

The next generation of cryogenic hydrogen targets:

Innovations surrounding target systems for particle and plasma physics

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Zusammenfassung

Die Cluster-Jet Targets der AG Khoukaz wurden schon an diversen Teilchenbeschleunigerexperimenten wie COSY-11, ANKE und A1 eingesetzt, aber auch an Plasmaphysikexperimenten wie CryoFlash. Für die zukünftigen Experimente $\bar{\text{PANDA}}$ und MAGIX sind Cluster-jet Targets auch schon fest vorgesehen. Möglich wird dieser Erfolg durch die konstante Verbesserung und Innovation von diesen Targetsystemen, weshalb sich diese Arbeit ihrer Weiterentwicklung widmet.

Es gibt Bedenken, dass das Cluster-Jet Target am $\bar{\text{PANDA}}$ Experiment für signifikante Mengen an Restgas sorgen wird, unter der die Präzision des Experiments und die Lebensdauer des Beschleunigerstrahls leiden könnte. Um dem zu begegnen wurde in dieser Arbeit eine Kryopumpe designt. Eine solche Pumpe besitzt die Vorteile, dass sie bei einem kleinen Formfaktor enorme Pumpleistungen bereitstellen kann während ihre Form an die örtlichen Gegebenheiten angepasst werden kann, zum Beispiel um den Leitwert zu maximieren. Die Kryopumpe für $\bar{\text{PANDA}}$ sollte so designt werden, dass sie unmittelbar in das Beschleunigerstrahlrohr eingebaut werden kann. Dazu wurden mithilfe von Vakuumsimulationen mehrere rohrartige Kryopumpengeometrien auf ihre Tauglichkeit getestet und festgestellt, dass sie alle das Restgas ähnlich stark vermindern können. Jedoch wurde festgestellt, dass die Regenerationsintervalle der einzelnen Kryopumpen sich deutlich unterscheiden, sodass hier eine Vorauswahl getroffen werden konnte.

Zusätzlich wurde beobachtet, dass die Pumpen desto effektiver sind, je näher sie am Interaktionspunkt zwischen Beschleuniger- und Targetstrahl montiert sind. Aufgrund der sehr begrenzten Auswahl an möglichen Installationspunkten für die Kryopumpe an $\bar{\text{PANDA}}$ wird diese Information so ausgenutzt, dass die Kryopumpe mit möglichst großer Länge gestaltet werden sollte, damit sie möglichst nah an den Interaktionspunkt gelangen kann. Es gibt aber nur begrenzt viel Kühlleistung, die bereitgestellt werden kann, sodass Temperatursimulationen vonnöten waren um die maximale Länge auszuloten. Somit wurde insgesamt bestimmt, dass die Kryopumpe in der sogenannten Finnengeometrie bei einer Länge von 80 cm konstruiert werden sollte und mit einem Wärmeschild ausgestattet werden sollte. Zusätzlich wurde die Machbarkeit eines neuartigen Regenerationsverfahrens überprüft, der die Betriebsunterbrechung durch Regeneration minimisieren soll.

Das Cluster-jet Target für $\bar{\text{PANDA}}$ soll in Zukunft auch als Pellettargget einsetzbar sein. Die dazu nötigen Modifikationen wurden am Cluster-jet Target MCT-D getestet, wobei festgestellt wurde, dass es große Schwierigkeiten gab, genügend Kühlleistung bereitzustellen und dass andauernde Düsenverstopfungen den Fortschritt verlangsamten. Aus diesen Gründen wurde entschieden, mit einem neuen, dedizierten Pellettargget weiterzuarbeiten, dem MDT-H. Mit diesem Target gab es keinerlei Schwierigkeiten mit

der Kühlung und auch die Frequenz an Düsenverstopfungen wurde dank der verbesserten Sauberkeit stark reduziert.

Es wurden MDT-Hs Resonanzfrequenzen bestimmt, aber es konnten noch keine Pellets erzeugt werden. Grund hierfür ist, dass der Targetstrahl im Vakuum so schnell ausfriert, dass er keine Chance hat aufzubrechen. In Zukunft könnte durch gezielte Verschlechterung des Vakuums in der Nähe der Düse Abhilfe geschaffen werden. Nichtsdestotrotz konnte auf anderen Gebieten Fortschritte erzielt werden. So wurde ein neues System zum ersten Mal getestet, mit dem der Targetstrahl ohne großen mechanischen Aufwand gelenkt werden kann. Diese Innovation ist besonders vielversprechend, da sie eine Möglichkeit bietet den Winkel des Strahls sowie seine Position zu kontrollieren, während seine Stabilität größtenteils gewahrt bleibt. Zusätzlich wurde die Stabilität des Targets über einen Zeitraum von 100 h untersucht und ein Elektronenmikroskop verwendet um die Herkunft der Düsenverstopfungen genauer zu verstehen, was entscheidend für ihre Bekämpfung ist.

Mit dem Cluster-jet Target MCT-D wurde in enger Zusammenarbeit mit dem Team von Prof. Dr. O. Willi der HHU Düsseldorf die plasmabasierte Beschleunigung von Protonen untersucht. Dazu wurde der Clusterstrahl von einem Hochleistungslaser beleuchtet, wodurch ein Protonenplasma erzeugt wurde, dass anschließend explodierte und beschleunigte Protonen erzeugte.

Dabei wurden ähnliche Protonenenergien im Multi-MeV Bereich wie in vergleichbaren Experimenten erzeugt, es konnte aber zusätzlich gezeigt werden, dass in vielen Fällen die Beschleunigung anisotropisch erfolgt und zudem vom Laserkontrast abhängt. Zusätzlich konnte mit diesen Messungen der Clusterstrahl an sich untersucht werden. So wurde ein neuer mittlerer Abstand der Cluster untereinander bestimmt, der eine Größenordnung kleiner ist als frühere Messungen. Da das frühere Ergebnis nur den Abstand von Clustern mit Größen im Mikrometerbereich betrachtet und die neue Messung auch Cluster mit Durchmessern im Bereich von ca. 160 nm aufwärts berücksichtigt, wird nahegelegt, dass der Clusterstrahl eine große Menge solcher kleiner Cluster beherbergt.

Abstract

The AG Khoukaz cluster-jet targets have not only found use in several particle physics experiments such as COSY-11, ANKE and A1 but also in plasma physics experiments such as CryoFlash. Furthermore, they are already firmly planned for future experiments such as $\bar{\text{PANDA}}$ and MAGIX. This continued success is only possible through constant improvement and development of the target systems, which is the reason why this thesis is dedicated to innovation.

There are concerns that the rest-gas introduced by a cluster-jet target during operation might adversely effect $\bar{\text{PANDA}}$'s precision and the accelerator beam lifetime. To alleviate these issues a cryopump to remove this gas was proposed, as these pumps have the advantage of large pumping speeds while maintaining a small form factor and have an easily adaptable geometry, for example to optimise conductivity. In the context of this thesis, a cryopump was designed to be installed directly into the accelerator beam pipe. To do so, several tube shaped cryopump geometries were tested with vacuum simulations and it was found that all of them reduce the rest-gas by a similar amount. However, it was found that they all possess significantly different regeneration intervals so that an initial selection could already be made.

Additionally, it was observed that the pumps perform better the closer they are mounted to the interaction point between accelerator and target beam. Due to the limited choice of cryopump installation points, this information is interpreted as that the pump should be designed as long as possible to move it nearer to the interaction point. As this length is limited by the available cooling power, temperature simulations were performed to determine the maximum length. In addition, simulations were made to test the feasibility of a novel regeneration procedure designed to minimise downtime. Altogether, it was determined that the cryopump should possess a heat shield and be constructed in the "fin geometry" at a length of 80 cm.

In future, the cluster-jet target for $\bar{\text{PANDA}}$ is supposed to also be useable as a pellet target. The necessary modifications have been tested with the cluster-jet target MCT-D, where large difficulties in achieving sufficient cooling were noted while constant nozzle blockages greatly slowed down progress. For these reasons it was decided to proceed further with a dedicated pellet target, the MDT-H. With this target, no cooling issues were observed and the much lower rate of nozzle blockages enabled rapid progress.

MDT-H's resonance frequencies were experimentally determined to facilitate pellet generation, however, proper break up into pellets remains to be observed. The reason for this is that the target beam freezes out so quickly in vacuum that it has no chance to break up. In future, this issue could be solved by deliberately degrading the vacuum conditions near the nozzle. Nonetheless, progress could be made in other areas. A novel system was tested with which the beam direction can be controlled with little

effort. This innovation is especially promising as it provides the possibility of controlling the target beam in all spatial and angular dimensions while maintaining its stability. Additionally, target reliability and stability was studied over a time period over 100 h while an electron microscope was employed to better understand the origins of the nozzle blockages, key information for effectively combatting them.

The cluster-jet target MCT-D was used to study plasma based proton acceleration in close cooperation with the group of Prof. Dr. O. Willi from the HHU Düsseldorf. To this end, the cluster beam was illuminated by a high power laser system, creating a plasma which subsequently explodes and thus accelerates protons.

Similar to comparable experiments, proton energies in the multi-MeV regime were reached. In addition, our experiments proved that the acceleration is often anisotropic and dependent on the laser contrast. Apart from particle acceleration, these measurements were also used to gain more knowledge on the cluster beam. As a result, a new mean distance between clusters could be determined, which is one order of magnitude smaller than previously calculated. Since the previous effort only considered clusters in the micron diameter range and above and the new value also takes clusters with diameters down to 160 nm into account, this suggests that the beam contains a large amount of clusters in the size regime of a few 100 nm.

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1. Introduction

Things are only impossible until
they're not.

(Captain Jean-Luc Picard)

At the target division of the AG Khoukaz, we specialise in the Münster cryogenic jet targets, which provide a high quality, continuous and windowless internal target. They all function based on the same principle. By pressing cryogenic gas, mostly hydrogen, through a de Laval nozzle, a directed jet is created. Depending on the exact operation parameters, the jet can either take the form of clusters, frozen hydrogen particles with sizes ranging from tens of nanometres to several microns in diameter [Kohl 15, Mann 19, Eick 23], thus forming a cluster-jet, or remain as a gas jet. With this simple design, they have been remarkably successful in particle physics, specifically in experiments studying hadrons such as COSY-11 (COoler SYnchrotron) [Prze 07] or ANKE (Apparatus for Studies of Nucleon and Kaon Ejectiles) [Bars 01] and they are now firmly planned as the targets for upcoming experiments such as $\bar{\text{P}}\text{ANDA}$ (antiProton ANnihilation at DArmstadt) [Baru 21, Beli 23] or MAGIX (MESA Gas Internal target eXperiment) [Grie 18b] which will study hadrons and the proton radius respectively, among other topics. They have even found application in other fields such as plasma physics, where a cluster-jet target was used to study proton and electron acceleration as well as X-ray generation as part of the CryoFlash experiment [Aura 19]. These achievements were only possible due to the constant improvement and development of the target systems and so to guarantee further success, innovating and advancing the targets as well as surrounding systems was the main focus of the work in the scope of this thesis.

An example can readily be found at the future $\bar{\text{P}}\text{ANDA}$ experiment, which will use proton anti-proton interactions for QCD studies, for example the search for exotic particles [Baru 21]. Here, a cluster-jet target will be used as the Phase One target. While the target reaches high thicknesses of $> 1 \cdot 10^{15}$ atoms/cm², it will simultaneously introduce high amounts rest-gas into the vacuum system [Klos 20], with possible adverse effects on the beam life time. While the studies to determine the root causes are still ongoing [Weid 23, Weid 24] preparations to tackle this issue have already begun.

The plan is to remove the gas through a cryopump, as this technology possesses both a high pumping speed as well as the capability of being installed directly in the beam pipe, thus maximising conductance. Currently, there is no commercial design optimally suited to $\bar{\text{P}}\text{ANDA}$, so the decision was made to construct a custom pump, the design of which is presented in exhaustive detail in this thesis (cf. chapter 3). This entails determining possible locations for the pump at $\bar{\text{P}}\text{ANDA}$ and simulating its impact on the vacuum with the most advanced target beam models available to determine

1. Introduction

the optimal geometry. In addition, detailed temperature simulations give additional insight into the possible sizes the pump can reach, so that important information such as pumping speed, regeneration interval and effect on the rest-gas can be given even before a first prototype is built.

In addition to a cluster-jet target, $\overline{\text{PANDA}}$ will also employ a pellet target¹, providing a steady supply of mono-sized, well separated hydrogen pellets with diameters in the tens of microns. To optimise the experiment's efficiency, we performed extensive studies within the framework of this thesis to determine the feasibility of using a cluster-jet target as a pellet target with minimal modifications (cf. chapter 4). While we found that this was possible quite easily, we encountered significant issues concerning the reliability of the pellet target, which have already been seen previously [Frag 15, DePo 08]. So we installed a new dedicated pellet target, the first of its kind at the University of Münster, with an innovative cooling system which brought improved cleanliness and stability with it. Thus further innovations could be unlocked, such as a novel and powerful method to control the target beam called cryobending.

As alluded to before, Münster cluster-jet targets have found use in plasma physics as part of CryoFlash. This thesis presents a follow up to these experiments (cf. chapter 5), accelerating protons to multi-MeV energies while providing new insights into the underlying reactions compared to other recent publications [Jinn 22]. The rate at which such energies can be reached remains quite poor, however, the newly developed pellet target provides the possibility to solve this issue, giving an exciting perspective to make use of our innovations.

¹This target type is also frequently referred to as a droplet target in this thesis, since the pellets start out as liquid droplets before invariably freezing out in vacuum. For our purposes, pellets and droplets are synonymous.

2. The $\overline{\text{PANDA}}$ experiment

The $\overline{\text{PANDA}}$ experiment plays a prominent role in this thesis, as both the cryopump and the droplet target are being developed with this experiment in mind. $\overline{\text{PANDA}}$ (antiProton ANnihilation at DArmstadt) will be located at the accelerator facility FAIR (Facility for Antiproton and Ion Research) which is currently under construction at GSI (GSI Helmholtzzentrum für Schwerionenforschung) and will use proton-antiproton reactions to analyse properties of the strong interaction.

This chapter introduces the basics of hadron physics and the open questions remaining therein before giving a detailed overview of the $\overline{\text{PANDA}}$ experiment and how the Münster targets will be implemented.

2.1. Hadron physics

The standard model is an incredibly successful theory which describes three of the four fundamental forces in the universe, namely the strong interaction, the weak interaction and electromagnetism. Nonetheless, there are some areas where open questions remain, for example the existence of exotic particles or the behaviour of quantum chromodynamics in the low energy limit. This section will give a basic overview over the fundamental physics governing the strong interaction and hadronic matter, which are necessary to understand $\overline{\text{PANDA}}$'s purpose.

2.1.1. The Standard Model and the Strong Interaction

The standard model divides the elementary particles into quarks, leptons, gauge bosons and the Higgs boson (cf. fig. 2.1).

The quarks are further subdivided into six types, three up-type ones which carry a charge¹ of $\frac{2}{3}e$ and three which are of down-type with $-\frac{1}{3}e$. All of them are point like with a spin of $\frac{1}{2}$ and an associated anti-particle with opposite charge. In addition, all quarks carry one of six possible colour charges, (anti-)red, (anti-)green and (anti-)blue. The strong interaction acts exclusively upon these colour charges by exchanging colours between quarks via the massless gluons (cf. fig. 2.2). This means that gluons necessarily carry a colour charge of their own which enables them to perform self interactions (cf. fig. 2.2). At the same time, the coupling constant α_s of the strong interaction is not constant, instead it is described by [Klem 01]

$$\alpha_s = \frac{12\pi}{(33 - 2N_f) \ln |q^2/\Lambda^2|}, \quad (2.1)$$

¹in this context, e denotes the elementary charge.

2. The $\bar{P}ANDA$ experiment



Figure 2.1.: The standard model of particle physics, consisting of six quarks, six leptons and 5 bosons. (Based on [Rump 19] with data from [Nava 24])

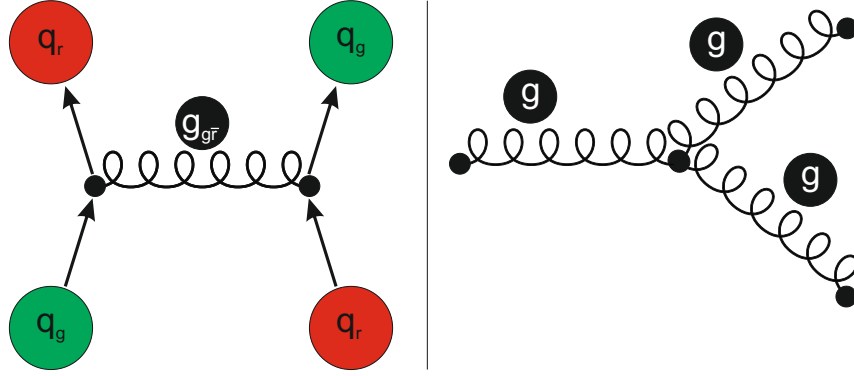


Figure 2.2.: **Left:** Two quarks interact via a gluon. By exchanging a gluon with the colours green anti-red, the two quarks swap colours. **Right:** Gluon self interaction. As gluons carry a colour charge of their own, they can interact with other gluons or even themselves via the strong interaction.

where N_f is the number of quark flavours, q^2 the momentum transfer and Λ^2 a scaling factor. Together with gluon self interaction this "running" coupling gives rise to a unique feature of the strong interaction: confinement. Confinement describes the phenomenon that individual quarks cannot be observed, instead only appearing in colourless states. As an example one can consider a meson, which consists of a quark and anti-quark. If one would try to separate the quark pair from each other (cf. fig. 2.3), α_s would increase, as a larger distance constitutes a small q^2 . The resultant quark-antiquark potential V_s is given by

$$V_s = -\frac{4}{3} \frac{\alpha_s}{r} + kr \quad (2.2)$$

with the distance between quarks given by r and the QCD string tension by k . With this potential, increasing the distance requires more and more energy until there is so much contained in this field that the gluon self interaction creates a new quark anti-quark pair, thus maintaining confinement.

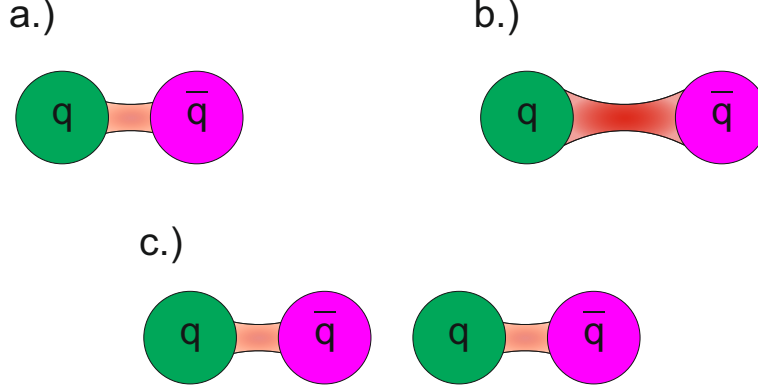


Figure 2.3.: Separation of an anti-quark quark pair. Increasing the distance from a.) to b.), in turn leads to an increase in the strength of the strong interaction until enough energy is contained in the field for a new anti-quark quark pair to be formed (c.).

2.1.2. Hadronic matter

Hadrons are qualified as matter formed by the strong interaction and are thus necessarily colour-free. To achieve this, hadrons either take the form of states called baryons consisting of three quarks with the colours red, green and blue, respectively, so that the particle is colourless in total, or hadrons appear as a quark anti-quark state, also called meson, where the combination of colour and corresponding anti-colour leads to a colourless state. There are further possibilities to achieve colourless particles, which are called exotics and will be discussed in more detail below (cf. section 2.1.3).

To further classify baryons two quantum number are used: The total angular momentum $\vec{J}$ and the total parity P while for mesons the charge conjugation C is used in addition.

The total angular momentum is given by adding the particle's total spin $\vec{s}$ and total orbital angular momentum $\vec{l}$

$$\vec{J} = \vec{s} + \vec{l}. \quad (2.3)$$

The parity operator $\hat{P}$ reverses the spatial coordinate of a wave function ψ :

$$\hat{P}\psi(t, \vec{x}) = \psi(t, -\vec{x}). \quad (2.4)$$

Applying $\hat{P}$ to a quark is defined as positive $\hat{P}(q) = 1$ while doing the same to an anti-quark is negative $\hat{P}(q) = -1$. So for the parity of a baryon and a meson following

2. The $\overline{\text{PANDA}}$ experiment

expressions are found:

$$P(qqq) = P(q)P(q)P(q)(-1)^l = (-1)^l \quad (2.5)$$

$$P(q\bar{q}) = P(q)P(\bar{q})(-1)^l = (-1)^{l+1}. \quad (2.6)$$

The charge conjugation operator $\hat{C}$ transforms a particle into the corresponding anti-particle. The C-parity of a particle can be calculated by

$$C = (-1)^{l+s}. \quad (2.7)$$

Using these quantum numbers, hadrons can be classified, for example, baryons are divided into the baryon octet ($J^P = 1/2^+$) or decuplet while mesons are sorted into the pseudo scalar mesons ($J^{PC} = 0^{-+}$) or vector mesons ($J^{PC} = 1^{--}$) among other categories.

2.1.3. Exotic particles

However, baryons and mesons are not the only conceivable matter states formed by the strong interaction. For example, matter consisting of more than three (anti-) quarks is theoretically possible, such as the tetraquark which consists of two quark-antiquark pairs ($qq\bar{q}\bar{q}$), the quark molecule which is made up of two mesons bound together or the pentaquark, which is formed by four quarks and a lone anti-quark ($qqqq\bar{q}$). There already exists evidence for quark molecules, such as the $a_0(980)$ or the $f_0(980)$ [Yao 06] and at least one pentaquark has already been identified, the $P_c(4450^+)$ [Aaij 19].

But states of matter only containing quarks are not the only candidates for exotic particles. Instead, there could also be particles with gluons as constituents, either in the form of being made up entirely from gluons as a glueball or as a hybrid containing both quarks and gluons ($q\bar{q}g$). There are also candidates for these types of particles, such as the $f_0(1370)$, $f_0(1500)$ and $f_0(1700)$ in the case of the glueball [Amsl 04], or the $\pi_1(1600)$ in the case of hybrids [Amsl 04].

One of $\overline{\text{PANDA}}$'s key aims will be the investigation of such exotic particles which appear as meson-like states.

2.2. The $\overline{\text{PANDA}}$ experiment

$\overline{\text{PANDA}}$ will be located at the future FAIR facility, which is currently being constructed at the pre-existing GSI located near Darmstadt. This section will briefly introduce FAIR and explain the mechanisms generating the anti-proton beam before introducing $\overline{\text{PANDA}}$'s physics goals, its experimental setup and the requirements it has on its targets.

2.2.1. FAIR

Overall, the FAIR facility will have four major scientific focal points [Fort 12]:

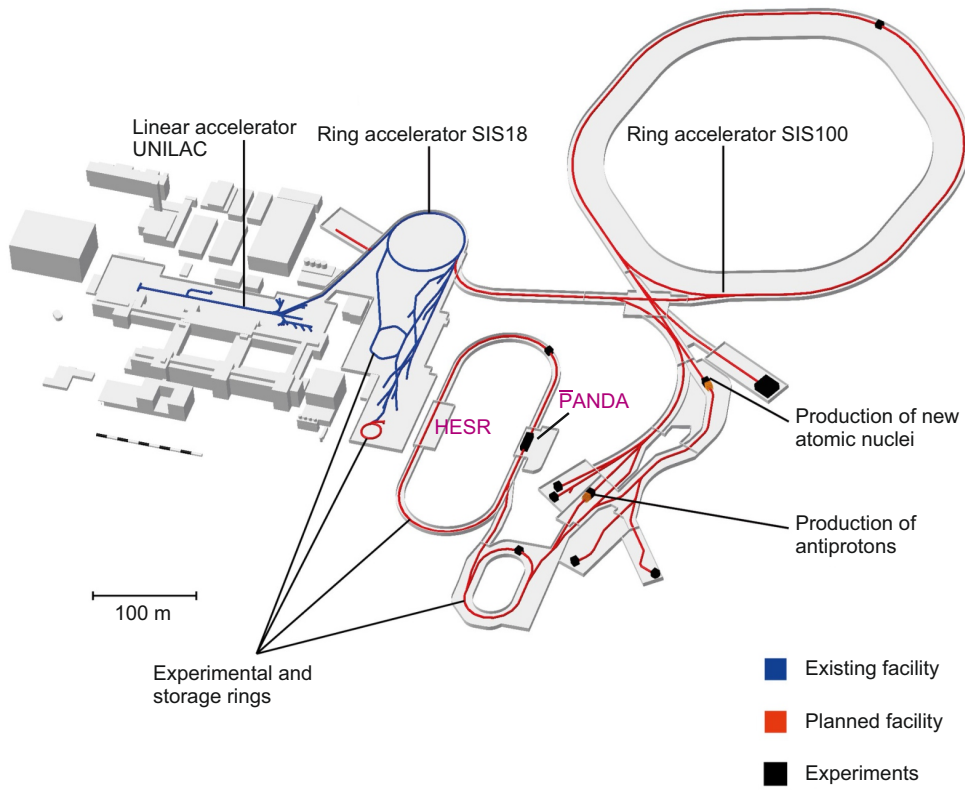


Figure 2.4.: A schematic depiction of the future FAIR facility. Pre-existing accelerators are marked in blue while new facilities are in red. The various experiment stations are shown as black squares. (Taken from [GSI 18], adapted)

- Atomic, Plasma Physics and Applications (APPA).
Here, a variety of different projects such as BIOMAT (BIOlogy and MAtErial science) or SPARC (StoRed Particles Atomic Research Collaboration) among others will explore various subjects in atomic and plasma physics.
- Compressed Baryonic Matter (CBM).
CBM will employ high intensity heavy ion beams to create and study quark gluon plasmas.
- Nuclear Structure, Astrophysics and Reactions (NUSTAR).
Similar to APPA, NUSTAR is comprised of several projects, including but not limited to DESPEC/HISPEC (DEcay SPEcTrosCopy/High-resolution SPEcTrosCopy), LaSpec (Laser Spectroscopy) and SuperFRS (Super FRagment Separator) which will be used to study ultra short lived nuclei near the proton/neutron drip line.
- antiProton ANnihilation at DArmstadt ($\bar{\text{PANDA}}$). Using anti-proton proton

2. The $\overline{\text{PANDA}}$ experiment

collisions, $\overline{\text{PANDA}}$ will study various topics in hadron physics

To facilitate so many different fields of study, FAIR will be comprised of several modular accelerator facilities (cf. fig. 2.4).

For the facilities reliant on accelerated heavy ions, the already existing UNILAC and SIS 18 accelerators pre-accelerate these ions before an average beam intensity of $\approx 3 \cdot 10^{11}$ ions/s at an energy of 1 GeV/nucleon are achieved with the SIS 100 [Fort 12] and fed to the various experimental facilities such as CBM or SuperFRS.

For $\overline{\text{PANDA}}$, the beam starts its life as a proton beam, accelerated to 70 MeV in the p-LINAC. After subsequent acceleration in the SIS 18 and SIS 100 synchrotrons, it reaches an energy of 29 GeV at a bunch size of $2 \cdot 10^{13}$ protons [Fort 12]. This beam is steered onto a nickel or copper target [Baru 21], thus producing a bunch of $1 \cdot 10^8$ antiprotons at an average energy of 3 GeV [Fort 12, Beli 23]. Many such bunches are then collected until up to $1 \cdot 10^{11}$ antiprotons are reached [Fort 12], which are then injected as one bunch into the HESR.

HESR

The $\overline{\text{PANDA}}$ experiment will be located at the HESR, which is a race track shaped synchrotron. It can accommodate up to $1 \cdot 10^{11}$ protons at momenta between 1.5 GeV and 15 GeV. To achieve such a wide momentum range, HESR will be equipped with Radio Frequency (RF) cavities [Stas 08], which will however cause beam heating, an unintended increase in transversal and longitudinal beam dimensions. To combat this issue, the HESR will be equipped with stochastic cooling [Beli 23], where the beam momentum is determined in the pick up and corrected in the kicker to enable high-precision beam energy scans.

HESR will be operable in two modes. High resolution mode with a beam momentum spread in the order of a few $1 \cdot 10^{-5}$ and a high luminosity mode achieving a maximum luminosity of up to $2 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ [Beli 23].

2.2.2. $\overline{\text{PANDA}}$ physics goals

The anti-proton proton collisions in $\overline{\text{PANDA}}$ have many interesting properties [Baru 21]:

- Such collisions have a large cross section for hadronic interaction.
- Meson-like states can be generated without limitation of their J^{PC} quantum numbers.
- Various baryons of different flavours, spins and parities can be produced.
- The annihilation process might be mediated by gluons, possibly producing a "gluon-rich environment".

These properties make $\overline{\text{PANDA}}$ optimally suited to study hadron physics and thus explore the strong interaction in a variety of ways.

Analysis of charm and exotics

For example, $\overline{\text{PANDA}}$ will be a powerful tool in determining the masses, widths and line shapes of meson-like states. To scan the line shape, the beam momentum is varied in small steps and the production rate is measured [Baru 21] (cf. fig. 2.5). As the measured production rate is given by the convolution of the beam momentum spread and the real line shape, $\overline{\text{PANDA}}$'s excellent resolution (85 keV at a centre-of-mass energy of 3.8 GeV [Baru 21]) makes it ideal for such high precision measurements.

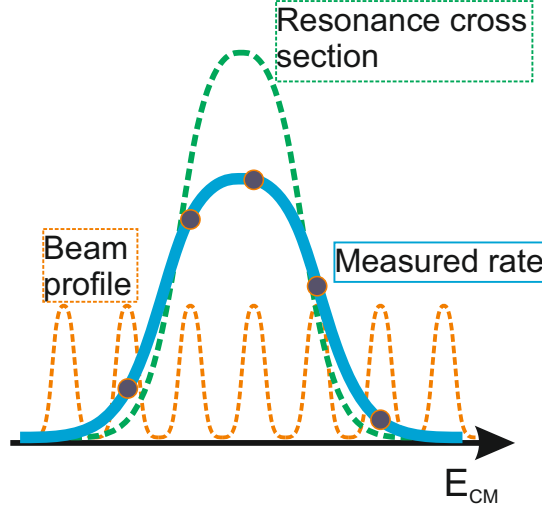


Figure 2.5.: The procedure for the resonance energy scan. The beam momentum (orange) is varied and the event rate (blue) measured. This rate is given by the convolution of the real resonance line shape (green) and the beam momentum spread, making a good beam momentum resolution imperative to accurately measure the line shape. (Based on [Baru 21])

In an e^+e^- annihilation experiment, the only quantum numbers allowed for first order reactions ($e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}$) are $J^{PC} = 1^{--}$, limiting the viability of this technique precisely to particles with these quantum numbers. Here, other quantum numbers are generated by the decay of the initial $q\bar{q}$ state and the state of interest needs to be identified by its decays in turn. In such a case, the line shape resolution is limited by that of the detector, which is in general several orders of magnitude worse than the beam momentum spread. An ideal candidate for study with $\overline{\text{PANDA}}$ is the meson-like state $X(3872)$ [Baru 21], an exotic state whose quantum numbers (1^{++}) preclude it from analysis via precision line scans with a contemporary e^+e^- collider experiment.

Study of hyperons

Hyperons are baryons containing strange quarks [Povh 13] with many open questions still surrounding them [Baru 21]. For example, describing their formation process has proven to be a difficult task for QCD which is hindered by a lack of experimental data

2. The $\overline{\text{PANDA}}$ experiment

[Baru 21]. Fortunately, $p\bar{p}$ annihilation has a large cross section for such reactions in $\overline{\text{PANDA}}$'s energy range [Baru 21] so that large data samples can be provided in future. Further related fields of study where $\overline{\text{PANDA}}$ can contribute are hyperon spectroscopy and the behaviour of antihyperons as well as mesons in nuclei [Baru 21].

Determination of electromagnetic form factors

Electromagnetic Form Factors (EMFFs) are used to describe the shapes of hadrons in dependence of the squared four-momentum transfer q^2 . As q^2 is defined over the complex plane, EMFFs are referred to as space-like for $q^2 < 0$ and time-like for $q^2 > 0$. $\overline{\text{PANDA}}$ will provide measurements for the proton form factor with accuracies at least three times better than current efforts via the reactions $p\bar{p} \rightarrow l^+l^-$, ($l = e, \mu$) with the muon channel being studied for the first time [Baru 21]. At the same time $\overline{\text{PANDA}}$ will be the first experiment to explore the so called unphysical region of the proton EMFF via $p\bar{p} \rightarrow l^+l^-\pi^0$, which plays a role in finding theoretical constraints [Baru 21].

2.2.3. The $\overline{\text{PANDA}}$ detector and target setup

The various $\overline{\text{PANDA}}$ detector systems will be arranged around the interaction point in an onion shape, thus nearly achieving 4π coverage (cf. fig. 2.6). Since $\overline{\text{PANDA}}$ is a fixed target experiment, the interaction products will experience a boost in forward direction, explaining the asymmetric placement of certain detector systems.

The detector is subdivided into two major components, the Target Spectrometer (TS) and the Forward Spectrometer (FS) [Beli 23]. The former is centred around a superconducting solenoid magnet of 2 T magnetic field strength which surrounds the interaction region [Beli 23]. The TS is comprised of several detector systems such as the Micro Vertex Detector (MVD), the Straw Tubes Tracker (STT), the Gas Electron Multiplier (GEM) and the Detector for Internally Reflected Cherenkov light (DIRC). The FS will be operated with a 2 Tm dipole magnet and analyse interaction products with forwards boost [Beli 23]. Its detector system comprises of the Ring Imaging CHerenkov (RICH) detector and the LUMInosity (LUMI) detector. In addition, there will be several systems dedicated to both the TS and FS: the ElectroMagnetic Calorimeter (EMC), the MUOn (MUO) detector and the Time Of Flight system (TOF).

For this thesis, the LUMI detector plays a special role, since preservation of its performance is one of the key motivations for the $\overline{\text{PANDA}}$ cryopump (cf. chapter 3). The LUMI detector will utilise following relation to determine the time integrated luminosity L [coll 18]:

$$N = L\sigma, \tag{2.8}$$

with N being the amount of events over a time period dt and σ the cross section. Now, the basic idea is that the detector will measure anti-protons scattered through interaction with protons at small polar scattering angles φ of $3 < \varphi[\text{mrad}] < 8$ [coll 18], delivering N . Simultaneously, the KOALA experiment will measure the differential cross section of $p\bar{p}$ scattering at correspondingly low momentum transfers [Zhou 21], thus delivering σ so that L can be calculated. However, this entire procedure hinges on

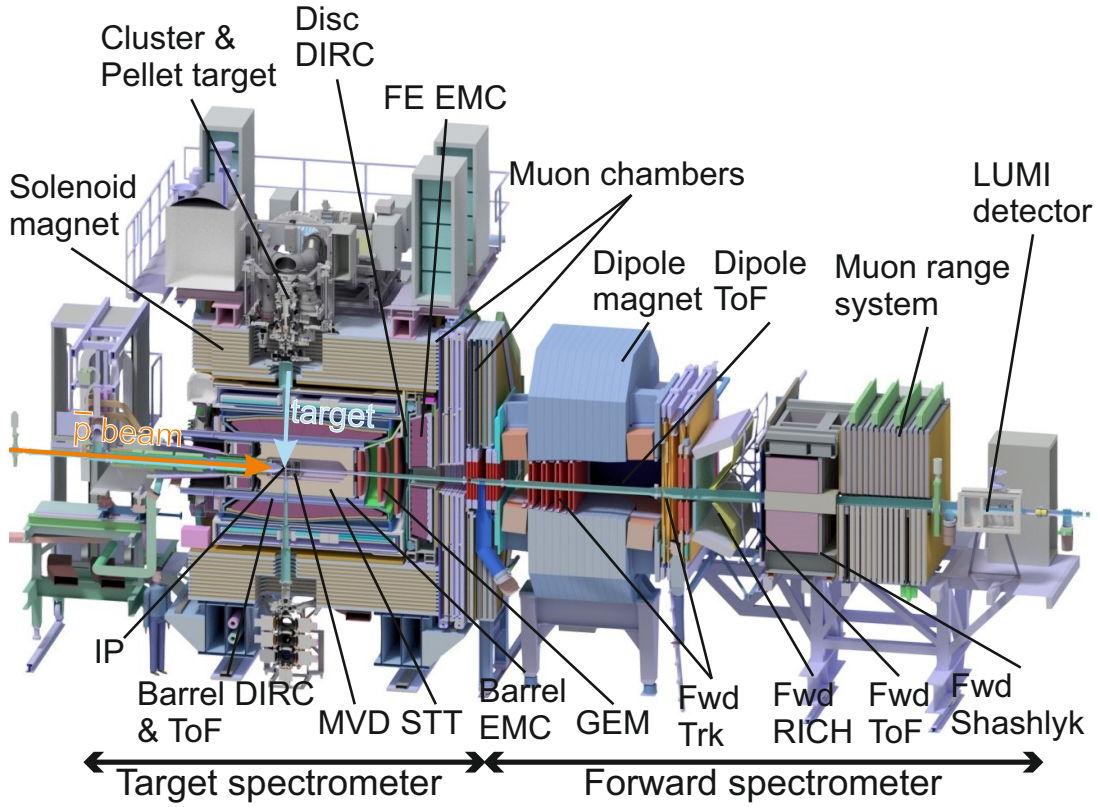


Figure 2.6.: The $\bar{P}$ ANDA detector and its various subsystems. Overall, the detector is subdivided into two parts, the target spectrometer and the forward spectrometer, each instrumented with their own detector systems. (CAD drawing generated by D. Bonaventura and picture taken by S. Vestrick for [Vest 24])

accurate determination of the scattering angle, as without it the counts in the detector and the cross section can no longer be correlated. Since there is no detector for this task, one has to assume that all antiprotons originate from the interaction point and use this to calculate the scattering angle. This is not perfectly accurate, since antiprotons may also scatter on rest-gas outside the IP, but the assumption holds as long as one has exact knowledge of the vacuum conditions and can ensure sufficiently low vacuum pressures. Thus the rest-gas stemming from the $\bar{P}$ ANDA cluster-jet target threatens the validity of the assumption, possibly significantly worsening the measured luminosity's accuracy. Notably, recent simulations suggest that these concerns are unfounded [Li 24], however, the cryopump will still help in maximising the antiproton beam lifetime (cf. appendix C).

2. The $\bar{\text{PANDA}}$ experiment

Targets for $\bar{\text{PANDA}}$

To achieve luminosities in the range of $1 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, $\bar{\text{PANDA}}$ will require target thicknesses of around $4 \cdot 10^{15} \text{ atoms/cm}^2$. At the same time, higher thicknesses are also undesirable as they would lead to increased accelerator beam heating effects. This effectively rules out solid targets, such as foils, which have thicknesses in the order of $1 \cdot 10^{17} \text{ atoms/cm}^2$ to $1 \cdot 10^{19} \text{ atoms/cm}^2$ [Ekst 95]. In addition, such targets would be challenging to install and replace considering $\bar{\text{PANDA}}$'s 4π geometry and would have the further disadvantage of not being purely composed of protons, possibly inducing unwanted background. Keeping these points in mind, a jet-like target made from hydrogen is optimally suited for $\bar{\text{PANDA}}$. Such a target jet can be continuously generated outside of the detector and travel to the interaction point, thus providing $\bar{\text{PANDA}}$ with a low background, windowless target while providing easy access to the target generation facilities. The remaining challenge is to find methods to generate a hydrogen jet which can reach thicknesses above $1 \cdot 10^{15} \text{ atoms/cm}^2$ at distances above 2 m.

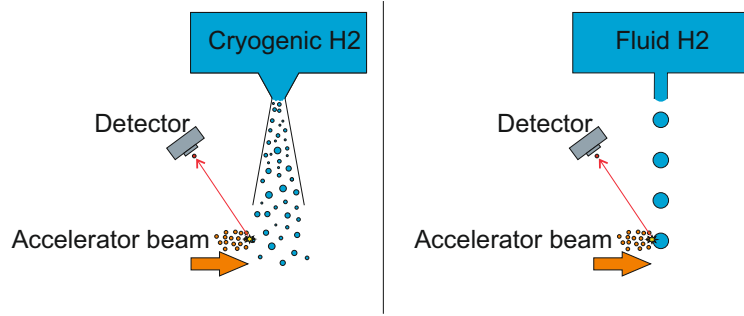


Figure 2.7.: The functioning principles of cluster-jet and pellet targets. **Left:** By pressing cryogenic H_2 through a de Laval nozzle, a jet consisting of many small clusters is generated, which can be transmitted through vacuum before interacting with a particle accelerator beam. **Right:** Fluid hydrogen dropping from an orifice forms individual, well separated pellets, which are suitable for interaction with accelerator beams.

One such method is a hydrogen cluster-jet target. Here, cryogenic hydrogen is pressed through a de Laval nozzle, creating a beam of many frozen hydrogen clusters in the size range from nanometres to micrometers [Kohl 15, Mann 19, Eick 23] and thus enabling high densities even several metres away from the nozzle (cf. fig. 2.7). Another method is a pellet target, where the accelerator beam hits individual pellets of frozen hydrogen with identical diameters in the diameter range of low tens of microns (cf. fig. 2.7).

The $\bar{\text{PANDA}}$ experiment will use both types of targets. The Münster cluster-jet target for $\bar{\text{PANDA}}$ was already in use at the COSY accelerator [Klos 20, Eick 23, Weid 23] and has successfully reached thicknesses of more than $1 \cdot 10^{15} \text{ atoms/cm}^2$ [Bran 24]. Simultaneously, investigations are on going on how to transform this target into a pellet target (cf. chapter 4²).

²Here, the words pellets and droplets are used synonymously.

3. A cryopump for the $\overline{\text{PANDA}}$ beam line

Previous investigations have revealed that the $\overline{\text{PANDA}}$ cluster-jet target will have a significant impact on the vacuum conditions of the HESR beam line by introducing considerable amounts of gaseous hydrogen [Klos 20, Weid 23]. This could possibly have adverse effects on luminosity determination¹ (cf. section 2.2.3), because the vertex point is washed out due to background gas, and the beam lifetime, as the anti-protons incur higher losses due to random interactions with gas particles. To combat this issue, a cryopump is proposed, which is foreseen to be installed directly into the beam pipe for maximum effectiveness, necessitating a unique geometry. This requirement precludes the use of a commercial pump, instead a custom designed one becomes necessary.

This chapter describes the design process of this unique cryopump. At the beginning, the basics of cryogenic refrigeration as well as the underlying principles of cryogenic pumping are introduced, which set the requirements and properties our pump needs to fulfil to function properly. Then, the simulations which were performed for the design of the pump are described in exhaustive detail. They are divided into two types: Vacuum simulations and temperature simulations. The former type aims to determine the optimal shape, length and position for the pump while the latter checks whether the pumps obtained through the vacuum simulations reach sufficiently low temperatures for hydrogen pumping to take place, finally resulting in an optimal shape which is ready to be engineered, constructed and experimentally tested.

3.1. Construction principles of cryopumps

To combat the rest-gas in the $\overline{\text{PANDA}}$ beam line efficiently, a pump is required which can deliver high pumping speeds while being installed as closely as possible to the rest-gas source, ideally inside the beam pipe. Optimal candidates which fulfill both these requirements are cryopumps which function by freezing incoming gas to cryogenic surfaces, thus creating a pumping mechanism. In addition to possessing excellent pumping speeds, such surfaces can be installed directly into the volume one wishes to pump, offering maximum conductance, making cryopumps an ideal candidate for installation in the $\overline{\text{PANDA}}$ beam line. The following chapter provides a brief description of the basics for the generation of cryogenic surfaces before examining the properties of cryopumps.

¹Although recent investigations suggest that the effect is quite low [Li 24].

3. A cryopump for the $\bar{P}$ ANDA beam line

3.1.1. Theory of cryogenic refrigeration - the Gifford McMahon process

Usually for cryopumps, a cooling method based on gas cooling cycles is chosen over a steady supply of liquid coolant such as liquid helium. The basic principle of the cooling cycle is that there are two temperature levels, room temperature and the cryogenic temperature, and two differing pressure levels. When gas expands from the higher pressure to the lower pressure, the gas is cooled down from room temperature to the cryogenic temperature [Jits 09]. Of course there are many different technical implementations of this idea, however the focus will be on the Gifford-McMahon process, which is used in the Coolpower 10 MD [Leyb 22] (cf. fig. 3.1), the cold head which will be used for the cryopump.

The four principle steps of this process are depicted in fig. 3.2, alongside the accompanying p-V-diagram. The cold head is made up of two gas-filled volumes, V_1 and V_2 , where the former is warm and the latter is cold, separated by a gas permeable displacer. The displacer is movable and can be used to force the gas through it from one volume to the other. By doing so, the gas passes the regenerator, a heat reservoir built into displacer which acts as a heat exchanger. Furthermore, the cold head is connected to two gas pressure lines, one at high pressure, p_H and one at low pressure p_L . These lines are in turn connected to a compressor, where gas from the low pressure line is compressed and fed into the high pressure line, thus creating a closed loop [Umra 97].

In the first step (cf. fig. 3.2a), the displacer with the cold regenerator is positioned all the way to the left, minimising the size of V_2 . The high pressure line is open while the low pressure line is closed, leading to warm gas entering the cold head with p_H . Then (cf. fig. 3.2b), the displacer is moved to the right, maximising V_2 . The gas is forced through the cold regenerator from V_1 to V_2 , which cools the gas down. During this time the high gas pressure line remains open.

In the third step (cf. fig. 3.2), the high pressure gas line is closed and the low pressure gas line is opened. The gas expands while the pressure sinks from p_H to p_L , causing the gas to cool down further. Meanwhile the displacer remains stationary.

In the last step (fig. 3.2d), the displacer is moved to the left. This forces the cold gas from V_2 through the displacer, thus cooling the regenerator down while the gas pressure remains at p_L . Next, the high pressure valve is opened and the low pressure valve is closed, which is the exact situation of fig. 3.2a, thus closing the loop. With each cycle the gas is cooled down further until

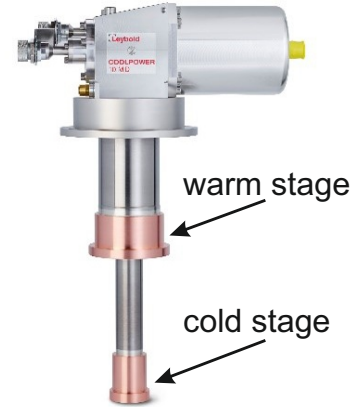


Figure 3.1.: The Coolpower 10 MD cold head. The copper surfaces of the cold stage reach 8 K, while the warm stage reaches 28 K. (Picture kindly provided by Leybold GmbH)

3.1. Construction principles of cryopumps

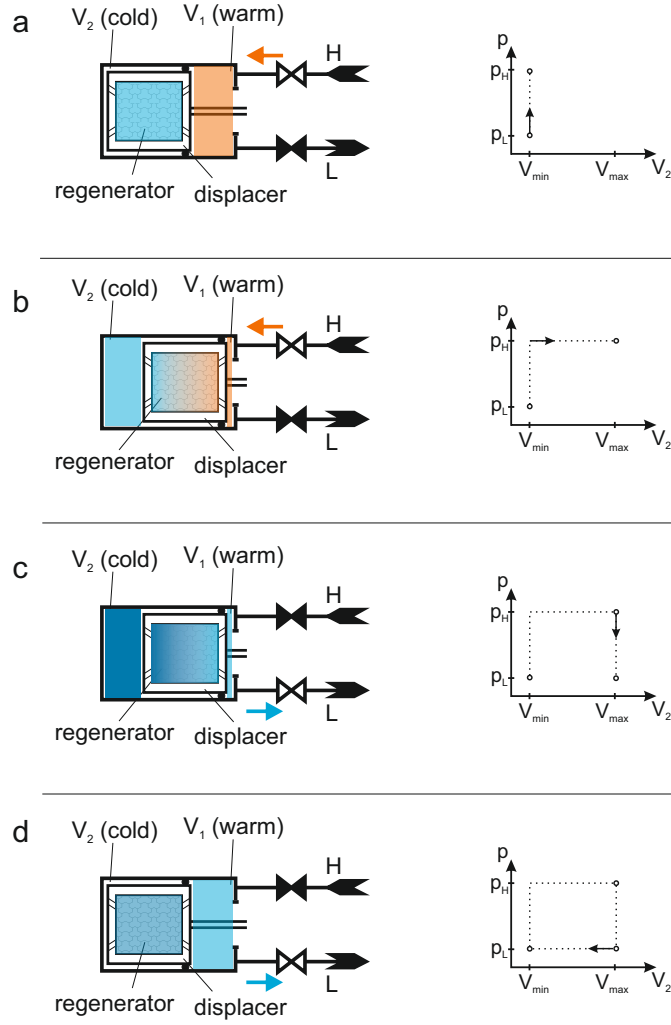


Figure 3.2.: A schematic visualisation of the Gifford-McMahon process. **a** depicts warm gas entering the cold head at the high pressure level. Then, in **b** the displacer moves to the right, cooling the warm gas. In the next step **c**, the low pressure line is opened while the other is closed, letting the gas expand which cools it down further. Finally, in **d** the displacer is moved to the left, through the cold gas, cooling down the regenerator before the cycle begins again at **a**. (Based on [Umra 97])

3. A cryopump for the $\bar{P}$ ANDA beam line

an equilibrium is reached, where the cooling power equals the heat flux from outside sources such as heat conductance or radiation. The cooling power can be calculated using

$$W = (V_{2,\max} - V_{2,\min}) \cdot (p_H - p_L) \cdot f, \quad (3.1)$$

where W is the cooling power, f is the cycle frequency $V_{2,\max}$ and $V_{2,\min}$ are the maximum and minimum values of V_2 [Umra 97].

Coolpower 10 MD

The Coolpower 10 MD (cf. fig. 3.1) uses a slight variation of this process by possessing two stages, the warm stage (final temperature: <28 K) and the cold stage (final temperature: <8 K, [Leyb 22]). Both are Gifford McMahon cryocoolers where one operates as a pre-cooling stage for the next, enabling even lower temperatures. However, the warm stage can be used as a source of cooling in its own right, as it has a larger cooling power than the cold stage, albeit with higher end temperatures (cf. tables 3.10 and 3.11). Thus the cold stage is used to achieve the lowest possible temperatures, for example when operating a cryopump, and the warm stage to cool down larger volumes of material to slightly warmer temperatures, such as is the case for the cryopump's heat shield (cf. section 3.4.3).

3.1.2. Cryogenic pumping mechanisms

The cooling power provided by the Gifford McMahon process can be utilised to cool surfaces to cryogenic temperatures, which are capable of trapping gas molecules and atoms via two processes based on van der Waals forces, namely gas condensation and cryogenic adsorption.

Gas condensation

As the name implies, in this process gas is bound to a cryogenic surface by condensating to it. In this case no exact distinction is made whether the gas is frozen to the surface or is still fluid, as this often has no influence on the vacuum. To determine the efficacy of this mechanism, the sublimation equilibrium pressure is of great interest since one usually cannot achieve pressures below it using gas condensation, thus the terminal pressure is roughly in the same order of magnitude (cf. table 3.1) [Jits 09].

In table 3.1 one can see how the vapour pressure changes for different temperatures for several relevant gases. As a general trend, the vapour pressure increases with growing temperatures. Of particular interest are the temperatures at $1 \cdot 10^{-9}$ Torr, which are used as a rough estimation of what temperatures need to be reached to achieve effective pumping for a particular gas.

For the primary components of air (nitrogen and oxygen) these values are quite small, in the twenties of Kelvin, while hydrogen pumping even requires temperatures below the condensation point of helium, which is not reachable by the Coolpower 10 MD [Leyb 22].

3.1. Construction principles of cryopumps

A further property of this pumping mechanism is that only a finite amount of gas can be pumped. The reason is that during the pumping process a frozen gas layer is continuously being built up on the cryogenic surfaces. As the layers grow, the surface temperature increases due to the finite thermal conductivity of the ice until no further gas can be adsorbed. The amount of gas at which effective pumping ceases is called the capacity of the respective pump, which can be quite large with frozen layers of above 10 mm being observed in practical applications [Jits 09].

Table 3.1.: The vapour pressures for various gases at several temperatures [Jits 09].

Gas	Temperature in K for a corresponding vapour pressure in Torr					
	$1 \cdot 10^{-12}$	$1 \cdot 10^{-9}$	$1 \cdot 10^{-7}$	$1 \cdot 10^{-5}$	$1 \cdot 10^{-3}$	$1 \cdot 10^{-1}$
Nitrogen	19.0	22.3	25.2	29	34.1	41.7
Oxygen	22.8	26.6	29.9	34.1	39.8	48.1
Hydrogen	2.88	3.45	4.03	4.84	6.05	8.03

Cryogenic adsorption

The Coolpower 10 MD does not reach the temperatures necessary to pump hydrogen through gas condensation which seems like a major issue since hydrogen will be the main rest-gas component of HESR. However, a second gas trapping scheme called cryogenic adsorption enables hydrogen pumping at slightly higher temperatures. As the name implies, instead of condensing, the gas is adsorbed to the cryogenic surface via van der Waals forces [Umra 97]. The probability for adsorption not only depends on temperature but also strongly on the material of the cryogenic surface, with porous materials proving the most advantageous. For this reason, the cryogenic surfaces of cryopumps are often covered in activated charcoal, which can achieve specific surfaces of around $1 \cdot 10^6 \text{ m}^2/\text{kg}$ [Umra 97]. Analogously to gas condensation, there exists a quantity called adsorption equilibrium which is equivalent to the vapour pressure curve. While the adsorption equilibrium is strongly dependent on the exact type of activated charcoal being used [Jits 09], its value is normally smaller than the vapour pressure for a given temperature, which means that cryogenic adsorption becomes effective at higher temperatures than gas condensation.

Using this mechanism, effective pumping for hydrogen can be achieved at temperatures of around 13 K [Rung 21], a much more readily achievable temperature than the 4 K necessary for gas condensation, albeit with reduced capacities [Jits 09].

3.1.3. Key performance indicators of cryopumps

As with every kind of pump, cryopumps possess several performance indicators which can be crucial to their capabilities. In this section, the ones most relevant to the PANDA experiment will be explained in further detail.

3. A cryopump for the $\overline{\text{PANDA}}$ beam line

Minimal pressure

The minimum achievable pressure for a cryopump utilising gas condensation can be calculated with following equation [Jits 09]:

$$p_{\min} = p_v \sqrt{\frac{T_w}{T_c}}, \quad (3.2)$$

where $p_{\min}$ is the minimal pressure, p_v the vapour pressure as shown in table 3.1, T_w the temperature of the container the cryopump is pumping and T_c the temperature of the cryopump's cryogenic surfaces. As an example, let's assume $T_w = 300$ K with $T_c = 3.45$ K which corresponds to $p_v = 1.33 \cdot 10^{-9}$ mbar (cf. table 3.1). Inserting these values into eq. (3.2) leads to $p_{\min} = 1.24 \cdot 10^{-8}$ mbar.

For a slightly higher T_c , such as $T_c = 6.05$ K, p_v is already several orders of magnitude higher ($p_v = 1.33 \cdot 10^{-3}$ mbar [Jits 09]) which leads to $p_{\min} = 9.37 \cdot 10^{-3}$ mbar. This result reinforces what was mentioned in section 3.1.2: To effectively use gas condensation it is of utmost importance to achieve and maintain as low temperatures as possible. For this reason, cryopumps coated with activated charcoal are used, which operate via cryogenic adsorption, enabling lower minimum pressures at higher temperatures, as already explained in the section concerning cryogenic adsorption above. Please note that pressures below p_v are possible, however they require that the cryopump's container is colder than the cryopump itself, which is often quite unlikely [Jits 09].

Pumping speed

The pumping speed of a cryopump operating via gas condensation can be calculated via

$$S = \frac{1}{4} \sigma_c \bar{c}_W A_c \left(1 - \frac{p_v}{p} \sqrt{\frac{T_w}{T_c}} \right), \quad (3.3)$$

where σ_c is the condensation coefficient for a specific gas, $\bar{c}_W$ the mean velocity of the gas molecules, A_c the area of the cryogenic surfaces and p the current pressure in the vacuum chamber [Jits 09]. The other variables were already introduced when explaining eq. (3.2).

When in the gas condensation regime, the condensation coefficient for all gases is close to 1 [Jits 09, Umra 97], while for cryogenic adsorption similar values can be achieved, with Helium being the exception [Jits 09]. To get an idea of the potency of a cryopump, the surface specific pumping speed S_A is considered, which is simply defined as

$$S_A = \frac{S}{A_c}. \quad (3.4)$$

Some typical upper limits for S_A are given in table 3.2. Values in the same order of magnitude have also been achieved for pumps covered in activated charcoal operating via cryogenic adsorption (cf. section 3.3.1). It quickly becomes clear that cryopumps potentially possess immense pumping speeds, since a small pumping surface of 10 cm x

3.2. Consideration of interactions between particle accelerator beam and the cryopump

10 cm already has a pumping speed between hundreds and thousands of L/s, depending on the gas to be pumped. Indeed, typical pumping speeds for commercial cryopumps are in the region of several thousands of L/s [Jits 09].

Table 3.2.: The upper limits for surface specific pumping speeds for various gases at two different temperatures [Jits 09].

T_w in K	S_A in $Ls^{-1}cm^{-2}$		
	O ₂	N ₂	H ₂
293	11.0	11.8	43.9
77	5.7	6.1	22.5

Capacity

The capacity of a cryopump is defined as the amount of gas it can bind until the pumping speed falls to 50 % of its initial value. The capacity of the $\bar{P}$ ANDA cryopump will be of great interest since a cryopump which has reached its capacity needs to be regenerated. Regeneration means that the pump is warmed up so that all stored gas is released and the original pumping capability is restored once the pump is cooled back down again. This process can be relatively time consuming, with regeneration cycles on the time scale of hours. Furthermore, the regeneration process will inevitably introduce additional gas into the accelerator vacuum which means that no measurements can be taken during that time. For this reason, maximising the capacity is a large concern for the design of the $\bar{P}$ ANDA cryopump to keep the effects on the running experiment to a minimum.

3.2. Consideration of interactions between particle accelerator beam and the cryopump

Inserting the cryopump into the accelerator beam pipe may be the optimal choice in respect to the vacuum conditions, however, doing so leads to two major interactions between the particle beam and the cryopump which will be carefully considered here before moving on to discussing the cryopump design: The cryopump distorting the particle beam's shape and the particle beam inducing heat in the cryopump.

The first effect stems from the fact that the cryopump represents a sudden change in pipe diameter for the particle beam. Combined with the large electric conductance of copper, which the cryopump is primarily made of, electric and magnetic fields would be created when the beam passes the pump, potentially distorting the beam's shape. The solution is to install an impedance "ramp" in front and behind of the cryopump in the form of a thin mesh (cf. fig. 3.3), introducing a gradual impedance change to avoid inductance effects.

In addition to this effect, the passage of the accelerator beam through the cryopump inducts heat into the pump, potentially heating it up so much it ceases to function. To

3. A cryopump for the $\bar{P}$ ANDA beam line

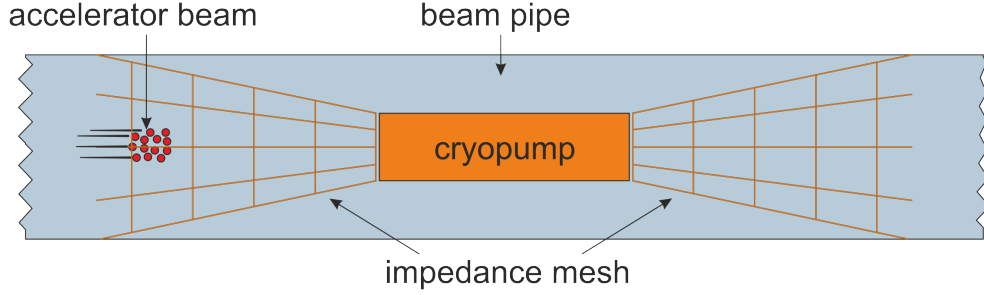


Figure 3.3.: Schematic depiction of the impedance mesh's functioning principle. The approaching accelerator beam experiences a gradual change of impedance due to the mesh, resulting in only minor induction effects.

estimate this effect, the passage of the accelerator beam is modelled as a coax cable, with the inner conductor being the beam and the outer one being the cryopump. For such a geometry, simple equations are available to calculate the power loss, which would be transformed into heat in this case.

The first step of the calculation is to determine the skin depth of both conductors. This quantity stems from the fact that at high frequencies, the current densities of conductors decreases with depth, meaning that charges are only transmitted near the surface [Micr 01]. The value of this depth is called skin depth (δ) and can be calculated via [Micr 01]

$$\delta = \sqrt{\frac{\rho}{\pi f \mu \sigma}} \quad (3.5)$$

where f is the frequency, μ is the magnetic permeability and ρ the specific resistivity. For the outer conductor (cryogenic copper), μ is nigh identical to the vacuum permeability² $\mu_0 = 1.257 \cdot 10^{-6} \text{ N/A}^2$ [Simo 92] and the specific resistivity has a value of $\rho = 1 \cdot 10^{-9} \Omega\text{m}$. f is calculated from the HESR circumference $d = 575 \text{ m}$ [Beli 20] and the proton speed (c , the speed of light) resulting in $f = c/d = 521.1 \text{ kHz}$. Plugging in these values gives a skin depth of $\delta = 22 \mu\text{m}$ which is much smaller than the copper thickness in the range of mm. The inner conductor (vacuum) has a specific resistivity of $0 \Omega\text{m}$ since per definition it contains nothing which would impede the conductance of electrical charges and thus has an infinite electric conductance, leading to a skin depth of $\delta = 0 \mu\text{m}$. For the present case, where skin depth is much smaller than conductor thickness, the resistivity per length (R/l) of a coax cable can be calculated via [Micr 01]

$$R/l = \sqrt{\frac{f \mu_0}{\pi}} \left[\sqrt{\frac{\mu_{R1} \rho_1}{d_1}} + \sqrt{\frac{\mu_{R2} \rho_2}{d_2}} \right] \quad (3.6)$$

where the numbered indices indicate whether the values belong to the outer or inner conductor and $\mu_{R1,R2}$ as well $d_{1,2}$ denote the respective relative permeabilities (defined

²The permeability is calculated according to $\mu = \mu_0(1 + \kappa)$ [Demt 17a], where κ denotes the susceptibility of cryogenic copper. Since in this case $\kappa = -9.21 \cdot 10^{-6}$ [Simo 92], $\mu \approx \mu_0$ is valid.

3.3. Vacuum simulations of the $\overline{\text{PANDA}}$ cryopump

as $\mu_R = \mu/\mu_0$) and diameters. Since for the inner conductor of vacuum $\rho = 0 \Omega\text{m}$ applies, the equation simplifies to:

$$R/l = \sqrt{\frac{f\mu_0}{\pi}} \left[\sqrt{\frac{\mu_{R1}\rho_1}{d_1}} \right]. \quad (3.7)$$

The relative susceptibility of cryogenic copper can be approximated to $\mu_R = 1$ and the outer diameter should be in the range of centimetres, in this case $d = 10 \text{ cm}$ was assumed, leading to $R/l = 0.1 \text{ m}\Omega/\text{m}$. The resultant power per length available for heating the cryopump can then be calculated with [Demt 17a]

$$P/l = \frac{RI^2}{l}. \quad (3.8)$$

The electric current I can be calculated using its definition $I = \Delta Q/\Delta t$. The charge ΔQ is obtained by multiplying the amount of anti-protons per bunch envisioned for HESR ($1 \cdot 10^{11}$) [Smyr 12] with the frequency obtained above, leading to an average charge of 8 mA. Together with eq. (3.8), this leads to 1 nW/m being available to heat the cryopump, a vanishingly small amount compared to the cooling power which is on the order of Watts, so that this heating effect can be safely ignored.

3.3. Vacuum simulations of the $\overline{\text{PANDA}}$ cryopump

As explained in further detail above, cryopumps provide an attractive option to combat $\overline{\text{PANDA}}$'s rest-gas issues, with easy to minimise influence on the anti-proton beam. However, to achieve maximum effect, the cryogenic surfaces need to be installed directly into the $\overline{\text{PANDA}}$ beam pipe. This design request necessitates a custom cryopump which we developed ourselves. This chapter provides an overview of the first step of the design process, the vacuum simulations. At the beginning, the design constraints imposed by $\overline{\text{PANDA}}$ are discussed before several potential designs are evaluated concerning various performance metrics.

3.3.1. Possible designs for the $\overline{\text{PANDA}}$ cryopump

Several possible designs for the $\overline{\text{PANDA}}$ cryopump were considered with the four most promising ones depicted in fig. 3.4. In the various following simulations, all surfaces shown are considered to be covered in activated charcoal, however for the purposes of prototyping the complex implementation of activated charcoal was omitted. From left to right and top to bottom the pumps are named screw, fin, tube and aperture cryopump, inspired by their unique geometries. Nevertheless they all share the same basic cylindric form as they are designed to be inserted into the $\overline{\text{PANDA}}$ beam pipe, which is also the reason why they all have an opening in the middle to accommodate the accelerator beam. The aim with each geometry is to maximise the available surface which could be coated with activated charcoal while also maximising the probability for gas to impinge on these surfaces and to be pumped.

3. A cryopump for the $\overline{\text{PANDA}}$ beam line

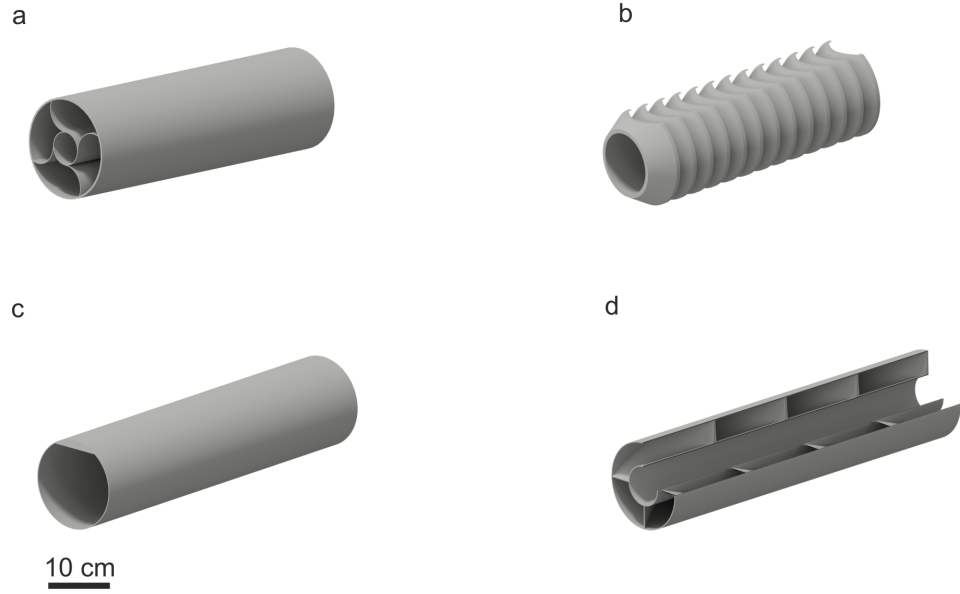


Figure 3.4.: Several potential cryopump designs. Each one was named after a characteristic design feature. **a:** fin cryopump. **b:** aperture cryopump. **c:** tube cryopump. **d:** screw cryopump. Please note that this particular pump is shown in three quarter section for added visual clarity. For simulation purposes, all depicted inner and outer surfaces are considered to be covered in activated charcoal, however, this is not shown here.

Table 3.3.: The surface area which can be covered with activated charcoal of the various pumps along with the resultant pumping speeds.

	Surface area in cm^2	Pumping speed in l/s
fin	5910	135086
aperture	3011	68822
tube	3155	72114
screw	4515	103200

The surface areas which can be covered with activated charcoal of the various pump geometries depicted in fig. 3.4 are listed in table 3.3. It becomes obvious that the respective pumping areas varies between a factor of two which leads to large differences in pumping speed, which were calculated on the basis of a specific pumping speed of $S_A = 23.4 \text{ L}/(\text{s} \cdot \text{cm}^2)$, which was experimentally obtained in [Rung 21]. Intuitively, one might expect the design with the maximum pumping speed to be the most optimal, however, one still needs to consider other effects and boundary conditions such as the conductance of the pumps or their positioning in the beam pipe, which is why extensive vacuum simulations were performed using Molflow+.

3.3.2. Vacuum simulations using Molflow+

Molflow+ was chosen as the most suitable program for the vacuum simulations due to its excellent computation speed, precision and usability. The reason for these properties lies in its unique simulation scheme, as it uses the test particle Monte Carlo (TPMC) method instead of the direct simulation Monte Carlo (DSMC) method [Mart 16].

In general, the DSMC method is considered the most advanced simulation scheme [Mart 16], where the vacuum chamber is subdivided into many 3D cells while the position and evolution of test particles is tracked in individual time steps. These particles represent a larger amount of real gas molecules with their properties scaled to match reality, effectively simulating the rest-gas in vacuum. DSMC allows for precise description of all vacuum regimes, even rough vacuum (1 mbar to 1000 mbar) where inter-molecular collisions play a significant role. However, it also comes with drawbacks, especially when it comes to computational speed [Mart 16]. In DSMC simulations the size of the time step needs to be scaled to the smallest feature of the vacuum chamber. If the time step is too large the test particles travel too long distances for the vacuum conditions at the small feature to be accurately described. Furthermore creating the necessary 3D cells for the simulation becomes highly computationally expensive and error prone with increasing size and complexity of the model.

For these reasons Molflow+ uses the TPMC method. Here the vacuum chamber is not subdivided into cells. Instead it is transformed into polygons, so called facets [Mart 16]. Like in DSMC, test particles are introduced into this geometry and their paths traced, with collisions with walls being registered and stored. TPMC is event driven which means that it first searches for any collisions between test particles and walls (also called hits) and then retro actively calculates the time of the hit. This way one avoids the issues inherent to 3D cells and discrete time steps, allowing for the fast, efficient simulations of large vacuum chambers, such as the $\bar{P}$ ANDA beam pipe. The drawback of TPMC is that it does not allow for the description of rough vacuum effects, however, since the aim for $\bar{P}$ ANDA is to achieve vacua in the range of

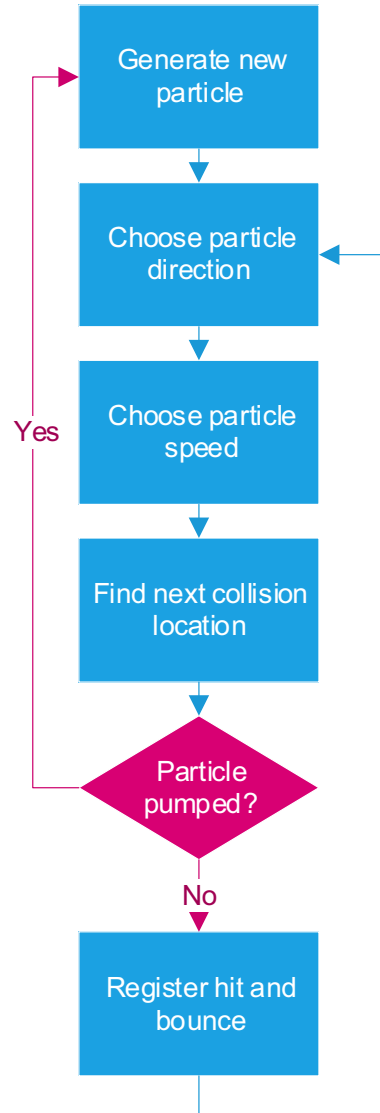


Figure 3.5.: A flow chart depicting the principal steps of the Molflow+ algorithm.

3. A cryopump for the $\bar{P}$ ANDA beam line

$1 \cdot 10^{-8}$ mbar to $1 \cdot 10^{-10}$ mbar, this is not an issue, making Molflow+ the ideal software for our simulations.

3.3.3. Molflow+ simulation scheme

Due to the comparative simplicity of the simulation method one can compactly summarise it in a flow chart as shown in fig. 3.5 [Mart 16]. In the beginning, Molflow+ generates a test particle and assigns a direction and speed to it. Then it locates where the particle will collide with a facet and decides whether the particle is pumped or not. If it is, a new particle is generated and the cycle begins anew. If it is not, one returns to the step where the particle direction is chosen. In the following, a brief breakdown of the processes in each individual step will be given as well as how essential values such as pressure are calculated.

Particle generation

To generate particles in Molflow+ one assigns an outgassing rate $Q_f = \frac{d(pV)}{dt}$ to a facet, where p is the pressure, V Volume and t time. Through the ideal gas law one can convert this outgassing rate to an influx of real physical particles according to [Mart 16]:

$$\frac{dN_{f,\text{real}}}{dt} = \frac{d(pV)}{dt} \frac{1}{k_B T_f} = \frac{Q_f}{k_B T_f}, \quad (3.9)$$

where $N_{f,\text{real}}$ is the number of real physical particles being emitted from the facet, k_B is the Boltzmann constant and T_f the facet temperature. This large flow of particles is converted into an absolute number of test particles which are used for the simulation. This means that each test particle represents a flow rate of real particles. Therefore, when a test particle hits a facet it counts as a certain amount of real hits per second. To translate between real (N_{real}) and test particles (N_{virt}) it is useful to introduce a factor K [Mart 16]. For a total of N_{virt} test particles, each one represents a flow of real particles according to:

$$K = \frac{\sum \frac{dN_{\text{real}}}{dt}}{N_{\text{virt}}}. \quad (3.10)$$

Particle direction

Initial particle generation and rebounds from surfaces follows Knudsen's cosine law [Knud 67]:

$$ds = d\omega \pi \cos \theta, \quad (3.11)$$

which describes the probability ds of a particle being emitted in the solid angle $d\omega$. Here, θ describes the angle between the particle's direction vector and the surface normal (cf. fig. 3.6). For the initial particle generation, there are also other direction distributions, such as uniform emittance in all directions or custom, user designated schemes.

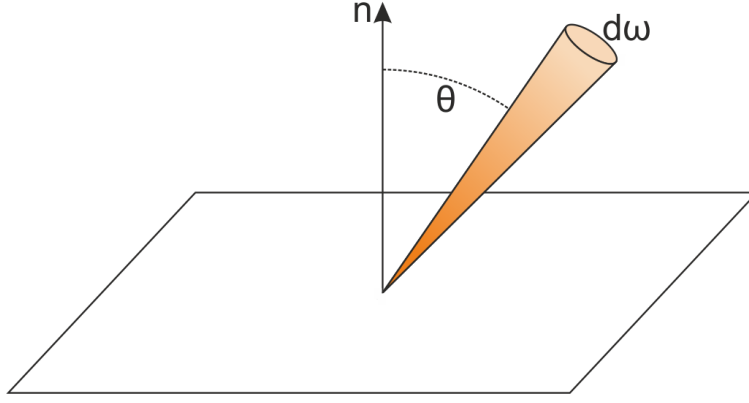


Figure 3.6.: The Knudsen law describes the probability ds of a particle being emitted under a solid angle $d\omega$ after rebounding on a surface in vacuum. From eq. (3.11) it becomes apparent that the probability is highest along the surface normal. (Based on [Fere 04])

Particle velocity

In a real physical system, the speed of the gas molecules follows the Boltzmann distribution [Maxw 03]. However, the test particles represent a flow of physical particles over time, which means they do not follow the Boltzmann distribution but instead one which results in following probability density function [Mart 16]:

$$f(v) = \frac{v^3}{2a^4} \exp\left(-\frac{v^2}{2a^2}\right) \quad (3.12)$$

with v being the particle velocity and

$$a = \sqrt{\frac{RT}{M}}. \quad (3.13)$$

Here, R is the ideal gas constant, T the gas temperature and M the molar mass. The resultant average particle velocity $\langle v \rangle$ can be calculated according to:

$$\langle v \rangle = \int_0^\infty v f(v) dv = 3a\sqrt{\frac{\pi}{8}}. \quad (3.14)$$

The average test particle speed as they enter the vacuum is described by eq. (3.14). When these particles impact a surface they change their speed and direction (cf. eq. (3.11)) which is unintuitive if one expects the particles to perform elastic scattering. Instead, the particles undergo thermalisation. To model this process and the resultant velocity change a new speed v_{wall} is chosen from the distribution in eq. (3.12) with the wall temperature plugged in for T [Mart 16]. Starting from here, a new particle speed

3. A cryopump for the $\bar{P}$ ANDA beam line

v_{new} can be calculated from the old one v_{old} and the thermalisation coefficient A_{Acc} ³ according to following equation.

$$v_{\text{new}}^2 = v_{\text{old}}^2 + A_{\text{Acc}}(v_{\text{wall}}^2 - v_{\text{old}}^2) \quad (3.15)$$

Collision detection

A ray-tracing algorithm determines the location where the test particle hits a facet. The particle then rebounds according to Knudsen's law unless the facet is marked as a pumping facet. In that case, there is a certain probability for the test particle to be pumped and a new particle to be introduced into the simulation, with further details following below.

particle pumping

Every facet is assigned a sticking factor between zero and one, which indicates the probability of the test particle being pumped when impacting on a particular facet. The default is zero, signifying a non-pumping surface while any other value leads to the facet acting as a pump. The pumping speed S of such a facet can be calculated from the sticking factor s , the mean particle velocity $\langle v \rangle$ and the facet area A according to [Mart 16]

$$S = \frac{1}{4} s \langle v \rangle A. \quad (3.16)$$

Hit registration and particle bouncing

Whenever a particle hits a facet three values of the impact are stored [Mart 16]. Firstly, the counter for the amount of hits on this particular facet is increased by one, which allows for the calculation of the impingement rate as well as giving the user important information to evaluate the statistical accuracy of the simulation. Secondly, the change in orthogonal momentum between incoming and outgoing particles $I_{\perp}$ is recorded, as it is essential for pressure calculation, and thirdly the inverse of the orthogonal speed component $1/v_{\perp}$ is registered to later calculate the particle density.

Pressure calculation

As particles rebound from a surface, the sum of the change in their momentum $\sum dI$ imparts a force F on the surface A leading to a pressure p

$$p = \frac{F}{A}. \quad (3.17)$$

Plugging in $F = \sum dI/dt$ leads to

$$p = \frac{\sum dI}{dtA}. \quad (3.18)$$

³In Molflow+ A_{Acc} is assumed to be one per default, implying complete thermalisation.

3.3. Vacuum simulations of the $\overline{\text{PANDA}}$ cryopump

Now one needs to translate this result from real particles into test particles. As mentioned above, $I_{\perp}$ is recorded for each test particle rebound. By multiplying it with K (cf. eq. (3.10)) one can translate $I_{\perp}$ into the real momentum change per time unit [Mart 16] according to

$$\frac{dI}{dt} = I_{\perp} K \quad (3.19)$$

which leaves us with

$$p = \frac{\sum I_{\perp} K}{A}. \quad (3.20)$$

3.3.4. Adaptation of the $\overline{\text{PANDA}}$ vacuum system for use in vacuum simulations

For the vacuum simulations, a strongly simplified model of the $\overline{\text{PANDA}}$ detector was used⁴. Everything which does not concern the vacuum system was stripped away, leaving only the bare vacuum pipes (cf. fig. 3.7). Then, minor objects such as vacuum connections of the various individual pipes were removed, leaving only the objects which actually impact the vacuum quality, the pipes of varying diameters and the various pumps mounted along the beam pipe.

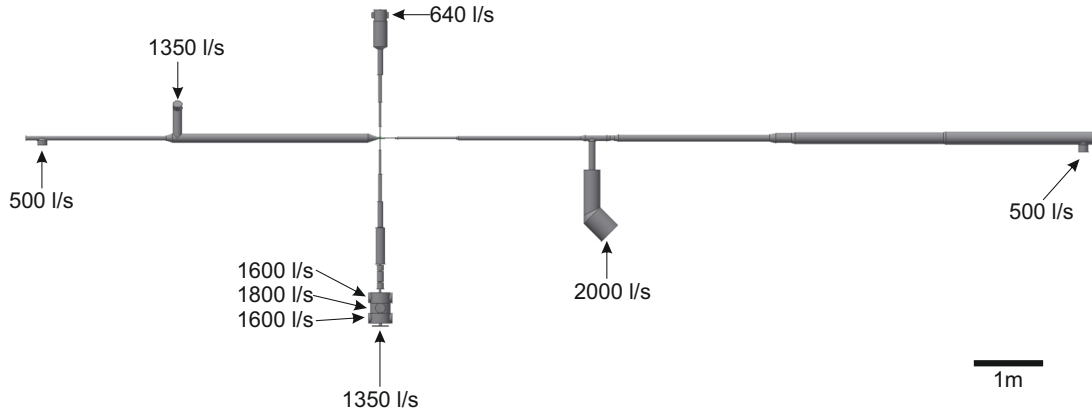


Figure 3.7.: The model of the $\overline{\text{PANDA}}$ vacuum system used for vacuum simulations. (Model originally generated by D. Klostermann)

The position of these pumps is marked by their location along the z -axis, with the interaction point marked as $z = 0$, the upstream region with respect to the accelerator beam defined as negative z -values and the downstream region subsequently as positive z . At $z = -512.1$ cm a 500 l/s turbo pump is located followed by a twin turbo pump setup with a combined pumping speed of 1350 l/s at -307.1 cm. The next turbo pump is located at 320.8 cm with 2000 l/s. The final turbo pump in the model is placed at 1065.5 cm with a pumping speed of 500 l/s [Klos 20]. It is of note that the nearest pumps to the interaction point are more than 3 m away, leaving the vacuum system

⁴The model was generated by D. Klostermann for [Klos 20]

3. A cryopump for the $\bar{\text{PANDA}}$ beam line

at risk of being under equipped to handle the gas introduced into the system by the cluster-jet target.

However, these are not the only pumps included in the model. There are additional pumps located in the vertical target beam pipe (cf. fig. 3.7), two turbo pumps at the top with an effective pumping speed of 3201/s each and the target beam dump at the bottom. The beam dump is subdivided into three distinct stages, each pumped by two turbo pumps. The first, uppermost stage has an effective pumping speed of 16001/s, the second stage has 18001/s and the third is pumped with 16001/s. Additionally, a final turbo pump with a pumping speed of 13501/s is mounted below the last stage in such a way as to directly pump any arriving clusters.

3.3.5. Vacuum simulations of the $\bar{\text{PANDA}}$ vacuum system without a cryopump

The first step was to simulate the $\bar{\text{PANDA}}$ vacuum system without an additional cryopump. The $\bar{\text{PANDA}}$ model shown in fig. 3.7 was inserted into Molflow+ and the pumps implemented with the pumping speeds mentioned in section 3.3.4. To create a realistic outgassing scheme for the cluster-jet target, two contributions needed to be considered: Firstly, the cluster beam itself traversing the vacuum, which creates a contribution through back flow of gas out of the beam dump, and secondly, the clusters evaporating while travelling through the beam pipe.

The first contribution requires the implementation of beam like outgassing in Molflow+, by using custom outgassing distributions. This feature was used to give the test particles the same properties as the cluster beam.

Simulation of the Cluster beam in Molflow+

To achieve a simulated cluster beam which is accurate to reality, the test particles need to follow the real cluster-jet trajectory. To do this, it is not necessary to simulate the whole beam, including emittance from the nozzle and passage through various systems such as skimmer and collimator. Instead it is sufficient to determine the length and width of the cluster beam when entering the $\bar{\text{PANDA}}$ vacuum, so that one may then create an accurate outgassing facet⁵ in the simulation model, and then to implement an accurate emittance angle model for the beam, as first performed in [Klos 20].

To determine the dimensions of the outgassing facet, all clusters were assumed to originate from a point like source, the smallest diameter of the nozzle, and that they have to pass through the skimmer and collimator orifices before entering the $\bar{\text{PANDA}}$ vacuum system. Furthermore, the trajectories of the clusters were assumed to be straight. These assumptions allow for the use of the intercept theorem to calculate the width of the cluster beam when entering the $\bar{\text{PANDA}}$ vacuum system (cf. fig. 3.8). The collimator and entrance to $\bar{\text{PANDA}}$ are 120 mm and 320 mm away from the point like source, respectively. Using this knowledge, along with the dimensions of the collimator

⁵The term "outgassing facet" describes a facet which was assigned an outgassing rate.

3.3. Vacuum simulations of the $\bar{\text{PANDA}}$ cryopump

(around $200\text{ }\mu\text{m} \times 800\text{ }\mu\text{m}$ [Hetz 17]) the dimensions of the cluster beam when entering $\bar{\text{PANDA}}$ are calculated to be $0.53\text{ mm} \times 2.13\text{ mm}$.

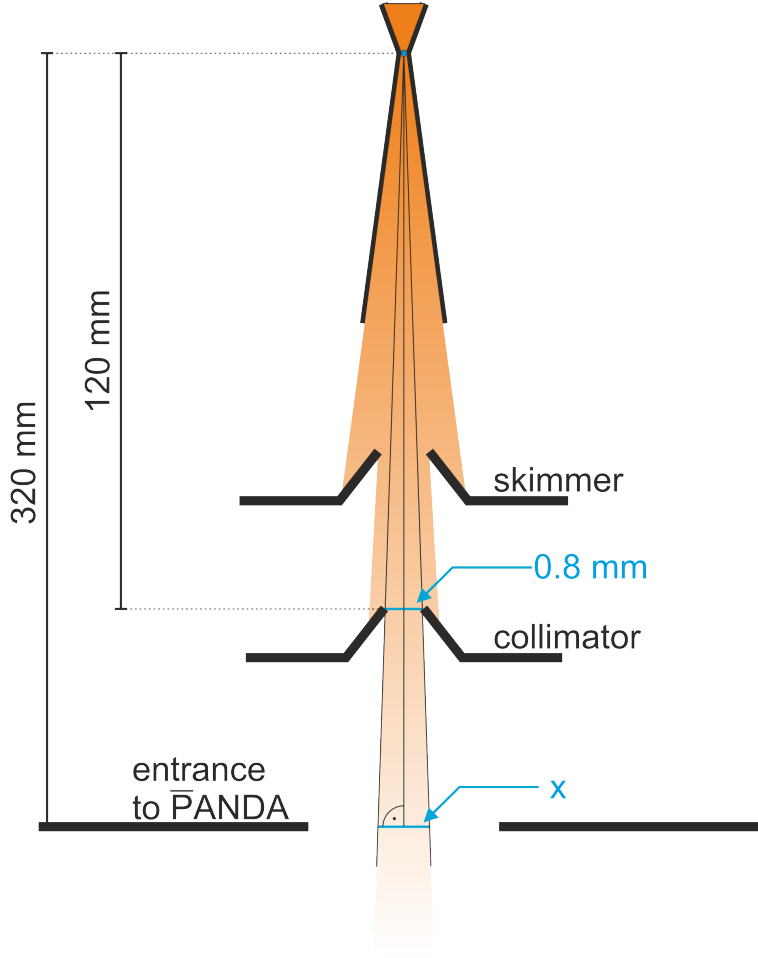


Figure 3.8.: A schematic representation of the target beam entering the $\bar{\text{PANDA}}$ vacuum system. The cluster-jet originates from a point like source and must then pass through skimmer and collimator. With the given dimensions, one can calculate the beam width x when entering $\bar{\text{PANDA}}$, using the intercept theorem.

The second step was to determine and implement the trajectory these particles will be issued with. Molflow+ does not support beam like outgassing per default, so a custom outgassing scheme needed to be created. To this end, a truncated pyramid was constructed in the AutoCAD software Autodesk Inventor, with the larger base area possessing the same dimensions as the cluster beam when entering $\bar{\text{PANDA}}$. The height of the pyramid was chosen arbitrarily to be 300 mm and the dimensions of the smaller base area were calculated according to the intercept theorem with the values depicted in fig. 3.8, leading to a length and width of 0.13 mm and 0.03 mm, respectively. Thus the truncated pyramid has the same shape and dimensions the cluster beam does.

3. A cryopump for the $\overline{\text{PANDA}}$ beam line

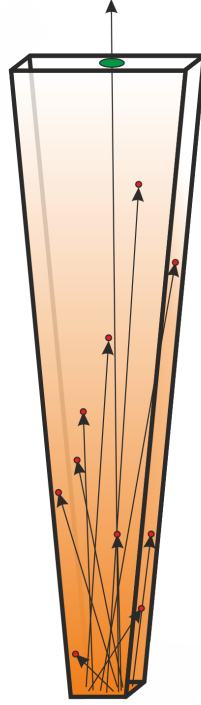


Figure 3.9.: A schematic depiction of the cluster beam simulation scheme in Molflow+. The truncated pyramid has the same dimensions as the cluster beam and test particles are emitted from the lower base area with an arbitrary outgassing rate. particles which hit the walls are immediately pumped. Only those which follow the trajectory of the cluster beam reach the larger base area, where the angle with which they pass through the (transparent) area is recorded.

The next step was to import it to Molflow+ and apply an arbitrary outgassing rate to the smaller base area while at the same time applying a sticking factor of 1 to the walls. This means that the only test particles to reach the larger base area were the ones following the same trajectory as the cluster beam particles (cf. fig. 3.9). The larger base area was then set to transparent and the angles of the test particle trajectories which manage to reach this base area were recorded with a function built into Molflow+. These recorded trajectories could then be applied to an outgassing facet to create a test particle beam with the characteristics of the real cluster beam.

Now that the trajectory of the test particles and the size of the outgassing facet were implemented, one last detail needed to be considered, which is the outgassing rate of the facet. This value could not be taken directly from the experimental data concerning gas flow through the target and the associated gas pressure, because a lot of this material does not contribute to the cluster beam, either due to not being clustered or being blocked by skimmer and collimator. Instead one needed take the target thickness at the interaction point between accelerator beam and cluster beam and use it to calculate

3.3. Vacuum simulations of the $\overline{\text{PANDA}}$ cryopump

the outgassing rate of the facet using following formula⁶.

$$q_{pV} = \frac{1}{2} \frac{\rho_T v}{\text{erf}\left(\frac{b_x}{2s}\right)} b_x \frac{RT_N}{N_A} \quad (3.21)$$

The outgassing rate q_{pV} is computed mainly from the target thickness ρ_T , the cluster speed v and the target width at the interaction point b_x . The other values are constants such as the universal gas constant R , the Avogadro constant N_A , the normal temperature T_N and the smearing factor s which takes into account that the real cluster beam is not a sharp step function, but instead experiences a certain amount of smearing, here assumed to be 2 mm. By plugging in a target density of $2 \cdot 10^{15}$ atoms/cm² as well as realistic values for cluster speed and beam width, 278 m/s and 5 mm, one obtains an outgassing rate of 0.578 mbar · l/s. One should note that the cluster speed, unlike the beam width, was not experimentally measured as experimental values are unavailable for the $\overline{\text{PANDA}}$ cluster-jet target. Instead the values were calculated with a program based on [Tasc 13] which agree quite well with experimental values taken for a different cluster-jet target [Kohl 15].

Simulation of cluster evaporation in Molflow+

To simulate the cluster evaporation, a row of outgassing facets was implemented along the beam axis from the top of the target beam pipe to the final stage of the beam dump (cf. fig. 3.10), each one with an outgassing rate of $3.82 \cdot 10^{-4}$ mbar · l/s. This outgassing rate is a theoretical value for a cluster diameter of 5 μm and a target thickness of $2 \cdot 10^{15}$ atoms/cm². It was calculated by Benjamin Hetz and already used to successfully describe the vacuum situation of the $\overline{\text{PANDA}}$ cluster-jet target at the COSY accelerator [Hetz 21], however, as of writing, further and more detailed investigations concerning cluster sizes and outgassing rates are currently ongoing [Weid 23, Weid 24].

3.3.6. $\overline{\text{PANDA}}$ vacuum system simulation results

Using the simulation setup explained in detail above, simulations of the $\overline{\text{PANDA}}$ vacuum system without a cryopump were performed, assuming a target with $2 \cdot 10^{15}$ atoms/cm² thickness. The resulting axial vacuum distribution is depicted in fig. 3.11. The highest vacuum pressure is found at the interaction point, as expected. In the upstream and downstream regions the vacuum conditions improve due to the installed pumps with the shoulders in the vacuum distribution stemming from an increase of the pipe diameter at the shoulder positions. Using this distribution, one can then calculate the rest-gas thickness, which is a measure for how much rest-gas the accelerated particles have to fly through when traversing the $\overline{\text{PANDA}}$ interaction

⁶originally derived by the one and only Philipp Brand (cf. appendix A).

3. A cryopump for the $\bar{P}$ ANDA beam line

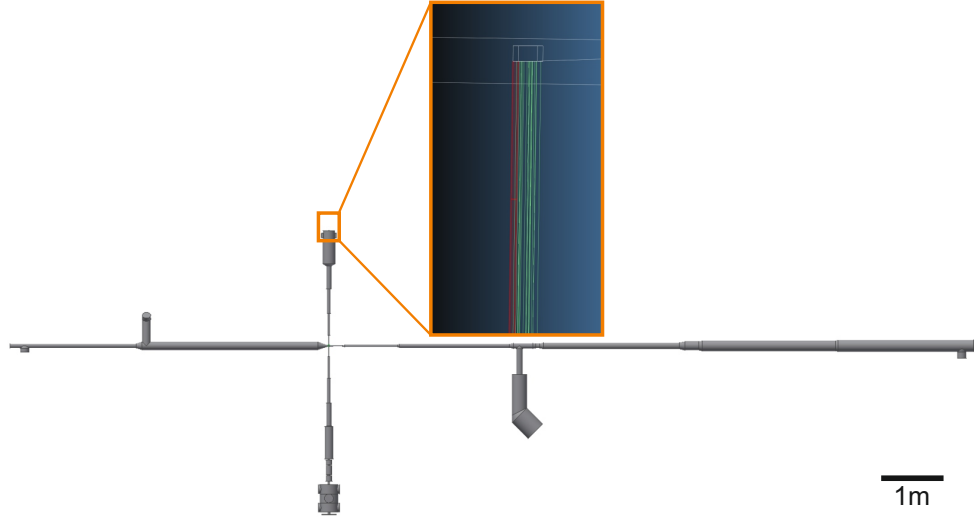


Figure 3.10.: Illustration of the outgassing scheme used in Molflow+. The cutout illustrates the situation at the top of the target beam pipe. The green lines indicate the test particles' beam like trajectory, which originate from a small facet at the top of the model. The facets marked in red are used to simulate cluster evaporation by outgassing in uniform direction at a constant rate all along the target beam axis.

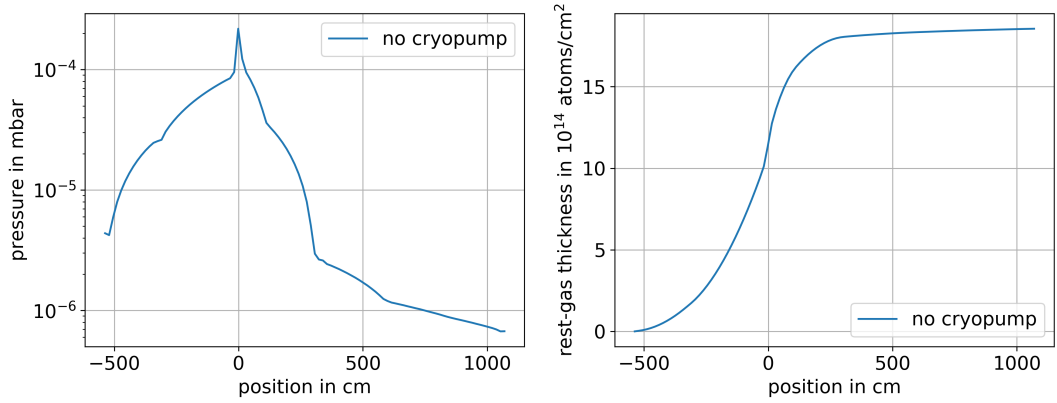


Figure 3.11.: Vacuum simulation of the $\bar{P}$ ANDA vacuum system without a cryopump. As can be seen in the axial vacuum distribution on the left, the highest vacuum pressure is found at the interaction point, with the installed pumps improving the vacuum along the beam axis. The shoulders originate from increases in pipe diameter at the shoulder positions. The resultant rest-gas distribution can be seen on the right, revealing that the rest-gas thickness is nearly as high as the target thickness itself.

region, using eq. (3.22).

$$\rho(x) = \alpha \int_0^x p(x') dx' \quad (3.22)$$

3.3. Vacuum simulations of the $\bar{\text{PANDA}}$ cryopump

Here, $\rho(x)$ is the rest-gas thickness the accelerator has flown through to arrive at location x ⁷, $\alpha = 495 \cdot 10^{14}$ atoms/(mbar · cm³) a conversion factor which is derived in appendix B, x the spatial coordinate in axial direction and $p(x)$ the pressure at location x ⁸. Applying eq. (3.22) to the data depicted on the left of fig. 3.11 leads to the plot on its right. There, the most important value is the rest-gas thickness taken at the most downstream point of the simulation (also referred to as 'final rest-gas thickness'), as it represents the amount of gas the accelerator beam needs fly through when passing through $\bar{\text{PANDA}}$. It becomes apparent that the final rest-gas thickness is nearly as large as the target thickness and thus steps need to be undertaken to minimise the impact of the rest-gas.

3.3.7. Vacuum simulation of the cryopump designs

After simulating the "pure" $\bar{\text{PANDA}}$ vacuum, now the various cryopump designs introduced in section 3.3.1 are added to our simulations to determine their respective effectiveness in different categories, such as the improvement of the vacuum or the interval between two regeneration cycles, among other things, to determine the optimal geometry.

Possible locations for the $\bar{\text{PANDA}}$ cryopump

As previously discussed, the cryopump will be installed into the $\bar{\text{PANDA}}$ beam line for maximum efficacy. Ideally, it would be installed at the interaction point, which is, however, not possible due to the $\bar{\text{PANDA}}$ detector encasing this position. Instead, the closest possible location is depicted in fig. 3.12, around 3 m upstream of the interaction point, which has the unforeseen benefit of already providing two turbo pumps for regeneration purposes. In the following simulations the various cryopumps will be exclusively located at this position.

Vacuum improvement results achieved by the cryopump

The four cryopump geometries mentioned in section 3.3.1 were each added to the simulation, with the cryopump surfaces being given a sticking factor of $s = 0.45$. This value is calculated by taking eq. (3.16) and solving for s :

$$s = \frac{4S}{<v>A}. \quad (3.23)$$

Applying eqs. (3.13) and (3.14) leads to

$$s = \frac{4S}{3A} \sqrt{\frac{8M}{\pi RT}} \quad (3.24)$$

⁷So if $\rho(0 \text{ cm}) = 1 \cdot 10^{15}$ atoms/cm², the accelerator beam has experienced $1 \cdot 10^{15}$ atoms/cm² of rest-gas thickness before arriving at the interaction point.

⁸ x' denotes the use of x as an integration variable with no further significance

3. A cryopump for the $\bar{\text{P}}\text{ANDA}$ beam line

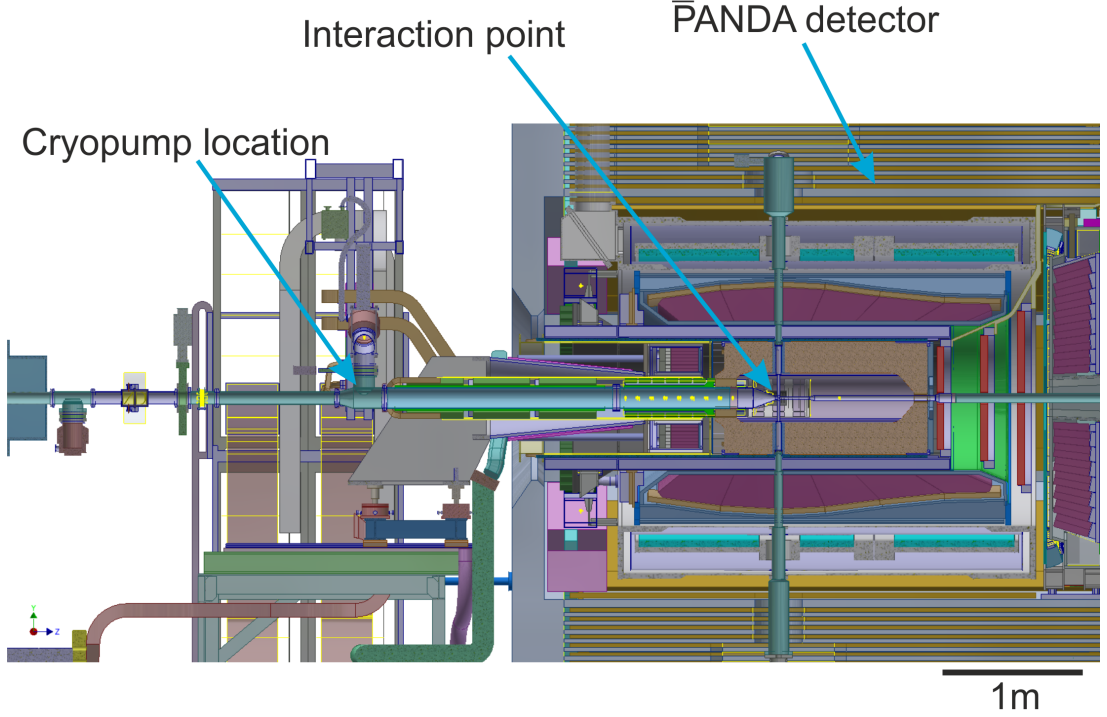


Figure 3.12.: Technical drawing of the $\bar{\text{P}}\text{ANDA}$ interaction region. Due to space constraints, the cryopump cannot be installed right at the interaction point, instead a location around 3 m further upstream is foreseen. (CAD model generated by D. Bonaventura)

Here M is the molar mass of a hydrogen molecule and R the Avogadro constant. Under the assumption that the remaining gas in the vacuum has room temperature, $T = 293.15 \text{ K}$ is valid and $S = 8201/\text{s}$ is the experimentally determined pumping speed of a cryopump with $A = 35 \text{ cm}^2$ [Rung 21]. Inserting all these values finally leads to $s = 0.45$.

The respective vacuum distribution and rest-gas density were determined and are depicted in fig. 3.13. The impact of a cryopump becomes immediately clear when

Table 3.4.: Rest-gas thicknesses for various $\bar{\text{P}}\text{ANDA}$ vacuum simulation scenarios, each with a different cryopump geometry. Each thickness value is taken at the most downstream point of the respective simulation.

	No cryo.	W. tube	W. apert.	W. screw	W. fin
final rest-gas thickness [$1 \cdot 10^{14} \text{ atoms/cm}^2$]	18.6	11.1	11.3	11.1	11.1

looking at the vacuum in the upstream region, where the improvement reaches several orders of magnitude in certain regions. As can be expected, the effect in the downstream region is quite negligible. Furthermore, it becomes apparent that, no matter the exact

3.3. Vacuum simulations of the $\bar{\text{PANDA}}$ cryopump

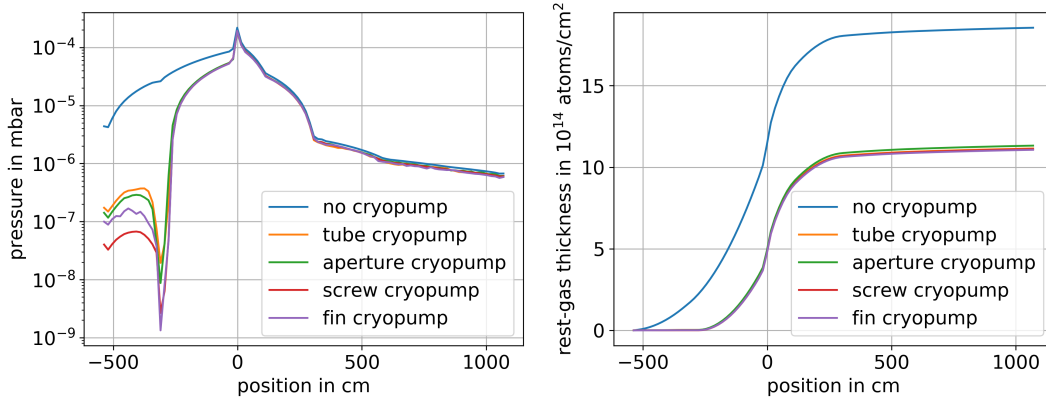


Figure 3.13.: Vacuum simulation results for different cryopump geometries. The achieved vacuum pressures are depicted on the left while the right shows the resulting rest-gas distributions. All of the cryopumps achieve nigh identical results.

cryopump geometry, the effectiveness is quite similar. This becomes even more obvious when regarding the rest-gas thickness (cf. fig. 3.13, right side), where the cryopumps deliver nigh identical results, each one reducing the expected rest-gas thickness by around 39 % (cf. table 3.4). Considering the differing pumping speeds given in table 3.3, this might seem unintuitive, but it can be explained by taking a closer look at how exactly the pumps improve the vacuum. In the upstream region, the rest-gas is pumped when it reaches the cryopump, reducing the time it spends in the beam pipe and thus improving the vacuum. The pumping speeds of each of the cryopumps is so great that all gas molecules are instantly pumped away as soon as they reach the pump, so that an increase of pumping speed no longer leads to a better vacuum.

Nonetheless, including a cryopump into the $\bar{\text{PANDA}}$ beam line leads to a 39 % lower final rest-gas thickness as demonstrated by the simulations, which is a significant improvement. For example, it means that the beam life time will be lengthened by roughly 20 %⁹(cf. appendix C), a good value for the valuable anti-proton beam.

⁹If one only considers target related losses such as the beam-target interaction and rest-gas.

3. A cryopump for the $\bar{P}$ ANDA beam line

Investigating the effect of cryopump length on the $\bar{P}$ ANDA vacuum

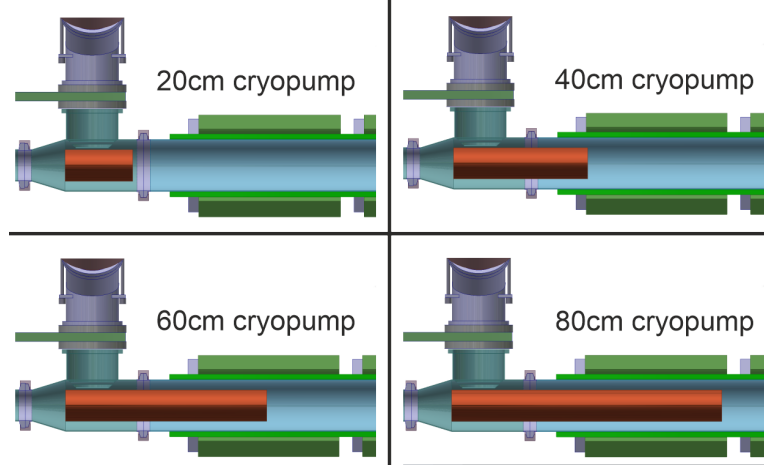


Figure 3.14.: Four tube cryopumps with differing lengths implemented into a CAD model of $\bar{P}$ ANDA. (Original CAD model generated by D. Bonaventura)

To further explore how to optimise the cryopump's effect on the vacuum, vacuum simulations with the same setup as before were run varying its length instead of its geometry.

The results for the four tube cryopumps of differing lengths from 20 cm to 80 cm (cf. fig. 3.14) are depicted in table 3.5 which demonstrate a visible dependence of the vacuum conditions on the cryopump length. Intuitively, one might ascribe this behaviour to the increase of pumping speed with length but this interpretation contradicts the explanation in the previous section. Instead, the improvement of the vacuum with increasing cryopump length can be explained by considering that by making the cryopump longer, it is also moved closer to the interaction point, the de facto rest-gas source. This means that the particles bouncing in the beam pipe are pumped quicker which improves the vacuum. To verify this line of argumentation, a 20 cm long tube cryopump was implemented as depicted in fig. 3.15, so that its rear end is at the same

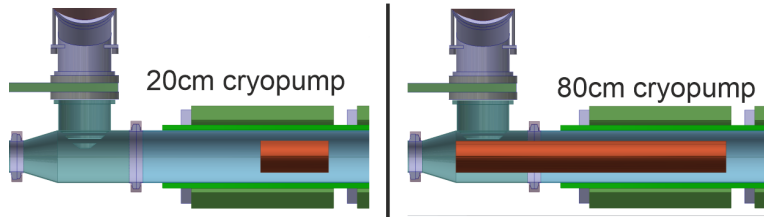


Figure 3.15.: Two tube cryopumps with differing lengths implemented into a CAD model of $\bar{P}$ ANDA. Although the cryopumps have greatly differing pumping speeds the resultant rest-gas thicknesses are nigh identical (cf. fig. 3.16). (Original CAD model generated by D. Bonaventura)

3.3. Vacuum simulations of the $\overline{\text{PANDA}}$ cryopump

Table 3.5.: Rest-gas thicknesses for various $\overline{\text{PANDA}}$ vacuum simulation scenarios, each with a different tube cryopump length. Each thickness value is taken at the most downstream point of the respective simulation.

	No cryopump	20 cm	40 cm	60 cm	80 cm
final rest-gas thickness [$1 \cdot 10^{14}$ atoms/cm ²]	18.6	12.6	11.9	11.1	10.5

height as the 80 cm long pump. If the arguments above are correct, the short cryopump with inferior pumping speed should perform just as well as the large pump, which is exactly the result obtained in fig. 3.16, thus proving the claims previously made.

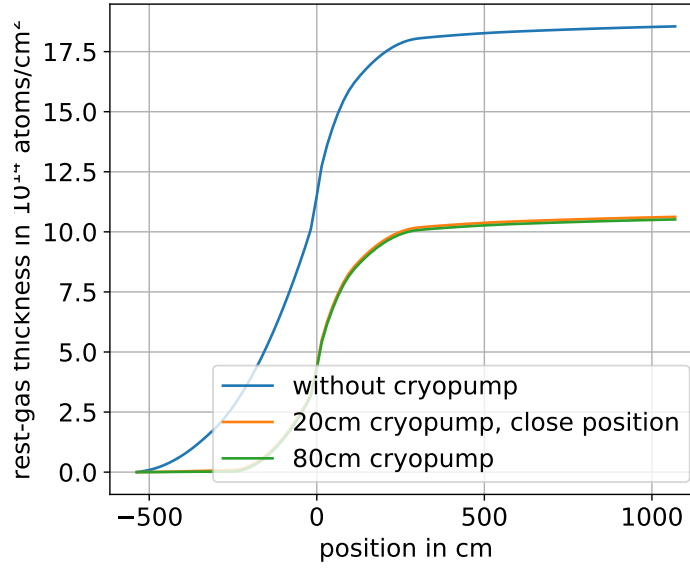


Figure 3.16.: Rest-gas thickness results comparing an 80 cm long cryopump and a 20 cm long cryopump mounted closer to the interaction point, so that both of their rear ends are at the same axial position, which leads to identical results.

3. A cryopump for the $\overline{\text{PANDA}}$ beam line

Investigating the regeneration intervals of cryopumps

Table 3.6.: Capacity for various cryopump geometries. All data is for pumps which are 60 cm long.

	surface area in cm^2	capacity in $\text{mbar} \cdot \text{m}^3$
fin	6324	74.6
aperture	3011	35.5
screw	4515	53.3
tube	3155	37.2

So far, the simulations have shown how the length and exact geometry of the cryopump are not of great importance for its performance. This changes when considering how cryopumps need to be regenerated regularly, necessitating an interruption of accelerator operation. Thus, long regeneration intervals are favoured and the cryopump designs are evaluated concerning this aspect, which requires knowledge of their capacity and the incoming hydrogen gas flow.

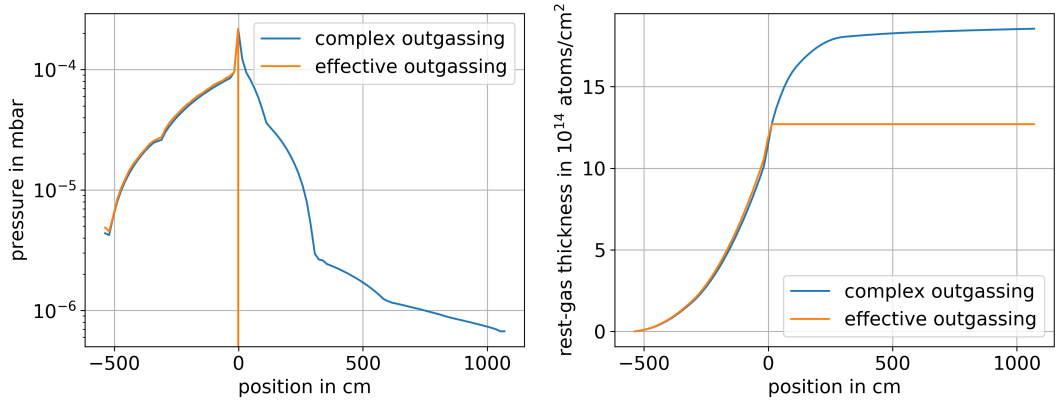


Figure 3.17.: Results of the vacuum simulations used to determine the effective outgassing rate. "Complex outgassing" describes the outgassing schemes used in the previous simulations which considered contributions such as backflow out of the beam dump and cluster evaporation while "effective outgassing" describes a much simpler outgassing scheme with a single outgassing facet. Through an iterative process the effective outgassing is adjusted until it perfectly matches the complex outgassing. As the blockers used in this simulation (cf. fig. 3.18) prohibit any gas from entering the downstream region, the vacuum abruptly drops to zero when it reaches the blocker.

As explained in section 3.1, a cryopump is considered to be "full" when its pumping speed has fallen to half of its original value. For a cryopump of $F = 35 \text{ cm}^2$ this occurs when it has adsorbed $C = 0.413 \text{ mbar} \cdot \text{m}^3$ of hydrogen [Rung 21] resulting in a specific capacity of $C_{\text{spec}} = C/F = 118 \text{ mbar} \cdot \text{m}$. These experimental values were measured using the same activated charcoal which is also intended for use with the $\overline{\text{PANDA}}$

3.3. Vacuum simulations of the $\bar{P}$ ANDA cryopump

cryopump, allowing for the precise determination of the projected capacities for the individual cryopump geometries, as listed in table 3.6.

Now the incoming gas flow into the cryopumps needs to be determined. This value is not trivially obvious to determine as the gas flow into the cryopumps consists of several contributing factors, such as the cluster evaporation along the target beam and the backflow out of the beam dump, both of which are difficult to determine analytically. So instead, a simulation based approach was used. A simulation was created which does not consider cluster evaporation nor backflow, instead it only has one outgassing facet at the interaction point which consolidates all contributions into one outgassing rate (cf. fig. 3.18). Furthermore, the entrances to the target beam pipe and the downstream region are blocked. This simulation was run iteratively, with

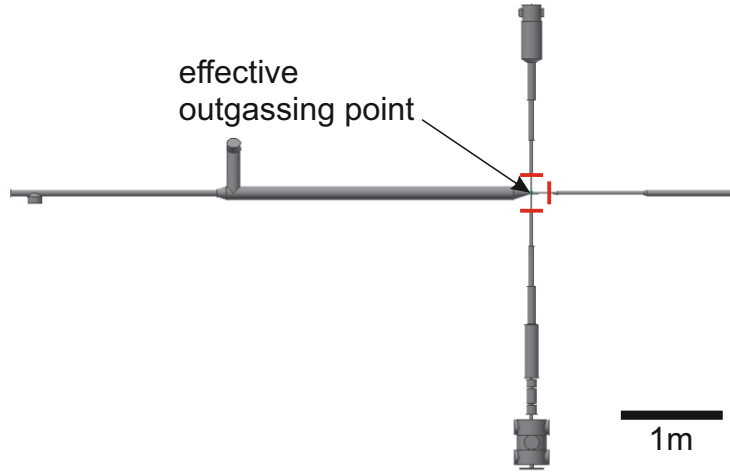


Figure 3.18.: Setup for the simulation to determine the gas flow into the cryopumps. All individual outgassing contributions are combined into one effective outgassing point and all pathways except the one into the upstream region are blocked, which is marked in red.

the effective outgassing rate being adjusted after every run until the results perfectly matched the ones obtained with all rest-gas contributions being considered separately (cf. fig. 3.17). The blockers are important because without them the obtained effective outgassing rate would describe the gas flow into the entire $\bar{P}$ ANDA vacuum system, while what we require is the gas flow which enters the upstream region. Thus, with the blockers the effective outgassing rate can be identified as the gas flow entering the cryopumps:

$$q_{\text{cryo}} = 2.45 \cdot 10^{-2} \text{ mbar} \cdot \text{l/s} \quad (3.25)$$

and the regeneration interval t_{reg} of the individual cryopump geometries can be easily determined through $t_{\text{reg}} = C/q_{\text{cryo}}$ as shown in table 3.7. All cryopumps have regeneration intervals in the order of several weeks with the fin geometry performing the best by a wide margin. At such timescales, there is a significant likelihood for interruptions in accelerator operation during which a cryopump may be regenerated, however such an

3. A cryopump for the $\overline{\text{PANDA}}$ beam line

Table 3.7.: The regeneration intervals for the different cryopump geometries. Here, A is the surface area, C the capacity and t_{reg} the regeneration interval. All data is for pumps which are 60 cm long.

	A in cm^2	C in $\text{mbar} \cdot \text{m}^3$	t_{reg} in weeks
fin	6324	69.7	5.0
aperture	3011	35.5	2.4
screw	4515	53.2	3.6
tube	3155	37.2	2.5

occurrence cannot be guaranteed, which means the cryopump might become a source of accelerator downtime.

Performance of partly full cryopumps

Apart from the theoretical regeneration intervals calculated above, one still needs to consider that the vast majority of the rest-gas which will enter the pump will originate from the interaction point. This means that the parts of the pump closest to it will accumulate gas quicker than the rest, which could lead to performance degradation significantly earlier than the regeneration intervals suggest.

To investigate this potential issue, the performance of the various cryopump geometries after about a month of use at $\overline{\text{PANDA}}$ was analysed. After around three days of continuous target operation, the cryopumps should have adsorbed about $6 \text{ mbar} \cdot \text{m}^3$. To simulate the situation that the cryopump is unevenly loaded, the assumption was made that this amount of gas was exclusively accumulated by the parts on one side, so that in this case the closest 500 cm^2 to the interaction point are assumed to be completely filled with no pumping capability left whatsoever (cf. fig. 3.19).

Of course this is a large simplification, however, determining the exact impingement rate of gas at every position of every respective cryopump geometry would be extremely time consuming using the tools we currently possess. Furthermore, one would then also have to consider that the surfaces at full capacity warm up considerably, which would have a large effect on the pumping capabilities of the other parts of the cryopump which is difficult to estimate. Ultimately, it was decided that this simplified simulation was sufficient for a qualitative estimation how different cryopump geometries would react to long term use at $\overline{\text{PANDA}}$, which is the primary goal at this point.

Using the same simulation setup and methods as before (cf. section 3.3.5), albeit now with partly full cryopump geometries, leads to the rest-gas thicknesses depicted in fig. 3.19. The results for an empty fin cryopump, which here represents all the other cryopumps as their results are nigh identical, are shown in blue. One can clearly see how all pumps show some kind of degradation when compared to this benchmark, especially the aperture geometry which leads to significantly higher thicknesses with a value of $12.8 \cdot 10^{14} \text{ atoms/cm}^2$ while other geometries remain at or below around $11.8 \cdot 10^{14} \text{ atoms/cm}^2$.

Further simulations were made for the cryopumps after 9 days of continuous use (cf.

3.3. Vacuum simulations of the $\bar{P}$ ANDA cryopump

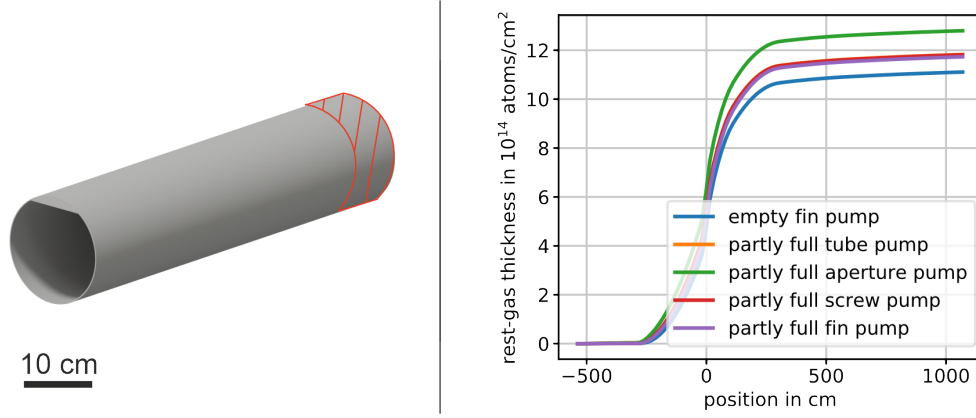


Figure 3.19.: Left: Illustration of a partly full cryopump. The parts closest to the interaction point no longer possess any pumping speed (here marked in red). **Right:** rest-gas thicknesses of various cryopump geometries after 3 days of use in comparison to a freshly regenerated cryopump (blue). Except for the aperture geometry, which shows significantly higher rest-gas thicknesses than the rest, all the other geometries show the same slight degradation in performance. Please note that the data for the tube geometry is hidden beneath the data for the partly full fin and screw cryopumps.

fig. 3.20). As expected, the final rest-gas thickness is highest for the aperture cryopump (around $15.7 \cdot 10^{14}$ atoms/cm²), while the tube and screw geometries achieve similar results (around $13.2 \cdot 10^{14}$ atoms/cm²) with the best result being reserved for the fin cryopump at around 12.7 atoms/cm².

There are two mechanisms which lead to the observed vacuum degradation. Firstly, the non-pumping surfaces may impede gas from impinging on pumping surfaces, effectively decreasing the conductance. Secondly, by assuming that the cryopump surfaces closest to the interaction point no longer pump, one effectively shortens the cryopump, which worsens the vacuum conditions as previously investigated. For this reason the fin cryopump performs best. It has the largest surface of all the geometries, so when a certain amount of surface area is declared to be non-pumping, the fin pump is shortened less compared to the other geometries.

In conclusion, the effectiveness of all cryopump geometries will start deteriorating within days due to the uneven gas load, significantly earlier than might be expected from just the capacity. The aperture geometry is most affected: After only nine days the final rest-gas has already nearly reached thicknesses as if no cryopump was installed at all, excluding this geometry from further consideration. The other pumps fare better with less performance losses. The fin geometry does the best here, making it the design with the best prospects.

3. A cryopump for the $\overline{\text{PANDA}}$ beam line

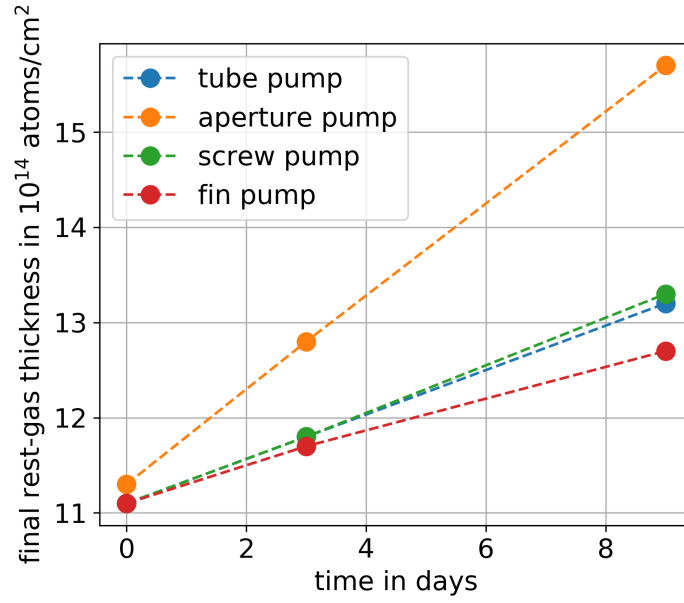


Figure 3.20.: Performance of the various cryopump geometries over time. The aperture cryopump clearly shows the strongest increase in rest-gas thickness while the tube and screw cryopump show very similar performance and the fin geometry performs the best.

3.3.8. Conclusion concerning the vacuum simulations of the different cryopump geometries

The vacuum simulations with Molflow+ have demonstrated that all the cryopump geometries which were tested perform nearly identically in most criteria, such as the achieved rest-gas thicknesses (cf. table 3.4). This might seem unintuitive when considering that the pumps have clearly differing pumping speeds from each other (cf. table 3.2) but this behaviour is understandable when one considers that all of the pumps remove gas nigh instantly, regardless of their exact pumping speeds.

Additionally, the simulations have shown that the uneven gas load the cryopump will face could potentially reduce its effectiveness within days. To minimise this effect, the surface of the pump should be maximised. This can be done by choosing a geometry with maximum surface, such as the fin design but also by making the pump as long as possible. The main factor limiting cryopump size is the available cooling power, so the next step is to perform temperature simulations to determine the maximum length cryopump which can still be adequately cooled.

However, not all geometries are considered. The aperture geometry performs significantly worse than the others when it is partly filled with gas. Taking into account that it does not perform better than the other pumps in any other category it was eliminated from contention, alongside the screw cryopump which possesses a design which promises to be challenging to engineer and assemble. Since it does not show any

performance advantages compared to the other, simpler, designs, there is no reason to choose it over the others. Instead the decision was made to only consider the fin and tube cryopump for further analysis.

3.4. Temperature simulations of the $\overline{\text{PANDA}}$ cryopump

As explained above, extensive vacuum simulations performed on various cryopump geometries revealed the importance of their size on their performance. To make sure that the available cooling power is sufficient, temperature simulations were performed with the software Autodesk CFD.

3.4.1. Theoretical background

Autodesk CFD is designed to simulate fluid flow and heat transfer by numerically solving three coupled non-linear equations: the continuity equation, the Navier-Stokes equation and the energy equation [Auto 24d]. To establish a basic background of the inner workings of our chosen simulation software, these three equations are introduced in this chapter and how they are numerically solved by Autodesk CFD.

The continuity equation describes the conservation of mass for both inviscid and viscous fluids [Wols 16]:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0, \quad (3.26)$$

where ρ is the density and $\vec{v}$ the speed of the fluid.

The equations of motion of a moving viscous fluid are given by the Navier-Stokes equations

$$\rho \left[\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} \right] = -\nabla p + \eta \Delta \vec{v} + \left(\zeta + \frac{\eta}{3} \right) \nabla (\nabla \cdot \vec{v}), \quad (3.27)$$

where η is the shear viscosity and ζ the bulk viscosity. Finally, there is the heat transfer equation, given here for non compressible liquids

$$\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T = \frac{\kappa}{\rho c_p} \Delta T + \frac{\nu}{2c_p} \left[\frac{\partial v_i}{\partial k} + \frac{\partial v_k}{\partial i} \right]^2 \quad (3.28)$$

which depends on the two additional constants κ , the thermal conductivity, and c_p , the specific heat capacity for constant pressure. i and k denote directions for the spatial derivatives.

This system of five non-linear coupled equations has no known general analytical solutions which makes numerical ones necessary [Auto 24d]. In Autodesk CFD, the geometry to be simulated is divided into a number of small volumes (elements), and the variables of interest, such as temperature or speed, are replaced by shape functions [Auto 24a], which interpolate the values between individual elements. These shape functions, which are often low order polynomials [Wien 24], are then plugged into the equations above, which are then integrated over the elements' volume, with a weight function of the same form as the shape function being applied. The results are algebraic

3. A cryopump for the $\overline{P}$ ANDA beam line

equations for the respective value which can be solved individually, independent from the others using this scheme [Auto 24c]:

1. Read in geometry, boundary conditions, and analysis data
2. Create data structures
3. Solve x-momentum equation
4. Solve y-momentum equation
5. Solve z-momentum equation
6. Solve pressure equation and correct velocities
7. Solve energy equation
8. Solve turbulent kinetic energy equation
9. Solve turbulent energy dissipation equation
10. Check convergence (go to step 3 in case of no sufficient conversion)
11. Perform output calculations
12. Write out data
13. Exit

The equations are solved iteratively, which means that at first estimates for the solution variables are taken and plugged into the equations which are then solved, providing new values which are plugged into the equations for the next iteration until convergence is achieved.

3.4.2. Simulation workflow

In practice, most of the time the user does not need to interact with the algorithms which govern the simulation's behaviour. Instead, one needs to focus more on choosing suitable materials, boundary conditions and solving options for the geometry at hand, which will be detailed in the following sections.

Creating and modifying the geometry

The first step, before any simulations can be run, is to create a CAD model of the geometry one wants to analyse. As before with the Molflow+ simulations, this is done with Autodesk Inventor. For the temperature simulations, the section of the accelerator beam pipe which is going to house the cryopump is taken as a basis (cf. figs. 3.12 and 3.14). The tube which houses the two turbopumps foreseen for this section is omitted as it plays no part in the temperature simulations. Instead, a tube is added

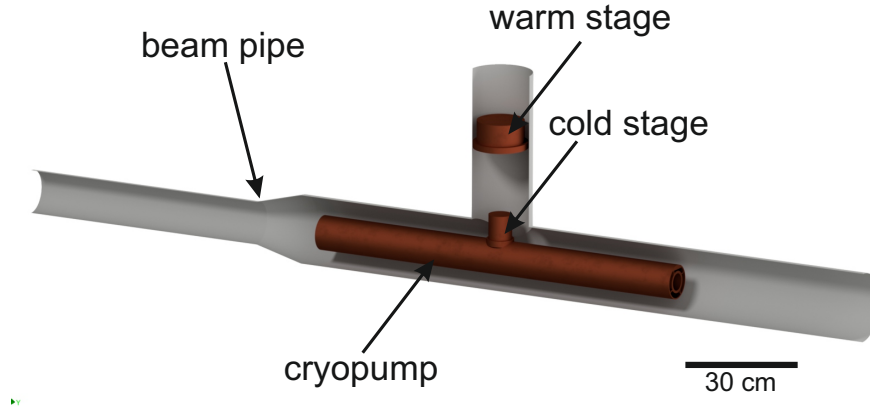


Figure 3.21.: Basic setup for the cryopump temperature simulations. Depending on the exact simulation, the cryopump is replaced by a different model while the other components and their respective positions remain the same. Despite possibly appearing to do so, the warm stage has no contact with the beam pipe.

which houses the warm and cold stage of the cold head¹⁰ which powers the cryopump. As discussed before, the pumping surfaces themselves are located in the beam pipe (cf. fig. 3.21).

The models can then be directly imported into Autodesk CFD, where the next step is to perform slight modifications to the geometry. Some are to minimise the probability of errors when creating the volume elements, for example, all small geometrical features under a certain size are erased so that they don't lead to issues¹¹ when the simulations are run. Others are more substantial, such as the void fill tool which is used to fill cavities with an unspecified material.

Assigning materials

Once all modifications are performed, the user needs to assign a material to all parts of the geometry. For the cryopump simulations, the relevant ones are stainless steel, copper and vacuum. The beam pipe enclosing the cryopump is assumed to be stainless steel. As there will be no direct contact between the pipe and any cryogenic surface the exact temperature dependent properties of this material are irrelevant, furthermore, since the exact type of stainless steel in use at $\bar{P}$ ANDA is unknown as of writing¹², a generic steel found in the pre-configured materials database is used (cf. appendix D). Copper is a much more critical material as it will be used for all cryogenic surfaces.

¹⁰more details on the cold head can be found in section 3.1.1.

¹¹Such features often show divergent behaviour for their observables, if they don't cause the entire simulation to crash outright.

¹²Although a likely candidate is the stainless steel EN 1.4429.

3. A cryopump for the $\bar{P}$ ANDA beam line

Table 3.8.: Thermal conductivity (κ) and specific heat (c_P) of copper in dependence of temperature [Simo 92, Arbl 15]. Only selected values are listed here. A more complete table as well as the empiric formulas used for the specific heat can be found in appendix D.

T in K	κ in W/(m · K)	c_P in J/(g · K)
10	454	0.0087
20	843	0.0073
30	999	0.0265
50	900	0.0971
100	421	0.2521
150	396	0.3221
200	391	0.3551
250	388	0.3733

Table 3.9.: Relevant material property settings for vacuum in Autodesk CFD [Auto 24e].

Density	$1 \cdot 10^{-18} \text{ g/cm}^3$
Viscosity	$1 \cdot 10^{-15} \text{ Pa} \cdot \text{s}$
Thermal conductivity	$1 \cdot 10^{-15} \text{ W/(m} \cdot \text{K)}$
Specific heat	$0.001 \text{ J/(g} \cdot \text{K)}$

The most important values for temperature simulations are the thermal conductivity κ and specific heat c_P which are thus defined temperature dependently (cf. table 3.8). The values for the thermal conductivity are taken from [Simo 92] while the specific heat is calculated using empiric formulas found in [Arbl 15] (cf. appendix D). The third relevant material is vacuum. In the physical world, vacuum is characterised by an absence of material in a volume, however for technical reasons it needs to be specified as a material in Autodesk CFD with exceedingly low values for density, viscosity, thermal conductivity and specific heat [Auto 24e] (cf. table 3.9).

Assigning boundary conditions

After the materials have been chosen, the boundary conditions need to be determined. For example, the beam pipe surrounding the cryopump is given a temperature of 20 °C. Additionally, the cold head's warm and cold stage are given cooling powers. These values were experimentally determined for a cold head of identical type [Bals 17], where they were found to be temperature dependent with some amount of "cross-talk", e.g. the cooling power at the cold stage not only depends on the temperature of said stage but also on the temperature of the warm stage. Since the effect of the cross talk is quite small, it is ignored and the values in tables 3.10 and 3.11 [Bals 17] are used. At 300 K a cooling power of -900 W is assumed which was not experimentally determined. Instead the -900 W were chosen arbitrarily high to ensure that the simulation quickly reaches the relevant cold temperatures. Furthermore, the vacuum is assigned an arbitrary flow and direction. This is done by giving the vacuum a flow speed of 0.1 m/s at one end of

3.4. Temperature simulations of the $\bar{P}$ ANDA cryopump

Table 3.10.: Cooling power of the warm stage in dependence of temperature [Bals 17]. All values correspond to a cold stage at its lowest possible temperature, which is the approximate temperature the stage reaches in the simulations. The first value was not experimentally determined, instead it is set to an arbitrarily high value so that the simulation quickly reaches relevant temperatures

Temperature in K	Cooling power in W
300	-900
111.3	-120
66.8	-80
41.9	-40
30.4	0

Table 3.11.: Cooling power of the cold stage in dependence of temperature [Bals 17]. All values correspond to a warm stage at roughly 60 K, which is the approximate temperature the stage reaches in the simulations. The first value was not experimentally determined, instead it is set to an arbitrarily high value so that the simulation quickly reaches relevant temperatures.

Temperature in K	Cooling power in W
300	-900
155.9	-40
109.8	-35
63.5	-30
42.3	-25
33.6	-22.5
25.1	-20
21.2	-17.5
18.3	-15
15.2	-10
12.6	-5
11.1	0

the model and giving it a pressure of 0 Pa at the other ends, thus defining an inlet and two outlets. Of course these boundary conditions do not describe physical reality in any way, but they are necessary as the simulation would crash immediately without them. because the vacuum does not meaningfully interact with the other materials in the simulation, this compromise was deemed acceptable.

Solver settings

Finally, the solver settings, where various physics and simulation settings are included, need to be configured. For our purposes, only heat transfer in general as well as radiative heat transfer is enabled, as that is the only physics of interest for us. Furthermore, the solver settings are set to transient solution. In this mode, the individual simulation steps

3. A cryopump for the $\bar{P}$ ANDA beam line

represent the chronological sequence of the cooling process. There are two meaningful options for this type of simulation: Time step size and number of inner iterations. The first value determines how much time passes between simulation steps and is set to 30 s. The latter decides how often the thermodynamic equations (cf. section 3.4.1) are solved iteratively and is set to 1. Both values are set in accordance to [Auto 24b].

Now, all that is left to do is to start the simulations and to evaluate the results.

3.4.3. Heat shield simulation results

The first step is to determine the influence of heat shielding on temperature. As the cryopump is surrounded by vacuum, the only mechanism which introduces heat is radiation. For two bodies, where one surrounds the other concentrically, the power transmitted via heat radiation from body 2 to body 1 ($I_{\text{rad},2 \rightarrow 1}$) is calculated via

$$I_{\text{rad},2 \rightarrow 1} = A_1 \frac{\sigma}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2} \left(\frac{1}{\epsilon_2} - 1 \right)} (T_2^4 - T_1^4) \quad (3.29)$$

where $A_{1,2}$ denotes the respective surface area, $\epsilon_{1,2}$, the respective emissivity and σ the Stefan Boltzmann constant [Jits 09]. Crucially, the power scales $\propto T^4$, thus large temperature differences such as between the cryopump surfaces (10 K) and room temperature (293.15 K) can lead to significant cooling power requirements. To illustrate this fact, simulations of a fin cryopump with and without heat shielding were performed using the materials and settings discussed in section 3.4.2. The results without heat

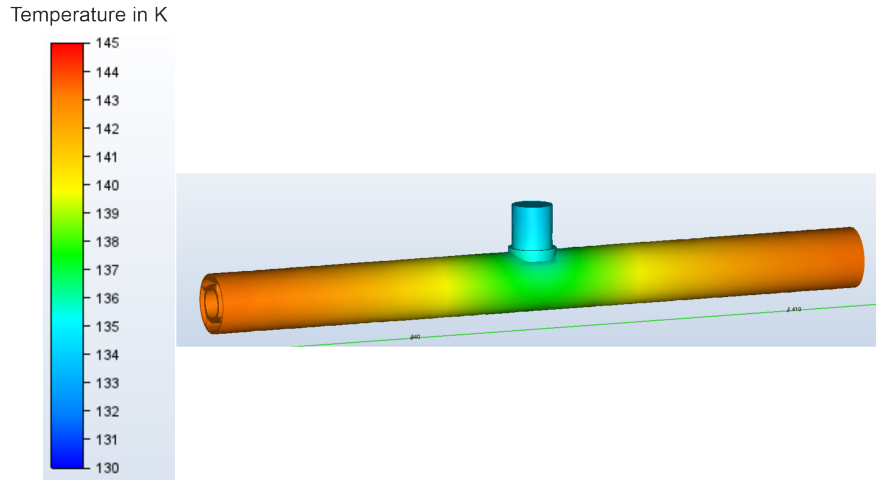


Figure 3.22.: Temperature simulation of an 80 cm long cryopump without heat shielding. The achieved temperatures are nowhere near the ones necessary for pumping hydrogen. The other parts of the simulation are hidden for visibility purposes.

shielding are depicted in fig. 3.22. As can be expected, the surface of the cold stage itself is coldest, with the temperature increasing the further away one moves from it. Overall, the lowest reached temperature is 134 K and warmest one 143 K, both far away

3.4. Temperature simulations of the $\bar{P}$ ANDA cryopump

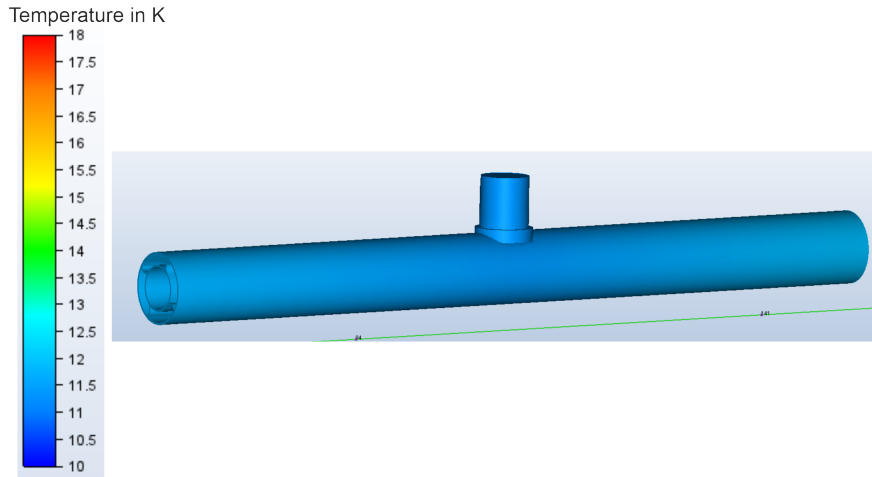


Figure 3.23.: Temperature simulation of the 80 cm long cryopump encased by a heat shield. Compared to fig. 3.22 much lower temperatures of around 12 K are achieved. The heat shield and the other parts of the simulation are hidden for visibility purposes.

from the 13 K necessary to pump hydrogen [Rung 21].

The situation changes considerably with the addition of heat shielding. The shield encloses the cryopump and is thermally connected to the cold head's warm stage achieving temperatures of 118 K at either end (cf. fig. 3.24). Now that the cryopump is no longer exposed to 293.15 K but 118 K instead, much cooler temperatures of around 12 K are reached (cf. fig. 3.23). It is clear that a heat shield is necessary for the

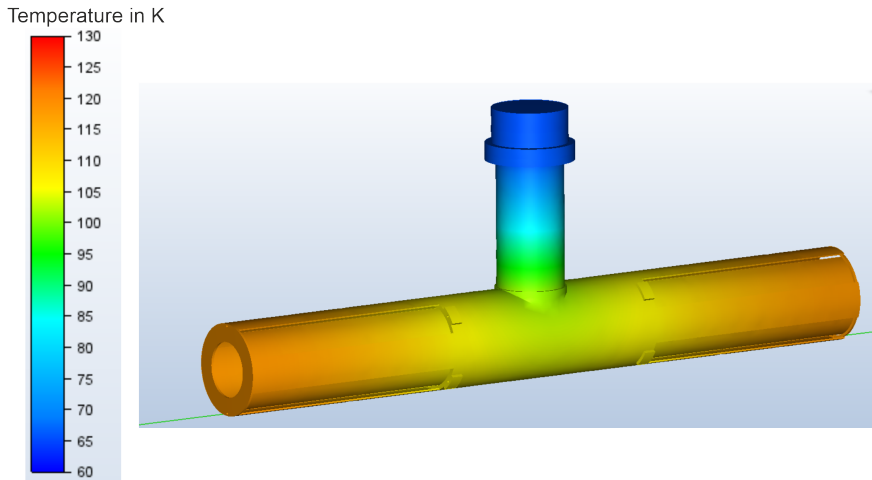


Figure 3.24.: Temperature simulation of the heat shield encasing an 80 cm long cryopump. The heat shield has maximum temperatures of around 118 K. The other parts of the simulation are hidden for visibility purposes.

$\bar{P}$ ANDA cryopump, however it comes at a slight price. The pump needs to be smaller

3. A cryopump for the $\bar{P}$ ANDA beam line

to accommodate the shielding, which decreases capacity and thus the regeneration interval. The 80 cm long fin cryopump used for the simulations here has an area of 4999 cm^2 resulting in a regeneration interval of 4 weeks. For comparison, an 80 cm long fin cryopump of the same dimensions as were used for the vacuum simulations described in section 3.3.7 achieves a significantly longer regeneration interval of 6.3 weeks. Additionally, a smaller cryopump leads to smaller pumping speeds. As established in section 3.3.7, this does not meaningfully influence the pump's efficacy, however the addition of heat shielding might influence the pump's conductance, adversely affecting performance. To quantify any effect, additional vacuum simulations with Molflow+ were performed, using the same setup and analysis methods as established in section 3.3.5. In total, two simulations were run: One with the cryopump and the heat shield and the other with just the bare cryopump. The heat shield leads to a slight increase of the final rest-gas thickness from $10.6 \cdot 10^{14} \text{ atoms/cm}^2$ to $11.0 \cdot 10^{14} \text{ atoms/cm}^2$, which is deemed to be perfectly acceptable, as the rest-gas thickness is still reduced by around 40 % and thus the beam life time increased by 20 % (cf. appendix C).

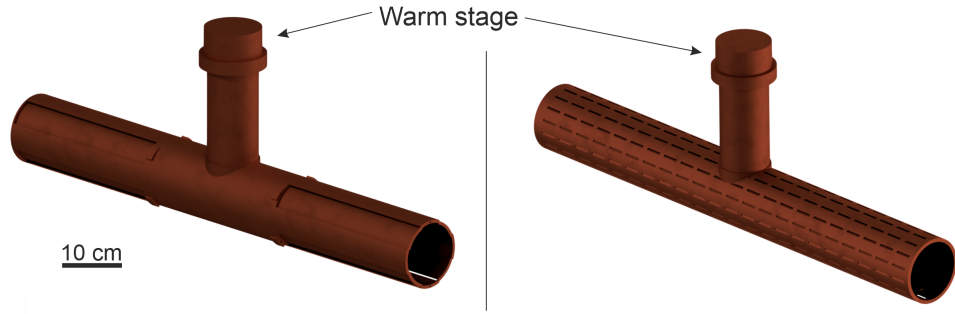


Figure 3.25.: **Left:** The gap shield, named after the elongated gap running along its length. **Right:** The hole shield, named after the many holes covering it.

Nonetheless, optimisation of the heat shielding was attempted. The heat shield used for the simulations so far, called gap shield, features elongated holes along its length to allow hydrogen trapped on the outside of the shield to enter the cryopump (cf. fig. 3.25). An alternative design, called hole shield, features many smaller holes for the same purpose. Using this shield, the cryopump reaches a temperature of 14.8 K and a rest-gas thickness of $11.1 \cdot 10^{14} \text{ atoms/cm}^2$. While the latter result is functionally indistinguishable from the one obtained for the gap shield ($11.0 \cdot 10^{14} \text{ atoms/cm}^2$), the former result is significant for cryopump performance since experimental results have shown (cf. [Rung 21]) a large loss of pumping speed at 15 K compared to 13 K. Thus for all future simulations the better performing shield, the gap shield, is used.

The reason for the better performance of the gap shield is that the hole shield contains more holes which let radiation in. While these holes also allow gas to enter the cryopump, the simulations show that the impact on the vacuum is negligible compared to the impact on the temperatures.

3.4.4. Simulations considering various cryopump lengths

Now that the heat shield's crucial role has been proven, more detailed simulations were run to determine an optimal cryopump geometry length, as long cryopumps are advantageous for their large effect on the rest-gas thickness as well as their long regeneration intervals (cf. section 3.3.7) but might not be sufficiently coolable above a certain length. To investigate the possibilities, temperature simulations of fin and tube cryopumps of various lengths were run with the setup as described in section 3.4.2. The results (cf. fig. 3.26) show that for both tube and fin geometries, satisfactory

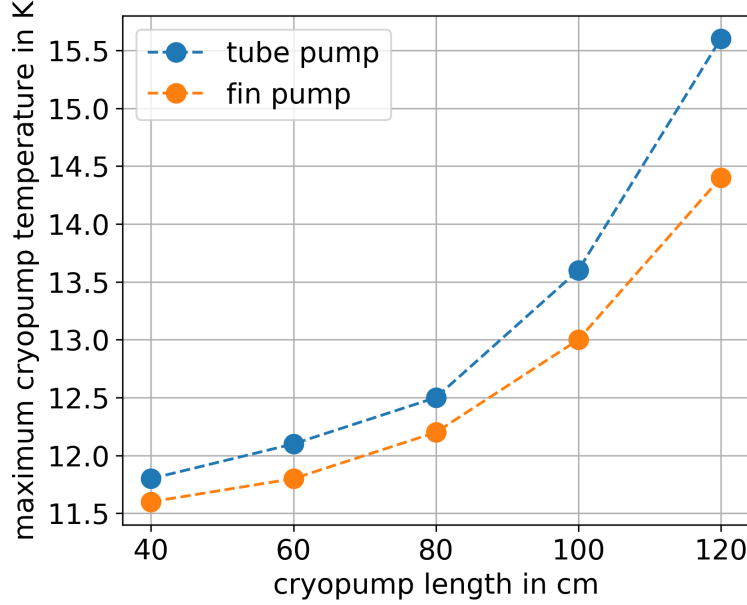


Figure 3.26.: The maximum temperature the cryopumps reach in dependence of their length for both the tube and fin geometries. Up until a length of 100 cm, both geometries achieve temperatures at or below the critical 13 K mark.

temperatures of around 13 K can be achieved up until lengths of 100 cm, with the fin cryopump performing slightly better overall. This behaviour is due to the fins, which act as thermal conductors and spread the cooling power along the entire cryopump. Above 100 cm, temperatures start exceeding 13 K which leads to a massive loss in pumping speed as experimentally demonstrated in [Rung 21]. By keeping some safety distance from this critical temperature value, long cryopumps of around 80 cm are possible, which is highly encouraging, since the vacuum simulations have identified pump length as a key attribute in optimising cryopump performance.

3.4.5. Simulation of a cryopump covered in activated charcoal

Up until now, only the copper surfaces have been considered for cooling. Of course, this is not a completely accurate representation of the cryopump as the finite heat

3. A cryopump for the $\bar{P}$ ANDA beam line

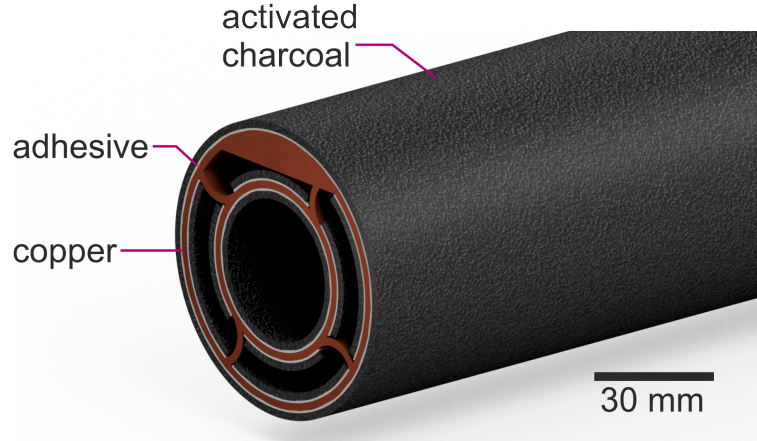


Figure 3.27.: A fin cryopump covered in adhesive (white layer) and activated charcoal (black layer). This model was used for the temperature simulations to determine whether the activated charcoal has any significant effect on the achievable temperatures.

conductivity of the activated charcoal and the adhesives used to fix it to the copper surfaces could possibly lead to temperature gradients. To alleviate such concerns, a simulation was run including adhesive and activated charcoal.

In this simulation, an 80 cm long fin cryopump was coated with the adhesive Polytec TC 433 [Poly 23], modelled as a thin layer (cf. fig. 3.27) with a thickness of 0.5 mm. The physical properties relevant for the simulation are given in appendix D. The charcoal was similarly modelled as a layer lying on top of the glue (cf. fig. 3.27), its thickness of 2 mm corresponding to the size of the charcoal pellets (cf. appendix D for its properties).

Using this setup, simulations were run as described in section 3.4.2. The charcoal reached maximum temperatures of around 12.7 K, only 0.1 K more than the copper surfaces, so that the temperature gradient between the two is negligible.

3.4.6. Simulation of a heated cryopump

As seen in section 3.3.7, the cryopump will only have a regeneration interval in the order of weeks, while first decreases of performance will be seen within days. During cryopump regeneration, the accelerator beam operation needs to be suspended while the pump is heated up and then cooled down again. This will cause large amounts of hydrogen to be introduced into the beam pipe which will have to be removed before the experiment can resume, possibly suspending operation on the order of hours.

There is a plan to minimise the time of this interruption as well as preserving the accelerator beam line vacuum through a novel regeneration scheme. The cryopump will be warmed up until it starts outgassing at a controlled rate, so that acceptable vacuum conditions are maintained. This way, less time is lost waiting for the vacuum to normalise. Additionally, much time is saved in warming and cooling the pump, as outgassing starts happening at around 20 K [Umra 97].

To evaluate how realistic such a plan is, simulations were run, modelling a cryopump

3.4. Temperature simulations of the $\bar{P}$ ANDA cryopump

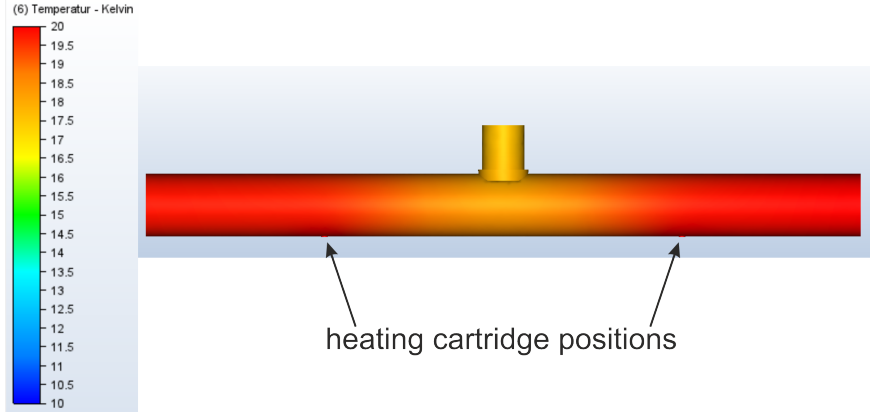


Figure 3.28.: Simulation of the 80 cm long cryopump being heated with a shared heating output of 12 W. The other parts of the pump such as warm shield are also simulated, but not shown, for visibility purposes.

being heated by heating cartridges. Two cartridges were installed in an 80 cm long fin cryopump (cf. fig. 3.28) and given a shared heating output ranging from 4 W to 20 W, depending on the simulation scenario, with the heating power being divided equally in every case.

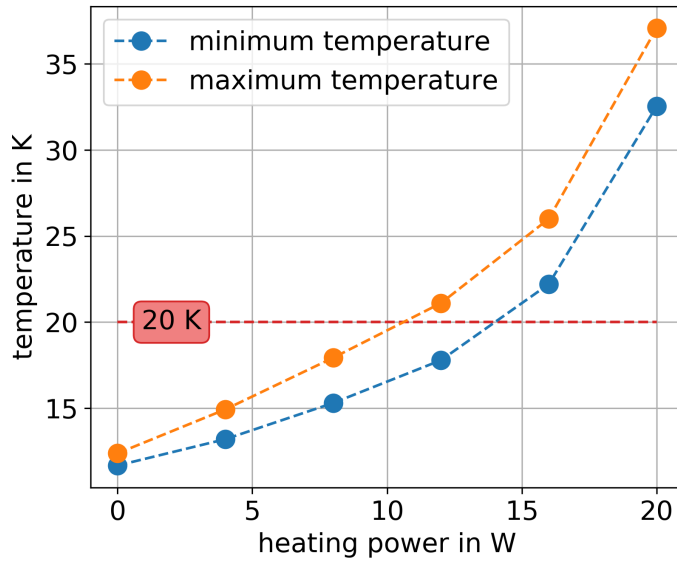


Figure 3.29.: The cryopump temperature in dependence of heating power. Both the minimum and maximum temperatures of the cryopump are depicted.

The results of the simulation for an overall heating power of 12 W is shown in fig. 3.28. At both ends the pump is at around 20 K while in the middle it remains well below

3. A cryopump for the $\bar{P}$ ANDA beam line

that temperature at roughly 17 K. To warm up the central areas several Watts more power is necessary, as demonstrated in fig. 3.29. The results show that the cryopump's temperature up to 20 K shows a close to linear dependency on the heating power, which is ideal for control. In practise, one could perform the regeneration by first heating just enough for the cryopump's ends to reach 20 K and to start controlled outgassing. Then, when these parts have finished, the heat could be slightly increased so that other parts start outgassing. This process can then be repeated until the entire cryopump is regenerated with minimal loss of time and impact on the vacuum.

3.5. Conclusions regarding the optimal cryopump geometry

Based on the extensive simulations described in sections 3.3 and 3.4, solid conclusions can be drawn as to how the cryopump should be constructed. Overall, the fin geometry has performed the best. While in some categories, for example pumping speed, all geometries perform equally well, the fin cryopump has demonstrated its superiority by achieving the longest regeneration interval, even when considering the uneven gas load. Additionally, temperature simulations have demonstrated that this geometry has no issues reaching the necessary temperatures to pump hydrogen at large lengths up to 80 cm.

A fin cryopump at such a length is estimated to improve the accelerator beam life time by around 20 % by removing approximately 40 % of the rest-gas thickness. Unfortunately, even though it possesses the longest regeneration interval, the first signs of a decrease in performance are expected to appear within several days, thus it is important to keep the length of time necessary to regenerate the pump as short as possible. To this end a gentle regeneration scheme was developed through simulation studies, revealing a possibility for controlling the outgassing rate of the pump for minimal impact on vacuum conditions and minimal loss of time.

The next step is to engineer a design for the fin cryopump and the heat shield which can be constructed and experimentally tested. A new round of simulations should be run with the resultant geometry to ensure that no weak spots have been introduced, for example connections between individual parts which conduct insufficient cooling power. Only after passing these tests should a prototype be constructed with which the simulations can be verified. For maximum flexibility, this cryopump should be constructed in such a way that it can be modularly lengthened and shortened, to react in case of any inaccuracies in the results of the temperature simulations.

In conclusion, the simulations performed here have proven to be a powerful tool when designing the cryopump. They allow us to understand the vacuum conditions at $\bar{P}$ ANDA and how a cryopump would influence it. Furthermore, it reveals the criteria such a pump needs to fulfil to optimise its efficacy, allowing for informed decisions on its design long before any experimental tests are performed or prototypes are built.

4. Development of cryogenic, hydrogen based droplet targets

For the $\overline{\text{P}}\text{ANDA}$ experiment, the use of both a cluster-jet target as well as a pellet target¹ is foreseen [Beli 20]. However, realising them each as their own discrete installation makes swapping between the two a complex undertaking. For greater speed and efficiency, it would be beneficial to combine the two into one machine.

In this chapter, the basic theory and functioning principle of these targets are explained (cf. section 4.1) which makes the necessary steps to combine them clear. Then, two droplet targets are presented. One of them is MDT-D (Münster droplet target Diva), which started its life as a cluster-jet target (cf. section 4.3). Here, the focus lies on its commissioning and performance. The lessons learnt from this target were used for the other one, called MDT-H (Münster droplet target Houdini). With this target, many previous challenges could be overcome and in this chapter its comprehensive characterisation and use as a test bed for further innovations is explored in detail (cf. section 4.4).

4.1. Underlying principles for the generation of droplet and cluster-jet beams

To understand droplet as well as cluster-jet target systems, the underlying theoretical principles are of great importance, as they directly inform the technical design.

4.1.1. Generation of droplet beams

In this section, the basic principles of droplet production are explained. First, the mechanisms which lead a fluid beam to break up into droplets are examined before the conditions which have to be met for this process to occur are considered. Finally, the practical consequences for the droplet generation with hydrogen are explained, which are essential to consider when building a functioning droplet target.

¹At different points of this thesis, pellet targets or droplet targets will be mentioned, with the principle difference being that pellets are solid and droplets are fluid. For our targets, we inject droplets into vacuum which near instantly freeze to pellets [Gris 18, Weid 23], so that both of these terms are used synonymously.

4. Development of cryogenic, hydrogen based droplet targets

The Plateau-Rayleigh instability

The Plateau-Rayleigh instability describes the process of a liquid beam breaking up into droplets [Bush 04].

The principal idea is that a fluid beam experiences naturally occurring perturbations, which, given the right circumstances, may grow larger until they cause the beam to break up into droplets.

This process can be understood intuitively by considering a sinusoidal perturbation [Bres 10, Hegd 13] as depicted in fig. 4.1. There will be regions where the fluid beam is swollen, leading to an enlarged beam radius r_1 and regions where the beam contracts, leading to a small r_1 . Simultaneously, the enlarged regions possess a positive beam curvature radius r_2 so that $r_2 > 0$ holds, while in the contracted regions $r_2 < 0$ is true (cf. fig. 4.1).

Now one can consider the Young-Laplace equation [Siv 21] for this particular situation:

$$\Delta p = \sigma \left(\frac{1}{r_1} + \frac{1}{r_2} \right) \quad (4.1)$$

where Δp is the pressure difference between the fluid beam and the surrounding medium, for example air, and σ is the surface tension. For the swollen sections, r_1 is large, which decreases Δp_{swol} , while r_2 is positive, thus increasing Δp_{swol} . For the contracted sections, the contributions are reversed: r_1 is small, increasing Δp_{contr} , and r_2 is negative, decreasing Δp_{contr} . If $\Delta p_{\text{swol}} < \Delta p_{\text{contr}}$, fluid is forced from the contracted regions to the swollen ones, increasing the contraction and swelling until breakup is achieved. Should the other case be true ($\Delta p_{\text{swol}} > \Delta p_{\text{contr}}$), the perturbation wanes and the beam stabilises. Which case occurs thus only depends on r_1 and r_2 which take part as competing contributions. In general, large perturbations, which coincide with large differences for r_1 between contracted and swollen regions, have a better chance of fulfilling the conditions for break up. Should break up take place, surface tension seeks to minimise the surface area, leading to the droplets taking a spherical shape [Osse 78].

To gain further insight, a more quantitative approach will be outlined here. For the form of the perturbation, following Ansatz is chosen [Bush 04]:

$$\tilde{R} = R_0 + \epsilon e^{\omega t + i k z} \quad (4.2)$$

where R_0 denotes the radius of the unperturbed fluid beam, ϵ is the the perturbation's amplitude with $\epsilon \ll R_0$, ω its rate of growth and k its wave number. Finally, t and z are the time and position in beam propagation direction, respectively. By inserting this Ansatz into the Navier-Stokes equations as well as the momentum and continuity equations, a solution can be found for its dispersion relation [Bush 04]:

$$\omega^2 = \frac{\sigma}{\rho R_0^3} k R_0 \frac{I_1(k R_0)}{I_0(k R_0)} (1 - k^2 R_0^2) \quad (4.3)$$

where apart from the values previously introduced ρ is the density and $I_1(k R_0)$ as well

4.1. Underlying principles for the generation of droplet and cluster-jet beams

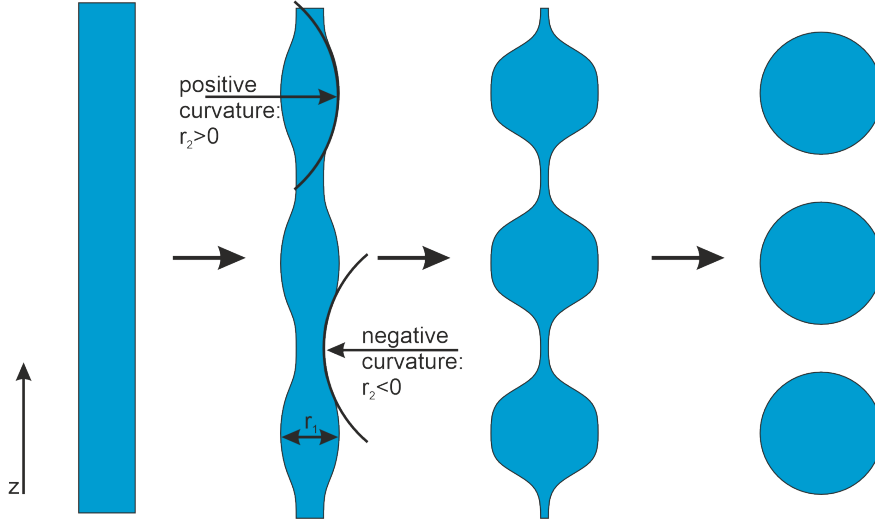


Figure 4.1.: Schematic depiction of the droplet break up. The initial fluid beam experiences periodical oscillations which increase in strength until break up occurs. (Taken from [Haus 22], modified)

as $I_0(kR_0)$ are Bessel functions of the first kind. The dispersion relation can now provide us with further insight into the droplet break up. Should $kR_0 < 1$ hold, the perturbation will grow, as then ω is real and thus eq. (4.2) will diverge. The perturbation's growth rate ω is maximal for $kR_0 = 0.697$, which leads to an optimal perturbation wavelength of $\lambda_{\max} = 9.02R_0$ via the relation $\lambda = 2\pi/k$. For naturally occurring droplet beams, where the initial perturbation is induced by, for example, friction between the fluid beam and the emitting orifice, the perturbation mode with the maximum growth rate will dominate the others, leading it to be the one to cause the break up.

Knowing this allows for the estimation of a naturally occurring droplet's diameter. If one considers a fluid beam being perturbed with the optimal frequency, at the beginning of the break up the distance between slightly contracted regions is $\lambda_{\max}$, before the constriction grows and droplets are created. So the volume contained in the beam spanning one wavelength equals the volume of a droplet. By equating both equations of volume and solving for the droplet radius R_d , following expression is found:

$$R_d = 1.89R_0 \quad (4.4)$$

which depends solely on the initial radius of the fluid beam.

Fluid dynamics

The droplet break up as described above can only occur if the fluid fulfils certain requirements. These requirements can be described by the Reynolds number, the Weber number and the Ohnesorge number.

The Reynolds number is used to determine whether a fluid flow is laminar, where the

4. Development of cryogenic, hydrogen based droplet targets

fluid flows in distinct, non-mixing layers, or turbulent, where the layers mix, causing complex flow patterns [Uron 12]. The Reynolds number N_R is defined as

$$N_R = \frac{\rho v d}{\eta} \quad (4.5)$$

where ρ is the fluid density, v and η the fluid's speed and viscosity and finally d the characteristic length, for example, the width of a tube through which the fluid is flowing or the diameter of a nozzle emitting a fluid. For $N_R < 2000$ the flow is considered laminar, while a $N_R > 3000$ is indicative of turbulent flow. $2000 < N_R < 3000$ is considered an unstable region where flow might randomly switch between laminar and turbulent modes [Uron 12].

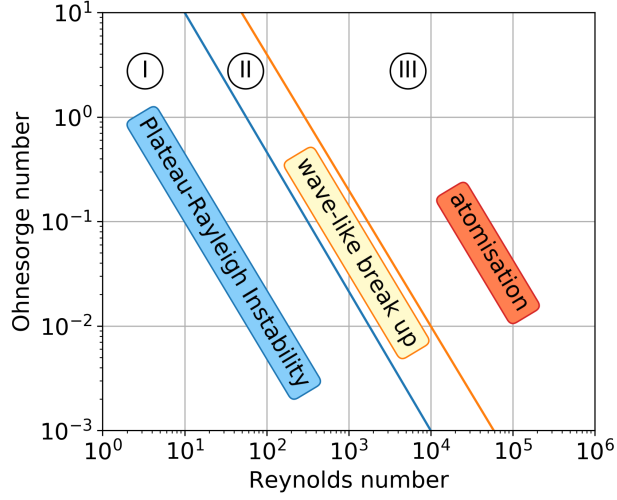


Figure 4.2.: A plot to determine which kind of beam break up will take place. Should the Ohnesorge and Reynolds number position the beam in section I, Plateau-Rayleigh break up will take place. Wave-like break up happens in II and finally in section III the beam atomises. (Based on [Ohne 36])

The Weber number describes whether a droplet will break up due to distortions induced by aerodynamic forces caused by the surrounding gas and is defined as

$$We = \frac{2r\rho v^2}{\sigma} \quad (4.6)$$

where r is the droplet radius, ρ its density, v its speed and σ its surface tension [Froh 00]. In the case of

$$We > \frac{8}{C_D}, \quad (4.7)$$

with C_D being the drag coefficient between droplet and surrounding gas, the droplet will distort and break up.

4.1. Underlying principles for the generation of droplet and cluster-jet beams

Finally, the Ohnesorge number connects these two values [Froh 00]:

$$Z = \frac{\sqrt{\text{We}}}{N_R} = \frac{\eta}{\sqrt{\rho\sigma d}} \quad (4.8)$$

and together with the Reynolds number allows for the determination of how a beam will break up after exiting a nozzle (cf. fig. 4.2), [Ohne 36]. Should the beam fall into section I, it will experience Plateau-Rayleigh break up as explained above. In section II, the beam will take a wave like shape before breaking up and finally, in section III, it will atomise into a spray consisting of many small droplets. It should be noted, that fig. 4.2 was determined empirically so that the borders between sections are not sharp lines, instead the sections should be interpreted more as general areas where different forms of break up are predominant.

Droplet generation with hydrogen

As discussed above, reliably generating droplets requires a low Ohnesorge and Reynolds number. Both values are dependent on fluid properties such as density ρ , viscosity η and surface tension σ , but also on values which can be more directly controlled such as the nozzle diameter d or the fluid speed v . The latter value can be controlled via the fluid's pressure p due to following relation [Vare 11]

$$v = \sqrt{\frac{2p}{\rho}}. \quad (4.9)$$

The now arising task is to choose optimal values for d , p and the temperature T^2 for fluid hydrogen to create droplets. In general, decreasing the values is beneficial as can be seen in fig. 4.3, where the lowest parameters lead to the best result. However, decreasing the values even further than for the green point is unfeasible. Hydrogen freezes at 14 K, strongly limiting how much lower one can go with the temperature. Hydrogen pressures below room pressure enable the possibility of air entering the gas system which can lead to nozzle blockages due to foreign gases freezing to it. A similar reason makes decreasing the nozzle diameter unviable, as smaller nozzles become increasingly susceptible to blockages [DePo 08] due to foreign objects such as dust particles or other, frozen gases. So, in conclusion, for a hydrogen based droplet target one should aim for temperatures in the range of around 16 K while applying pressures at roughly 1 bar (cf. fig. 4.4) and using a nozzle of around 10 μm .

A further point to consider is that instead of relying on natural occurring perturbations, in a Münster droplet target they are induced with the frequency f , for example by generating vibrations in the nozzle with a piezoelectric element. Ideally, this frequency should be chosen close to the optimal frequency f_{opt} which is determined by $f_{\text{opt}} = v/\lambda_{\text{max}}$ [Froh 00]. Under the assumption that the beam's radius is identical to the nozzle radius, so that $R_0 = d/2$, one can use eq. (4.9) and $\lambda_{\text{max}} = 9.02R_0$ to

²as all fluid properties vary with temperature.

4. Development of cryogenic, hydrogen based droplet targets

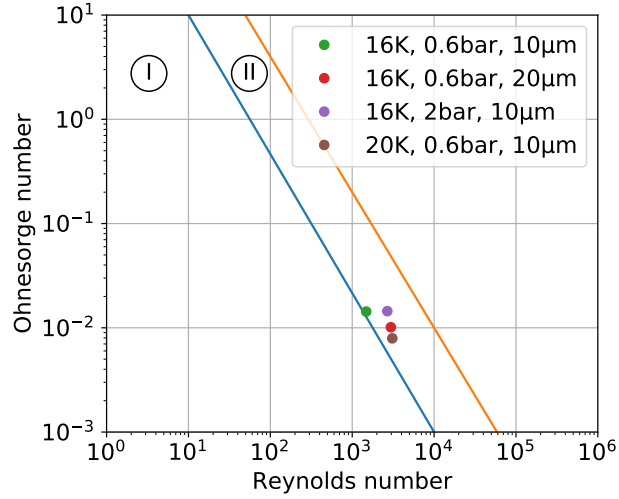


Figure 4.3.: A plot to determine the break up type as shown in fig. 4.2. Here, the dots show where liquid hydrogen at different conditions would fall.

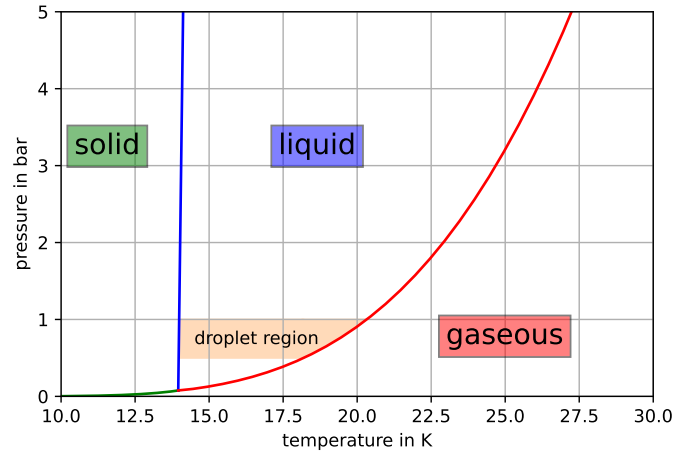


Figure 4.4.: Phase diagram of hydrogen. The area where droplets can be generated is especially marked. (Taken from [Fron 23])

calculate $f_{\text{opt}} = 884.7 \text{ kHz}$ for the following parameters: $p = 0.6 \text{ bar}$, $d = 10 \mu\text{m}$ and $\rho(16 \text{ K}, 0.6 \text{ bar}) = 75.3 \text{ kg/m}^3$ [NIST 23b]. This result means that frequencies in the range of hundreds of kHz are necessary for effective droplet break up.

4.1.2. Generation of cluster-jets

For the generation of cluster-jets, both gaseous and liquid fluids can be used. This section introduces the production principles of cluster-jet beams for both cases and explains which requirements need to be fulfilled for hydrogen to create such beams, informing the design of the target.

Generation of cluster-jets with gaseous fluids

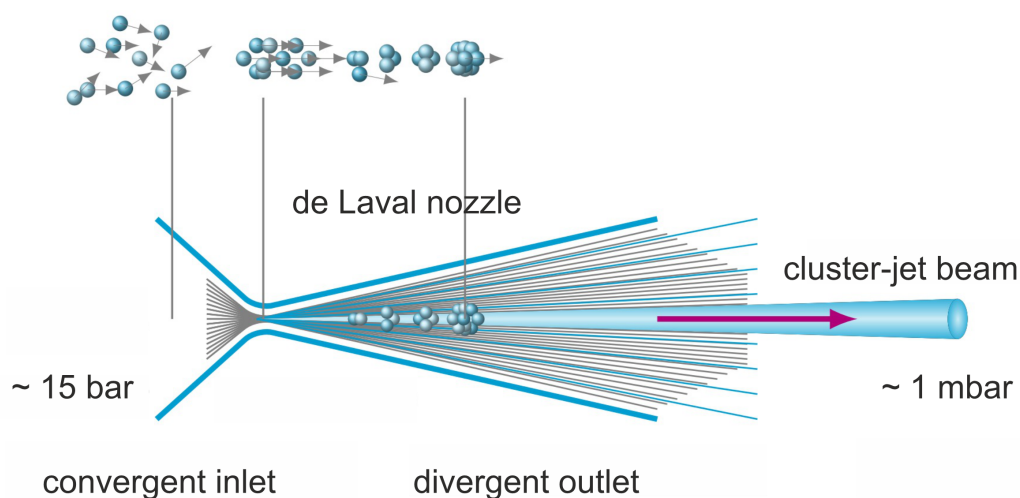


Figure 4.5.: Schematic depiction of the clusterisation process for gaseous fluids. Gas is pressed through a de Laval nozzle at pressures of around 15 bar, causing it to accelerate until it reaches the narrowest diameter and clusterise in the outlet. (Generated by E. Köhler, edited)

To create a cluster-jet, gas is pressed through a de Laval nozzle, which sports a convergent inlet and divergent outlet (cf. fig. 4.5), separated by the point of narrowest inner diameter. The gas enters the inlet at pressures of ~ 15 bar and accelerates until it reaches the narrowest diameter before exiting through the outlet which has an ambient pressure of ~ 1 mbar. Transferring from a high pressure to a low pressure environment causes the gas to cool adiabatically [Demt 21], lowering the gas molecules' relative velocity so much that three body collisions take place [Paul 00], where two gas molecules transmit their surplus energy to a third so that the first two bond via van der Waals forces. These bonded molecules then act as condensation germs where further gas molecules can accumulate until a cluster consisting of hundreds up to hundred thousands of molecules [Kohl 15] are formed, propagating through vacuum with speeds of hundreds of metres per second [Tasc 13].

4. Development of cryogenic, hydrogen based droplet targets

Generating cluster-jets with gaseous hydrogen

A useful empirical parameter to judge whether given conditions lead to clusterisation is the Hagena parameter [Smit 98]:

$$\Gamma^* = \frac{kp \left(\frac{0.74d}{\tan \alpha_{1/2}} \right)^{0.85}}{T^{2.29}} \quad (4.10)$$

where p , T and d are gas pressure, temperature and nozzle diameter given in bar, K and μm , respectively. k is a gas specific constant, with $k = 184$ being valid for hydrogen [Smit 98], and $\alpha_{1/2}$ is the halved opening angle of the nozzle outlet. For $\Gamma^* < 200$ no clusterisation is expected, $200 < \Gamma^* < 1000$ marks a partial clusterisation and $\Gamma^* > 1000$ marks massive clusterisation [Hage 87]. Using eq. (4.10), it becomes clear that compared to droplet generation, the requirements for cluster-jets are much less strict. Using hydrogen at conditions of $p = 3$ bar, $T = 60$ K, a nozzle with $d = 40 \mu\text{m}$ and $\alpha_{1/2} = 3.5^\circ$ already leads to massive clusterisation ($\Gamma^* = 8955$), which only increases if one increases pressure, nozzle diameter or decreases temperature, allowing for cluster-jet beams over a wide range of parameters.

The Hagena parameter additionally allows for the prediction of the amount of molecules in a cluster (N) through

$$N = A_N \left(\frac{\Gamma^*}{1000} \right)^{\gamma_N}, \quad (4.11)$$

where A_N and γ_N are empirical constants depending on Γ^* . For $\Gamma^* > 1800$ $A_N = 33$ and $\gamma_N = 2.35$ hold [Hage 92], although more recent measurements have put A_N at 86 ± 3 for hydrogen [Kohl 15]. N can be used to determine the cluster diameter via

$$V = \frac{mN}{\rho} \quad (4.12)$$

where V is the cluster volume m , the mass of a hydrogen molecule and ρ the cluster's density. Furthermore,

$$V = \frac{4}{3}\pi r^3 \quad (4.13)$$

where r is the radius, is valid under the reasonable assumption that the clusters are approximately spherical. Combining eqs. (4.12) and (4.13), then solving for r leads to

$$r = \left(\frac{3mN}{4\pi\rho} \right)^{1/3}. \quad (4.14)$$

Plugging in the following values for hydrogen: $m = 3.321 \cdot 10^{-27}$ kg [NIST 22c, NIST 24] and $\rho = 88 \text{ kg/m}^3$ [Silv 80]³ leads to a cluster radius r of 10 nm for the previous example where $\Gamma^* = 8955$, which demonstrates that a gaseous cluster-jet beam is made up of

³Here, one assumes that hydrogen clusters are solid.

4.1. Underlying principles for the generation of droplet and cluster-jet beams

many cluster particles in the range of tens of nm, which is corroborated by experimental studies [Kohl 15, Mann 19].

Generation of cluster-jets with liquid hydrogen

While for a gaseous fluid clusters are created via an aggregation process, for a liquid they are instead generated by atomising the beam, which can be achieved for a large Weber number as described in section 4.1.1. Particularly, fig. 4.2 can be used to predict whether a liquid fluid will atomise. For example, hydrogen at a temperature of 28 K being pressed through a nozzle of 40 μm diameter with 16 bar of pressure results in fig. 4.6, well in the atomisation regime.

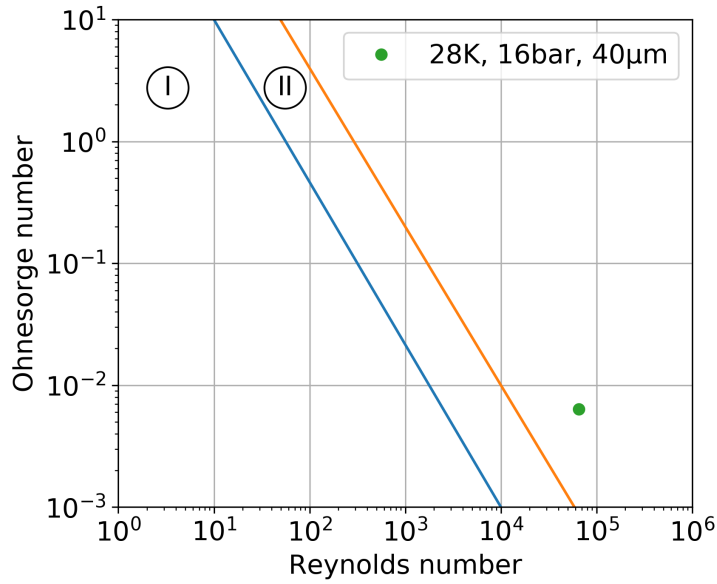


Figure 4.6.: A plot to determine the break up type as already seen in fig. 4.2. Under the given conditions, the liquid will undergo atomisation.

The exact processes leading to atomisation are complex [Mess 04], however a simple equation can be used to estimate the cluster diameter under the assumption that break up is primarily caused by a large pressure gradient [Mess 04]:

$$r = \sqrt{\frac{\sigma}{\nabla p(x)}} \quad (4.15)$$

where $\nabla p(x)$ is the pressure gradient along the nozzle. One can now use the values for hydrogen given just above to gain an estimation which cluster sizes are to be expected through atomisation. A typical cluster-jet nozzle has a length of around 17 mm from the narrowest diameter to the maximum outlet diameter. In this distance, the

4. Development of cryogenic, hydrogen based droplet targets

pressure decreases from 16 bar to 1 mbar, so that $\Delta p \approx 16$ bar. Using the assumption that the pressure decrease is linear, the pressure gradient can thus be estimated to 0.94 bar/mm. For a more precise calculation, the exact pressure gradient in the region where clusterisation takes place would need to be known, however, such data is unknown as of writing. The surface tension for hydrogen at 28 K is $\sigma = 6.4 \cdot 10^{-4}$ N/m [NIST 23a], with which the cluster radius is calculated to $r = 2.6 \mu\text{m}$, consistent with recent experimental results [Eick 23].

For our purposes, operating a cluster-jet target with liquid hydrogen is more attractive than using gaseous hydrogen, as higher target densities can be reached with the former [Grie 18a], which is highly relevant for $\bar{\text{P}}\text{ANDA}$. Additionally, larger cluster sizes are highly advantageous for achieving high proton energies in laser-cluster interactions (cf. chapter 5).

4.2. Practical realisation of cryogenic hydrogen target systems

The principles of hydrogen droplet and cluster-jet targets demand temperatures in the range of tens of Kelvins as well as backing pressures of around 1 bar, in the case of a droplet target, and several bars in the case of a cluster-jet target. This section explores how these conditions are experimentally reached.

4.2.1. The MCT-D/MDT-D combined target system

The main parameters which need to be controlled to generate droplet and cluster-jet beams are hydrogen temperature and pressure. While for cluster-jet and droplet beam generation there is no overlap in the ranges of these values, the devices powering our targets are still capable of reaching both parameter ranges, enabling the possibility of a combined target system. This section presents such a target, the MCT-D/MDT-D which began its life as a cluster-jet target, before being adapted to serve as a droplet target.

To this end, first MCT-D (Münster cluster-jet target Düsseldorf) is introduced and its various systems and components explained, before the necessary modifications are presented which transform it into MDT-D (Münster droplet target Diva).

Cooling and vacuum system of MCT-D

The central component of MCT-D is its two stage cold head (Coolpower 10 MD [Leyb 22]), which generates the target's cooling power⁴ in conjunction with a compressor (Coolpak 6000 H). A wound copper pipe is wrapped around the warm and cold stage, cooling the hydrogen flowing through it (cf. fig. 4.7). The part of the pipe between the two stages is made of stainless steel which has a low thermal conductivity of $\lambda = 15 \text{ W/mK}$ [Kuch 04]) compared to copper (cf. appendix D.4.2) Thus, it keeps the pipe from accidentally warming up the cold stage through the warm stage. After

⁴more details on the cold head can be found in section 3.1.1

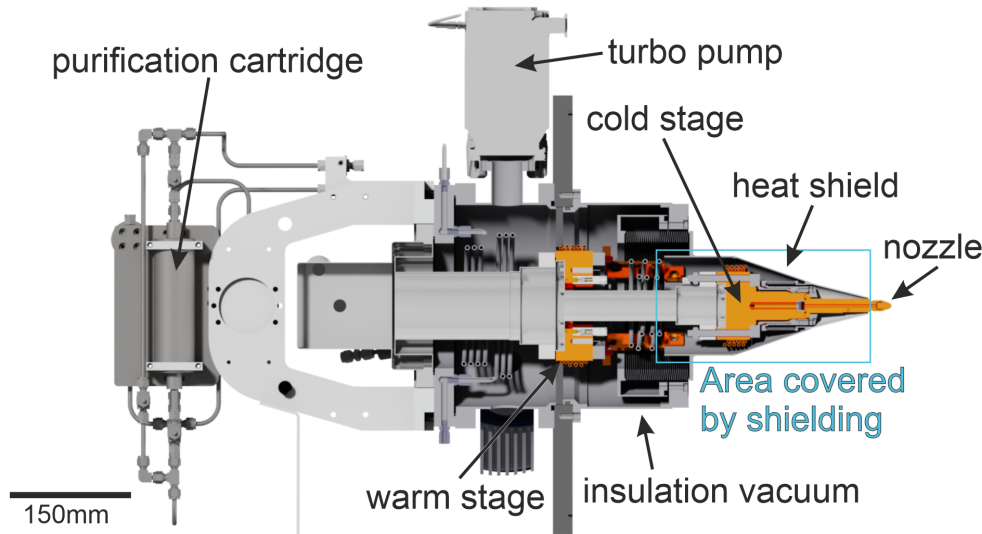


Figure 4.7.: A half section depicting MCT-D. After passing through the purification cartridge, the hydrogen enters the target and is cooled by the warm and cold stage, Finally the gas exits through the nozzle as a cluster-jet beam (Generated by D. Veith, edited)

passing the cold stage, the hydrogen enters the cold finger, a copper cylinder housing the de Laval nozzle at its tip.

The cold head has no internal temperature control which enables accurate regulation, instead it will continue cooling until it reaches equilibrium with external influences. So to achieve temperature control, four heating cartridges are installed: two with 50 W heating power (Lakeshore HTR-50 [Cryo 24b]) at the cold stage and two with 100 W (Lakeshore HTR-25-100 [Cryo 24b]) at the warm stage. Only one cartridge each is used during operation, the other one is there for redundancy purposes. Additionally, two temperature diodes Lakeshore DT 670-B [Cryo 24a] are installed per stage, with only one each being actively used like for the heating cartridges. The diodes and cartridges are both connected to a temperature controller (Lakeshore Model 336 temperature controller [Cryo 24c]). There, one can input a temperature set point and the heating cartridge will adjust its power until the diodes detect that the set point is met and maintained in a closed PID loop.

To ensure that the lowest possible temperatures can be reached, outside sources of heat need to be minimised, namely heat radiation and thermal conduction with gases in the environment. Radiation is minimised through a heat shield powered by the warm stage, comparable to the situation for the $\bar{\text{P}}\text{ANDA}$ cryopump (cf. section 3.4.3). The heat shield takes the form of a cylindrical 'hat' covering the cold stage and cold finger (cf. fig. 4.7). Thermal conduction is minimised by housing all the cryogenic components in a vacuum chamber, such as the nozzle ejecting hydrogen. Additionally, the warm and cold stages are housed in their own vacuum chamber. This so called

4. Development of cryogenic, hydrogen based droplet targets

insulation vacuum becomes necessary because without it, MCT-D at full operation degrades vacuum conditions so much that the gas contained in the vacuum chamber would act as a significant source of heating power for the nozzle, making liquefaction of hydrogen impossible and greatly limiting the target's potential use. The insulation vacuum is generated by a combination of a fore pump (Leybold TRIVAC D 25 B [Leyb 21]) and turbo pump (Leybold TURBOVAC 90i [Leyb 22]) reaching vacua in the range of 10^{-6} mbar. For comparison, injecting a liquid hydrogen cluster-jet into vacuum leads to vacua in the range of 10^{-2} mbar to 10^{-1} mbar.

Gas system of MCT-D

Hydrogen gas is provided by a 200 bar bottle with a 99.999 % purity. Since this pressure is too high for the target systems to handle, the pressure is immediately reduced to around 20 bar by a pressure regulator mounted at the bottle. Although extremely high, the gas purity needs be enhanced further to keep impurities from blocking the nozzle. This can be done either by a purification cartridge⁵ (SAES MicroTorr 904 [Gas 16]) or a palladium hydrogen gas purifier (MegaTorr PS7-PD Hydrogen Gas Purifier [Ente 21]), installed in line after the pressure regulator, both of which boost gas purity to ppb level (99.999 999 99 %).

Just before the gas enters the target, (cf. fig. 4.8) it passes through a pressure controller (Brooks Instruments Pressure Controller SLA 5810 [Inst 24b]) and flow meter (Brooks Instruments Mass Flow Meter SLA 5860 [Inst 24c]). The former allows for fine control and regulation of the gas pressure up to a maximum of 20 bar, while the latter measures flows up to $10 \text{ l}_n/\text{min}$ and is used to determine the target's nozzle diameter, a very relevant value to detect blockages (cf. section 4.2.3). Both instruments are read out and controlled by a Brooks Model 0254 Secondary Electronics [Inst 24a]. After entering the target, the gas is cooled as explained above and exits through the nozzle. However, an additional safety pipe is also connected to the gas line, leading away from the nozzle (cf. fig. 4.8). This pipe is instrumented with a baratron pressure gauge (722B, MKS [MKS 24a], read out by a MKS PR 4000B [MKS 24b]), measuring the nozzle pressure, and a relief valve, which is used to prevent over pressure, for example when liquid hydrogen starts vaporising as a consequence of the target being warmed up.

Transformation of MCT-D into MDT-D

As was alluded to before, the three main differences between a cluster-jet target and a droplet target are their respective temperature and gas pressure ranges as well as the differing nozzle systems.

A droplet target needs hydrogen temperatures $\approx 16 \text{ K}$ while for a cluster-jet target temperatures in the twenties of Kelvin are already sufficient. As the Coolpower 10 MD reaches minimum temperatures of around 10 K , no modification is necessary.

⁵This method was used during the proton acceleration measurements at the HHU Düsseldorf. At all other times, the palladium hydrogen gas purifier was used.

4.2. Practical realisation of cryogenic hydrogen target systems

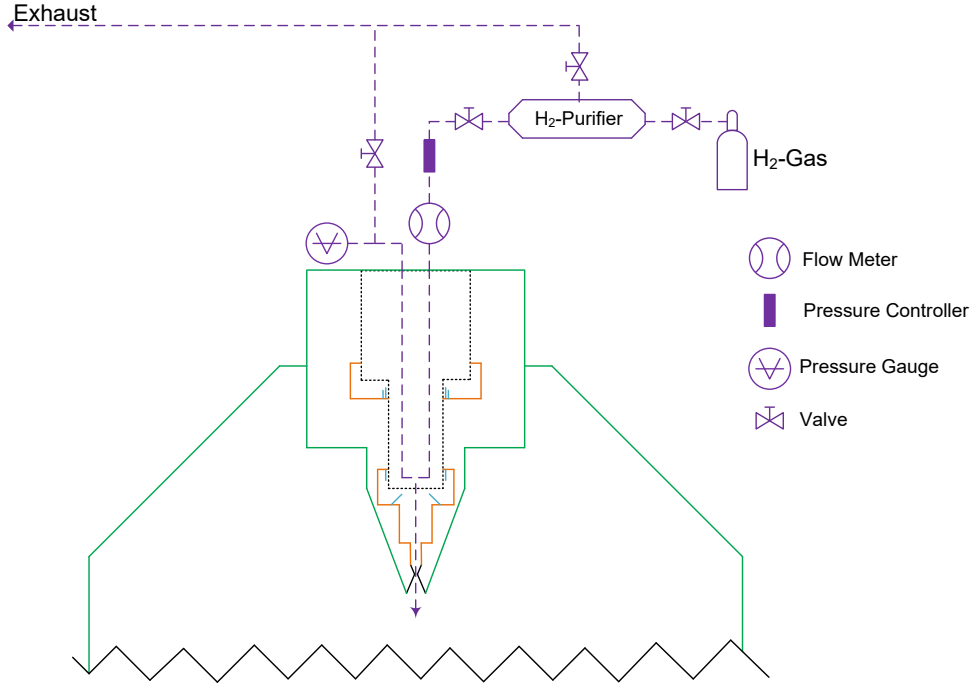


Figure 4.8.: Schematic depiction of MCT-D's gas system. A hydrogen bottle supplies gas which is purified to ppb level in the hydrogen purifier. After passing through a pressure controller and flow meter it enters the target where it is cooled and finally passes through the nozzle. An additional relief pipe is connected to the gas line, where a baratron pressure gauge measures the gas pressure at the nozzle. (Taken from [Less 21], adapted)

In theory, the same is true for gas pressure. If a pressure controller is capable of withstanding and regulating 20 bar then 1 bar doesn't pose an issue. However, the pressure controllers and flow meters optimised for controlling large values have trouble reaching the same accuracy for significantly smaller ones. So the SLA 5810 was replaced by another SLA 5810 optimised for pressures up to 3 bar and the SLA 5860 is succeeded by a 5850E optimised for low flows up to 1 l_n/min. Previous studies, however, have demonstrated that such a setup cannot supply sufficient gas to liquefy hydrogen [Haus 22] so that a bypass line was installed with a pressure controller and flow meter (again, a SLA 5810 and a 5850E) capable of significantly higher flows (cf. fig. 4.9).

The largest modification is done at the nozzle system. The de Laval nozzle is replaced by one consisting of a copper body and platinum-iridium alloy aperture welded to the top (cf. fig. 4.10). In itself this change is very minor since the body can be shaped identically to the de-Laval nozzles, however, in addition, the nozzle vibration system needs to be installed. To do so, the cold finger is replaced by the so called piezo head which houses a piezo actuator ((HPCh 150/15-8/3 [Piez 21]) and the nozzle (cf. fig. 4.11), thus completing the transformation from MCT-D to MDT-D. The piezo is driven by a frequency generator (PEAKTECH 3 MHz DDS Function Generator 4055 [Peak 24]) and an amplifier (Pendulum High Voltage Linear Amplifier F20A [Pend 20])

4. Development of cryogenic, hydrogen based droplet targets

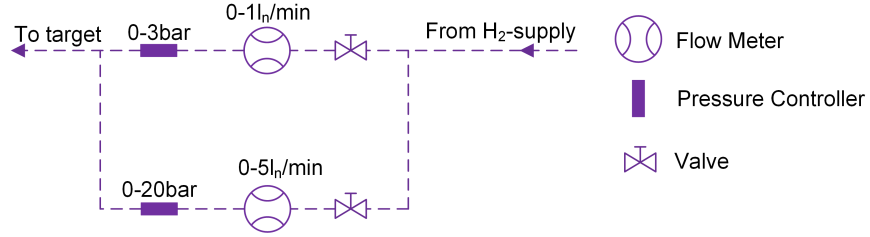


Figure 4.9.: The gas control system for MDT-D: The main gas line offers more control while the bypass line is used to supply sufficient gas for liquefaction.

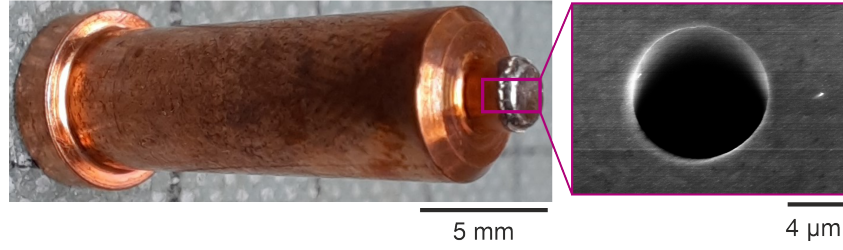


Figure 4.10.: An example of a droplet nozzle. It consists of a copper body and an aperture welded to the top. The cut out shows an electron microscope image of the aperture which has a diameter of 10 μm .

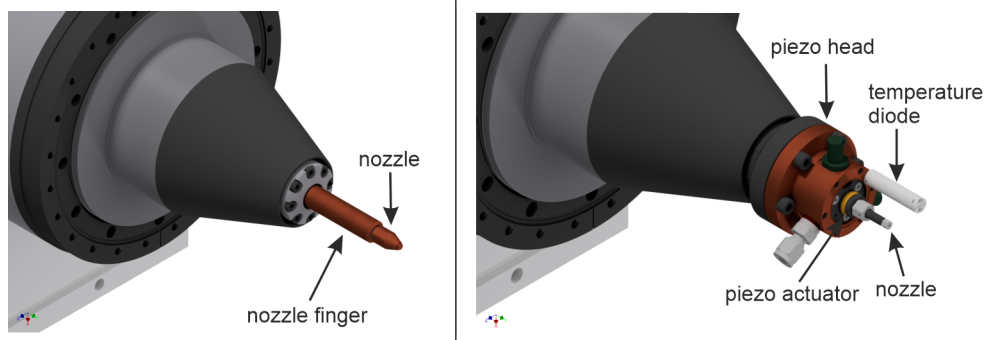


Figure 4.11.: **Left:** The nozzle system for MCT-D, consisting of nozzle finger and nozzle. **Right:** The nozzle system of MDT-D. The nozzle finger is replaced by the piezo head, which houses the nozzle, the piezo actuator and is additionally instrumented with a temperature diode (DT 670-B).

which multiplies the input value by 20.

Overall, adapting a cluster-jet target for use as a droplet target is a quick and quite minor process. This opens up new avenues for experiments where both target types are of interest, such as $\overline{\text{PANDA}}$, as one now has access to two targets in one.

4.2.2. MDT-H

MDT-H (Münster droplet target Houdini) is specifically designed to tackle the long standing nozzle clogging issues previous droplet targets suffered from [Frag 15, DePo 08]. To do so, the cooling system was fundamentally redesigned. Instead of long coiling copper pipes, the cooling system is realised by several heat exchanger cartridges, also made of copper (cf. fig. 4.12). These cartridges are easier to clean than the pipes, as dirt does not need to travel far until it is expelled from them and one can more easily visually verify the cleanliness. Additionally, a new cleaning solution which is specialised for copper (JE 25 [Jent 19]) was used.

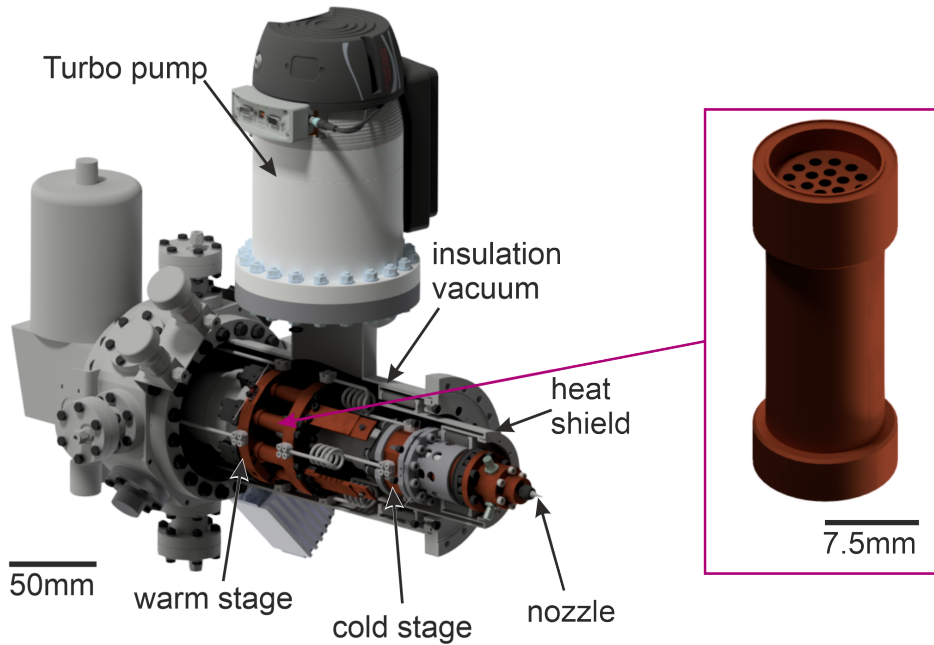


Figure 4.12.: The MDT-H target. The target has the same principal components as MCT-D, such as warm stage, cold stage, heat shield etc.. The cooling system however is no longer realised by pipes wrapped around the cold head but by copper heat exchanger cartridges instead, one of which is shown in enlarged form on the right.

Altogether, twelve heat exchangers were installed. Two are mounted on the warm stage and one on the cold stage for hydrogen in flow direction, while the same number was used to realise the safety pipe. The other six are used for the co-flowing gas (cf. the section below), which represents a completely separate gas system from the one used for hydrogen. The other parts of the target, such as warm stage, cold stage, heat shield etc., function identically to MDT-D, with the largest difference being that now a Leybold TURBOVAC 450i [Leyb 22] is used instead of a Leybold TURBOVAC 90i for the insulation vacuum.

4. Development of cryogenic, hydrogen based droplet targets

The co-flowing system

Droplet size scales with nozzle size, as seen in eq. (4.4), which makes decreasing droplet size a matter of choosing smaller nozzles. However, with decreasing nozzle size, the probability of nozzle blockages increases [DePo 08]. An alternative is presented through the use of a co-flowing gas.

The idea is to install a second, larger nozzle, completely encasing the one generating the hydrogen beam and injecting helium into it (cf. fig. 4.13). When exiting the larger nozzle to enter vacuum, the helium flow exerts a force onto the hydrogen beam, forcing it to become narrower (cf. fig. 4.13). Such systems have already been successfully applied to droplet targets to generate $20\text{ }\mu\text{m}$ diameter sized droplets from $50\text{ }\mu\text{m}$ diameter nozzles [DePo 08]. Thus this system presents an attractive alternative to the use of small nozzles of $10\text{ }\mu\text{m}$ diameter which have proven to be prone to clogging issues. [Frag 15, DePo 08]

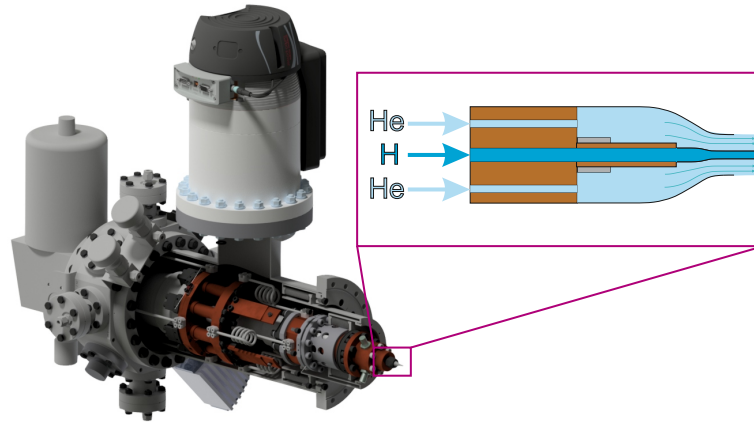


Figure 4.13.: The functioning principle of the co-flowing system. Helium, cooled to the same temperature as the fluid hydrogen beam, is injected into a nozzle encasing the one the hydrogen passes through. When the gas exits the outer nozzle, it exerts a force onto the hydrogen beam, forcing it to become narrower, thus enabling smaller beam diameters as well as droplets.

For MDT-H, the co-flowing gas is cooled to the same temperature as the main gas, as it runs through identical heat exchangers in parallel to the hydrogen in its own gas system. This way, the main nozzle is not warmed by the co-flowing gas, ensuring there is no thermal input.

Cryo leaks at MDT-H

Unfortunately, the co-flowing system at MDT-H is currently not usable due to significant leakages which appear when cooling down the target to cryogenic temperatures, so called cryo leaks.

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As part of the commissioning process, both of the target's gas systems were filled with helium and the target cooled down to its final temperature with the vacuum pressure being constantly monitored. In case of a cryo leak, this pressure will start to rise until it reaches unsustainable levels. During this test, leakages appeared in both the gas systems for hydrogen and the co-flowing gas, with the insulation vacuum becoming worse than 10^{-2} mbar before the warm stage even reached 50 K [Fron 23], making target operation impossible. Analysis of both gas systems with a mass spectrometer leak detector revealed that the leakages occurred at the warm stage, so all the nuts sealing this stage were tightened and the test re-run until finally the hydrogen gas system was leak free, with the vacuum not exceeding $3 \cdot 10^{-6}$ mbar at final temperatures [Fron 23]. However, the co-flowing gas system remained leaky with no further tolerance left to tighten the nuts, so that this system is unfortunately inoperational.

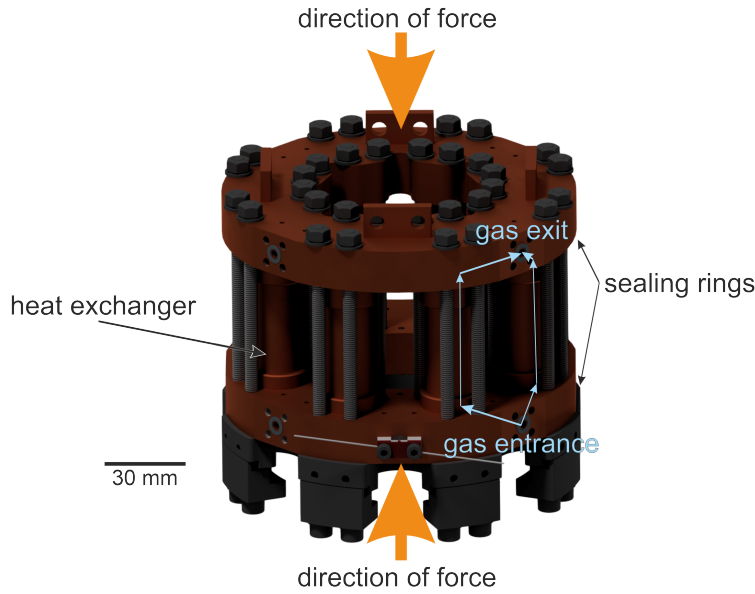


Figure 4.14.: The warm stage setup for MDT-H. Headless screws and nuts press the two sealing rings onto the heat exchangers. Gas passes through the rings and heat exchangers, necessitating a tight seal between the two types of components.

The cause for the cryo leak most likely lies in the warm stage's design. It is realised by two copper rings which press down on eight heat exchangers, sealed by a total of 16 indium rings (cf. fig. 4.14), one for each side of a heat exchanger. The two rings have to seal all heat exchangers simultaneously to prevent leaks, however, the rings shrink due to cooling, and even a small percentage of shrinkage can be significant when applied to an object of this size, causing imperfections in the sealing. To combat this issue in a future target, one would have to redesign the warm stage so that each heat exchanger is sealed individually. Temperature simulations as performed in [Fron 23] would help in this task, as they can quickly and effectively test possible geometries without committing significant resources.

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4.2.3. Target slow control

It is necessary for the target systems to be completely remote controllable, as physical access to the target can be strongly limited, for example due to safety regulations concerning radiation during particle accelerator experiments. To this end, the targets, namely MDT-D and MDT-H, can be completely computer controlled via a slow control.

The slow control is realised in LabVIEW [Nati 24a] and uses a different program structure compared to previous ones [Sohn 13, Habe 19], allowing for excellent speed and responsivity through a high grade of parallelisation.

Slow control interface

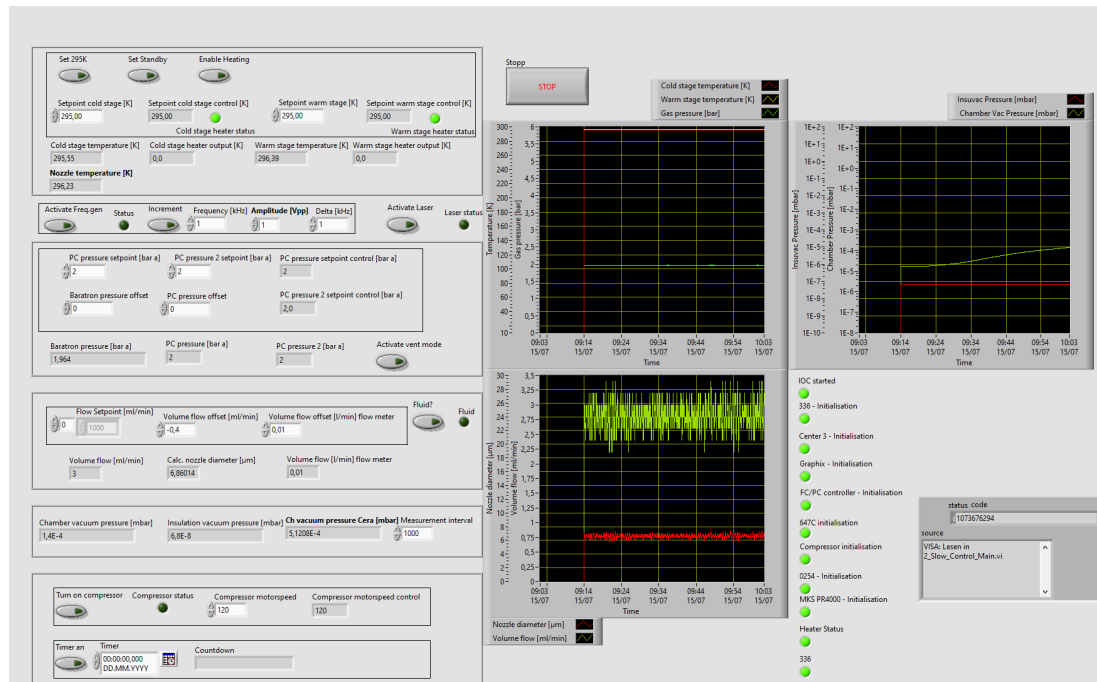


Figure 4.15.: Overview over the slow control interface. The graphs depict the most important values allowing for an assessment of target status at a glance. Additionally, the numerical values are also depicted on the left, where set points and various other controls can be accessed.

The central task of the slow control is to allow for the control of temperature and gas pressure and to show further various values of relevance for the target operation, such as vacuum pressures and nozzle diameter.

The most important of these values are shown in the three graphs on the user interface which allows the user to determine the target's "health" at a glance (cf. fig. 4.15). Warm stage and cold stage temperatures are grouped in one graph alongside nozzle pressure. Interaction chamber⁶ pressure is shown together with the insulation chamber vacuum.

⁶For our current purposes, the interaction chamber is the one in which the nozzle sits (cf. fig. 4.18).

4.2. Practical realisation of cryogenic hydrogen target systems

Finally, the gas flow is depicted in a graph together with the nozzle diameter, which possibly is the one given the most attention by the operators. The exact numerical values for these parameters as well as for other, less critical ones are shown on the left, where also the target controls are located.

Target control is realised via inputting set points for the cold stage, the warm stage, for the two pressure controllers and the frequency as well as amplitude of the frequency generator driving the piezo actuator. Additionally, cooling is started or stopped by operating the compressor via a button.

The other various controls are quality of life improvements. For example, there is a button which sets the target to stand by conditions (50 K and 35 K at cold and warm stage respectively) and a timer with which the compressor can be started at a time of the operator's choosing.

Should the connection with a device fail for any reason, an error message is displayed in the bottom right and its associated status lamp will turn red. The most prevalent cause of error is that no connection can be made with a piece of equipment, for example because a previous connection has not been properly shut off. To easily identify such a case, each device has its own lamp showing whether it has been successfully initialised during start of the slow control.

Slow control structure

Overall, the slow control software operates in four principal steps as depicted in fig. 4.16:

1. Initialise connections
2. Import setpoints
3. Control and monitor
4. Close connections

In the first step, the slow control connects with all of the target's various hardware components such as the Model 336 temperature controller, the Brooks Model 0254 Secondary Electronics, the Coolpak 6000 H etc.. Then, in the second step, these devices send their current set points (such as temperature set points) to the slow control where they are promptly adopted. This is a safety feature: Should the software crash, it can be simply restarted without any risk of unforeseen behaviour due to a sudden change of set points.

Most of the time, the slow control remains in the third step. Here, the connected devices can be controlled while they are continuously read out at 1 Hz. Each device is monitored by its own independent while loop which greatly improves readability and modifiability of the program, since everything relevant to a certain device is contained in the same loop. Furthermore, this structure allows Labview to automatically parallelise the slow control, enabling a read out frequency of 1 Hz, an improvement by a factor of five compared to previous versions [Less 21]. Additionally, the data is logged with the

4. Development of cryogenic, hydrogen based droplet targets

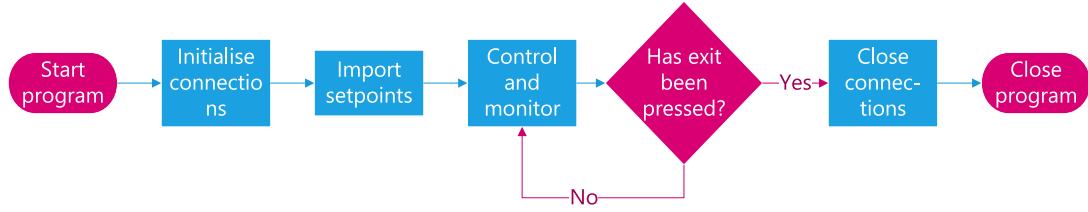


Figure 4.16.: A flow chart depicting the principal steps of the slow control software.

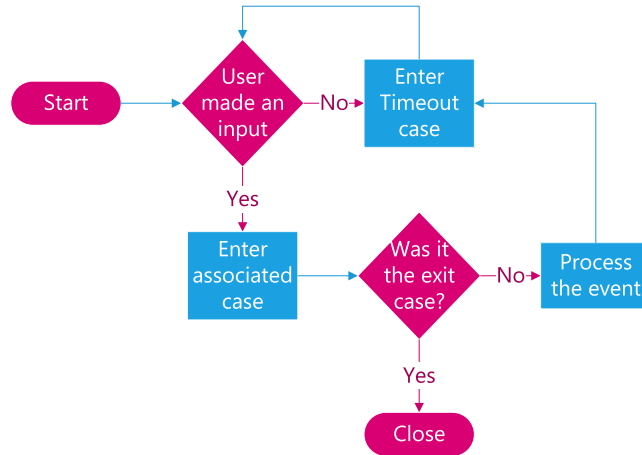


Figure 4.17.: Flow chart depicting Labview's event structure.

same frequency in an EPICS archiver [Shan 24] which can be accessed with CS-Studio [Cont 24], allowing for easy reconstruction of previous experimental conditions.

To control devices which do not only monitor certain values, for example vacuum pressure gauges, but also require user input, such as the temperature controller, Labview's event structure [Nati 24b] is used (cf. fig. 4.17). This structure is made up of several substructures, or cases, which are associated with one particular user input each. Should no input be detected, the event structure will remain in the Timeout case, for example measuring temperature, in the case of the temperature controller. When an input is detected, the structure immediately reacts, entering the associated case and executing the commands contained within, for example sending the new temperature set point to the Model 336 when the user changes it in the Labview program. Using this structure, the user's commands are executed immediately, independent of the read out frequency, improving the slow control's responsiveness.

Should the user press the STOP Button, the program enters the fourth step before closing. Here, it terminates all connections to the various devices so that other programs can connect to them in turn.

Nozzle diameter calculation

The nozzle diameter is an important value which is monitored in the slow control, as it allows for the immediate identification of any blockages. For gaseous hydrogen it is calculated through [Grie 18a]

$$d = 2 \sqrt{\frac{q_V p_N}{\pi p T_N}} \sqrt{\frac{M T}{\kappa R}} \left(\frac{2}{\kappa + 1} \right)^{\frac{\kappa - 1}{\kappa + 1}} \quad (4.16)$$

where T , p and q_V are the current cold stage temperature, gas pressure and volume flow, $p_N = 1013.25$ mbar and $T_N = 273.15$ K the normal pressure and temperature, M the molar mass of hydrogen, $R = 8.314$ J/(molK) the molar gas constant [NIST 22b] and κ the heat capacity ratio. Since eq. (4.16) is only valid for gaseous hydrogen, for liquids the nozzle diameter is calculated via [Habe 19]

$$d = 2 \sqrt{\frac{1}{\pi} \frac{M p_N}{N_A T_N} q_V} \sqrt{\frac{1}{2 p \rho}}, \quad (4.17)$$

where the only new variables are the hydrogen density⁷ $\rho = 75$ kg/m³ [NIST 23b] and the Avogadro constant $N_A = 6.022 \cdot 10^{23}$ mol⁻¹ [NIST 22a].

⁷Although ρ varies with temperature and pressure, the variation was deemed slight enough that this fixed value was implemented.

4.3. Characterisation and performance of MDT-D

As alluded to before (cf. section 4.2.1), MDT-D represents the first attempt of transforming a cluster-jet target into a droplet target. While adapting the target for its new role was uncomplicated, operating it revealed several challenges which needed to be tackled before stable target operation became achievable.

4.3.1. Experimental setup

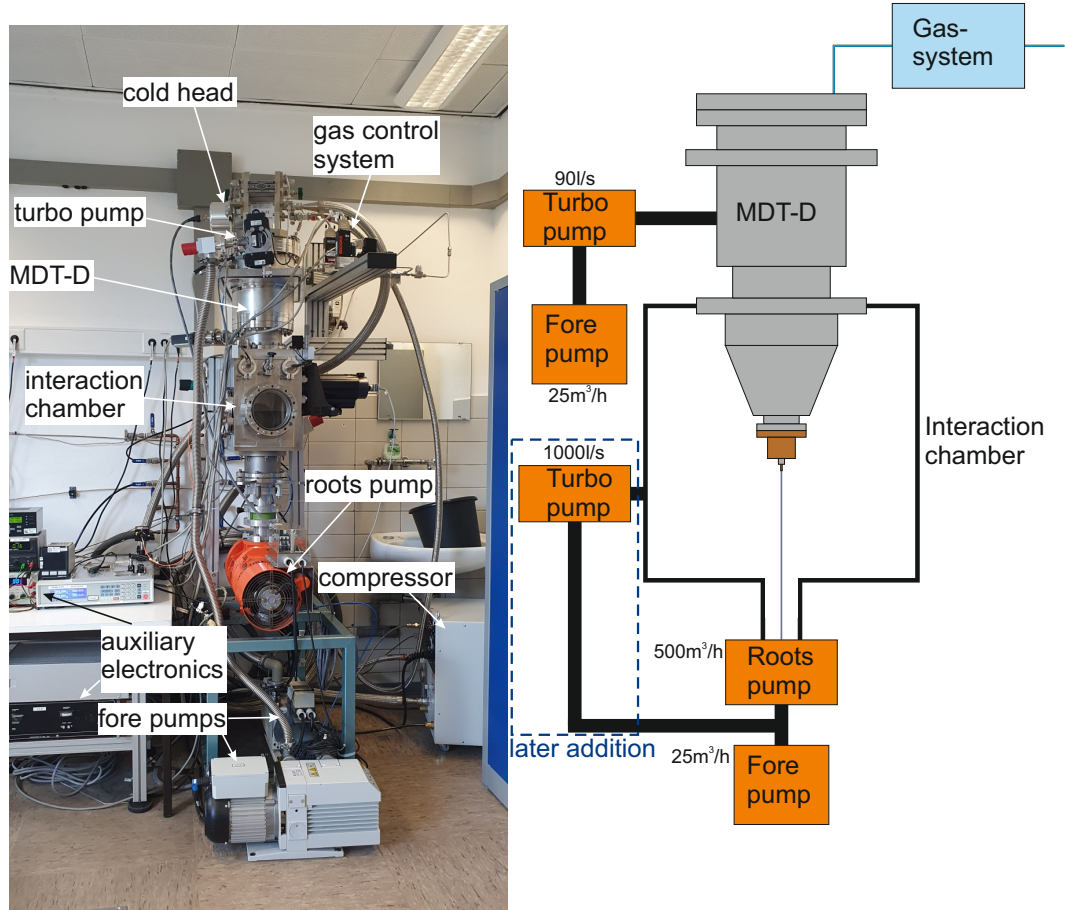


Figure 4.18.: Experimental setup of MDT-D. The target is mounted on the interaction chamber, which is pumped by a combination of roots pump and fore pump from underneath. (Left picture taken from [Haus 22])

MDT-D was mounted on top of a vacuum chamber which will subsequently be called the interaction chamber (cf. fig. 4.18). A roots pump (Alcatel RSV 601 B) was mounted underneath which generated a chamber vacuum of $\approx 10^{-3}$ mbar together with a forepump (Leybold TRIVAC D 25 B [Leyb 21]). At a later date a turbo pump (Leybold Turbovac 1000 [Leyb 17a]) was installed and the roots pump no longer used, achieving

vacua in the range of $\approx 10^{-5}$ mbar. However, this value worsens to $\approx 10^{-3}$ mbar when operating the target at fluid conditions due to the limited compression of the turbo pump for hydrogen. The target itself is set up as described in section 4.2.1.

4.3.2. Optimising cooling efficiency at MDT-D

All cryogenic targets are reliant on reaching the necessary cold temperatures, especially the droplet target which needs to reach ≈ 16 K to function at all.

There are two major environmental factors which need to be controlled to ensure that these temperatures are reliably reached: Heat radiation and vacuum conditions. As part of a bachelor's thesis [Haus 22], the impact of both these factors was experimentally investigated to develop optimisations to MDT-D's geometry.

To this end, MDT-D was cooled down at a gas pressure of 2 bar while its temperature was constantly monitored at the cold stage as well as the nozzle itself (cf. fig. 4.11). The measurement revealed that at a cold stage temperature of around 22 K, the nozzle is over 16 K warmer [Haus 22]. Under such conditions, liquefaction of hydrogen and, thus, droplet generation, is impossible (cf. fig. 4.4). The reasons for this large temperature difference seemingly⁸ lie in the fact that the piezo head, as opposed to the cold stage, does not possess a heat shield and that it is surrounded by a vacuum which is several orders of magnitude worse than the insulation vacuum (10^{-2} mbar in contrast to 10^{-6} mbar). However, this simple measurement cannot make a statement about the respective impact of heat radiation and vacuum conditions.

For more informative results, a hydrogen supply was connected to the interaction chamber, thus allowing for the exact adjustment of the vacuum. The vacua were varied at cold stage temperatures of $T_{CS} = 25$ K and $T_{CS} = 28$ K, which caused the temperature at the nozzle to vary in turn, leading to the results depicted in fig. 4.19 which show a clear exponential dependence between the temperature difference and interaction chamber pressure. Intuitively, one might expect a linear dependence, since pressure scales linearly with the number of particles, given constant volume and temperature. In turn, the total energy transmitted to the piezo head by rest-gas collisions and thus its temperature increase scales linearly with the number of particles, so that overall a linear dependence between pressure and temperature seems likely. However, this logic neglects that the piezo head is cooled by the cold stage. With increasing temperature difference the thermal conduction and therefore the cooling power transferred from the cold stage increases, counteracting the increased heat from the pressure and leading to the overall exponential trend.

Importantly, by extrapolating the data to 0 mbar and examining the temperature difference there, one can separate the contributions of vacuum and the only other factor, heat radiation. For $T_{CS} = 25$ K, radiation contributes (2.4 ± 0.3) K and at $T_{CS} = 28$ K it contributes (3.6 ± 0.3) K (cf. table 4.1) [Haus 22]. These results indicate that vacuum conditions are the dominant factor, since vacua in the range of 10^{-2} mbar impart temperature differentials above 10 K, seemingly making the minimisation of

⁸Indeed, it was later discovered that ensuring sufficient thermal conduction to the piezo head also plays a significant role. However, this effect was only discovered with MDT-H (cf. section 4.4.2).

4. Development of cryogenic, hydrogen based droplet targets

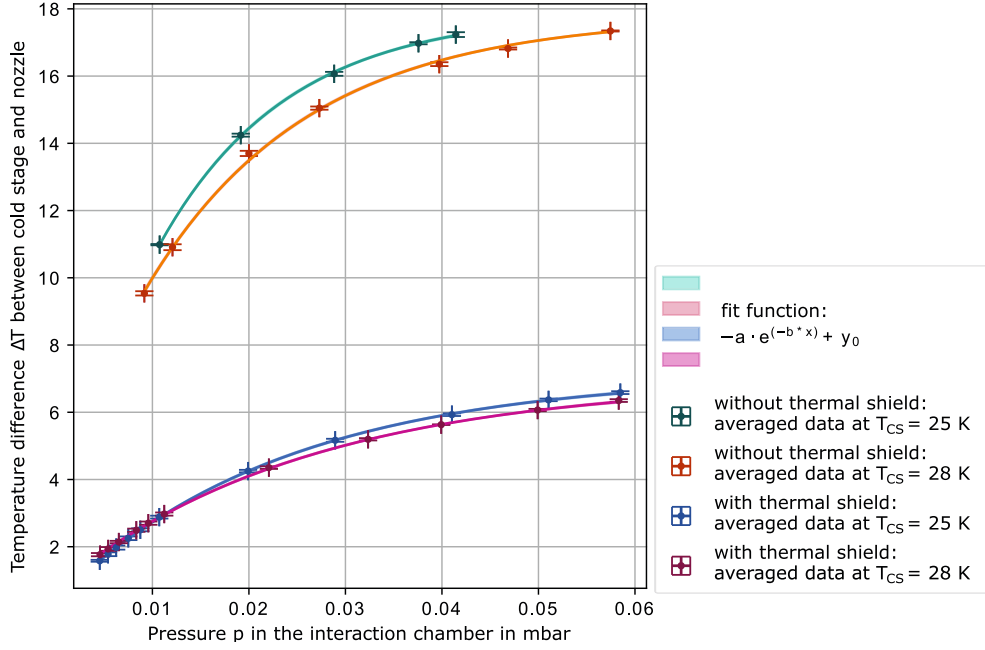


Figure 4.19.: Measurement of the temperature differential between cold stage and nozzle in dependence of chamber pressure. The measurement was performed for two constant cold stage temperatures: 25 K and 28 K and was done once each without and with heat shielding. (Generated by E.-M. Hausch with data taken from [Haus 22])

heat radiation a secondary concern. However, a heat shield (cf. section 3.4.3), does not only combat radiation, but also lowers the temperature of the rest-gas between shield and nozzle area, mitigating the impact of vacuum conditions.

Table 4.1.: Effect of the heat shield on the temperature offset between cold stage and nozzle caused by heat radiation [Haus 22].

	Without heat shield	With heat shield
For $T_{CS} = 25$ K	(2.4 ± 0.3) K	(0.86 ± 0.03) K
For $T_{CS} = 28$ K	(3.6 ± 0.3) K	(0.41 ± 0.05) K

So a copper heat shield covering the piezo head (cf. fig. 4.20) was manufactured and installed by connecting it to the heat shield already covering the cold stage. Once again, the vacuum conditions were varied at a constant 25 K and 28 K cold head temperature, leading to the results shown in fig. 4.19. Overall, the temperature differences have been significantly reduced from maxima of around 18 K to 7 K [Haus 22]. As expected, the radiation contribution has been strongly diminished to only (0.41 ± 0.05) K for $T_{CS} = 25$ K while it is (0.86 ± 0.03) K at $T_{CS} = 28$ K (cf. table 4.1) [Haus 22]. Counter intuitively, the heat radiation contribution is slightly higher for $T_{CS} = 28$ K than for $T_{CS} = 25$ K regardless of shielding and seemingly in conflict to eq. (3.29), which clearly predicts the opposite. However, copper has higher heat conduction at 25 K than at

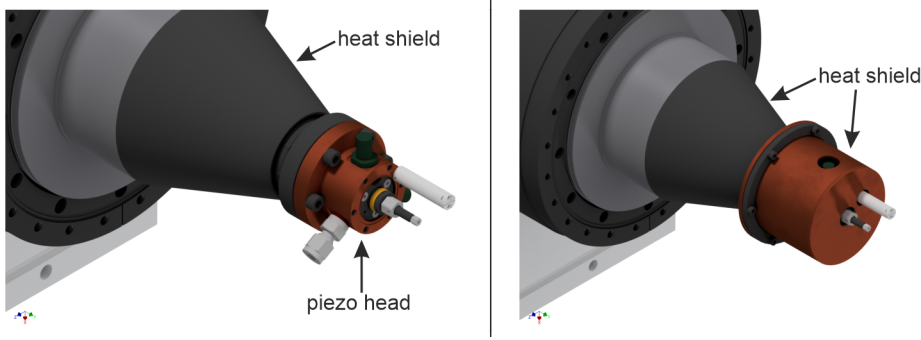


Figure 4.20.: **Left:** MDT-D without heat shield covering the piezo head. **Right:** MDT-D with a heat shield covering the piezo head.

28 K [Toul 66], enabling the cold stage to more effectively cool the piezo head at lower temperatures.

To combat the heat imparted by vacuum conditions, the roots pump was replaced by a Leybold Turbovac 1000 [Leyb 17b] with a nominal pumping speed of $3960 \text{ m}^3/\text{h}$, mounted at the back of the interaction chamber. Unfortunately, due to the poor compression of the turbo pump for hydrogen, only a slight vacuum improvement was achieved from around $(5.44 \pm 0.06) \cdot 10^{-3} \text{ mbar}$ to $(2.3 \pm 2.1) \cdot 10^{-3} \text{ mbar}$ ⁹ for target conditions of $T_{\text{CS}} = 15 \text{ K}$ and $p_{\text{gas}} = 1.4 \text{ bar}$. Nonetheless, it was enough to improve the temperature difference slightly from $(3.4 \pm 0.1) \text{ K}$ to $(2.5 \pm 0.3) \text{ K}$.

Theoretically, a temperature difference of only 2.5 K at $T_{\text{CS}} = 15 \text{ K}$ should be more than sufficient to liquefy hydrogen and produce a beam, however, at the time, the nozzle was not yet made of copper, but of stainless steel. The low heat conduction of this material meant that the nozzle remained too warm for liquefaction. Only with a copper nozzle (cf. fig. 4.10) could the first beam be generated [Haus 22] albeit with very limited reliability and repeatability.

4.3.3. Instability of MDT-D operation

Despite the improvements made to MDT-D's cooling setup, liquefying hydrogen remained difficult, leading to the peculiar and unpredictable target behaviour first analysed in depth in [Fron 23] and summarised here.

To liquefy hydrogen, the target is cooled down to 18 K at a gas pressure of 2 bar with an open bypass line (cf. fig. 4.21, phase 1). Once the temperature is low enough for liquefaction to start, phase 2 (cf. fig. 4.21) begins and the gas pressure drops as the system struggles to supply sufficient hydrogen. When liquefaction is complete the pressure rises back to 2 bar. Simultaneously, the temperatures at the nozzle and cold stage rise again as they have to cool more hydrogen while the chamber pressure suddenly starts to oscillate over several orders of magnitude (cf. fig. 4.21, phase 3).

⁹this value has much larger uncertainties than the other, due to strong fluctuations in the vacuum. The underlying reasons are discussed in section 4.3.3.

4. Development of cryogenic, hydrogen based droplet targets

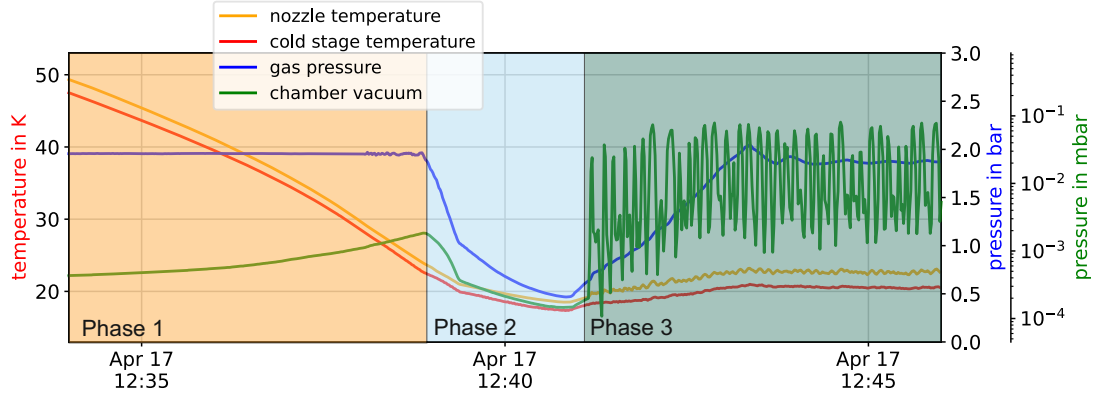


Figure 4.21.: Development of relevant parameters over time during the liquefaction of hydrogen at MDT-D. In phase 1 the temperature sinks continuously at constant pressure, before liquefaction begins in phase 2 and the gas system can no longer supply enough hydrogen to maintain constant pressure. Finally, in phase 3 the liquefaction is complete, the gas pressure re-stabilises and the vacuum pressure begins to wildly oscillate. (Adapted from [Fron 23])

This oscillation is a symptom of the target struggling to maintain conditions suitable for liquid hydrogen. At a low vacuum pressure, the target can cool down enough to liquefy hydrogen. Thus considerably more hydrogen is injected into the interaction chamber, worsening the vacuum pressure p_V and warming up the target again (cf. fig. 4.22). Hydrogen turns back to gas, the vacuum improves once again and the cycle repeats indefinitely. This behaviour can be described as the target "sticking" to the vapour pressure curve and is also observed for other gas pressures, making reliable liquefaction impossible.

Even when the system manages to stabilise in the liquid state, unpredictable peaks in gas pressure make target operation unreliable [Fron 23]. Since the temperature is still stuck right at the liquid side of the interface between liquid and gaseous phase, slight fluctuations in gas flow can already cause the nozzle to heat up sufficiently for a phase change from liquid to gas to occur, causing the gas pressure to rapidly increase by several bars in a few seconds [Fron 23].

Thus, despite all efforts, MDT-D remained capricious¹⁰, and no stable droplet beam could be generated, except for one notable occasion [Haus 22]. Nonetheless, through the work on this target many valuable insights could be gained. The necessary modifications to transform a cluster-jet target into a droplet target were developed and implemented, revealing them to be quite minor and quickly applicable within one or two hours. Furthermore, the importance of ensuring sufficient cooling was revealed, leading to an initiative to gain a better understanding of target cooling through simulations [Fron 23]. Apart from this issue, the second impediment to progress was nozzle clogging, which occurred every single time the target was cooled to liquid hydrogen temperatures. The down time thus incurred was significant, as the target had to be warmed up, the nozzle

¹⁰true to its name

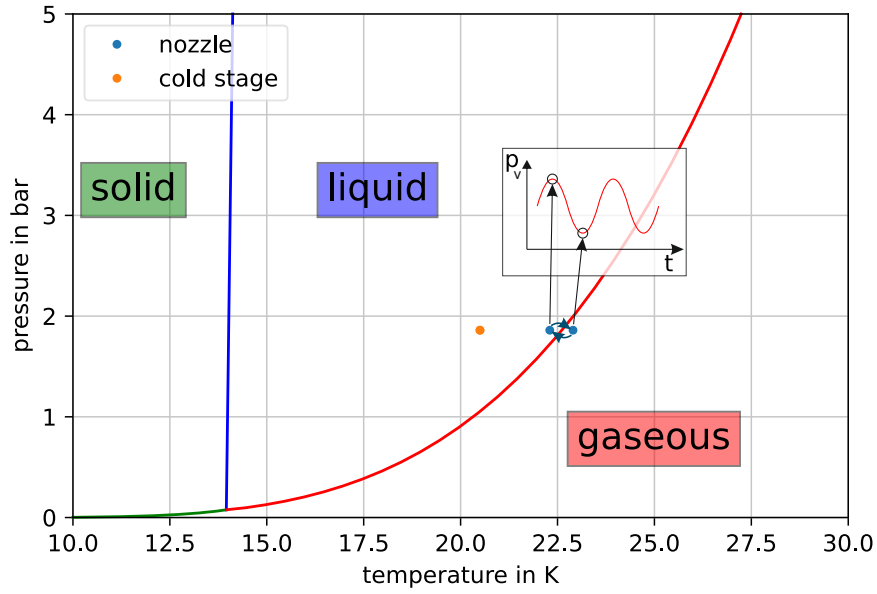


Figure 4.22.: The nozzle temperature "sticking" to the vapour pressure curve. Fluid hydrogen at the nozzle causes high vacuum pressure p_V , which in turn causes the nozzle to heat up sufficiently for hydrogen to become gaseous. The pressure p_V subsequently decreases, enabling the gas to liquefy again and thus the cycle begins anew. (Adapted from [Fron 23])

unmounted and cleaned in an ultrasound bath before it was reinstalled and the target flushed, meaning hydrogen was run through the nozzle at room temperature to remove any traces of air in the target's gas system. Overall, this process takes around a day, greatly slowing down the rate at which experiments can be run.

4.4. Characterisation and performance of MDT-H

Work on MDT-D revealed two key issues which needed to be addressed for reliable and stable target operation. Insufficient cooling and nozzle clogging. MDT-H was designed and constructed especially to combat the latter issue (cf. section 4.2.2), while additional pumping speed was installed at the experimental setup to improve cooling.

4.4.1. Experimental setup

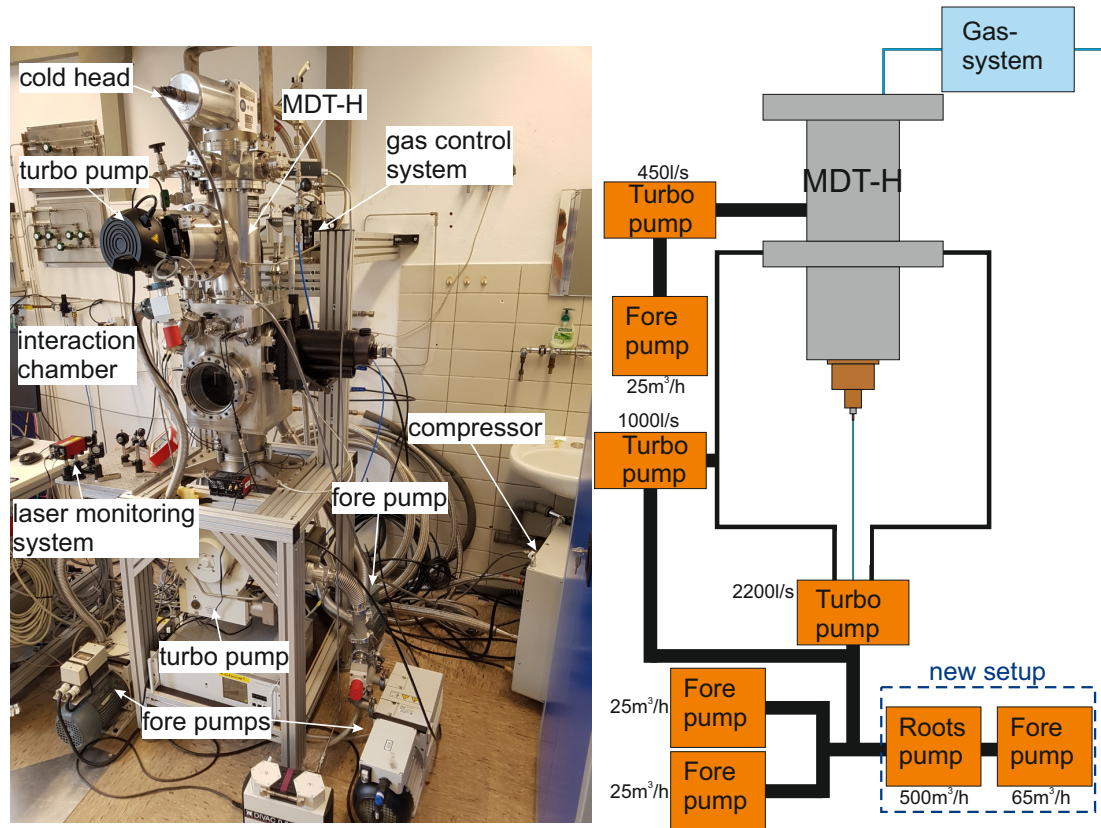


Figure 4.23.: Experimental setup of MDT-H. This target is mostly set up like MDT-D, with the biggest change being that an additional turbo pump is installed at the former position of the roots pump. At a later date, the two fore pumps were replaced by a system consisting of a new roots pump and a larger fore pump. (Left picture taken from [Fron 23])

The experimental setup remains essentially as described in section 4.3.1. The main difference is that MDT-D was replaced by MDT-H and an additional turbo pump (Pfeiffer TPH 2200 [Pfei 97]) was installed at the position of the roots pump (cf. fig. 4.23), providing an additional 2200l/s to the 1000l/s of pumping speed provided by the Leybold Turbovac 1000 [Leyb 17a], however, due to their poor compression, vacua

remained in the area of 10^{-3} mbar during target operation, even though a second Trivac D 25 B was added to ensure better fore vacuum conditions. At a later point, these two pumps were replaced by a system consisting of a roots pump (WSU 501 [Leyb 16b]) with a pumping speed of $500 \text{ m}^3/\text{h}$ and a fore pump (Trivac D65 B [Leyb 21]) with $65 \text{ m}^3/\text{h}$ (cf. fig. 4.23). With this new system, 10^{-4} mbar at target operation conditions could be reached.

Laser monitoring system

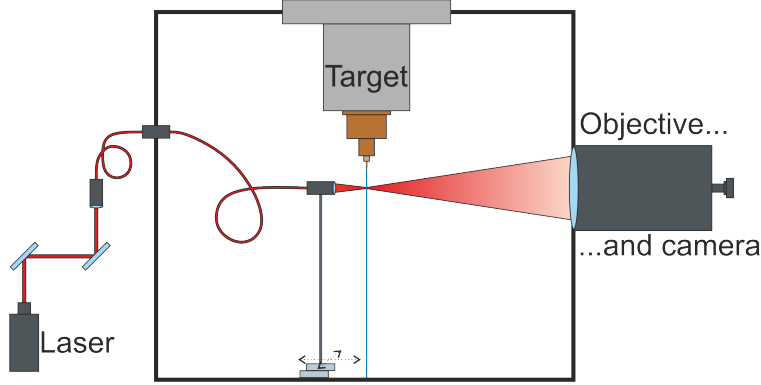


Figure 4.24.: The optical monitor system for MDT-H. ns-pulses are guided into the vacuum chamber by glass fibres where it is used to illuminate the target beam. The light is collected by a telescope objective and imaged onto a camera.

The key diagnostic system in use at MDT-H is the laser monitoring system (cf. fig. 4.24). It mainly consists of a short pulse laser (NPL 64 B [Thor 23a]) providing pulses between $(5 \pm 1) \text{ ns}$ and $(39 \pm 3) \text{ ns}$ in length at repetition rates and average powers up to 10 MHz and 20 mW, respectively. The laser beam is coupled into a multi mode glass fibre via two mirrors and a collimator. This fibre then connects to a vacuum feedthrough which is in turn connected to a second glass fibre. Finally, the light exits the fibre and is focussed onto the target beam by a lens. The laser focus can be moved horizontally in two dimensions by a piezo motor system (PD1D/M [Thor 23b]), enabling the target operator to react to changes in target beam position. The light is collected by a telescope objective (Questar QM100 [Poly]) and imaged by a camera (M2590 Dalsa Genie Nano GigE PoE [Tele 16], later replaced by a Mako G-125B PoE [Alli 24]).

By using ns-pulses to illuminate the beam it is possible to acquire sharp pictures of the target beam. Normal cameras possess shutter times in the range of tens of μs , too slow to sharply depict droplets with a diameter of roughly $20 \mu\text{m}$ moving at tens of m/s of speed. So instead of decreasing shutter speed further, the time of illumination is reduced by pulsing the laser, leading to an effective shutter time of only a few ns. Previous monitoring systems [West 20] used stroboscopic images to overcome the limited shutter speed, where they synchronised the rate of illumination with the piezo frequency and thus also with the droplet frequency. This way, one always illuminates

4. Development of cryogenic, hydrogen based droplet targets

the droplets when they arrive at the same spot, creating the illusion that one is imaging a single droplet when one is in reality imaging a superposition of thousands of droplets [West 20]. This mode is still possible with the ns-laser, however, due to its high intensity, only around 12 images need to be superimposed to create a similarly bright picture, greatly enhancing the accuracy of the resultant image.

4.4.2. Cooling efficiency of MDT-H

One of the core issues of MDT-D was the large offset between cold stage temperature and nozzle temperature, making target operation extremely unreliable. Heat radiation and vacuum conditions were identified as key factors leading to this issue and appropriate counter measures, e.g. heat shielding, were taken. To verify the effectiveness of these counter measures and to identify any factors that might have been missed, the cooling efficiency of MDT-H was studied.

Impact of heat shielding

To investigate the effect of heat shielding, MDT-H was operated at a cold stage temperature of $T_{CS} = 16$ K and a gas pressure of $p_{gas} = 0.6$ bar with and without heat shield. Unlike for MDT-D, no significant change could be observed for the offset between cold stage and nozzle which remained at around 1.9 K, with no sticking behaviour being observed. However, after installing a heat shield (cf. fig. 4.25) the volume flow increased from around (62 ± 8) ml_n/min to (103 ± 3) ml_n/min which can be interpreted as evidence that the nozzle without heat shield was significantly warmer than the measured temperature, as the diode measuring it remains quite far from the nozzle itself (cf. fig. 4.25) and the flow is strongly dependant on the nozzle temperature.

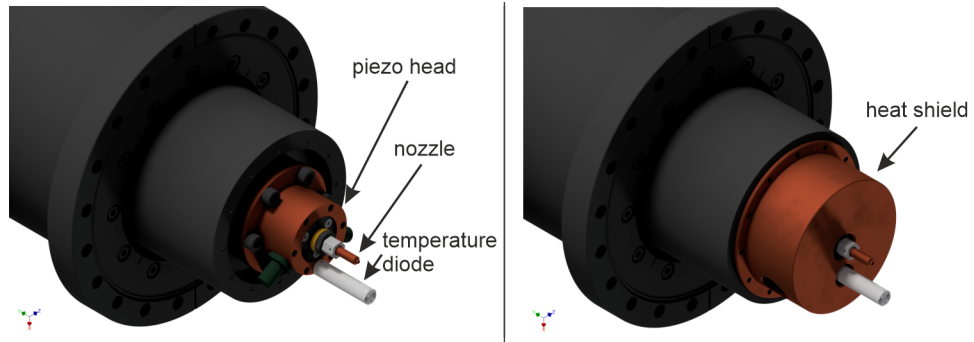


Figure 4.25.: **Left:** MDT-H without heat shield. **Right:** MDT-H with a heat shield covering the piezo head.

The alternative explanation would be that the nozzle is partly blocked for the measurement at (62 ± 8) ml_n/min flow. However, a target beam could be seen under these conditions, which only appears when the nozzle is perfectly clean. During the work on MDT-H, it was observed that impurities which do not have any visible effect

on nozzle flow and diameter already lead to the beam's destruction, making a slightly obstructed nozzle an unlikely candidate for explaining the difference in flow.

So in conclusion, while the effect of the heat shielding could not be directly detected, there is enough evidence to conclude that it is still there, even if not as strong as for MDT-D. This might seem surprising, given how much of an improvement heat shielding brought to MDT-D, however, MDT-H's geometry was already shown to reach 1.7 K lower temperatures at the cold stage than MDT-D in temperature simulations [Fron 23], demonstrating improved cooling capabilities. Additionally, physical contact between the piezo head and the rest of the target might not have been sufficiently high for efficient heat conduction at MDT-D as explained below. A combination of these two effects could possibly lead to the heat shielding having such a stronger effect on MDT-D than on MDT-H.

Impact of the interaction vacuum

The aforementioned temperature offsets of 2 K were measured at interaction chamber vacua similar to the conditions at MDT-D, meaning vacua in the range of 10^{-3} mbar. After replacing the two fore pumps with a much stronger system based on a roots pump and fore pump (cf. section 4.4.1), the vacuum conditions during target operation improved to a range of 10^{-4} mbar and the temperature offset was reduced, as was expected based on the measurements performed with MDT-D, reaching a temperature offset of around 0.8 K.

Impact of thermal conduction

AT MDT-H, it was observed that over a time period of two months the temperature offset ¹¹ increased from around 2 K to over 5 K. After tightening the screws attaching the piezo head to the rest of the target to a torque of 3 Nm, the offset was further reduced to only 1.6 K, demonstrating the importance of providing sufficient contact between copper parts to maintain good heat conduction. While such an effect has also been seen in simulations [Fron 23], it was discovered too late to check whether MDT-D also suffered from such an issue.

Possibly, the large temperature offsets observed at MDT-D were caused at least in part by insufficient heat conduction and not only by heat radiation and the vacuum conditions. Indeed, for perfect connection of the copper parts, simulations [Fron 23] predict a temperature offset of 0 K. Only when imperfect connections are added, does the simulation begin to start showing an offset which can be reduced by heat shielding [Fron 23]. One should note that these simulations neglect the influence of the vacuum conditions which weren't possible to model in the used software, which leads to the simulation's values being better than the ones seen experimentally. Nonetheless, the same trends are visible, enabling a solid qualitative understanding which can be improved in future by more detailed simulations.

¹¹at target settings of $T_{\text{CS}} = 16$ K and $p_{\text{gas}} = 1$ bar

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Stability of MDT-H operation

Through a combination of the factors explained above (cf. section 4.4.2), for MDT-H, the nozzle temperature doesn't stick to the vapour pressure curve as observed for MDT-D. Instead, hydrogen can be reliably liquefied, finally enabling stable target operation. A demonstration of this stability can be seen in fig. 4.26 where the target is operated at a temperature of $T_{CS} = 16$ K and differing gas pressures, ranging from $p_{gas} = 1$ bar to $p_{gas} = 0.6$ bar in 0.2 bar steps. With each decrease in gas pressure, the

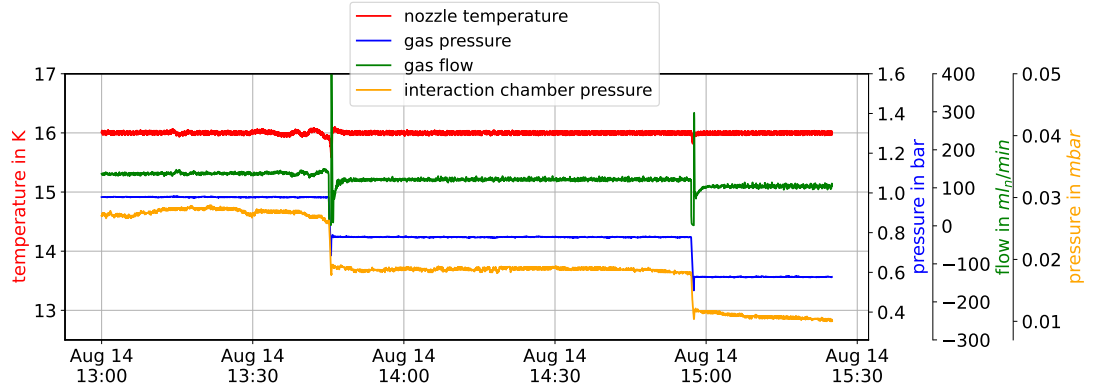


Figure 4.26.: Evolution of important target parameters over time. At the beginning, the target is operated at a hydrogen pressure of 1 bar which is reduced to 0.6 bar in two 0.2 bar steps. The vertical lines in gas pressure and flow indicate the points of time when the set points of the former were changed.

volume flow and the interaction chamber pressure decreases, as would be intuitively expected, but the most important finding gleaned from fig. 4.26 is how stable the target parameters remain, which is indicated in table 4.2 where their mean values and their respective standard deviations are shown.

Table 4.2.: Important target parameters and their fluctuation for three different target settings. These settings are given by the cold stage temperature in K and the hydrogen pressure in bar. With decreasing gas pressure, volume flow and interaction chamber pressure decrease as expected and all values show excellent stability with fluctuations remaining below the 1 % mark for all parameters except for the interaction chamber pressure and flow where it is around 3 % and 4 % respectively, at worst.

	16 K/1 bar	16 K/0.8 bar	16 K/0.6 bar
Temperature (cold stage) in K	16.00 ± 0.03	16.00 ± 0.02	16.00 ± 0.02
gas pressure in bar	0.979 ± 0.001	0.778 ± 0.001	0.577 ± 0.001
Volume flow in ml_n/min	137.73 ± 3.06	121.74 ± 2.52	103.83 ± 3.17
Interaction chamber pressure in $1 \cdot 10^{-2}$ mbar	2.78 ± 0.05	1.84 ± 0.02	1.08 ± 0.03

4.4. Characterisation and performance of MDT-H

The results demonstrate the excellent stability of MDT-H. The target's set points for temperature and gas pressure are maintained with an accuracy better than 1 %. There is a slight deviation for the measured gas pressure from the set point because of small calibration differences between the pressure controller and the baratron which is used to read out the pressure. The exact size of this difference has been observed to be room temperature dependent, so that it cannot be removed by simply adding an offset, and it was decided to accept it, as it makes no difference when operating the target.

In addition, the flow and interaction chamber pressure are shown as two essential indicators of target stability. When a target is unstable, for example because its temperature is stuck to the vapour pressure curve, the flow might show periods of 0 ml_n/min because of gas expanding in the target or the interaction chamber pressure might fluctuate over several orders of magnitude as seen in fig. 4.21. None such behaviour is visible in fig. 4.26 and table 4.2. Instead, these two parameters remain excellently stable, with a relative fluctuation below 4 % for the volume flow and below 3 % for the pressure.

Apart from target parameter stability, the target beam's stability is of essential interest. It was determined in conjunction with the pilot measurements of the cryobending system (cf. section 4.4.5) while the long term stability is analysed in section 4.4.7.

As the last point already suggests, MDT-H is not only much more stable than its predecessor concerning its target parameters and beam, but also in respect to nozzle clogging. While previously, target operation invariably ended in a blocked nozzle, MDT-H has proven far more robust, with blocked nozzles only appearing roughly once a month. Analysis of nozzle blockages revealed them to at least partially stem from the environment (cf. section 4.4.6) so that MDT-H's improved cleanliness also leads to greatly increased reliability.

4.4.3. Droplet generation attempts with MDT-H

Now that a stably operating target was available, first attempts were made in generating a droplet beam. As explained in section 4.1.1, the piezo element should ideally vibrate with the optimal frequency f_{opt} , which is in the range of hundreds of kHz for hydrogen. However, one should keep in mind that the piezo element in conjunction with the piezo head also possess resonance frequencies where the vibration amplitudes become maximal. Thus, to optimise the efficiency of droplet generation, the resonance frequencies of MDT-H's piezo head in the range of hundreds of kHz were determined in the context of a bachelor's thesis [Hann 24].

Theory of resonant piezo behaviour

To understand the shape of the piezo resonances, this section will briefly explain the underlying theory of piezo resonance.

A piezo element as part of an electric circuit can be understood by the van Dyke equivalent circuit [Van 28], where it is modelled as a parallel circuit, consisting of a part representing the electrical components of the piezo and a mechanical one. As a

4. Development of cryogenic, hydrogen based droplet targets

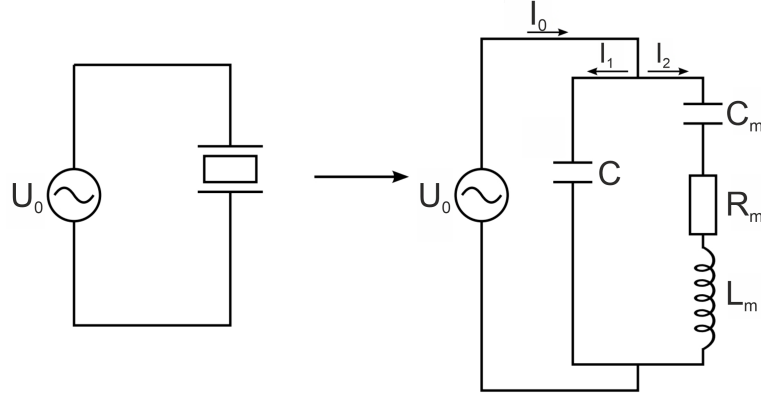


Figure 4.27.: Representation of a piezo element as an equivalent circuit diagram. A piezo can be represented as a parallel circuit, consisting of a capacity in one branch and an inductivity, a capacity and a resistance in the other. (Adapted from [Husm 12])

piezo element is made up of a ceramic plate sandwiched between two electrodes, the electrical part can be easily identified as a capacitor with the impedance Z_C [Demt 17b]

$$Z_C = \frac{1}{i\omega C} \quad (4.18)$$

where i is the imaginary unit, ω the frequency and C its capacity. The mechanical part can be modelled as a series connection of a capacity C_m , an inductivity L_m and a resistance R_m ¹² [Van 28] resulting in following equation for their overall impedance Z_m :

$$Z_m = i\omega L_m + \frac{1}{i\omega C_m} + R_m. \quad (4.19)$$

Thus, for the total impedance following equation is found:

$$Z(\omega) = \frac{1}{\frac{1}{Z_C} + \frac{1}{Z_m}} = \frac{R_m + i\left(\omega L_m - \frac{1}{\omega C_m}\right)}{1 - \omega C\left(\omega L_m - \frac{1}{\omega C_m}\right) + i\omega C R_m} \quad (4.20)$$

and for its norm:

$$|Z(\omega)| = \frac{\sqrt{R_m^2 + \left(\omega L_m - \frac{1}{\omega C_m}\right)^2}}{\sqrt{\left(1 - \omega C\left(\omega L_m - \frac{1}{\omega C_m}\right)\right)^2 + (\omega C R_m)^2}} \quad (4.21)$$

whose frequency dependent behaviour is plotted in fig. 4.28, where the piezo's resonant behaviour is clearly recognisable. The minimum corresponds to a resonance and the maximum to an anti-resonance whose locations (ω_R and ω_A) can be calculated via

¹²A nice derivation why this can be done is found in [Hann 24]

4.4. Characterisation and performance of MDT-H

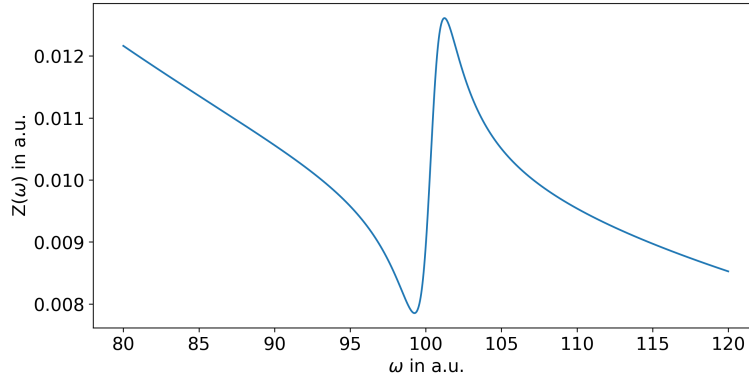


Figure 4.28.: Graphic representation of eq. (4.21). The minimum and maximum correspond to the resonance and anti-resonance respectively.

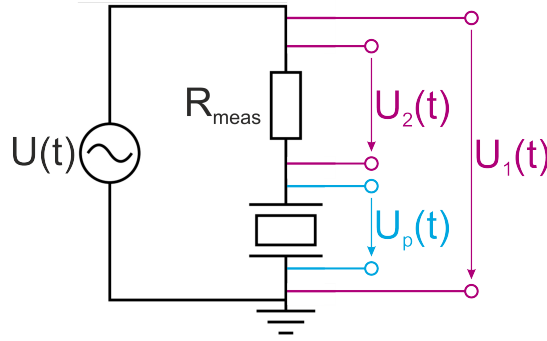


Figure 4.29.: Experimental setup to determine the piezo impedance. By measuring U_{a1} and U_{a2} , U_p and I_p can be determined and thus the impedance $|Z|$. (Adapted from [Husm 12])

[Kess 12]

$$\omega_R = \frac{1}{\sqrt{L_m C_m}} \quad (4.22)$$

and

$$\omega_A = \sqrt{\frac{1}{L_m} \left(\frac{1}{C} + \frac{1}{C_m} \right)} \quad (4.23)$$

under the assumption of a negligible R_m .

Experimental determination of piezo resonance frequencies

In principle, the task is to experimentally measure the frequency dependent behaviour of the impedance's norm, as already plotted in fig. 4.28. To do so, the experimental setup as shown in fig. 4.29 is used. The basic idea is to use [Demt 17b]

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$$|Z| = \frac{U_p}{I_p} \quad (4.24)$$

where U_p and I_p are the voltage and electric current amplitudes flowing through the piezo element. To determine U_p and I_p , a sinusoid voltage is applied to the experimental setup with the amplitude U_0 , the frequency ω , the phase ϕ and the constant offset U_{off} :

$$U(t) = U_0 \cos(\omega t + \phi) + U_{\text{off}}, \quad (4.25)$$

resulting in the voltages

$$U_1(t) = U_{a1} \cos(\omega t + \phi_1) \quad (4.26)$$

$$U_2(t) = U_{a2} \cos(\omega t + \phi_2), \quad (4.27)$$

shown in fig. 4.29. The amplitudes U_{a1} and U_{a2} are measured and U_p is calculated from their difference

$$U_p = U_{a1} - U_{a2} \quad (4.28)$$

while I_p is determined via

$$I_p = \frac{U_{a2}}{R_{\text{meas}}} \quad (4.29)$$

with the known ohmic resistance $R_{\text{meas}} = 1000 \Omega$. By combining eq. (4.24) with eqs. (4.28) and (4.29) an equation to calculate $|Z|$ from experimental data can be found which leads to eq. (4.30). Crucially, the amplitudes U_{a1} and U_{a2} are frequency dependent, so that varying it leads to the impedance behaving as described in eq. (4.21) and fig. 4.28.

$$|Z|(\omega) = \frac{R_{\text{meas}}(U_{a1}(\omega) - U_{a2}(\omega))}{U_{a2}(\omega)}. \quad (4.30)$$

So to determine the piezo resonances for MDT-H, the piezo was driven by a frequency generator and a linear amplifier (cf. section 4.2.1) and the applied frequency varied from 1 kHz to 1 MHz in 1 kHz steps. For each step, an oscilloscope (Rohde & Schwarz RTB 2004 [Rohd 22]) measured the voltage curves $U_1(t)$ and $U_2(t)$ over time, averaging 100 times to smoothen them and automatically calculating U_{a1} and U_{a2} . The measurement and logging of the the relevant values was automatised by a Labview program as detailed in [Hann 24].

Experimental results and observed droplet break up

For target settings of $T_{\text{CS}} = 16 \text{ K}$ and $p_{\text{gas}} = 1 \text{ bar}$ and a voltage of $U_0 = 10 \text{ V}$ at an offset of $U_{\text{off}} = 10 \text{ V}$ the results depicted on the left of fig. 4.30 were achieved. The characteristic form as already seen in fig. 4.28 is clearly recognisable, however, as the piezo possesses several oscillation modes in reality, there are also several (anti-)resonances, a behaviour which was not modelled in eq. (4.21).

Pictures of the target beam were taken with the laser monitoring system, searching for droplets at the same target conditions as used for fig. 4.30. The piezo frequencies for

which the target beam begins breaking up are noted in fig. 4.30, which mostly coincide with resonance frequencies, demonstrating the worth of the impedance measurement for efficiently searching for droplet frequencies.

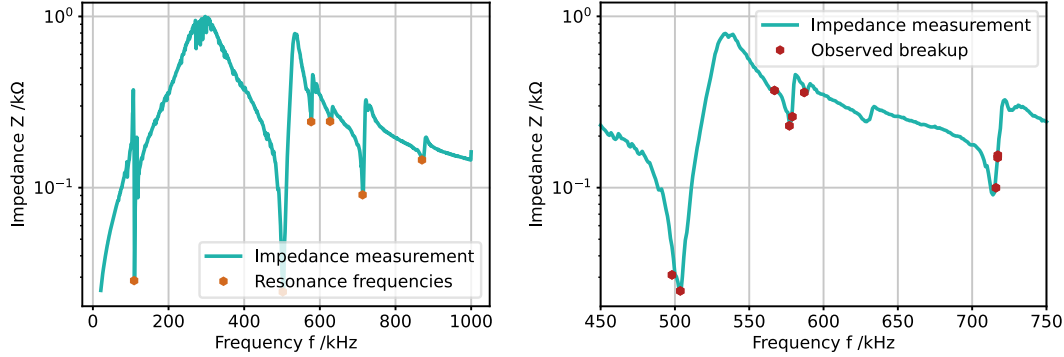


Figure 4.30.: **Left:** Measurement of the frequency dependent impedance for a voltage of $U_0 = 10$ V at an offset of $U_{\text{off}} = 10$ V. As discussed before, resonances coincide with minima in this spectrum. **Right:** The frequencies where droplet break up is observed are marked in the spectrum, which coincide reliably with a piezo resonance. (Graphs modified from [Hann 24])

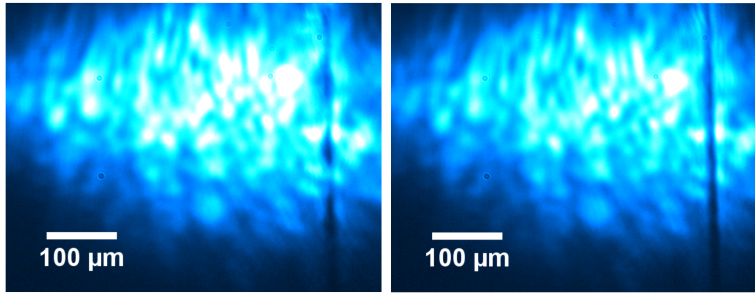


Figure 4.31.: **Left:** The target beam (with target settings of $T_{\text{CS}} = 16$ K and $p_{\text{gas}} = 1$ bar) is excited at a frequency of 503.6 kHz and an amplitude of $U_0 = 85$ V without offset, nearly causing it to break up. **Right:** For comparison purposes, the unperturbed beam is shown at identical target conditions. The conversion scale from pixel to μm was determined in [Fron 21].

An example of such a break up is depicted in fig. 4.31, however, no complete break up into droplets has been observed yet, no matter the target conditions nor the applied frequency and voltage. fig. 4.31 suggests that a slight increase in voltage to increase the vibration's intensity might be the solution, however we were already at or close to the maximum. Furthermore, it is highly doubtful that a further increase would yield success as such high voltages incur signal distortions. These are caused by the piezo's comparatively large capacity which is explained below in further detail. Thus the solution seems to be to use a different piezo with lower capacity.

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Nonetheless, the piezo currently in use has previously been used to successfully generate droplets [Frag 15]. The crucial difference to the current setup is that there the nozzle was surrounded by a triple point chamber (TPC) generating worse vacuum conditions than in the current interaction chamber. Without the TPC, no droplets could be generated [Frag 15] because hydrogen freezes within 2 mm of leaving the nozzle [Gris 18], confirming our current observations (cf. section 4.4.4). So to solve this issue and generate droplets, a system similar to the TPC could be designed and constructed, or, alternatively, the co-flowing system repaired. In the meanwhile, MDT-H is used as a filament target (cf. right side of fig. 4.31).

Measurement of impedance at different temperatures and voltages

The impedance measurement was repeated for several different target temperatures and voltage amplitudes U_0 . In the right of fig. 4.32 it is clearly visible how the spectrum changes for different temperatures. When going from 16 K to 50 K one can see how the resonances are slightly shifted to lower frequencies. When going to 295 K the shift is more pronounced, as can be expected, and many resonances are less pronounced or vanish completely. This behaviour is expected, since the mechanical properties of the materials involved are temperature dependent which in turn informs their resonance frequencies, however, how strong the temperature's influence is can be difficult to estimate, making it essential that the impedance measurement is performed at target operation conditions.

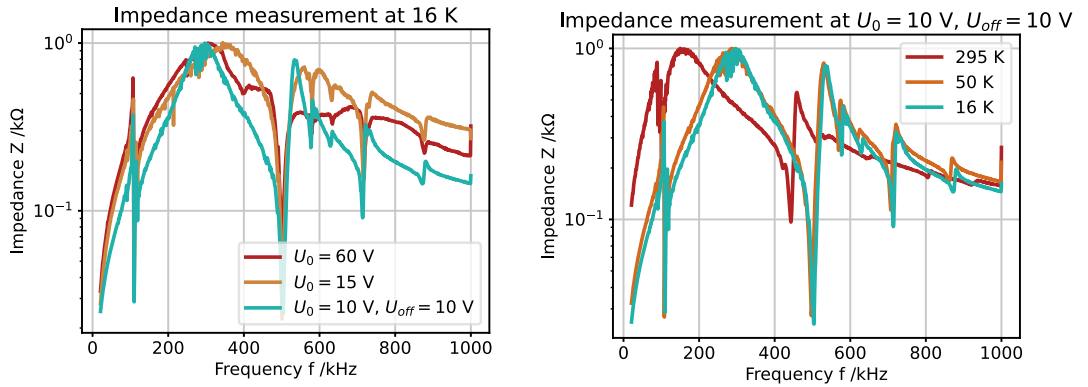


Figure 4.32.: Left: Impedance measurement at different voltage amplitudes U_0 and offsets U_{off} for constant target conditions $T_{\text{CS}} = 16 \text{ K}$ and $p_{\text{gas}} = 1 \text{ bar}$. The line shapes vary substantially, although the impedance is not voltage dependent (cf. eq. (4.21)). **Right:** Impedance measurement at different target temperatures T_{CS} for constant voltage amplitude $U_0 = 10 \text{ V}$ and offset $U_{\text{off}} = 100 \text{ V}$. For higher temperatures, the resonances are shifted to lower frequencies. (Graphs modified from [Hann 24])

When operating the piezo at different voltages, the positions of (anti-)resonances remains the same for all the measurements, however the line shape changes, with the characteristic curve form as expected from fig. 4.28 being most visible for the lowest

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voltage $U_0 = 10$ V (cf. left side of fig. 4.32). This is unexpected, as the impedance is voltage independent (cf. eq. (4.21)). The reason for this behaviour lies in the piezo's power consumption P which is given by [Piez]

$$P = \frac{1}{2} C U_{\max}^2 f \quad (4.31)$$

where C is the piezo's capacity, $U_{\max}$ the maximum voltage applied to the piezo and f is

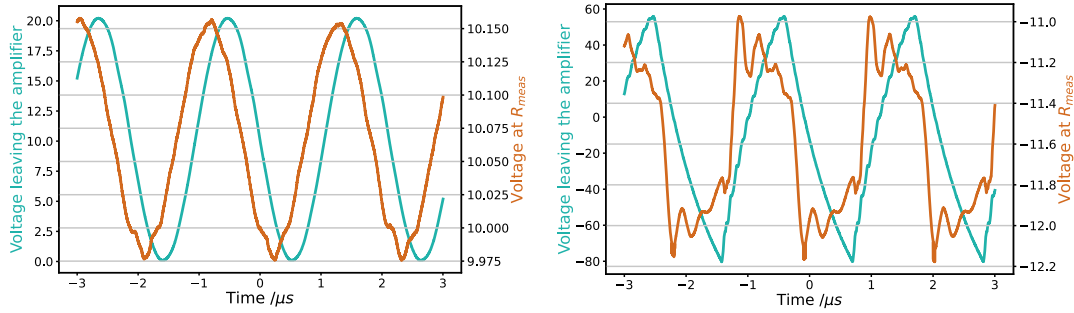


Figure 4.33.: The voltage curve exiting the amplifier alongside the voltage curve measured over R_{meas} . **Left:** For small amplitudes, $U_0 = 10$ V and $U_{\text{off}} = 10$ V, both curves show the same shape. **Right:** However, for large amplitudes, $U_0 = 10$ V and $U_{\text{off}} = 10$ V, the curves distort and lose their sinusoid shape. (Modified from [Hann 24])

its frequency of operation. The piezo in use (HPCh 150/15-8/3 [Piez 21]) has a capacity of $C = 190$ nF at 20 K [Frag 15] and a typical voltage and frequency which might be applied are $U = 60$ V and $f = 500$ kHz, resulting in a power consumption of $P = 171$ W. However, the linear amplifier has a power limit of around 30 W [Pend 20] so that the piezo is operated at insufficient power. The result can be seen in fig. 4.33, where the voltage curve exiting the amplifier is plotted alongside the voltage curve measured over the resistor ($U_2(t)$). Ideally, both curves should be of identical shape. For the low voltage amplitude of $U_0 = 10$ V with an offset of $U_{\text{off}} = 10$ V this is approximately the case, however for the large voltage amplitude ($U_0 = 60$ V, $U_{\text{off}} = 0$ V) the signals show strong distortions and lose their sinusoid shape, which effects the values of U_{a1} and U_{a2} . So the distortion strength is voltage dependent which in turn causes $|Z(\omega)|$ to seemingly become voltage dependent as the measurement relies on accurate values for U_{a1} and U_{a2} .

4.4.4. Experimental determination of the target beam's aggregate state

While travelling through vacuum, the hydrogen produced by our target loses heat due to surface evaporation [Faub 88] until it reaches a temperature where it begins to freeze. This process has been experimentally observed to rapidly occur after the beam leaves the nozzle with hydrogen being completely frozen after 2 mm travel distance [Gris 18], corroborated by recent simulations [Weid 23]. These results have large implications for the operation of a droplet target, as a frozen beam can no longer break up into droplets. Thus we performed our own studies to determine the hydrogen beam's aggregate state in the context of a bachelor's thesis [Hann 24].

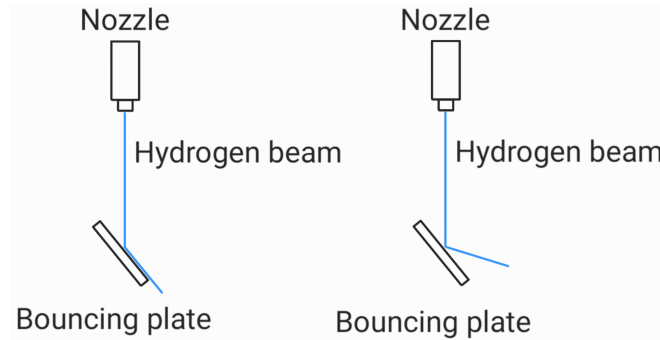


Figure 4.34.: **Left:** In the case of a fluid hydrogen beam, it is expected to flow off the angled plate. **Right:** Should it be solid, the beam is expected to bounce off. (Taken from [Hann 24])

The bouncing plate setup

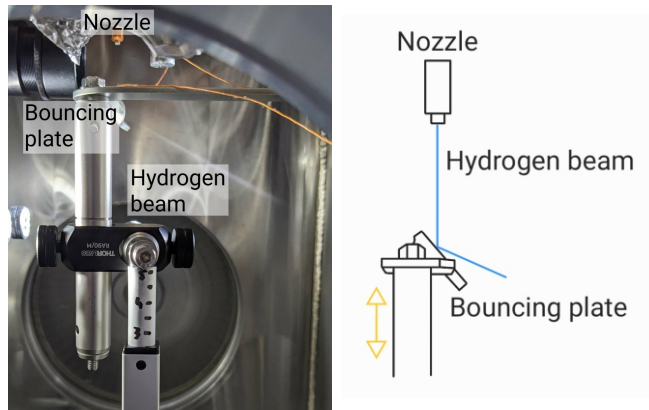


Figure 4.35.: Experimental setup of the bouncing plate measurements. The plate is placed underneath the nozzle, deflecting the target beam to the right at an adjustable height. (Taken from [Hann 24])

The principal idea for these measurements is to exploit the different behaviours of

4.4. Characterisation and performance of MDT-H

liquids and solids when interacting with obstacles, by aiming the target beam at an angled plate (cf. fig. 4.34). In the case of a fluid beam, it is expected to flow off, while a solid is expected to bounce off, giving the setup its characteristic name.

The resultant experimental setup is shown in fig. 4.35. The metal bouncing plate is installed under the nozzle with a 45° angle relative to the beam. This setup is motorised so that the plate's distance to the nozzle can be varied.

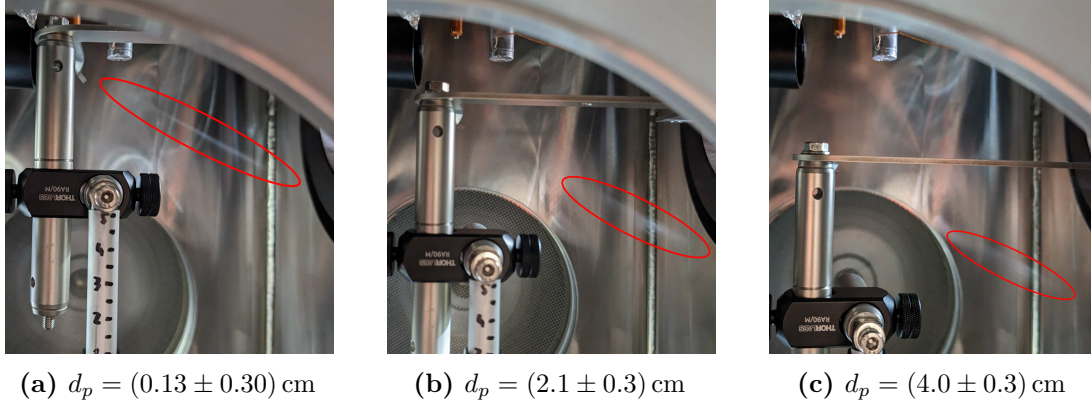


Figure 4.36.: The target beam bouncing of the plate (marked in red) for different distances from the nozzle d_p . No matter the distance, the behaviour remains the same. (Taken from [Hann 24])

At target operation conditions of $T_{\text{CS}} = 16 \text{ K}$ and $p_{\text{gas}} = 1 \text{ bar}$, the beam bounces off the plate no matter its distance d_p from the nozzle (cf. fig. 4.36). While this is strong evidence that the beam is frozen for every distance, it is not yet conclusive. At these target conditions, the beam travels through vacuum at around 50 m/s (cf. eq. (4.9)) and it is plausible for a fluid beam to also bounce off the plate at these speeds.

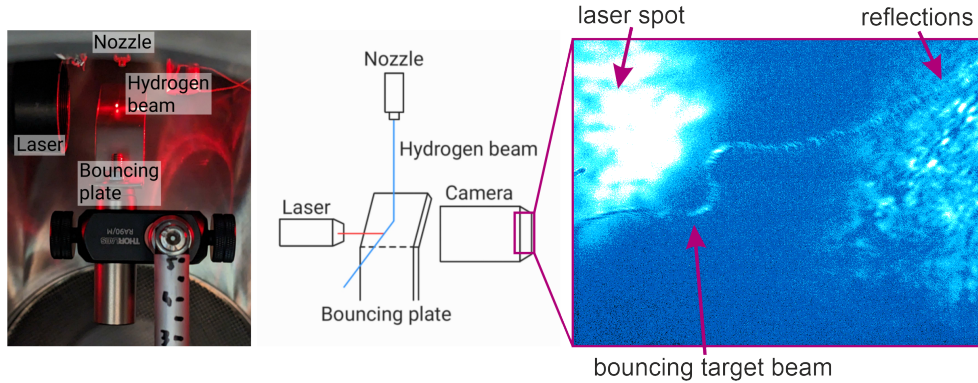


Figure 4.37.: The modified bouncing plate setup. The plate deflects the beam to the front, enabling the laser monitor system to take pictures of the deflected beam, thus revealing its string like behaviour. (left and middle pictures taken from [Hann 24])

For more conclusive results the setup was modified by installing a new bouncing

4. Development of cryogenic, hydrogen based droplet targets

plate which deflected the target beam to the front, enabling the laser monitor system to take pictures of the reflected beam (cf. fig. 4.37). Such a picture can be seen in fig. 4.37, which was taken with the plate being a mere (0.2 ± 0.3) cm away from the nozzle, revealing that the reflected beam behaves akin to a piece of string, which is only possible for a solid beam, confirming the previous studies [Gris 18, Weid 23].

Unfortunately, the plate could not be moved closer to the nozzle without components being in the way so that the exact distance at which the beam freezes out could not be determined, however, considering the simplicity of the experimental setup, the measurements are a great success and in future more detailed studies could be performed using a Raman spectroscopy setup like in [Gris 18].

4.4.5. Cryobending system

Due to small irregularities in the nozzle aperture shape, the target beam does not leave the nozzle perfectly perpendicular to the floor. For an experiment like $\bar{\text{P}}\text{ANDA}$, this poses a significant issue as the deviation gained over several metres flight could well be enough that there is no possible overlap between the target and accelerator beam. Previous targets have solved this issue by tilting the target generator [Grie 18a] or even moving it laterally in addition [Winn 11], which greatly complicates target design. We propose a novel system which can achieve the same effect with much less engineering effort. We bend the target beam to the desired direction by blowing gas onto it through a secondary nozzle (cf. fig. 4.40), called the cryobending system.

Theoretical description

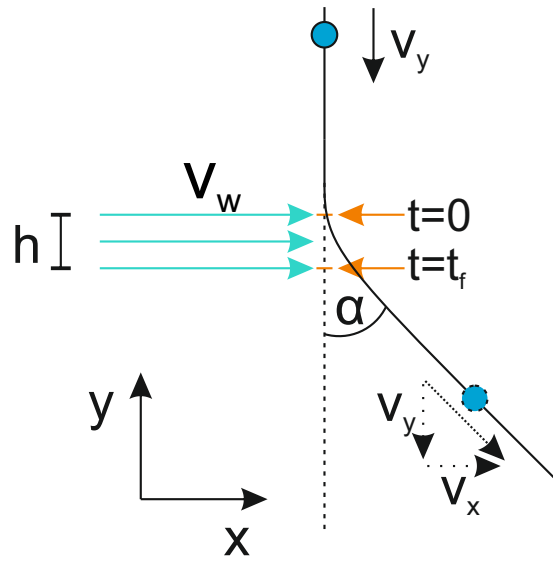


Figure 4.38.: Simplified theoretical model of cryobending. The droplet initially travels downwards with the speed v_y , before its trajectory is bent by wind applying drag force in x-direction. The most important value to be studied here is the bending angle α for which a formula is determined.

To gain insight into the expected behaviour of the cryobending system, a simplified theoretical model is analysed. The target beam is represented by a spherical droplet with a diameter equal to that of the target nozzle which is falling in y-direction with a constant speed v_y (cf. fig. 4.38). At the point of time $t = 0$ the droplet enters the zone of influence of the bending gas, which is modelled as a source of drag force which acts in x-direction with a constant absolute value. The droplet exits the zone at $t = t_f$, while its height is given by h . Through this force, the droplet speed gains a component in x-direction v_x which means that the beam is bent by an angle α . Being able to calculate α is essential to determine whether a bending system is feasible, as knowing

4. Development of cryogenic, hydrogen based droplet targets

it allows for the estimation of the necessary bending gas pressures and nozzle distances.

The equation for drag force F_d is given by [Hall 23]

$$F_d = \frac{1}{2} \rho v_W^2 C_d A \quad (4.32)$$

where ρ is the ambient gas density, v_W the wind speed, C_d the drag coefficient which is assumed to be $C_d = 0.5$ [Hoer 65] for spherical objects and A is the droplet's 2D cross sectional area. With this equation v_x becomes obtainable.

$$F_d = m\dot{v} = \frac{1}{2} \rho v_W^2 C_d A \quad (4.33)$$

here m is the droplet mass and $\dot{v}$ its acceleration in x-direction. Solving for v with the boundary conditions $v(t=0) = 0$ and $v(t=t_f) = v_x$ leads to

$$v_x = \frac{\rho v_W^2 C_d A t_f}{2m} \quad (4.34)$$

t_f is determined via $h = v_y \cdot t_f$ so that

$$v_x = \frac{\rho v_W^2 C_d A h}{2m v_y} \quad (4.35)$$

and

$$\tan(\alpha) = \frac{v_x}{v_y} = \frac{\rho v_W^2 C_d A h}{2m v_y^2}. \quad (4.36)$$

Some of these values such as A and m are easy to calculate while v_y is determined by eq. (4.9). However, there are larger uncertainties concerning ρ and v_W . The latter is dependent on the type of nozzle being used. For these estimations, a de-Laval nozzle was assumed for which [Tasc 13]

$$v_W = \sqrt{\frac{2\kappa}{\kappa - 1} \frac{RT}{M}} \quad (4.37)$$

is valid where κ is the heat capacity ratio ($\kappa = 5/3$ for helium and $\kappa = 7/5$ for hydrogen, both at room temperature [Demt 21]), $R = 8.314 \text{ J/(molK)}$ the molar gas constant [NIST 22b], M the molar mass and T the gas temperature.

To determine the ambient density ρ , the shape of the bending gas beam is of great importance. Again operating under the assumption of using a de Laval nozzle, the beam can be modelled as originating from a point like source and expanding in a cone shape with a divergence determined by the nozzle's opening angle α (cf. fig. 4.39). As will become clear in due course, calculating h is essential in obtaining ρ .

The height h can be calculated via the equation

$$h = s + 2s' \quad (4.38)$$

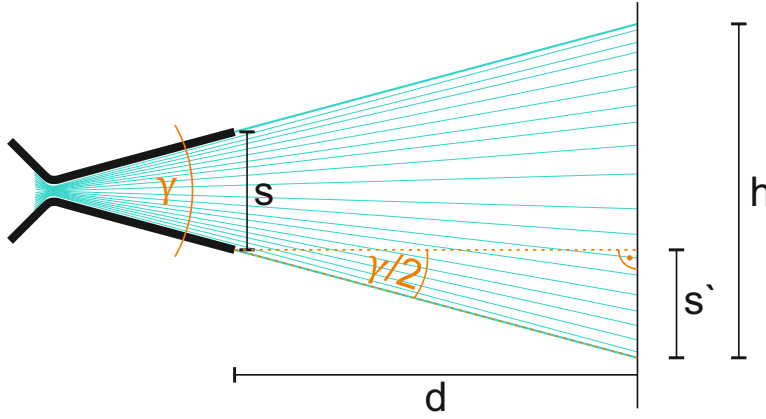


Figure 4.39.: Auxiliary sketch to determine the height h , which depends on the nozzle's exit diameter s and it's opening angle γ .

which follows from geometrical considerations in fig. 4.39. The variable s is the nozzle's inner diameter at its exit while s' is obtained through

$$s' = d \tan(\gamma/2) \quad (4.39)$$

where γ is the nozzle's opening angle and d its distance to the target beam so that

$$h = 2d \tan(\gamma/2) + s. \quad (4.40)$$

The ambient density ρ can now be calculated by dividing the mass flow through the nozzle $\dot{m}$ by the wind speed v_W (cf. eq. (4.37)) and the bending beam's cross section at the interaction region F which is given by $F = \pi h^2/4$, hence the previous focus on determining h . For $\dot{m}$ following equation is valid [Grie 18a]

$$\dot{m} = \frac{q_V M p_N}{R T_N} \quad (4.41)$$

where the new variables p_N and T_N are pressure and temperature under standard conditions and q_V is the volume flow, leading to

$$\rho = \frac{\dot{m}}{v_W F} = \frac{M p_N}{R T_N} \frac{q_V}{v_W \pi h^2/4}. \quad (4.42)$$

Solving eq. (4.16) for q_V leads to

$$q_V = \pi \frac{d_N^2}{4} \frac{p}{\sqrt{M T}} \frac{T_N}{p_N} \left(\frac{2}{\kappa + 1} \right)^{\frac{\kappa+1}{2(\kappa-1)}} \sqrt{\kappa R} \quad (4.43)$$

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with the nozzle diameter d_N . Plugging eq. (4.43) into eq. (4.42) leads to

$$\rho = d_N^2 p \sqrt{\frac{M}{T}} \left(\frac{2}{\kappa + 1} \right)^{\frac{\kappa+1}{2(\kappa-1)}} \sqrt{\frac{\kappa}{R}} \frac{1}{v_W h^2} \quad (4.44)$$

and by inserting eqs. (4.37), (4.40) and (4.44) into eq. (4.36) one obtains

$$\tan \alpha = \frac{C_d A d_N^2}{2 m v_y^2} \left(\frac{2}{\kappa + 1} \right)^{\frac{\kappa+1}{2(\kappa-1)}} \kappa \sqrt{\frac{2}{\kappa - 1}} \frac{p}{2 d \tan(\gamma/2) + s}. \quad (4.45)$$

A can be calculated via $A = \pi r^2$ where r is the droplet radius and the mass m is $m = 4/3 \pi r^3 \cdot \rho_{H2}$. Together with use of eq. (4.9) one can then finally arrive at an expression only containing variables under the experimentalist's control:

$$\tan \alpha = \frac{3}{16} \frac{C_d d_N^2}{r p_{H2}} \left(\frac{2}{\kappa + 1} \right)^{\frac{\kappa+1}{2(\kappa-1)}} \kappa \sqrt{\frac{2}{\kappa - 1}} \frac{p}{2 d \tan(\gamma/2) + s}, \quad (4.46)$$

where C_d is the drag coefficient, d_N the bending gas nozzle diameter, γ its opening angle, s its inner diameter at the exit, d the nozzle's distance to the target beam, κ the heat capacity ratio of the bending gas, p its pressure, r the droplet's radius and p_{H2} the pressure in the target nozzle.

From eq. (4.46) one can see that the bending angle scales linearly with bending gas pressure p (at least for small angles) making it the ideal control parameter, especially since it can be easily varied with a pressure regulator or pressure controller. Furthermore, the calculations reveal that significant bending angles are already achievable with pre-existing nozzles. For example, a typical de-Laval nozzle with a narrowest diameter of $d_N = 100 \mu\text{m}$, an opening angle of $\gamma = 7^\circ$ and an inner exit diameter of $s = 3.5 \text{ mm}$ acting on a hydrogen droplet with a diameter of $10 \mu\text{m}$ at a distance of $d = 2 \text{ cm}$ results in bending angles between 2.5° for an operating pressure of $p = 1 \text{ bar}$ and 17.1° for $p = 7 \text{ bar}$.

To achieve such a simple equation to describe cryobending, significant simplifications have been made. Instead of a hydrogen string, we evaluated a spherical droplet and we made the assumption that the gas is ejected in a cone with a divergence identical to the nozzle's opening angle with constant speed, independent of ejection angle. This is a large simplification, since in general ejection patterns are highly complex, leading to a different divergence as well as gas speed and density, contrary to the above assumption. Nonetheless, the analytical solution provides insight into cryobending's feasibility and helps to determine the most important parameters, which is valuable in designing the experiment. To achieve a better theoretical understanding, CFD simulations of cryobending could be performed which would then include much more realistic gas ejection patterns.

Dependency on gas pressure and gas type

The complete experimental setup for the first iteration of the cryobending system is depicted in fig. 4.40 and the shown measurements were performed in the context of a bachelor's thesis [Hann 24]. A convergent bending nozzle with a diameter of 100 μm injected gas into the interaction vacuum chamber at a distance of 2 cm to the target beam, thus redirecting it. The laser monitor system was installed underneath and used to determine the stability of the bent beam.

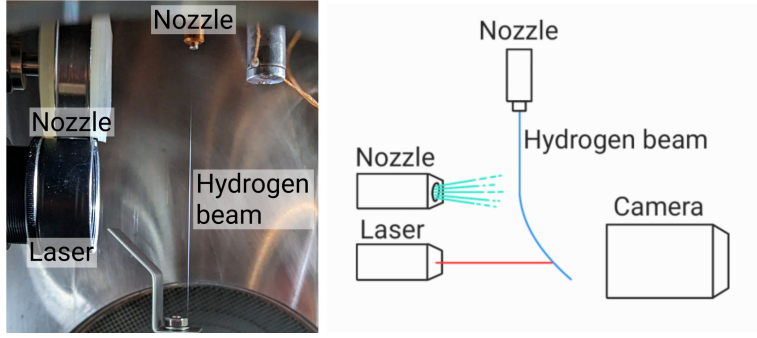


Figure 4.40.: The experimental setup for the cryobending system tests. Gas flowing through the secondary nozzle bends the beam to the right while the laser monitoring system underneath is used to determine its stability. (Taken from [Hann 24])

Two gases were used for bending, hydrogen and helium, the only elements which are not solid at target operation conditions. For helium, the gas pressure p_{He} was varied between 1 bar and 7 bar and pictures were taken for each pressure (cf. fig. 4.42). At higher pressures, one can readily recognise the strong impact of the cryobending system. To achieve a more quantitative understanding, the bending angles were determined by aligning two tangents to the target beam, one in the original direction and one in the direction after bending (cf. fig. 4.41). The angle α between the two can be determined by their slopes m_1 and m_2 according to

$$\alpha = \arctan \left(\left| \frac{m_1 - m_2}{1 + m_1 m_2} \right| \right). \quad (4.47)$$



Figure 4.41.: Determination of bending angles through aligning tangents to the beam. [Hann 24]

The results are shown in table 4.3. Most importantly, the measurement confirms the theoretical prediction that large bending angles over 10° can be achieved at moderate gas pressures of over 5 bar. This is important, as higher pressures massively increase interaction chamber pressure from $9.2 \cdot 10^{-4}$ mbar without bending to $5.1 \cdot 10^{-2}$ mbar for $p_{\text{He}} = 7$ bar [Hann 24], which is close to the maximum operating pressures of the turbo pumps. The measurements were repeated for

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Table 4.3.: Bending angles in dependence of pressure at a distance of 2 cm between bending nozzle and target beam. (Experimental data taken from [Hann 24])

He pressure p_{He} in bar	Angle α in $^\circ$	th. prediction in $^\circ$
1.0 ± 0.5	1.9 ± 0.2	3.5
2.0 ± 0.5	3.0 ± 0.2	7.0
3.0 ± 0.5	7.1 ± 0.2	10.5
4.0 ± 0.5	8.2 ± 0.2	13.8
5.0 ± 0.5	12.3 ± 0.2	17.1
6.0 ± 0.5	21.9 ± 0.2	20.3
7.0 ± 0.5	27.0 ± 0.2	23.3

distances d of 3 cm and 5 cm, yielding decreasing bending angles at constant pressures (cf. table E.1) as expected.

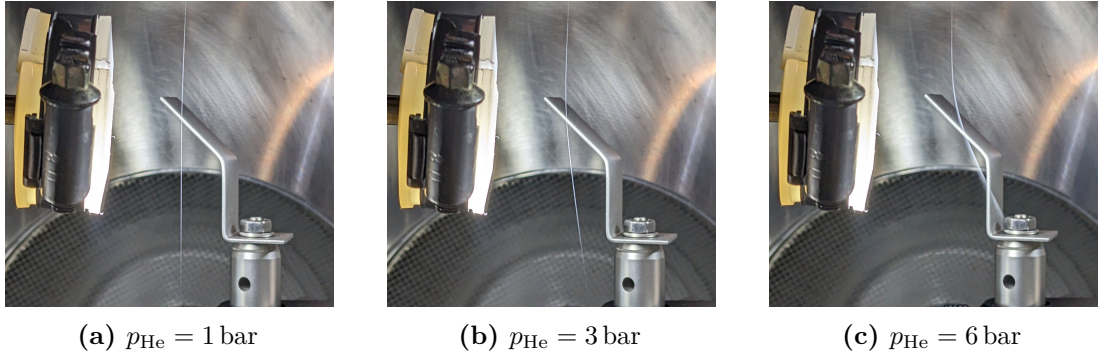


Figure 4.42.: The effect of the cryobending system on the target beam in dependence of the helium gas pressure p_{He} . (Taken from [Hann 24]).

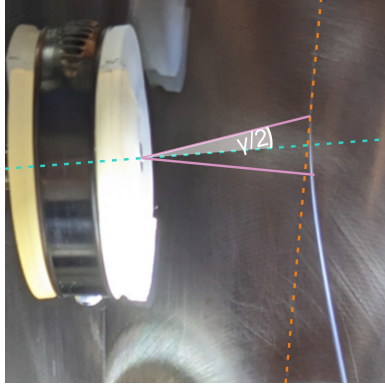


Figure 4.43.: Determining the bending beam's opening angle.

To enable a more substantial comparison between experimental values and calculations than the extremely brief one afforded above, the convergent nozzle geometry needs to be taken into account. The speed achieved by gas flowing through a convergent nozzle (v_W) is described by [Rao 21]

$$v_W = \sqrt{\frac{2\kappa}{\kappa - 1} \frac{RT}{M} \left(1 - \left(\frac{p_e}{p} \right)^{\frac{\kappa-1}{\kappa}} \right)} \quad (4.48)$$

where the only new variable is P_e , the ambient pressure at the nozzle exit. Since $p_e \ll p$ the equation becomes identical to the equivalent expression for the de-Laval nozzle (cf. eq. (4.37)). The only other factors which change due to the different geometry are the inner diameter at the exit s and the beam's

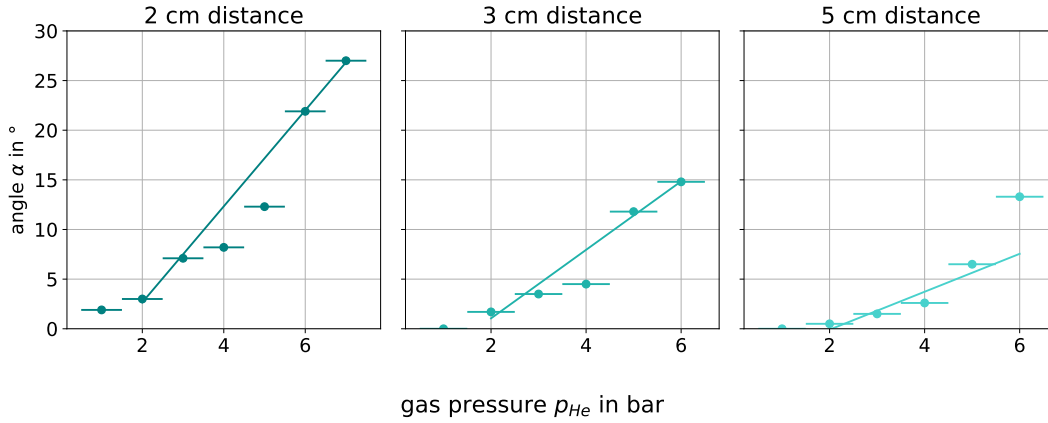


Figure 4.44.: The change of bending angle in dependence of pressure at different distances between nozzle and target beam. While a linear trend can be seen as anticipated, there are still significant deviations which could stem from both limitations of the experimental setup as well as gas ejection patterns changing in dependence of pressure, leading to the observed non-linearities. The uncertainties of the angles are included but too small to be resolved. (Experimental data taken from [Hann 24])

opening angle γ . The former becomes $s = 100 \mu\text{m}$ as in a convergent nozzle the narrowest inner diameter also marks its exit, while the other was determined by visually estimating the point at which bending commences and drawing a line between it and the nozzle's centre (pink line in fig. 4.43). The half opening angle $\gamma/2$ is then determined by this line and the direction the nozzle is pointing (cf. turquoise line in fig. 4.43), which results in $\gamma = (11.8 \pm 0.2)^\circ$.

The theoretical values thus obtained are shown alongside the experimental ones in tables 4.3 and E.1, matching surprisingly well to each other, if one considers the large amount of simplifications which have been made. The predicted linear increase with pressure can also be observed in fig. 4.44, albeit with reservations. For example, the data point at 1 bar for each measurement shows a non-linear relationship to the others, which could be explained by the bending beam behaving differently at lower pressures, however, there are also other points (4 bar and 5 bar at 2 cm distance or 4 bar at 5 cm distance) which do not follow a linear trend. While this behaviour might also be explained by complex changes in the bending beam's shape and divergence, it could also be due to the experimental setup. For these pilot measurements, the bending gas pressure was regulated using an analogue pressure regulator designed for pressure ranges in the tens of bar, thus offering only limited accuracy in the considered pressure range which could already be enough to explain the non-linearities.

In addition, the calculations predict that the bending angle will increase when using hydrogen instead of helium as bending gas (cf. table 4.4). This behaviour is confirmed experimentally, however, the effect is larger than anticipated. A hydrogen pressure of (0.5 ± 0.5) bar is already enough to effect an angle α of $(5.0 \pm 0.2)^\circ$, which is only achieved with helium by increasing the pressure to over 4 bar. This large impact is an

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Table 4.4.: Bending angles in dependence of pressure at varying distances d between bending nozzle and target beam. In this case hydrogen is used for bending. In addition to the theoretical predictions for hydrogen, theoretical values for helium are shown to demonstrate the gas dependent change in bending angle. (Experimental data taken from [Hann 24])

p_{H_2} in bar	d in cm	α in $^\circ$	Th. pred. (H_2) in $^\circ$	Th. pred. (He) in $^\circ$
0.5 ± 0.5	3.0 ± 0.1	5.0 ± 0.2	1.3	1.2
1.0 ± 0.5	3.0 ± 0.1	6.5 ± 0.2	2.6	2.4
0.5 ± 0.5	5.0 ± 0.1	2.0 ± 0.2	0.8	0.7
1.0 ± 0.5	5.1 ± 0.1	2.5 ± 0.2	1.6	1.4

indicator that the beam shape of the bending gas might change substantially when using different gases as it is the only assumption which could introduce such a strong gas type dependency. Unfortunately, this effect could not be studied for larger bending pressures, as the vacuum pumps have such low pumping speeds and compressions for hydrogen that higher pressures would have resulted in untenable vacuum conditions.

Influence of cryobending on target beam stability

While the achieved bending angles are already very encouraging, it is essential that the target beam is not destabilised through bending. To verify that this is not the case, the laser monitoring system as depicted in fig. 4.40 was used to determine cryobending's influence on beam stability.

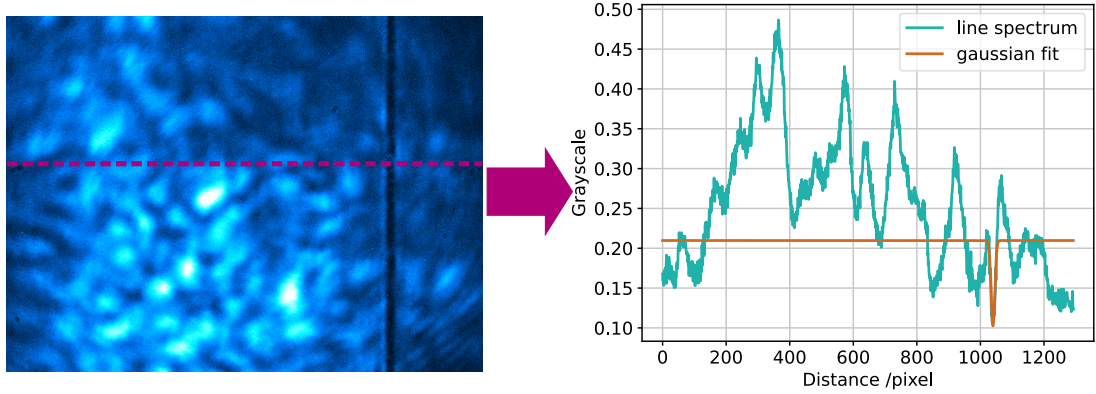


Figure 4.45.: Determination of the beam position. A line spectrum is taken, where the deepest minimum (usually) corresponds with the beam position. This minimum is then fitted with a gaussian function, revealing the beam position. This data was first analysed in [Hann 24]

To do so, 100 pictures of the target beam were taken within 10s at various bending gas pressures. For each picture, the beam position was determined by taking the intensity profile running along a horizontal line over its entirety (cf. fig. 4.45). Usually,

the deepest minimum corresponds with the beam's position which is thus determined by fitting a Gauss curve [Zeid 13]:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (4.49)$$

where μ and σ^2 the distribution's mean and variance, the former representing the beam's position. Plotting all the means over time results in plots such as in the left

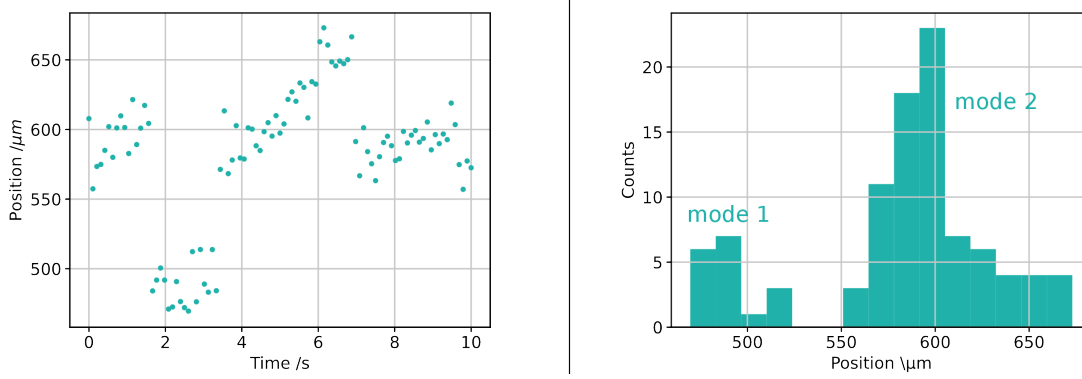


Figure 4.46.: **Left:** Beam fluctuation over time of a target beam without any bending. (Taken from [Hann 24]) **Right:** Histogram of the left plot. The two modes between which the beam switches are clearly visible.

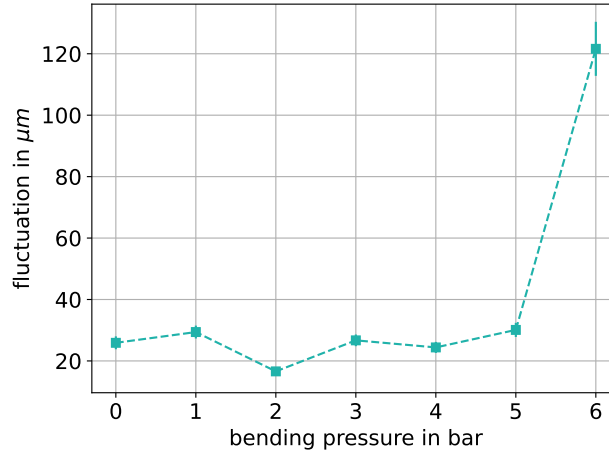


Figure 4.47.: Fluctuation of the target beam in dependence of bending gas pressure. Up until a pressure of 6 bar is applied, the beam remains remarkably stable. (The data which was used to determine the fluctuations first appeared in [Hann 24])

of fig. 4.46 which shows the target beam's fluctuation over time without bending. By taking the standard deviation over all beam positions one can then obtain a numerical

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value for the fluctuation and thus an expression for beam stability. Interestingly, in the histogram on the right of fig. 4.46 one can see two distinct "modes" between which the beam switches. These jumps (and generally higher instability) are often observed shortly after the target achieves fluid conditions, with their frequency diminishing over a time period of around an hour. Probably, they are caused by the various target components slowly reaching their equilibrium temperature, however, since the impact on target operation is minimal, this effect is currently classified as a curiosity. To obtain a meaningful standard deviation, the data points where the beam is in mode 1 are omitted.

For all the other measurements at different bending pressures (cf. fig. E.1), no mode jumping was observed and the resultant fluctuations can be seen in fig. 4.47. Up until a pressure of 6 bar, the beam's stability remains stable with values better than 30 μm . This is an excellent result, as it means that over a wide range of the available parameter space, cryobending has no discernible influence on the target beam.

Through the intercept theorem, the fluctuations can be extrapolated to $\bar{\text{PANDA}}$ conditions. The laser is located around 3.8 cm under the nozzle, while at $\bar{\text{PANDA}}$ the distance to the interaction point will be 2.25 m. Assuming a fluctuation of 30 μm at 3.8 cm, this results in an effective target diameter of 1.8 mm at 2.25 m, much smaller than the cluster-jet target which sits at around 1.5 cm [Bran 24].

4.4.6. Analysis of nozzle impurities

As alluded to in section 4.3.3, nozzle clogging was a substantial challenge, which greatly slowed down experimental progress. Combatting this issue has proven challenging, not least because the material of the impurities is unknown and thus the choice of counter measures is based more on assumptions than on evidence. To finally change this, analytical microscope techniques were successfully applied.

Raman microscopy

The basic idea of Raman microscopy is to take advantage of inelastic light scattering processes.

In the energy band model, when light scatters on a molecule, the incident photon is absorbed and the molecule enters a virtual excited state before ultimately de-exciting and emitting a photon [Lark 17]. In the case of Rayleigh scattering, the emitted photon (λ_{em}) has the same wavelength as the original one (λ_{in}) and thus the process is elastic (cf. fig. 4.48a). However, instead of relaxing back into the ground state, the molecule can instead enter an excited vibration state. Thus, the scattered light is red shifted ($\lambda_{\text{in}} < \lambda_{\text{em}}$) in this process which is called Raman-Stokes scattering (cf. fig. 4.48b). Should the incidental photon scatter on a molecule which is already in the excited state, the emitted light is blue shifted ($\lambda_{\text{in}} > \lambda_{\text{em}}$), in a process called Raman-Anti-Stokes scattering (cf. fig. 4.48c).

The exact wavelength of the scattered Raman(-Anti)-Stokes light depends on the properties of the molecular bonds, such as which elements participate, the type of bond

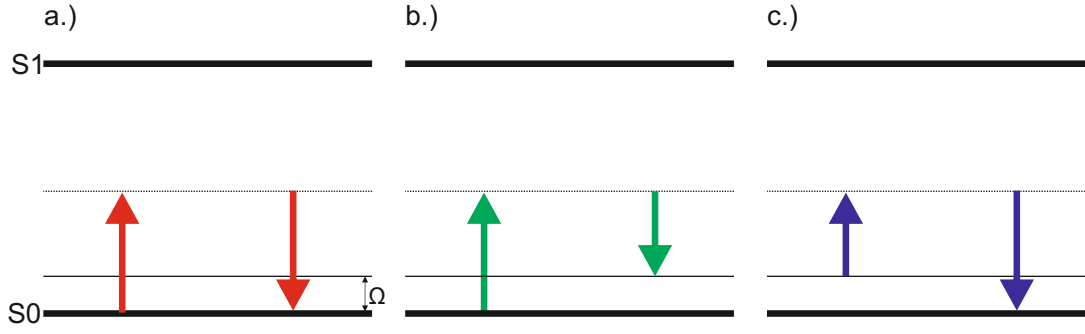


Figure 4.48.: Scattering processes as described in the energy band model. For Rayleigh scattering (cf. a.)), the incident and emitted light have identical wavelengths, while for Raman-Stokes scattering (b.)) and Raman-Anti-Stokes scattering (c.)) the light is red shifted and blue shifted, respectively. (Taken from [Mann 16])

(for example single or double bond) or which form the vibration takes (for example stretch or shear vibration). As a result, the scattered light is not monochromatic like Rayleigh scattered light, but instead is a spectrum. Since the wavelength of the emitted light is dependent on the incident light, wavelength is not a good parameter to use on the abscissa of the spectrum if one aims to preserve comparability between different experiments. Instead, wave number is often used. This value is defined as $w = 1/\lambda_{\text{in}} - 1/\lambda_{\text{em}}$ and makes the spectrum independent of incident wavelength.

While in theory both types of inelastic scattering can be used, Raman-Stokes light was used in this particular experiment as it appears considerably more often than Raman-Anti-Stokes scattering [Schr 08], but still with a probability six orders of magnitude lower than Rayleigh scattering [Smit 19], necessitating highly sensitive sensors.

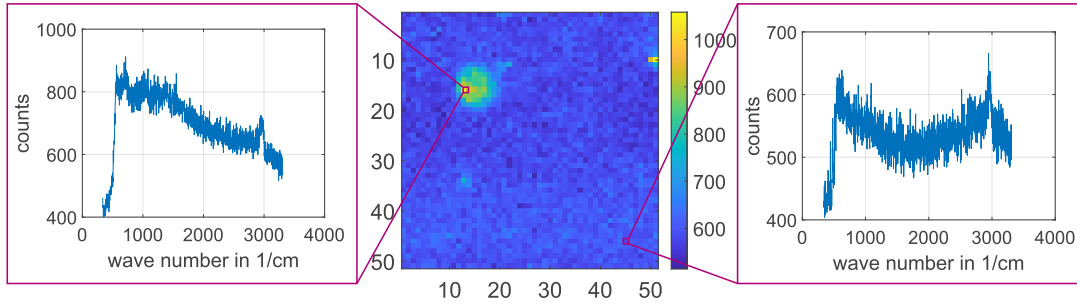


Figure 4.49.: Results of the Raman microscopy measurements. As the Raman spectra in the blocked nozzle are significantly different from the ones outside of it, the nozzle region becomes clearly visible in the heat map. Nonetheless, due to the featureless spectra, exact identification of the blockage material is not possible. (This data first appeared in [Mann 23])

For our experiment, we used a self built Raman microscope of the Fallnich work group of the University of Münster. It operates as a laser scanning microscope, where

4. Development of cryogenic, hydrogen based droplet targets

a focussed laser scanned one of our blocked nozzles in $1\text{ }\mu\text{m}$ steps. At each one, the Raman-Stokes light was collected, creating a map of our nozzle which can be used to detect the location of various materials on its surface. The results are shown in fig. 4.49. The colour map in the middle depicts the spatial intensity at the wave number $w = 560$ which leaves the blocked nozzle opening clearly visible. As can be seen in the two sample spectra, there is a clearly different material in the nozzle opening, compared to the surrounding area, however, as the spectra are devoid of any characteristic peaks, the material blocking the nozzle is unidentifiable. Nonetheless, these broad non-specific spectra are sometimes seen for metals (for example platinum [Scot]) which is a hint for further investigations.

Energy dispersive electron microscopy

Since the exact nature of the blockage was unidentifiable with Raman microscopy, identification with a different technology was attempted: a scanning electron microscope (SEM) with an energy dispersive X-ray module (EDX).

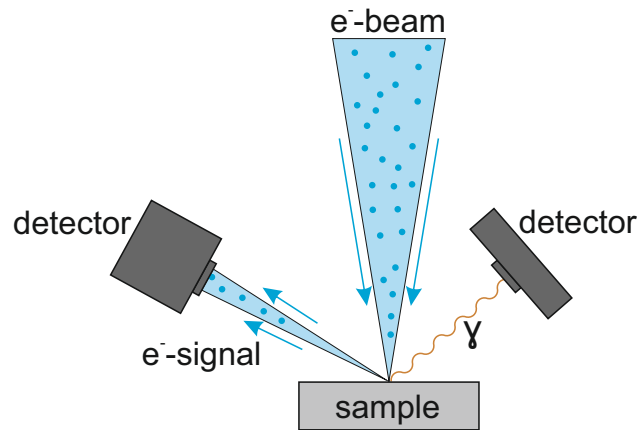


Figure 4.50.: The functioning principle of an SEM with EDX module. The electron beam scans the sample, thus creating secondary electrons which are used to gain a picture. At the same time, characteristic X-ray radiation is also created which can be used for sample identification.

In an SEM a focussed electron beam scans the specimen (cf. fig. 4.50). At the focus point, this beam creates secondary electrons through inelastic scattering processes which are then detected. As the scan progresses, the amount of secondary electrons varies due to the sample's geometry and material, providing contrast and ultimately a picture [Mich 19].

One of the ways to create secondary electrons is for the primary electron beam to remove an electron from one of the atom's inner shells. This vacancy is quickly filled, for example by an electron from an outer shell, and the released energy is used to create an X-ray photon or an Auger electron [Knol 10], the latter of which is not relevant here. The photon energy depends on the energy difference between the participating shells

which in turn depends on the atom's element, so that measuring the X-ray spectrum (cf. fig. 4.50) can identify the material, a technique called EDX.

For our blockage analysis we used a Hitachi S-4000 SEM with a Bruker X-Flash 4010 EDX module which we focussed onto one of our blocked nozzles. A result of such an analysis can be seen in fig. 4.51. On the left, one can see an electron microscopic image

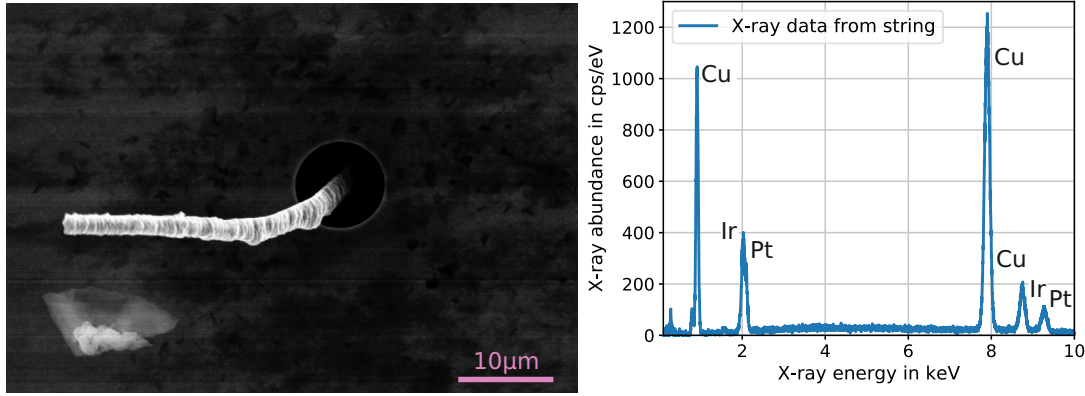


Figure 4.51.: **Left:** Electron microscope image of the nozzle aperture. A piece of "string" obstructing it is clearly visible. **Right:** The X-ray spectrum obtained when focussing on the "string". Apart from platinum and iridium signals stemming from the nozzle, copper signals are also clearly visible.

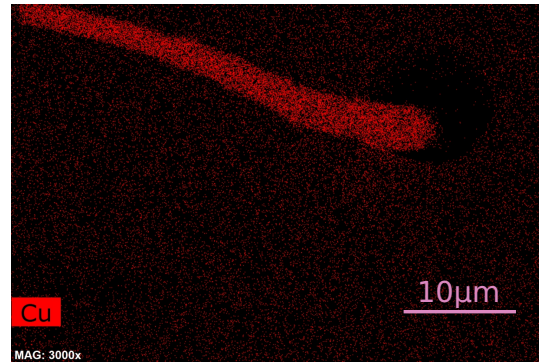


Figure 4.52.: Electron microscope image of the nozzle. In this picture, the colour red indicates wherever copper is found, revealing a strong signal stemming from the "string". Seemingly, copper can be found also in most other areas of the nozzle, however, this is just due to electrons from the incident electron beam scattering off the platinum/iridium surface and then hitting the copper string where they finally generate X-rays. Thus a copper signal is created which is misattributed to the spot where the electron beam first impacts the nozzle.

of the nozzle's aperture and very clearly how a string-like foreign object is blocking it. By focussing on the string and running the EDX module one gains the spectrum on the right, with the X-ray energy on the abscissa and the abundance on the ordinate.

4. Development of cryogenic, hydrogen based droplet targets

The abundance is given in units of counts per second divided by the detector energy resolution, which is used to make spectra generated by different machines comparable. Apart from platinum and iridium, the materials the nozzle is made from, one can also see peaks stemming from copper, and indeed, the spatial distribution of the elements clearly shows that the string is made of copper (cf. fig. 4.52). Most likely this object was a shaving left over from machining the nozzle, highlighting the need to thoroughly clean them before installation.

Unfortunately, not every blockage is analysable in such a fashion. Often, they are located too deep in the nozzle for us to acquire an EDX signal so that the statistics on the types of materials found in nozzles remain relatively slim. However, the analysis of other blocked nozzles has turned up sodium oxides and carbon (cf. appendix E.3) as well as calcium [Hann 24], suggesting that the blockages often stem from dirt and dust which remain in the gas system even after cleaning.

4.4.7. Longterm target stability

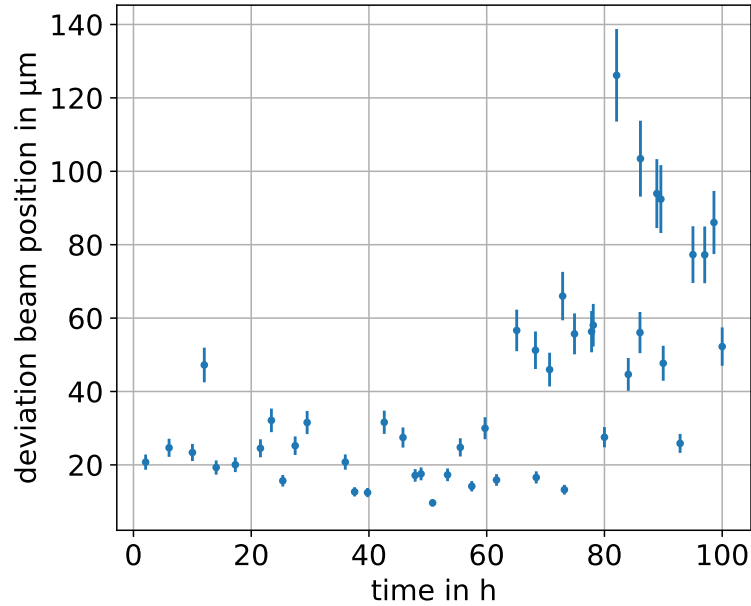


Figure 4.53.: The target beam deviation over time. Until 60 h the target remains stable after which the fluctuations begin increasing. (Analysis performed by J. Froning)

As concluded above, dirt and dust are likely the chief culprits blocking the nozzles. Fortunately, MDT-H was designed with this in mind, being the first hydrogen based target built in Münster to feature a modular gas system and to be cleaned with a specialised cleaning solution (JE 25 [Jent 19]). Instantly, this target was more reliable than MDT-D, enabling us to perform studies on its long term stability.

To do so, MDT-H was operated continuously for over 100 h at target conditions of $T_{CS} = 16$ K and $P_{gas} = 1.2$ bar, without use of the cryobending system. Every two

hours, 100 pictures of the beam were taken over a time period of 25 s and the beam stability calculated as detailed in section 4.4.5. The results are depicted in fig. 4.53 where the strength of fluctuation is shown against time.

Until around 60 h, the deviation remains in a plateau before it starts to increase. Unfortunately, the measurement did not run long enough to verify whether the fluctuation has reached a new plateau or if it would have increased further over time.

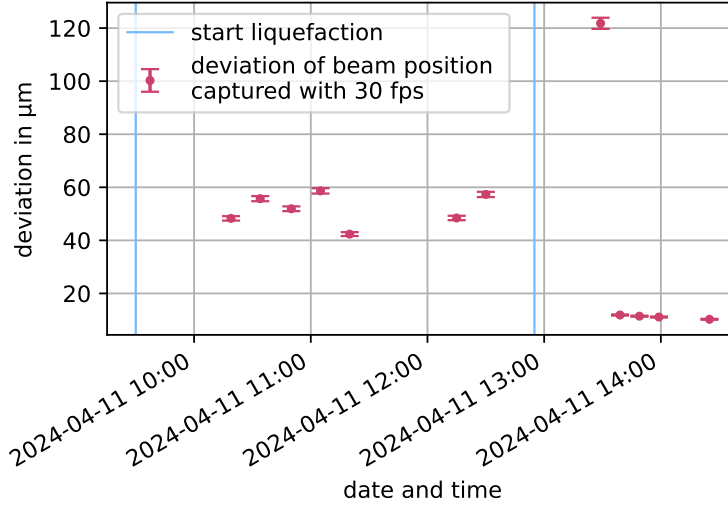


Figure 4.54.: The target deviation over time. At first the fluctuation is at around 50 μm but after warming up the target to stand-by conditions and then cooling it back down again (signified by the blue line), the stability could be greatly improved. Generated by E.-M. Hausch

The increase in instability over time is of course undesirable. To conclusively understand and combat it requires much more statistics concerning long term operation. To more easily facilitate more and longer measurements, in future more advanced safety features should be considered to nullify the need for constant target supervision, such as, for example, installing pressure relief valves should the cooling system fail and large amounts of hydrogen suddenly vaporise. First efforts in exploring the target's stability have shown that returning the target to stand-by conditions ($T_{CS} = 50\text{ K}$ and $P_{\text{gas}} = 2\text{ bar}$) and then returning to operation conditions can increase stability. This is seen in fig. 4.54, where the target beam deviation is shown over time. First the beam shows a fluctuation of around 50 μm at target conditions of $T_{CS} = 16\text{ K}$ and $P_{\text{gas}} = 1.2\text{ bar}$. Then the target is warmed up to standby conditions before being returned to the previous ones, as signified by the blue line in fig. 4.54. At first it is noticeably more unstable, which is normal as alluded to in section 4.4.5, but soon after it settles down to an excellent stability well below 20 μm . Thus it is shown how the target can be "regenerated". A possible solution to the instability could be to perform such a regeneration every few dozens of hours, which could be done during brief accelerator down times as the time needed for regeneration can be shortened to around 30 min.

4.4.8. Conclusion and outlook concerning the droplet target systems

In this chapter two droplet target systems were presented, MDT-D and MDT-H, as well as the experimental results of each. MDT-D represents the first attempt of adapting a former cluster-jet target for use as a droplet target and thus experienced many growing pains. Despite all of our efforts, large difficulties remained in achieving sufficiently low temperatures for a hydrogen beam (cf. section 4.3.3) while constant nozzle clogging greatly hindered and slowed down progress.

After switching to MDT-H these issues vanished quickly. There were no problems concerning temperature from the start (cf. section 4.4.2), most likely due to improved contact between individual copper components and soon it turned out that nozzle clogging issues were also much reduced. Instead of having to clean the nozzle twice a week, we could now continuously use the same nozzle for over a month on average. With such improved conditions, fast progress could be made.

We determined the target's resonant vibration modes to facilitate droplet break up (cf. section 4.4.3), however, no droplets have been observed up to now. The reason for this is that the hydrogen beam freezes out near instantly (tens of ps [Weid 23]) after leaving the nozzle [Gris 18], which is insufficient time for break up to occur as already observed in [Frag 15]. Nonetheless we performed our own investigations using a simple bouncing plate setup (cf. section 4.4.4) and verified these previous results. A possibility to achieve droplet generation with the existing system would be to repair the co-flowing system, which is currently out of service due to cryo-leak issues (cf. section 4.2.2).

Although no droplets have been produced yet, progress could be achieved in other areas. As alluded to above, the MDT-H runs much more stably than his predecessor. This enabled us to study its performance under conditions more alike to the ones found at particle accelerators, which in practice means continuous operation in the order of days (cf. section 4.4.6). During this experiment, the target produced a beam without any interruption, demonstrating its suitability for accelerator experiments, however after around 60 h the beam started fluctuating more. To properly understand and combat this behaviour, more long term operation experience is necessary which in turn requires the target setup to be adjusted so that it can run permanently without on-site supervision. Nonetheless, we could already identify procedures which can be used to regain stability with minimal downtime.

Previous hydrogen beam targets have been reliant on complex mechanical systems to control the beam direction [Grie 18a, Winn 11]. Instead, we have pioneered a novel system called cryobending, where the beam is blown into the desired direction by helium gas injected into the vacuum chamber through nozzles (cf. section 4.4.5). First experimental studies have shown that the necessary nozzles and gas pressures for significant bending angles are easily obtainable, without overly straining the vacuum conditions and still maintaining target stability. Thus, this innovation holds great potential, in future it could be used not only to change the beam's direction, but also to enable complete control over it (cf. fig. 4.55). This could be utilised to realise powerful diagnostic functions, such as determining the exact position and size of an accelerator beam at the interaction point by varying the target beam position while monitoring

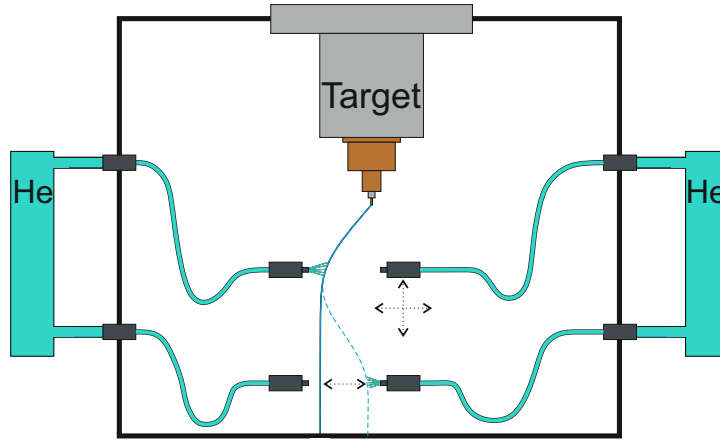


Figure 4.55.: Sketch of a future bending system. By installing two arrays of nozzles on top of each other, the target beam can not only redirected, but its entire positioning controlled. In addition to the nozzles shown here, there will be two more per array, located perpendicular to the image plane.

the reaction rate.

Now that target stability has been demonstrated and the proof of principle for a novel target beam control system has been delivered, the next step is to try to control the target over long distances, especially considering its later application at $\bar{\text{PANDA}}$, where the nozzle will be located over 2 m away from the interaction point. To this end, the vacuum chamber the target is mounted on will be lengthened until $\bar{\text{PANDA}}$'s nozzle to IP distance can be recreated. Then, using the laser monitoring system as well as a more advanced bending system, the target's performance under these more challenging conditions can be studied and necessary adjustments as well as innovations made to suit $\bar{\text{PANDA}}$'s needs.

However, one should keep in mind that MDT-H will not be installed at $\bar{\text{PANDA}}$. In future, there will be renewed efforts to transform a cluster-jet target into a reliable droplet target. This will require applying the lessons learnt from the first attempt. Special attention will have to be paid towards guaranteeing a strong thermal connection between individual parts and one should consider cleaning the gas system with a specialised cleaning solution like JE 25 [Jent 19] before target installation. The work on MDT-H has shown how reliable, stable droplet targets can be constructed which will help immensely when the idea of a combined target system is revisited.

5. Proton acceleration by laser-cluster interaction

Plasmas are highly relevant for use in future particle accelerator experiments as they can sustain electric field strengths of $> 100 \text{ GeV/m}$ [Yano 08] which greatly exceeds current capabilities of several tens of MeV/m in classical accelerators. Thus plasmas provide great potential in miniaturising accelerator facilities, possibly enabling more widespread use outside of particle physics, for example in radiation therapy or industrial research.

To investigate new avenues for proton acceleration, the cluster-jet beam produced by the MCT-D target was illuminated with a high powered laser beam exceeding an intensity of $1 \cdot 10^{20} \text{ W/cm}^2$, produced by the ARCTURUS laser facility of the HHU Düsseldorf [Cerc 19]. When the laser hits a hydrogen cluster, it strips it of its electrons, resulting in a proton plasma which subsequently explodes due to Coulomb repulsion, thus accelerating protons to energies up to several MeV. Similar results have previously been reported [Jinn 22], however their hydrogen cluster-jet target operates at temperatures and pressures of 25 K and 60 bar with a nozzle diameter of $250 \mu\text{m}$. This results in a gas flow of over $900 \text{ l}_n/\text{min}$ which can only be sustained by pulsed target operation. By contrast, our target only causes a flow of several l_n/min , enabling continuous operation and taking advantage of ARCTURUS' high frequency of 5 Hz [Cerc 19].

This chapter introduces the necessary physics to understand the generation of such high powered laser beams and how they interact with atoms to create a plasma, as well as the exact process leading to the proton acceleration. The ARCTURUS laser is described, which is the central component of this experiment alongside the MCT-D. Most importantly, the measurements and their analysis are explained in detail, before perspectives are given on how to achieve a better stability and higher energies.

All of the experiments presented below were performed in cooperation with the group of Prof. Dr. O. Willi from the HHU Düsseldorf, without whose expertise and tireless efforts they would not have been possible.

5.1. Generation of high powered laser beams

There are two necessary components to high powered laser beams. The generation of a seed pulse through a mode locked laser and its subsequent amplification. Here, both of these steps will be discussed.

5. Proton acceleration by laser-cluster interaction

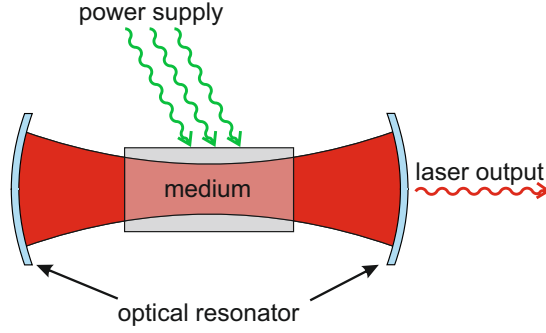


Figure 5.1.: The laser principle. A power supply pumps a medium which emits light. Through an optical resonator, the light is repeatedly fed through the medium, creating laser light.

5.1.1. Generation of mode-locked laser beams

In general a laser requires three components [Sale 08]. A gain medium, for example some form of crystal, an optical resonator, for example two mirrors, and a power supply, for example light or electricity, all arranged as shown in fig. 5.1. The power supply excites the atoms of the gain medium, which is also called pumping the medium. Incident light with the correct wavelength can de-excite an atom, creating a second photon with the same wavelength and phase as the original one (cf. fig. 5.2). Through the resonator, this light is returned to the gain medium which provides a steady supply of excited atoms for the light to interact with, amplifying it until an equilibrium state between gain and losses is reached. Here, the largest source of loss is the intentional partial transmissivity of one of the resonator mirrors, through which the coherent laser light can exit and be of further use.

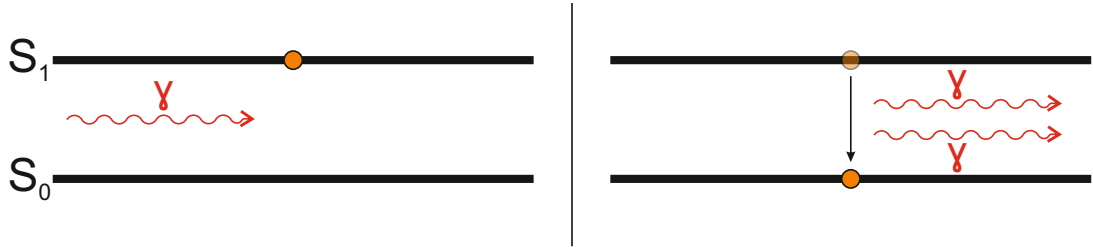


Figure 5.2.: The principle of stimulated emission shown in the energy band model. An excited atom is de-excited by a passing photon. Thus a second photon is emitted with the same wavelength and phase as the original one.

Often, lasers do not have a single possible wavelength, also called (longitudinal) mode, but have the choice of several, each spectrally separated by the resonance condition $\nu_F = \frac{c}{2d}$, where c is the speed of light and d is the resonator length. When these modes interfere while all possessing a constant phase relation to each other (so they are "mode-locked"), they will interfere destructively most of the time, however there

5.1. Generation of high powered laser beams

will be periodic moments in time when they interfere constructively, resulting in short, intense pulses of laser light. Mathematically, the resultant intensity I can be calculated according to [Sale 08]

$$I(t, z) = |A|^2 \frac{\sin^2(M\pi(t - z)c/T_F)}{\sin^2(\pi(t - z)c/T_F)} \quad (5.1)$$

where $|A|$ is a pre-factor, M the amount of modes, t is time, z the location in laser propagation direction and T_F the inverse of ν_F .

The resulting intensity curve is shown in fig. 5.3. Most notably, the length of the pulse decreases sharply with an increase of modes, while the intensity amplitude scales according to $I = M\bar{I}$, where $\bar{I}$ is the median intensity.

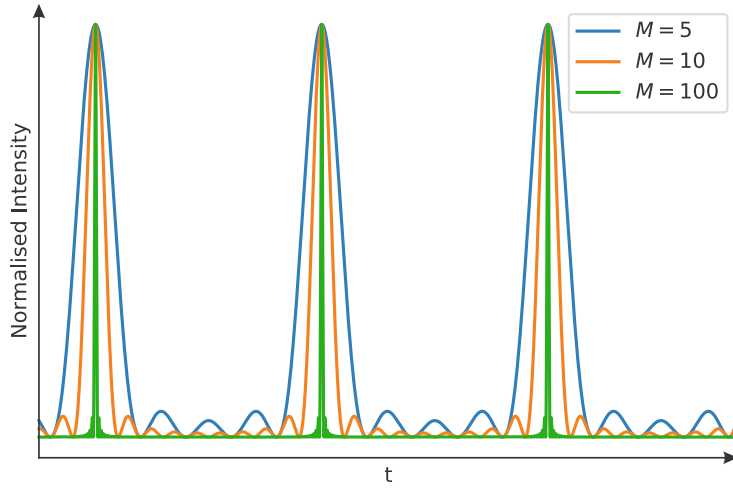


Figure 5.3.: Graphical depiction of mode-locking. With an increase of modes, the resultant pulses decrease in length. Additionally, the amplitude also increases, which is not shown here. (Taken from [Mann 19])

To create such a mode-locked laser in practice, one requires a laser medium with a broad amplification bandwidth such as a Ti:Sa crystal with a width of 100 THz [Sale 08]. To induce mode locking, the laser light can be amplitude modulated with the frequency ν_F , thus introducing side bands into the frequency spectrum with equal phase as the original frequency. These bands are subsequently amplified by the medium so that the amplitude modulation then also starts acting on them, creating further mode-locked frequencies until the entire bandwidth is used and laser pulses down to a width of only a few fs are emitted [Sale 08].

5.1.2. Basics of chirped pulse amplification

The basic procedure to amplify a laser beam is to let it pass through a pumped laser medium several times until it is depleted. However, this method reaches its limits when

5. Proton acceleration by laser-cluster interaction

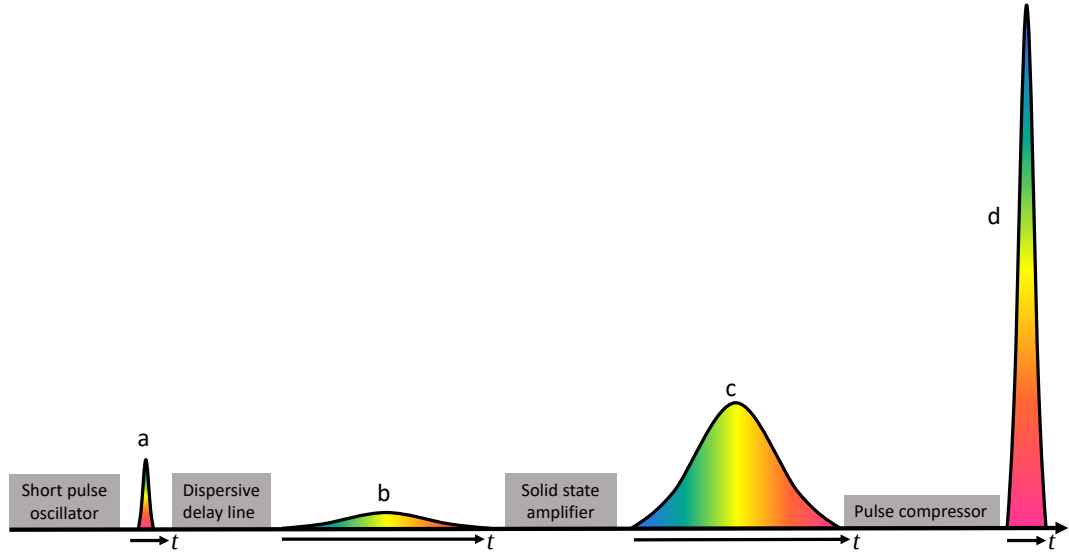


Figure 5.4.: The functioning principle of CPA. The pulse is expanded in time, amplified and then recompressed to its original length, achieving a higher grade of amplification than otherwise possible. (Taken from [Mann 19], adapted from [Treb 18])

the amplified beam achieves sufficient energies to destroy the gain medium.

The solution is chirped pulse amplification [Stri 85]. First, the pulse is stretched in time, for example by a diffraction grating, then this "chirped" pulse is amplified to high energies by a strongly pumped laser medium, or even a series of mediums, before finally being compressed to its original length, for example by another diffraction grating, which grants it a boost in peak power. This method can be further enhanced by expanding the beam diameter, thus minimising beam intensity and allowing for even higher amplifications.

With this method, high power laser systems seeded by Ti:Sa oscillators have reached intensities in excess of $1 \cdot 10^{23} \text{ W/cm}^2$ [Yoon 21].

5.2. Interaction of high powered laser pulses with hydrogen clusters

The laser pulses interact with the hydrogen atoms contained in the clusters, ionising them and thus creating a plasma. This plasma subsequently explodes via Coulomb explosion, isotropically accelerating protons.

In this section, these interactions are explored in more detail to explain the necessary laser and cluster characteristics for effective proton acceleration.

5.2.1. Ionisation through high powered laser beams

When a high power laser pulse hits a cluster, the first thing to happen is for the cluster to be ionised. At the high intensities of the ARCTURUS laser beam ($>1 \cdot 10^{20} \text{ W/cm}^2$ [Cerc 19]) two ionisation schemes dominate: multi photon ionisation and tunnelling ionisation.

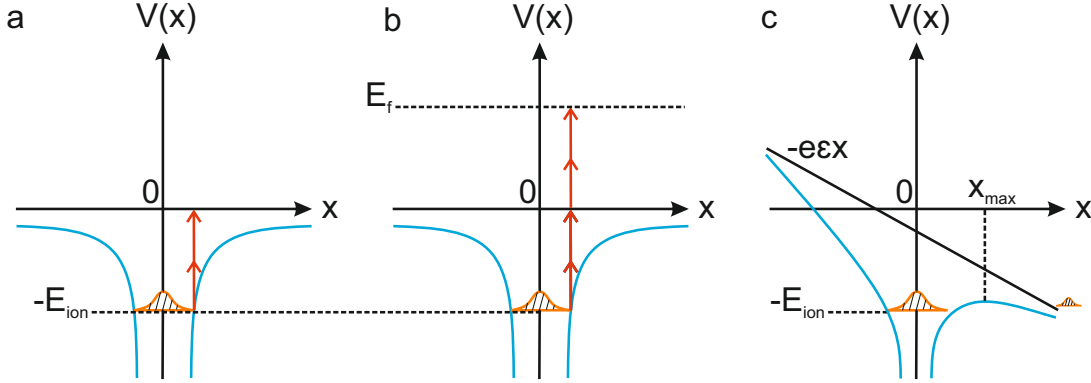


Figure 5.5.: Schematic depiction of several ionisation schemes available with high powered laser systems. **Left:** Multiple photons are absorbed simultaneously, so that the atom is ionised (MPI). **Middle:** If more photons are absorbed than strictly necessary, the excess energy is transformed into the ejected electron's kinetic energy (ATI). **Right:** At sufficiently high light intensities, the atomic potential (blue line) is distorted by the laser field (black line), resulting in the possibility of an electron escaping through quantum tunnelling. (Adapted from [Grie 18a], based on [Gibb 05])

Multi photon ionisation

A well known ionisation scheme is the photoelectric effect, where a photon is absorbed by an atom and an electron is ejected [Knol 10]. A necessary requisite for this process to happen, is that the incident photon possesses a higher energy than the electron's binding energy, so that the process is restricted to X-ray energies and above. However, there is also the possibility of the atom absorbing several low energy photons simultaneously [Gibb 05] to be ionised in a process called multi photon ionisation (MPI) (cf. fig. 5.5). The probability for MPI increases with light intensity, so that even the low energy radiation from a Ti:Sa laser ($\lambda = 800 \text{ nm}$ [Gibb 05]) can ionise atoms at intensities of $> 1 \cdot 10^{10} \text{ W/cm}^2$ [Gibb 05]. It even becomes possible for the atom to absorb more photons than strictly necessary for ionisation (cf. fig. 5.5), which is called above-threshold ionisation, where the excess energy is translated to the electron's kinetic energy.

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Tunnelling ionisation

At even higher intensities ($1 \cdot 10^{14} \text{ W/cm}^2$ [Gibb 05]), the laser field distorts the atomic potential enough for electrons to escape through quantum tunnelling.

A simple way of modelling the distorted field is to add a linear term to the atomic potential [Gibb 05]

$$V(x) = -\frac{Ze^2}{x} - \epsilon ex \quad (5.2)$$

where Z is the atomic number, ϵ the absolute permittivity, e the elementary charge and x a spatial coordinate. The effect is schematically shown in fig. 5.5c, where the laser field is shown as a black line and the resultant atomic potential in blue. One can clearly see how the potential on the right hand side is barely high enough to bind the electron, allowing for it to escape through quantum tunnelling. At higher intensities the distortion can even become strong enough for the potential to be lower than the ionisation energy, a process which is called over-the-barrier ionisation (OTB ionisation).

Depending on the laser, either MPI or tunnelling ionisation dominate which can be determined through the factor γ [Gibb 05]

$$\gamma = \omega_L \sqrt{\frac{2E_{\text{ion}}}{I_L}} \quad (5.3)$$

where ω_L and I_L are the laser frequency and intensity respectively while E_{ion} is the atom's ionisation energy. For $\gamma > 1$, so for small laser intensities, MPI dominates, while for $\gamma < 1$ and thus for large laser intensities, tunnelling ionisation is predominant.

5.2.2. Electron motion in intense laser fields

Now that the laser has created a large amount of free electrons it starts to exert a force on them.

The resultant behaviour is described by the Lorentz equation and the energy equation [Gibb 05]

$$\frac{d\vec{p}}{dt} = -e(\vec{E} + \frac{1}{c}\vec{v} \times \vec{B}) \quad (5.4)$$

$$\frac{d}{dt}(\gamma m_e c^2) = -e(\vec{v} \cdot \vec{E}), \quad (5.5)$$

where $\vec{B}$ and $\vec{E}$ are the magnetic and electric field, $\vec{v}$ the charged particle's speed, e the elementary charge, m_e the electron mass, $\vec{p} = \gamma m_e \vec{v}$ the momentum and finally $\gamma = \sqrt{1 + p^2/(m_e^2 c^2)}$ the relativistic factor. Assuming that the laser field takes the shape of a linearly polarised plane wave oscillating in x-direction and propagating in

5.2. Interaction of high powered laser pulses with hydrogen clusters

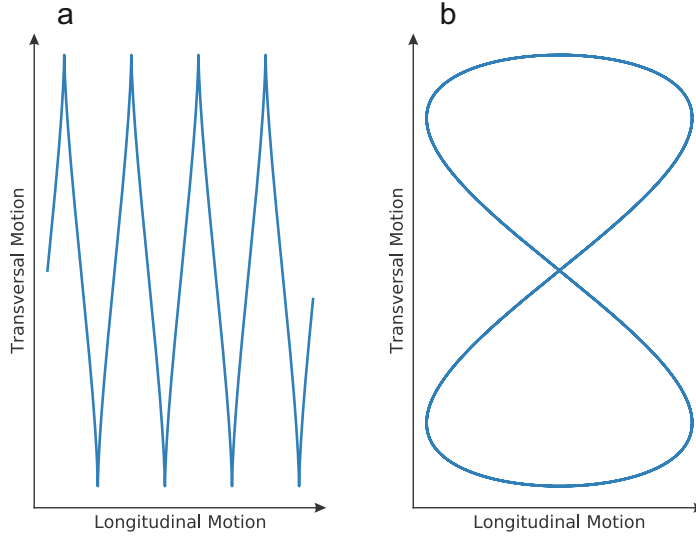


Figure 5.6.: Relativistic movement of charged particles in the laser field. **Left:** In the laboratory frame. **Right:** In the average rest frame. (Taken from [Mann 19])

z-direction, following trajectories are attained [Jack 09]

$$x = -\frac{a_0 c}{\omega_L} \sin \varphi \quad (5.6)$$

$$z = \frac{a_0 c}{4\omega_L} \left(\varphi + \frac{1}{2} \sin(2\varphi) \right), \quad (5.7)$$

where ω_L is the laser's frequency and $\varphi = \omega_L t - kz$ contains the time t , and the wave number k . a_0 is the relativistic laser amplitude, which can be expressed as [Jack 09]

$$a_0 = \frac{E_L e}{\omega_L m_e c} = \sqrt{\frac{I_L \lambda_L^2}{1.37 \cdot 10^{18} \text{ W} \cdot \mu\text{m}^2/\text{cm}^2}} \quad (5.8)$$

with the laser's electric field, intensity and wavelength being expressed by E_L , I_L and λ_L , respectively. For $a_0 > 1$ the electron motion is relativistic while $a_0 \ll 1$ corresponds to the non-relativistic regime. A high power laser pulse (e.g. ARCTURUS), with $I_L = 1 \cdot 10^{20} \text{ W/cm}^2$ and $\lambda_L = 800 \text{ nm}$, has an a_0 of $a_0 = 6.8$, so the electron motion here is well in the relativistic regime.

Drawing eq. (5.6) reveals that the electron trajectory takes the shape of a figure of eight in the average rest frame and a zig-zag structure in the laboratory frame (cf. fig. 5.6). The resultant drift speed in z-direction is calculated via [Gibb 05]

$$v_D = \frac{a_0^2}{4 + a_0^2} c, \quad (5.9)$$

5. Proton acceleration by laser-cluster interaction

demonstrating how in the relativistic regime electrons are removed from the cluster at appreciable fractions of the speed of light.

The trajectories given above assume a plane electromagnetic wave which is not an accurate representation of a high power laser pulse. Instead they are usually focussed in the interaction area, showing a strong gradient in time as well as space. The laser's radial gradient corresponds to a ponderomotive force, which forces the electron out of the laser beam by acting in a direction perpendicular to the laser propagation axis. The force can be expressed via [Jack 09]

$$\vec{F}_{\text{pond}} = -\frac{e^2}{4m_e\omega_L\bar{\gamma}}\vec{\nabla}\vec{E}_L^2(x) \quad (5.10)$$

where $\bar{\gamma} \approx \sqrt{1 + a_0^2}$.

The final electron trajectory is a superposition of the contributions caused by Lorentz force and ponderomotive force (cf. fig. 5.7), resulting in the electrons being ejected from the cluster.

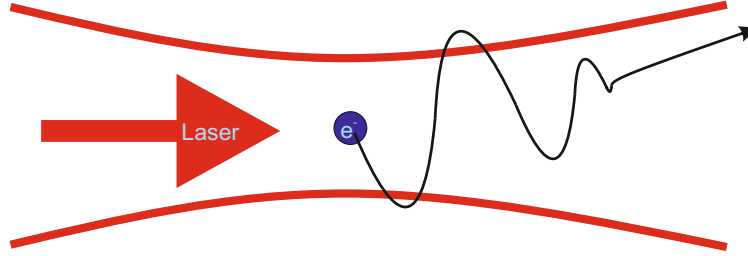


Figure 5.7.: Motion of an electron in an intense laser field. The oscillating movement is due to Lorentz force while the motion perpendicular to the beam axis stems from the ponderomotive force. (Taken from [Mann 19], based on [Gibb 05])

All of the results above are not only applicable to electrons, but also to protons as they are charged particles too. However, protons have 1836 times more mass than electrons [Nava 24]. In this case, v_D as well as the ponderomotive force become much smaller, so that proton acceleration through direct interaction between the protons in the cluster and the laser pulses is negligible. Instead, Coulomb explosion plays a much greater role.

5.2.3. Proton acceleration through Coulomb explosion

When a high intensity laser like ARCTURUS impacts a hydrogen cluster (cf. fig. 5.8a), the electrons will be ionised through the mechanisms introduced in section 5.2.1 and radially forced out of the laser focus due to the ponderomotive force (cf. fig. 5.8b). The proton plasma thus left behind (cf. fig. 5.8c) will then finally experience a Coulomb explosion, isotropically accelerating ions (cf. fig. 5.8d).

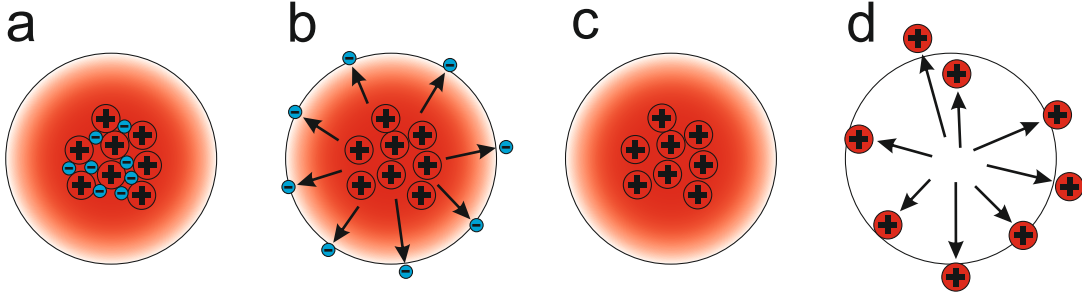


Figure 5.8.: The principal steps of Coulomb explosion. The laser (red, travelling towards the reader) interacts with the cluster (a), radially accelerating the electrons out of the cluster due to the ponderomotive force (b). Finally, the resultant plasma (c) explodes due to Coulomb repulsion (d). (Based on [Schr 18])

The maximum energy $E_{\max}$ which can be reached is given by [Saka 04]

$$E_{\max} = \frac{4}{3}\pi Z^2 e^2 n R^2 = 300 Z^2 \sqrt{\frac{n}{5 \cdot 10^{22} \text{ cm}^{-3}}} \cdot \left(\frac{R}{1 \mu\text{m}}\right) \text{ MeV} \quad (5.11)$$

where n and R are the cluster density and radius. Thus it remains entirely independent of laser parameters such as intensity, instead only depending on cluster properties, especially its radius. This remains the case under the condition that the laser is sufficiently intense to completely ionise the cluster, which can be quantitatively expressed via [Saka 04]

$$a_0 > \sqrt{\frac{8\pi Z e^2 n}{3mc^2}} = 34 \sqrt{\frac{Zn}{5 \cdot 10^{22} \text{ cm}^{-3}}} \left(\frac{R}{1 \mu\text{m}}\right). \quad (5.12)$$

Plugging in a typical cluster with a diameter of $2.5 \mu\text{m}$ and an atomic density¹ of $2.65 \cdot 10^{28} \text{ atoms/m}^3$ into eq. (5.11) gives a maximum proton energy of $E_{\max} = 1.0 \text{ GeV}$, which is already in the energy range of the anti-proton beam at PANDA. However, according to eq. (5.12), ARCTURUS, with a maximum laser intensity in the range $1 \cdot 10^{20} \text{ W/cm}^2$, is restricted to ionising clusters with diameters in the range of hundreds of nanometres, which is still enough to reach over 10 MeV .

5.2.4. X-ray generation

laser-cluster interaction gives rise to X-rays, and while they do not play a direct role in our measurements, the diagnostic systems which we employed relied upon them, so that a brief description of their creation mechanisms is given here.

The plasma created through laser-cluster interaction possesses a strong magnetic field, which causes the accelerated electrons to oscillate in a process called betatron

¹This value is reached by dividing the density of solid hydrogen in kg/m^3 by the mass of a hydrogen molecule given in kg.

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oscillation [Rous 04]. Similarly to synchrotron radiation, this leads to a collimated X-ray beam.

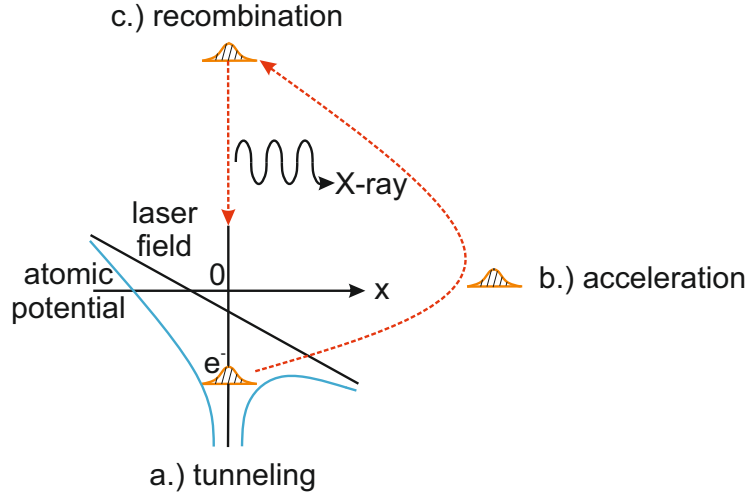


Figure 5.9.: Creation of X-rays through high harmonic generation. An electron is ionised and accelerated (a.) and b.)) before recombining (c.)), thus creating X-rays. (Adapted from [Grie 18a], based on [Gibb 05])

A second process for generating X-rays is through high harmonic generation [Eike 15]. As explained above, laser-cluster interaction leads to ionisation and the acceleration of electrons. In high harmonic generation, they recombine with ions, thus creating photons in the X-ray range due to their high energy (cf. fig. 5.9).

5.3. The ARCTURUS laser system

The ARCTURUS laser is a high power laser system located at the HHU Düsseldorf [Cerc 19] and is the second central component for the production of multi-MeV protons from clusters, the other being the cluster-jet target MCT-D which has already been introduced in section 4.2.1. For our purposes, ARCTURUS' contrast is of further interest so special attention is paid to it in the following.

Contrast is defined here as the ratio between peak laser intensity and the background level which stems from ASE light. In a laser, amplified spontaneous emission (ASE) is light which is created due to spontaneous luminescence in the gain medium and unintentionally amplified to provide a constant background to the laser [Pasc]. Considering the strength of amplification the ARCTURUS beam line possesses, ASE can play a significant role in the experiments.

At the beginning, the laser is seeded with a Ti:Sa oscillator, possessing a pulse energy of 5 nJ and pulse length below 20 fs [Cerc 19] at a frequency of 76 MHz. The pulses are then subsequently amplified in two CPA stages (cf. fig. 5.10).

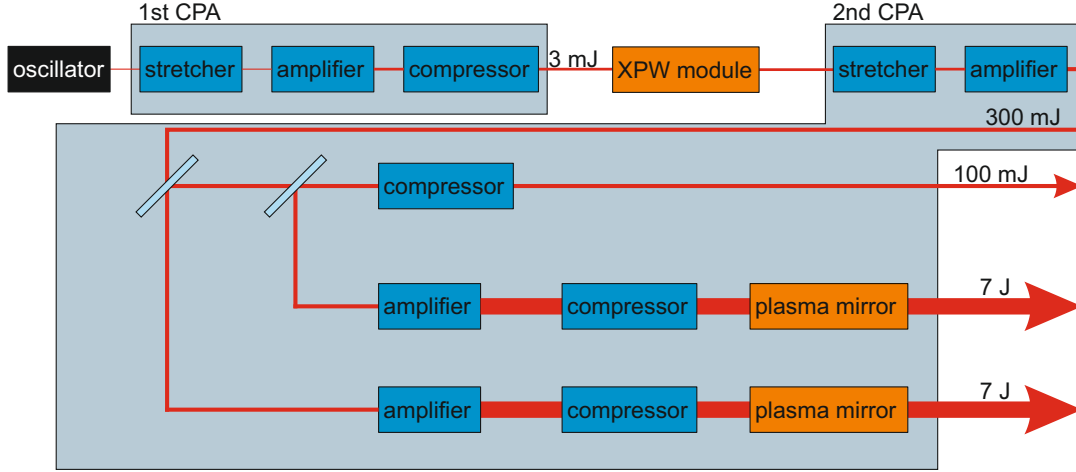


Figure 5.10.: Simplified schematic of the ARCTURUS laser. The seed is provided by a Ti:Sa oscillator and its pulses subsequently amplified up to multi-Joule energies by two CPA stages.

In the first stage, the frequency is reduced to 10 Hz, stretched to 500 ps, amplified to 3 mJ and the compressed down to 40 fs, completing the CPA procedure. By letting the beam pass through a saturable absorber, which becomes transmissive for high intensities, the contrast is improved from $3 \cdot 10^{-7}$ to $6 \cdot 10^{-8}$. The next step, before

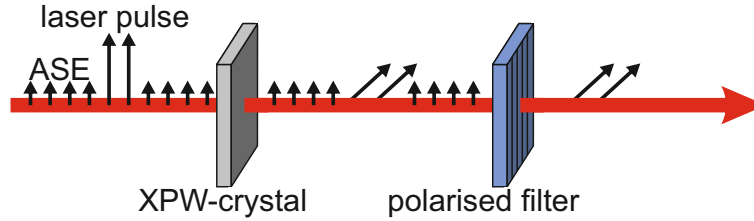


Figure 5.11.: Sketch depicting the functioning principle of an XPW-module. A non-linear crystal turns the polarisation of the high intensity laser pulse while ASE keeps its original one, enabling a polarised filter to effectively remove the ASE.

the second CPA, is to improve the contrast further through an XPW-module. Here, the pulse passes through a crystal, which turns the light's polarity by 90° through a non-linear process. Crucially, the strength of the effect is proportional to laser intensity by the third power, so that only the pulse itself is affected. The unwanted ASE remains in the original polarity and can be removed by a polarised filter (cf. fig. 5.11). With this module, the background can be further reduced to a level of $1 \cdot 10^{-12}$.

In the second amplification stage, the beam frequency is reduced to 5 Hz and amplified to 300 mJ using CPA before being split into three parts with a ratio of 30:35:35. One beam is not amplified any further, instead, it is compressed back down to 30 fs for use as a probe beam. The other two are amplified further, until they reach energies up to

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7 J each and are compressed back to 30 fs pulse length.

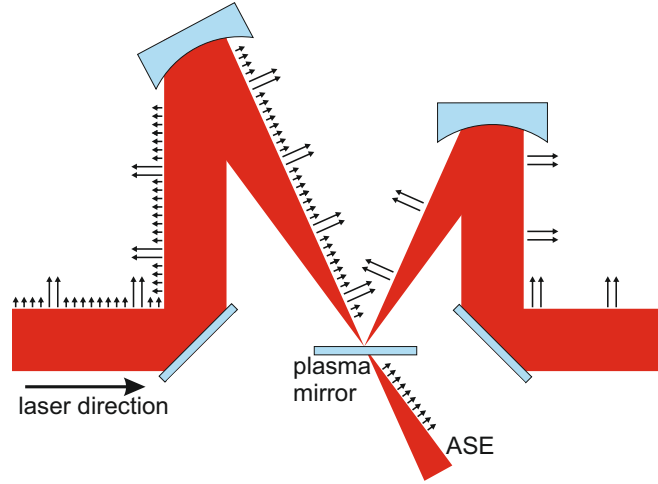


Figure 5.12.: A diagram of the plasma mirror. Low intensity light is transmitted while high intensity light is reflected.

Finally, before entering the experiment chambers, the contrast is cleaned up again by a plasma mirror (cf. fig. 5.12). This mirror is coated with a special substrate which forms a reflective plasma when intensities above $1 \cdot 10^{16} \text{ W/cm}^2$ impact it. All light with a lower intensity is simply transmitted, allowing the mirror to function as an effective filter. With this method, the contrast 6.6 ps in front of the laser pulse is improved from $1 \cdot 10^{-7}$ to $1 \cdot 10^{-9}$ [Cerc 19].

5.4. The Thomson parabola

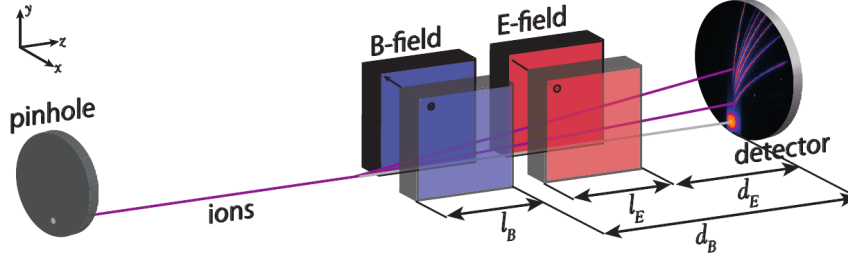


Figure 5.13.: Schematic depiction of a Thomson parabola. The accelerated ions entering the parabola are separated via an electric and magnetic field according to their charge to mass ratio and energy. (Taken from [Schr 18])

The Thomson parabola (TP) is a method to determine the energy of accelerated ion species through electromagnetic fields. The basic idea is shown in fig. 5.13. The ions enter the Thomson parabola through a pinhole, after which they are separated according to their charge to mass ratio and energy before finally their trajectories are recorded on a detector, for example a multi channel plate imaging on a phosphor screen.

If one assumes that the magnetic field takes the form of a box with a constant magnetic field strength ($\vec{B} = B_0 \vec{e}_x$) and that the ions are flying in z -direction with the speed v_0 ($\vec{v} = v_0 \vec{e}_z$), the Lorentz force deflects the ions in y -direction, leading them to possess following y -coordinate when they hit the detector screen [Heym 07]

$$y_{\text{mag}} = \frac{q}{m} B_0 \frac{l_B}{v_0} \left(d_B + \frac{l_B}{2} \right). \quad (5.13)$$

Here, q/m are the charge to mass ratio and l_B as well as d_B are the distances depicted in fig. 5.13. The y -coordinate y_{mag} depends on the charge to mass ratio and on the ion energy through v_0 , thus achieving energy separation.

If one requires separation by ion species, the electric field is necessary. Under the assumption of a perfectly homogeneous and box shaped field ($\vec{E} = E_0 \vec{e}_x$), the ion's trajectory leads to following x -coordinate

$$x_{\text{el}} = \frac{q}{m} E_0 \frac{l_E}{v_0^2} \left(d_E + \frac{l_E}{2} \right), \quad (5.14)$$

which again depends on charge to mass ratio and ion energy.

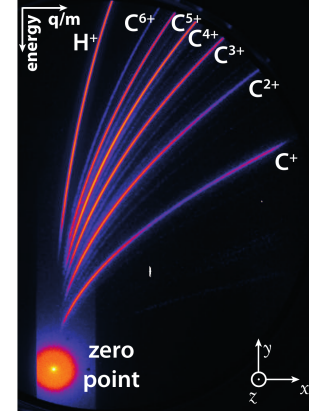


Figure 5.14.: Ion traces recorded by a TP. The zero point originates from X-ray radiation created during the laser plasma interaction. Each trace corresponds to one ion species (Taken from [Schr 18])

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Combining eqs. (5.13) and (5.14) leads to

$$y^2 = \frac{q}{m} \frac{B_0^2}{E_0} \frac{l_B^2}{l_E} \frac{(d_B + l_B/2)^2}{d_E + l_E/2} x, \quad (5.15)$$

which has the shape of a parabola. Crucially, every charge to mass ratio has its own parabola (cf. fig. 5.14), so that energy as well as ion species separation is achieved. In the case that there is only one ion species, such as hydrogen ions for us, only one type of field is already sufficient.

5.5. Experimental setup

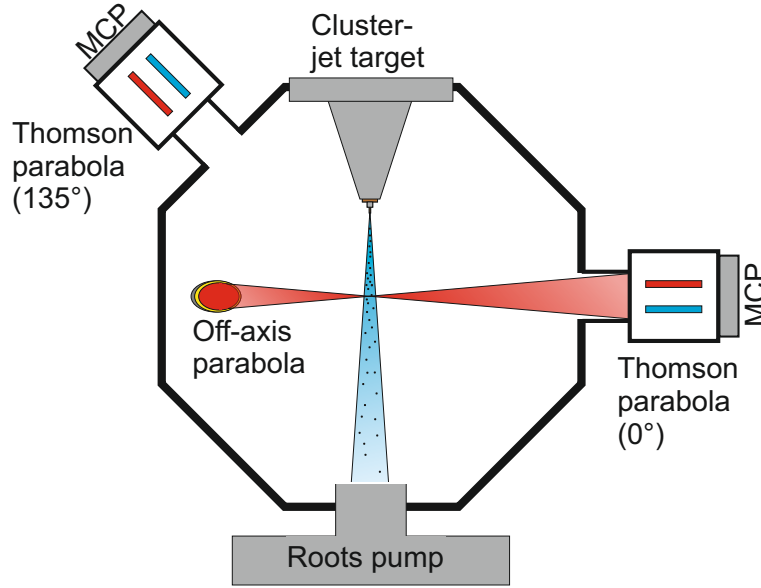


Figure 5.15.: The experimental setup of the proton acceleration measurements. ARCTURUS' laser beam is focussed perpendicularly on the cluster-jet beam. Two Thomson parabolas are used to record the proton energy spectra, one under 0° and one under 135° with respect to the laser beam direction.

MCT-D (cf. section 4.2.1) was mounted onto an experiment chamber at the ARCTURUS laser facility. Opposite of it, a powerful pumping setup consisting of two roots pumps (Leybold RUVAC WH 7000 [Leyb 16a], Leybold RUVAC WSU 1001 [Leyb 16b]) and a fore pump (Leybold SOGEVAC SV 300 [Leyb 21]) with respective pumping speeds of $7800 \text{ m}^3/\text{h}$, $1000 \text{ m}^3/\text{h}$ and $240 \text{ m}^3/\text{h}$ acted as a beam dump for the cluster beam. The target was operated at a temperature of $T_{\text{CS}} = 28 \text{ K}$ and hydrogen pressure of $p_{\text{gas}} = 16 \text{ bar}$ with a nozzle diameter of $42 \text{ }\mu\text{m}$. At such conditions, hydrogen is fluid, leading to the formation of large clusters in the μm diameter range [Eick 23].

The ARCTURUS laser beam was focussed perpendicularly onto the cluster-jet 2.8 cm

downstream of the nozzle by an off-axis parabola. With a pulse energy of 3 J and a focus diameter of 5 μm , intensities of over $1 \cdot 10^{20} \text{ W/cm}^2$ were reached.

Two Thomson parabolas were installed as diagnostics, one under 0° and the other under 135° with respect to the laser direction. Both had their own vacuum chamber with pressures $\approx 1 \cdot 10^{-6} \text{ mbar}$, connected to the experiment chamber by their pin holes with a diameter of 2 mm under 0° and 1 mm under 135° . Both were operated solely with a magnetic field possessing a length and strength of $l_B = 50 \text{ mm}$ and $B = 0.5 \text{ T}$ each. The fields were located 195 mm away from the MCP for the TP under 0° and 170 mm for the TP under 135° . With this setup, proton energies from around 400 keV to 10 MeV for the 0° TP and 200 keV to 10 MeV for the 135° TP could be resolved.

5.6. Proton acceleration results

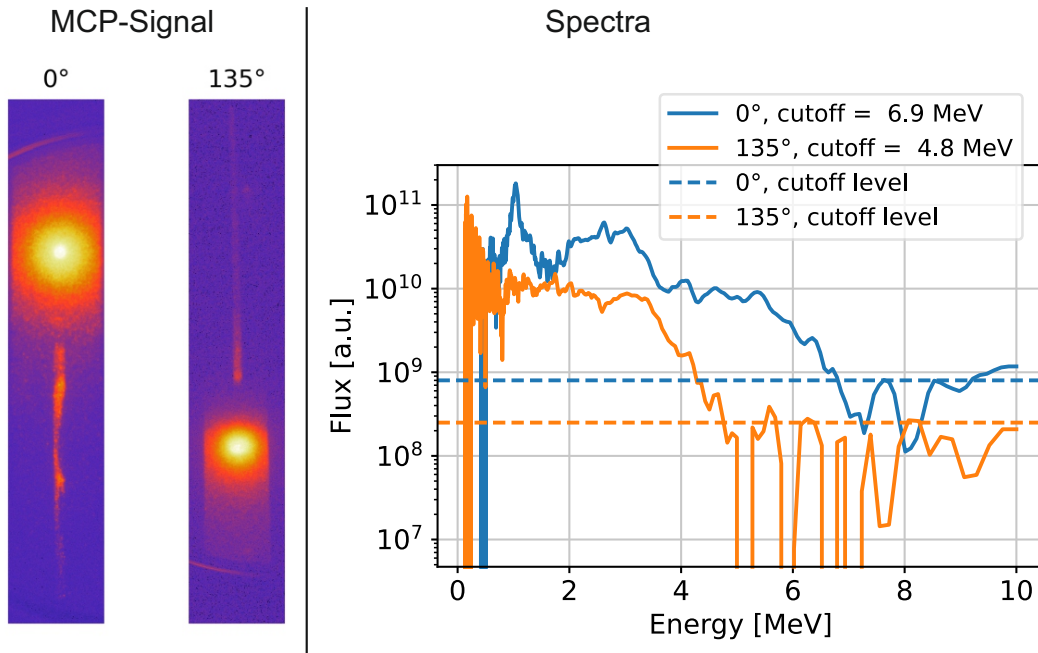


Figure 5.16.: **Left:** Signal observed on the TPs under 0° and 135° . **Right:** The resultant energy spectra. As is clearly visible, the spectrum under 0° has a higher cutoff energy than the one under 135°

On the left of fig. 5.16, one can see the signal observed on the Thomson parabolas under 0° and 135° . The large spot visible for both is the zero spot, generated by X-ray light (cf. section 5.2.4) originating from the interaction spot between cluster and laser beam. The trace below (or above, in the case of the 135° Thomson parabola) is created by the accelerated protons, the reversed trajectories being caused by the Thomson parabolas possessing opposing magnetic field polarities. The electric field was omitted because only a single ion species was accelerated, so that the traces take the form of

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straight vertical lines.

These signals were analysed using a Matlab routine written by Aaron Jose Alejo Alonso of the Universidade de Santiago de Compostella, with which the traces were projected unto the vertical axis and assigned an energy depending on their position. The result is shown on the right of fig. 5.16. After a certain maximal energy, also called cutoff energy, the traces remain in a plateau, indicating that no protons of higher energies are contained in the particular signal. To determine the cutoff energy, the plateau height is determined by eye. The energy at which the proton signal intersects the plateau is the cutoff, which is in the range of several MeV for this shot (cf. fig. 5.16) and confirms the acceleration of protons to such energies.

5.6.1. Anisotropic proton acceleration

In fig. 5.16, it is clearly visible how the maximum energy under 0° is considerably higher than under 135° . Comparison of over 30 such shots reveals that the cutoff proton energy in laser direction is systematically higher than the corresponding one under 135° (cf. fig. 5.17), a hypothesis mentioned in [Jinn 22] which they could not verify at the time. This is evidence that the acceleration mechanism is not exclusively due to Coulomb

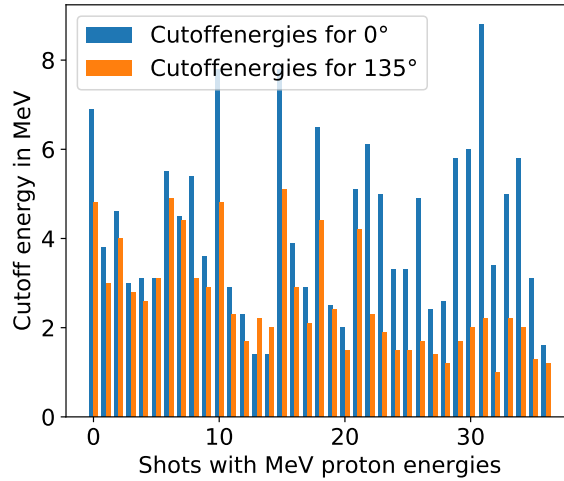


Figure 5.17.: The cutoff energies under 0° and 135° grouped per shot. The cutoff energies are always higher under 0° , except for two exceptions.

explosion, which would lead to an isotropic proton energy distribution. An alternative acceleration mechanism is given in [Jinn 22], obtained through particle-in-cell (PIC) simulations.

For the interaction between large clusters in the μm diameter range and a laser pulse with a peak intensity in the range of $1 \cdot 10^{20} \text{ W/cm}^2$, eq. (5.12) predicts that Coulomb explosion is not the only mechanism to contribute to the acceleration. This is also seen in the PIC simulations where over 90 % of the electrons remain in the cluster, so

that only the outer regions undergo Coulomb explosion. Furthermore, the electric field strength at the front of the cluster rises earlier than at the back (cf. fig. 5.18), causing electrons to be accelerated in laser propagation direction, which in turn drags protons along in the same direction, thus causing the anisotropy.

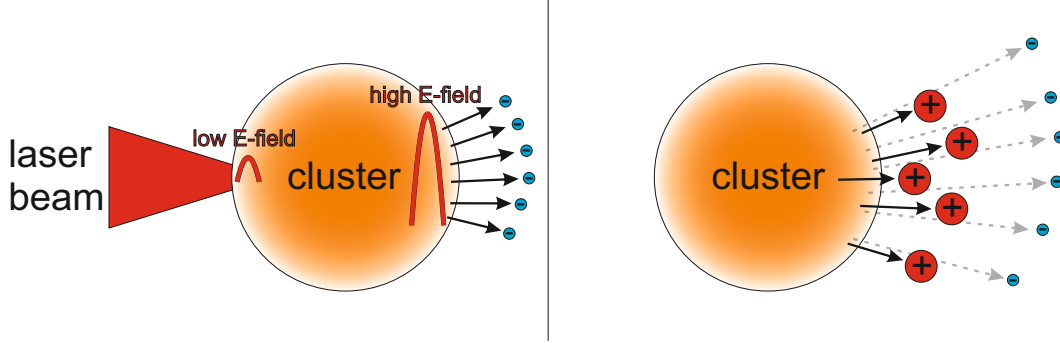


Figure 5.18.: Simplified sketch of the acceleration scheme presented in [Jinn 22]. Most of the electrons remain in the cluster while the electric field rises earlier at the front than at the back of the cluster. This causes the few electrons which have been ionised to be accelerated in forwards direction, dragging protons along with them and thus causing an anisotropy in the Coulomb explosion.

Following this line of argumentation, the shots leading to anisotropic cutoff energies stem from interaction with μm sized clusters. However, there are also a few isotropic shots, one reaching energies over 4 MeV. Employing eqs. (5.11) and (5.12), it could be verified that this energy could be reached through Coulomb explosion of a cluster with a diameter of 320 nm and that ARCTURUS reaches high enough intensities to cause such an explosion. This is evidence that the proton energies we observe stem from two distinct interaction regimes, depending on the cluster size. Large ones undergo an anisotropic Coulomb explosion while for small ones the laser intensity is high enough for a pure Coulomb explosion, with both of them achieving multi-MeV energies. Interestingly, isotropic acceleration occurs less often in our dataset, suggesting that small clusters appear less often.

Another curiosity appears when one considers that shots with higher shot numbers were taken at later dates than the ones with lower numbers, with the entirety of fig. 5.17 being taken over a time period of three weeks. It appears that the anisotropy seems to become more pronounced with time. Why this is the case cannot be conclusively determined, however, there is the possibility that the properties of the cluster beam changed with time. For example, for higher shot numbers the laser might have interacted with a region of the target beam with especially high density (a so called core beam [Vest 24]) possibly containing a large amount of large clusters, which was not there for earlier dates.

With more data to immune the observation from statistical fluctuations as well as more diagnostics to determine the exact target conditions, in future such measurements could be combined with independent cluster size measurements using Mie-scattering

5. Proton acceleration by laser-cluster interaction

[Mann 19] and shadowgraphy [Eick 23] to provide detailed information on the cluster-size distribution.

5.6.2. Exploration of contrast dependence

To further explore the properties of laser-cluster interaction, the laser contrast was varied. To do so, the plasma mirror was either included in the laser's beam path or bypassed, which allowed us to switch the contrast between $1 \cdot 10^{-9}$ and $1 \cdot 10^{-7}$. Without plasma mirror, not a single shot with proton energies above 1 MeV was recorded in over 800 attempts, while with the plasma mirror 128 out of 924 shots led to cutoff energies of > 1 MeV, a rate of close to $(14 \pm 1) \%$. As the target conditions for both types of measurements were identical ($T_{\text{CS}} = 28$ K and $p_{\text{gas}} = 16$ bar) this result suggests that at worse contrasts the laser pre-pulse plays a significant part in the interaction. Possibly, it pre expands the cluster to such a degree that the ion density is insufficient for reaching proton energies above 1 MeV. That (comparatively) low intensities of $5.8 \cdot 10^{17}$ W/cm² are sufficient to pre expand a hydrogen filament² with a diameter of 5 μm has already been demonstrated [Rehw 23]. However, the peak intensity of ARCTURUS' pre-pulse remains at the level of $1 \cdot 10^{15}$ W/cm² [Cerc 19], which is sufficiently different to necessitate further simulations to verify our hypothesis.

Furthermore, the contrast dependency offers an explanation why the maximum energy observed in our experiments (8.8 MeV) is considerably lower than what was observed in [Jinn 22] (12.4 MeV). Of course, the dataset is sufficiently small that this might just be a statistical effect, however, their laser operated with a contrast ratio of $1 \cdot 10^{-11}$, which could enable higher energies as observed when ARCTURUS' contrast was improved from $1 \cdot 10^{-7}$ to $1 \cdot 10^{-9}$. The uncertainty in this matter only reiterates the need for further simulations.

5.6.3. Shot-to-shot stability

As can be already surmised through fig. 5.17 and that only around $(14 \pm 1) \%$ of shots lead to > 1 MeV energies, shot-to-shot stability is poor. This can be nicely seen in box plot form (cf. fig. 5.19), which demonstrates the large spread of cutoff energies.

The reason for this lies in the size of the clusters. While the size dependency for the anisotropic Coulomb explosion (cf. fig. 5.18) is less pronounced than for a pure Coulomb explosion, it is nonetheless still there [Jinn 22]. Since the cluster size distribution is quite broad [Eick 23], the laser pulses impact clusters of varying sizes, leading to a broad cutoff energy distribution in turn. This would not be an issue if many clusters took part in the interaction, since then the cluster sizes and thus the proton energies would average out. However, since the proton energy in $(86 \pm 3) \%$ shots remains below 1 MeV, it can be safely assumed that most of the time the high energies stem from a single cluster.

²similar in shape to the filament achieved by MDT-H, cf. fig. 4.31

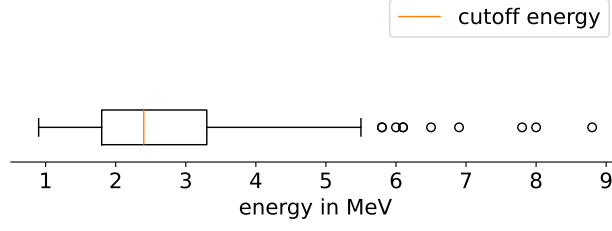


Figure 5.19.: Boxplot depicting the spread of the cutoff energies. Here, the whiskers extend to the largest(or smallest, in the case of the lower whisker) data point contained in the interquartile range above(or below) the box.

Determination of the mean distance between clusters

This observation can be used to learn more about the cluster beam, namely the mean distance between clusters. Under the assumption that the ARCTURUS laser beam possesses a gaussian profile, the focus volume can be calculated via (cf. appendix F)

$$V_{\text{focus}} = \frac{8}{3}\pi^2 \frac{w_0^4}{\lambda} n, \quad (5.16)$$

where n is the transmission medium's refractive index, w_0 the beam waist and λ the laser wavelength. In our case, $n = 1$ as the laser is transmitted through vacuum, $w_0 = 2.5 \mu\text{m}$ and $\lambda = 800 \text{ nm}$ so that $V_{\text{focus}} = 1285.1 \mu\text{m}^3$.

In $(14 \pm 1) \%$ of the shots, there is a cluster capable of achieving at least 1 MeV cutoff energy in this volume, so that a volume of $V = V_{\text{focus}}/0.14$ should contain one cluster on average. Of course, here one assumes that the $> 1 \text{ MeV}$ energies only stem from the interaction with a single cluster, which is reasonable as explained above. One can then use [Chan 43]

$$\bar{r} = \Gamma\left(\frac{4}{3}\right) \left(\frac{4\pi N}{3V}\right)^{-1/3} \quad (5.17)$$

to calculate the mean distance $\bar{r}$, where Γ is the gamma function and N/V the amount of clusters divided by volume. Plugging in our result for eq. (5.16) leads to an estimated $\bar{r} = 12 \mu\text{m}$ distance between clusters capable of $> 1 \text{ MeV}$ cutoff energies. To achieve such energies, a cluster needs to undergo Coulomb explosion³ at a minimum diameter of 160 nm, so that in conclusion, the mean distance of clusters with diameters $> 160 \text{ nm}$ is around $12 \mu\text{m}$.

This value is much smaller than what was found for clusters with diameters larger than around $3 \mu\text{m}$ ($\bar{r} = (115.8 \pm 7.1) \mu\text{m}$ [Eick 23]), presenting strong evidence for a large abundance of clusters with diameters in the range of hundreds of nanometres to a few microns.

³Evidence that this acceleration scheme occurs for our measurements is presented in section 5.6.1

5.7. Conclusion and outlook for laser-cluster interactions

By letting a cluster-jet interact with the ARCTURUS laser beam, proton energies in the multi-MeV range could be generated (cf. section 5.6) and new insights could be gained concerning the interaction mechanism.

Against initial expectations, it was observed that the acceleration was often anisotropic (cf. section 5.6.1), which was already hypothesized to be the case in [Jinn 22], but not yet experimentally verified. To explain this anisotropy, an alternative acceleration scheme to Coulomb explosion has already been presented [Jinn 22], where only the surface regions of the cluster explode. This mechanism occurs when the laser possesses insufficient intensity to completely ionise the cluster. For ARCTURUS with an intensity in the range of $1 \cdot 10^{20} \text{ W/cm}^2$, this is the case for cluster diameters in the μm range, indicating that many of the protons observed in our measurements stem from such clusters.

Additionally, there are also some isotropic proton energies belonging to Coulomb explosions, evidence that smaller clusters are occasionally hit, too. The dataset shown in fig. 5.17 indicates that the large clusters interact more often, however, the sample size is much too small and the exact properties of the target beam too unknown for any conclusions concerning the abundance of the various cluster sizes, necessitating more statistics and better target diagnostics for reliable statements. However, the target can be operated continuously to make the most of ARCTURUS high repetition rate so that this setup would be ideal for such a measurement campaign.

Low statistics might also be the reason why the maximum energy of over 12 MeV achieved in [Jinn 22] could not be reproduced, despite possessing comparable laser intensities and cluster diameters. However, another reason might be the contrast dependency of the interaction (cf. section 5.6.2) which was varied between $1 \cdot 10^{-9}$ and $1 \cdot 10^{-7}$. It was observed that no proton energies above 1 MeV were achieved with the lower contrast. This behaviour can be interpreted such as that at worse contrasts, the pre-pulse already has enough intensity to pre-expand the cluster, thus lowering its density to such a degree that the maximum acceleration can no longer be reached.

Since the laser used for [Jinn 22] had a contrast ratio of $1 \cdot 10^{-11}$, it is plausible that their higher energy ceiling stems from their improved contrast, however, simulations are needed to verify this hypothesis.

Apart from gleaning new insights into the mechanisms of laser-cluster interaction, in addition new information could be gained on the properties of the cluster beam. By exploiting the (rather low) rate at which sufficiently large clusters for energies $> 1 \text{ MeV}$ are hit by the laser beam, a mean distance of around $\bar{r} = 12 \mu\text{m}$ between clusters with diameters $> 160 \text{ nm}$ could be determined. This value is much lower than the previous one of $\bar{r} = (115.8 \pm 7.1) \mu\text{m}$ [Eick 23]), which is unsurprising considering only clusters with diameters above $3 \mu\text{m}$ were considered.

While our investigations on laser-cluster interactions have been successful in accelerating protons to multi-MeV energies and have provided insight into the properties of the interaction mechanisms, there is still room for improvement. The acceleration suffers from poor shot to shot stability due to the varying cluster sizes the laser impacts.

5.7. Conclusion and outlook for laser-cluster interactions

One solution would be to increase the size of the laser focus to interact with more clusters, however this would quickly reduce the laser intensity. Another solution would be to use a target with well defined dimensions, such as a droplet target like MDT-H. Even in its current form as a filament target it could prove to be very useful, as a very similar target has already been used to generate protons with energies above 80 MeV [Rehw 23]. However, MDT-H currently possesses beam fluctuations on the order of low tens of microns, which is still too much if one aims to gain reliable overlap with a laser beam of 5 μm diameter. To achieve better stability, the first step is to decouple the target from its surroundings, for example the strongly vibrating vacuum pumps. While this can be done relatively easy via mechanical means, the cold head powering the target remains a constant source of vibrations. A solution could be to use a pulse tube refrigerator [Jits 09], which vibrates less in comparison to the cold heads conventionally used for the Münster targets.

6. Conclusion and outlook

Within the scope of this thesis, several innovations concerning the Münster cryogenic target systems were developed.

Due to the outgassing of the Münster cluster-jet target for $\overline{\text{PANDA}}$, there are concerns that the rest-gas will have significant impact on detector performance and accelerator beam life time at the $\overline{\text{PANDA}}$ experiment. Although recent investigations suggest that at least the luminosity detector is insensitive to rest-gas [Li 24], the beam life time will definitely be affected. So to combat this issue, a cryopump was proposed to remove the gas. This technology was chosen due to its high pumping speed at moderate size and its flexible form, enabling it to be installed directly in the $\overline{\text{PANDA}}$ beam line. However, as there are no commercial cryopumps which fulfil $\overline{\text{PANDA}}$'s unique needs, it was decided to build a custom designed one.

To this end, we performed exhaustive simulations of the cryopump's effect on $\overline{\text{PANDA}}$'s vacuum system, revealing that the exact geometry barely has any effect on the rest-gas thickness (cf. section 3.3.7). However, the geometry has a significant impact on the regeneration interval allowing for a pre-selection of suitable designs. Additionally, it was observed that longer cryopumps perform better. So to determine the greatest length which can still be adequately cooled, we performed temperature simulations (cf. section 3.4).

Through these exhaustive studies we developed a novel cryopump geometry, the so called "fin cryopump" (cf. fig. 3.4). It achieves sufficiently cool temperatures below 13 K for hydrogen pumping at a large length of 80 cm, resulting in a rest-gas reduction of around 40 % which would lead to a beam life time improvement of 20 %. Unfortunately, the cryopump's performance is expected to decrease within several days, necessitating regeneration. To minimise downtime, we propose a novel regeneration scheme, where the pump is gently heated until it starts to outgas in a controlled fashion, preserving beam line vacuum and saving as much time as possible (cf. section 3.4.6).

While these simulations have proven to be valuable tools in designing the cryopump, they still need to be verified by experiments. Thus the next step is to construct and build a cryopump on basis of the simulations for thorough testing. Ideally, this pump should be designed in such a way that it can be modularly lengthened or shortened should there be any inaccuracies in the simulations.

As the $\overline{\text{PANDA}}$ experiment will make use of both a pellet as well as a cluster-jet target [Baru 21], investigations were made on combining them. Since the operating parameters of both target types can be reached by our cooling and gas systems, we transformed the cluster-jet target MCT-D into the pellet target MDT-D (cf. section 4.2.1) using simple mechanical means. However, the nozzles used for pellet targets tend to be considerably smaller than the ones in use for cluster-jet targets, leading to frequent interruption of

6. Conclusion and outlook

operation due to nozzle clogging (cf. section 4.3.3). To tackle this issue, which has frequently been seen at other, similar experiments [Frag 15, DePo 08], we built and installed new pellet target, MDT-H. Due to its novel design and improved cleanliness, the occurrence of nozzle clogging could be drastically reduced while the target's stability was greatly improved, enabling rapid progress (cf. sections 4.4.2 and 4.4.7).

We determined the target's resonance frequencies and while they were found to coincide with frequencies where the target beam was attempting to break up, no proper pellet generation could be achieved (cf. section 4.4.3) as the beam freezes out too quickly in vacuum. In future, this issue can be solved by installing a triple point chamber or repairing the co-flowing gas system. Nonetheless, we made great progress on other fronts, especially concerning the control over the target beam. While it was previously controlled via complex mechanical means [Winn 11, Grie 18a] we have successfully run first tests with the cryobending system (cf. section 4.4.5) which gently directs the beam into the desired direction by blowing on it with helium. This new system is much less costly and complicated than previous ones while promising to deliver an unprecedented level of control.

Despite MDT-H's great performance and the progress we have made, one should keep in mind that the aim of achieving a stable target which can be operated both as a cluster-jet target and a pellet target has not yet been achieved. However, our recent investigations with an electron microscope show that dirt and dust seem to be likely culprits for many blockages (cf. section 4.4.6) suggesting that performing a deep clean of the target gas system using JE 25, the cleaning solution used for MDT-H, could be the solution. Alternatively, considering that several years still remain until PANDA will be operational, it is even thinkable to completely rebuild the target's gas system in the same vein of the one successfully in use in MDT-H. Previous simulations [Fron 23] have already suggested that this should be possible without any compromises in achievable gas temperatures and pressures.

Münster cluster-jet target systems are not only used in particle physics, but have also found application in plasma physics as part of the CryoFlash experiment exploring proton and electron acceleration as well as X-ray generation through the interaction of clusters and a high intensity laser beam [Grie 18a, Aura 19, Less 21]. In subsequent measurements presented in this thesis (cf. chapter 5), we reached proton energies of several MeV, comparable to other recent experiments [Jinn 22] and around an order of magnitude more energy than previous efforts [Aura 19, Less 21]. Additionally, we gained insight into the reaction mechanisms as well, which take the form of both Coulomb explosions as well as an incomplete, anisotropic Coulomb explosions (cf. section 5.6.1). In addition, it was found that energies increase with laser contrast, however additional simulations are needed for more substantial claims on the contrast's influence (cf. section 5.6.2). Shot to shot stability was quite low due to the broad cluster size distribution, with only around 14 % of shots leading to MeV protons (cf. section 5.6.3). This was useful as it enabled us to estimate the mean distance between clusters, however, for future applications a greater stability would be necessary. A possibility to achieve this could be to use MDT-H for future experiments, either as a pellet target or filament target, as then the laser would only interact with a target

of identical size, however, our current target beams still fluctuate too much to ensure reliable overlap with the laser beam. A large step to improve on this front would be to decouple the target from any vibrations, much of which stems from its cold head. Thus vibration-less pulse tube coolers become an attractive technology for this application and possibly the next step of target design.

A. Calculating volume flow from target thickness

This chapter briefly derives an equation with which volume flow through the nozzle can be determined from target thickness. This computation was originally performed by Philipp Brand.

The basic idea is to consider the atomic flow q_N , which can be expressed as follows

$$q_N = v \iint_A \rho_N(x, z) dx dz, \quad (\text{A.1})$$

where v is the cluster speed and $\rho_N(x, z)$ the cluster beam's atomic density. That this relation is plausible is easily verified by considering the units. The right side of the equation gives $[\text{m/s}] \cdot [\text{atoms/m}^3] \cdot [\text{m}^2]$ which corresponds to the left side given in atoms/s. Since q_N can quite simply be converted to the pV flow¹ q_{pV} , and $\rho_N(x, z)$ is related to target thickness ρ_T , the integral in eq. (A.1) is the central component which needs to be solved.

A.1. The target density $\rho_N(x, z)$

Solving the integral requires more knowledge about $\rho_N(x, z)$. The target density can be further described by

$$\rho_N(x, z) = \rho_0 \tilde{\rho}(x, z) \quad (\text{A.2})$$

where $\rho_N(x, z)$ is separated into two contributions. $\tilde{\rho}(x, z)$ describes the density's form while ρ_0 represents its amplitude. This amplitude is given by [Herg 13]:

$$\rho_0 = \frac{\rho_T}{\text{erf}\left(\frac{b_x}{2s}\right)b_z}. \quad (\text{A.3})$$

Here, b_x and b_z describe the target beam dimensions in the respective directions while s is a smearing factor. Meanwhile, $\tilde{\rho}(x, z)$ is given by [Herg 13]

$$\tilde{\rho}(x, z) = \underbrace{\frac{2}{\left(\text{erf}\left(\frac{b_x}{2s}\right) - \left(\text{erf}\left(\frac{-b_x}{2s}\right)\right)\right)}}_{\tilde{\rho}(x)} \cdot \underbrace{\frac{2}{\left(\text{erf}\left(\frac{b_z}{2s}\right) - \left(\text{erf}\left(\frac{-b_z}{2s}\right)\right)\right)}}_{\tilde{\rho}(z)} \quad (\text{A.4})$$

¹Also called outgassing rate in this context.

A. Calculating volume flow from target thickness

A.2. Solving the integral

Thus, using eqs. (A.2) and (A.3), eq. (A.1) can be expressed as

$$q_N = v \frac{\rho_T}{\operatorname{erf}\left(\frac{b_x}{2s}\right) b_z} \iint_A \tilde{\rho}(x, z) dx dz. \quad (\text{A.5})$$

The integral can be separated into two parts according to

$$\iint_A \tilde{\rho}(x, z) dx dz = \int_{-\infty}^{\infty} \tilde{\rho}(x) dx \int_{-\infty}^{\infty} \tilde{\rho}(z) dz \quad (\text{A.6})$$

and $\tilde{\rho}(x)$ as well as $\tilde{\rho}(z)$ can be expressed as the convolution between a rectangular function and a gaussian curve [Herg 13]:

$$f(x) = \frac{1}{s\sqrt{\pi}} \exp\left(-\frac{1}{2} \frac{x^2}{s^2}\right) \quad (\text{A.7})$$

$$g(x) = \operatorname{rect}\left(\frac{x}{b_x}\right) = \begin{cases} 1, & \text{for } -b_x/2 \leq x \leq b_x/2 \\ 0, & \text{else} \end{cases} \quad (\text{A.8})$$

$$\tilde{\rho}(x) = f(x) * g(x) = \int_{-\infty}^{\infty} f(\tau) g(x - \tau) d\tau. \quad (\text{A.9})$$

The equations for $\tilde{\rho}(z)$ are achieved by replacing the x with z in the above equations. Using eq. (A.9), eq. (A.6) can be solved. Take for instance the part dependent on x :

$$\int_{-\infty}^{\infty} \tilde{\rho}(x) dx = \int_{-\infty}^{\infty} dx \int_{-\infty}^{\infty} d\tau f(\tau) g(x - \tau) \quad (\text{A.10})$$

$$= \underbrace{\int_{-\infty}^{\infty} d\tau f(\tau)}_1 \underbrace{\int_{-\infty}^{\infty} dx g(x - \tau)}_{b_x} \quad (\text{A.11})$$

$$= b_x, \quad (\text{A.12})$$

So that overall the result is

$$\iint_A \tilde{\rho}(x, z) dx dz = \int_{-\infty}^{\infty} \tilde{\rho}(x) dx \int_{-\infty}^{\infty} \tilde{\rho}(z) dz = b_x \cdot b_z. \quad (\text{A.13})$$

A.3. Calculating the volume flow

Inserting eq. (A.13) into eq. (A.5) leads to

$$q_N = v \frac{\rho_T}{\operatorname{erf}\left(\frac{b_x}{2s}\right)} b_x. \quad (\text{A.14})$$

The atomic flow q_N can be transformed into the molecular flow q_{H_2} via

$$q_{\text{H}_2} = \frac{1}{2} q_N, \quad (\text{A.15})$$

since hydrogen is a diatomic molecule. The mass flow q_m can then be calculated through

$$q_m = q_{\text{H}_2} \frac{M_{\text{H}_2}}{N_A}, \quad (\text{A.16})$$

with the molar mass of hydrogen M_{H_2} and the Avogadro constant N_A . The pV flow and mass flow are connected via the ideal gas law:

$$q_{pV} = p\dot{V} = \dot{m} R_s T, \quad (\text{A.17})$$

where $\dot{m}$ is identified as q_m , R_s is the specific gas constant given by the universal gas constant and molar mass as $R_s = R/M_{\text{H}_2}$, and the temperature T is assumed to be the normal temperature T_N , so that overall

$$q_{pV} = q_m \frac{R}{M_{\text{H}_2}} T_N \quad (\text{A.18})$$

is reached. Thus, by combining eqs. (A.15), (A.16) and (A.18) one arrives at

$$q_{pV} = \frac{1}{2} q_N \frac{RT_N}{N_A} \quad (\text{A.19})$$

and with eq. (A.14) finally

$$q_{pV} = \frac{1}{2} \frac{\rho_T v}{\operatorname{erf}\left(\frac{b_x}{2s}\right)} b_x \frac{RT_N}{N_A} \quad (\text{A.20})$$

B. The conversion factor

This chapter briefly derives the conversion factor α , which transforms the rest-gas thickness from units of $\text{mbar} \cdot \text{cm}$ to atoms/cm^2 .

We start with the ideal gas law

$$pV = Nk_B T \quad (\text{B.1})$$

where p is the pressure, V the volume, N the number of particles, k_B the Boltzmann constant and T the temperature. We rearrange this equation

$$\rho = \frac{N}{V} = \frac{p}{k_B T} \quad (\text{B.2})$$

so that we can identify the left side as the density ρ . We now insert following values $p = x \text{mbar}$, $k_B = 1.38 \cdot 10^{23} \text{ J/K}$ and $T = 293 \text{ K}$. x is the value in mbar we are trying to convert. Now, the values' respective units are massaged until the correction factor is attained:

$$\rho = x \frac{\text{mbar}}{1.38 \cdot 10^{23} \text{ J/K} \cdot 293 \text{ K}} \quad (\text{B.3})$$

$$\rho = x \frac{1 \cdot 10^2 \text{ Pa}}{1.38 \cdot 10^{23} \text{ J} \cdot 293} \quad (\text{B.4})$$

$$\rho = x \frac{1 \cdot 10^2 \text{ kg}/(\text{ms}^2)}{1.38 \cdot 10^{23} \text{ kg} \cdot \text{m}^2/\text{s}^2 \cdot 293} \quad (\text{B.5})$$

$$\rho = x \frac{1}{1.38 \cdot 10^{-19} \cdot 293 \text{ cm}^3} \quad (\text{B.6})$$

$$\rho = x \frac{1}{4.04 \cdot 10^{-17} \text{ cm}^3} \quad (\text{B.7})$$

The target thickness n_T is given in units of $1 \cdot 10^{14} \text{ atoms}/\text{cm}^2$, which is achieved here by multiplying both sides of the equation with cm and extending the fraction with $1 \cdot 10^{14}$. Furthermore, hydrogen possesses two atoms per molecule so that a factor of 2 needs to be included, leading to:

$$n_T = x \cdot \frac{2}{4.04 \cdot 10^{-3}} \left[10^{14} \text{ atoms}/\text{cm}^2 \right] \quad (\text{B.8})$$

$$n_T = x \cdot 495 \left[10^{14} \text{ atoms}/\text{cm}^2 \right] \quad (\text{B.9})$$

which gives us a conversion factor between $\text{mbar} \cdot \text{cm}$ to atoms/cm^2 of $\alpha = 495 \text{ atoms}/(\text{mbar} \cdot \text{cm}^3)$.

C. The beam lifetime

This chapter will briefly demonstrate how the beam life time increase due to the cryopump is calculated.

The accelerator beam will lose particles according to [Myer 20]

$$N(t) = N(0) \cdot e^{-\frac{t}{\tau}} \quad (\text{C.1})$$

where $N(t)$ is the amount of particles at the time t and τ is the beam intensity lifetime. τ is determined by various factors such as beam-gas scattering, thermal photon scattering, intra-beam scattering and many more contributors [Myer 20]. We are only interested in beam decay caused due to interaction with the target and rest-gas, so the rest will be neglected.

The first step is to show how the beam life time τ scales with the gas thickness ϕ . Beam-gas scattering scales with gas density according to [Myer 20]

$$\frac{1}{\tau_{\text{gas}}} = v\sigma\rho, \quad (\text{C.2})$$

where τ_{gas} is the beam life time caused by beam interaction with gas, v the beam's speed, σ the cross section for beam-gas interaction and ρ the gas density. In eq. (C.2), the density ρ is assumed to be constant along the entire beam path. At PANDA, this will certainly not be the case, so that the equation is instead

$$\frac{1}{\tau_{\text{gas}}} = \frac{\sigma}{t} \int_0^s \rho(x) dx, \quad (\text{C.3})$$

with t being the time the beam spends in the accelerator, s the corresponding distance and x as an integration variable. Since HESR is a synchrotron the beam will pass k times through the same distance d with the round trip time t_d and the gas density $\rho(x)$, the equation can be expressed as

$$\frac{1}{\tau_{\text{gas}}} = \frac{\sigma}{k \cdot t_d} k \cdot \int_0^d \rho(x) dx. \quad (\text{C.4})$$

The integral can be identified as the gas thickness ϕ (cf. eq. (3.22)) so that

$$\frac{1}{\tau_{\text{gas}}} = \frac{\sigma}{t_d} \phi \propto \phi. \quad (\text{C.5})$$

C. The beam lifetime

The thickness is constituted of the target thickness, the rest-gas contribution and the gas contained in the rest of the accelerator. However, under the assumption that the HESR will be operated at extremely high vacua in the range of $1 \cdot 10^{-8}$ mbar to $1 \cdot 10^{-10}$ mbar, this last contribution can be neglected so that

$$\tau \propto \frac{1}{\phi} = \frac{1}{\phi_{\text{target}} + \phi_{\text{rest-gas}} + \phi_{\text{acc}}} \approx \frac{1}{\phi_{\text{target}} + \phi_{\text{rest-gas}}}. \quad (\text{C.6})$$

Now that the relationship between beam life time and gas thickness is clear, one can calculate the amount of time (t_n) it takes until $1/n$ of the beam is left with the help of eqs. (C.1) and (C.5):

$$t_n = \ln(n)\tau \propto \frac{\ln(n)}{\phi}. \quad (\text{C.7})$$

Now, to determine how much longer the accelerator beam survives with cryopump (t_{cryo}) than without ($t_{\text{no cryo}}$), one can compute:

$$\frac{t_{\text{no cryo}}}{t_{\text{cryo}}} = \frac{\phi_{\text{cryo}}}{\phi_{\text{no cryo}}}. \quad (\text{C.8})$$

With ϕ_{cryo} being given by

$$\phi_{\text{cryo}} = \phi_{\text{target}} + \phi_{\text{rest-gas}} = 2.00 \cdot 10^{15} \text{ atoms/cm}^2 + 1.11 \cdot 10^{15} \text{ atoms/cm}^2 \quad (\text{C.9})$$

$$= 3.11 \cdot 10^{15} \text{ atoms/cm}^2 \quad (\text{C.10})$$

and analogously $\phi_{\text{no cryo}}$ by

$$\phi_{\text{no cryo}} = \phi_{\text{target}} + \phi_{\text{rest-gas}} = 2.00 \cdot 10^{15} \text{ atoms/cm}^2 + 1.86 \cdot 10^{15} \text{ atoms/cm}^2 \quad (\text{C.11})$$

$$= 3.86 \cdot 10^{15} \text{ atoms/cm}^2. \quad (\text{C.12})$$

Inserting these values into eq. (C.8) finally leads to a ratio of 80 % which means that the beam survives 20 % longer with cryopump.

D. CFD simulation materials

In this chapter, relevant material properties for the materials used in the cryopump temperature simulations (cf. section 3.4.2) are listed.

D.1. Stainless steel

This section gives the thermal conductivity and specific heat of stainless steel. These values are temperature independent and taken from the materials database supplied by Autodesk CFD.

Table D.1.: thermal conductivity (κ) and and specific heat (c_P) of stainless steel.

Thermal conductivity in $\text{W}/(\text{m} \cdot \text{K})$	Specific heat in $\text{J}/(\text{gK})$
16.2	0.5

D.2. Polytec 433

This section gives the thermal conductivity and and specific heat of the adhesive Polytec TC 433. The value for the thermal conductivity was taken from its data sheet (cf. [Poly 23]), which unfortunately does not provide a value for the specific heat. Similar Epoxy resins show specific heats in the range of tenths of $\text{J}/(\text{gK})$ for cryogenic temperatures [Sche 85], so that an estimation could be made.

Table D.2.: thermal conductivity (κ) and and specific heat (c_P) of the adhesive Polytec TC 433.

κ in $\text{W}/(\text{m} \cdot \text{K})$	Specific heat in $\text{J}/(\text{gK})$
2	0.1

D.3. Activated charcoal

This section gives the thermal conductivity and specific heat of activated charcoal. The value for the thermal conductivity was taken from [Verm 19], while the specific heat stems from [Anup 13].

Table D.3.: The thermal conductivity of activated charcoal in dependence of temperature.

Temperature in K	Thermal conductivity in W/(mK)
4.5	0.30
10	0.35
20	0.39
40	0.42
60	0.45
80	0.48
100	0.50
150	0.54
200	0.57
250	0.60
300	0.63

Table D.4.: The specific heat of activated charcoal in dependence of temperature.

Temperature in K	Specific heat in J/(gK)
124.9	0.60
155.0	0.66
260.2	0.93
311.7	1.10

D.4. Copper

D.4.1. Specific heat

The specific heat in units of J/(gK) of copper is calculated by a series of equation given in [Arbl 15], each one relevant for a certain temperature range. The resultant values are given in table D.5.

4.2 to 30 K

$$c_P = 6.94000 \cdot 10^{-4}T + 4.76249 \cdot 10^{-5}T^3 + 1.05866 \cdot 10^{-9}T^5 + 1.02870 \cdot 10^{-10}T^7 - 1.68191 \cdot 10^{-13}T^9 + 9.01270 \cdot 10^{-17}T^{11} - 1.13003 \cdot 10^{-20}T^{13} \quad (\text{D.1})$$

30 to 50 K

$$c_P = 4.13788 - 0.457798T + 1.73771 \cdot 10^{-2}T^2 - 1.81035 \cdot 10^{-4}T^3 + 6.57663 \cdot 10^{-7}T^4 \quad (\text{D.2})$$

50 to 70 K

$$c_P = -3.44481 + 2.71874 \cdot 10^{-2}T + 5.82694 \cdot 10^{-3}T^2 - 5.92990 \cdot 10^{-5}T^3 \\ + 2.93875 \cdot 10^{-7}T^4 \quad (\text{D.3})$$

70 to 100 K

$$c_P = -11.52550 + 0.418850T - 1.13549 \cdot 10^{-3}T^2 - 5.92034 \cdot 10^{-5}T^3 \\ - 2.93875 \cdot 10^{-8}T^4 \quad (\text{D.4})$$

100 to 200 K

$$c_P = -15.14608 + 0.577212T - 3.639869 \cdot 10^{-3}T^2 + 1.12101 \cdot 10^{-5}T^3 \\ - 1.363615 \cdot 10^{-8}T^4 \quad (\text{D.5})$$

200 to 298.15 K

$$c_P = 6.33481 + 0.162424T - 5.78862 \cdot 10^{-4}T^2 + 9.95052 \cdot 10^{-7}T^3 \\ - 6.62868 \cdot 10^{-10}T^4 \quad (\text{D.6})$$

Table D.5.: The specific heat of copper in dependence of temperature.

Temperature in K	Specific heat in J/(gK)
4	$0.9 \cdot 10^{-4}$
10	$8.7 \cdot 10^{-4}$
20	$7.3 \cdot 10^{-3}$
30	$2.7 \cdot 10^{-2}$
40	$5.9 \cdot 10^{-2}$
50	$9.7 \cdot 10^{-2}$
60	$1.3 \cdot 10^{-1}$
70	$1.7 \cdot 10^{-1}$
80	$2.0 \cdot 10^{-1}$
90	$2.3 \cdot 10^{-1}$
100	$2.5 \cdot 10^{-1}$
110	$2.7 \cdot 10^{-1}$
120	$2.9 \cdot 10^{-1}$
130	$3.0 \cdot 10^{-1}$
140	$3.1 \cdot 10^{-1}$
150	$3.2 \cdot 10^{-1}$
160	$3.3 \cdot 10^{-1}$
170	$3.4 \cdot 10^{-1}$
180	$3.4 \cdot 10^{-1}$
190	$3.5 \cdot 10^{-1}$
200	$3.6 \cdot 10^{-1}$
210	$3.6 \cdot 10^{-1}$
220	$3.6 \cdot 10^{-1}$
230	$3.7 \cdot 10^{-1}$
240	$3.7 \cdot 10^{-1}$
250	$3.7 \cdot 10^{-1}$
260	$3.8 \cdot 10^{-1}$
270	$3.8 \cdot 10^{-1}$
280	$3.8 \cdot 10^{-1}$
290	$3.8 \cdot 10^{-1}$
300	$3.8 \cdot 10^{-1}$

D.4.2. Thermal conductivity

The thermal conductivity is taken from [Simo 92] for copper with a purity of $\text{RRR} = 30$, the lowest value given. RRR stands for residual-resistance ratio and is given by following ratio $\text{RRR} = R_{300\text{K}}/R_{0\text{K}}$, where $R_{300\text{K}}$ and $R_{0\text{K}}$ are the material's electric resistivities at 300 K and 0 K. As of writing, the exact copper which will be used for the cryopump as well as its purity are unknown, so it appears prudent to perform the simulations with an impure one with correspondingly low thermal conductivities.

Table D.6.: The thermal conductivity of copper in dependence of temperature.

Temperature in K	Thermal conductivity in W/(m · K)
10	454
12	541
14	624
16	703
18	777
20	843
25	960
30	999
35	970
40	900
45	814
50	731
60	597
70	513
80	465
90	437
100	421
150	396
200	391
250	388
300	386

E. Experimental results of cryobending

E.1. Bending angles in dependence of pressure and distance

Table E.1.: Bending angles α in dependence of pressure at varying distances d between bending nozzle and target beam. (Experimental data taken from [Hann 24]).

p_{He} in bar	d in cm	α in $^{\circ}$	Th. prediction in $^{\circ}$
1	2.0 ± 0.1	1.9 ± 0.2	3.5
2	2.0 ± 0.1	3.0 ± 0.2	7.0
3	2.0 ± 0.1	7.1 ± 0.2	10.5
4	2.0 ± 0.1	8.2 ± 0.2	13.8
5	2.0 ± 0.1	12.3 ± 0.2	17.1
6	2.0 ± 0.1	21.9 ± 0.2	20.3
7	2.0 ± 0.1	27.0 ± 0.2	23.3
1	3.0 ± 0.1	-	2.4
2	3.3 ± 0.1	1.7 ± 0.2	4.3
3	3.1 ± 0.1	3.5 ± 0.2	6.9
4	3.1 ± 0.1	4.5 ± 0.2	9.1
5	3.2 ± 0.1	11.8 ± 0.2	11.0
6	3.2 ± 0.1	14.8 ± 0.2	13.1
1	5.4 ± 0.1	-	1.3
2	5.4 ± 0.1	0.5 ± 0.2	2.7
3	5.3 ± 0.1	1.5 ± 0.2	4.1
4	5.3 ± 0.1	2.6 ± 0.2	5.4
5	5.4 ± 0.1	6.5 ± 0.2	6.6
6	5.4 ± 0.1	13.3 ± 0.2	7.9

E.2. Beam stability in dependence of bending pressure

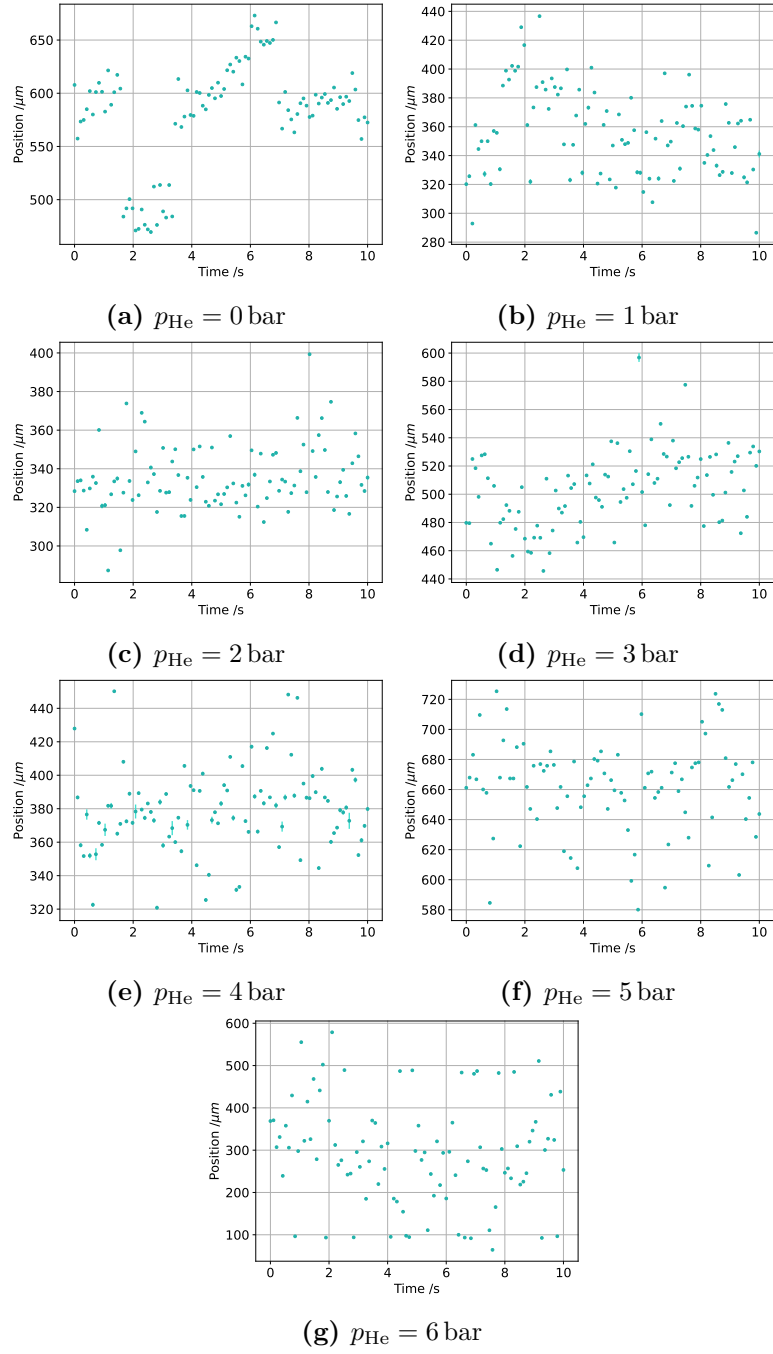


Figure E.1.: The beam fluctuation over time for different helium bending pressures.
(Taken from [Hann 24])

E.3. Materials found in nozzle blockages

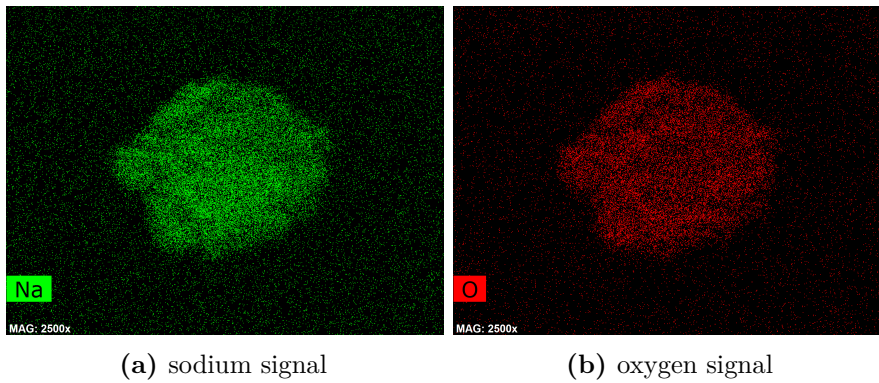


Figure E.2.: EDX pictures of a nozzle blockage made up of a form of sodium oxide.

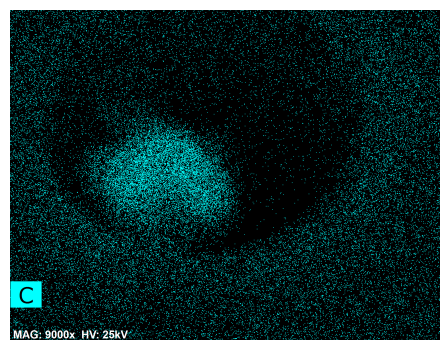


Figure E.3.: EDX pictures of a nozzle blockage made up of carbon

F. The focus volume of a Gaussian beam

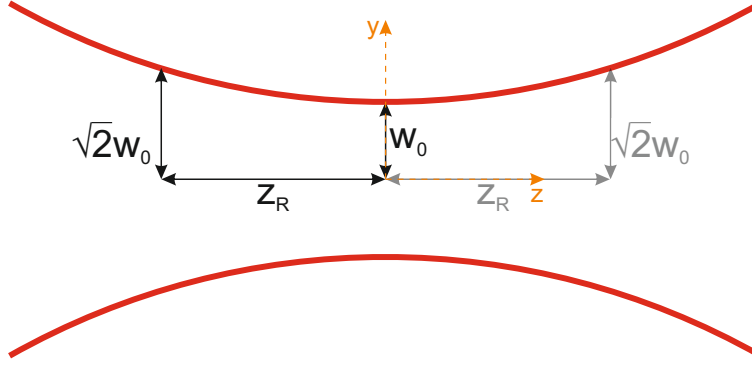


Figure F.1.: Sketch of a gaussian beam with all relevant values for the current computation

The shape of a gaussian beam is shown in fig. F.1. The beam width $w(z)$ along the z -axis is described according to [Sale 08]

$$w(z) = \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \quad (\text{F.1})$$

where the Rayleigh range is given itself by

$$z_R = \frac{\pi w_0 n}{\lambda}. \quad (\text{F.2})$$

Here, w_0 is the waist radius, n the medium's refraction index and λ the laser wavelength. The depth of focus is defined as the axial distance where the beam width is no larger than $\sqrt{2}w_0$, which is given by z_R . To calculate the volume contained in this focus, disc integration [Eric 24] is used so that

$$V_{\text{focus}} = \pi \int_{-z_R}^{z_R} w(z)^2 dx \quad (\text{F.3})$$

$$V_{\text{focus}} = \pi w_0^2 \int_{-z_R}^{z_R} 1 + \left(\frac{z}{z_R}\right)^2 dx \quad (\text{F.4})$$

$$V_{\text{focus}} = \frac{8}{3} \pi w_0^2 z_R. \quad (\text{F.5})$$

F. The focus volume of a Gaussian beam

Plugging in eq. (F.2) finally leads to

$$V_{\text{focus}} = \frac{8}{3}\pi^2 \frac{w_0^4}{\lambda} n \quad (\text{F.6})$$

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When talking about the AG Khoukaz I have up to now omitted the part which

¹at the very least in my mother's book

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²which is in itself a statement about your work and my own cognitive abilities

Eidesstattliche Erklärung

Hiermit versichere ich, dass die vorliegende Arbeit über *The next generation of cryogenic hydrogen targets: Innovations surrounding target systems for particle and plasma physics* selbstständig verfasst worden ist, dass keine anderen Quellen und Hilfsmittel als die angegebenen benutzt worden sind und dass die Stellen der Arbeit, die anderen Werken - auch elektronischen Medien - dem Wortlaut oder Sinn nach entnommen wurden, auf jeden Fall unter Angabe der Quelle als Entlehnung kenntlich gemacht worden sind.

(Datum, Unterschrift)

Ich erkläre mich mit einem Abgleich der Arbeit mit anderen Texten zwecks Auffindung von Übereinstimmungen sowie mit einer zu diesem Zweck vorzunehmenden Speicherung der Arbeit in einer Datenbank einverstanden.

(Datum, Unterschrift)

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