spectrometers A (red), B (blue), and C (green). The electron beam enters the hall from the lower right (image from [Ber10]). Right: Schematic view of spectrometer A with three different trajectories of particles with the same momentum, that are focused to the same point at the focal plane. The spectrometers are equipped with Vertical Drift Chambers (VDCs) for position measurement, scintillators as trigger detector, and Cherenkov detectors for particle identification (created by H. Merkel, JGU, edited).

wires perpendicular to the wires in the first plane, the s-plane consists of wires with an angle of 40° to the x-wires [Blo⁺98].

Following the VDCs, two layers of plastic scintillators are used as trigger detectors. These are divided into 15 parts in case of spectrometers A and C and 14 for spectrometer B. They are read out by photomultiplier tubes and besides giving the timing signal, they also give a ΔE information. Following these trigger detectors, a Cherenkov detector is installed for particle identification. These have a 6 m^3 radiator volume filled with $(\text{CF}_2\text{Cl})_2$ at atmospheric pressure. Within this radiator gas, electrons and positrons with an energy of more than 10 MeV emit Cherenkov light, while pions would already need an energy of more than 2.7 GeV that cannot be achieved with MAMI. Therefore, the Cherenkov detector can efficiently separate electrons and positrons from pions and other particles [Blo⁺98].

While the detector concepts for all three spectrometers are very similar, the magnet design differs. Spectrometer A consists of a quadrupole followed by a sextupole and two dipole magnets between the collimator at the entrance and the focal plane. In contrast,

spectrometer C has the same components with a slightly reduced size, resulting in a smaller bending radius and thus a smaller maximum accessible momentum. Spectrometer B, on the other hand, has a more compact design that allows it to be positioned closer to the beam line, enabling measurements at smaller scattering angles. It consists only of one dipole in a clamshell design. This dipole has a wedge-shaped gap between the poles with an angle of 3.495° [Blo⁺98]. The magnetic field of the dipoles can be measured using Hall probes or more precise NMR probes [Ber10]. This spectrometer setup allows for a momentum resolution of $\Delta p/p < 10^{-4}$ and an angular resolution better than 3 mrad [Blo⁺98]. More details on the detector setup are shown in table 7.1.

Table 7.1: Design and performance parameters of the three A1 spectrometers [Blo⁺98].

		Spec. A	Spec. B	Spec. C
Configuration		QSDD	Clamshell D	QSDD
Max. Momentum	[MeV/c]	735	870	551
Max. central Momentum	[MeV/c]	665	810	490
Momentum Acceptance	[%]	20	15	25
Solid Angle	[msr]	28	5.6	28
Scattering Angle	[$^\circ$]	18 – 160	7 – 62	18 – 160
Momentum Resolution		$\leq 10^{-4}$	$\leq 10^{-4}$	$\leq 10^{-4}$
Angular Resolution	[mrad]	≤ 3	≤ 3	≤ 3

Additionally to the spectrometers, a neutron detector can be used, that consists of five layers of 10 cm thick plastic scintillators with 2 cm thick copper plates between the layers. Two layers of 1 cm thin scintillators are mounted in front of the detector for separation of protons and neutrons [Sch12]. Furthermore, the KAOS spectrometer can be installed in forward direction to detect kaons [Ach10].

7.1.3 The MAGIX Target at A1

While the MESA facility and the MAGIX experiment are currently in the final installation phase, the target is already available and was mounted at the A1 experiment [Gri18]. Therefore, a dedicated scattering chamber with a height of 610 mm and a diameter of 510 mm was installed in the center of the A1 experiment. This is equipped with Kapton windows with a height of 210 mm as entrance windows for the spectrometers. These windows allow for scattering angles in the range of 21.5° to 135° on the left side of the beam pipe, where spectrometer A was located and a range of 11° to 122.5° on the right, where spectrometers B and C were located during the beam

times with this setup. The target was installed on top of the chamber as shown on the left of figure 7.3 [Sch⁺21].

The target gas is provided from gas bottles located outside the A1 hall. The distribution towards the target is then done within a gas rack standing next to the target, where several pneumatic valves, pressure gauges, and a flow controller are located. Next to the gas rack (see left image in figure 7.3) a pumping station is located with a Leybold SCROLLVAC SC30D scroll pump as roughing pump. Furthermore, a screw pump of type Leybold DRYVAC DV650C is used as additional roughing pump especially for gases heavier than hydrogen and helium. These are followed by three roots pumps: Leybold RUVAC WH700, Leybold RUVAC WH2500, and Leybold RUVAC WH7000. This powerful pumping station is needed to efficiently pump away the up to 40 l_n/min that are foreseen as gas flow rate for the target operation. To increase the efficiency of the pumping system, in a distance of about 10 mm below the nozzle a conical catcher is installed (see right image in figure 7.3) and connected to the pumping

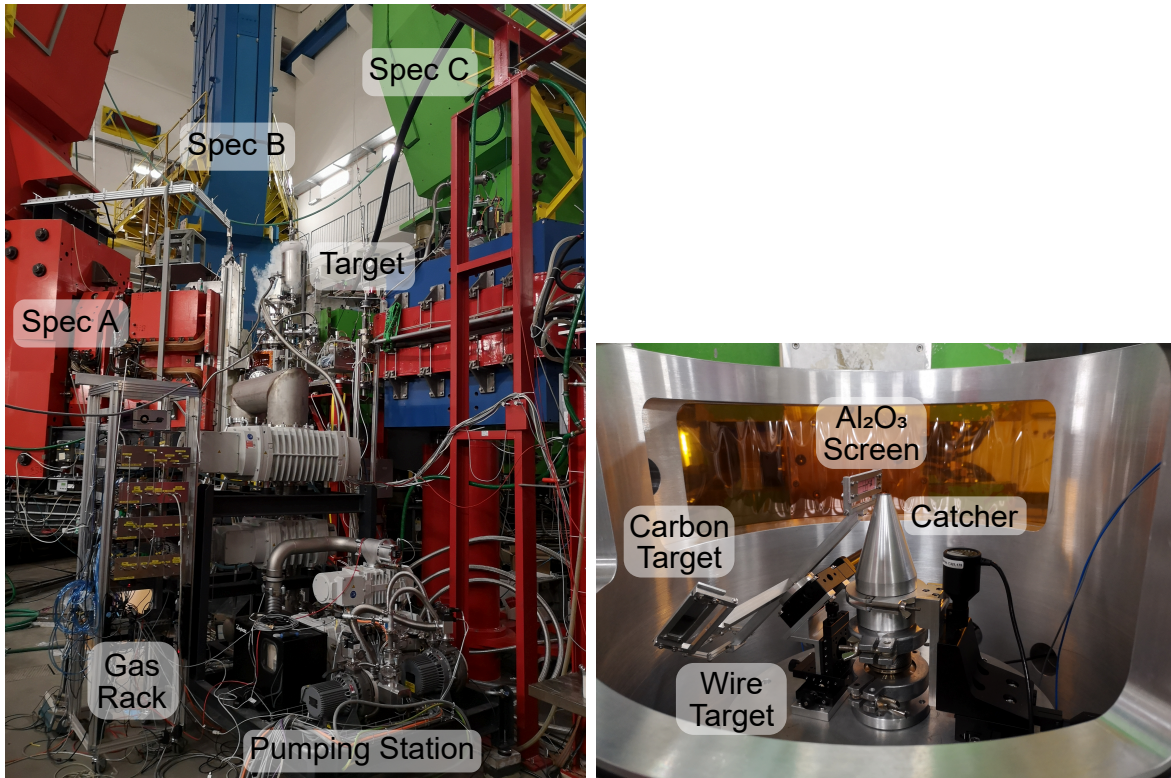


Figure 7.3: Left: Photograph of the scattering chamber with the MAGIX target installed in the center of the three A1 spectrometers. In front of the target, the pumping station and the gas rack are located. Right: Photograph of the inner of the scattering chamber with the movable catcher system and the rotatable holder for the luminescent Al₂O₃ screen, the carbon target, and the tungsten wire.

station, which shall reduce the backflow of gas into the scattering chamber. The remaining gas in the chamber was foreseen to be pumped by a turbomolecular pump of type Leybold TURBOVAC MAG W2800C with a Leybold SCROLLVAC SC15D as roughing pump [Sch⁺21]. It finally turned out, that this has a too small pumping speed. Instead, the vacuum below the catcher was connected to the fore vacuum of the pump at the scattering chamber. This resulted in a much better pumping performance of the turbomolecular pump.

Within the scattering chamber, several systems are installed as shown in the right image in figure 7.3. The already mentioned catcher is installed in the center of the chamber directly below the nozzle. It can be moved in all three dimensions by motor-driven micrometer screws. Furthermore, a rotatable holder is installed that can move three different solid state targets into the beam. There is a luminescent Al_2O_3 screen that can visualize the electron beam and can be used for exact positioning of the beam. A carbon target can be used for detector calibration and a tungsten wire can be used to scan through the electron beam to, e.g., determine the beam width [Sch⁺21].

7.2 The optimized Nozzle for the MAGIX Target

The MAGIX jet target was already operated several times in beam times since its installation at the A1 experiment in 2017. This includes several weeks of measurements in 2017 and 2018, where the jet divergence was studied. For this purpose, in front of the A1 experiment a wobbler is located, that can deflect the electron beam in horizontal and vertical direction in a sinusoidal way to scan the beam over the target. This is an important feature for solid state targets as it can distribute the resulting heat over a larger area and thus reduces the risk of a target damage. For the jet target, this wobbler can be used to scan the beam over the jet and by analyzing the rate as a function of the horizontal vertex position, the width of the jet can be determined. This was done at different distances from the nozzle within [Bra19] showing a large divergence of the jet. Following numerical simulations confirmed this, and based on these simulations, a new nozzle design with a cup-shaped geometry was proposed, as described in section 6.4. This new nozzle geometry was installed at the MAGIX target during this thesis and the measurements with the wobbler were repeated. In contrast to the data with the old nozzle, where a beam energy of about 450 MeV and central scattering angles of spectrometer B of 21° and 22° were used, the beam energy in the beam times with the new nozzle was set to 315 MeV with spectrometer B at an angle of roughly 15° . This results in a higher cross section and thus a higher rate that allows for much shorter measurement times to gather similar statistics. On the other hand

it also results in more background due to the location of spectrometer B closer to the beam pipe. The analysis of these measurements are presented in the following briefly as they are identical to the analysis presented in [Bra19] for the data with the old nozzle design. The results are already published as part of [Sch⁺21].

7.2.1 Detector and Wobbler Calibration

Before analyzing the data, the detector and the wobbler need to be calibrated. For these measurements only spectrometer B was used and so also only this spectrometer will be calibrated. The momentum of the reference trajectory of the spectrometer can be set to different values, according to the expected momentum of the scattered electron, which in the case of elastic electron-proton scattering follows equation 1.14. This is done by changing the magnetic field of the spectrometer dipoles. The field is then measured by either a Hall probe or an NMR probe. Unfortunately, the more precise NMR probe was not available during the beam times, and therefore the Hall probe was used and afterwards, the detector was calibrated. This procedure was already described in [Bra19] and is thus only briefly summarized here.

The exact reference momentum can be determined by varying it slightly in the analysis of the data and comparing it to simulations until data and simulation perfectly fit. In the calibration procedure, this is done by a fit process, which varies the reference momentum, reanalyzes the data, performs a new simulation, and then compares both in different histograms and minimizes the χ^2 value

$$\chi^2 = \sum_i \frac{(N_i^{\text{data}} - a \cdot N_i^{\text{sim}} - f_b(x_i))^2}{(\sigma_i^{\text{data}})^2 + (a \cdot \sigma_i^{\text{sim}})^2 + (\sigma_a \cdot N_i^{\text{sim}})^2 + \sigma_f^2} \quad (7.1)$$

with the scaling factor a determined by a separate fit that scales the simulation N^{sim} to the data N^{data} , the linear background function $f_b(x)$, the uncertainty of the data σ^{data} , the uncertainty of the simulation σ^{sim} , the uncertainty of the scaling factor σ_a , and the uncertainty of the background function σ_f [Bra19]. For this comparison, several histograms are used and the χ^2 value of all of them are added and minimized. The used histograms are mainly the histogram of the momentum distribution and the histogram of the missing mass

$$m_{\text{miss}} = |k + p - k'|, \quad (7.2)$$

which is calculated from the four-momenta of the beam electron k , the scattered electron k' , and the target proton p . The calibration is additionally also used to calibrate for the momentum and angular resolution for the simulation and for the

vertex position and width, so that also the histograms of the scattering angle θ , the azimuthal angle ϕ , and the vertex position z in beam direction are used. Figure 7.4 shows the missing mass distribution before and after the calibration. While the missing mass peaks in data and simulation were slightly shifted before the calibration, it now perfectly fits. Only the radiative tail and the background is not correctly described as here only a linear fit was used while the background partly consists of electrons that have scattered at, e.g., the nozzle. This is not a problem for the following analysis as there it is only important, that the missing mass peak is correctly located at the correct position as no detailed cross section analysis is performed. More details about the exact calibration procedure can be found in [Bra19].

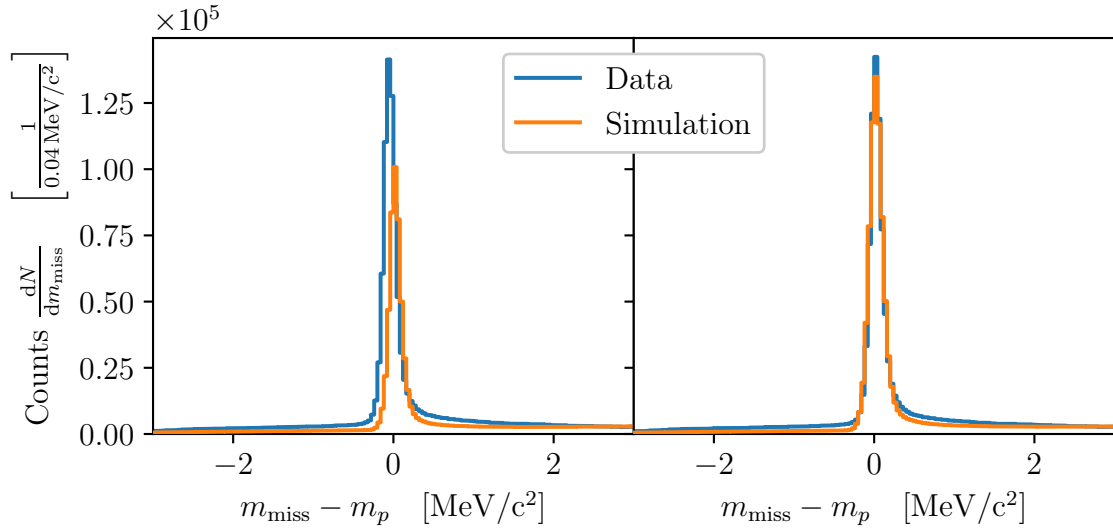


Figure 7.4: Left: Missing mass distribution of data and simulations for the elastic electron-proton scattering before the calibration. The simulations are scaled to the data via a fit. Right: Missing mass distribution after the calibration.

In a similar procedure also the wobbler needs to be calibrated, which is also described in detail in [Bra19]. The wobbler consists of two dipoles and the current through them is proportional to the deflection. Therefore, the horizontal vertex position can be calculated from the raw value of the current measurement by a slope and an offset parameter. These two need to be calibrated. For this purpose, the wire target on the rotatable holder in the scattering chamber is used which is a tungsten wire with a diameter of 100 μm . The position is slowly changed from -5 mm to 5 mm in 0.5 mm steps every 120 s. Simultaneously, the wobbler scans the beam over the wire, which results in a signal in the detector when the beam hits the wire as shown in the histogram in figure 7.5. When the wire is moved, the scaler of the detectors are set to a maximum

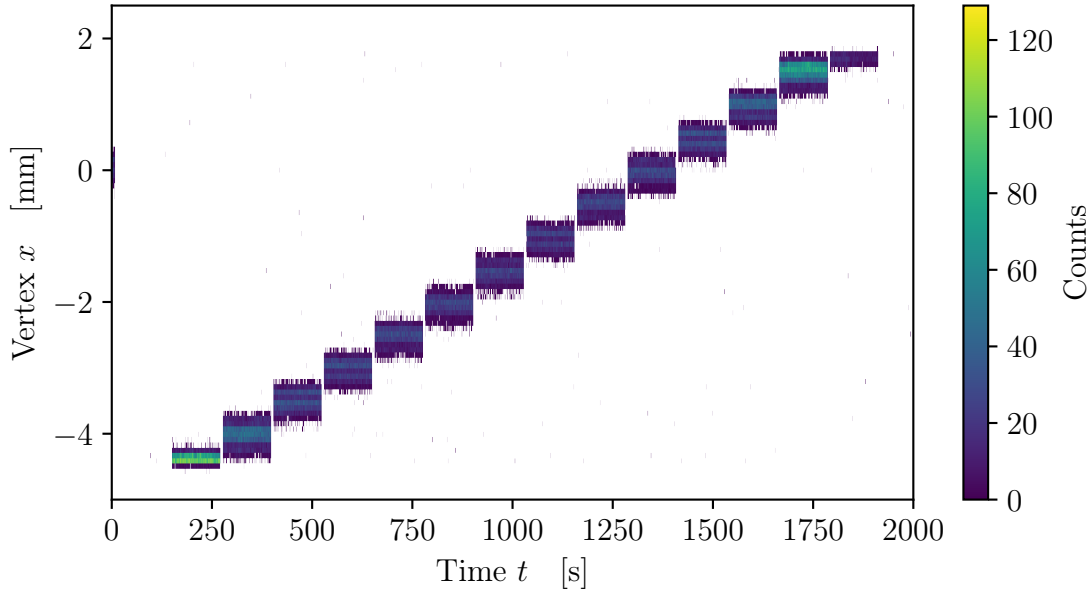


Figure 7.5: Histogram showing the horizontal vertex position as a function of the time of data taking for the wobbler calibration measurement. Simultaneously, the wire target was moved in 0.5 mm steps from -5 mm to 5 mm. Between the steps, the scaler of spectrometer B was set to its maximum for a short time, leading to nearly no data between the steps.

for a short time. This scaler is the number of events that are rejected before accepting the next event. It can be used to reduce the count rate and, consequently, the dead time of the data acquisition. Setting it to the maximum results in nearly no data during this time interval. Therefore, the time steps can be easily identified in the data. The data of every time step is now filled into a vertex histogram and fitted with a Gaussian function to extract the vertex position of the wire. These reconstructed vertex positions x for every wire step are then plotted against the actual wire position x_w , which should result in $x = x_w$, if the wobbler is calibrated correctly. Therefore, the offset and slope parameter are varied in a fit that minimizes

$$\chi^2 = \sum_i \frac{(x_i - x_{w,i})^2}{\sigma_i^2} \quad (7.3)$$

with σ_i as the uncertainty of the reconstructed vertex position x_i and the corresponding wire position $x_{w,i}$ at the same time. Figure 7.6 shows the reconstructed vertex position as a function of the wire position before and after the calibration. While the vertex position was not correctly reconstructed before the calibration, it now perfectly fits the wire position.

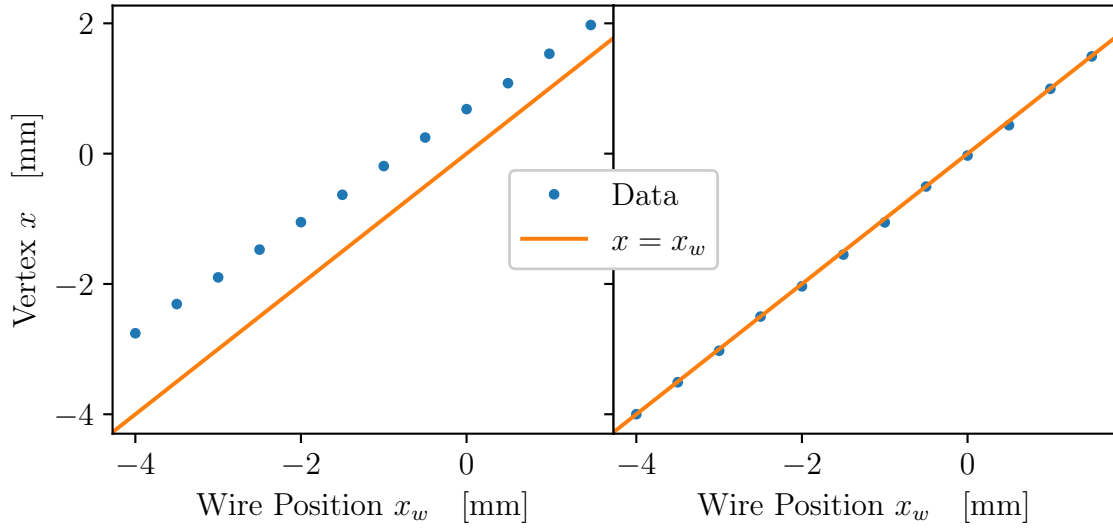


Figure 7.6: Left: Horizontal vertex position as a function of the wire position before the wobbler calibration. Right: Horizontal vertex position as a function of the wire position after the wobbler calibration. The statistical uncertainties of the vertex position are too small to display.

7.2.2 Wobbler Data Analysis

After the calibration of the wobbler, the data can be analyzed. This procedure is also the same as used in [Bra19] and thus perfectly comparable to the results obtained there. For this purpose, the data needs to be divided into small intervals in the horizontal vertex position. Additionally, the data is also binned in the scattering angle θ to fit it to the differential elastic electron-proton cross section and extract the target thickness, and in the missing mass for a background reduction. In the first step, the missing mass histogram for every vertex and scattering angle bin is analyzed as shown in figure 7.7. A linear fit is performed to the data to describe the background. Therefore, like in [Bra19], the same part around the peak of the elastic scattering is excluded. This central region between the vertical, red lines in figure 7.7 is chosen asymmetrically to reflect the radiative tail of the peak towards higher missing mass values. The data within the central region is then summed, and the background is subtracted. To correct for effects of this method, the same is also performed for the simulations.

After performing this background subtraction for every scattering angle interval, the data is divided by the same result from the simulation. This reflects the geometrical acceptance and furthermore in the simulation an integration over the solid angle is performed, so that the ratio of data and simulation is the differential count rate $dN/d\Omega$. This can then be scaled to the differential cross section with the parametrization from

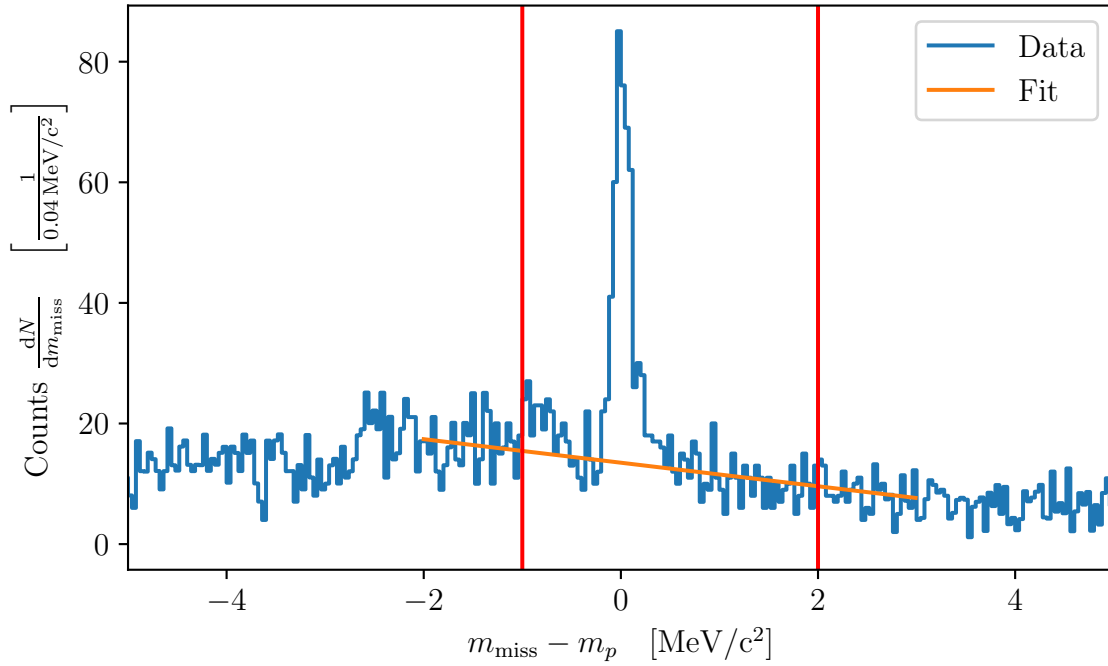


Figure 7.7: Missing mass distribution for the vertex interval $-0.6 \text{ mm} < x < -0.3 \text{ mm}$ and the scattering angle interval $15.5^\circ < \theta < 15.7^\circ$. The background is fitted with a linear function in the interval $-2 \text{ MeV}/c^2 < m_{\text{miss}} - m_p < 3 \text{ MeV}/c^2$ where the data in the central region between the red lines is excluded as here the signal is expected. The asymmetry of the excluded region is chosen to reflect the radiative tail of the peak towards higher missing mass values.

[Ber10]. Figure 7.8 shows the differential cross section as a function of the scattering angle with the data scaled to it via a fit. The scaling parameter can be interpreted as the integrated luminosity L_{int} for every vertex interval.

This resulting integrated luminosity is shown in the upper plot of figure 7.9. It shows a clear peak in the center which can be identified as the gas-jet, but it also increases at its edges. The reason for that is the sinusoidal deflection of the wobbler. This results in a longer period of time, where the electron beam is deflected to the edges. To correct for this, the wobbler profile was recorded by operating the wobbler without the electron beam, using an equally distributed signal in time from a pulse generator. This wobbler profile is also shown in the upper plot in figure 7.9. It is normalized so that the sum of all vertex bins equals 1. The luminosity is divided by this profile to correct for the wobbler profile. The corrected luminosity can then be interpreted as the value if the electron beam would be deflected into the corresponding vertex interval all the time. It is fitted by a Gaussian profile as shown in the lower plot in figure 7.9 leading to a

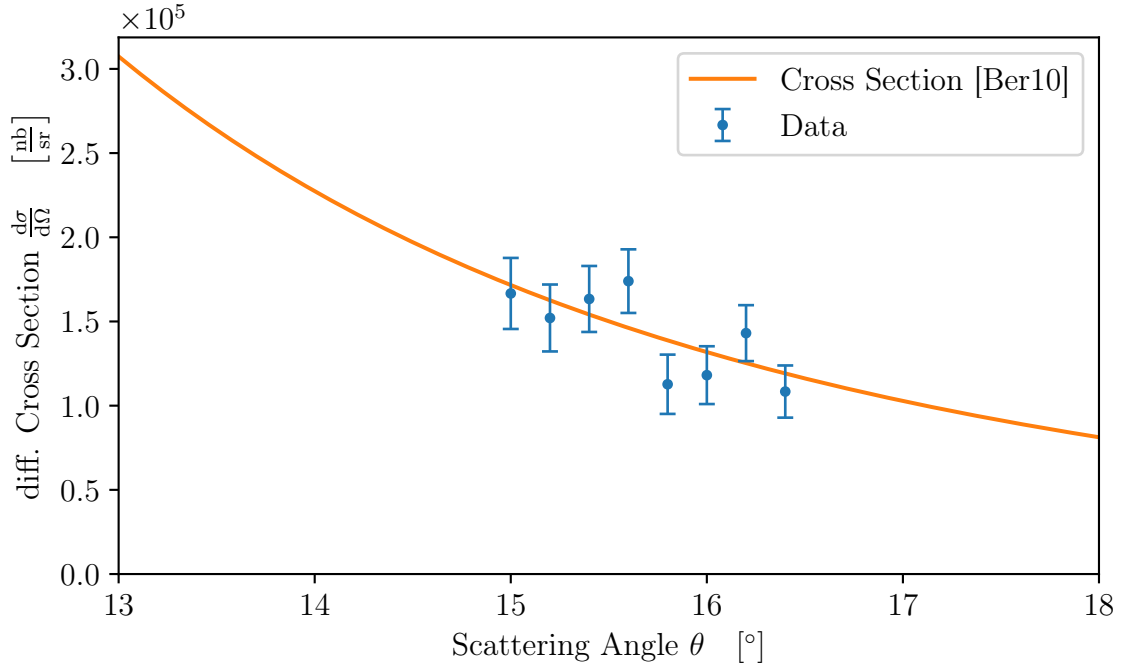


Figure 7.8: Differential cross section for the vertex interval $-0.6 \text{ mm} < x < -0.3 \text{ mm}$ as a function of the scattering angle. The data is scaled to the cross section [Ber10] via a fit.

width of $\sigma_L = (0.535 \pm 0.019) \text{ mm}$ for this profile, which was recorded at a distance of roughly 3 mm from the nozzle. The profile is a convolution of the jet profile and the electron beam profile so that the electron beam profile also needs to be known to extract the width of the gas-jet.

The electron beam profile can be determined by a similar procedure as the wobbler calibration. The wire target is used without the wobbler and slowly moved through the electron beam in 50 μm steps. The resulting rate as function of the position of the wire is shown in figure 7.10. It can be described as convolution of the target thickness profile of the wire and the electron beam profile. The wire has a homogeneous density and a circular cross-section. The electron beam profile is assumed to be Gaussian and the convolution of both can then be described as

$$f(x) = n_{T,w}(x) * \phi(x) = a \int_{-d/2}^{d/2} \sqrt{(d/2)^2 - x'^2} \exp\left(-\frac{(x - x')^2}{2\sigma_{x,e}^2}\right) dx' \quad (7.4)$$

with the width $\sigma_{x,e}$ of the electron beam and the scaling factor a [Bra19]. This function is fitted to the measured profile as shown in figure 7.10. The extracted electron

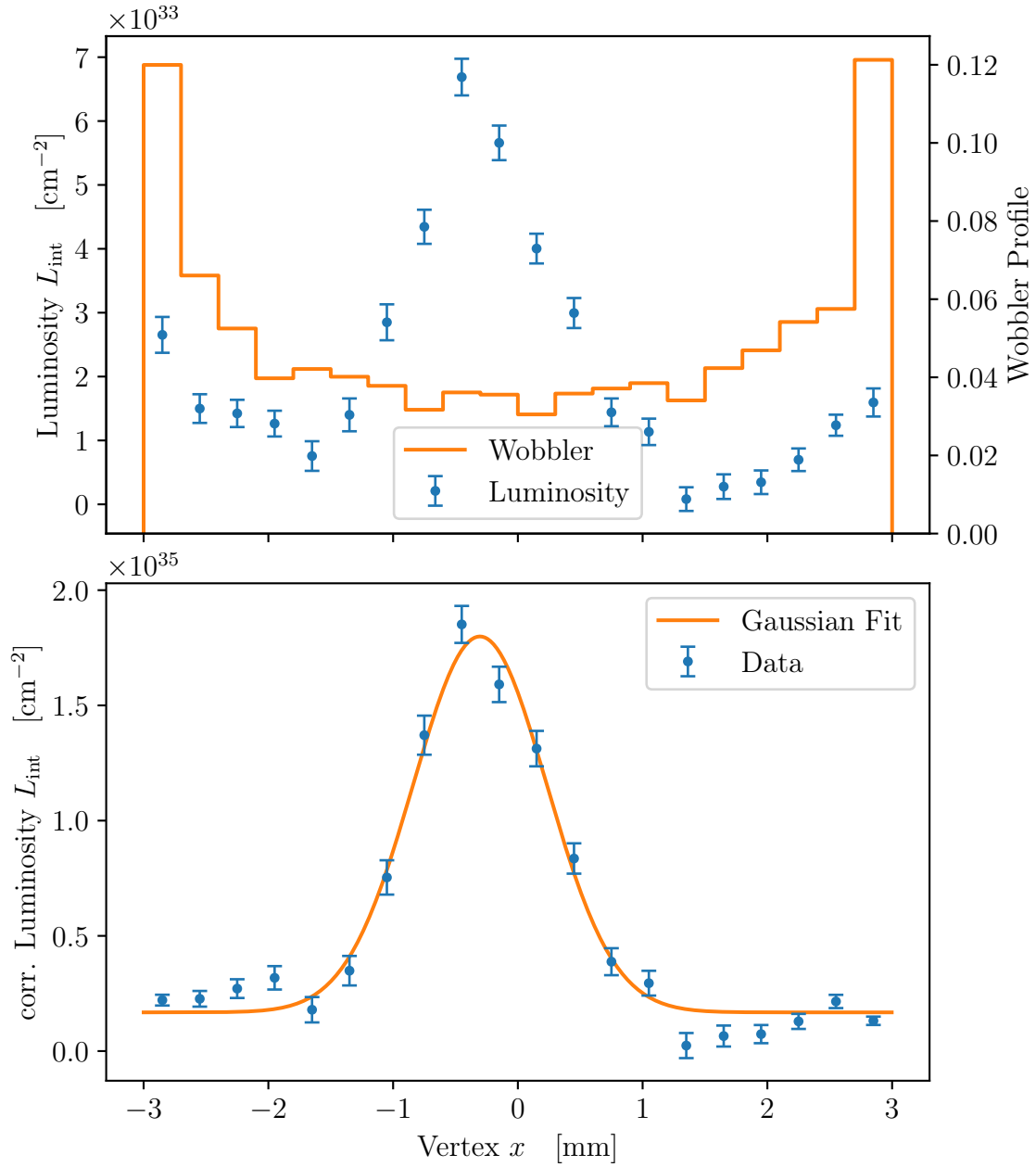


Figure 7.9: Top: Luminosity of each vertex interval and wobbler profile as a function of the vertex position. The wobbler profile was recorded by operating the wobbler without the electron beam, using an equally distributed signal in time from a pulse generator. The distribution is normalized so that the sum of all vertex bins equals 1. It gives the fraction of time the electron beam was deflected into every vertex interval. Bottom: Luminosity corrected for the wobbler profile and fitted with a Gaussian function resulting in a width of $\sigma_L = (0.535 \pm 0.019)$ mm. This profile is a convolution of the jet profile and the electron beam profile. It was recorded at a distance of roughly 3 mm from the nozzle.

beam width measured during this thesis was $\sigma_{x,e} = (98.66 \pm 0.14) \mu\text{m}$, while it was $\sigma_{x,e} = (62.9 \pm 0.2) \mu\text{m}$ in the beam time with the old nozzle analyzed in [Bra19]. Both values are significantly lower than the width of the luminosity profile shown in figure 7.9 so that the electron beam width has only a small influence.

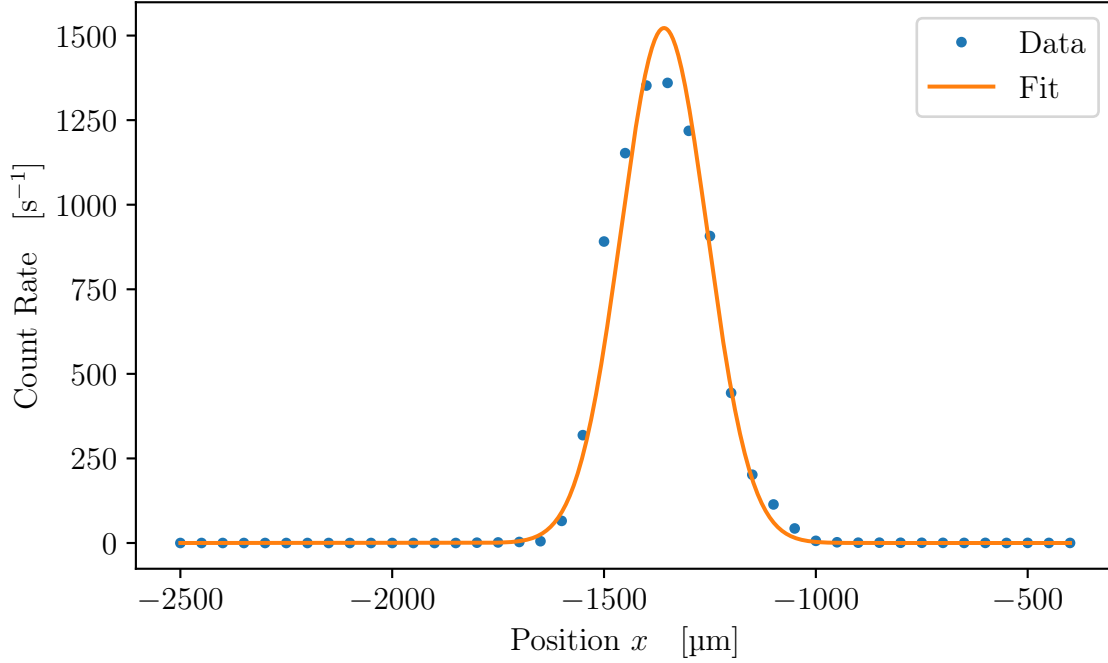


Figure 7.10: Measurement of the electron beam profile by scanning a tungsten wire in $50 \mu\text{m}$ steps through the electron beam. The rate as a function of the wire position is shown, which is fitted by a convolution of the target thickness distribution of the wire and the electron beam profile. The extracted width of the electron beam was $\sigma_{x,e} = (98.66 \pm 0.14) \mu\text{m}$. The statistical uncertainties of the data points are too small to display.

Within [Bra19] it was shown, that the luminosity profile in the lower plot of figure 7.9 can be described by a convolution of the electron beam profile and the jet profile. When assuming both as Gaussian this results in a Gaussian distribution with the width

$$\sigma_L^2 = \sigma_{x,e}^2 + \sigma_{x,j}^2 \quad (7.5)$$

so that the width $\sigma_{x,j}$ of the jet profile can be calculated from σ_L and $\sigma_{x,e}$. The results are discussed in the following.

7.2.3 Jet Divergence Studies

The measurements with the wobbler were performed at different distances from the nozzle to study the jet divergence. This can be compared to the jet divergence with the old nozzle design and the simulations of both nozzles from [Bra19]. All the data was recorded with the target operating at a gas flow rate of 20 l_n/min and a temperature of 50 K. The results of this comparison are shown in figure 7.11. The width of the jet increases with increasing distance and is fitted by a linear function to extract the divergence. The data with the old nozzle shows a larger divergence with a slope of 0.31 ± 0.04 which corresponds to a half opening angle of $(17.2 \pm 2.1)^\circ$. With the new nozzle, the divergence is reduced to a slope of 0.16 ± 0.02 or a half opening angle of $(9.1 \pm 1.2)^\circ$. Thus, the jet divergence was reduced by approximately a factor of two which leads to a higher target thickness and better vacuum conditions in the scattering chamber due to the higher efficiency of the catcher system. The reduction of the jet divergence also reflects the expected benefit of the new nozzle design from numerical CFD simulations [Bra19], although there are also some discrepancies in the

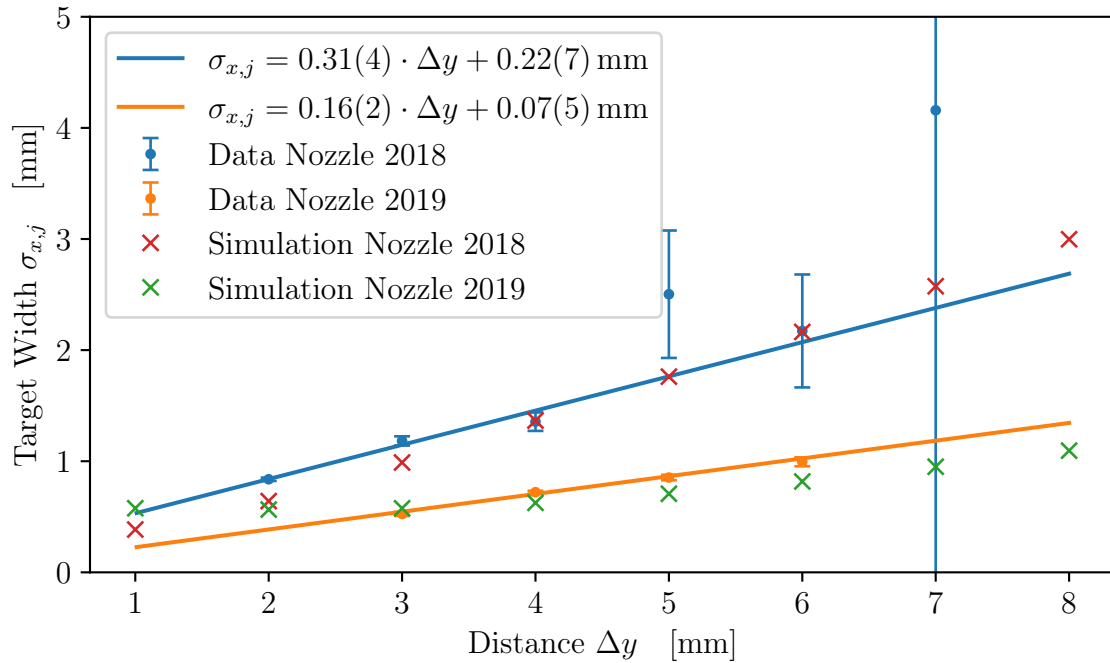


Figure 7.11: Width of the gas-jet for the old nozzle design (2018) and the new nozzle design (2019) at different distances from the nozzle compared to simulations for both nozzle geometries. The data for both nozzle designs is fitted by a linear function to extract the divergence. The data from 2018 and both simulations are from [Bra19].

exact evolution of the jet. One reason for this is, that the simulation only considers the expansion of a real gas. It cannot describe the formation of clusters, which is possible at the operation temperature of $T_0 = 50$ K in these measurements. Nevertheless, these measurements prove the importance of further studies on the nozzle geometry based on simulations and the importance of the nozzle design for the operation of the MAGIX target.

In addition to these measurements at different distances from the nozzle, the jet profile was also studied for different flow rates through the nozzle. The results are shown in the upper plot of figure 7.12. Unfortunately, the width of the profiles with a small gas flow rate has large uncertainties due to the limited statistics here and limited time to measure the profiles. Hence, no clear trend can be seen, but for flow rates above $10 \text{ l}_n/\text{min}$ the width seems to remain constant.

An interesting study is also to look at the background L_b of these luminosity profiles for different gas flow rates as this background should result from the residual gas background in the scattering chamber (see figure 7.9). This background can be divided by the electron beam current, thereby providing the background target thickness. The resulting background target thickness n_T^{back} is shown in the lower plot of figure 7.12. It increases with increasing gas flow rate but shows a kink around $q_V = 5 \text{ l}_n/\text{min}$. Unfortunately, no data at other values of q_V are available, but since the background target thickness should be proportional to the pressure in the scattering chamber, the pressure can be used for the further study. In the lower plot of figure 7.12 also the pressure in the scattering chamber is shown. Here, the sudden change of the slope can be confirmed. It was therefore fitted by the unsteady linear function

$$f(x) = \begin{cases} m_1x + b_1 & \text{for } x \leq x_0 \\ m_2(x - x_0) + m_1x_0 + b_1 & \text{for } x > x_0 \end{cases} \quad (7.6)$$

that changes its slope at $x = x_0$. This function with the resulting fit parameters was additionally scaled to the measured background target thickness by a fit which also describes this data perfectly. This confirms the expected correlation between the background target thickness and the pressure in the scattering chamber and thus the whole analysis method and additionally proves that the appearance of the jet suddenly changes at a gas flow rate of around $q_V = 5 \text{ l}_n/\text{min}$. The reason for this change is not yet clear and needs further studies. Profile measurements at different gas flow rates could help to understand this effect, as they can show, if, e.g., the profile width changes for small gas flow rates before getting constant at higher values. Such a change could lead to a different efficiency of the catcher system and thus a different background level.

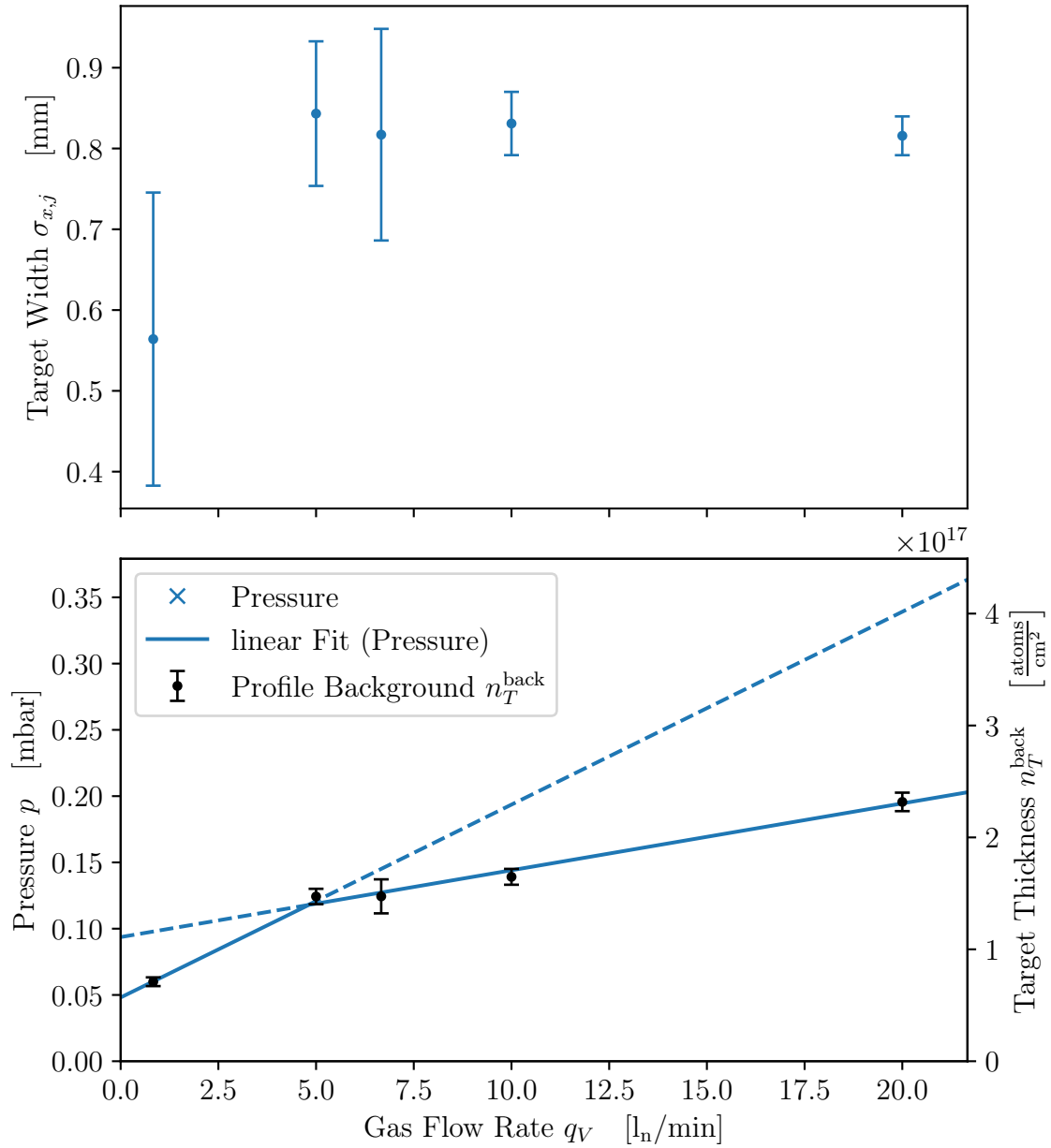


Figure 7.12: Top: Width of the gas-jet for the new nozzle design at different gas flow rates through the nozzle. The large uncertainties result from the very limited time for these measurements, especially with the small target thickness when using a small gas flow rate. Bottom: Background target thickness (right axis) extracted from the luminosity profiles as a function of the volume flow through the nozzle. The pressure (left axis) in the scattering chamber is also shown. The sudden change of the slope is fitted by an unsteady linear function. This function is also scaled to the background target thickness.

Additionally, for every gas flow rate, also the divergence of the jet should be studied by performing wobbler scans at different distances from the nozzle to monitor a possible change of the jet geometry. All the results with the new nozzle and the comparison with the old nozzle design presented in this section are already published as part of [Sch⁺21].

7.3 The first Operation with Argon

The MAGIX experiment aims to use different target materials. Besides hydrogen, other fluids like helium and oxygen are foreseen. While the target was primarily designed for hydrogen, the operation with other fluids is also possible, although this requires an appropriate preparation. The necessary considerations for the target operation with argon are discussed in this section.

In 2021, a first measurement at the A1 experiment was performed with argon as target gas. This is motivated by neutrino experiments that require a precise knowledge of the neutrino-nucleus cross section for the interactions inside the neutrino detectors. These cross sections are provided by theory but need experimental data for more precise predictions. Here, electron-nucleus interaction can play a crucial role as the theory predicts terms that contribute to both, the electron-nucleus and neutrino-nucleus cross section. As some experiments will use argon in their detectors such as the time projection chamber of the future DUNE experiment, which will be filled with liquid argon [Acc⁺16], the electron scattering measurement on argon at A1 was proposed [Dor23].

In order to make this experiment work, the target had to be adapted. Especially, the nozzle geometry needs to be optimized for the operation with a new fluid and the operation parameters have to be found. For the nozzle, especially the narrowest inner diameter plays a crucial role as it alone determines the gas flow rate through the nozzle for the respective operating parameters. These were initially selected so that they are in the gaseous regime, as it is also foreseen for the operation with hydrogen. The flow can be calculated according to equation 3.5, which can be reformulated to determine the operating pressure

$$p_0(q_V, T_0) = \frac{\sqrt{MT_0}}{A^*} \frac{p_N}{T_N} q_V \left(\frac{\kappa + 1}{2} \right)^{\frac{\kappa+1}{2(\kappa-1)}} \frac{1}{\sqrt{\kappa R}} \quad (7.7)$$

as a function of the needed gas flow rate q_V and operating temperature T_0 . Here, A^* is the cross-sectional area, M the molar mass, $p_N = 1.013\,25$ bar and $T_N = 273.15$ K the

pressure and temperature at normal conditions, κ the heat capacity ratio, and R the universal gas constant. Figure 7.13 shows the required pressure for gas flow rates of up to 30 l_n/min at a temperature of 40 K for the 200 μ m nozzle used for hydrogen and for two larger nozzles with inner diameters of 300 μ m and 400 μ m. This shows, that operating the target with gaseous argon would require an increase in diameter, as the pressure for the 200 μ m nozzle would exceed the maximum allowed pressure of 20 bar already for a gas flow rate of 10 l_n/min. On the other hand, increasing the narrowest inner nozzle diameter would then reduce the benefit of the new nozzle design that was proven previously. The reduction of the narrowest inner diameter and by this the increase of the outlet divergence is a key feature of this new geometry.

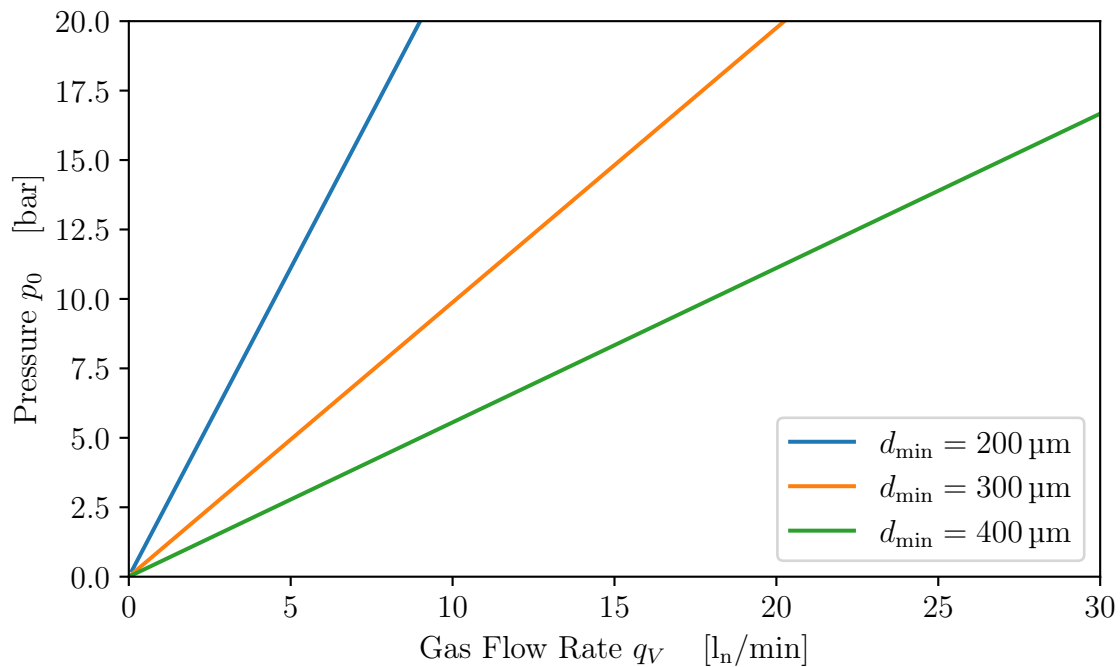


Figure 7.13: Operating pressure as a function of the gas flow rate through the nozzle for gaseous argon at 140 K and different narrowest inner diameters of the nozzle.

Therefore, instead of operating the target with gaseous argon, an operation with liquid argon was considered, as it is routinely done at the $\overline{\text{P}}$ ANDA cluster-jet target with hydrogen. In principle, also the MAGIX target is able to operate with a liquid fluid, although the cooling power is too small to liquify hydrogen at the high gas flow rates foreseen for MAGIX. However, due to the higher temperatures of the phase transition of argon and the higher cooling power of the cryogenic cold head at higher temperatures, it is possible for argon which will be proven later. For a liquid, the

volume flow through a nozzle can also be estimated. The actual volume flow is given as

$$\dot{V} = A^* \cdot v \quad (7.8)$$

with the cross-sectional area A^* at the narrowest point and the velocity v of the fluid at the same position within the nozzle. This velocity can be estimated as

$$v = \sqrt{\frac{2p_0}{\rho}} \quad (7.9)$$

from the operating pressure p_0 and the density ρ of the liquid fluid [Var11]. The corresponding volume flow at normal conditions is then derived from the ideal gas law and the mass flow rate $\dot{m} = \rho \dot{V}$ as

$$q_V = \dot{m} \frac{RT_N}{Mp_N} = A^* \frac{\sqrt{2p_0\rho}}{M} \frac{RT_N}{p_N} . \quad (7.10)$$

These formulas are also routinely used for the operation of pellet or droplet targets [Hab19, Man24]. Finally, this can be used to calculate the operating pressure as

$$p_0(q_V, T_0) = \frac{1}{2\rho(p_0, T_0)} \left(\frac{M}{A^*} \frac{p_N}{RT_N} q_V \right)^2 , \quad (7.11)$$

where the density also depends on the pressure, and therefore the pressure cannot be analytically calculated. Instead, an iterative approach is done starting with a random value of 5 bar. With this initial guess, the density and from this a new pressure value is calculated. These steps are repeated as long as the pressure changes by more than 0.01 bar between two iterations. The density is calculated by interpolating the data from [LM25]. The results for the pressure as a function of the gas flow rate is shown in figure 7.14 for different nozzle sizes at an operating temperature of 95 K. This calculation is only performed in the liquid regime, which explains why the curves in the plot do not start at $q_V = 0$. To cover the flow range of 20 l_n/min to 25 l_n/min as used during the hydrogen program, the nozzle with a diameter of 120 µm was chosen, which allows for achieving these flows at an appropriate pressure of less than 20 bar. Furthermore, compared to the larger nozzle that would be needed for the operation with gaseous argon, the smaller nozzle will guarantee a better beam quality due to the larger divergence in the nozzle outlet.

After finding an appropriate nozzle geometry, the optimal operating conditions have to be chosen. Since the volume flow will be varied according to the needs of the experiment and the pressure will follow from this, a constant operating temperature has

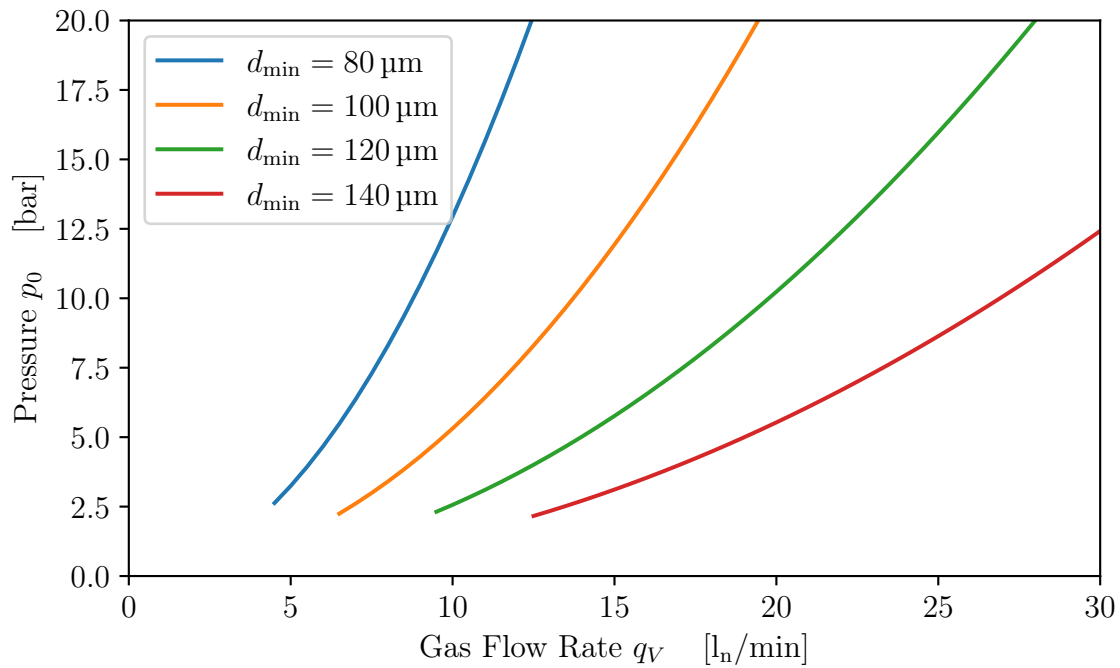


Figure 7.14: Operating pressure as a function of the gas flow rate through the nozzle for liquid argon at 95 K and different narrowest inner diameters of the nozzle. The lines start at the vapor pressure curve.

to be chosen. Therefore, the same calculations as before are repeated with a constant diameter of 120 μm but with different temperatures. This is shown in figure 7.15. The resulting pressures are very similar because the density in the liquid phase depends only slightly on the temperature. Therefore, the only important difference is, that for higher temperatures the vapor pressure curve is located at higher pressures and therefore, the lines start at larger flows for higher temperatures. Thus, a smaller temperature has the benefit that also smaller gas flow rates are achievable when operating the target in the liquid phase of argon. A too small temperature on the other hand, leads to an operation close to the melting curve, where argon would freeze. Therefore, the target was operated at 95 K, which allows for flows down to 10 $\text{l}_\text{n}/\text{min}$ while still being far away from the freezing point of argon which has a normal boiling point of 87.302 K [LM25].

The last preparatory step is to check if the operating parameters can be achieved with the target since an operation in the liquid regime is foreseen. This is not possible for hydrogen at large gas flow rates due to the limited cooling power of the cryogenic cold head even when using it in combination with the booster stage. This can be checked for argon by looking at the cooling power of the cold head. The cooling power

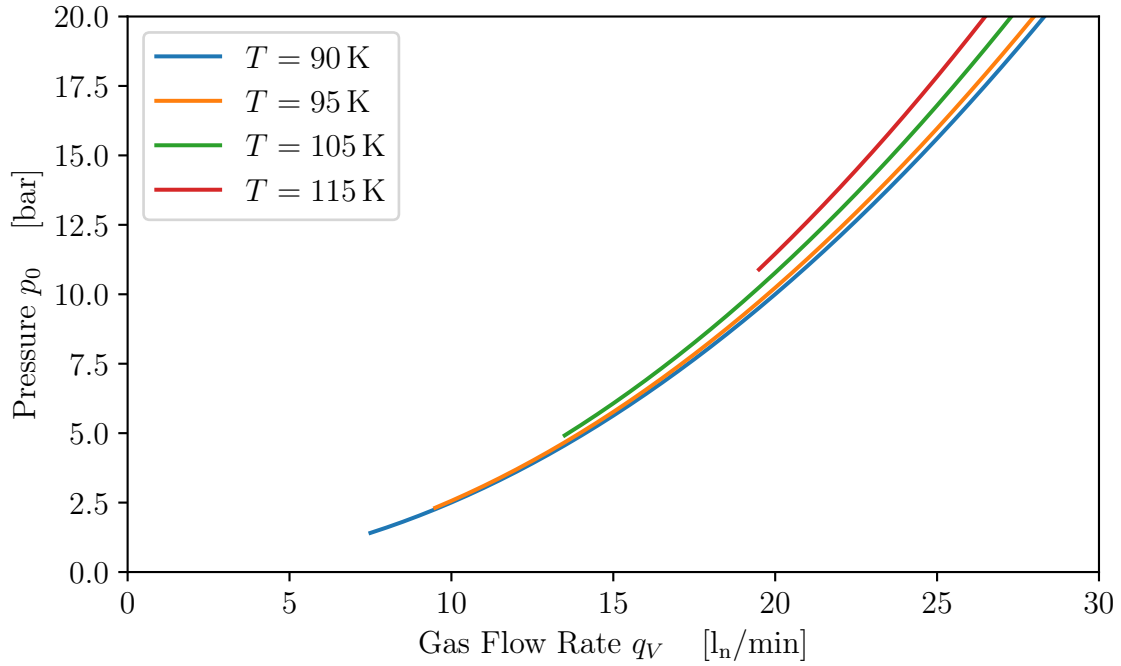


Figure 7.15: Operating pressure as a function of the gas flow rate through the 120 μm nozzle for liquid argon at different temperatures. The curves start at the vapor pressure curve and only cover the liquid region.

of the two stages of the cold head are coupled and depend on the temperature of these two stages. It was measured at the assembled MAGIX target within [Bal17] and is shown in figure 7.16.

When a gas flow is applied to the target, it is cooled down by the cooling power of the cold head. However, the warm gas entering the target introduces a heating power

$$P = \dot{m}\Delta h = \dot{m} \int_{T_{\text{out}}}^{T_{\text{in}}} c_p(T) dT \quad (7.12)$$

that depends on the mass flow rate $\dot{m}$ and the specific enthalpy difference Δh of the warm gas entering the stage and the cold gas leaving the stage. This can also be expressed as integral over the specific heat capacity c_p between the outgoing and incoming temperatures T_{out} and T_{in} [Lan⁺20]. The mass flow can be expressed by the gas flow rate q_v at normal conditions using the perfect gas law as

$$\dot{m} = \frac{Mp_N}{RT_N} q_v . \quad (7.13)$$

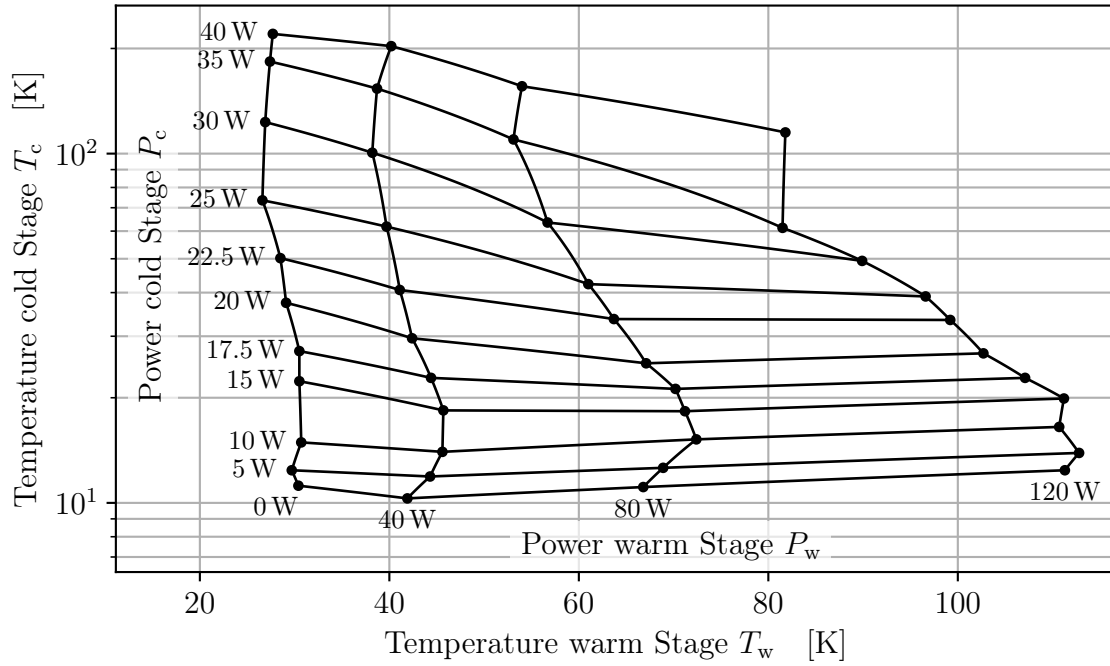


Figure 7.16: Cooling power of the two stages of the cryogenic cold head as a function of the temperature and power of the other stage. The data was recorded within [Bal17].

The equilibrium temperature at a stage is then given as the temperature, where the cooling power of the cold head is equal to the heating power of the flowing gas. For the warm stage, the equation to be solved is

$$P_w(T_w, P_c) = \frac{Mp_N}{RT_N} q_V \cdot (h(T_{in}) - h(T_w)) + P_{ext,w} \quad (7.14)$$

with the cooling powers P_w and P_c of the warm and cold stage, the temperature T_w of the warm stage, and the gas inlet temperature T_{in} that is assumed to be room temperature ($T_{in} = 293.15$ K). Additionally, an external heating power $P_{ext,w}$ can be added that reflects the heating cartridges that are installed at the MAGIX target and all Münster cluster-jet targets to regulate the temperature. Important to note here is, that this equation depends on both sides on T_w which requires a numerical solution. Furthermore, the power P_w of the warm stage also depends on the power P_c of the cold stage. Similarly, the equation for the cold stage can be derived as

$$P_c(T_c, P_w) = \frac{Mp_N}{RT_N} q_V \cdot (h(T_w) - h(T_c)) + P_{ext,c} \quad (7.15)$$

where now the inlet temperature was assumed to be equal to the outlet temperature of the warm stage, as the gas has passed this stage before.

This system of two equations needs to be solved iteratively. In the first step, the cooling power at the cold stage is set to $P_c = 0$. The power curve $P_w(T_w, P_c)$ for the warm stage is extracted from the data [Bal17] and additionally the data for the enthalpy is extracted from [LM25]. With this, equation 7.14 is solved numerically for the warm stage temperature T_w . Afterwards, this can be used to get the power curve of the warm stage and to solve equation 7.15 for the cold stage temperature. This process is then repeated until finally both temperatures and the pressures have a relative change between two iteration steps of less than 10^{-6} . As an example, the result of the final iteration for an argon flow of $q_V = 20 \text{ l}_n/\text{min}$ at a pressure of $p_0 = 10 \text{ bar}$ and heating powers of $P_{\text{ext},w} = 20 \text{ W}$ and $P_{\text{ext},c} = 25 \text{ W}$ is shown in figure 7.17 leading to final temperatures of $T_w = 111.4 \text{ K}$ and $T_c = 92.7 \text{ K}$ with cooling powers of $P_w = 162.4 \text{ W}$ and $P_c = 37.9 \text{ W}$. The upper plot in this figure shows the multidimensional cooling power of the cold head from figure 7.16 with the power curves at the calculated conditions. The red line is the power curve $P_w(T_w, P_c)$ for $P_c = 37.9 \text{ W}$ which was interpolated from the data within [Bal17]. The power curve $P_c(T_c, P_w)$ of the cold stage shown by the blue line corresponds to the cooling powers measured in [Bal17] for $P_w = 120 \text{ W}$ as this was the maximum power applied during the measurements of the power curve. Therefore, the actual cooling power is expected to be even a bit higher. In the lower plot, the same power curves for the warm and cold stage are shown against the temperature of the corresponding stage. Additionally, the heating power introduced by the target flow and the additional, external heat is shown. The point where the heating power is equal to the cooling power of the warm stage corresponds to the warm stage temperature (second dashed line). In this case, the power curve at the warm stage had to be extrapolated linearly, as the cooling power needed exceeds the maximum of 120 W in the measured power curve. From this point on, the heating power introduced by the gas and the heaters at the cold stage increases and also crosses the power curve leading to the cold stage temperature. In this example, the calculation converged after 5 iterations.

This calculation can be used to determine the expected temperatures at the warm and the cold stage for different gas flow rates applied to the MAGIX target with the $120 \mu\text{m}$ nozzle. The challenge here is, that the enthalpy includes the phase transition and is thus pressure dependent. On the other hand, the pressure for a given gas flow rate depends on the temperature of the gas at the nozzle. Therefore, in a first step a pressure of 0 bar is assumed, which corresponds to the enthalpy of an ideal gas. The resulting temperature is then used, to calculate the pressure according to equation

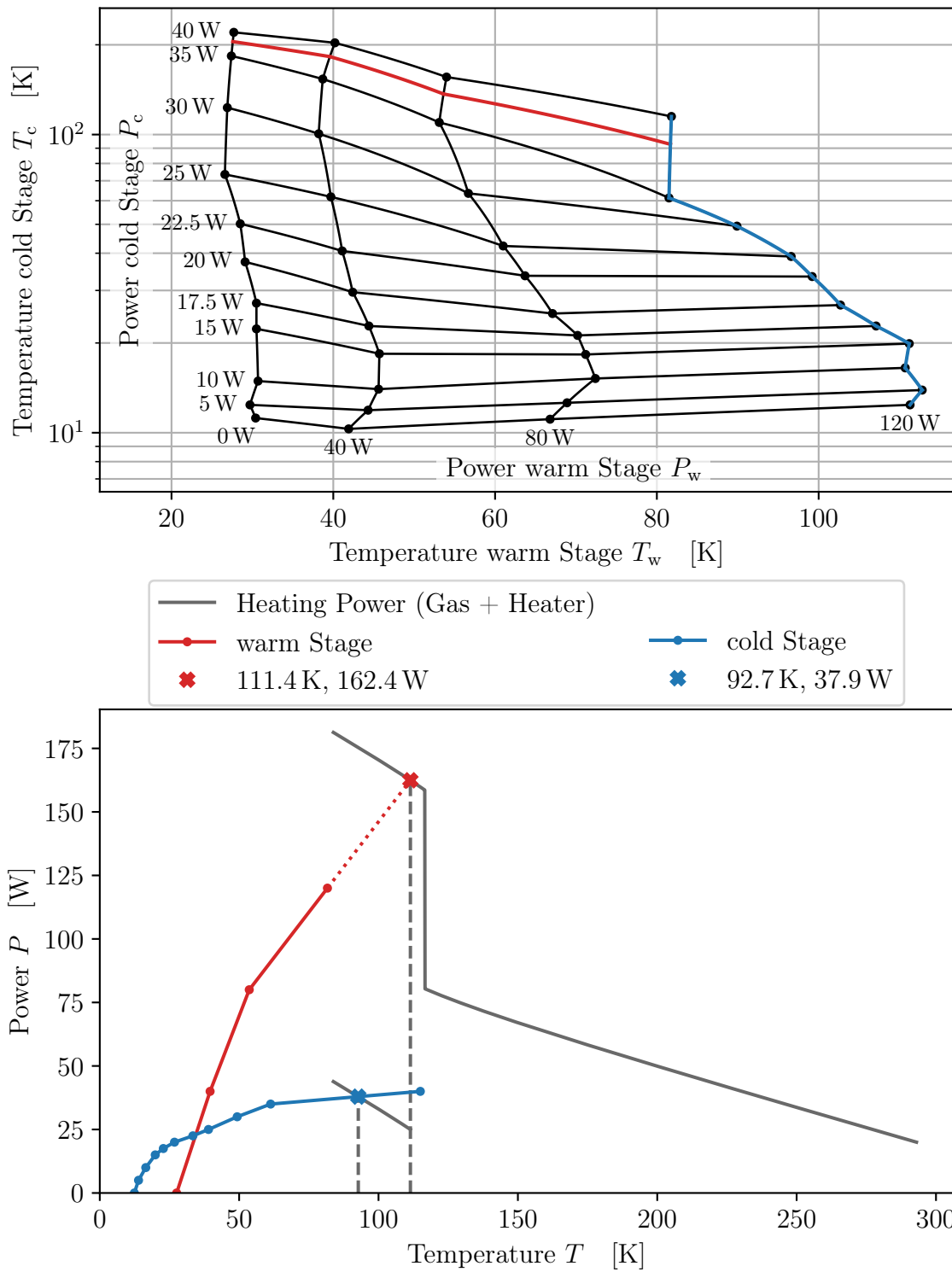


Figure 7.17: Final result after 5 iterations for the solution of equations 7.14 and 7.15 for an argon flow of $q_V = 20 \text{ l}_n/\text{min}$ at a pressure of $p_0 = 10 \text{ bar}$ and external heating powers of $P_{\text{ext,w}} = 20 \text{ W}$ and $P_{\text{ext,c}} = 25 \text{ W}$.

7.7, when the operating conditions are in the gaseous phase or equation 7.11 for the liquid regime. This is repeated iteratively until it converges with a change of less than 0.01 bar. This calculation is done without additional heating power supplied at both stages and with the maximum heating power of $P_w = 100$ W and $P_c = 50$ W. The results of this calculation in figure 7.18 show, that the cooling power of the cold head at the comparably high temperatures for the operation with argon is so large, that without additional heating power, the argon would always freeze at the cold stage, for small gas flow rates even at the warm stage. However, it must be noted, that the enthalpy used from [LM25] does not include data below the triple point and thus for temperatures below that point the enthalpy was linearly interpolated without a phase transition, because operating the target in this regime is not possible at all. For the maximum heating power at both stages, the results are slightly different. First of all, at very low gas flow rates the end temperature at the cold stage even decreases, when increasing the flow rate. The reason for this is, that the warm stage will get colder than the cold stage so that in this case the gas flow does not induce a heating power at the cold stage, but instead cools it further down. Therefore, a higher gas flow rate results in a larger effective cooling power and a smaller temperature. This behavior changes once the vapor pressure curve is reached. The cold head is not able to cool down the gas into the liquid phase, when the maximum heating power is supplied. However, at the warm stage the gas is always in the liquid regime and can even freeze there for very small flows. Here, also some oscillations are visible due to instabilities in the calculations, when operating the target at one stage at the phase transition from gaseous to liquid argon. These results show that the cooling power is more than sufficient to cool down the gas to the liquid phase, but it is even too large. Ideally, it should be possible to operate the target with a small heating power in the liquid regime, while with the maximum power, the fluid should be gaseous at both stages. This can be achieved by reducing the cooling power of the cold head. Therefore, the frequency of the compressor of the cold head needs to be reduced. By this, a safe operation of the target with argon can be achieved.

During a beam time in 2021, this was proven by the first operation of the MAGIX target with argon. The target was first cooled down with the default compressor frequency of 2 Hz as proposed by the manufacturer and when getting closer to the vapor pressure curve, it was reduced to only 0.5 Hz. This allowed for stable operation with argon in the gaseous phase and cooling down into the liquid regime. Unfortunately, the vacuum system only allowed to increase the flow up to a final pressure inside the scattering chamber in the order of 10^{-3} mbar which was not expected since for hydrogen the limit was in the order of 10^{-1} mbar. The reason for this is that, although

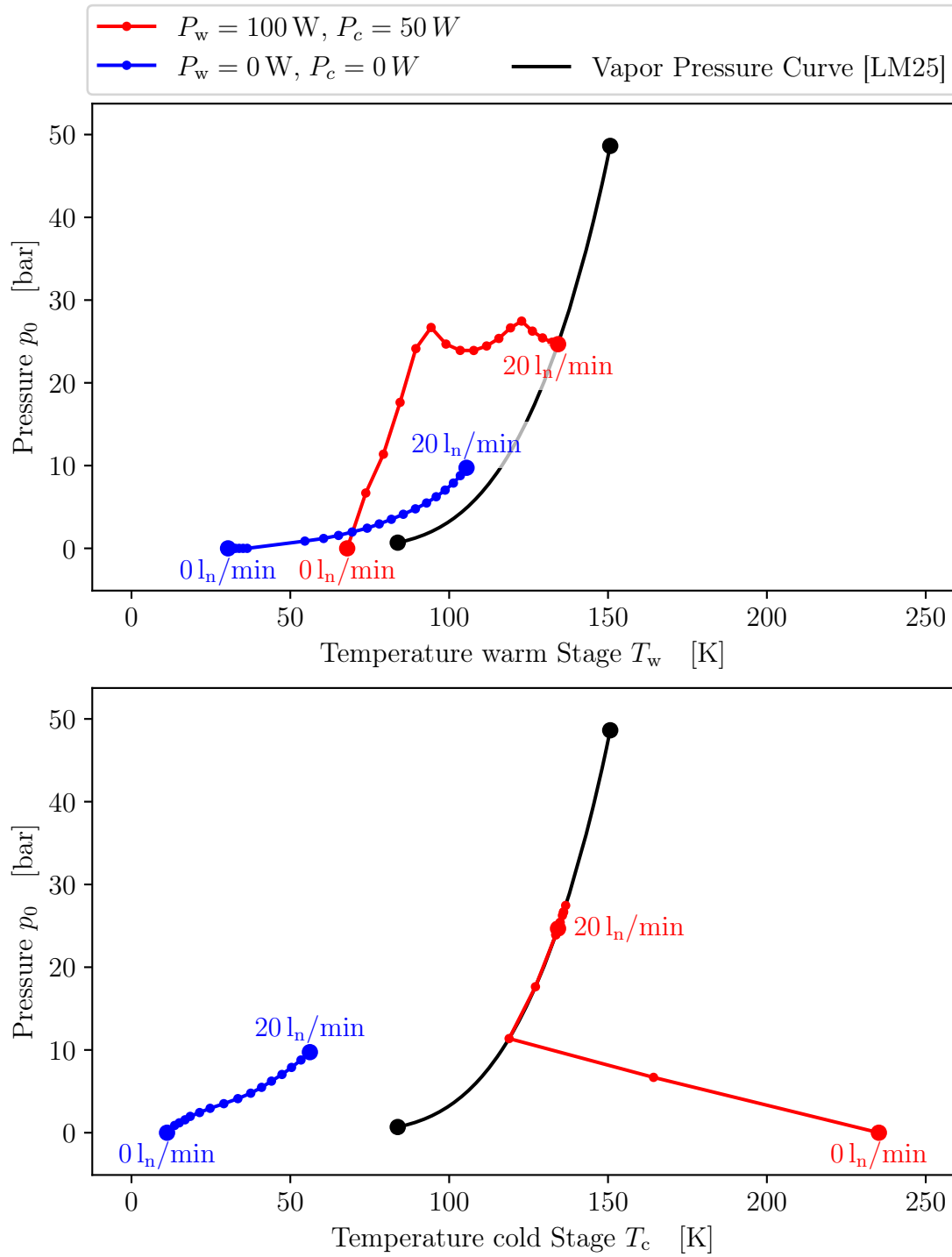


Figure 7.18: Expected temperatures and pressures at the warm (top) and cold stage (bottom) without additional heating power (blue) and with maximum heating power (red) in the phase diagram of argon [LM25]. Temperatures smaller than the triple point are no valid values as here the gas is in the solid phase. These just show, that the cooling power is too large, and the argon would freeze inside the target.

the pumping speed of turbomolecular pumps for heavier and slower gases is larger, the pumps heat up faster and thus stop operation earlier. This is especially relevant for heavier noble gases like argon, as they only dissipate a small part of the heat to the housing of the pump due to their low specific heat [Pfe13]. This problem limited the gas flow rate to $5\text{ l}_n/\text{min}$, which is too small to reach the liquid phase. Instead, the target had to be operated directly on the vapor pressure curve. However, the MAGIX target still provided a stable jet that was visible by eye as shown in figure 7.19 and that showed nearly no divergence. In this configuration, it was operated over several days and showed a stable operation and a good beam quality. This allowed for a nearly background free measurement of the electron scattering on argon that is currently analyzed. Preliminary results are published in [Dor23]. The successful operation of the target with argon shows, that the target is able to operate with different fluids and that the new nozzle design is able to provide a stable jet even for heavier gases like argon. Additionally, this nozzle design is also suitable for the operation with a liquid. However, the nozzle diameter and operating parameters must be adapted to every fluid.



Figure 7.19: Photograph of the argon jet leaving the nozzle of the jet target from top to bottom. Below the nozzle it enters the catcher and is pumped away by the pumping station. The picture was taken through a small vacuum window. In the background, the Mylar window of the chamber towards spectrometer B of the A1 experiment can be seen.

7.4 Alternative Target Concepts for MAGIX

Although the MAGIX target was already successfully operated with hydrogen and argon in several beam times at the A1 experiment, also other target concepts are considered for the future. One of these concepts is a droplet target as it is currently developed in Münster for the $\overline{\text{PANDA}}$ experiment [Man24]. In such a droplet target a liquid fluid like hydrogen flows through a nozzle with a smaller diameter compared to the nozzles of cluster-jet targets. The resulting flow leaving the nozzle is then broken up by the vibration of a piezoelectric element. Typically, the Münster droplet targets are operated with liquid hydrogen at, e.g., a temperature of $T_0 \approx 16 \text{ K}$, a pressure of $p_0 = 1 \text{ bar}$, and a piezo frequency in the order of $f = 500 \text{ kHz}$. The nozzle consists of a copper body with a welded-on aperture with a diameter of $d_0 = 10 \mu\text{m}$ [Man24].

For an experiment like MAGIX such a droplet target could be ideal as it provides a beam with nearly no divergence. Furthermore, such a target can achieve similar or even higher target thicknesses with a much smaller gas flow rate, which might be interesting for MAGIX due to the high gas load that is induced by the jet target. Therefore, within this section the achievable target thickness and luminosity for a droplet target will be calculated theoretically and compared to the expectations for the jet target. Assuming a homogeneous density distribution inside a perfectly spherical droplet, the local target thickness in the center of the droplet will be given by

$$n_{T,d}^{\max} = 2 \frac{\rho d N_A}{M} \quad (7.16)$$

with the volume mass density ρ and the droplet diameter d . The Avogadro constant N_A and the molar mass M are used to convert the mass density into a molecular density and the factor 2 represents the number of atoms in a hydrogen molecule. The volume density for the operating conditions given above is found to be $\rho(T_0, p_0) = 75.34 \text{ kg/m}^3$ [LM25]. The droplet diameter on the other hand can be calculated, from the distance l_d of the individual droplets and the demand that the volume of a cylinder with diameter d_0 and height l_d is equal to the volume of a sphere with diameter d . This results in

$$d = \sqrt[3]{\frac{3}{2} \cdot l_d \cdot d_0^2}, \quad (7.17)$$

where the distance l_d is given as

$$l_d = \frac{v}{f} \quad (7.18)$$

with the droplet velocity v and the piezo frequency f . The velocity can be calculated according to equation 7.9. Since the beam at MAGIX will not be point-like but even

larger than the single droplets, not only the target thickness for a beam hitting the droplet in its center but the atomic density distribution

$$\rho_a(x, y, z) = \begin{cases} 2\rho \frac{N_A}{M} & \text{for } x^2 + y^2 + z^2 \leq \left(\frac{d}{2}\right)^2 \\ 0 & \text{else} \end{cases} \quad (7.19)$$

is needed. Furthermore, to calculate the luminosity, the beam intensity distribution is needed. Here, in the most simple approach, a homogeneous intensity distribution with z being the beam direction is assumed leading to the beam flux

$$\phi(x, y) = \begin{cases} \Phi_0/A_b & \text{for } x^2 + y^2 \leq \left(\frac{d_b}{2}\right)^2 \\ 0 & \text{else} \end{cases} \quad (7.20)$$

where $\phi(x, y)$ is the number of electrons per area and time, Φ_0 the total number of electrons per time, and $A_b = \pi(d_b/2)^2$ the cross-sectional beam area with the beam diameter d_b . The luminosity for a droplet target can then be calculated by integrating the product of the atomic density and the beam flux [Bra19]:

$$\begin{aligned} L_d &= \iiint \rho_a(x, y, z) \phi(x, y) dx dy dz \cdot \frac{d_b}{l_d} \\ &= 2\rho \frac{N_A}{M} \cdot \frac{\Phi_0}{\pi(d_b/2)^2} \int_0^{d/2} r^2 dr \int_0^\pi \sin \theta d\theta \int_0^{2\pi} d\varphi \cdot \frac{d_b}{l_d} \\ &= \frac{2}{3} \cdot 2 \frac{\rho d N_A}{M} \cdot \Phi_0 \cdot \frac{d^2}{d_b^2} \cdot \frac{d_b}{l_d} \\ &= \frac{2}{3} n_{T,d}^{\max} \cdot \Phi_0 \frac{d^2}{d_b^2} \cdot \frac{d_b}{l_d} \end{aligned} \quad (7.21)$$

where the additional factor d_b/l_d describes the average number of droplets that are simultaneously in the beam. The meaning of this equation becomes clear when dividing it into three factors. The first one is the mean density of a droplet when not only assuming the beam to hit its center. This can be calculated from the target thickness distribution of a droplet target

$$n_{T,d}(x, y) = \int \rho_a(x, y, z) dz = n_{T,d}^{\max} \sqrt{1 - \frac{x^2 + y^2}{(d/2)^2}} \quad (7.22)$$

by averaging it over the cross-section of the droplet:

$$\begin{aligned} n_{T,d}^{\text{mean}} &= \frac{1}{\pi(d/2)^2} \int n_T(x, y) dA \\ &= \frac{n_{T,d}^{\text{max}}}{\pi(d/2)^2} \int_0^{d/2} r \sqrt{1 - \frac{r^2}{(d/2)^2}} dr \int_0^{2\pi} d\varphi = \frac{2}{3} n_{T,d}^{\text{max}}. \end{aligned} \quad (7.23)$$

The second factor is the fraction of the total beam flux that hits the droplet. This is given by the ratio of the cross-sectional area of the droplet (A_d) and the beam (A_b) as

$$\Phi_d = \Phi_0 \frac{A_d}{A_b} = \Phi_0 \frac{d^2}{d_b^2}. \quad (7.24)$$

The third factor is the already mentioned average number of droplets in the beam. The luminosity can then be also expressed as product of the mean target thickness, the total beam current hitting the droplet, and the average number of droplets in the accelerator beam as

$$L_d = n_{T,d}^{\text{mean}} \cdot \Phi_d \cdot \frac{d_b}{l_d} = \frac{2}{3} n_{T,d}^{\text{max}} \cdot \Phi_0 \frac{d^2}{d_b^2} \cdot \frac{d_b}{l_d} \quad (7.25)$$

leading to the same result. This can also be expressed as

$$L_d = n_{T,d}^{\text{eff}} \cdot \Phi_0 \quad (7.26)$$

with the effective target thickness

$$n_{T,d}^{\text{eff}} = \frac{L_d}{\Phi_0} = \frac{2}{3} n_{T,d}^{\text{max}} \frac{d^2}{d_b^2} \frac{d_b}{l_d} = \frac{4}{3} \frac{\rho N_A}{M} \frac{d^3}{d_b l_d} = 2 \frac{\rho N_A}{M} \frac{d_0^2}{d_b} \quad (7.27)$$

where equations 7.16 and 7.17 were used. Thus, the effective target thickness of a droplet target does not depend on the piezo frequency and the resulting droplet diameter and distance, but only on the nozzle diameter and the accelerator beam diameter.

This effective target thickness can also be compared to the value that can be achieved with the MAGIX jet target. The jet target provides a Gaussian shaped jet with a width in the order of $\sigma = 1$ mm as shown in section 7.2 with the optimized nozzle geometry. The target thickness in the center of a jet target can therefore be calculated by

$$n_{T,j}^{\text{max}} = \frac{N}{\sqrt{2\pi}\sigma^2} \frac{q_V p_N N_A}{R T_N v} \quad (7.28)$$

with $N = 2$ being the number of atoms in a hydrogen molecule, the gas flow rate q_V , the velocity v from equation 3.4, the normal temperature T_N , the normal pressure p_N , the Avogadro constant N_A , and the universal gas constant R . Assuming that the jet is much wider than the electron beam and that the beam hits the jet in its center the luminosity can be calculated as

$$L_j = n_{T,j}^{\max} \cdot \Phi_0 \quad (7.29)$$

and the effective target thickness is given as

$$n_{T,j}^{\text{eff}} = n_{T,j}^{\max} . \quad (7.30)$$

The ratio of the effective target thicknesses of the droplet and the jet target is then given by

$$\frac{n_{T,d}^{\text{eff}}}{n_{T,j}^{\text{eff}}} = \frac{2}{3} \frac{n_{T,d}^{\max}}{n_{T,j}^{\max}} \frac{d^2}{d_b^2} \frac{d_b}{l_d} . \quad (7.31)$$

Table 7.2 shows the results of the comparison between a droplet and a jet target at typical operation parameters. The effective target thickness of the droplet target is larger by a factor of roughly 3, although for the jet target already the maximum flow of 40 l_n/min at 40 K was assumed, while the thickness of the droplet target could be easily increased by increasing the nozzle diameter. According to equation 7.27 increasing the droplet nozzle diameter by factor of 2 would increase the effective droplet target thickness by another factor of 4. This shows the great potential of using a droplet

Table 7.2: Comparison of typical operation parameters and resulting target thicknesses of a droplet target, the MAGIX jet target, and a filament target.

		Droplet Target	Jet Target	Filament Target
Nozzle Diameter d_0	[μm]	10	200	10
Pressure p_0	[bar]	1	10.67 ¹	1
Temperature T_0	[K]	16	40	16
Gas Flow Rate q_V	[l _n /min]	0.203 ²	40	0.203 ²
Jet Width σ	[mm]	—	1	—
$n_T^{\max}$	[atoms/cm ²]	$1.12 \cdot 10^{20}$	$1.57 \cdot 10^{18}$	$4.50 \cdot 10^{19}$
n_T^{mean}	[atoms/cm ²]	$7.48 \cdot 10^{19}$	—	$3.54 \cdot 10^{19}$
n_T^{eff}	[atoms/cm ²]	$4.50 \cdot 10^{18}$	$1.57 \cdot 10^{18}$	$4.50 \cdot 10^{18}$

¹ Calculated from d_0 , T_0 , and q_V using equation 7.7.

² Calculated from d_0 , p_0 , and T_0 using equation 7.10.

target at MAGIX. Another big advantage is the volume flow. While for the jet target 40 l_n/min are flowing through the nozzle, for the droplet target under the assumed conditions only 0.2 l_n/min are needed. These advantages of the droplet target seem to be very promising for the future operation of MAGIX. However, it must be noted, that the operation of the droplet target is more challenging and the problem of regular nozzle clogging needs to be solved, which should be reduced when using a larger nozzle. Furthermore, the droplet target relies on the operation of the target in the liquid regime of the fluid. Therefore, an operation with helium is not possible so that here the jet target is the best option.

Another alternative target concept is the operation of a droplet target without the piezo element. Instead of a discrete droplet beam, this will result in a continuous filament operation that is currently explored at the Münster droplet target [Man24]. For such a target, the diameter of the filament corresponds to the diameter of the nozzle ($d = d_0$) and the atomic volume density distribution is given by

$$\rho_a(x, z) = \begin{cases} 2\rho \frac{N_A}{M} & \text{for } x^2 + z^2 \leq \left(\frac{d_0}{2}\right)^2, \\ 0 & \text{else} \end{cases}, \quad (7.32)$$

which is constant in target direction (y). The luminosity can then be calculated by

$$\begin{aligned} L_f &= \iiint \rho_a(x, z) \phi(x, y) dx dy dz \\ &= 2\rho \frac{N_A}{M} \cdot \frac{\Phi_0}{\pi(d_b/2)^2} \int_0^{d_0/2} r dr \int_0^{2\pi} d\varphi \int_{-d_b/2}^{d_b/2} dz \\ &= n_{T,f}^{\max} \cdot \Phi_0 \cdot \frac{d_0}{d_b} \end{aligned} \quad (7.33)$$

with the maximum target thickness

$$n_{T,f}^{\max} = 2 \frac{\rho d_0 N_A}{M} \quad (7.34)$$

in the center of the filament. This leads to the effective target thickness

$$n_{T,f}^{\text{eff}} = L_f / \Phi_0 = 2 \frac{\rho N_A}{M} \frac{d_0^2}{d_b} \quad (7.35)$$

which is exactly equal to the effective target thickness of the droplet target. This result is also expected as the same nozzle and operation parameters are used, which lead to the same gas flow rate and thus the same amount of target material in the electron

beam. Also the mean target thickness can be calculated with the target thickness distribution

$$n_{T,f}(x) = n_{T,f}^{\max} \sqrt{1 - \frac{x^2}{(d_0/2)^2}} \quad (7.36)$$

leading to

$$n_{T,f}^{\text{mean}} = \frac{1}{d} \int_{-d/2}^{d/2} n_{T,f}(x) dx = \frac{\pi}{4} n_{T,f}^{\max} . \quad (7.37)$$

The fraction of the total beam flux that hits the filament is given by

$$\Phi_f = \Phi_0 \frac{d_0 \cdot d_b}{\pi (d_b/2)^2} = \Phi_0 \frac{4 d_0}{\pi d_b} \quad (7.38)$$

so that the luminosity can also be expressed as

$$L_f = n_{T,f}^{\text{mean}} \cdot \Phi_f = n_{T,f}^{\max} \cdot \Phi_0 \frac{d_0}{d_b} \quad (7.39)$$

leading again to the same results as before. The results for the filament target are also summarized in table 7.2 showing that while the effective target thickness is the same as for the droplet target, the maximum thickness differs drastically. The reason for this is the periodic droplet beam that will also lead to a non-constant target thickness in time. Therefore, a filament target in combination with the continuous beam of MESA will guarantee a more stable data rate with the same average luminosity. The calculations presented here, used the approximation of a homogeneous electron beam. At MAMI, this beam was found to be of a Gaussian shape, which will partly change the effective target thickness presented here. In that case, the smaller diameter of the filament compared to the droplet will lead to a slightly larger luminosity due to the higher beam current in the center of the electron beam. However, also with this approximation, the droplet and especially the filament target seem to be very promising for the future operation of MAGIX. Therefore, a first operation of the MAGIX target at the A1 experiment in a filament mode is currently prepared [Ded25, Fro25]. While a droplet mode requires a dedicated droplet target with a piezo element coupled to the nozzle, a filament mode requires in the simplest approach only a change of the nozzle of the MAGIX target and a replacement of the used flow controller to be able to regulate the much smaller gas flow rate.

Chapter 8

Conclusion and Outlook

This thesis has focused on two jet targets: the $\overline{\text{PANDA}}$ cluster-jet target and the MAGIX gas-jet target. Both targets are designed and built for future experiments, but as they already exist, they can be operated under realistic conditions at particle accelerators to study the beam-target interaction and the influence on the beam, to study monitor systems, and to upgrade the targets for the final experiments.

For the $\overline{\text{PANDA}}$ cluster-jet target, several hardware and software upgrades were designed and realized within this thesis. The biggest topic here is the design of a new beam dump. This beam dump is based on the previous design with its three vacuum stages equipped with seven turbomolecular pumps. While the old beam dump was built as compact as possible, the new one now allows for the integration of several monitor systems that will simplify the adjustment of the cluster-jet target through the $\overline{\text{PANDA}}$ target beam line with a length of more than 5 m and a minimum diameter of only 20 mm. The target will include a new absolute thickness monitor system and an MCP system. The MCP system will be mounted on a movable arm in the third stage of the beam dump and can thus be removed when its operation is not needed. This system enables live monitoring of the jet profile. However, the jet needs to be ionized for this purpose, which can be done by either the accelerator beam, which then ionizes only the interaction region, or by an electron gun that can ionize the whole cluster-jet. For the $\overline{\text{PANDA}}$ target, a new electron gun was designed with N. Humberg [Hum21] based on numerical simulations and finally commissioned with M. Scharpey [Sch22]. This new electron gun is based on a modular design that allows easy replacement of, e.g., the electrodes or the filament. It proved to have a stable operation with a higher beam current than the old gun used at the Münster prototype target. Furthermore, the new MCP monitor system will also allow for time-of-flight measurements. For these measurements, a new electronic setup based on a programmable logic unit was proposed and partly commissioned together with M. Scharpey [Sch22], which was later realized within [Sch24, Ves24]. The new beam dump also houses three orifice systems between

the three stages and in front of the first stage. These have a rectangular opening that can be changed in size and position in one direction to perfectly align it with the cluster-jet and to minimize the gas backflow. This is realized by two Faulhaber motors in every orifice system. All these new systems require an integration into the EPICS slow control system. To simplify this, the system was upgraded from a hybrid system, which consists of an internally programmed part and a gateway that sends the variables into EPICS, to a purely EPICS based system. This allowed the integration of the high voltage sources for the electron gun and the MCP system together with M. Scharpey [Sch22]. Furthermore, the Faulhaber motors of the orifice system were integrated into EPICS in cooperation with L. Deda [Ded24]. These are integrated in a way that enables an easy integration of more systems with the same type of motors as foreseen for the new AMS and the MCP monitor system. This was already demonstrated for the new motors for the skimmer and collimator at the Münster prototype target [Ded24]. In the meantime, the beam dump with the three orifice systems and the new AMS was installed and commissioned at the $\bar{\text{P}}\text{ANDA}$ target in Jülich, where its impact on the vacuum situation will be studied [Eic25].

The installation of the $\bar{\text{P}}\text{ANDA}$ target at the COSY accelerator in Jülich enabled the main focus of this thesis: physics measurements on the interaction of the target with the accelerator beam. These studies systematically examined the influence of the target in combination with the HESR stochastic cooling and a barrier bucket cavity on the beam. Such conditions are very similar to those later at FAIR. Within this thesis, three beam times were carried out. This enabled the gathering of a large data sample, where the momentum spread of the COSY beam in the equilibrium was measured for different combinations of target thickness and COSY beam intensity. In the course of these measurements a new record target thickness of $(3.14 \pm 0.17) \cdot 10^{15} \text{ atoms/cm}^2$ was achieved. The results of the beam quality studies show the expected increase of the momentum spread when increasing the target thickness or the beam intensity. However, due to large variations resulting from the need for manual adjustment of the stochastic cooling and the unstable operation of the target at very high target thickness, the predicted power law behavior with an exponent of $p_1 = p_2 = 1/3$ does not describe the data better than a linear dependence. Nevertheless, these studies show how important such a measurement is for the HESR and provide a guide on how to repeat it there. The dependence can be used to find the optimal combinations of target thickness and accelerator beam intensity leading to the lowest momentum spread. This is of utmost importance, especially for the line scan program of $\bar{\text{P}}\text{ANDA}$, where the resolution mainly depends on the momentum spread and its variation. The studies also showed that even when the target is more unstable at highest target thicknesses, it still leads

to a variation of the momentum spread of less than 10 % of its absolute value and the variations are even negligible at more moderate target settings. This is comparable to the variations resulting from the beam loss due to hadronic interactions during a cycle. Furthermore, the change of the momentum spread due to the beam loss was studied intensely. Here, it was confirmed that the momentum spread decreases linearly during a cycle when only the beam intensity changes, but with a constant target thickness and without changing the setting of the stochastic cooling. This is an important result that matches the theoretical predictions [SKM16] and thus solidifies the theoretical understanding of the beam-target interaction and the performance of the stochastic cooling in the presence of a target. Additionally, the stability of the mean momentum was proven to be in the order of 10^{-6} , which is thus also quite small compared to the momentum spread. During the last beam time, a simplified version of the new MCP monitor system was used, showing its great potential as an online monitoring system. Studies on the dependence of the MCP intensity on the target thickness, the accelerator beam intensity, and the MCP voltage showed that such a system can be calibrated and used as a rough luminosity monitor. However, since its dependence differs for the target thickness and the beam intensity, one of these quantities needs to be measured independently. Nevertheless, with the MCP monitor system, luminosity changes can be monitored in real time. Unfortunately, the phosphor screen of the MCP system was damaged during the beam time, probably due to chemical degradation from exposure to atomic hydrogen ionized by the accelerator. Therefore, an alternative YAG:Ce screen has been studied in [Sch24, Ves24] with promising results.

The topic of the second part of this thesis was the MAGIX gas-jet target. This target is currently installed at the A1 experiment at the MAMI facility, where several measurements were performed. The first one was the operation of the MAGIX target with an optimized nozzle design, which should reduce the divergence of the jet by roughly a factor of two [Bra19]. The A1 facility allowed for a high-frequency scan over the target with the electron beam, and by analyzing the rate of the elastic electron-proton scattering measured by the A1 spectrometers as a function of the vertex position, the width of the resulting jet could be determined. This was repeated at different distances from the nozzle. These measurements confirmed the significant reduction of the jet divergence, which results in a higher target thickness and improved vacuum conditions. This is very important due to the high gas load of the target. These results prove the predictions from computational fluid dynamics simulations [Bra19] and thus enable further improvements of the nozzle with this tool for other conditions. The new nozzle design was also successfully adapted for argon. While the operation with gaseous argon would have required an increase of the narrowest inner diameter of the

nozzle, which would reduce the benefits of the new nozzle, the narrowest inner nozzle diameter was instead reduced and optimized for the operation with liquid argon. With this new nozzle optimized for the operation with argon, a stable argon jet was created, although the vacuum conditions limited the flow and forced to operate the target on the vapor pressure curve. Nevertheless, the stable operation allowed for a beam time to measure the electron argon scattering cross section. Finally, also the droplet and filament target as alternative target concepts are proposed within this thesis, which can increase the target thickness by at least a factor of 3 while decreasing the gas flow rate through the nozzle by an order of magnitude. These results are very promising for some measurements at the future MAGIX experiment.

Therefore, this thesis provides important aspects for the successful start of the future $\bar{\text{P}}\text{ANDA}$ and MAGIX experiments. This includes several hardware and software upgrades, such as the new $\bar{\text{P}}\text{ANDA}$ beam dump with the possibility to include several monitor systems, or the improved nozzle design for the MAGIX experiment that can also be used for similar target setups at other experiments. Furthermore, the operation at accelerator facilities like COSY and MAMI allowed the study of the interplay between the target and the accelerators to optimize the beam conditions for the experiments and led to important physics results on the beam-target interaction that support the theoretical predictions. Finally, new ideas like the droplet or filament target are presented, with plans for their implementations already made [Ded25, Fro25].

A COSY Measurements

A.1 Beam Quality Studies

In the following, some additional plots for the beam quality analysis described in section 5.3 are shown. Figures A.1, A.2, and A.3 show the achieved momentum spread in the equilibrium separately for each of the three beam times, along with the global fit, where the fit function is scaled with s_{bt} , which is different for each beam time. These plots show the need of this scaling factor, as the resulting momentum spread significantly differs between these beam times with the smallest values achieved in 2023.

Furthermore, in figure A.4 the fit for the horizontal and vertical IPM data is shown for $p_1 = p_2 = 1$ as discussed in section 5.3.6. The resulting fit parameters are given there in table 5.8.

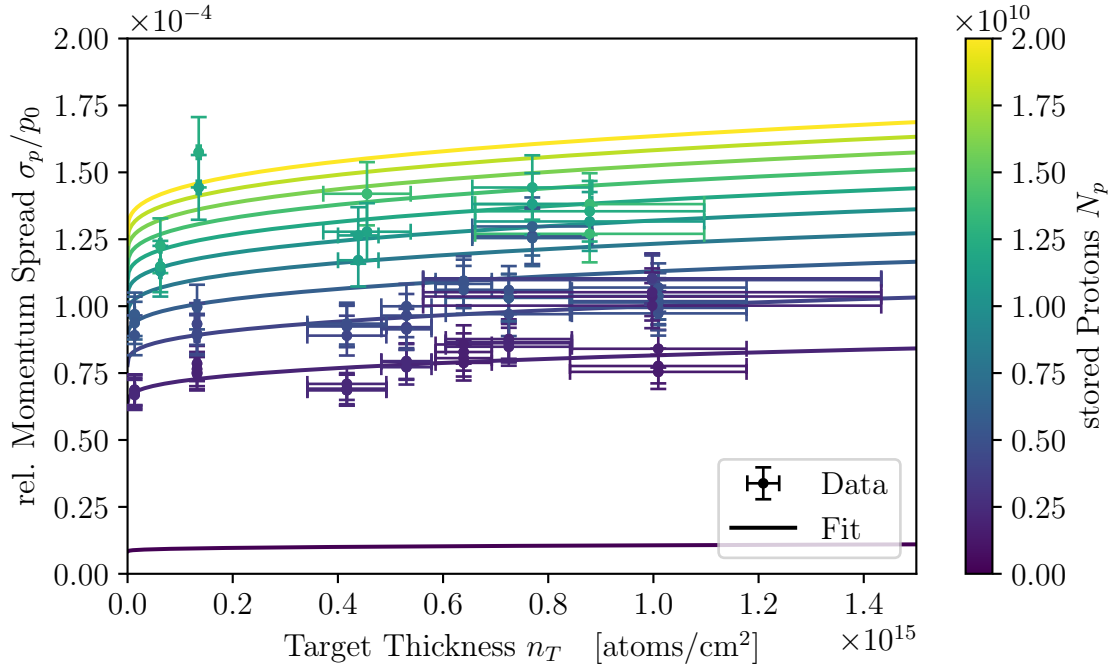


Figure A.1: Dependence of the momentum spread on the target thickness for the 2021 beam time with a fit with $p_1 = p_2 = 1/3$. The lines show the fit scaled by the scaling factor s_{2021} .

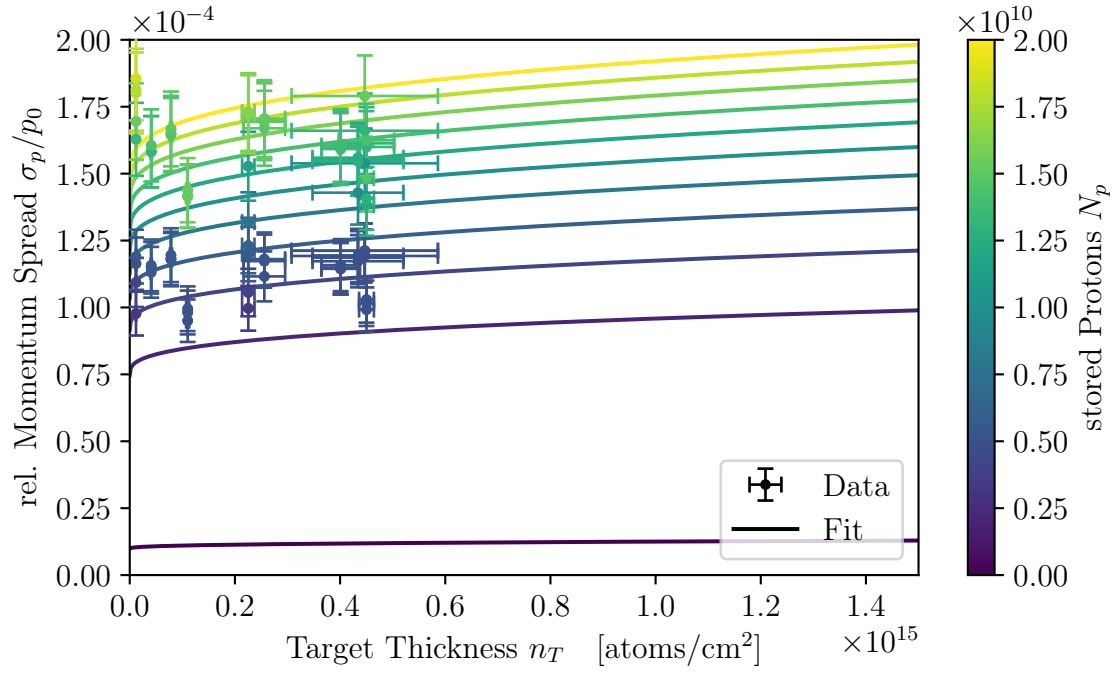


Figure A.2: Dependence of the momentum spread on the target thickness for the 2022 beam time with a fit with $p_1 = p_2 = 1/3$. The lines show the fit scaled by the scaling factor s_{2022} .

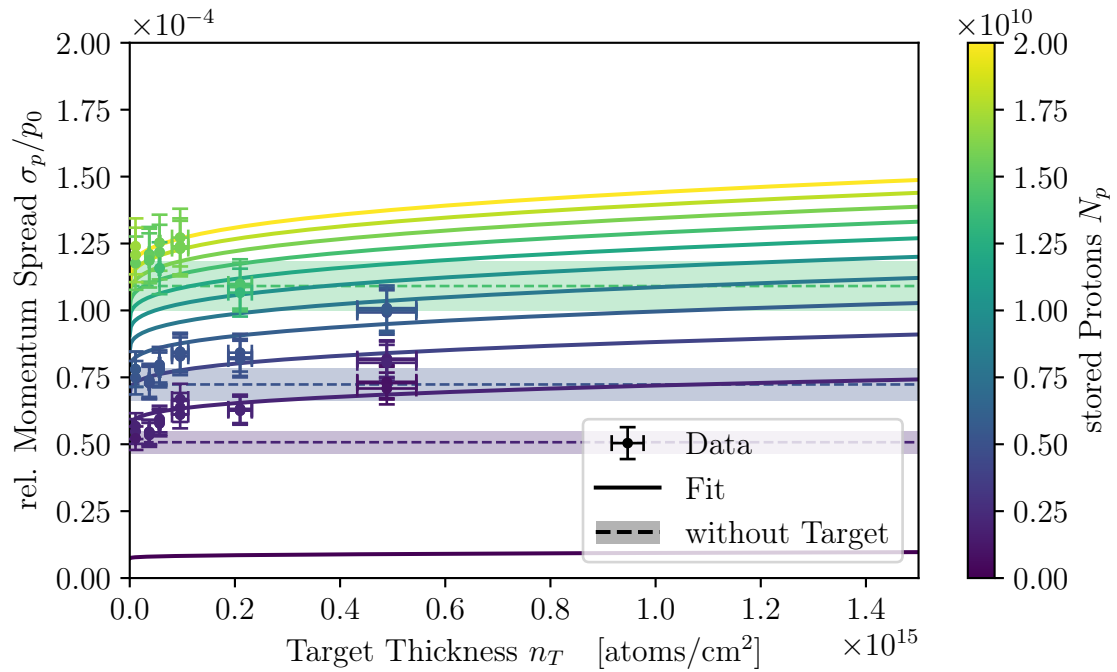


Figure A.3: Dependence of the momentum spread on the target thickness for the 2023 beam time with a fit with $p_1 = p_2 = 1/3$. The lines show the fit, where the scaling factor was set to $s_{2023} = 1$.

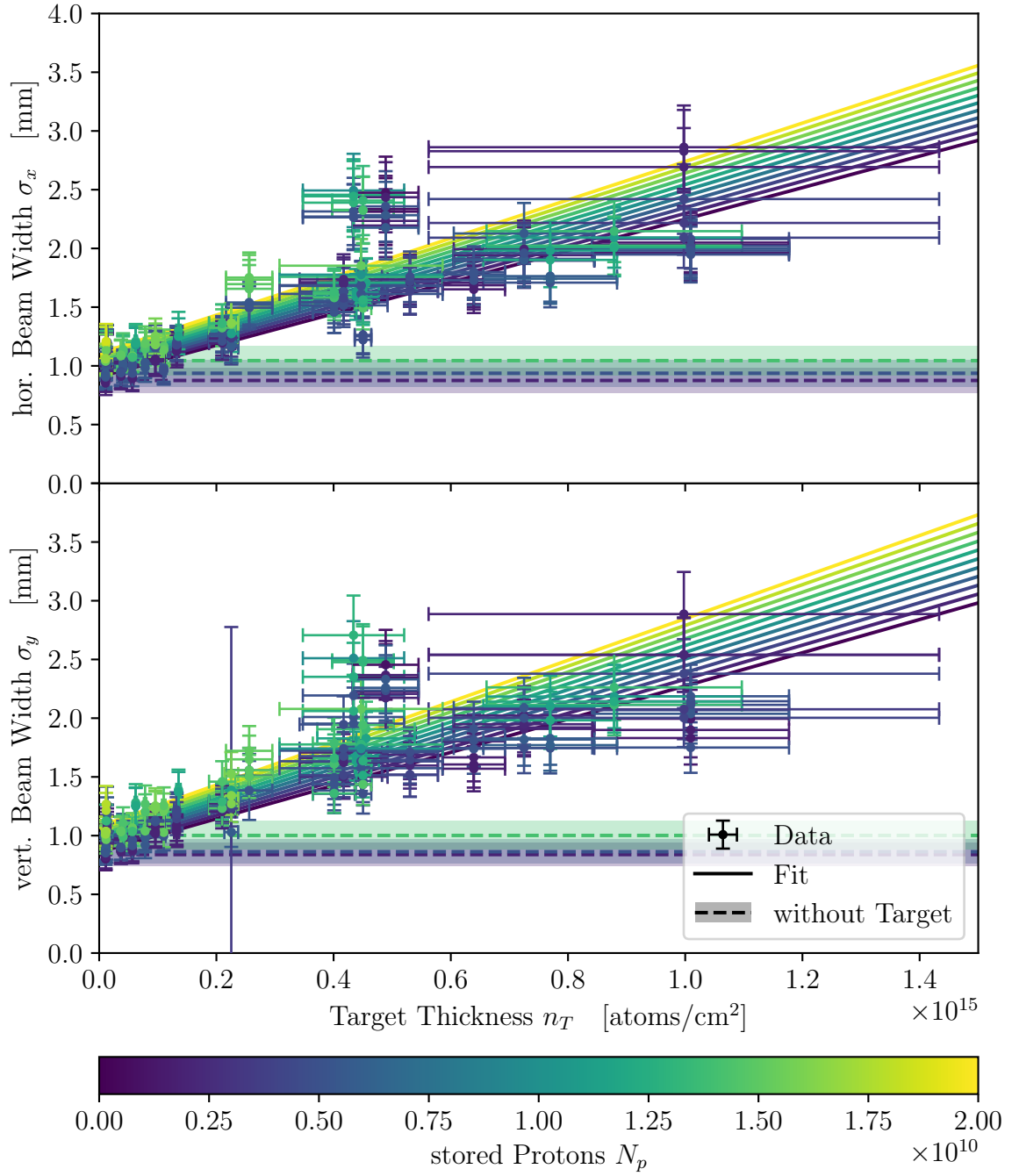


Figure A.4: Dependence of the horizontal (top) and vertical (bottom) beam width at the target location on the target thickness for all beam times with a fit with $p_1 = p_2 = 1$. The data is scaled with $1/s_{bt}$ that was determined via the fit. The colored lines show the fit for different numbers of stored protons from 0 to $2 \cdot 10^{10}$ in steps of $2 \cdot 10^9$. An additional uncertainty reflecting the adjustment of the stochastic cooling was added leading to $\chi^2_{red} = 1$.

Table A.3: Relative momentum spread and beam width at the target location for all settings with the COSY beam in the center of the target (continued).

	T [K]	p [bar]	n_T [atoms/cm ²]	N_p	σ_p/p_0	σ_x [mm]	σ_y [mm]
2021	35	18	$6.2(3) \cdot 10^{13}$	$1.202(3) \cdot 10^{10}$	$1.15(1) \cdot 10^{-4}$	0.60(1)	0.940(15)
	28	18	$4.4(4) \cdot 10^{14}$	$1.155(3) \cdot 10^{10}$	$1.264(12) \cdot 10^{-4}$	0.796(15)	1.22(3)
	28	18	$4.4(4) \cdot 10^{14}$	$1.121(4) \cdot 10^{10}$	$1.171(13) \cdot 10^{-4}$	0.815(17)	1.26(3)
2022	28	18	$4.50(15) \cdot 10^{14}$	$4.778(19) \cdot 10^9$	$1.03(1) \cdot 10^{-4}$	0.82(3)	1.21(4)
	28	18	$4.50(15) \cdot 10^{14}$	$4.88(3) \cdot 10^9$	$1.02(1) \cdot 10^{-4}$	0.84(3)	1.28(4)
	28	18	$4.50(15) \cdot 10^{14}$	$4.78(3) \cdot 10^9$	$9.92(9) \cdot 10^{-5}$	0.85(3)	1.31(3)
	28	18	$4.50(15) \cdot 10^{14}$	$1.457(4) \cdot 10^{10}$	$1.482(12) \cdot 10^{-4}$	1.002(18)	1.28(3)
	28	18	$4.50(15) \cdot 10^{14}$	$1.232(4) \cdot 10^{10}$	$1.383(11) \cdot 10^{-4}$	1.03(3)	1.35(4)
	28	18	$4.50(15) \cdot 10^{14}$	$1.277(4) \cdot 10^{10}$	$1.408(11) \cdot 10^{-4}$	1.05(3)	1.46(4)
	32	18	$1.10(4) \cdot 10^{14}$	$5.19(3) \cdot 10^9$	$9.95(12) \cdot 10^{-5}$	0.662(17)	0.889(18)
	32	18	$1.10(4) \cdot 10^{14}$	$5.09(3) \cdot 10^9$	$9.81(8) \cdot 10^{-5}$	0.643(12)	0.911(18)
	32	18	$1.10(4) \cdot 10^{14}$	$4.79(3) \cdot 10^9$	$9.50(8) \cdot 10^{-5}$	0.648(13)	0.92(3)
	32	18	$1.10(4) \cdot 10^{14}$	$1.547(4) \cdot 10^{10}$	$1.438(11) \cdot 10^{-4}$	0.767(11)	1.080(18)
	32	18	$1.10(4) \cdot 10^{14}$	$1.478(3) \cdot 10^{10}$	$1.42(1) \cdot 10^{-4}$	0.783(15)	1.12(3)
	32	18	$1.10(4) \cdot 10^{14}$	$1.519(3) \cdot 10^{10}$	$1.414(13) \cdot 10^{-4}$	0.763(14)	0.917(17)
	24.5	12	$4.5(14) \cdot 10^{14}$	$4.68(3) \cdot 10^9$	$1.192(9) \cdot 10^{-4}$	1.13(3)	1.46(4)
	24.5	12	$4.5(14) \cdot 10^{14}$	$5.14(3) \cdot 10^9$	$1.212(16) \cdot 10^{-4}$	1.08(3)	1.40(3)
	24.5	12	$4.5(14) \cdot 10^{14}$	$5.03(3) \cdot 10^9$	$1.212(17) \cdot 10^{-4}$	1.13(3)	1.54(4)
	24.5	12	$4.5(14) \cdot 10^{14}$	$1.320(4) \cdot 10^{10}$	$1.660(17) \cdot 10^{-4}$	1.18(3)	1.58(3)
	24.5	12	$4.5(14) \cdot 10^{14}$	$1.031(3) \cdot 10^{10}$	$1.54(3) \cdot 10^{-4}$	1.19(4)	1.55(6)
	24.5	12	$4.5(14) \cdot 10^{14}$	$1.519(5) \cdot 10^{10}$	$1.79(3) \cdot 10^{-4}$	1.24(3)	1.85(5)
	26	18	$2.6(4) \cdot 10^{14}$	$4.99(3) \cdot 10^9$	$1.116(11) \cdot 10^{-4}$	1.004(17)	1.35(3)
	26	18	$2.6(4) \cdot 10^{14}$	$5.42(3) \cdot 10^9$	$1.181(17) \cdot 10^{-4}$	1.034(18)	1.39(3)
	26	18	$2.6(4) \cdot 10^{14}$	$5.39(4) \cdot 10^9$	$1.173(19) \cdot 10^{-4}$	1.021(18)	1.23(17)
	26	18	$2.6(4) \cdot 10^{14}$	$1.473(4) \cdot 10^{10}$	$1.670(20) \cdot 10^{-4}$	1.11(3)	1.341(19)
	26	18	$2.6(4) \cdot 10^{14}$	$1.492(4) \cdot 10^{10}$	$1.69(3) \cdot 10^{-4}$	1.139(16)	1.388(20)
	26	18	$2.6(4) \cdot 10^{14}$	$1.503(4) \cdot 10^{10}$	$1.70(3) \cdot 10^{-4}$	1.177(20)	1.47(3)
	26	18	$2.6(4) \cdot 10^{14}$	$1.511(4) \cdot 10^{10}$	$1.71(3) \cdot 10^{-4}$	1.164(17)	1.54(3)
	35	18	$7.8(3) \cdot 10^{13}$	$5.42(3) \cdot 10^9$	$1.179(19) \cdot 10^{-4}$	0.661(12)	0.821(13)
	35	18	$7.8(3) \cdot 10^{13}$	$5.66(3) \cdot 10^9$	$1.195(17) \cdot 10^{-4}$	0.691(18)	0.873(16)
	35	18	$7.8(3) \cdot 10^{13}$	$5.50(3) \cdot 10^9$	$1.183(19) \cdot 10^{-4}$	0.69(3)	0.893(18)
	35	18	$7.8(3) \cdot 10^{13}$	$1.435(3) \cdot 10^{10}$	$1.65(4) \cdot 10^{-4}$	0.769(18)	1.07(3)
	35	18	$7.8(3) \cdot 10^{13}$	$1.446(3) \cdot 10^{10}$	$1.645(20) \cdot 10^{-4}$	0.79(3)	1.13(4)
	35	18	$7.8(3) \cdot 10^{13}$	$1.496(4) \cdot 10^{10}$	$1.667(19) \cdot 10^{-4}$	0.799(18)	0.93(3)
	22	14	$4.3(9) \cdot 10^{14}$	$5.12(3) \cdot 10^9$	$1.194(8) \cdot 10^{-4}$	1.52(4)	1.74(4)
	22	14	$4.3(9) \cdot 10^{14}$	$5.04(4) \cdot 10^9$	$1.19(1) \cdot 10^{-4}$	1.55(5)	1.79(6)
	22	14	$4.3(9) \cdot 10^{14}$	$4.98(4) \cdot 10^9$	$1.173(7) \cdot 10^{-4}$	1.53(3)	1.96(5)
	22	14	$4.3(9) \cdot 10^{14}$	$1.246(13) \cdot 10^{10}$	$1.560(13) \cdot 10^{-4}$	1.65(4)	2.10(5)
	22	14	$4.3(9) \cdot 10^{14}$	$9.63(9) \cdot 10^9$	$1.429(12) \cdot 10^{-4}$	1.67(6)	2.24(8)
	22	14	$4.3(9) \cdot 10^{14}$	$1.290(18) \cdot 10^{10}$	$1.546(14) \cdot 10^{-4}$	1.60(3)	2.41(7)
	22	14	$4.3(9) \cdot 10^{14}$	$1.253(13) \cdot 10^{10}$	$1.554(18) \cdot 10^{-4}$	1.64(4)	1.84(4)
	35	14	$4.08(12) \cdot 10^{13}$	$5.39(3) \cdot 10^9$	$1.131(13) \cdot 10^{-4}$	0.657(13)	0.895(17)
	35	14	$4.08(12) \cdot 10^{13}$	$5.73(3) \cdot 10^9$	$1.16(1) \cdot 10^{-4}$	0.682(14)	0.922(18)

to be continued on the next page

Table A.4: Relative momentum spread and beam width at the target location for all settings with the COSY beam in the center of the target (continued).

	T [K]	p [bar]	n_T [atoms/cm ²]	N_p	σ_p/p_0	σ_x [mm]	σ_y [mm]	
2022	35	14	$4.08(12) \cdot 10^{13}$	$5.54(3) \cdot 10^9$	$1.148(13) \cdot 10^{-4}$	0.673(16)	0.942(18)	
	35	14	$4.08(12) \cdot 10^{13}$	$1.386(3) \cdot 10^{10}$	$1.58(3) \cdot 10^{-4}$	0.748(18)	0.882(16)	
	35	14	$4.08(12) \cdot 10^{13}$	$1.326(3) \cdot 10^{10}$	$1.582(20) \cdot 10^{-4}$	0.755(17)	0.932(17)	
	35	14	$4.08(12) \cdot 10^{13}$	$1.437(3) \cdot 10^{10}$	$1.605(20) \cdot 10^{-4}$	0.764(17)	0.986(15)	
	27	12	$4.0(4) \cdot 10^{14}$	$5.12(3) \cdot 10^9$	$1.149(14) \cdot 10^{-4}$	1.04(3)	1.235(19)	
	27	12	$4.0(4) \cdot 10^{14}$	$5.15(3) \cdot 10^9$	$1.158(14) \cdot 10^{-4}$	0.98(3)	1.209(17)	
	27	12	$4.0(4) \cdot 10^{14}$	$5.16(3) \cdot 10^9$	$1.145(16) \cdot 10^{-4}$	0.979(18)	1.283(19)	
	27	12	$4.0(4) \cdot 10^{14}$	$5.02(3) \cdot 10^9$	$1.145(18) \cdot 10^{-4}$	1.015(19)	1.33(3)	
	27	12	$4.0(4) \cdot 10^{14}$	$1.400(4) \cdot 10^{10}$	$1.61(3) \cdot 10^{-4}$	1.062(20)	1.44(3)	
	27	12	$4.0(4) \cdot 10^{14}$	$1.327(4) \cdot 10^{10}$	$1.60(3) \cdot 10^{-4}$	1.084(19)	1.48(3)	
	27	12	$4.0(4) \cdot 10^{14}$	$1.390(4) \cdot 10^{10}$	$1.60(3) \cdot 10^{-4}$	1.086(20)	1.59(4)	
	27	12	$4.0(4) \cdot 10^{14}$	$1.358(4) \cdot 10^{10}$	$1.59(3) \cdot 10^{-4}$	1.09(3)	1.212(20)	
	30	10	$2.25(12) \cdot 10^{14}$	$3.95(3) \cdot 10^9$	$1.056(14) \cdot 10^{-4}$	0.78(3)	1.10(3)	
	30	10	$2.25(12) \cdot 10^{14}$	$7.629(20) \cdot 10^9$	$1.32(3) \cdot 10^{-4}$	0.807(15)	1.132(15)	
	30	10	$2.25(12) \cdot 10^{14}$	$6.10(3) \cdot 10^9$	$1.231(17) \cdot 10^{-4}$	0.789(17)	1.13(3)	
	30	10	$2.25(12) \cdot 10^{14}$	$5.78(3) \cdot 10^9$	$1.199(19) \cdot 10^{-4}$	0.785(20)	0.918(13)	
	30	10	$2.25(12) \cdot 10^{14}$	$3.47(3) \cdot 10^9$	$9.97(11) \cdot 10^{-5}$	0.83(4)	1.1(14)	
	30	10	$2.25(12) \cdot 10^{14}$	$1.154(3) \cdot 10^{10}$	$1.53(3) \cdot 10^{-4}$	0.856(17)	1.24(3)	
	30	10	$2.25(12) \cdot 10^{14}$	$1.588(3) \cdot 10^{10}$	$1.73(3) \cdot 10^{-4}$	0.913(18)	1.36(3)	
	30	10	$2.25(12) \cdot 10^{14}$	$1.616(3) \cdot 10^{10}$	$1.73(3) \cdot 10^{-4}$	0.915(18)	1.134(19)	
	30	10	$2.25(12) \cdot 10^{14}$	$1.626(4) \cdot 10^{10}$	$1.72(3) \cdot 10^{-4}$	0.92(3)	1.20(3)	
	35	11.5	$1.19(4) \cdot 10^{13}$	$5.44(3) \cdot 10^9$	$1.190(19) \cdot 10^{-4}$	0.671(14)	0.782(14)	
	35	11.5	$1.19(4) \cdot 10^{13}$	$5.14(3) \cdot 10^9$	$1.164(14) \cdot 10^{-4}$	0.687(18)	0.810(18)	
	35	11.5	$1.19(4) \cdot 10^{13}$	$3.14(3) \cdot 10^9$	$9.77(12) \cdot 10^{-5}$	—	—	
	35	11.5	$1.19(4) \cdot 10^{13}$	$4.15(3) \cdot 10^9$	$1.093(13) \cdot 10^{-4}$	0.69(3)	0.86(3)	
	35	11.5	$1.19(4) \cdot 10^{13}$	$1.335(3) \cdot 10^{10}$	$1.628(18) \cdot 10^{-4}$	0.776(19)	1.004(19)	
	35	11.5	$1.19(4) \cdot 10^{13}$	$1.759(3) \cdot 10^{10}$	$1.81(3) \cdot 10^{-4}$	0.798(14)	1.083(19)	
	35	11.5	$1.19(4) \cdot 10^{13}$	$1.779(3) \cdot 10^{10}$	$1.80(3) \cdot 10^{-4}$	0.798(13)	1.130(19)	
	35	11.5	$1.19(4) \cdot 10^{13}$	$1.527(3) \cdot 10^{10}$	$1.70(3) \cdot 10^{-4}$	0.760(15)	0.862(17)	
	35	11.5	$1.19(4) \cdot 10^{13}$	$1.853(3) \cdot 10^{10}$	$1.86(3) \cdot 10^{-4}$	0.811(20)	0.923(18)	
	22	14	$4.5(6) \cdot 10^{14}$	$1.328(8) \cdot 10^{10}$	$1.600(17) \cdot 10^{-4}$	1.62(4)	2.21(5)	
	22	14	$4.5(6) \cdot 10^{14}$	$1.306(6) \cdot 10^{10}$	$1.613(16) \cdot 10^{-4}$	1.56(3)	2.22(5)	
22	14	$4.5(6) \cdot 10^{14}$	$1.412(7) \cdot 10^{10}$	$1.624(18) \cdot 10^{-4}$	1.56(4)	1.73(4)		
2023	28	10	$2.1(3) \cdot 10^{14}$	$1.95(3) \cdot 10^9$	$6.25(8) \cdot 10^{-5}$	1.19(3)	1.239(17)	
	28	10	$2.1(3) \cdot 10^{14}$	$2.079(17) \cdot 10^9$	$6.32(8) \cdot 10^{-5}$	1.23(3)	1.274(18)	
	28	10	$2.1(3) \cdot 10^{14}$	$1.97(3) \cdot 10^9$	$6.29(7) \cdot 10^{-5}$	1.21(3)	1.205(19)	
	28	10	$2.1(3) \cdot 10^{14}$	$5.00(3) \cdot 10^9$	$8.18(9) \cdot 10^{-5}$	1.273(15)	1.288(17)	
	28	10	$2.1(3) \cdot 10^{14}$	$5.14(3) \cdot 10^9$	$8.4(1) \cdot 10^{-5}$	1.261(19)	1.229(14)	
	28	10	$2.1(3) \cdot 10^{14}$	$4.996(19) \cdot 10^9$	$8.2(1) \cdot 10^{-5}$	1.211(16)	1.250(13)	
	28	10	$2.1(3) \cdot 10^{14}$	$1.436(5) \cdot 10^{10}$	$1.099(13) \cdot 10^{-4}$	1.361(19)	1.459(16)	
	28	10	$2.1(3) \cdot 10^{14}$	$1.445(5) \cdot 10^{10}$	$1.087(11) \cdot 10^{-4}$	1.324(16)	1.233(12)	
	28	10	$2.1(3) \cdot 10^{14}$	$1.335(4) \cdot 10^{10}$	$1.066(13) \cdot 10^{-4}$	1.36(3)	1.289(15)	
	35	18	$5.67(16) \cdot 10^{13}$	$2.02(3) \cdot 10^9$	$5.78(6) \cdot 10^{-5}$	0.892(19)	0.884(12)	
	to be continued on the next page							

Table A.10: Relative momentum spread and beam width at the target location for all settings with the COSY beam on the left of the target (continued).

	T [K]	p [bar]	n_T [atoms/cm ²]	N_p	σ_p/p_0	σ_x [mm]	σ_y [mm]
2022	27	12	$4.0(4) \cdot 10^{14}$	$1.400(3) \cdot 10^{10}$	$1.68(3) \cdot 10^{-4}$	1.046(20)	1.35(3)
	27	12	$4.0(4) \cdot 10^{14}$	$1.512(3) \cdot 10^{10}$	$1.77(4) \cdot 10^{-4}$	1.059(16)	1.433(20)
	27	12	$4.0(4) \cdot 10^{14}$	$1.374(3) \cdot 10^{10}$	$1.67(3) \cdot 10^{-4}$	1.037(19)	1.47(3)
	30	10	$2.25(12) \cdot 10^{14}$	$5.89(3) \cdot 10^9$	$1.266(20) \cdot 10^{-4}$	0.769(17)	0.999(17)
	30	10	$2.25(12) \cdot 10^{14}$	$3.72(3) \cdot 10^9$	$1.063(19) \cdot 10^{-4}$	0.79(3)	1.05(3)
	30	10	$2.25(12) \cdot 10^{14}$	$6.22(3) \cdot 10^9$	$1.27(3) \cdot 10^{-4}$	0.803(18)	1.074(19)
	30	10	$2.25(12) \cdot 10^{14}$	$5.45(3) \cdot 10^9$	$1.230(20) \cdot 10^{-4}$	0.793(17)	1.10(3)
	30	10	$2.25(12) \cdot 10^{14}$	$5.45(3) \cdot 10^9$	$1.220(16) \cdot 10^{-4}$	0.790(17)	0.886(15)
	30	10	$2.25(12) \cdot 10^{14}$	$1.275(3) \cdot 10^{10}$	$1.675(19) \cdot 10^{-4}$	0.868(15)	1.142(19)
	30	10	$2.25(12) \cdot 10^{14}$	$1.347(3) \cdot 10^{10}$	$1.72(4) \cdot 10^{-4}$	0.854(17)	1.21(3)
	30	10	$2.25(12) \cdot 10^{14}$	$1.314(3) \cdot 10^{10}$	$1.69(3) \cdot 10^{-4}$	0.90(3)	1.007(20)
	30	10	$2.25(12) \cdot 10^{14}$	$1.533(4) \cdot 10^{10}$	$1.81(4) \cdot 10^{-4}$	0.90(3)	1.088(20)
	35	11.5	$1.19(4) \cdot 10^{13}$	$5.30(3) \cdot 10^9$	$1.242(13) \cdot 10^{-4}$	0.690(15)	0.786(15)
	35	11.5	$1.19(4) \cdot 10^{13}$	$5.31(3) \cdot 10^9$	$1.221(16) \cdot 10^{-4}$	0.704(16)	0.823(15)
	35	11.5	$1.19(4) \cdot 10^{13}$	$5.33(3) \cdot 10^9$	$1.216(13) \cdot 10^{-4}$	0.71(3)	0.845(16)
	35	11.5	$1.19(4) \cdot 10^{13}$	$5.37(3) \cdot 10^9$	$1.242(15) \cdot 10^{-4}$	0.702(20)	0.868(19)
	35	11.5	$1.19(4) \cdot 10^{13}$	$1.608(3) \cdot 10^{10}$	$1.91(8) \cdot 10^{-4}$	0.803(15)	1.030(20)
	35	11.5	$1.19(4) \cdot 10^{13}$	$1.227(3) \cdot 10^{10}$	$1.657(19) \cdot 10^{-4}$	0.78(3)	1.034(18)
	35	11.5	$1.19(4) \cdot 10^{13}$	$1.302(3) \cdot 10^{10}$	$1.72(4) \cdot 10^{-4}$	0.788(20)	1.08(3)
	22	14	$4.5(6) \cdot 10^{14}$	$1.098(6) \cdot 10^{10}$	$1.515(13) \cdot 10^{-4}$	1.72(4)	2.25(6)
22	14	$4.5(6) \cdot 10^{14}$	$1.440(5) \cdot 10^{10}$	$1.76(3) \cdot 10^{-4}$	1.53(3)	2.12(5)	
22	14	$4.5(6) \cdot 10^{14}$	$1.477(7) \cdot 10^{10}$	$1.73(3) \cdot 10^{-4}$	1.63(4)	1.72(3)	
2023	28	10	$2.1(3) \cdot 10^{14}$	$1.95(3) \cdot 10^9$	$6.29(7) \cdot 10^{-5}$	1.215(20)	1.131(17)
	28	10	$2.1(3) \cdot 10^{14}$	$1.93(3) \cdot 10^9$	$6.32(6) \cdot 10^{-5}$	1.25(3)	1.191(15)
	28	10	$2.1(3) \cdot 10^{14}$	$2.00(4) \cdot 10^9$	$6.21(8) \cdot 10^{-5}$	1.26(3)	1.164(15)
	28	10	$2.1(3) \cdot 10^{14}$	$5.13(3) \cdot 10^9$	$8.34(8) \cdot 10^{-5}$	1.315(18)	1.222(13)
	28	10	$2.1(3) \cdot 10^{14}$	$5.244(20) \cdot 10^9$	$8.45(8) \cdot 10^{-5}$	1.261(17)	1.187(14)
	28	10	$2.1(3) \cdot 10^{14}$	$5.23(3) \cdot 10^9$	$8.27(8) \cdot 10^{-5}$	1.268(18)	1.202(11)
	28	10	$2.1(3) \cdot 10^{14}$	$1.436(3) \cdot 10^{10}$	$1.213(12) \cdot 10^{-4}$	1.349(19)	1.350(15)
	28	10	$2.1(3) \cdot 10^{14}$	$1.418(4) \cdot 10^{10}$	$1.195(14) \cdot 10^{-4}$	1.373(18)	1.159(11)
	28	10	$2.1(3) \cdot 10^{14}$	$1.410(3) \cdot 10^{10}$	$1.145(12) \cdot 10^{-4}$	1.397(18)	1.216(13)
	35	18	$5.67(16) \cdot 10^{13}$	$1.960(20) \cdot 10^9$	$5.86(7) \cdot 10^{-5}$	0.90(3)	0.862(13)
	35	18	$5.67(16) \cdot 10^{13}$	$1.989(19) \cdot 10^9$	$6.00(6) \cdot 10^{-5}$	0.91(3)	0.845(12)
	35	18	$5.67(16) \cdot 10^{13}$	$1.989(20) \cdot 10^9$	$5.98(5) \cdot 10^{-5}$	0.947(20)	0.851(15)
	35	18	$5.67(16) \cdot 10^{13}$	$5.205(14) \cdot 10^9$	$8.10(7) \cdot 10^{-5}$	0.965(17)	0.91(1)
	35	18	$5.67(16) \cdot 10^{13}$	$5.356(18) \cdot 10^9$	$8.35(9) \cdot 10^{-5}$	0.964(17)	0.905(12)
	35	18	$5.67(16) \cdot 10^{13}$	$5.10(4) \cdot 10^9$	$8.10(9) \cdot 10^{-5}$	1.015(18)	0.911(12)
	35	18	$5.67(16) \cdot 10^{13}$	$1.638(3) \cdot 10^{10}$	$1.290(20) \cdot 10^{-4}$	1.136(19)	1.050(13)
	35	18	$5.67(16) \cdot 10^{13}$	$1.4641(20) \cdot 10^{10}$	$1.217(11) \cdot 10^{-4}$	1.17(3)	1.017(13)
	35	18	$5.67(16) \cdot 10^{13}$	$1.659(3) \cdot 10^{10}$	$1.303(18) \cdot 10^{-4}$	1.136(18)	1.032(12)
	24	12	$4.9(6) \cdot 10^{14}$	$1.03(5) \cdot 10^9$	$7.44(8) \cdot 10^{-5}$	2.42(8)	2.26(6)
	24	12	$4.9(6) \cdot 10^{14}$	$1.03(4) \cdot 10^9$	$7.18(7) \cdot 10^{-5}$	2.29(7)	2.11(5)
24	12	$4.9(6) \cdot 10^{14}$	$8.5(4) \cdot 10^8$	$6.98(9) \cdot 10^{-5}$	2.35(9)	2.13(5)	
to be continued on the next page							

Table A.11: Relative momentum spread and beam width at the target location for all settings with the COSY beam on the left of the target (continued).

	T [K]	p [bar]	n_T [atoms/cm ²]	N_p	σ_p/p_0	σ_x [mm]	σ_y [mm]
2023	24	12	$4.9(6) \cdot 10^{14}$	$2.40(8) \cdot 10^9$	$8.21(9) \cdot 10^{-5}$	2.15(6)	1.97(5)
	24	12	$4.9(6) \cdot 10^{14}$	$2.15(7) \cdot 10^9$	$8.23(7) \cdot 10^{-5}$	2.33(8)	2.10(6)
	24	12	$4.9(6) \cdot 10^{14}$	$2.32(7) \cdot 10^9$	$8.11(9) \cdot 10^{-5}$	2.17(6)	2.00(5)
	24	12	$4.9(6) \cdot 10^{14}$	$6.69(19) \cdot 10^9$	$1.050(13) \cdot 10^{-4}$	2.06(7)	1.97(6)
	24	12	$4.9(6) \cdot 10^{14}$	$6.67(19) \cdot 10^9$	$1.056(13) \cdot 10^{-4}$	2.09(7)	1.96(6)
	24	12	$4.9(6) \cdot 10^{14}$	$6.61(18) \cdot 10^9$	$1.050(12) \cdot 10^{-4}$	2.07(8)	1.96(6)
	35	16	$3.71(9) \cdot 10^{13}$	$2.03(3) \cdot 10^9$	$5.62(6) \cdot 10^{-5}$	0.95(3)	0.835(14)
	35	16	$3.71(9) \cdot 10^{13}$	$1.93(3) \cdot 10^9$	$5.59(8) \cdot 10^{-5}$	0.93(3)	0.835(14)
	35	16	$3.71(9) \cdot 10^{13}$	$2.00(3) \cdot 10^9$	$5.69(6) \cdot 10^{-5}$	0.947(20)	0.825(14)
	35	16	$3.71(9) \cdot 10^{13}$	$5.02(3) \cdot 10^9$	$7.84(6) \cdot 10^{-5}$	0.98(3)	0.872(15)
	35	16	$3.71(9) \cdot 10^{13}$	$4.91(3) \cdot 10^9$	$7.55(6) \cdot 10^{-5}$	0.961(19)	0.883(15)
	35	16	$3.71(9) \cdot 10^{13}$	$5.15(3) \cdot 10^9$	$7.66(7) \cdot 10^{-5}$	0.97(3)	0.886(14)
	35	16	$3.71(9) \cdot 10^{13}$	$1.454(3) \cdot 10^{10}$	$1.213(19) \cdot 10^{-4}$	1.088(19)	0.998(13)
	35	16	$3.71(9) \cdot 10^{13}$	$1.427(3) \cdot 10^{10}$	$1.201(17) \cdot 10^{-4}$	1.09(3)	0.986(13)
	35	16	$3.71(9) \cdot 10^{13}$	$1.554(3) \cdot 10^{10}$	$1.186(19) \cdot 10^{-4}$	1.097(19)	1.008(12)
	30	18	$9.6(16) \cdot 10^{13}$	$2.02(3) \cdot 10^9$	$6.33(9) \cdot 10^{-5}$	1.055(19)	1.024(13)
	30	18	$9.6(16) \cdot 10^{13}$	$1.91(3) \cdot 10^9$	$6.36(12) \cdot 10^{-5}$	1.059(19)	1.021(17)
	30	18	$9.6(16) \cdot 10^{13}$	$1.99(3) \cdot 10^9$	$6.39(11) \cdot 10^{-5}$	1.04(3)	0.959(13)
	30	18	$9.6(16) \cdot 10^{13}$	$5.20(3) \cdot 10^9$	$8.28(9) \cdot 10^{-5}$	1.167(18)	1.067(16)
	30	18	$9.6(16) \cdot 10^{13}$	$4.93(3) \cdot 10^9$	$8.3(1) \cdot 10^{-5}$	1.15(3)	1.025(13)
	30	18	$9.6(16) \cdot 10^{13}$	$1.706(3) \cdot 10^{10}$	$1.29(3) \cdot 10^{-4}$	1.26(3)	1.183(14)
	30	18	$9.6(16) \cdot 10^{13}$	$1.518(3) \cdot 10^{10}$	$1.250(17) \cdot 10^{-4}$	1.227(20)	1.160(17)
	30	18	$9.6(16) \cdot 10^{13}$	$1.602(3) \cdot 10^{10}$	$1.26(3) \cdot 10^{-4}$	1.217(18)	1.181(14)
	35	12	$1.10(3) \cdot 10^{13}$	$2.122(15) \cdot 10^9$	$5.95(7) \cdot 10^{-5}$	0.91(3)	0.793(13)
	35	12	$1.10(3) \cdot 10^{13}$	$1.43(3) \cdot 10^9$	$5.26(7) \cdot 10^{-5}$	0.89(3)	0.785(20)
	35	12	$1.10(3) \cdot 10^{13}$	$1.92(3) \cdot 10^9$	$5.62(7) \cdot 10^{-5}$	0.90(3)	0.786(11)
	35	12	$1.10(3) \cdot 10^{13}$	$5.400(15) \cdot 10^9$	$7.99(8) \cdot 10^{-5}$	0.93(3)	0.837(11)
	35	12	$1.10(3) \cdot 10^{13}$	$5.22(3) \cdot 10^9$	$7.80(8) \cdot 10^{-5}$	0.94(3)	0.839(12)
	35	12	$1.10(3) \cdot 10^{13}$	$5.12(3) \cdot 10^9$	$7.81(6) \cdot 10^{-5}$	0.94(3)	0.837(12)
	35	12	$1.10(3) \cdot 10^{13}$	$1.493(3) \cdot 10^{10}$	$1.206(18) \cdot 10^{-4}$	1.07(3)	0.966(12)
	35	12	$1.10(3) \cdot 10^{13}$	$1.635(3) \cdot 10^{10}$	$1.222(19) \cdot 10^{-4}$	1.10(3)	0.986(11)
	35	12	$1.10(3) \cdot 10^{13}$	$1.638(3) \cdot 10^{10}$	$1.208(19) \cdot 10^{-4}$	1.099(19)	0.977(12)
	—	—	0	$1.980(20) \cdot 10^9$	$5.38(6) \cdot 10^{-5}$	0.919(18)	0.828(13)
	—	—	0	$5.29(3) \cdot 10^9$	$7.62(7) \cdot 10^{-5}$	0.95(3)	0.848(13)
	—	—	0	$1.472(3) \cdot 10^{10}$	$1.146(17) \cdot 10^{-4}$	1.07(3)	0.991(13)

Table A.16: Relative momentum spread and beam width at the target location for all settings with the COSY beam on the right of the target (continued).

	T [K]	p [bar]	n_T [atoms/cm ²]	N_p	σ_p/p_0	σ_x [mm]	σ_y [mm]
2023	24	12	$4.9(6) \cdot 10^{14}$	$1.04(5) \cdot 10^9$	$7.0(1) \cdot 10^{-5}$	2.29(7)	2.33(5)
	24	12	$4.9(6) \cdot 10^{14}$	$1.02(4) \cdot 10^9$	$7.3(1) \cdot 10^{-5}$	2.27(6)	2.42(6)
	24	12	$4.9(6) \cdot 10^{14}$	$1.07(4) \cdot 10^9$	$7.2(1) \cdot 10^{-5}$	2.27(7)	2.34(5)
	24	12	$4.9(6) \cdot 10^{14}$	$2.27(8) \cdot 10^9$	$8.09(7) \cdot 10^{-5}$	2.31(7)	2.31(6)
	24	12	$4.9(6) \cdot 10^{14}$	$2.41(7) \cdot 10^9$	$7.88(8) \cdot 10^{-5}$	2.17(6)	2.19(5)
	24	12	$4.9(6) \cdot 10^{14}$	$2.69(8) \cdot 10^9$	$8.1(1) \cdot 10^{-5}$	2.10(7)	2.20(5)
	24	12	$4.9(6) \cdot 10^{14}$	$6.4(3) \cdot 10^9$	$1.03(1) \cdot 10^{-4}$	2.20(8)	2.35(7)
	24	12	$4.9(6) \cdot 10^{14}$	$6.78(18) \cdot 10^9$	$1.033(12) \cdot 10^{-4}$	2.10(6)	2.16(5)
	24	12	$4.9(6) \cdot 10^{14}$	$6.22(16) \cdot 10^9$	$9.94(11) \cdot 10^{-5}$	2.14(8)	2.22(7)
	35	16	$3.71(9) \cdot 10^{13}$	$2.04(3) \cdot 10^9$	$5.18(8) \cdot 10^{-5}$	0.90(3)	0.873(15)
	35	16	$3.71(9) \cdot 10^{13}$	$2.00(3) \cdot 10^9$	$5.56(8) \cdot 10^{-5}$	0.93(3)	0.865(16)
	35	16	$3.71(9) \cdot 10^{13}$	$1.96(3) \cdot 10^9$	$5.27(6) \cdot 10^{-5}$	0.89(3)	0.869(13)
	35	16	$3.71(9) \cdot 10^{13}$	$4.997(19) \cdot 10^9$	$7.56(7) \cdot 10^{-5}$	0.94(3)	0.905(14)
	35	16	$3.71(9) \cdot 10^{13}$	$4.880(18) \cdot 10^9$	$7.14(8) \cdot 10^{-5}$	0.96(3)	0.921(17)
	35	16	$3.71(9) \cdot 10^{13}$	$4.87(3) \cdot 10^9$	$7.28(9) \cdot 10^{-5}$	0.940(17)	0.910(15)
	35	16	$3.71(9) \cdot 10^{13}$	$1.557(3) \cdot 10^{10}$	$1.235(16) \cdot 10^{-4}$	1.080(20)	1.051(15)
	35	16	$3.71(9) \cdot 10^{13}$	$1.714(3) \cdot 10^{10}$	$1.24(3) \cdot 10^{-4}$	1.071(17)	1.071(13)
	35	16	$3.71(9) \cdot 10^{13}$	$1.442(3) \cdot 10^{10}$	$1.160(19) \cdot 10^{-4}$	1.064(20)	1.034(15)
	30	18	$9.6(16) \cdot 10^{13}$	$2.03(3) \cdot 10^9$	$6.05(11) \cdot 10^{-5}$	1.06(3)	1.065(17)
	30	18	$9.6(16) \cdot 10^{13}$	$1.90(4) \cdot 10^9$	$5.9(1) \cdot 10^{-5}$	1.00(3)	1.028(14)
	30	18	$9.6(16) \cdot 10^{13}$	$1.866(18) \cdot 10^9$	$6.06(12) \cdot 10^{-5}$	1.04(3)	1.021(17)
	30	18	$9.6(16) \cdot 10^{13}$	$5.11(3) \cdot 10^9$	$8.07(8) \cdot 10^{-5}$	1.152(20)	1.111(14)
	30	18	$9.6(16) \cdot 10^{13}$	$5.03(3) \cdot 10^9$	$8.07(11) \cdot 10^{-5}$	1.106(17)	1.091(12)
	30	18	$9.6(16) \cdot 10^{13}$	$5.08(3) \cdot 10^9$	$8.29(14) \cdot 10^{-5}$	—	—
	30	18	$9.6(16) \cdot 10^{13}$	$1.454(3) \cdot 10^{10}$	$1.23(3) \cdot 10^{-4}$	1.22(3)	1.233(18)
	30	18	$9.6(16) \cdot 10^{13}$	$1.353(4) \cdot 10^{10}$	$1.166(18) \cdot 10^{-4}$	1.161(16)	1.220(19)
	30	18	$9.6(16) \cdot 10^{13}$	$1.679(3) \cdot 10^{10}$	$1.27(3) \cdot 10^{-4}$	1.182(15)	1.255(16)
	35	12	$1.10(3) \cdot 10^{13}$	$1.887(16) \cdot 10^9$	$5.54(8) \cdot 10^{-5}$	0.89(3)	0.800(13)
	35	12	$1.10(3) \cdot 10^{13}$	$1.449(19) \cdot 10^9$	$5.2(1) \cdot 10^{-5}$	0.87(3)	0.787(16)
	35	12	$1.10(3) \cdot 10^{13}$	$2.038(14) \cdot 10^9$	$5.69(6) \cdot 10^{-5}$	0.89(3)	0.796(13)
	35	12	$1.10(3) \cdot 10^{13}$	$5.33(3) \cdot 10^9$	$7.85(9) \cdot 10^{-5}$	0.922(16)	0.877(11)
	35	12	$1.10(3) \cdot 10^{13}$	$4.794(17) \cdot 10^9$	$7.42(7) \cdot 10^{-5}$	0.91(3)	0.867(13)
	35	12	$1.10(3) \cdot 10^{13}$	$5.38(3) \cdot 10^9$	$7.76(8) \cdot 10^{-5}$	0.919(19)	0.861(15)
	35	12	$1.10(3) \cdot 10^{13}$	$1.5265(20) \cdot 10^{10}$	$1.201(16) \cdot 10^{-4}$	1.06(3)	1.031(14)
	35	12	$1.10(3) \cdot 10^{13}$	$1.615(3) \cdot 10^{10}$	$1.208(17) \cdot 10^{-4}$	1.054(19)	1.027(15)
	35	12	$1.10(3) \cdot 10^{13}$	$1.5119(20) \cdot 10^{10}$	$1.204(18) \cdot 10^{-4}$	1.03(3)	1.000(13)
	—	—	0	$2.03(3) \cdot 10^9$	$4.97(9) \cdot 10^{-5}$	0.88(3)	0.863(14)
	—	—	0	$5.03(3) \cdot 10^9$	$6.95(6) \cdot 10^{-5}$	0.92(3)	0.883(14)
	—	—	0	$1.370(3) \cdot 10^{10}$	$1.081(11) \cdot 10^{-4}$	1.051(20)	1.010(14)

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