Development of a Hydrogen Pellet Target for the PANDA Experiment

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Abstract

The aim of the proposed PANDA detector at the new FAIR facility is to study the strong interaction in the annihilation of antiprotons with protons. The physics goals put stringent requirements on all detector parts. This thesis concentrates on the aspect of the target and its implementation into PANDA. In particular the consequences of introducing a target consisting of frozen hydrogen droplets, so-called pellets, into the PANDA arrangement are discussed. Since PANDA is planned as an internal detector inside a storage ring particular attention has to be paid to the vacuum conditions at the point where the target interacts with the antiproton beam. A vacuum system allowing to measure the background pressure under conditions realistic for the PANDA detector was designed and installed at the Pellet Test Station at TSL Uppsala. Pellet beam studies carried out at the existing WASA pellet target show that with the average target density already achieved the luminosity at the PANDA detector will reach its design value of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$. The performance of the pellet target is limited by the angular divergence of the pellet stream, making further optimization studies necessary.
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Chapter 1

Introduction

The most accepted theory of the strong interaction is called Quantum Chromodynamics. It is very successful in describing the high energy regime while its prediction power for low energy phenomena is still insufficient. The study of exotic matter like glueballs and hybrids, i.e. bound states containing excited glue, is hoped to give deeper insight into its properties. Theoretical models like Lattice Quantum Chromodynamics simulations predict the glueball spectrum to start between 1 GeV and 2 GeV [1]. For this mass range a large amount of data is available, and first successes in the identification of glueballs are believed to be made by experiments like CRYSTAL BARREL or OBELIX [2]. The majority of glueballs are predicted to have higher masses between 2 GeV and 5 GeV. Up to date, however, the experimental study of this mass region by hadron spectroscopy has been relatively scarce. One of the aims of the PANDA project [3] is to perform high-accuracy meson spectroscopy in this mass range to either verify or exclude the expected states. PANDA is an internal experiment inside the HESR ring at GSI Darmstadt and will use the gluon-rich environment of proton-antiproton collisions to collect data of exotic matter with high statistics.

The detector’s 4π-geometry together with the necessity to use pure hydrogen as target element make it a demanding task to construct an adequate target system. A design luminosity of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$, corresponding to an average target density of about $3 \times 10^{15}$ hydrogen atoms/cm$^2$ is to be reached while at the same time the background pressure has to stay sufficiently low for storage ring operation. Gas-target systems need to be significantly improved to fulfill those requirements. Therefore a hydrogen pellet target as developed for the WASA detector at TSL Uppsala seems to be a promising
alternative.

The principle of operation of such a pellet target system is to introduce frozen droplets of hydrogen into the ion beam via a narrow pipe system: A jet of liquid hydrogen is injected into a helium environment at conditions close to its triple point. It is broken up into droplets of about 30\(\mu\)m diameter by acoustical excitations from a piezoelectric transducer. The micro-spheres are then injected into vacuum via a glass capillary where they experience an angular spread arising from turbulences in the gas flow. They freeze on their way to a skimmer that removes pellets with too high deviation, thus forming a collimated beam. At a distance of about 2 m below the skimmer the pellets intersect the ion beam and are finally collected in a dump.

In order to proof the suitability of a pellet target system for the PANDA detector both a sufficiently high average target density and a low enough background pressure spoiling the beam pipe have to be guaranteed. The Pellet Test Station at TSL Uppsala, a facility similar to the one installed at the WASA detector was built to allow further research and development on the pellet target. It was chosen for studies on background pressure, with a suitable vacuum system to be designed and installed. This system simulates vacuum conditions expected at the PANDA detector by providing the same effective pumping power in the interaction region. A number of pressure gauges allow to survey the pressure at this point as well as along the pellet beam.

Investigations concerning pellet beam properties were carried out at the WASA pellet facility. From numerical simulations based on pellet beam profiles an average target density of about \(4.5 \times 10^{15}\) hydrogen atoms/cm\(^2\) results. For the conditions envisaged at the PANDA detector this corresponds to a mean luminosity of \(3 \times 10^{32}\) cm\(^{-2}\)s\(^{-1}\). Future research should focus on a reduction of beam divergence and on providing smaller pellets at a higher rate.
Chapter 2

PANDA Project

Exact spectroscopy on exotic hadronic matter like glueballs will help to improve our understanding of Quantum Chromodynamics. The PANDA collaboration will study those gluonic excitations in proton-antiproton collisions using a universal 4π-detector scheduled to be installed at GSI Darmstadt by 2011. Investigations in order to determine which internal target systems are suited best to fulfill the stringent requirements of the PANDA detector are currently carried out.

2.1 Physics Motivation

The theory of the strong interaction accepted today is Quantum Chromodynamics (QCD). It is very successful for high energy phenomena, where perturbation theory describing the interaction between quarks via the exchange of gluons in close analogy to Quantum Electrodynamics (QED) can be applied. For low energies, however, we enter the regime of strong coupling and encounter a number of phenomena representing open problems to date.

One of the most significant is the origin of hadronic mass: The summed masses of the quarks composing a hadron make up only a small fraction of the mass of the hadron itself. The fact that, in contrary to the charge-less photons in QED, gluons themselves carry color charge leads to the theoretical prediction of glueballs and hybrids. Glueballs are predominantly excited states of glue, while hybrids are resonances consisting largely of a quark, an antiquark and excited glue. The additional degrees of freedom carried by gluons allow glueballs and hybrids to have spin-exotic quantum numbers.
$J^{PC}$, e.g. $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$. These are forbidden for normal mesons and other fermion-antifermion systems, thus enormously facilitating their experimental discrimination from $q\bar{q}$ states. The fact that glueballs consist only of gluonic matter makes them an ideal field of investigation for mass creation. Obtaining precise information about their spectrum, which Lattice-QCD calculations predict to start at about 1.5 GeV [1], is thought to be the key for a deeper understanding.

The production of glueballs with rates sufficient for high statistics measurements requires a gluon-rich environment. The most adequate reactions to provide this are radiative decays of the $J/\Psi$ charmonium ($c\bar{c}$) states and proton-antiproton annihilations. The energetic limitation of the former given by the mass of $J/\Psi$ of 3.1 GeV leaves $p\bar{p}$-annihilations as the option of choice for full-range studies of the glueball spectrum.

2.2 FAIR at GSI

A new Facility for Ion and Antiproton Research (FAIR) is planned at GSI (Gesellschaft für Schwerionenforschung) Darmstadt. It shall provide high intensity and high brightness beams for research in nuclear and hadronic structure physics and will consist of a 1100 m circumference double ring synchrotron facility (100 Tm and 300 Tm respectively), based on fast ramped (4 T/s and 1 T/s) superconducting dipole magnets. Protons accelerated in this ring will allow the production of antiprotons to be stored in a second High Energy Storage Ring (HESR). The AntiProton Annihilations at Darmstadt-project (PANDA), an international collaboration of 44 institutes, will use this ring for proton-antiproton collisions to perform high-precision tests of the strong interaction [3].

2.3 PANDA Detector

The reactions envisaged to be studied in the experimental program of the PANDA detector lead to a high number of final state particles. For the reconstruction of the initial state and the determination of its quantum numbers all of them have to be analyzed. In order to keep the probability for complete particle detection high a nearly full coverage of the solid angle by the detector is mandatory. Further requirements are good particle identification and
excellent energy resolutions for charged particles and photons. The proposed detector (see Fig. 2.1) is divided into the target spectrometer consisting of a solenoid around the interaction region and a forward spectrometer based on a dipole to momentum-analyze the forward-going particles. This combination of two spectrometers allows full angular coverage as well as a good energy resolution of the detected particles.

(a) View from above.

(b) View from the side.

**Figure 2.1:** Schematic overview of the PANDA detector: The target spectrometer including straw tube tracker, calorimeter, solenoid coil, iron yoke and muon counter is shown to the left. A dipole magnet (center) and a forward calorimeter (right) allow a momentum analysis of the particles emitted in forward direction.
The spatial requirements on the target system are to a large extent defined by the target spectrometer, which will measure particles emitted with laboratory polar angles larger than 5°. Surrounding the interaction volume it is currently planned to have 4 diamond or silicon start detectors (each 20 mm × 30 mm) followed by 5 layers of a silicon micro-vertex detector. Starting from a radial distance of 15 cm from the beam line up to 42 cm, 15 double-layers of crossed straw tubes that extend from 40 cm upstream to 110 cm downstream of the target will be installed. As an alternative a time projection chamber is discussed. At a radial distance of 45 cm a cylindrical DIRC (Detection of Internally Reflected Cherenkov radiation) follows. The forward region will be covered by a Cherenkov detector read out by gas based photon detectors. These detectors are surrounded by an electromagnetic calorimeter consisting of PbWO₄ crystals that are read out with avalanche photo-diodes. In the region between the calorimeter and the end-cap there will be two sets of mini drift chambers. The whole target spectrometer is contained in a 2.5 m long solenoid of 90 cm radius. Behind the return yoke there will be scintillating bars for muon identification.

2.4 Target System

The restrictions caused by a detector located inside a storage ring and the dense detector arrangement make high demands onto the target system. The standard internal target systems currently used in storage rings include gas- and solid targets and are discussed in Chap. 3.

At the PANDA detector two different targets systems, a nuclear target for the study of in-medium reactions of different particles and a hydrogen target for proton-antiproton collisions are to be installed. For the former the wider range of possible target materials permits the use of a fiber or wire target. For the proton target however pure hydrogen as target material is mandatory, making it difficult to provide the required average target density while at the same time keeping the background pressure in the beam pipe, which contributes to background reactions, sufficiently low. A conventional cluster-jet target has to be improved compared to existing targets in order to reach the parameters desired by PANDA (see Sec. 3.2.2).

The novel development of a pellet target as described in Chap. 4 seems to offer a promising alternative.
In addition experimental studies concerning the development of superfluid helium target are currently carried out at the University of Frankfurt. A decision which target systems will be used for the different physics questions has to be answered during the R&D phase.

![Image](image.jpg)

**Figure 2.2:** Display of a possible arrangement of a pellet target inside the detector, showing pellet- and ion beam tubes, straw tube tracker and micro vertex detector.

### 2.4.1 Requirements

The dense assembly of detectors in the target spectrometer will leave minimal room for the internal target system. The basic geometrical properties are the diameter of the beam pipe which for the current proposal is 20 mm at the intersection. The beam pipe opens up in backward direction in several steps to 35 mm, 70 mm and 140 mm diameter in order to provide sufficient pumping power. In forward direction its diameter stays at 20 mm diameter until the end of the vertex tracker at a distance of 200 mm from the interaction point, where it will increase to 40 mm. A sketch of vacuum system inside the detector resulting from these specifications is shown in Fig. 5.1.

The design luminosity for the experiments envisaged at the PANDA detector is $2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$. Given a stored number of $10^{11}$ antiprotons cycling in the HESR at a repetition frequency of $7 \times 10^{9} \text{ Hz}$ this requires an average target density of about $3 \times 10^{15} \text{ hydrogen atoms/cm}^{2}$. 
Chapter 3

Internal Targets

Storage-ring operation with the combination of thin internal targets and phase-space cooling in the stored beam allows high-precision experiments to be made under very clean conditions. In addition optimal use of expensive beam particles like antiprotons is guaranteed.

Generally internal targets for storage rings can be divided into gas targets and solid targets. The main advantage of gas targets is that the target beam evenly covers the whole area of the ion beam; their disadvantages lie in the background caused by the pressure bump around the target beam, the solid angle lost for detection due to differential pumping and the limited target thickness. Solid targets are locally very thick, but occupy only a small fraction of the ion beam. Their main advantages lie in the large solid angle available for detectors, the possibility for high average target thickness and the fact that they do not affect the ring vacuum. Limited beam lifetimes and low duty-factors are seen as the main drawbacks in using these targets. In case an experiment requires a target material that is liquid or gaseous under normal conditions but should at the same time benefit from the advantages of a solid target, a pellet target, providing the appropriate substance in frozen form can be used [5].

3.1 Experimental Requirements

When building accelerators and targets it is important to remember that the main goal is to optimize the conditions for the physics experiments to
be made. The figure of merit for accelerator experiments is usually the luminosity, i.e., the target thickness (number of target atoms/cm$^2$) times the particle-beam intensity (number of projectiles passing through the target per second). The total reaction rate in the target is then given by the product of the luminosity and the total cross section for all reactions.

In a given experiment, one is normally interested in only a few specific, usually rare, channels. The detected count rate for each of these channels is obtained as the product between luminosity, differential cross section and detector efficiency integrated over the solid angle covered by the detector. The quality of the experiment is however not only given by the count rate but strongly dependent on other factors like background, energy resolution and angular resolution. These factors become of increasing importance in high-sensitivity experiments like on rare reactions and decays and in high-precision experiments.

Based on these considerations a number of - partially conflicting - requirements on internal targets for storage-ring experiments arise. The target should be sufficiently thick to provide a high luminosity. At the same time it should be thin enough not to heat the beam and decrease its lifetime too rapidly and to let heavy recoil products escape and be detected. To reduce background signals to a minimum the region around the target should be free of non-target material like narrow collimators, windows or support structures, and the disturbance of the ring vacuum should be kept at a minimum. From the experimental point of view, either a specific target material or a wide range of available materials may be required. In order to minimize the probability of particles escaping detection a large solid angle around the target being available for detector arrangement is desirable. This factor becomes increasingly important in case a higher number of particles need to be detected for the reconstruction of the reaction. Finally, most experiments require a well defined reaction vertex.

Obviously it is impossible to fulfill all those requirement with one target system, and a trade-off between the different advantages and disadvantages has to be made. Which system is to be chosen depends on the specific needs of an experiment.
3.2 Gas-Jet Targets

Gas-jet targets can be divided into the 'basic' molecular-beam targets, supersonic gas-jet targets and cluster-jet targets. If we assume a distance of 25 cm between the nozzle and intersection point between target beam and circulating beam to allow for differential pumping, a target thickness of $10^{12}$ atoms/cm$^2$ may be reached in case of molecular effusion through a nozzle. At higher input pressures we get a supersonic gas jet which at room temperature reaches thicknesses of typically $10^{13}$ atoms/cm$^2$. Another factor of 10 may be obtained by cooling the nozzle in the so-called cluster jet target. As molecular-beam targets are sparsely utilized in modern applications we will focus our discussion on the two latter target types.

3.2.1 Supersonic Gas-Jet Targets

Supersonic gas-jet targets are mainly used for experiments at extracted beams at a number of low-energy accelerators. In these set-ups different gases may be pressed through a tube and nozzle, passing a skimmer and being collected in a catcher. As there is only a narrow space for the ion beam to pass between the skimmer and catcher the detectors can occupy only a small solid angle in the horizontal plane. The closeness to the nozzle exit allows to achieve higher target thicknesses than for molecular-flow-targets, typically in the order of $10^{13}$ atoms/cm$^2$, but also reduces the solid angle available for detection.

Another drawback is the high pressure in the target region, in the order of $10^{-4}$ mbar, which is not compatible with storage-ring operation. To reach acceptable vacuum conditions inside the ring a number of differentially pumped stages on each side of the target region have to be added. These pumping stages require narrow tubings along the beam pipe, thus increasing the problem of background count rates and reducing the flexibility of mounting external detectors. Additionally, the dimensions of the gas target give a less definite vertex and contribute to the background.

3.2.2 Cluster-Jet Targets

The cluster beams in this kind of targets are formed by pressing a gas at temperature and pressure conditions close to its phase transition to liquid through a trumpet-shaped nozzle. The central part of the target beam is
forming large, weakly bound aggregates of typically $10^5$ atoms, so-called clusters. By using this technique one obtains a dense, well-collimated cluster-jet beam with target thicknesses of typically $10^{14}$ atoms/cm$^2$ [6]. This value needs to be improved by about one order of magnitude to meet the requirements of the PANDA detector (see Sec. 2.4.1).

The typical distance between the cluster-jet nozzle and the interaction region is in the order of 20 cm, causing less restrictions for wide-angle detection than supersonic gas-jet targets. Due to the constraints set by the PANDA detector’s 4$\pi$-geometry, however, this distance has to be increased as well. When trying to achieve those improvements special attention to the ring vacuum has to be paid, as the current proposal does not allow for differential pumping inside the detector.

The lateral spread of the hydrogen cluster in the target region is hoped to be optimized to less than 10 mm. The use of a focused ion beam defines the interaction point transversely, however, the need for reconstruction for the longitudinal degree of freedom is a problem.

Similar to other gas targets the main advantage of a cluster jet target is the homogeneous density profile, leading to constant luminosity and count rate. The possibility to use different gases as target elements provides the option to use it as nuclear target as well.

### 3.3 Polarized Targets

Important additional information on the nuclear interactions may be obtained in experiments using polarized targets and polarized beams. A general problem, however, is that the luminosities available in non-polarized experiments can not be reached this way. The polarized atomic-beam target may be obtained by state selection in multi-pole magnets or by optical pumping induced by laser light.

To increase the target thickness, the polarized target atoms may be introduced into a storage cell (compare Fig. 3.1). The gain factor in target thickness of 10 – 100 compared to polarized targets without storage cell has to be paid off by several drawbacks: As there is no dump for the injected gas the vacuum in the storage ring is affected. To keep the outflow of gas low, the pipes along the ion beam should be narrow, what may cause problems with background and beam operation. The increased target length results in an undefined reaction vertex, and the cell walls may disturb the reaction prod-
ucrets. Special attention also has to be paid to the wall coating and cooling to keep recombination and depolarization at low values.

![Diagram of a storage-cell with openings for the gas injection and the circulating beam.](image)

**Figure 3.1:** Schematic diagram of a storage-cell with openings for the gas injection and the circulating beam.

### 3.4 Solid Targets

The solid targets developed or under development for storage-ring experiments are in the form of thin fibers (or micro-ribbons) and micro-particle beams. Frozen micro-droplets, so called pellets, may be seen as a special case of the micro-particle targets.

The solid targets are locally very thick, of order $10^{17} - 10^{19}$ atoms/cm$^2$, but taking into account the ratio between the target area and stored-beam area, the effective target thickness comes into the range acceptable for storage-ring operation. A reduction of the effective target thickness may also be obtained in the case of fibers by a periodic sweeping of the beam over the target or reversely the target over the beam.

#### 3.4.1 Fiber Targets

The use of thin fibers as internal targets in storage-ring experiments has the advantages of simple target construction, good vacuum conditions and the possibility for close to $4\pi$ detection of the nuclear reaction products. The limited number of fiber materials and the problems connected with the manufacture and mounting of fibers sufficiently thin not to degrade the circulating beam too rapidly are the main drawbacks in using fiber targets. Furthermore, the detection of heavy recoils is prevented by the large local target thickness of the order of mg/cm$^2$ for fibers with $\mu$m diameters.
3.4.2 Micro-particle Targets

There are different ways of introducing micro-particles into the circulating beam. These so-called dust targets may be used in a storage cell, much the same as the storage cells mentioned in connection with the polarized gas targets (compare Fig. 3.1). Problems with charging and the uncontrollable diffusion of dust out to the cell have, however, turned the attention to producing micro-particle beams instead. So-called dust guns have been developed as well as systems for beams of gas-particle mixtures where the gas is differentially pumped off to give a beam of micro-particles. The advantages of the micro-particle targets are that there is very low target heating, that the target thickness can be matched to optimum storage-ring operation and that there are no special vacuum problems; the main disadvantage is the limited number of target substances.

3.4.3 Pellet Targets

In case an experiment requires a specific target material that is not solid at normal temperature and pressure conditions, e. g. hydrogen, an alternative is to introduce frozen droplets, so-called pellets, into the circulating beam. Using this technique the advantages of micro-particle targets like almost full solid angle available for detection and no need for differential pumping in the interaction region are conserved. The only hydrogen pellet target used in regular storage ring operation today was developed at The Svedberg Laboratory (TSL) in Uppsala and will be described in the following chapter.
Chapter 4

WASA Pellet Target

In order to allow the construction of a detector for high-luminosity and high-precision experiments with coverage of almost full solid angle a hydrogen pellet target system has been developed at the CELSIUS storage ring at TSL Uppsala. It produces a collimated stream of frozen hydrogen or deuterium micro-spheres under high-vacuum conditions and is in regular use in experiments at the WASA detector (see e. g. Ref. [7]).

4.1 Development

High-precision experiments on rare decays of light mesons (π and η) as carried out at the CELSIUS storage ring at TSL Uppsala require a solid angle close to 4π sr available for detection. This is provided by the 2 m-diameter central WASA-detector (Wide Angle Shower Apparatus) surrounding the reaction vertex. In addition luminosities of order 10^{32} cm^{-2}s^{-1}, corresponding to an effective target thickness of 10^{15}−10^{16} atoms/cm² are required. The reactions to be studied are proton-proton collisions. In order to minimize background reactions and target interferences with secondaries pure hydrogen has to be used as target element. Since no container walls can be allowed the hydrogen has to travel about 2 m in a narrow tube through the detector before reaching the intersection with the ion beam. Good vertex definition and acceptable perturbations to the stored beam and the ring vacuum are required. A conventional gas- or cluster-jet target has a divergence too large for achieving this.
In 1984 the idea of using a narrow stream of frozen hydrogen microspheres, so-called pellets, was put forward by Sven Kullander. Bertil Trostell got engaged in the pellet target project the same year, and after having studied a similar technique developed for fueling tokamak machines at the University of Illinois at Urbana-Champaign he started building up a pellet target prototype [8]. In 1993 funding for a pellet target test facility at the CELSIUS ring, including a modified version of the pellet generator was obtained. The design, construction, installation and testing were carried out by a group led by Curt Ekström [9]. In connection with the installation of the WASA facility at the CELSIUS ring, led by project manager Hans Calén, the pellet target system was further modified and integrated into the WASA detector. Its start-up after the reconstruction took place in May 1999 and was followed by a period of alignment and optimization for pellet target operation. Since 2000 the system is in regular operation for commissioning and data-taking within the CELSIUS/WASA project, thus being the first and only hydrogen pellet target in use.

4.2 Pellet Beam Formation

The process of pellet generation at the WASA pellet target can roughly be divided into three stages. First hydrogen gas is liquefied and cooled down close to its triple point by a two-stage cryogenic refrigerator. The liquid hydrogen is injected into a low-pressure helium environment in form of a thin jet via a glass nozzle and broken up into uniform droplets by means of acoustic excitations (for a sketch of principal see Fig. 4.1). In the next stage the droplets are injected into vacuum through a narrow capillary while they are cooling further down due to evaporation and freeze to form so-called pellets. Finally a collimated beam of pellets is formed by skimming off the fraction with too high angular deviation. After the interaction with the ion-beam the pellets are collected in a dump.

4.2.1 Droplet Generation

The cooling power is provided by a commercial, closed-cycle He-gas two-stage cryogenic refrigerator. The gaseous hydrogen is injected at pressures of 400 mbar—800 mbar and cooled down to about 50 K in the first stage. In the second stage a heating element is included which is used to regulate the
Figure 4.1: Principal of Pellet Beam Formation: The jet of liquid hydrogen formed by a glass nozzle (1) is broken up into uniform droplets. The injection into vacuum through a narrow capillary (2) causes an angular dispersion. The droplets freeze to pellets on their way to the skimmer (3), where those with too high angular deviation are removed to form a collimated pellet beam. Note: This figure is not to scale!

temperature to approximately 14 K; the hydrogen is thereby liquefied (at a pressure of 400 mbar hydrogen liquefies at 17.5 K).

A thin liquid jet is formed by a borosilicate glass nozzle (see Fig. 4.2) with an inner diameter of 12 μm at its exit. A stainless steel sintered filter is melted into the entrance of the glass nozzle to remove particles that would block the narrow exit. Acoustical excitations from a piezo-electric transducer attached to the nozzle are transmitted to the hydrogen jet, forcing it to break up into uniformly sized and evenly spaced droplets at the excitation frequency (see Fig. 4.3). Typical values lie in the region of 70 – 90 kHz, corresponding to droplets of 35 – 40 μm diameter which move at a speed of about 20 m/s.

The gas in the droplet formation chamber is a mixture of helium as background gas and hydrogen evaporated by the pellets. The total pressure is regulated to about 22 mbar, resulting in a partial pressure for hydrogen of about 8 mbar, i.e. below its triple point of 72 mbar at 13.8 K.

Due to evaporation the temperature of the droplets decreases further causing them to freeze and form pellets. Theoretical models describing the characteristics of the cool-down exist [10, 11], but due to super-cooling the freezing of the droplets is delayed and the exact place where it occurs can
not be calculated straightforward. From optical observations of the droplets’ behavior when hitting solid structures it can be seen that the micro-spheres are still liquid at the upper end of the vacuum injection capillary while they are frozen when they arrive at the skimmer.

**Figure 4.2:** Liquid jet nozzle: Liquid hydrogen enters through a copper channel (1) and passes a stainless steel sintered filter (2). A liquid jet is formed by the glass nozzle (3) and broken up into droplets by a piezo-electric transducer (4).

**Figure 4.3:** Droplet formation chamber: The liquid jet leaving the nozzle (upper part of figure) is broken up into a regular train of uniform droplets which enter the vacuum injection capillary (lower part).
4.2.2 Vacuum Injection

The process of injecting the droplets into vacuum is crucial for the angular distribution of the pellets as well as for their effective rate at the interaction point. The abrupt pressure drop from about 22 mbar in the droplet formation chamber to a vacuum of roughly $10^{-3}$ mbar causes a high speed gas flow which easily deflects or even destroys the fragile droplets while accelerating them to a speed\(^1\) of $60 - 90$ m/s. To minimize those effects a narrow vacuum injection capillary is used. Due to the difficulties in analytically calculating the properties of this continuous flow regime and its interaction with the moving droplets, an experimental approach of determining the optimal shape of the capillary has been chosen. It was found to be cylindrical with a slight contraction at the lower end (see Fig. 4.4), the latter reducing the angular spread of the droplets compared to a purely cylindrical shape. Photographic images taken at this point (compare Sec. 4.3.2) show that the initially spherical droplets experience a slight deformation here. The capil-

\[\text{Figure 4.4: Vacuum injection capillary: The capillary (1) is a glass tube of 7 mm length and 0.8 mm inner diameter contracting to 0.6 mm at its lower end. For matters of thermal insulation it is mounted inside another glass tube (2) which itself is attached to a stainless steel support (3).}\]

\(^1\)The exact value depends on the diameter of the droplets, where speed decreases with increasing size.
lary currently in use is a glass tube of 70 mm length and an inner diameter of 0.8 mm, ending in a contraction of 0.6 mm. It is mounted at a distance of 7 mm below the liquid jet nozzle.

4.2.3 Beam Alignment

After the injection into vacuum the pellet beam shows an angular spread of Gaussian shape (compare Sec. 5.3.1). To obtain a well-defined beam the pellets with too high deviation are removed by a circular skimmer mounted 0.7 m below the vacuum injection capillary. The skimmer can be changed to one of different size in order to vary the pellet beam diameter. Currently in use are skimmers with inner diameters ranging from 0.4 mm—1 mm, corresponding to an angular divergence of 0.6 mrad—1.4 mrad.

Through a pipe of 5 mm inner diameter the pellets reach the interaction point with the ion beam 2.4 m below the vacuum injection capillary. After another 1.2 m flight through a pipe of same size they are collected in a beam dump to avoid perturbations to the ring vacuum when they hit walls and burst into smaller fragments. The scheme of pellet beam alignment is shown in Fig. 4.5.

For the coordinate system used in the following the convention of denoting the direction of the ion beam as $z$-axis is adopted. The $y$-axis is chosen as the direction of the pellet stream, and the $x$-axis as perpendicular to the former two in a way to form a right-handed coordinate system.

The direction of the pellet beam can be changed via two separate coordinate tables of same design. Each of them has four degrees of freedom: Two that allow $\pm 5$ mm movement of the pellet beam in a plane perpendicular to its direction, i.e., in the $x$-$z$-plane; two to tilt it around the $x$- and $z$-axis for $\pm 25$ mrad respectively.\(^2\)

The upper coordinate table carries the liquid jet nozzle, the droplet formation chamber and the cryogenic refrigerator and allows to direct the droplet train into the vacuum injection capillary. The capillary, together with the whole system of the upper coordinate table is mounted on the lower table,

\(^2\)Note: This does not comply with the "internal" denotation of axes for the coordinate table that refers to the two directions in which the pellet beam can be moved as $x$- and $y$-axes.
thus making it possible to move the whole pellet beam and aligning it through the skimmer to the intersection with the ion beam.

Figure 4.5: Pellet beam alignment: The injection through the vacuum injection capillary (1) causes an angular spread of the pellet distribution. Pellets with too high deviation (2) are removed by the skimmer (3), thus forming a well-defined pellet beam (4). The pellet beam radius $R$ widens up linearly with distance $d$ from the vacuum injection capillary (compare Sec. 5.3.3). After the interaction with the ion beam (5) the pellets are collected in the pellet dump (6). The diagram shows the case of a skimmer with an inner diameter of 0.59 mm. The pellet beam diameter at the intersection with the ion beam is about 2 mm. Note: The axes for pellet beam radius and vertical distance are not to scale.

4.3 Diagnostics

Optical access to the droplet- and pellet beam is needed at several points to ensure its correct alignment and to allow the measurement of its properties. This is provided by a number of windows included into the vacuum system. Each observation point consists of four windows for the installation of diagnostic instruments on two perpendicular axes.
4.3.1 Droplet Train Imaging

The first set of windows is embedded into the droplet formation chamber to observe the droplet train. This is either done with a video camera or a digital photo camera equipped with a macro photo lens allowing to take pictures with magnification ranging from 1 to 5. For photos a flash lamp with flash duration of 100 ns is used. For video observation the droplets are lighted by stroboscope white light. The stroboscope light source is made of a standard diode lamp emitting light pulses of about same duration as the photo flash. The pulses are triggered by the jet excitation frequency for “frozen” visual observation, i.e. droplets are at the same spot each time the light is activated.

The images of the video camera are used to align the train of micro-spheres into the vacuum injection capillary, while pictures of the photo camera allow to determine size and velocity of the droplets. The distance between the droplets as well as their size are directly measured from an image with known magnification. Their velocity can then simply be calculated as distance times excitation frequency. An example of a photo taken at the droplet formation chamber is shown in Fig. 4.3.

4.3.2 Vacuum Injection Imaging

As mentioned in Sec. 4.2.2 a part of the the micro-spheres is deflected or destroyed at the vacuum injection, a process very sensitive to the parameters hydrogen driving pressure, excitation frequency and pressure in the droplet formation chamber. For their adjustment an observation point situated directly below the vacuum injection capillary is used. The pellet beam is illuminated by continuous white light and its concentration, indicating the amount of pellets to survive vacuum injection, is imaged by a video camera. For further optimization a pellet counting system (see Sec. 4.3.4) is used.

For detailed studies of single pellets the video camera can be replaced by a digital camera, currently a Fuji Finepix S2 Pro. To achieve the exposure time required by the high speed of the pellets up to 90 m/s a flash light (FX-Xenon from High-Speed Photo System) with flash duration of 100 ns is mounted opposite to the camera. Its light is focused onto the camera by two lenses of 145 mm and 80 mm focal length respectively, allowing to take pictures with discrete pellets. An example for such a picture can be seen in Fig. 4.6.
Figure 4.6: Image after vacuum injection: The micro-spheres have lost their uniformity in both shape and distance. In the upper part of the figure the lower end of the vacuum injection capillary can be seen. For the observation of the droplets' deformation a higher magnification was used.

4.3.3 Alignment at Skimmer

Directly above the skimmer, i.e. 0.7 m below the vacuum injection another set of windows allows the correct alignment of the pellet beam. It is lighted by a diode laser and observed by two video cameras, one at the window opposite to the diode laser and one perpendicular to its direction. The pellet beam can be seen on the image as a light spot, and the lower coordinate table is used to center it onto the skimmer.

4.3.4 Pellet Counter

Below the skimmer a pellet counting system is installed to determine the effective rate of pellets reaching the intersection with the ion beam. Light from a laser diode having a rectangular profile of 5 mm width and 1 mm height is directed onto the pellet beam (see Fig. 4.7). While the laser beam itself is deflected by a mirror, a circular collimator and iris extract the light scattered by the pellets to an angle of about 7°. It is focused by a lens and can either be observed by a camera or directed onto a photo multiplier.
tube, which provides a signal to be further processed by counting electronics. Typical measured pellet rates for hydrogen lie in the region of $9000 \text{ s}^{-1}$.

![Diagram of Pellet Counter]

**Figure 4.7**: Pellet counter: Light from a laser (1) enters through a observation window (2) and is scattered by the pellet beam (3). The scattered light passes a collimator (4) and a lens (5) is used to focus it onto a photomultiplier tube (6) connected to counting electronics (7). The laser beam is deflected by a mirror (8).

### 4.4 Vacuum Conditions

The cryogenic system is enclosed in an outer vacuum chamber, which is evacuated to $10^{-4}$ Pa by a 56 l/s turbomolecular pump. The droplet formation chamber is filled with a mixture of helium and hydrogen at a pressure of typically 22 mbar (see Sec. 4.2.1). A thin walled stainless steel bellows connects the droplet formation chamber to the main vacuum system. This allows the liquid jet nozzle being moved with respect to the vacuum injection capillary by the upper coordinate table. The bellows also serves as thermal insulation between the droplet formation chamber being kept at a temperature of about 15K and the vacuum chamber having room temperature.

Below the capillary high vacuum is generated by two-stage differential pumping, consisting of two 2300 l/s turbomolecular pumps each. The first pair of pumps is located between the vacuum injection and the skimmer, providing a pressure of about $10^{-3}$ mbar. The second pair operates below the skimmer, reaching a pressure on the order of $10^{-6}$ mbar.
Due to the restrictions caused by the narrow beam pipe in the WASA-detector the pressure at the intersection of pellet- and ion-beam, a value crucial for the amount of background reactions, can not be measured directly. A pressure gauge in the scattering chamber, situated at a distance of 0.95 m from the interaction point and close to two 1200 l/s turbomolecular pumps allows to draw only limited conclusions on the actual pressure in the interaction region.

4.5 Deuterium Pellets

The production of deuterium pellets in the WASA target facility is possible as well and can be performed without major changes in the setup used for hydrogen. The triple point of deuterium at 18.63 K/171 mbar lies considerably higher in both temperature and pressure than that of hydrogen. For operation with deuterium it is thus necessary to increase the temperature of the liquid jet nozzle to a value of about 18.9 K to allow a controlled liquefaction of the gas. The optimal pressure in the droplet formation chamber for obtaining a concentrated pellet beam after vacuum injection lies around 50 mbar. Compared to hydrogen the angular spread of deuterium pellets is significantly reduced (compare Sec. 5.3.5), resulting in pellet rates of typically 16000 s⁻¹.

4.6 Pellet Test Station

In order to further develop the pellet target system even during periods when the CELSIUS-ring is operating the construction of a Pellet Test Station (PTS) at TSL in Uppsala was started in 2002. The pellet formation system at the PTS shown in Fig. 4.8, including cryogenic refrigerator, liquid jet nozzle, droplet formation chamber and vacuum injection capillary (compare Secs. 4.2.1 and 4.2.2), equals that of the WASA pellet target to maintain compatibility of components and comparability of results.

However, the lower coordinate table which would allow to move the whole pellet formation system, thereby adjusting the direction of the pellet stream, is missing. The manually operated upper coordinate table, whose main purpose is to align the droplet train coming from the liquid jet nozzle into the vacuum injection capillary, allows to vary the direction of the pellet stream
Figure 4.8: Pellet formation unit: The gaseous hydrogen is liquefied in the cryogenic cold head (1). A liquid jet is formed at the borosilicate glass nozzle (2) and broken up into uniform droplets by acoustical excitations from a piezoelectric transducer (3). The micro-spheres are injected into vacuum via a narrow glass capillary (4). A steel bellows (5) allows to the alignment of the droplet formation chamber (6) with respect to the vacuum injection capillary.

after vacuum injection only to a very restricted extent. This inhibits the compensation of long term drifts caused by minimal changes of the conditions in the droplet formation chamber. It is thus not possible to keep the pellet stream centered onto a fixed skimmer of diameter in the order of the width of the pellet distribution, i. e. about 0.5 mm, to form a well-defined beam as required for storage ring operation. Furthermore, in the beginning of 2004 no lower vacuum system was existent at the Pellet Test Station.
Chapter 5

Studies for PANDA

A target system adequate for the PANDA detector has to meet high demands on average target thickness as well as on target spread and background pressure in the interaction region. As it is not possible to test all these conditions on either the existing WASA pellet target or the Pellet Test Station, the experimental program for this thesis was split up: Studies on pellet beam properties were carried out at the WASA target and the resulting luminosity for the PANDA detector was calculated. For the PTS a vacuum system allowing to measure the background pressure under conditions realistic for PANDA was designed and installed. The main task of this work was to pursue these two objectives.

5.1 General Considerations

In order to proof the suitability of a pellet target system for the PANDA detector the compliance with two main requirements is to be tested (compare Sec. 2.4.1):

- The average target density must be high enough to reach the PANDA design luminosity of $2 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1}$, i. e. about $3 \times 10^{15}$ hydrogen atoms/cm$^2$. In order to keep beam heating low small pellets intersecting the ion beam at high frequencies are preferred to big pellets at low frequencies.

- The background pressure in the interaction region has to be low enough not to degrade the ion beam too rapidly and to keep the amount of
background reactions caused by annihilations with the rest gas low, i.e. the rest gas pressure has to be in the order of $10^{-5}$ mbar or lower. To guarantee a solid angle close to $4\pi$ available for detector arrangement all pumps must be located outside the detector.

The preferred procedure of investigating these two conditions was to perform tests on both of them at the Pellet Test Station to avoid collisions with experimental runs at the WASA detector. However, the absence of the lower coordinate table prohibits the installation of a fixed skimmer with an inner diameter in the order of 5 mm as required to form a collimated pellet beam at the PTS (see Sec. 4.6).

To compensate for this the construction of a movable skimmer, operated by a separate coordinate table, was considered. Several design studies were carried out, but the idea was finally abandoned due to technical difficulties. Studies on properties like pellet beam profiles, average target thickness and luminosity were consequently carried out at the WASA pellet target facility (see Sec. 5.3).

The Pellet Test Station was instead chosen for tests on vacuum conditions: As explained in Sec. 4.4 it is not possible to measure the pressure at the intersection of ion- and pellet beam at the WASA pellet target. Therefore the PTS was equipped with a vacuum system allowing the measurement of the background pressure under PANDA-like conditions.

## 5.2 Background Pressure

After the decision to perform tests on vacuum properties for the PANDA project at the PTS was taken, the design, construction and installation of a vacuum system was started in the beginning of 2004. The objective of this process was to develop a system that allows in a first step the determination of the background pressure caused by a pellet beam under conditions expected at the PANDA-detector, while maintaining the possibility to upgrade the system for further research.
5.2.1 PANDA Vacuum System

The $4\pi$-geometry of the PANDA detector requires all vacuum pumps to be installed outside the detector, i.e. at a distance of 9 m downstream the interaction point in forward and about 2 m upstream in backward directions (compare Sec. 2.3). For a pellet target the only components of the vacuum system inside the PANDA detector would be the horizontal ion- and the vertical pellet beam pipes (see Fig. 5.1). Due to outgassing from the pellets

![Diagram of PANDA Vacuum System](image)

**Figure 5.1:** Vacuum system inside the PANDA detector: The ion beam pipes in forward (1) and backward (2) direction cross the upper (3) and lower (4) pellet beam pipes at the interaction point. Their dimensions as estimated from preliminary studies on detector arrangement are given in mm, where those for (4) should be considered to be equal to those of (3). Pumping power is provided by vacuum pumps (5,6) installed at the outer ends of the ion beam pipes.

...the latter represents a source of gas load, leaving the ion beam tube the only access for pumping power. Its dimensions in the region around the interaction point are determined by the physics requirements for the location of the micro vertex detector. Preliminary values from design studies are 20 mm in forward and 35 mm in backward direction, opening gradually up at larger distance. The diameter of the pellet beam tubes close to the interaction point will be about 6 mm.
5.2.2 Pumping Speed and Conductance

For hydrogen the conductance $C$ for a pipe of circular cross section of diameter $d$ and length $l$ fulfilling $l \gg d$ ('long pipe') in the regime of molecular flow (i.e. $d \cdot \bar{p} < 6 \times 10^{-2}$ mbar-cm with $\bar{p}$ the average pressure) is given as

$$C_{\text{long}} = 45.6 \frac{d^3}{l} \text{1/s}$$  \hspace{1cm} (5.1)

with $l$ and $d$ in cm, and thus independent of the pressure \footnote{The condition $l \gg d$ is not satisfactorily fulfilled for the part of the ion beam pipe in backward direction that is lying closest to the intersection. The formula for the transitional regime ($l \approx d$) has to be used to calculate the conductance to}

$$\frac{1}{C_{\text{tot}}} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_n}$$  \hspace{1cm} (5.2)

As these conditions will be fulfilled\footnote{The condition $l \gg d$ is not satisfactorily fulfilled for the part of the ion beam pipe in backward direction that is lying closest to the intersection. The formula for the transitional regime ($l \approx d$) has to be used to calculate the conductance to} under storage ring operation at the PANDA detector we can calculate the conductances of the pipes shown in Fig. 5.1 to $C_f = 2.8 \text{ l/s}$ for the forward and $C_b = 107 \text{ l/s}$ for the backward direction.

Both pipes will be connected to vacuum pumps at their outer ends. The effective pumping speed $S_{\text{eff}}$ of a pump with pumping speed $S$ connected to the volume of interest over a pipe of conductance $C$ is given as

$$\frac{1}{S_{\text{eff}}} = \frac{1}{S} + \frac{1}{C}$$  \hspace{1cm} (5.3)

Assuming a pumping speed of $S = 2400 \text{ l/s}$ for both pumps this leads to an effective pumping speeds of $S_f = 2.8 \text{ l/s}$ and $S_b = 103 \text{ l/s}$ for forward and backward direction respectively. The total effective pumping speed for PANDA adds up as the sum of those two values to

$$S_{\text{PANDA}} = S_f + S_b \simeq 106 \text{ l/s}.$$  \hspace{1cm} (5.4)
5.2.3 PTS Vacuum System

The design and installation of a vacuum system allowing vacuum measurements for the PANDA-project were started in February 2004. In this process a number of considerations had to be taken into account:

- The gas load of interest is caused by evaporation from the frozen microspheres, both continuously on their way down the beam pipe and due to heating from the interaction with the ion beam. Pellets hitting solid structures like the walls of the beam pipes burst into fragments, a process leading to an increase in pressure largely exceeding the one caused by evaporation. This effect prevents the correct measurement of the latter and has to be strictly avoided.

- At the PANDA detector the vacuum pumps outside the detector act as drain for the outgassing hydrogen. To simulate this situation at the PTS the same effective pumping speed as calculated for the PANDA detector in Sec. 5.2.2 has to be provided.

![Vacuum System Diagram]

**Figure 5.2:** The newly installed vacuum system at the Pellet Test Station shown as rendered 3D-graphics. A detailed description of the different parts is provided in Fig. 5.3.
• After their way through the vacuum system the pellets have to be removed with minimal back-flow of gas.

• In order to measure the background pressure the installation of a pressure gauge close to the (virtual) interaction point is mandatory. Additional diagnostics are needed to analyze possible perturbations of the vacuum and backtrack them to their sources.

• The intended future extension of studies on beam properties should be possible without major changes to the current setup.

An overview over the installed vacuum system can be seen in Fig. 5.3; its different parts are described in the following.
Figure 5.3: The PTS vacuum system: A valve (1) separates the vacuum system from the pellet formation unit. The skimmer (2) situated in the upper observation house (3) removes pellets that would otherwise hit the walls of the connection pipes (4,5). The interaction chamber (6) is connected to a turbomolecular pump (7) over a resistor pipe (8). The lower observation house (9) allows to survey the correct alignment of the pellet beam into the second connection pipe (5). In the pellet dump (10) the micro-spheres are deflected by a cone (11) and removed by another turbomolecular pump (12). A full range pressure gauge (13) is installed at the interaction chamber while each connection pipe is equipped with both a pirani- and a penning pressure gauge (14,15). Two bellows (16,17) allow the alignment of the system. All dimensions are given in \textit{mm}.
Skimmer

The absence of the lower coordinate table forbids a controlled alignment of the pellet stream and in consequence the installation of a fixed skimmer of diameter in the order of 0.5 mm, thus small enough to form a well-collimated pellet beam (see Sec. 5.1). Instead a skimmer large enough for the pellets to pass despite of possible long term drifts of the pellet beam position was designed (see Fig. 5.4).

![Skimmer Diagram](image)

Figure 5.4: Relocatable skimmer: To facilitate the exchange of skimmers with different sizes the skimmer (1) is screwed on a stainless steel plate (2). The plate itself is relocatably mounted onto the bottom flange of the observation house (3) to allow the compensation of permanent misalignment of the pellet stream with respect to the center of the observation house.

The purpose of this skimmer is to remove pellets with high angular deviation that would hit the wall of the beam tube, a process leading to a strong increase of pressure in the interaction region. The smaller fraction of pellets to be skimmed off results in a higher pellet rate below the skimmer and consequently to a higher pressure in the interaction region. Conclusions on the pressure to be expected at pellet rates realistic for storage ring operation can be drawn using the linear correlation of pellet rate and pressure shown in Fig. 5.6.

At the time of design a misalignment at the connection between the pellet formation unit and the vacuum system could not be ruled out. Accordingly a pellet beam not being centered with respect to the observation house could be expected. As it was unclear as well to which extent long term drifts of
the beam position could be compensated using the lower coordinate table, the ideal diameter of the skimmer could not be predicted. The possibility for easy exchange to one of different size should therefore be provided as well as for compensation of a lateral misalignment.

To fulfill those two conditions the skimmer is screwed on a separate stainless steel plate. The plate is mounted onto the bottom flange of the observation house and can be relocated for \( \pm 5 \text{ mm} \) in \( x \)- and \( z \)-direction. The inner diameter of the skimmer currently in use is 7 mm. Both exchange of the the skimmer and adjustment of the plate can be easily carried out after opening the vacuum system.

The installation of the skimmer in an observation chamber provides optical access in \( x \)- and \( z \)-direction. Two video cameras are used to monitor the correct alignment of the pellet stream.

**Interaction Chamber**

The interaction chamber represents the location where in storage ring operation the pellet- and ion beam would intersect (see Fig. 5.3). Therefore the parameter of interest, i.e. the background pressure in the interaction region, has to be measured here.

In order to establish realistic pressure conditions a similar total effective pumping speed as calculated for the PANDA detector in Sec. 5.2.2 has to be provided. This is ensured by a turbomolecular pump of pumping speed \( S = 1200 \text{ l/s} \) being attached to a ‘resistor pipe’. The pipe has an inner diameter of 34 mm and a length of 160 mm, representing a conductivity of 112 l/s (compare Eq. 5.1). The effective pumping speed for the the PTS calculated from Eq. 5.3 comes up as \( S_{PTS} = 104 \text{ l/s} \), thus being sufficiently close to \( S_{PANDA} = 106 \text{ l/s} \).

The interaction chamber is equipped with a full range vacuum gauge consisting of both a pirani- and a penning-element. Its measuring range down to \( 10^{-7} \text{ mbar} \) covers the expected pressures in the interaction chamber of \( 10^{-6} \text{ mbar} - 10^{-3} \text{ mbar} \).

The present purpose of the observation house below the interaction chamber is to survey the position of the pellet beam when entering the lower connection pipe to the pellet dump. This allows a correct alignment, ensuring that no pellets are hitting the pipe walls. For a later upgrade of the system the installation of a pellet counter at this point is planned.
Pellet Dump

The function of the pellet dump is to extract the pellets from the system with the lowest possible back-flow of gas. They are deflected on an acute-angled cone and the outgassing hydrogen is removed by a 1200 l/s turbomolecular pump (see Fig. 5.3). The size of the gap between the beam pipe and the cone is determined by the condition to let descending pellets pass while keeping the probability for deflected pellets to bounce back up into the pipe as low as possible.

Connection Pipes

The connection pipes between skimmer, interaction chamber and pellet dump have to be wide enough to prevent pellets from hitting their walls. Thereby the widening of the pellet beam in analogy to what is shown in Fig. 4.5 for the WASA pellet target as well as a possible eccentricity of the beam with respect to the beam pipes (see subsection ‘Skimmer’ of this section) have to taken into account. At the time of planning the extent of the latter was not clear, and a change in skimmer size would lead to a different beam widening. Accordingly the pipes were designed in a way to be easily changed. For the test setup the inner diameter of the upper beam pipe was chosen to be 16 mm, that of the lower one to 25 mm. For matters of adjustment bellows of same inner diameter were integrated into the pipes (see Fig. 5.3).

Information about the pressure in the connection pipes is necessary to locate the sources of possible perturbations to the vacuum in the interaction chamber like gas flow from the pellet dump. It furthermore allows the verification of evaporation models for the pellets on their way through the pipes. To measure these parameters each a pirani- and a penning pressure gauge are installed at the two cross connections shown in Fig. 5.3.
5.3 Pellet Beam Properties

Detailed information about the pellet beam properties allows to optimize the dimension of the skimmer, thus adjusting quantities crucial for storage ring operation like effective target thickness or pellet beam diameter to the desired values. Based on pellet beam profiles taken at the WASA detector the average target density is calculated. The resulting luminosity is compared to the design value for the PANDA detector of $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$.

5.3.1 Beam Profile

The profile of the uncollimated pellet beam, i.e. before the skimmer, is taken by sweeping it over the skimmer while measuring the number of passing pellets. The beam is tilted by a computer program automatically operating the lower coordinate table, while the pellet rate and the pressure in the scattering chamber are logged.

![Diagram of pellet beam sweeping](image)

**Figure 5.5:** Sweeping of the pellet beam over the skimmer: Using the servo motor $S_\phi$ of the lower coordinate table (1) the vacuum injection capillary (2) and the pellet beam are tilted by an angle $\phi$. The lateral movement $d$ has to be compensated by another servo motor $S_z$ resulting in a total shift $z_0$ at the skimmer (3).

The direction of the pellets to reach the scattering chamber is defined by the maneuverable vacuum injection capillary and the fixed skimmer (see Fig. 4.5). In order to stay in the axis defined by the pellet beam pipe, thus
avoiding pellets to hit the pipe and allowing them to be analyzed by the pellet counter, the vacuum injection capillary has to stay at the same spot in the x-z-plane.

An example for a scan in z-direction is sketched in Fig. 5.5: By operation the servo motor \( S_\phi \) of the lower coordinate table the vacuum injection capillary and with it the pellet beam are tilted by an angle \( \phi \). This causes a lateral shift \( d \) of the capillary, which has to be compensated by the servo motor \( S_z \), resulting in a total beam shift \( z_0 \) at the skimmer.

The number of pellets passing the skimmer can either be determined directly by the pellet counter or by the pressure in the scattering chamber (compare Sec. 4.4). The experimental data for the two different parameters show good agreement, with only a small offset due to background pressure visible for the latter at high \( z_0 \) (see Fig. 5.6). Taking that into account we can assume a linear correlation between pellet rate and pressure in the interaction region. As noise is lower for the pellet rate we will focus on this parameter for further analysis.

![Graph](image)

**Figure 5.6:** Pellet rate and pressure in the scattering chamber versus beam position for a scan in z-direction. Except for some background pressure the two curves show a linear correlation, with lower fluctuations for the pellet rate. Both curves are scaled to a maximum value of 1. Note: If not mentioned otherwise all shown data are for hydrogen.
Profile Shape

The curves obtained by the measurement described in the previous subsection do not represent the actual pellet beam profile, but its convolution with the aperture of the skimmer. As the inner diameter of the skimmer is of the same order of magnitude as the diameter of the pellet beam, this effect has to be accounted for when determining the actual pellet distribution.

Figure 5.7: Simulated pellet beam density $f(x, z)$ after a skimmer of 0.59 mm diameter with displacement $z_0 = 0.1$ mm. The pellet density used is a two-dimensional Gaussian of width $\sigma = 0.15$ mm. The expected pellet rate for this displacement is proportional to the integral over the density, $F(z_0)$.

Assume $f(x, z)$ being the pellet density in a plane perpendicular to the pellet beam. With a circular skimmer of radius $R$ displaced a distance $z_0$ in $z$-direction (i.e. the skimmer is centered at the point $(0, z_0)$ in the $x$-$z$-plane, see Fig. 5.7), the total number of pellets having passed the skimmer as a function of the displacement results as

$$F(z_0) = \int_{x^2 + (z-z_0)^2 < R^2} f(x, z) \, dx \, dz \quad (5.5)$$

To identify which function describes the pellet distribution best different test functions are inserted for $f(x, z)$ and adjusted to give a $F(z_0)$ with same
maximum and full width at half maximum (FWHM) as the experimental data. Due to the difficulties of analytically evaluating the integral in Eq. 5.5 for most functions \( f(x, z) \) the problem is solved numerically. A Gaussian test function

\[
f_g(x, z) = \frac{1}{2\pi \sigma^2} e^{\frac{-z^2}{2\sigma^2}}
\]

(5.6)
gives a very good reproduction of the experimental data, while e.g. a Lorentzian

\[
f_L(x, z) = \frac{\Gamma^2}{x^2 + z^2 + \Gamma^2}
\]

(5.7)
leads to considerable discrepancies for high displacements \( z_0 \) (see Fig. 5.8). We can therefore assume the pellet density distribution to be of Gaussian shape.

**Figure 5.8:** Comparison of experimental data from a scan in z-direction (histogram) with curves \( F(z_0) \) obtained from Gaussian and Lorentzian test functions \( f(x, z) \). Used fitting parameters are \( \sigma = 0.47 \) mm for the Gaussian and \( \Gamma = 0.51 \) mm for the Lorentzian. The initial Gaussian and Lorentzian are not shown.
Profile Width

Knowing the type of function, a Gaussian, to insert for \( f(x, z) \) we can now determine its width. This was done by comparing the experimental data to curves \( F(z_0) \) calculated from test functions with different \( \sigma \). Due to the excellent agreement of the curves obtained by the Gaussians this can be done with high precision. For the data of the scan in \( z \)-direction shown in Fig. 5.9 the resulting width is \( \sigma = (0.463 \pm 0.005) \text{ mm} \).

![Profile Width Graph](image)

**Figure 5.9:** Curves \( F(z_0) \) obtained by three Gaussian \( f(x, z) \) of different widths, compared to the same set of experimental data as shown in Fig. 5.8. For better visibility the differences in width shown here largely exceed the minimal distinguishable deviation.

The evaluated data (Tab. 5.1) show a variation in width for different runs of the pellet target as well as between \( x \)- and \( z \)-direction for one specific run (see Fig. 5.10 for an example for one run). While the former is relatively small and assumed to be a statistical fluctuation the deviation between the two directions seems to be of systematic origin. The average values are \( \sigma_x = (0.40 \pm 0.01) \text{ mm} \) and \( \sigma_z = (0.45 \pm 0.01) \text{ mm} \) respectively.\(^2\)

Given a distance \( d = 0.7 \text{ m} \) between vacuum injection capillary and skimmer this equals an angular spread of \( \sigma_x^	ext{ang} = (5.7 \pm 0.2) \text{ mrad} \) and \( \sigma_z^	ext{ang} = (6.4 \pm 0.1) \text{ mrad} \).

---

\(^2\)The errors are calculated from the fluctuations between the different runs.
### Table 5.1: Pellet beam widths

<table>
<thead>
<tr>
<th>Element</th>
<th>$\sigma_x$ [mm]</th>
<th>$\sigma_z$ [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2$</td>
<td>$0.425 \pm 0.005$</td>
<td>$0.463 \pm 0.005$</td>
</tr>
<tr>
<td></td>
<td>$0.394 \pm 0.005$</td>
<td>$0.444 \pm 0.005$</td>
</tr>
<tr>
<td></td>
<td>$0.391 \pm 0.005$</td>
<td>$0.453 \pm 0.005$</td>
</tr>
<tr>
<td>$\text{D}_2$</td>
<td>$0.194 \pm 0.004$</td>
<td>$0.238 \pm 0.004$</td>
</tr>
</tbody>
</table>

For the case that the deviation between $x$- and $z$-direction would originate in the same effect as the angular divergence of the pellet beam, i.e. the turbulences at the vacuum injection, a linear correlation to the total beam width would be expected. However, profiles taken from deuterium pellet beams, having about half the widths of hydrogen beams (compare Fig. 5.12), show that this difference between the $x$- and $z$-direction is constant within the accuracy of the measurements. Video images from the observation point at the skimmer show vibrations of the pellet beam in $z$- but not in $x$-direction, suggesting this to be the reason for the different widths. The reduction of

### Figure 5.10: Beam profiles in $x$- and $z$-direction, showing a significantly smaller width in $x$-direction.
those vibrations, caused by the compression cycle of helium in the cryogenic refrigerator, would thus possibly help to decrease the total angular spread of the pellets. An external cryogenic device for the liquefication of hydrogen, e. g. in connection with the liquid helium cycle used to cool the solenoid magnet, could be a solution for this problem.

Taking this x-z-deviation into account we can improve our model by using a Gaussian with different widths for the two directions:

\[
\hat{f}_g(x, z) = \frac{1}{2\pi \sigma_x \sigma_z} e^{\frac{x^2}{2\sigma_x^2} + \frac{z^2}{2\sigma_z^2}}
\]

This improved model was used to evaluate the data.

Assuming that the skimmer removes all pellets outside its radius and does not affect the pellet distribution inside we can now use three parameters to describe the pellet density after the skimmer: The pellet beam widths \(\sigma_x\) and \(\sigma_z\), referring to the underlying two-dimensional Gaussian and the pellet beam diameter \(D\) signifying where this distribution is cut off.

### 5.3.2 Micro-Sphere Survival Ratio

Using the results presented in the previous section and assuming a skimmer of diameter \(D = 2R = 0.59\) mm to be centered at the highest concentration of the pellet beam we can calculate the amount of pellets passing the skimmer as

\[
\hat{F}_g(0) = \int_{x^2+z^2<R^2} \hat{f}_g(x, z) \, dx \, dz = 0.214
\]

Due to the normalization of \(\hat{f}_g(x, z)\) this corresponds directly to a ratio of pellets passing the skimmer of 21.4\%. Assuming a complete elimination of the vibrations in z-direction we would obtain a symmetric pellet beam density with \(\sigma \equiv \sigma_x = \sigma_z = 0.4\) mm. For this case the ratio of passing pellets can be calculated analytically to 23.8\%:

\[
F_g(0) = \int_{x^2+z^2<R^2} f_g(x, z) \, dx \, dz = \int_{r=0}^{R} \int_{\varphi=0}^{2\pi} \frac{1}{2\pi \sigma^2} e^{-\frac{r^2}{2\sigma^2}} \, r \, dr \, d\varphi = \int_{r=0}^{R} e^{-\frac{r^2}{2\sigma^2}} \, dr = 1 - e^{-\frac{R^2}{2\sigma^2}} = 0.238
\]
This corresponds to an increase of pellet rate after the skimmer of 11\%, compared to the asymmetric case with vibrations.

The pellet rate below the skimmer was measured to be typically in the order of 9000 s\(^{-1}\). For the calculated passing ratio of 21.4\% this corresponds to a rate of about 42000 s\(^{-1}\) above the skimmer. A comparison with the used transducer frequency of 81 kHz gives a vacuum injection surviving ratio for the micro-spheres of 52\%.

### 5.3.3 Beam Diameter

The geometrical approach shown in Fig. 4.5 is based on the assumption of a pellet beam diameter increasing linearly with distance from the vacuum injection capillary, i.e. that the velocity of the pellets perpendicular to the beam direction is constant in vacuum and that their gravitational acceleration in beam direction is negligible. Its validity can be tested by tilting the beam in \(x\)- or \(z\)-direction around an (imagined) axis at the fixed skimmer. As soon as pellets at the edge of the beam hit the wall of the 5 mm wide beam tubes in the scattering chamber the pressure starts to rise (see Fig. 5.11).

![Graph showing pressure in the scattering chamber while tilting the beam. Scans in \(x\)- and \(z\)-direction are shown as dotted and solid line respectively. The pressure starts to rise when pellets hit the wall of the beam pipes. The used skimmer has a diameter of 0.59 mm.](image)

**Figure 5.11**: Pressure in the scattering chamber while tilting the beam: Scans in \(x\)- and \(z\)-direction are shown as dotted and solid line respectively. The pressure starts to rise when pellets hit the wall of the beam pipes. The used skimmer has a diameter of 0.59 mm.
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The higher pressure seen in the \( x \)-scan for negative tilting angles is observed in all measurements and most likely caused by irregularities in the welded seam of the beam pipe. We therefore concentrate on the data of the scan in \( z \)-direction for further investigations. From an angle of \((17 \pm 1) \text{ mrad}\) between the two points where the beam touches the wall and the distance of \(1.71 \text{ m}\) between skimmer and scattering chamber we obtain a free path of \((2.9 \pm 0.2) \text{ mm}\). Subtracting this from the tube diameter of \(5 \text{ mm}\) results in a pellet beam diameter of \((2.1 \pm 0.2) \text{ mm}\). The prediction of the geometrical model for the used skimmer of \(0.59 \text{ mm}\) diameter is a beam diameter at the interaction point of \(2.0 \text{ mm}\) and thus in good agreement with the measurement.

5.3.4 Expected Luminosity

Having verified the linear increase of pellet distribution with distance from the vacuum injection we can now extrapolate the values for beam diameter and widths at the interaction point \(2.41 \text{ m}\) below the vacuum injection to \(\bar{D} = 2 \bar{R} = 2 \text{ mm}\), \(\bar{\sigma}_x = (1.39 \pm 0.04) \text{ mm}\) and \(\bar{\sigma}_z = (1.56 \pm 0.02) \text{ mm}\) respectively. This allows us to define the beam density at the interaction point as

\[
\tilde{f}_g(x, y, z) = \begin{cases} 
  N \frac{e^{-\frac{x^2 + y^2}{2\sigma_x^2}}}{\sigma_x} & \text{for } x^2 + y^2 < \bar{R}^2 \\
  0 & \text{else}
\end{cases}
\]

(5.11)

where \(N\) is a normalization parameter that can be calculated from the average distance between the pellets, \(\bar{t}\). For typical values of pellet rate \(\nu = 9000 \text{ s}^{-1}\) and speed \(v = 80 \text{ m/s}\) we get \(\bar{t} = v/\nu \simeq 9 \text{ mm}\). \(N\) follows from the condition

\[
\int_{y=0}^{\bar{t}} \int_{x=0}^{\bar{R}} \tilde{f}(x, y, z) \, dx \, dy \, dz = 1
\]

(5.12)

In order to keep the luminosity as constant as possible it is desired that on average one pellet is interacting with the ion beam. Therefore the ion beam has to be adjusted to an appropriate height \(h\) in \(y\)-direction, while its width \(w\) in \(x\)-direction is matched with the diameter of the pellet beam. This results in an elliptic cross section with major axis \(w = \bar{D}\) and the minor axis \(h\) determined by the condition for the average number of pellets interacting
with the ion beam

$$\bar{n} = \int_{\frac{x^2}{w^2} + \frac{z^2}{h^2} < 1} \bar{f}(x, y, z) \, dx dy dz = 1 \quad (5.13)$$

For the values of $\bar{l}$, $\bar{\sigma}_x$, $\bar{\sigma}_z$ and $\bar{D}$ as given in this section the height and width of the ellipse are $h \approx 11$ mm and $w = 2$ mm respectively. With a typical pellet diameter of 30 $\mu$m and using the density of solid hydrogen of 89.9 kg/m$^3$ the average number of protons covered by the ion beam follows as $7.6 \times 10^{14}$, corresponding to an average target density of $4.5 \times 10^{15}$ hydrogen atoms/cm$^2$. Given a number of $10^{11}$ stored antiprotons and a repetition frequency of $7.8 \times 10^{11}$ Hz as envisaged in the HESR this results in a mean luminosity of $3.1 \times 10^{32}$ cm$^{-2}$s$^{-1}$.

This parameters already achieved today surpass the requirements of the PANDA detector (compare Sec. 2.4). However, a problem arises from the fact that the ion beam is not maximally focused. The contribution to beam heating caused by the electromagnetic small-angle scattering of antiprotons on the hydrogen atoms decreases with increasing angle of incidence. Consequently a highly focused ion beam is desired at the interaction point.

In order to allow a reduction of the height $h$ of the ion beam while keeping the average number of interacting pellets $\bar{n}$ constant the mean pellet distance $\bar{l}$ has to be reduced. The condition to keep at the same time the mean luminosity constant requires to reduce the pellet size accordingly. The seemingly obvious solution to this problem is to increase the transducer frequency at the liquid jet nozzle, resulting in the production of smaller droplets at a higher rate. Their decreased size, however, leads to a lower survival ratio and a higher angular spread of the micro-spheres at the vacuum injection.

The width $w$ of the ion beam at the interaction point is determined by the pellet beam size and thereby by the angular spread of the pellet beam. A reduction of this parameter would be favorably for the same reasons as mentioned for the height $h$.

Further research should therefore concentrate on improving the process of injecting the micro-spheres into vacuum. Detailed optimization studies on vacuum injection capillaries and liquid jet nozzles are seen as a suitable approach.
5.3.5 Deuterium Pellets

The production of deuterium pellets is possible without major changes in the setup of the pellet target (see Sec. 4.5). The use of deuterium reduces the angular spread of the pellets and results in a higher luminosity at the cost of increased background pressure in the scattering chamber.

Beam Properties

Compared to operation with hydrogen the main change in beam properties for deuterium pellets of same diameter is a significant decrease in width of the pellet density distribution (see Fig. 5.12). Focusing on the $x$-direction, thus avoiding the disturbance caused by the vibrations in $z$-direction (see Sec. 5.3.1) we obtain values for the beam widths at the skimmer of $\sigma_x^H = (0.40 \pm 0.01)$ mm and $\sigma_x^D = (0.19 \pm 0.01)$ mm.

![Beam profiles](image)

**Figure 5.12:** Beam profiles in $x$-direction for hydrogen (outer histogram) and deuterium pellets (inner histogram) of same diameter $D = 30 \, \mu$m. The deuterium beam is about half as wide as the one for hydrogen.

The resulting ratio of $\sigma_x^H / \sigma_x^D = 2.1 \pm 0.1$ lies close to 2.2, the ratio of the densities of solid hydrogen and deuterium. A possible interpretation is that both hydrogen and deuterium pellets experience similar forces at vacuum injection, however, due to their higher moment of inertia, the resulting lateral
The speed of the deuterium pellets is the corresponding factor lower than that of hydrogen.

The smaller beam width leads to a higher pellet rate after the skimmer. Typical rates are in the order of 16000 s\(^{-1}\). The values of \(\sigma_x = 0.19\) mm and \(\sigma_z = 0.24\) mm give a passing ratio of 61\% for a 0.59 mm diameter skimmer, compared to 21\% for hydrogen. Together with the transducer frequency of 81 kHz we can deduce a micro-sphere survival ratio at vacuum injection of 32\%. The average distance between two pellets after the skimmer is \(\bar{t} \simeq 5\) mm.

At the interaction point with the ion beam the extrapolated widths are \(\bar{\sigma}_x = (0.65 \pm 0.07)\) mm and \(\bar{\sigma}_z = (0.83 \pm 0.07)\) mm. As for hydrogen the pellet beam diameter \(\bar{D}\) in case of a 0.59 mm skimmer is about 2 mm. To keep the average number of interacting pellets at \(\bar{n} = 1\) the ion beam has to be adjusted to a height \(b \simeq 6\) mm while its width is matched with the diameter of the pellet beam to \(w = \bar{D} = 2\) mm.

For the parameters of HESR as mentioned in Sec. 5.3.4 (i.e. a number of \(10^{11}\) stored antiprotons and a repetition frequency of \(7.8 \times 10^{11}\) Hz), a pellet diameter of 30 \(\mu\)m and a density of solid deuterium of 89.9 kg/m\(^3\) this results in an average target density of \(9.1 \times 10^{15}\) deuterium atoms/cm\(^2\), corresponding to a luminosity of \(6.2 \times 10^{32}\) cm\(^{-2}\)s\(^{-1}\). The fact that the cross sections for most reactions are larger for deuterium than for hydrogen as target element contributes to a further increase in count rate.
Vacuum Conditions

A drawback in operation with deuterium lies however in the fact that the pumping speed for this isotope is lower than for hydrogen. This leads to a higher equilibrium pressure in the scattering chamber and thus to more background reactions as well as to a higher time constant for reaching the equilibrium (see Fig. 5.13). For same pellet rates and diameters the equilibrium pressure in the scattering chamber is $1.7 \pm 0.1$ times the value of deuterium.

![Graph showing pressure vs time for hydrogen and deuterium pellets.](image)

**Figure 5.13:** Pressure in the scattering chamber for hydrogen and deuterium pellets. In both cases the pellet rate was about $9000 \text{ s}^{-1}$ and the pellet diameter $32 \mu\text{m}$. The pellet beam is switched on at $t = 10 \text{ s}$ and switched off at $t = 95 \text{ s}$.  

Chapter 6

Conclusions

A hydrogen pellet target like developed for the WASA detector at TSL Uppsala seems to be adequate to fulfill the spatial requirements of the PANDA detector. The micro-spheres of frozen hydrogen are injected into the ion beam through narrow pipes of 6 mm diameter, thus consuming only a minimum of solid angle as desired for detector arrangement.

In order to determine the background pressure to be expected under storage ring operation a vacuum system imitating the conditions inside the PANDA detector was designed for the Pellet Test Station at TSL Uppsala. The installation of the system was completed in June 2004 and first results are expected to be available soon.

Pellet beam studies carried out at the WASA pellet target show that the beam is described best by a Gaussian profile. For the parameters achieved today an average target density of $4.5 \times 10^{15}$ hydrogen atoms/cm$^2$ was calculated. The resulting mean luminosity of $3 \times 10^{32}$ cm$^{-2}$s$^{-1}$ surpasses the design value of the PANDA detector. A drawback lies however in the high mean distance between the pellets and in their angular spread, making it necessary to use an ion beam not fully focused at the interaction point. An improvement of the present performance is hoped to be achieved by optimization studies on the vacuum injection of the micro-spheres.
Bibliography


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