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A GEM based Time Projection Chamber prototype
for the PANDA experiment -
Gas system development and forward tracking studies

Verfasser

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Abstract

The $\bar{\text{P}}\text{ANDA}$ collaboration is building a state-of-the-art universal detector for strong interaction studies at the High Energy Storage Ring (HESR) at the new Facility for Antiproton and Ion Research (FAIR) at Darmstadt, Germany. The facility will provide a high intensity, cooled antiproton beam. Together with the advanced particle identification system of the $\bar{\text{P}}\text{ANDA}$ detector a wide experimental program ranging from QCD studies to fundamental symmetry tests will be accessible.

One of two options for the $\bar{\text{P}}\text{ANDA}$ central tracker was a Gas Electron Multiplier (GEM) based Time Projection Chamber (TPC). The low material budget GEM based TPC is an ideal device for 3-dimensional space tracking, which features fulfill the $\bar{\text{P}}\text{ANDA}$ tracking system requirements, e.g. high rate capability, continuous operation, high momentum resolution, high spatial resolution and full solid coverage.

In the course of the detector developments for $\bar{\text{P}}\text{ANDA}$, a large GEM-TPC prototype was build and tested at GSI (Darmstadt, Germany) by the GEM-TPC collaboration. Within the framework of this work, an overview of the prototype general design will be given.

The main task of my thesis was the development of a closed gas supply system for the large GEM-TPC prototype. The detector requirements made it necessary to build it as closed circulation system with infrastructures for O_2 and H_2O measurement and purification as well as for precise pressure controlling inside the gas system. First tests showed a good performance of the system, in which all technical requirements could be fulfilled already in the first development phase.

The large GEM-TPC prototype was installed inside the FOPI detector system at GSI for first tests and was also operated during the physics experiment S339 of FOPI in June 2011. The goal of this experiment was the study of the in-medium properties of strangeness by the pion induced production of the $\Phi(1020)$ meson and its decay into charged kaons. In the course of the data analysis of this experiment, the problem to merge the GEM-TPC data and the FOPI spectrometer data had to be solved. The contribution of this work to the data analysis of the whole experiment was a data processing method, which matches individual track parts from the large GEM-TPC prototype and the FOPI detectors in a such way that a combined track of a single particle in forward direction could be reconstructed. Results of my data analysis showed that a substantial improvement of the PID properties of FOPI in forward direction could be achieved due to the upgrade with the GEM-TPC.

Zusammenfassung

Die $\bar{\text{PANDA}}$ Kollaboration baut einen universalen, state-of-the-art Detektor für die Untersuchung der Starken Wechselwirkung an FAIR (Facility for Antiproton and Ion Research) in Darmstadt, Deutschland. Mit dem von FAIR bereitgestellten, gekühlten Antiprotonenstrahl und dem hochentwickelten System zur Teilchenidentifikation von $\bar{\text{PANDA}}$ wird ein weites experimentelles Program möglich, welches von QCD Beobachtungen bis zu Tests der fundamentalen Symmetrie reicht.

Eine von zwei Optionen für den zentralen Tracking-Detektor für $\bar{\text{PANDA}}$ war eine auf der GEM-Technologie (Gas Electron Multiplier) basierende TPC (Time Projection Chamber). Eine GEM-TPC ist ein idealer Detektor für das Tracking von Teilchen im 3-dimensionalen Raum, welche die Anforderungen an das $\bar{\text{PANDA}}$ Tracking System erfüllt (z. B. hohe Raten, hohe Ortsauflösung, hohe Impulsauflösung, Abdeckung des vollen Raumwinkels, kontinuierliche Signalauslese).

Im Zuge der Detektorentwicklung für $\bar{\text{PANDA}}$ baute die GEM-TPC Kollaboration einen großen GEM-TPC Prototyp, welcher an der GSI (Gesellschaft für Schwerionenforschung) in Darmstadt, Deutschland getestet wurde. Das Design des Detektors wird im Rahmen dieser Arbeit überblicksmäßig beschrieben. Die Hauptaufgabe dieser Arbeit war die Entwicklung eines geschlossenen Gasversorgungssystems für die GEM-TPC. Die Anforderungen an den Detektor machten es notwendig, das Gassystem vor allem mit einer Sauerstoff Reinigungs- und Überwachungsanlage auszustatten und ein präzises Druckkontrollsystem zu entwickeln. Erste Tests zeigten, dass die technischen Anforderungen bereits in der ersten Entwicklungsphase erfüllt werden konnten.

Der GEM-TPC Prototyp wurde für Testmessungen als zentraler Tracking-Detektor in das FOPI Spektrometer an der GSI eingebaut und auch während dem FOPI Experiment S339 (Juni, 2011) betrieben. Das Experiment untersucht die Eigenschaften von Strangeness und Anti-Strangeness in Medium durch die Pion induzierte Produktion des $\Phi(1020)$ Mesons und seines Zerfalls in geladenen Kaonen.

Im Zuge der Datenauswertung für das S339 Experiment musste das Problem der Verbindung von GEM-TPC und FOPI Daten gelöst werden. Der Beitrag dieser Arbeit zur Datenauswertung ist die Entwicklung einer Methode, die von GEM-TPC und FOPI unabhängig detektierte Teilchenspuren in Vorwärtsrichtung zu einer gemeinsamen Flugbahn eines geladenen Teilchens verbindet. Die in dieser Arbeit präsentierten Ergebnisse zeigen, dass eine beachtliche Verbesserung der FOPI Eigenschaften zur Teilchenidentifikation mit Hilfe des großen GEM-TPC Prototypen erreicht werden konnte.

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1 Introduction

The strong force dominates the interaction between nucleons and it determines the quark interaction within the nucleons and other hadrons. The Quantum Chromo Dynamics (QCD) is the generally accepted basic theory of the strong interaction. QCD is very successful at short-distance ($< 10^{-15}$ m), where the quark interaction due to gluon exchange can be accurately described by applying the perturbation theory. However, if the distance between the interacting quarks reaches the size of a nucleon the perturbative approach fails and our understanding of the arising phenomena in this range is still rather marginal.

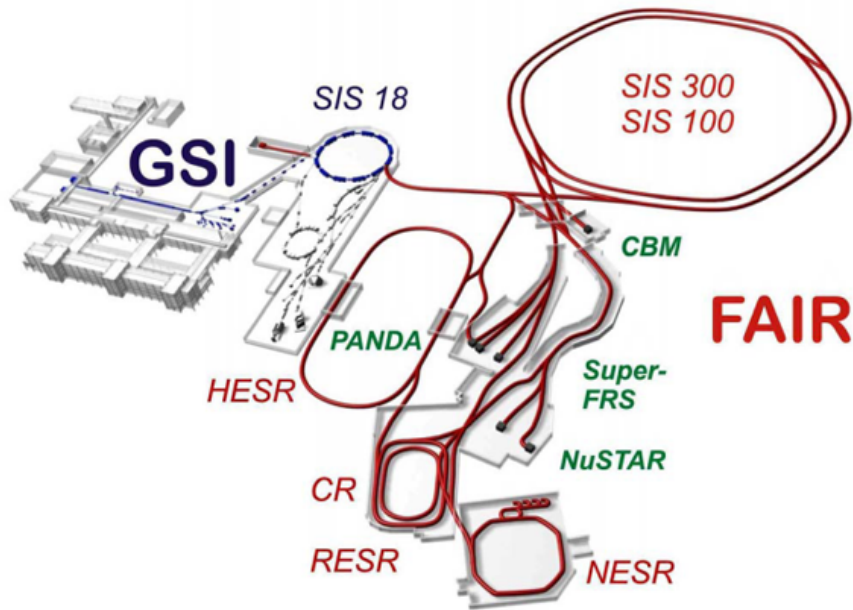


Figure 1.1: The new FAIR facility at GSI in Darmstadt, Germany.

In order to make progress in our understanding of the strong-interaction, spectroscopy has been one of the prime tools in the last century for the strong interaction studies. With spectroscopy experiments the interaction of fundamental particles and the existence of new forms of matter are investigated within the hadron physics. However, only if the precision and statistics of the experimental data can be enhanced by several orders of magnitude, extensive progress beyond our present understanding of the QCD can be achieved.

The $\bar{\text{P}}\text{ANDA}$ collaboration proposed to build a state-of-the-art universal detector for strong interaction studies [1], which provides an advanced particle identification system. The detector will be used at the High-Energy Storage Ring (HESR) at the new Facility for Antiproton and Ion Research (FAIR) at Darmstadt, Germany (see Figure 1.1).

This facility will provide a high intensity, phase space cooled antiproton beam in the energy range from 1 GeV to 15 GeV at a luminosity of about $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$. The combination of the antiproton beam and the $\bar{\text{P}}\text{ANDA}$ detector, will offer a broad experimental program, which extends from QCD studies to tests of the fundamental symmetries. The $\bar{\text{P}}\text{ANDA}$ detector consists of the target spectrometer surrounding the interaction region and the forward spectrometer (see Figure 1.2), which cover almost the full solid angle.

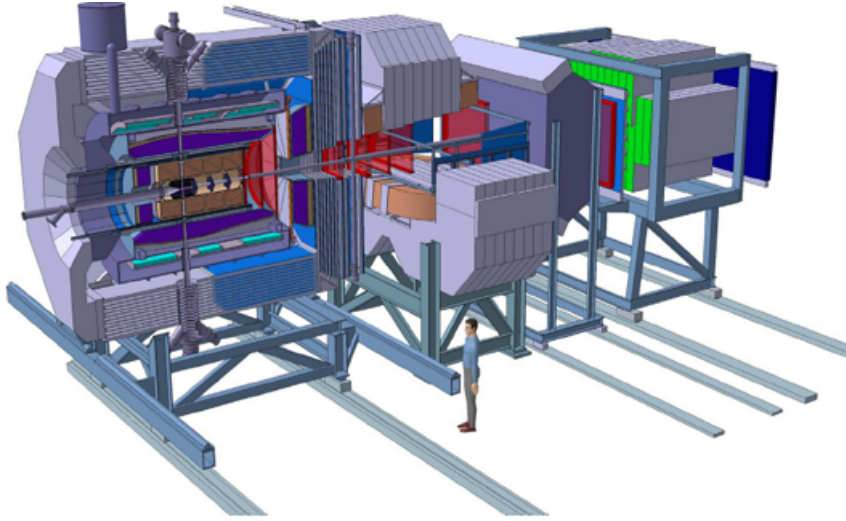


Figure 1.2: Schematical overview of the $\bar{\text{P}}\text{ANDA}$ detector [1].

The tracking system of the $\bar{\text{P}}\text{ANDA}$ detector has to fulfill the following requirements in order to efficiently reconstruct charged particle tracks:

- full solid angle coverage around the interaction point,
- high spatial resolution,
- minimal detector material for low energy loss and multiple scattering of passing particles,
- high momentum resolution of reconstructed trajectories,
- high rate capability,
- resistance against aging effects,

- continuous operating, e.g. without gating, due to the beam characteristics of the HESR.

In order to meet all of the requirements, the $\bar{\text{P}}\text{ANDA}$ detector takes advantage of state-of-the-art detectors and ongoing detector developments, e.g. EU-FP7, Hadron Physics 2 and Hadron Physics 3. The Gas Electron Multiplier (GEM) [2] based Time Projection Chamber (TPC) [3] was one of two options for the central tracker of the $\bar{\text{P}}\text{ANDA}$ tracking spectrometer [4].

1.1 Time Projection Chamber

A low material budget TPC is an ideal device for 3-dimensional space tracking of charged particles and fulfills all of the $\bar{\text{P}}\text{ANDA}$ tracking requirements listed above. TPCs are used in many experiments and detector systems like ALICE [5], DELPHI [6], ALEPH [7], NA49 [8, 9], STAR [10, 11] and PEP-4 [12].

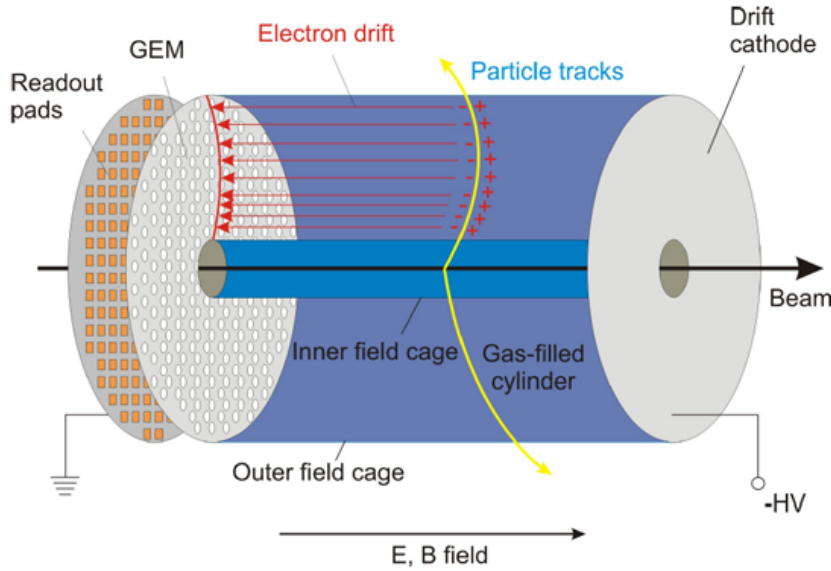


Figure 1.3: Scheme of a Time Projection Chamber (TPC) [13].

A TPC consists of a gas-filled, cylindrical volume, covering the full solid angle, which surrounds the interaction point[14]. A schematic view of a GEM-based TPC can be seen in figure 1.3.

By applying a voltage difference between the drift cathode and the readout plane, an electric field is generated along the cylindrical axis. Ionizing particles traverse the gas-filled volume of the TPC and ionizes gas atoms. The positive ions are separated from the electrons by the electric field. The primary electrons drift to the readout

anode and the ions towards the drift cathode, which are located at the opposed end caps of the drift cylinder. At the read out anode the signal is amplified by an avalanche amplification stage (e.g. Multiwire Proportional Chambers). A projection of the particle track on the readout plane is detected by an arrangement of pad electrodes. The third coordinate (z) of the track position can be determined by measuring the primary electron drift time, which needs accurate information about the electric drift field and drift velocity of the gas electrons.

In order to ensure a constant transport of the generated charges to the readout plane a homogeneous electric drift field has to be provided. Therefore, a field cage surrounds the drift volume which degrades the applied high voltage of the cathode end-cap stepwise to the anode end-cap.

By applying a homogeneous magnetic field along the z -direction, the trajectories of traversing charged particles are curved inside the detector volume. Due to the measurement of the particle track curvature in the detector volume, the momentum and the charge sign of the traversing particle can be calculated:

$$\frac{p_t}{z} = e \cdot r \cdot B \quad (1.1)$$

$$\frac{p}{z} = \frac{p_t/z}{\sin\Theta} \quad (1.2)$$

p_t is the transverse momentum of the particle and p the total momentum. z is the particle charge number, e the elementary charge, r the track radius, B the magnetic field strength, and Θ the polar angle of the track. The mean energy loss dE/dx of the traversing particle in the detector can also be determined by measuring the collected total charge of the track, which is proportional to the deposited energy over the track length. With the information about the momentum and dE/dx an identification of the charged particle mass using the Bethe-Bloch equation

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\frac{1}{2} \ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 T_{max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \quad (1.3)$$

is possible. E is the incident particle energy, N_A the Avogadro constant, r_e the electron radius, m_e the electron mass, ρ is absorber material density, Z and A the atomic and mass number of the absorber material, T_{max} the maximum kinetic energy imparted to a free electron in a single collision, I the mean excitation energy and $\delta(\beta\gamma/2)$ the density effect correction of the ionization energy loss.

1.2 Gas Electron Multiplier

The penetration of the avalanche ions, produced in the amplification stage of a TPC, into the drift volume has to be suppressed, in order to minimize the primary electron

losses due to recombination with the ions. Therefore, most of the TPCs had to be operated in a gate mode, where an electrostatic gate near the readout region is only opened if a target interaction has been observed and is afterwards immediately closed in order to suppress the penetration of avalanche ions into the drift volume.

As a consequence of the HESR beam properties, with its high $\bar{p}$ annihilation rate of $2 \times 10^7 \text{ s}^{-1}$, the TPC in $\bar{\text{P}}\text{ANDA}$ has to be operated continuously. Thus the gating technique can not be used and the back drifting of the avalanche ions into the drift volume has to be suppressed by other techniques.

One mean is the usage of the Gas Electron Multiplier (GEM) technology for the avalanche amplification stage. The development of GEM based detectors was lead by the COMPASS experiment at CERN [15–18]. GEM based detector systems in different configurations are nowadays used in other particle physics experiments like LHCb [19], PHENIX [20], TOTEM [21], KLOE-2 [22–24] and CMS [25].

The main features of GEM based detectors are:

- ion backflow suppression,
- high granularity,
- high rate capability,
- no $\mathbf{E} \times \mathbf{B}$ effect as for wires,
- low material budget inside the detection area,
- possible active areas of several m^2 .

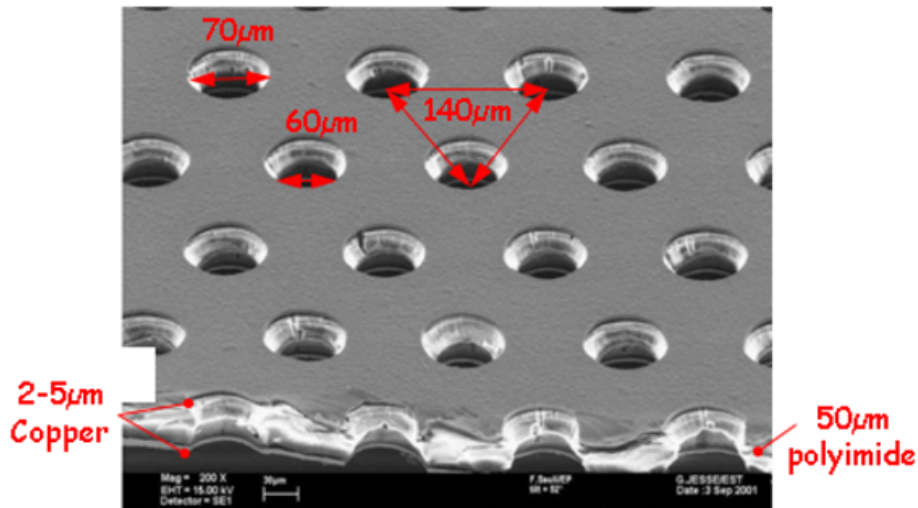


Figure 1.4: Microscopic image of a GEM foil [15].

A typical GEM foil consists of a $50\text{ }\mu\text{m}$ thick insulating polyimide foil with a $2\text{--}5\text{ }\mu\text{m}$ thin copper coating on both sides. Using photolithographic techniques, a regular pattern of microholes are chemically etched into the foil from both sides. Due to the etching procedure, the holes have a double-conical shape with an inner diameter of approximately $50\text{ }\mu\text{m}$ and an outer diameter of $70\text{ }\mu\text{m}$. The distance between the holes is typically $140\text{ }\mu\text{m}$. Figure 1.4 shows an electron microscope image of a GEM foil.

By applying a voltage difference of $300\text{--}400\text{ V}$ between the copper layers of the foil, very strong electric field strengths of several 10 kV/cm can be achieved inside the GEM holes, due to the small size of the holes. Primary electrons are guided by the drift field from the drift volume into the holes of the GEM foils, where they produce an avalanche due to the high electric field inside the holes. The avalanche electrons can be extracted from the bottom side of the GEM foil and be either transferred to another amplification stage or collected at a readout anode.

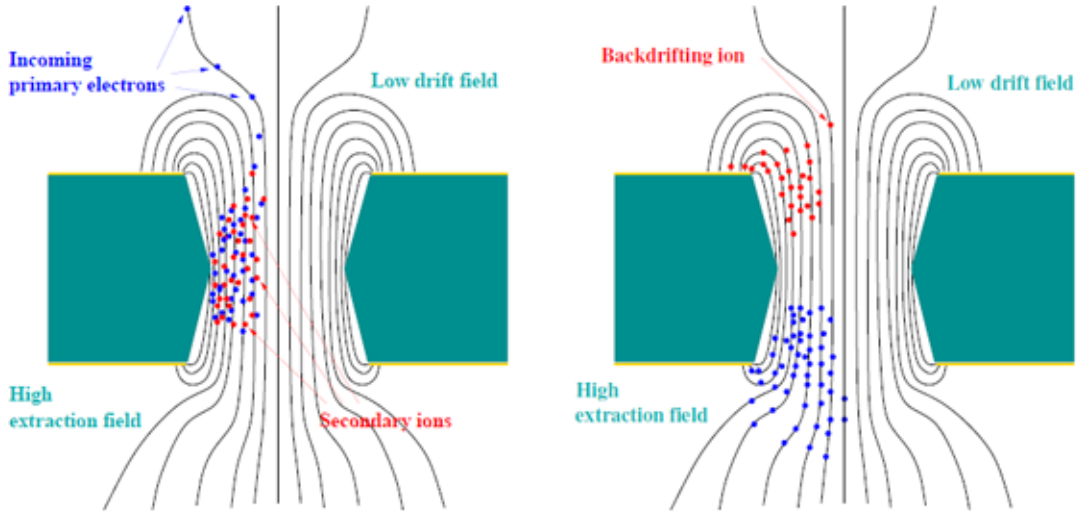


Figure 1.5: (left) Primary electrons are guided by the drift field into the holes. Due to the high electric field inside the holes, an electron-ion pair avalanche is created. (right) Back drifting ions are guided to the top surface of the GEM foil because of the asymmetric field configuration of low drift and high extraction field, while the avalanche electrons are transferred to the readout plane [13].

As shown in figure 1.5 the back flow of avalanche ions into the drift volume from the GEM foil is suppressed by the asymmetric electric field configuration. The larger part of the ions produced in the holes are collected on the top side of the GEM foil. An amplification stage consisting of three GEM foils, which can provide an effective gain in the range of $\sim 10^4$ [26].

A TPC with a GEM based amplification fulfills all $\bar{\text{PANDA}}$ central tracker requirements. Track momenta of particles not traversing the Micro-Vertex Detector

[1] can be determined with appropriate precision, because of the high stand-alone momentum resolution of the GEM-TPC. Its low material budget minimizes multiple scattering of charged particle and photon conversion. Therefore, it enhances the spectrometer resolution for charged particles. An additional contribution to particle identification can be achieved by the energy loss measurements dE/dx of each particle track, especially at momenta below 1 GeV/c. Finally, the pattern recognition in a complex and dense environment like PANDA is simplified by the large number of three dimensional space points measured for each track.

In the course of the GEM-TPC developments for PANDA, several detectors with GEM amplification have been built and tested in order to study their performance [4, 13]. One of these detectors is the large GEM-TPC prototype, which was build and tested at GSI by the GEM-TPC Collaboration [27]. An overview of the prototype general design, detector readout, calibration, cooling and slow control system will be given. One of the main goals of this PhD thesis was the development of a closed gas system for the large GEM-TPC prototype. Therefore, this part of the detector will be discussed in more detail. The physical properties of potential detector gases and detector requirements on the gases will be outlined as well as the design considerations, technical realization, and first tests of the gas system will be presented.

The large GEM-TPC prototype was installed inside the FOPI detector system [28] at GSI (Darmstadt, Germany) for performance tests of the detector. It was also operated within the scope of the physics experiment S339 of FOPI in June 2011. The goal of this experiment was the study of in-medium properties of strangeness and anti-strangeness by the pion induced production of the $\Phi(1020)$ meson and its decay into charged kaons [29]. Through the implementation of the GEM-TPC in the FOPI detector system an improvement of the overall spatial and momentum resolution was expected. Within the framework of this thesis, the FOPI detector and the experimental setup with the GEM-TPC for the S339 experiment will be described.

The contribution of this work to the data analysis of this experiment was the development of a data processing method, which should merge the experimental data of the GEM-TPC with the FOPI detector parts in forward direction. The goal was the extraction of combined tracks from the data of the single detector parts. The last part of this work will outline the data processing method for the data merging and will discuss the selection criteria, which were used for the combined track extraction. In conclusion the preliminary results will be presented.

2 Large GEM-TPC prototype

For the design of the large GEM-TPC prototype the experimental requirements of $\bar{\text{PANDA}}$ were taken into account. The requirements for the GEM-TPC as central tracker for the $\bar{\text{PANDA}}$ experiment include continuous readout due to the high rates in $\bar{\text{PANDA}}$, a spatial resolution of $\sigma_{r\varphi} \approx 150 \mu\text{m}$ in the (r, φ) -plane and $\sigma_z \approx 1 \text{ mm}$ in beam direction, a momentum resolution of about 1% and the property to measure the specific energy loss dE/dx at low momenta for particle identification [4]. The minimization of the material budget in the detection region was an additional technical challenge.

This chapter will only give an overview of the detector design and the individual parts of the GEM-TPC. For a more detailed discussion about the large prototype, please refer to [13].

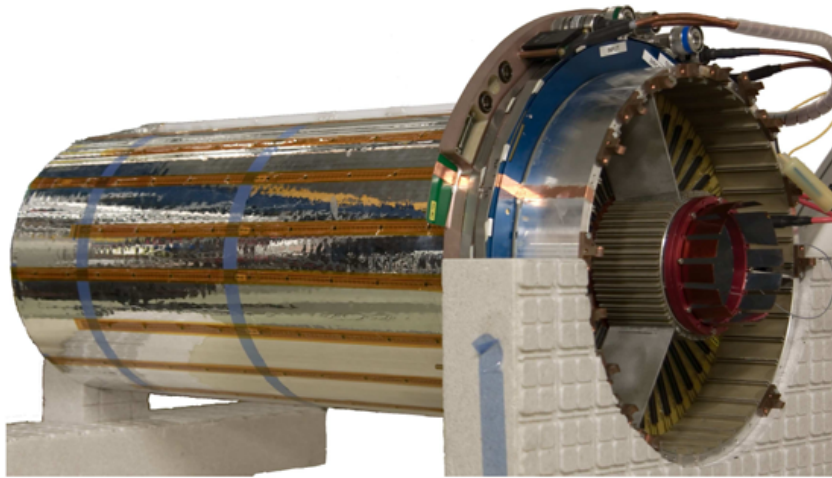


Figure 2.1: Picture of the large GEM-TPC prototype [13].

The GEM-TPC was employed during the FOPI experiment S339 within the existing FOPI spectrometer [28] at GSI. Therefore, the possibility of the implementation inside the CDC (Central Drift Chamber) of FOPI and also into the Crystal Barrel experiment [30] at ELSA (Electron Stretcher Accelerator) in Bonn were taken into account for the design of the GEM-TPC. Figure 2.2 shows an explosion view of the detector parts, while figure 2.1 shows a picture of the large prototype.

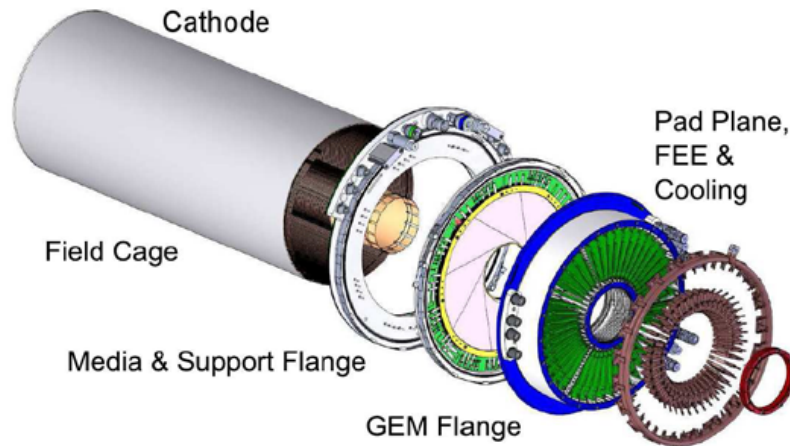


Figure 2.2: Explosion view of the large GEM-TPC prototype [13].

2.1 Field Cage

The drift volume of the GEM-TPC consists of two cylindrical field cages with a diameter of 104 mm of the inner field cage, a diameter of 308 mm of the outer field cage and a length of 727.8 mm [13]. The main purpose of the field cage is to define the homogeneity of the electric field within the detector drift volume. The field homogeneity ensures constant transport properties of the generated charges. The material composition of the field cage was selected in such way, that the radiation length X_0 is minimized. In order to avoid charge build-up and breakdowns, the surface resistivity had to be minimized by the insulator. Furthermore, the walls had to be gas tight and mechanically stable in order to compensate gas pressure and temperature changes.

Material	Thickness [μm]
Aluminized Mylar	0.2
Kapton	25
Kapton	125
Rohacell	2000
Kapton	125
Rohacell	2000
Kapton	125
Kapton	25

Table 2.1: List of materials used for the field cage and their thickness from the outside to the inside [13].

The field cage is a lightweight structure without any outer support, which consists

of a sandwich with a Rohacell core, Kapton insulation layers and two skins of fiber glass material arranged in two concentric cylinders. A list of the used materials and their thickness can be seen in table 2.1. The cathode end-cap is made of the same material sandwich.

The radiation length X_0 for the field cage has been computed with the PandaRoot analysis framework [31]. After the creation of a detailed large prototype geometry, the radiation length was evaluated along tracks with different polar angles (see Figure 2.3). Because the particles have to pass the cathode end cap in the polar angle region between 20° and 55° , the radiation length X_0 is therefore higher than for polar angles between 55° and 140° . Above an angle of 140° , the radiation length increases drastically, because of the relative high material budget of the media flange (see Figure 2.6). The high material budget in backward direction has little impact on the overall detector performance for fixed target experiments like $\bar{\text{P}}\text{ANDA}$ or FOPI, where the majority of the particles are emitted in forward direction.

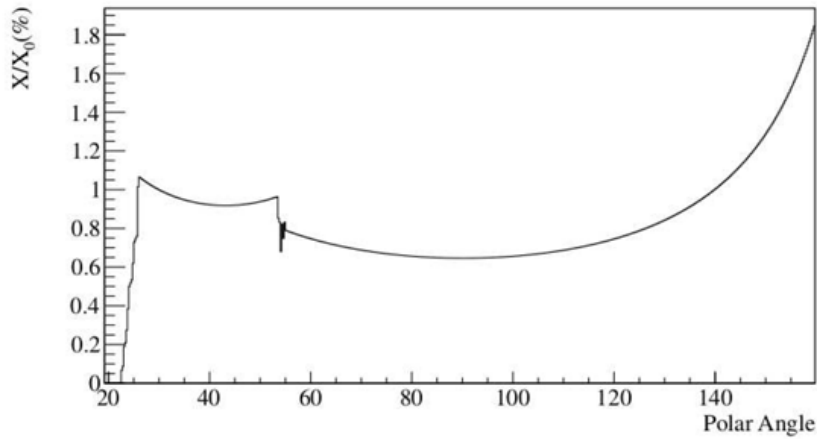


Figure 2.3: Radiation length X_0 of the large GEM-TPC prototype as a function of the polar angle [13].

In order to reduce the material budget, the high voltage supply lines for the cathode end-cap and the gas distribution system were incorporated in the field cage walls. They are glued to the surrounding structure and serve therefore also as mechanical stiffeners. The gas lines for the gas distribution coincide with the resistors soldered to the inner most foils of the outer field cage (see Figure 2.4). Due to this system, the gas could be homogeneously distributed over the detector volume and the resistors were cooled by the gas flow at the same time. The high-voltage lines are fully electrically insulated from the detector vessel.

The outside surface of the outer field cage is coated with a thin aluminum layer, which is connected to the detector ground potential. Thus, the field cage is shielded from outside electromagnetic fields. The innermost field cage layer is composed of

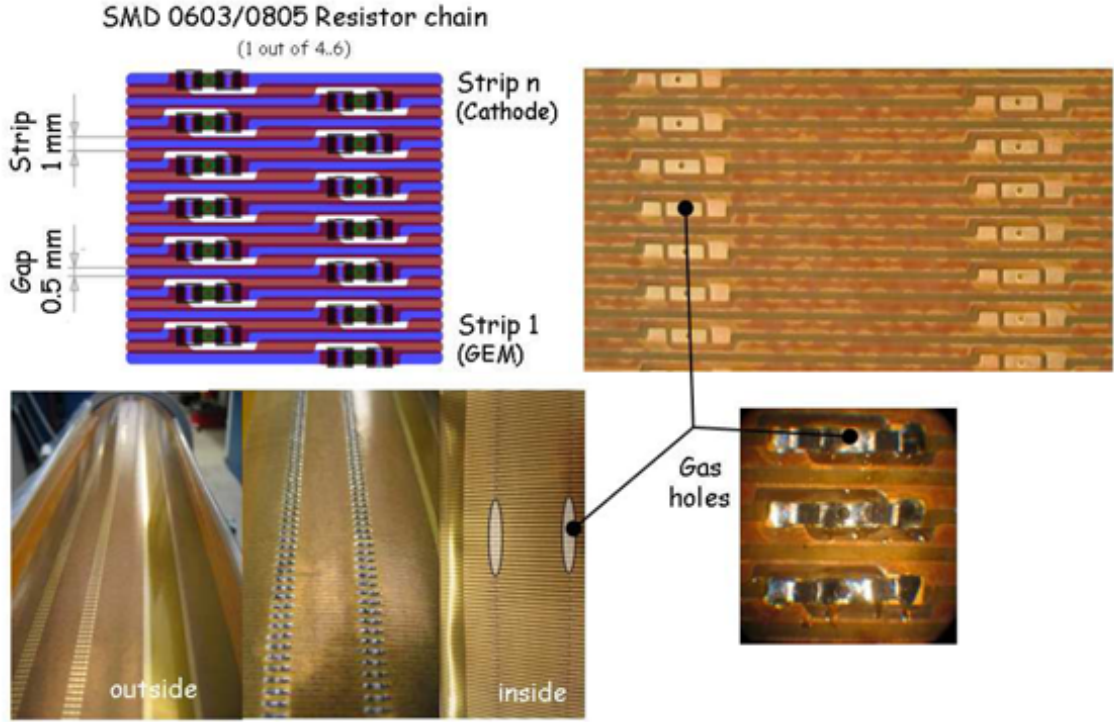


Figure 2.4: The lower left part shows pictures of the strip-line electrodes of the GEM-TPC. The upper left part gives a sketch on the principle layout details. The upper right show the technical realization and the lower right shows a picture of the soldered resistors [13].

a $50\ \mu\text{m}$ thick Kapton foil. It is coated on both sides with several hundred copper stripes ($25\ \mu\text{m}$ thickness), which are transversely aligned to the beam axis (see Figure 2.4).

The stripes width is 1 mm with a gap of 0.5 mm. These stripes degrade the high voltage U_D of the cathode end-cap stepwise to the voltage U_{LS} of the last stripe close to the first GEM-foil. The potential on the copper stripes is defined by a resistor chain. To improve the homogeneity of the field close to the field cage, the two sets of copper stripes on the innermost layer of the field cage are shifted by a half a pitch between stripes. A sketch of the arrangement of the field cage resistor chain is shown in figure 2.5. The total resistivity R_F of the two resistor chains is around $1\ \text{G}\Omega$. A high voltage power supply is connected to the last strip of the field cage, which is protected by the resistor R_G . This allows a decoupling of the high voltage of the field cage and the GEM-stage.

For additional mechanical stability, the upstream end of the field cage is connected to the media flange. The media flange is made of fiber glass material (PBT GF30). It hosts the GEM flange (see Section 2.2), connects the field cage with the readout part

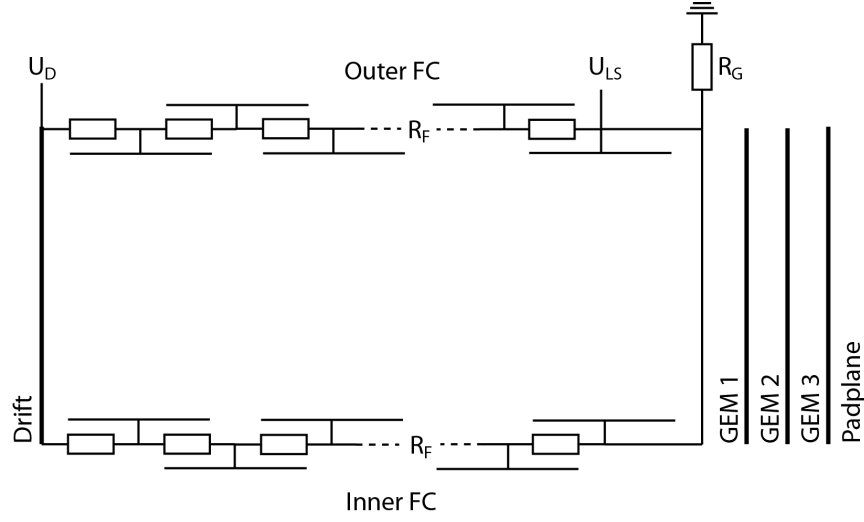


Figure 2.5: Sketch of the arrangement of the resistor chains of the GEM-TPC field cage.

of the large prototype and all the connections for gas and high voltage distribution are placed on the front side of this detector part. An explosion view of the flange can be seen in figure 2.6.

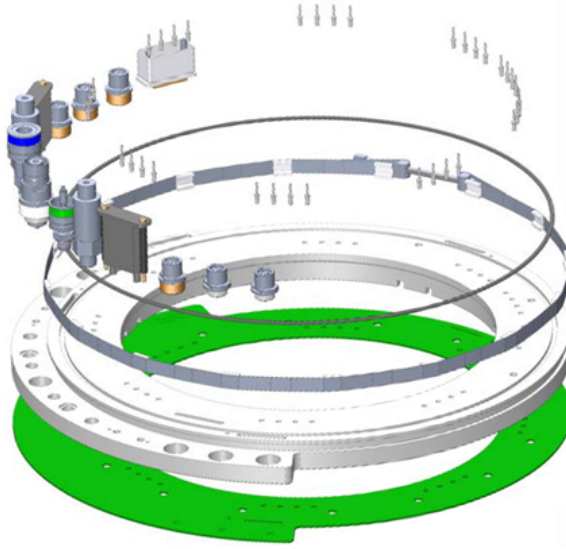


Figure 2.6: Explosion view of the media flange [32].

2.2 GEM Flange

The GEM-flange can hold up to four GEM foils. The foils are standard foils produced at CERN [2], which consists of a $50\,\mu\text{m}$ thick polyimide foil with a typically $2\text{--}5\,\mu\text{m}$ thick Cu-coating. The holes have a double-conical shape, an inner diameter of typically $50\,\mu\text{m}$ and an outer diameter of around $70\,\mu\text{m}$. The distance between two neighboring holes is approximately $140\,\mu\text{m}$. Figure 2.7 shows a picture of the large prototype GEM flange with one mounted GEM-foil. In figure 2.8 a scheme of the GEM stack with the distances between the different stages can be seen.

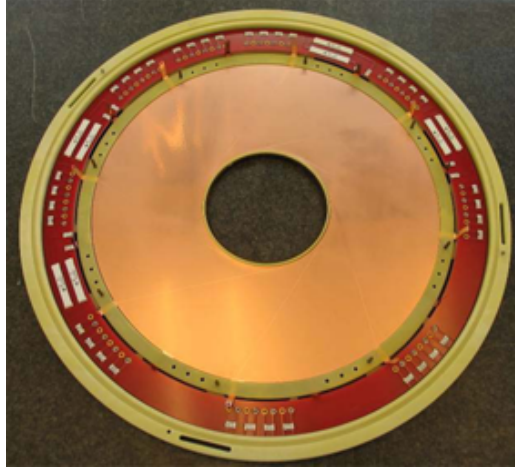


Figure 2.7: Picture of the GEM-flange with one GEM-foil mounted [32].

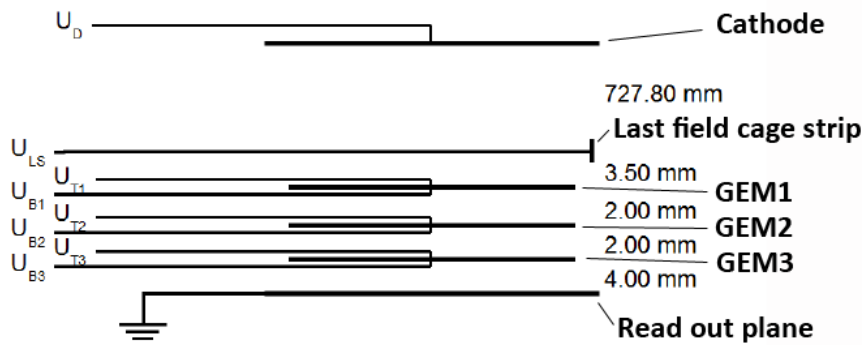


Figure 2.8: Scheme of the GEM stack. U_D is the drift voltage, U_{LS} the voltage of the last strip of the field cage before the GEM foils and U_T and U_B are the top and bottom voltages of the respective GEM foils [13].

The outer and inner diameters of the GEM foils follow the field cage diameters. Studies have shown that by reducing the capacitance between the two metal surfaces of a GEM foil, the probability of discharges is significantly reduced [26]. Therefore,

each GEM foil is segmented into eight sectors with its own loading resistor in order to reduce the discharge probability at the amplification stage. Due to the segmentation, it is also possible to run the TPC even with non operational sectors.

Table 2.2 shows an example for a typical voltage setting of the large GEM-TPC prototype during the performance tests.

Drift Field	0.4 kV/cm
ΔGEM_1	400 V
U_{trans1}	3.75 kV/cm
ΔGEM_2	365 V
U_{trans2}	3.75 kV/cm
ΔGEM_3	325 V
U_{Ind}	3.75 kV/cm

Table 2.2: Typical high voltage setting for drift field and GEM stack.

2.3 Readout Electronics

2.3.1 The Pad Plane

The readout anode of the GEM-TPC was designed as pixel-like read out with approximately 10000 pads. The pads have a hexagonal shape for a more uniform charge distribution on neighboring pads. In contrast to a non-uniform rectangular pad symmetry, the distance to all neighboring pads is constant. Thus, a deterioration of the spatial resolution due to angular effects is prevented. Figure 2.9 shows a closeup view of the pad plane. The hexagonal shape of the pads is clearly visible.



Figure 2.9: Picture of the pad plane of the GEM-TPC [13].

Monte Carlo simulations for the $\bar{\text{P}}\text{ANDA}$ GEM-TPC determined the optimum size of the outer radius for the pads. Figure 2.10 shows the pad cluster resolution perpendicular to the drift direction, which can be achieved for pions with a momentum of 0.5 GeV/c transversing the $\bar{\text{P}}\text{ANDA}$ GEM-TPC in a magnetic field of 2 T, as a function of outer pad radius for hexagonal symmetry [4]. The curves correspond to results with and without diffusion effects. One can recognize, that the effect of the electron diffusion has a minimum at a pad radius of 1.5 mm. Below a radius of 1.5 mm the spatial resolution and hence the momentum resolution is dominated by the electron diffusion.

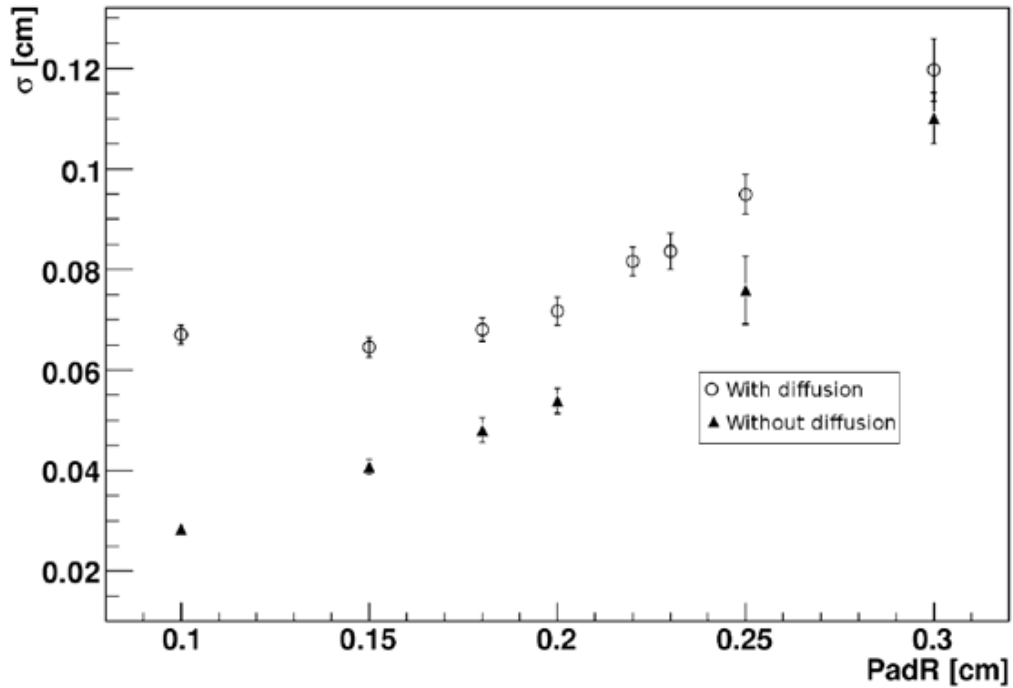


Figure 2.10: Residual distribution for reconstructed clusters as a function of the pad outer radius, with diffusion (open circles) in a 2 T magnetic field and without diffusion (full triangles) [4].

The connections from the pads to the signal output connectors of the pad plane were designed in such way, that crossing of the tracks is avoided. Thus, crosstalk of signals of different pads could be minimized.

The pad-plane encloses the gas volume at the backward end-cap and therefore had to be gas tight. This was achieved by a four-layer structure with tracks on all layers and staggered connections only between neighboring layers.

2.3.2 Front End Electronic

The AFTER ASIC, developed for the large T2K time projection chamber [33], was used for the read out electronics,. It is a low noise chip with 72 input channels, where preamplifier charge range and peaking time of the shaper can be set by the slow control of the chip. The continuously read out signal is sampled after the signal shaper and written in an analog buffer of the chip. The time signal for the sampling is provided from outside and can set between 10 MHz and 50 MHz. The analog buffer of each chip consists of two switched capacitor arrays (SCA) with 36 channels each and a depth of 511 samples. One SCA has two internal channels, which can be used for correction of SCA-leakage, common mode and fixed pattern noise. The readout of the SCAs work in such way, that the content of the buffer is multiplexed and forwarded to the output upon a trigger signal.

The main specifications of the AFTER chip can be found in table 2.3.

Parameter	Value
Number of channels	72
Samples per channel	511
Dynamic range	120 - 600 fC
Shaping Time	100 ns - 2 μ s
Sampling frequency	10 - 50 MHz
Readout frequency	20 - 40 MHz

Table 2.3: Main specifications of the AFTER ASIC [33].



Figure 2.11: Picture of one front end card [27].

Figure 2.11 shows one of the 42 front end cards used for data read out of the

GEM-TPC. One card hosts four AFTER chips, which can be parallel controlled and read out, and handle 256 channels of the GEM-TPC. The connection between the front end cards and the ADCs is made with flat cables and a connection board. The ADC cards read out the analog buffer of the AFTER chip at a trigger signal, which is distributed to the ADC cards via the GeSiCa modules. The ADC data is sent via optical fiber to the GeSiCa module, which combines the data of up to six ADCs and forwards it by a optical S-LINK with an bandwidth of 160 MB/s to a readout buffer. Zero suppression and baseline subtraction of the digital data is made by an FPGA on the ADC board. Each channel has an individual threshold, which includes the measured noise of the specific channel. These thresholds are used for the zero suppression. A scheme of the GEM-TPC read out can be seen in figure 2.12.

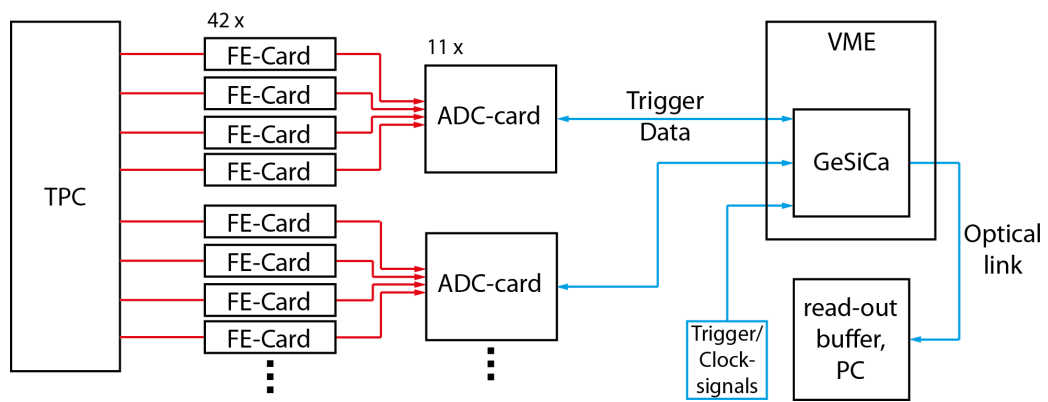


Figure 2.12: Scheme of the data acquisition system of the large GEM-TPC prototype.

2.4 Cooling system

An inhomogeneous thermal distribution along the drift volume of the detector could cause an inhomogeneous gas density distribution inside the drift volume, which is a source for a non-uniform drift velocity of the gas electrons inside the detector (see Section 3.1). In order to measure the temperature distribution around the detector volume, sensors were installed along the external surface of the outer field cage and along the outer radius of the pad plane. While 12 PT100 sensors were used for the temperature measurement on the pad plane, 210 semiconductor one-wire temperature sensors were placed around the field cage.

In figure 2.13 the temperature distribution along the field cage and on the pad plane surface during the tests inside the FOPI spectrometer can be seen. During the tests the temperature fluctuations inside the FOPI spectrometer were rather large, due to the heat emission of the RPC detectors (see Chapter 5). The 5 mm gap between the inner hole of the CDC and the outer walls of the large GEM-TPC prototype was therefore flushed with compressed air, in order to balance the heat fluctuations around the field cage.

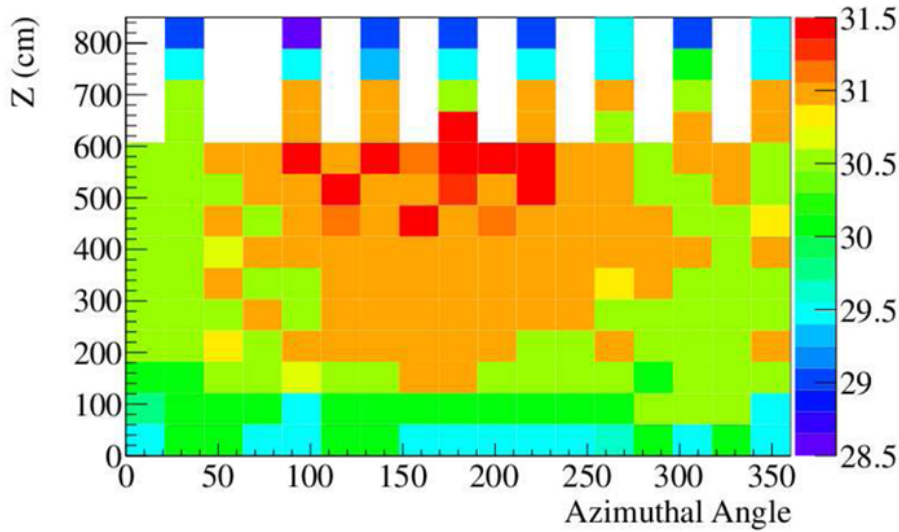


Figure 2.13: Field cage temperature as a function of the azimuthal angle ϕ and the position along the z coordinate (beam direction) during the tests inside the FOPI spectrometer [13].

Apart from the desired temperature uniformity around the field cage, a cooling of the read out system was also important. With a power consumption of 11 mW/ch for 10000 channels, the expected maximal heat load of the AFTER chips was 110 W. Therefore, the front end cards produce the majority of the heat load of the GEM-TPC. Each front end card, ADC board and the voltage regulators were cooled independently by a water driven cooling system. A UC080T-H chiller system regulated the water temperature to 20°C. The mixture of water and glysantin G48/BASF

(Clycol and Ethandiol) was circulating in a closed pipe system and was flowing through heat exchangers, which were connected to copper plates mounted on the front end cards. Two copper plates enclose one front end card and were connected to the four AFTER chips through heat conducting pads.

Figure 2.14 shows the drawing of the cooling copper plates and the connected heat exchangers for one front end card (left) and the whole cooling ring with mounted front end cards and heat exchangers (right).

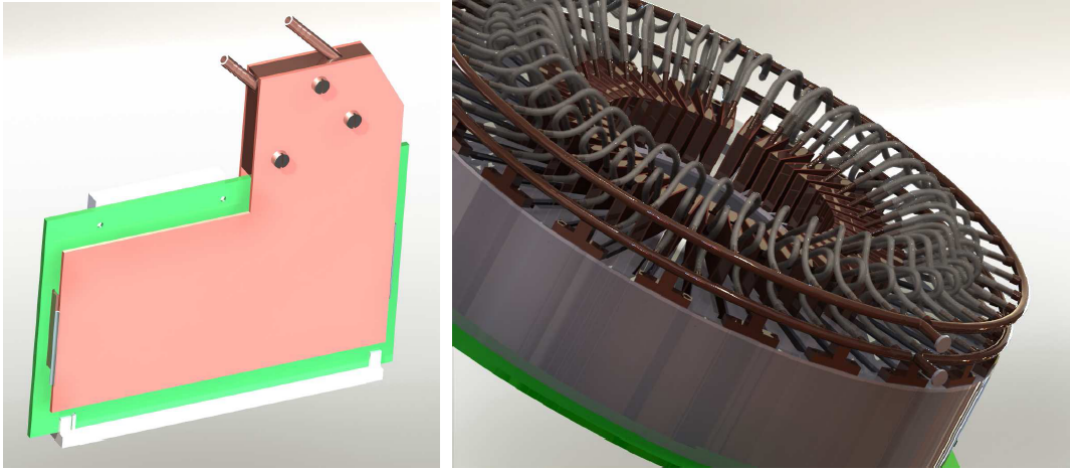


Figure 2.14: (left) Drawing of the cooling copper plates and the connected heat exchanger for one front end card. (right) Picture of the cooling ring equipped with all front end cards with copper plates and heat exchangers [13].

The length of the flexible pipes between cooling ring and heat exchangers should ensure the same impedance for all front end cards. The same system cools the ADC boards and the high voltage regulators after the front end cards.

2.5 Calibration

In order to optimize the spatial and energy resolution of the large GEM-TPC prototype, an absolute and relative gain calibration of the detector is needed. There could be several reasons for spatial gain fluctuations for each channel, e.g. gain variations in the front end cards and ADCs, GEM foil sector borders or different circuit lengths. Additionally, it was shown with GEM profile studies, that the spatial gain of double and triple GEM detectors varies strongly [34]. Due to stresses on the GEM frame and GEM foil bending, gain fluctuations up to 20% could be observed. Bending changes the induction fields and electron transfer between the GEM foils and thus changes the local effective gain.

Therefore a gain calibration of the whole detection area is necessary. The method of introducing gaseous radioactive ^{83m}Kr into the drift volume is a well known technique and has already been used in several TPCs (e.g. NA49 [9], ALICE [35], ALEPH [36], STAR [37]).

A bin containing a ^{83}Rb source is implemented in the gas supply line of the GEM-TPC. 76% of ^{83}Rb decays predominantly with a half life of 124 d into the isomeric state ^{83m}Kr at an energy level of 41.6 keV. This decays with a half life of 1.8 h into a short lived excited state at 9.4 keV and further into the ground state of ^{83}Kr . The energy spectrum of the decay has four main peaks in the energy range of 9.4 keV to 41.6 keV, coming from conversion electrons, which can be used for calibration of the large prototype. Figure 2.15 shows a decay scheme of $^{83}\text{Rb} \rightarrow ^{83}\text{Kr}$ and an energy spectrum of this decay simulated for the MWPCs of the NA49 Main TPC, showing the main peaks between 9.4 keV and 41.6 keV.

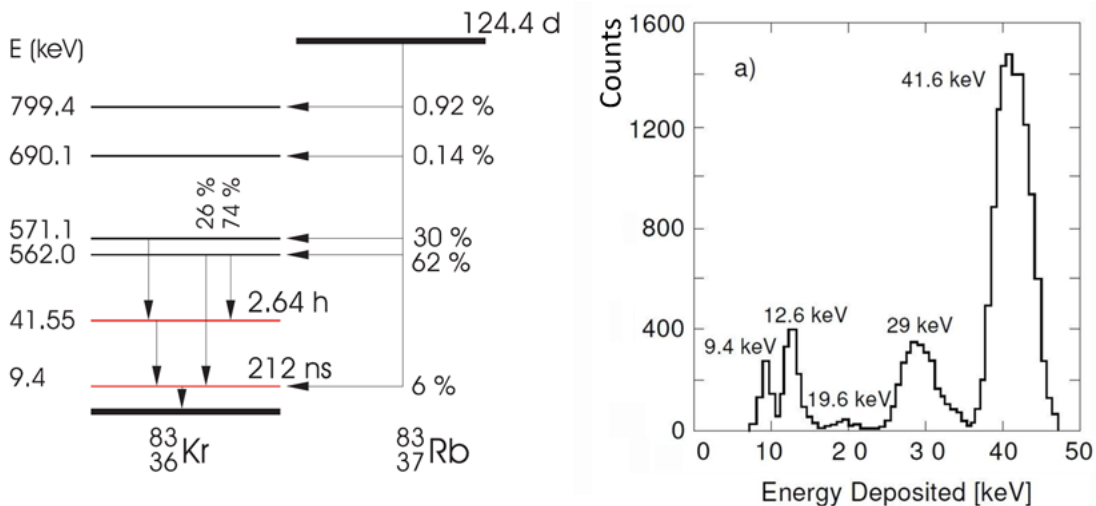


Figure 2.15: (left) Decay scheme of $^{83}\text{Rb} \rightarrow ^{83}\text{Kr}$ [38]. (right) Energy spectrum of the ^{83}Rb decay simulated for the MWPCs of the NA49 main TPC, showing the main peaks between 9.4 keV and 41.6 keV [9].

Figure 2.16 shows the container for the ^{83}Rb calibration source. The radioactive material is placed in a steel tube, which is shielded with 13 cm thick lead for the absorption of high energy decay photons. The calibration container has been mounted into the gas supply system via a short bypass shortly before the GEM-TPC (see Figure 2.17).

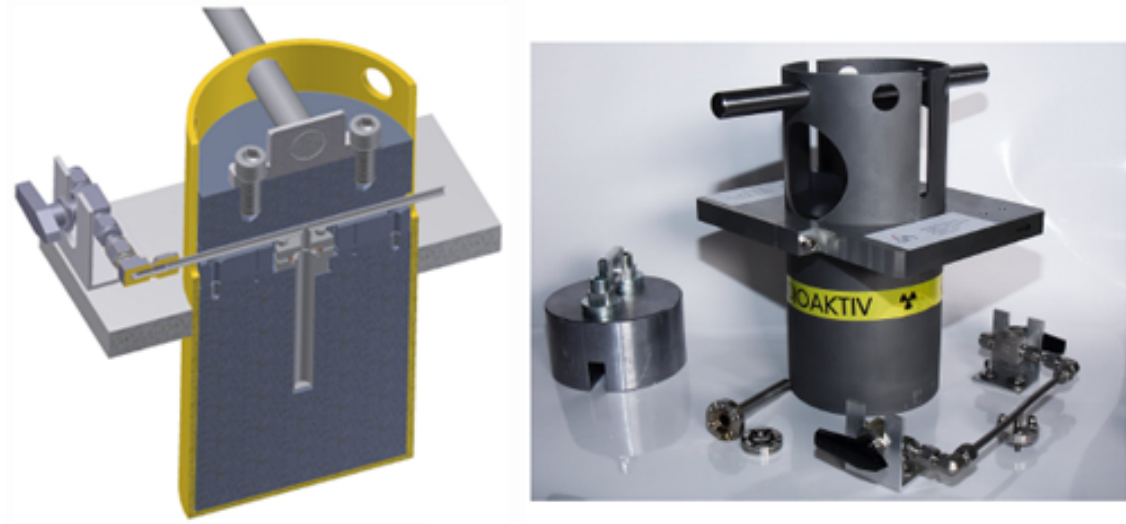


Figure 2.16: (left) Drawing of lead-shielded container for the ^{83}Rb calibration source. (right) Picture of ^{83}Rb container. [13].

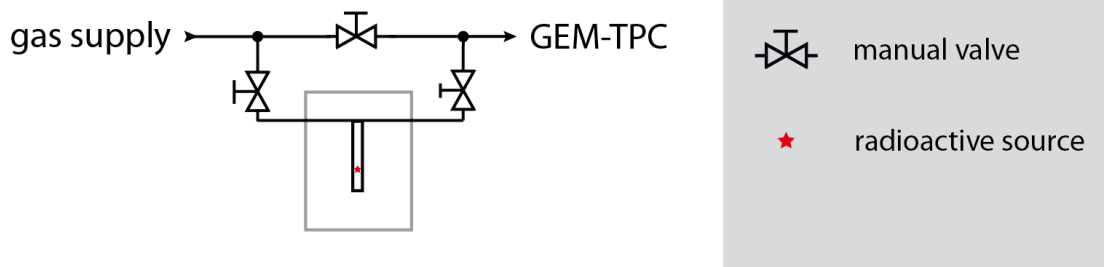


Figure 2.17: Layout of the bypass for the ^{83}Rb container in the gas supply line of the GEM-TPC.

During normal operation of the system, the container is bypassed by two valves. For the calibration operation, the gas supply line is disrupted via a third valve and the gas circulates through the calibration container transporting ^{83}Kr enriched gas to the GEM-TPC volume. After a calibration run where the calibration container was completely exhausted, reactivation time is needed for a full recovery of 100% ^{83}Kr activity (see Figure 2.18).

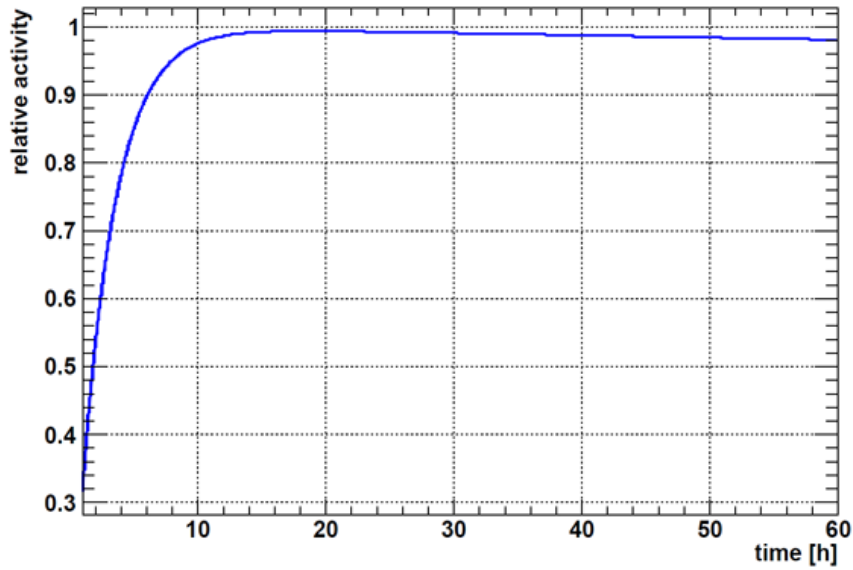


Figure 2.18: The graph shows the time needed to recover 100% ^{83}Kr activity after a exhausting of the krypton calibration container [13].

A ^{83}Rb source with an activity of 2.5 MBq has been produced at the HSKP cyclotron¹ in March 2011. An $^{81}\text{Br}(\alpha, 2n)^{83}\text{Rb}$ reaction with a cross section of $\sigma = 1300 \text{ mb}$ at an energy of 26 MeV was used [13]. This production method for an calibration source has also been used for the KATRIN experiment [39].

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3 Detector gas

The physical requirements on a gaseous detector influence the choice of the gas mixture. Further, the choice of the gas mixture also influences the performance of the detector and has a great impact on the design of the detector and its gas supply system. The requirements on the detector gas for the GEM-TPC are similar to the requirements for the ALICE-TPC [5]. Therefore, for both detectors nearly the same considerations can be taken into account for the choice of the detector gas mixture. In [40–42] detailed discussions about the study of the gas properties for the ALICE-TPC are presented. Because the physical properties of the gas mixture is an important point for the design of the GEM-TPC gas system, a short summary about the important gas properties of the GEM-TPC gas mixture is given in this chapter.

3.1 Gas properties

- **Electron drift velocity v_D :** The gas electron drift velocity v_D defines the maximal drift time of the gas electrons and therefore the dead-time of the GEM-TPC. A fast clearing of the drift volume decreases the storing time of the signal before it can be read out and reduces the pile up of events within the detector. Hence, a high electron drift velocity is highly recommendable for the GEM-TPC in order to cope with the high event rates produces in the $\bar{\text{PANDA}}$ experiment.

The drift velocity depends not only on the gas type but also on the electric drift field of the detector. Figure 3.1 shows the calculated electric drift field dependence of the drift velocity v_D for Ar/CO₂ and Ne/CO₂ gas mixtures (90:10) in a 0.6 T magnetic field. The calculations were performed with MAGBOLTZ [43, 44].

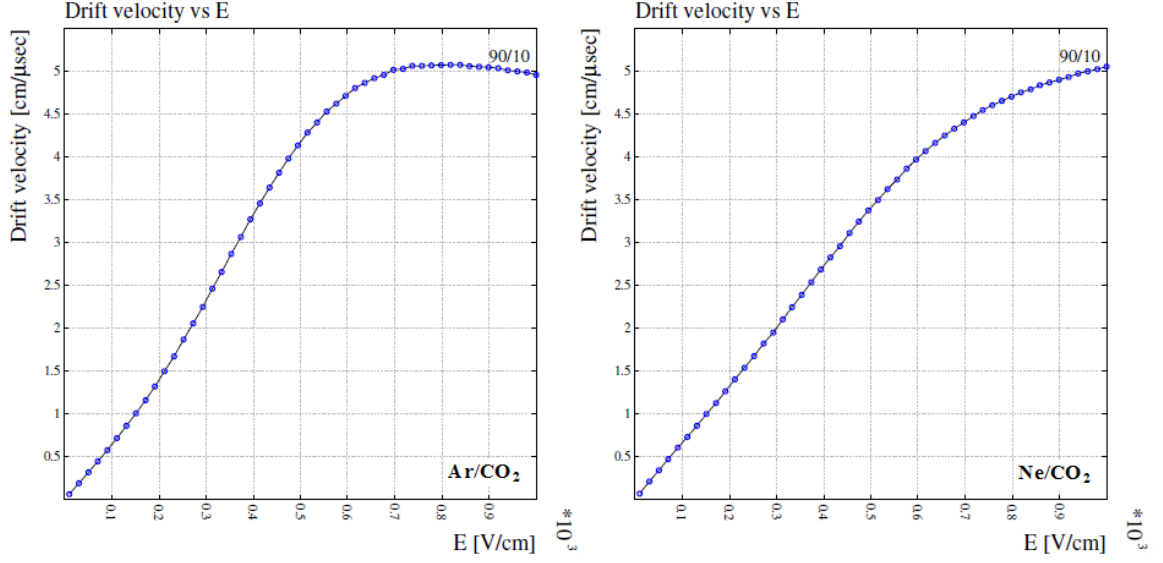


Figure 3.1: Drift velocity v_D as a function of the electric drift field of the detector for Ar/CO₂ (left) and Ne/CO₂ (right) gas mixtures (90:10) in a 0.6 T magnetic field [13].

- **Saturated drift velocity:** For an accurate determination of the track position in beam direction, an uniform drift velocity v_D over the whole detection area is needed. Therefore, the drift velocity should not be effected by external parameters like temperature. However, v_D depends on the gas density, which itself depends on gas temperature and pressure. An inhomogeneous heat distribution along the GEM-TPC could cause a inhomogeneous distribution of the gas density and furthermore a position dependent v_D .

At electric field regions, where the drift velocity has a local maximum, density variations have only little effects on v_D . In an Ar/CO₂ gas mixture (90:10) the maximum drift velocity is achieved at a rather high electric field region of about 650-750 V/cm (see Figure 3.2). For example, several TPCs benefit from the local maximum of the drift velocity at a nominal low drift field near 125 V/cm for a Ar/CH₄ (90:10) gas mixture.

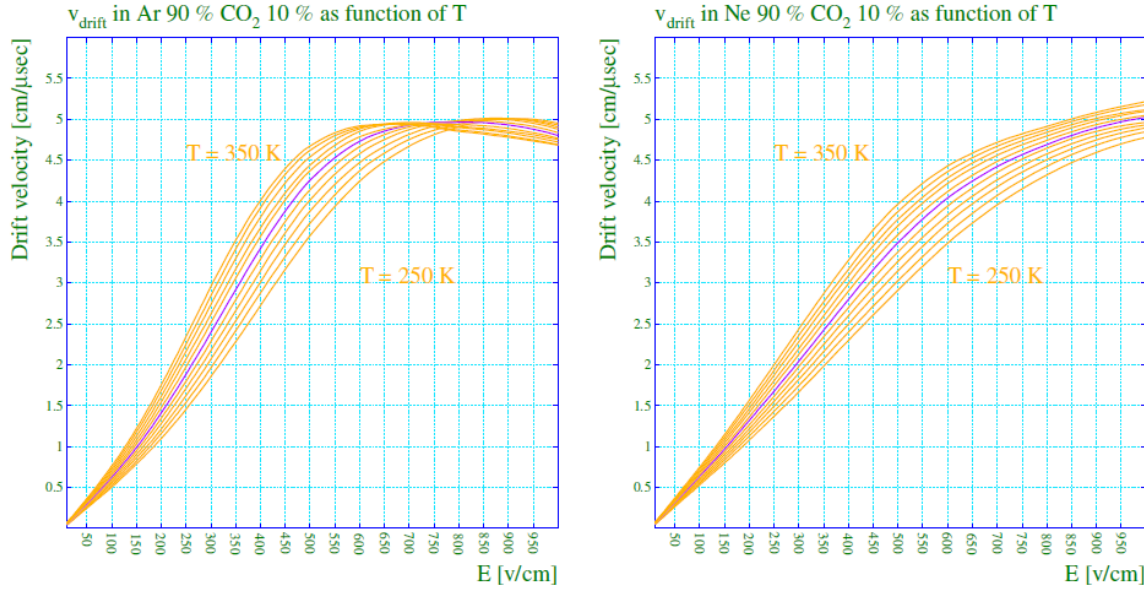


Figure 3.2: Temperature dependence of the drift velocity v_D for Ar/CO₂ (left) and Ne/CO₂ (right) with an CO₂ fraction of 10% [41].

- **Density and radiation length X_0 :** Preferably, the density of the TPC gas should be low and the radiation length X_0 high. Since charged particles fly a long distance through the gas and therefore can undergo multiple scattering.
- **Ion mobility:** Ionized gas atoms or molecules inside the drift volume of the GEM-TPC have two negative effects. First, these ions are a source of space charges within the drift volume. Space charges can distort the electric drift field and thus lead to electron diffusion, which decreases the spatial resolution. Space charges also increase the probability of discharges inside the detector volume, which are a high safety risk for the detector.

Furthermore, ionized gas atoms can recombine with signal electrons. These electron losses affects the position information and the energy resolution and therefore the dE/dx information of the signal, which are important for the particle identification properties of the detector.

Especially at the amplification stage of the GEM stack, a high ion mobility is important, because the discharge risk and the electron losses are particularly high in this region, due to the high ionization rate inside the GEM holes.

- **Ionization rate:** For the production rate of primary electron-ion pairs in the counting gas a compromise has to be found. On one hand with a higher ionization rate a larger number of signal electrons is produced, which improves the spatial and energy resolution of the detector. On the other hand, the total

drift time of the electron cloud through the drift volume of the GEM-TPC and the time to collect the electrons at the read-out pads rises with larger electron number. This leads to a larger dead-time of the detector.

Additionally, with a higher ionization rate also more ions are produced, which leads to an increase of space charges and electron losses due to recombinations.

- **Attachment coefficient:** Besides the ionization rate of the gas, the attachment coefficient influences the spatial and energy resolution of the detector. Due to electron attachment on gas atoms or molecules between the point of ionization and the read-out plane, losses of primary electrons appear. The loss of primary electrons is particularly weighty, since the signal amplification occurs at the very latest part of the drift chamber at the GEM stage right before the read-out plane. Therefore, a low attachment coefficient of the gas is preferable.
- **Electron diffusion:** To achieve a good spatial resolution a low electron diffusion in transverse (r, ϕ -plane) and in longitudinal (z -direction) direction is important. It also improves the separation capability of nearby detector hits, which is crucial for high rate experiments. The electron diffusion depends not only on the gas type but also on the electric drift field. Figure 3.3 shows the electron diffusion as a function of the electric field for Ar/CO₂ and Ne/CO₂ gas mixtures (90:10) in a 0.6 T longitudinal magnetic field.

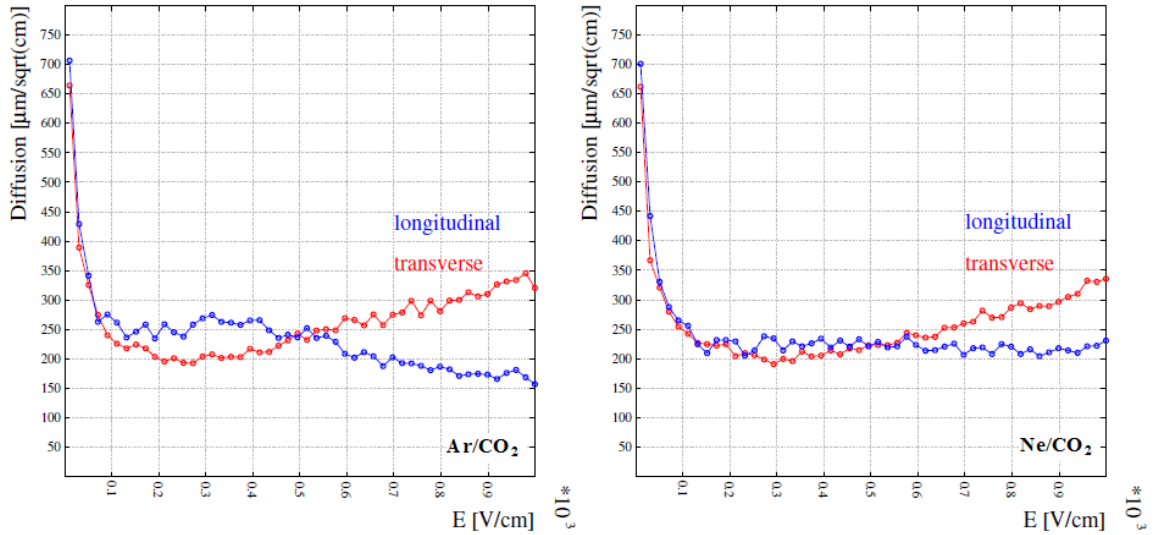


Figure 3.3: Electron diffusion as a function of the electric drift field of the detector for Ar/CO₂ (left) and Ne/CO₂ (right) gas mixtures (90:10) in a 0.6 T magnetic field [13].

- **Safety and aging:** Inflammability, toxicity and radioactivity are gas features, which have to be avoided. Such features are a potential safety risk for the experiment. They impose expensive safety equipment and complicates the operation of the detector during an experiment. In addition, the features can also cause aging effects and shorten the life time of detector components. In case of long term experiments, where repairing or exchange of detector parts are not at any time possible, aging effects are to be avoided.

3.2 Choice of gas mixture

Unfortunately, a single optimal gas for the GEM-TPC does not exist. Therefore, an ideal mixture of two or more gases has to be found. Usually a mixture of a counting gas and a quencher gas is used.

In addition to the ionization of neutral gas molecules by collisions with other particles, the gas molecule can also be excited. The excited gas molecule can decay to its ground state by the emission of a photon. Through photo electric interactions these photons could create additional ionization electrons elsewhere in the detector volume. These photon-induced ionizations lead to a deterioration of the spatial resolution. This can be suppressed by adding of so called "quencher" gases. These are polyatomic gases such as Methan or CO_2 , which absorb the photon in a non-ionization mode.

The design considerations for the GEM-TPC took the experimental requirements (e.g. high rate capability, fast readout and spatial resolution) for the $\bar{\text{P}}\text{ANDA}$ experiment (see Chapter 1) into account, which puts constraints on the gas mixture. Most of the physical requirements for the detector gas of the GEM-TPC are satisfied by noble gases. They are neither toxic nor inflammable nor, with the exception of radon, radioactive. They do not cause aging and most of them are non-reactive. Therefore, noble gases are ideal candidates for the counting gas of the GEM-TPC.

Helium has been used as TPC gas but has a high leakage rate. Krypton and Xenon are rare, which makes them unaffordable in larger quantities. Additionally, due to their high density, they have a high ionization rate, which leads to significant multiple scattering and therefore to a deterioration of the spatial resolution.

Argon and Neon appear to be a good compromise. Argon is the most common noble gas in the atmosphere. The Neon content in the atmosphere is by a factor of 2000 smaller than for Argon, which makes Neon much more expensive. But the radiation length X_0 of Neon is about three times larger than the radiation length of Argon. This leads to a lower photon conversion and multiple scattering in Neon compared to Argon. Additionally, the ion mobility of Ne-ions is by a factor of 2-3 larger, thus space charge effects will be significantly lower. On the other hand the primary ionization rate is two times smaller for Neon than for Argon, which requires a higher gain setting of the GEM stack high voltages for Neon. Table 3.1 shows

the density ρ , radiation length X_0 and primary ionization rate N_T at STP¹ of gases commonly used in TPCs.

Gas	ρ [g/l]	X_0 [g/cm ²]	N_T [1/cm]
He	0.1785	94-32	8
Ne	0.8999	28.94	40
Ar	1.784	19.55	97
CH ₄	0.717	46.22	54
CO ₂	1.977	36.2	100
C ₂ H ₆	1.356	45.47	112
CF ₄	3.93	36	120

Table 3.1: Property list of common TPC gases at standard temperature and pressure (T = 293.15 K, p = 1013.25 mbar). Density ρ , radiation length X_0 , primary ionization rate N_T .

As quencher gases many gases are suitable and a wide range of different gases are commonly used. The first candidates are organic gases like Methan (CH₄), Ethane (C₂H₆) or Isobutane (iC₄H₁₀). In particular the P10 gas mixture Ar/CH₄ with an ratio of 90:10 is very popular. This mixture has a maximum drift velocity of 5 cm/ μ s at a low electric field of 125 V/cm, which simplifies the detector design and operation. However, organic gas mixtures may cause aging by forming of polymeric deposits on the chamber, if the accumulated charge is large. Since aging of detector components is a big issue for long term operations, this is a big drawback of organic gases.

A second candidate is Nitrogen and nitrogen compounds like NH₃, NO and N₂O. They do not form solid polymers, but nitrogen containing gases can capture thermal neutrons and can emit photons due to the reaction (3.1). The photon can ionize gas molecules and makes therefore the GEM-TPC sensitive to neutron radiation background.

$$^{14}\text{N} + n \rightarrow ^{15}\text{N} + \gamma \quad (3.1)$$

Noble gases mixed with Freons like CF₄ form gas mixtures with a high drift velocity at low electric fields. This makes Freons to be attractive GEM-TPC quencher gases. But, apart from the prohibition of Freons due to environmental reasons, Freons can release highly aggressive and toxic fluorine by radiation induced disintegration. Furthermore, Freons attract electrons, which leads to a decrease of the energy resolution.

Therefore, CO₂ remains as an uncritical quencher gas. Although it has a lower drift velocity than CH₄, it has also lower electron diffusion.

¹Standard Temperature and Pressure (T = 293.15 K, p = 1013.25 mbar)

3.3 CO₂ fraction

In figure 3.4 the electron drift velocity v_D as a function of the drift field for Ar/CO₂ and Ne/CO₂ mixtures and increasing CO₂ fraction up to 10% can be seen. The graph shows that the maximum drift velocity increases with higher CO₂ fractions, but the electric drift field, where the maximal drift velocity can be achieved, also rises to higher values. Even at drift field regions, where v_D is unaffected by drift field variations, the drift velocity is sensitive to variations of the CO₂ fraction.

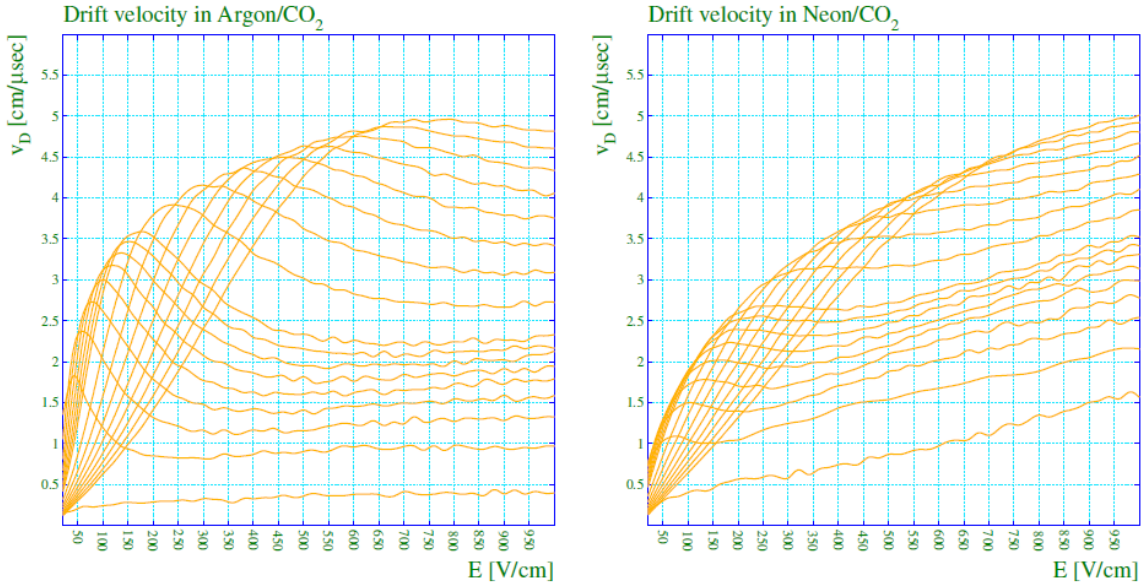


Figure 3.4: Drift velocity v_D as a function of the electric drift field for Ar/CO₂ (left) and Ne/CO₂ (right). Starting with the lowest, the curves corresponds to a CO₂ fraction of 0%, 0.25%, ..., 2%, 3%, ..., 9%, 10% [41].

Besides the effect on the drift velocity, the amount of CO₂ in the gas mixture has also a huge impact on the electron diffusion. Figure 3.5 shows the transversal and longitudinal diffusion in Ar/CO₂ and Ne/CO₂ gas mixtures as a function of the electric drift field and the CO₂ fraction. It can be seen, that the diffusion coefficient decreases with increasing CO₂ fraction, but it rises again with an increasing electric drift field. If the drift velocity is now compared with the diffusion, it can be observed that the drift field range, where a minimal diffusion can be achieved, is below the range of the maximal drift velocity for the same amount of CO₂.

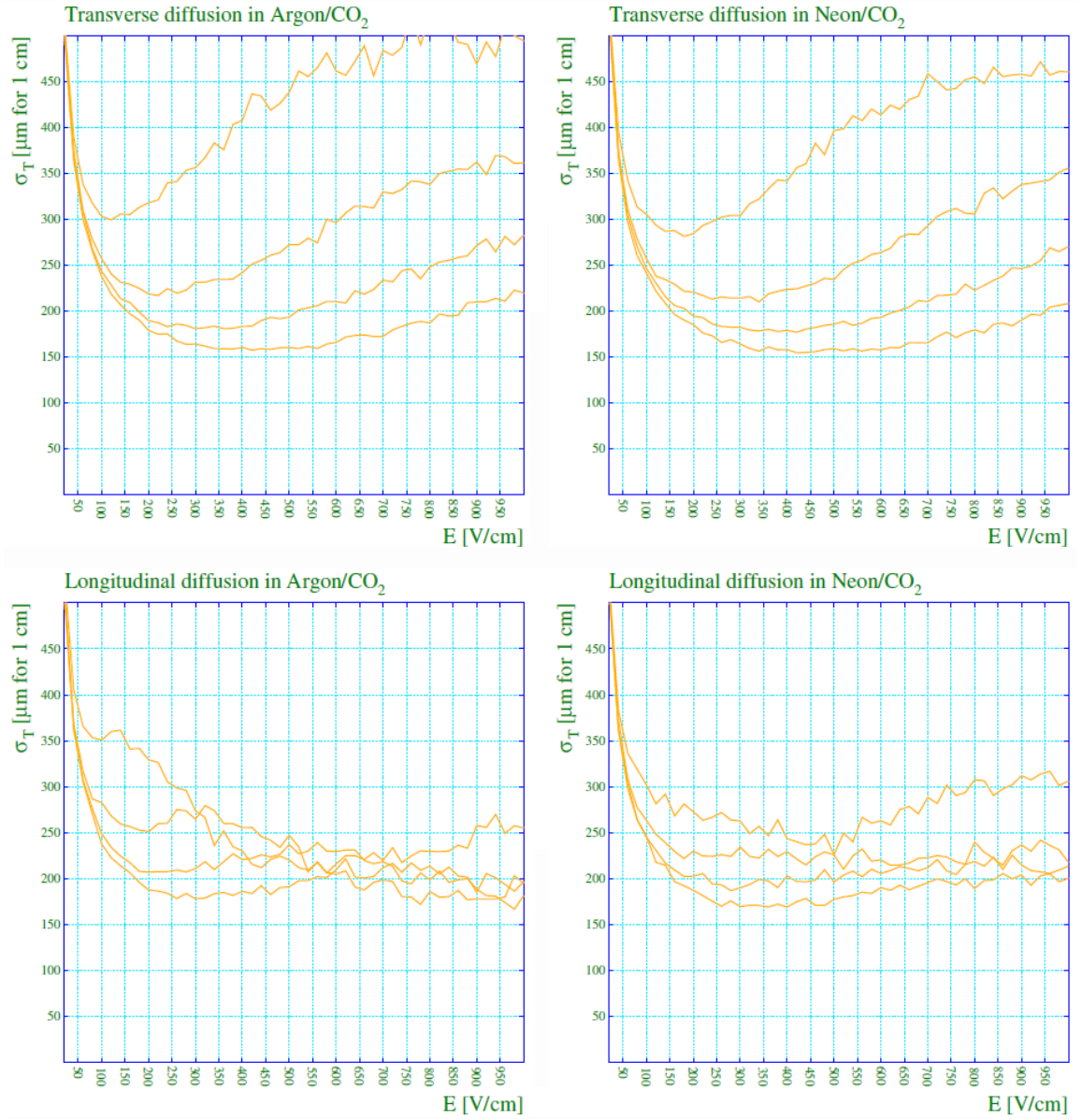


Figure 3.5: The top graphs show the transverse diffusion as a function of electric drift field and different CO_2 fractions (from top to bottom, 5%,10%,15%,20%) for Ar/ CO_2 (left) and Ne/ CO_2 (right)). The bottom graph shows the longitudinal diffusion [41].

3.4 Oxygen and water vapour

Contamination in the detector volume with disturbing impurities can not be excluded because of leaks and outgas

For example, figure 3.6 shows the electron attachment coefficient as a function of the oxygen content for different drift fields in a Ne/CO₂/N₂ (85:10:5) gas mixture.

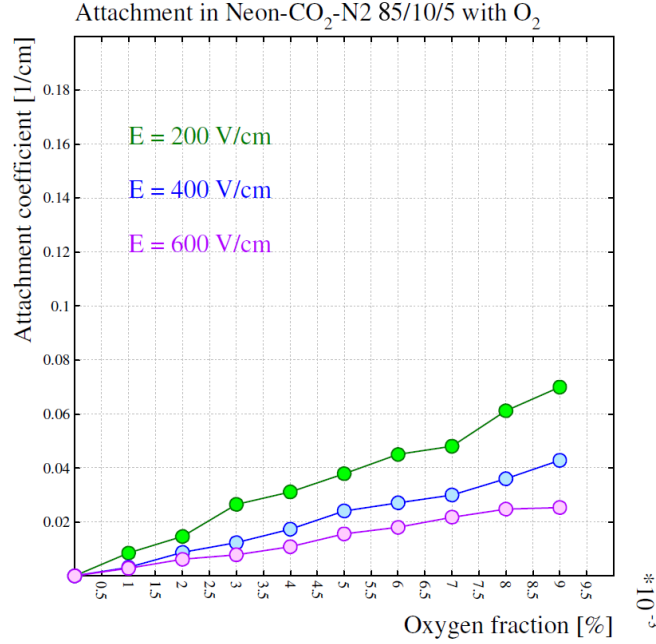


Figure 3.6: Electron attachment coefficient as a function of the oxygen content for different drift fields in a Ne/CO₂/N₂ (85:10:5) gas mixture [42].

The effects of water vapour on the properties of the detector gas are ambivalent. On the one hand, high amounts of water reduces the drift velocity in the detector gas. Due to the easy polarization of H₂O molecules, they can decrease the effective drift field thus reducing the drift velocity. Contamination of about 10 ppm can lead to a relative change of the drift velocity of about 0.05-0.07% [42]. In comparison, an oxygen content of 1 ppm already changes the drift velocity by approximately 1% per 1 m drift length.

On the other hand, an increasing water fraction leads to a decreased transverse and longitudinal diffusion coefficient. For example, figure 3.7 shows the water vapour dependence of the drift velocity and the longitudinal and transverse electron diffusion in a Ne/CO₂/N₂ (85:10:5) gas mixture.

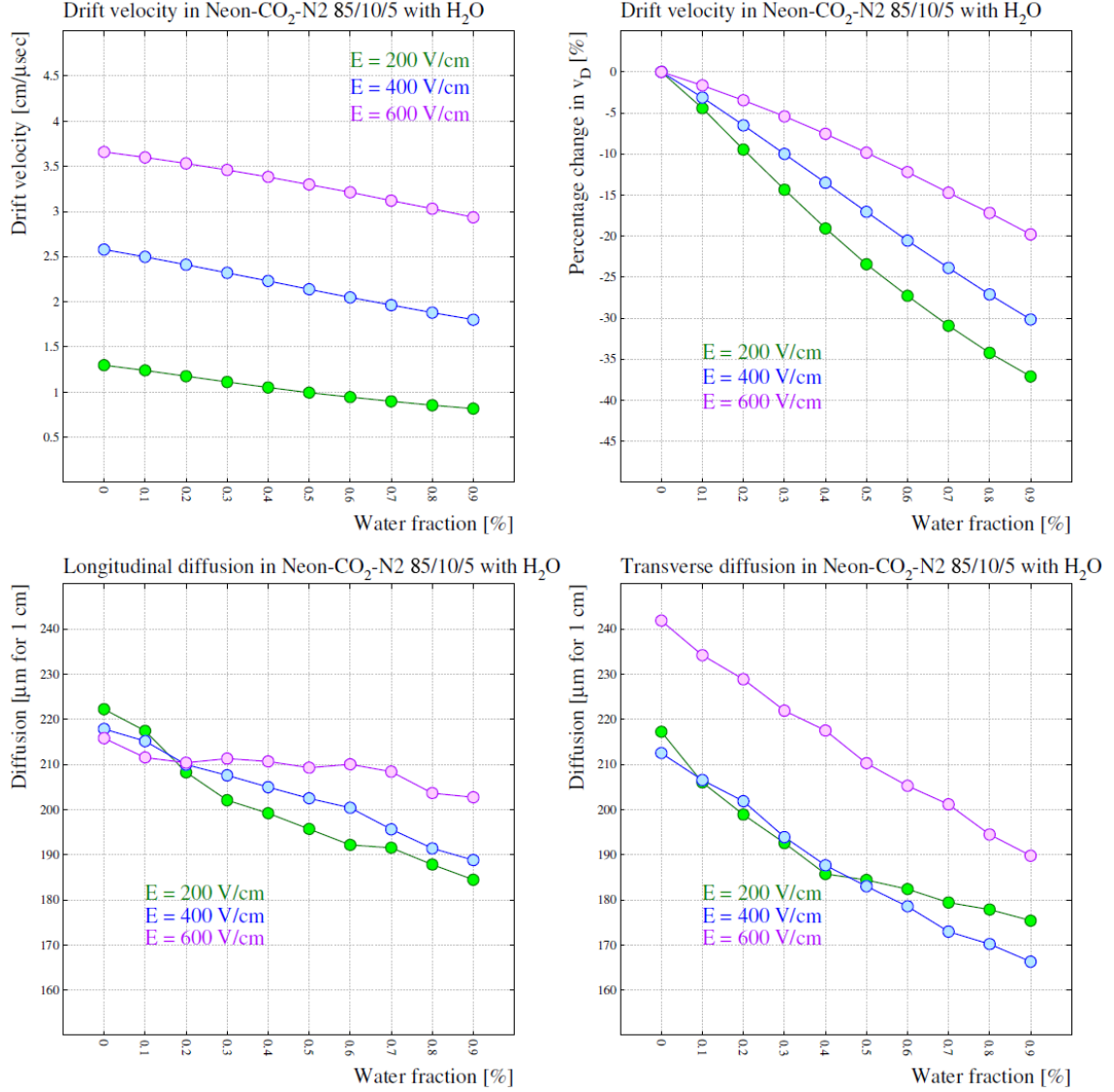


Figure 3.7: The top left graph shows the absolute change of the drift velocity for different electric drift fields as a function of the water content in a Ne/CO₂/N₂ (85:10:5) gas mixture. The top right graph shows the relative change of the drift velocity v_D in percent. The bottom left graph shows the longitudinal and the bottom right graph the transverse electron diffusion as a function of the water fraction [42].

4 Gas system

For the design of the GEM-TPC gas system several requirements had to be taken into account.

For experiments with the expensive Ne gas mixture, the gas system should be operable in a closed circulation mode in order to avoid unnecessary costs. Additionally, for the tests of the GEM-TPC, it was required to run the gas system with different gas mixtures (Ar/CO₂ and Ne/CO₂), where the mole ratios of the mixture components and the total gas flow through the detector can be changed during the tests.

An important point was the controlling of the O₂ and H₂O amounts in the gas mixture, in order to minimize electron losses caused by the electron attachment of these impurities (see Section 3.1). The contamination of the detector gas with oxygen and water vapour is mainly caused by bad sealing joints and permeation through the detector wall material. For the first GEM-TPC tests, the main focus for the gas purification lied on O₂, because of the greater deterioration of the spatial and dE/dx resolution of the detector compared with a H₂O contamination (see Section 3.4).

Another important requirement was the stability of the pressure inside the detector. The pressure control is on one hand important for the stability of the detector performance (see Section 3.1) and on the other hand crucial for the safety of the detector.

4.1 Gas system design

Figure 4.2 shows a scheme of the developed GEM-TPC gas system. It was designed as modular system, where parts of the gas system were build into 19" - racks. The modules of the closed gas system are the "Mixing" module, the "Flow control" module, the "Pressure control" module, the buffer volume, the gas purification cartridge (see Section 4.3) and the cRIO-module (see Section 4.4).

In the "Mixing" module the gas components are mixed with the selected mole ratio. A detailed description of the "Mixing" module is given in section 4.2. The gas mixture is filled into the gas system buffer volume, which is a 12 ℓ big pressure vessel. The vessel serves as gas reservoir within the closed gas system. The pressure inside is kept between 1.5 - 2.5 bar during normal operation, which is measured by a connected pressure gauge. The buffer volume has two gas inlets, which are connected to the "Mixing" module and the gas purification cartridge, and two gas outlets connected

to the "Flow control" module and an exhaust line, which is sealed off by a spring valve with a'n opening pressure limit of 2.7 bar. Due to the gas reservoir possible leaks in other parts of the gas system can be compensated and the required pressure difference between the inlet and outlet of a mass flow controller (MFC), which is located in the "Flow control" module, can be achieved.

The "Flow control" module regulates the total gas flow through the GEM-TPC. At the gas inlet of the MFC a 10 μm particle filter and a normally-closed (NC) pneumatic valve are installed. After the MFC an electromagnetic three-way valve is mounted in the module. With this valve the outlet of the MFC can be switched between an exhaust line and the gas line to the GEM-TPC. During the start-up of the gas system the MFC needs time to stabilize the gas flow. Thus, its outlet has to be connected to the exhaust line during the few minutes.

A gauge with an embedded differential pressure sensor with a measurement range of 0 - 100 mbar is installed after the MFC in the "Flow control" module. This pressure gauge measures the overpressure in the gas system upstream of the GEM-TPC. A top view of the "Flow control" module can be seen on the left picture of figure 4.1.

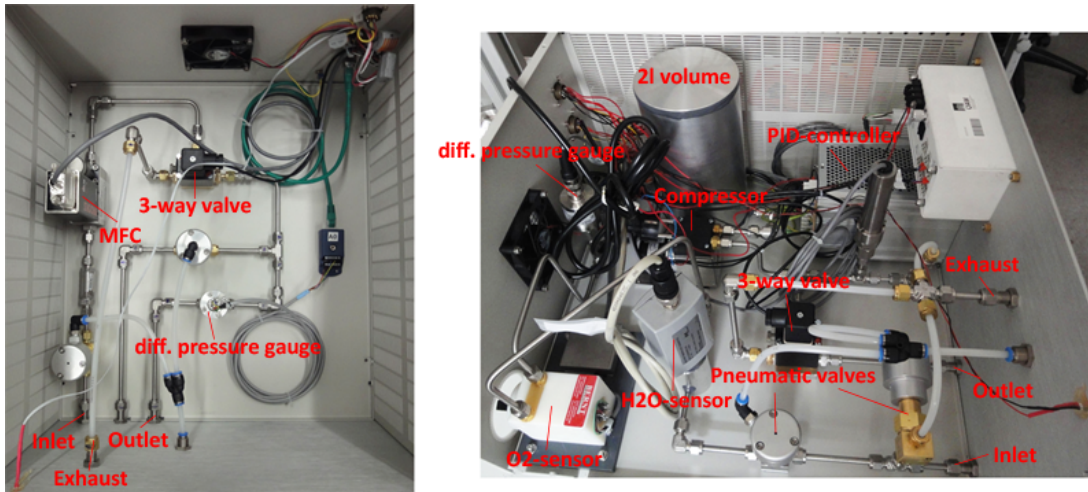


Figure 4.1: Top views of the "Flow control" module (left) and the "Pressure control" module (right) of the closed gas system.

The outlet of the "Flow control" module is connected to the approximately 20 m long gas supply line to the GEM-TPC. Right after the "Flow control" module, an additional gas line branch to the RGA setup (see Section 4.1.3) was installed (see Figure 4.2). A few meters before the GEM-TPC, the ^{83}Rb calibration container (see Section 2.5) was inserted into the gas line.

The "Pressure control" module was connected to the gas outlet line from the GEM-TPC. This module houses apart from the pressure regulation system, the oxygen and water vapour sensors (see section 4.5) and the compressor. The pressure regulation system consists of a differential pressure gauge, a magnetic valve with a maximum

flow of $2\ell/\text{min}$ and an OMEGA PID-controller. The gas line splits after the differential pressure gauge into two branches. During normal operation of the gas system, the gas flows through the gas line, where the oxygen and water vapor sensors are connected. The magnetic valve of the pressure controlling device is mounted behind the oxygen and water sensors. After the magnetic valve an additional small volume of 2ℓ was implemented. This volume serves as small buffer between the pressure regulation system and the compressor. Tests showed, that the time interval of the pressure oscillation due to the regulation procedure is too fast for the PID controller without the buffer volume and the pressure amplitude builds up. Therefore, the pressure could not be stabilized by the pressure regulation system.

The compressor is needed, to assure the circulation of the gas in the closed gas system. Due to the relative small gas flow of below $100\ell/\text{h}$ through the GEM-TPC, a rather small pump was needed. We selected a pump from KNF with a pump capacity of $6\ell/\text{min}$ at STP. In order to protect the pump from damage because of overpressure a spring valve is installed after the pump, which opens the gas line to an exhaust. Also a pressure gauge for pressure observation is mounted downstream of the compressor. Behind the pressure gauge another electromagnetic three-way valve was installed. This valve can switch between the exhaust line in the "Pressure control" module and the closed gas system line. During the filling of the gas system with the right gas mixture and purging of the GEM-TPC, the valve is opened to the exhaust line. A top view of the "Pressure control" module can be seen on the right picture of figure 4.1.

After leaving the pressure control module, the detector gas passes the gas purification cartridge and flow back into the buffer volume. The whole gas system is controlled by a Compact Reconfigurable I/O (cRIO) from National Instruments (see Section 4.4), which is mounted inside the cRIO-module.

Figure 4.3 shows a picture of the closed gas system with the gas purification cartridge as it was tested at GSI.

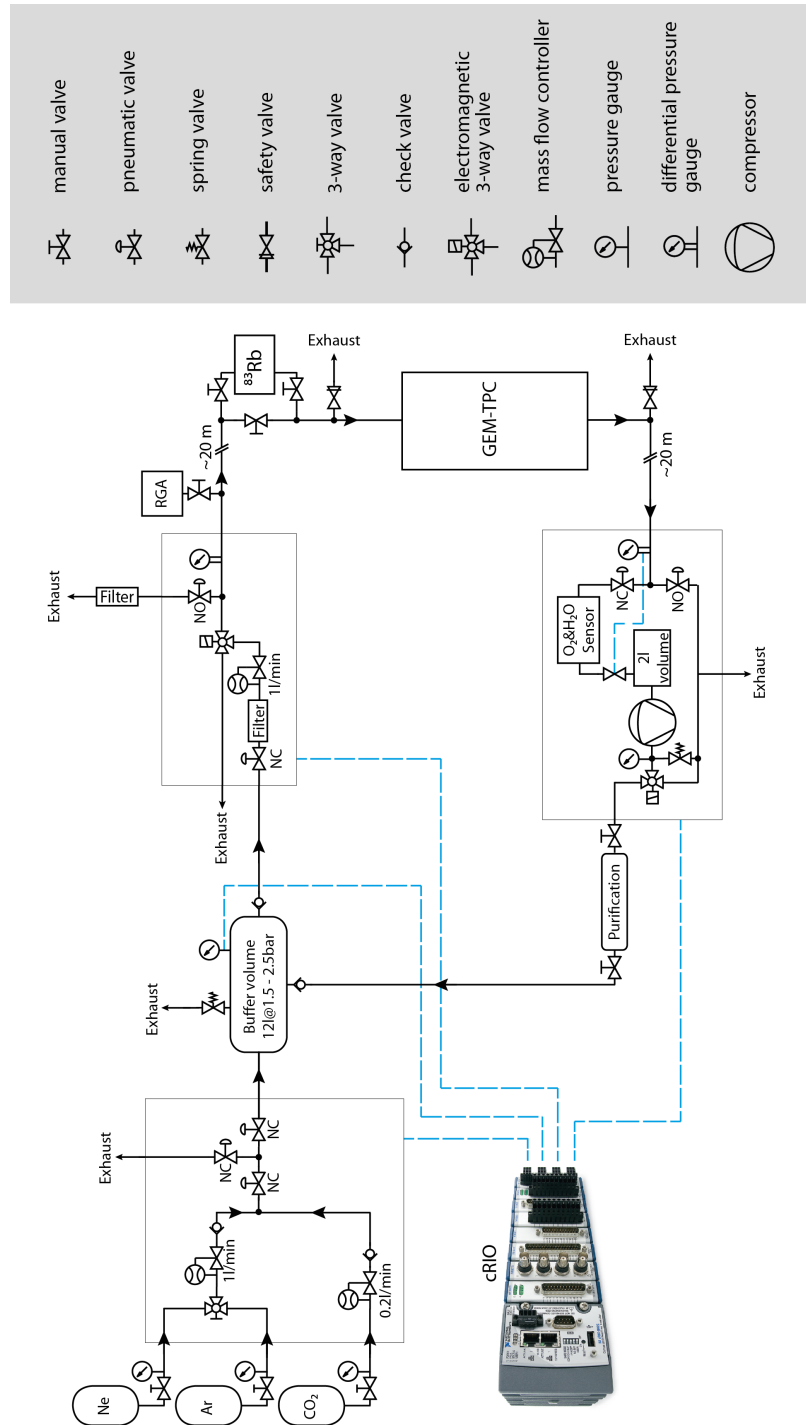


Figure 4.2: Scheme of the closed gas system for the large GEM-TPC prototype (NC...normally-closed, NO...normally-open).

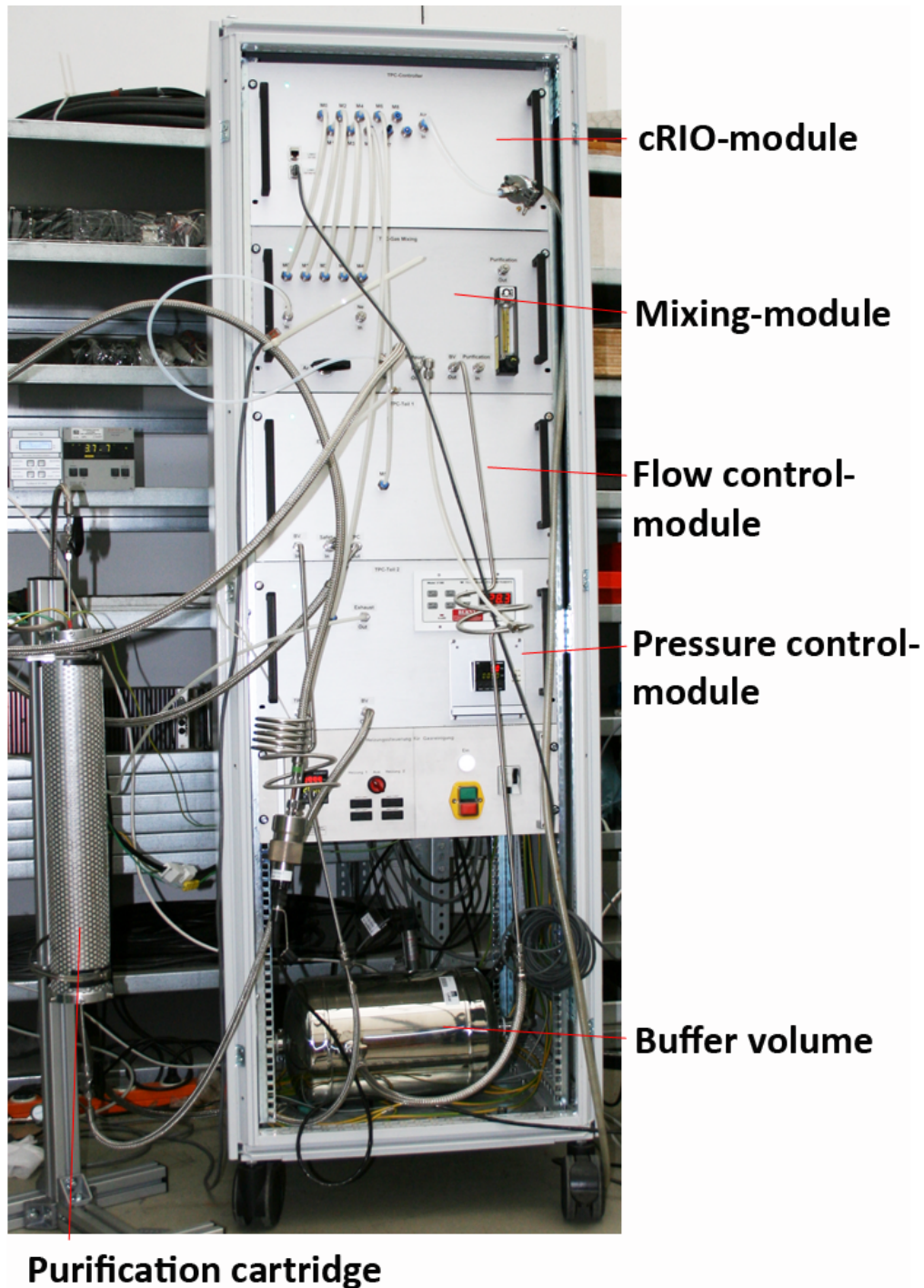


Figure 4.3: Picture of the closed gas system with gas purification cartridge for the large GEM-TPC prototype at GSI.

4.1.1 Pressure control

The regulation of the pressure in the gas system is a very important point for the gas system with respect to the detector safety. Due to the minimization of the material budget of the large prototype, the field cage walls are rather thin and therefore sensitive to differences between the detector volume pressure and room pressure. Due to the lightweight construction of the GEM-TPC field cage, the regulation to a fixed total pressure increases the risk of chamber wall distortions under room pressure variations. Although this kind of pressure control is preferred with respect to the stability of the physical properties of the detector (see Section 3.1), the pressure of the gas system was nevertheless regulated to a constant overpressure relative to the room pressure. Therefore, room pressure variations were compensated and the detector safety ensured.

Differential pressure gauges measure the differential pressure up- and downstream of the GEM-TPC (see Figure 4.2). The pressure of the gas system is controlled by the regulation system in the "Pressure control" module where the overpressure set point was set manually to 5 mbar at the PID-controller.

The regulation system itself is not included into the slow control software of the gas system. The pressure is controlled automatically by the PID controller and only the data of the differential pressure gauge is logged by the slow control software.

4.1.2 Oxygen and water vapour sensors

The oxygen content in the gas system was observed with a Teledyne Model 3190 oxygen transmitter with a A-2C trace oxygen micro-fuel-cell for CO₂ applications. The measurement range of the sensor is 0-100 ppm and the relative accuracy is 2% of the full measurement range. The oxygen transmitter has a 0-10 V analog output, which was connected to the cRIO (see Section 4.4) for the slow control data logging. The right picture of figure 4.4 shows the oxygen transmitter.

The active parts of the micro-fuel cell consist of a cathode, an anode and an electrolyte in which they are submerged. Oxygen starts a chemical reaction in the cell and the energy from this reaction is converted into an electric current by an external electric circuit [45]. Due to the chemical reaction, the life time of the micro-fuel cell is limited to 8-12 months. Therefore the trace oxygen sensor has to be regularly exchanged. The exchange of the sensor can be easily done via the cell-retainer cap of the cell block at the backside of the pressure control module.

A EE375 dew point transducer (see Figure 4.4) was used to measure the water vapour content in the gas system. The measurement range of the sensor is 0-100 ppm and the relative accuracy at standard temperature and pressure is 5 ppm plus 20% of the measured value. The dew point transducer has a 0-10 V analog output for data display and logging.



Figure 4.4: (Left) Picture of the dew point transducer EE375, (Right) Picture of the Model 3190 oxygen transmitter.

4.1.3 RGA setup

Several parameters of the closed gas system, e.g. gas mix or gas purity, need an observation of the ratio of the gas mixture components Ar respectively Ne and CO_2 .

The measurements were made with an HPQ2 Residual Gas Analyzer (RGA) from MKS. The analyzer is a high pressure quadrupole mass spectrometer. Gaseous atoms or molecules are ionized by electrons with an energy around 100 eV. The separation of the ions according to their mass to charge ratio, is made by a high frequency electric quadrupole field which is produced by four rod electrodes. The ions are detected by a Faraday cup. The ion currents of the single gas components are displayed as partial pressure of each component. In order to avoid long-term drift effects of the RGA, the measurement of the gas sample is done in-between calibration measurements.

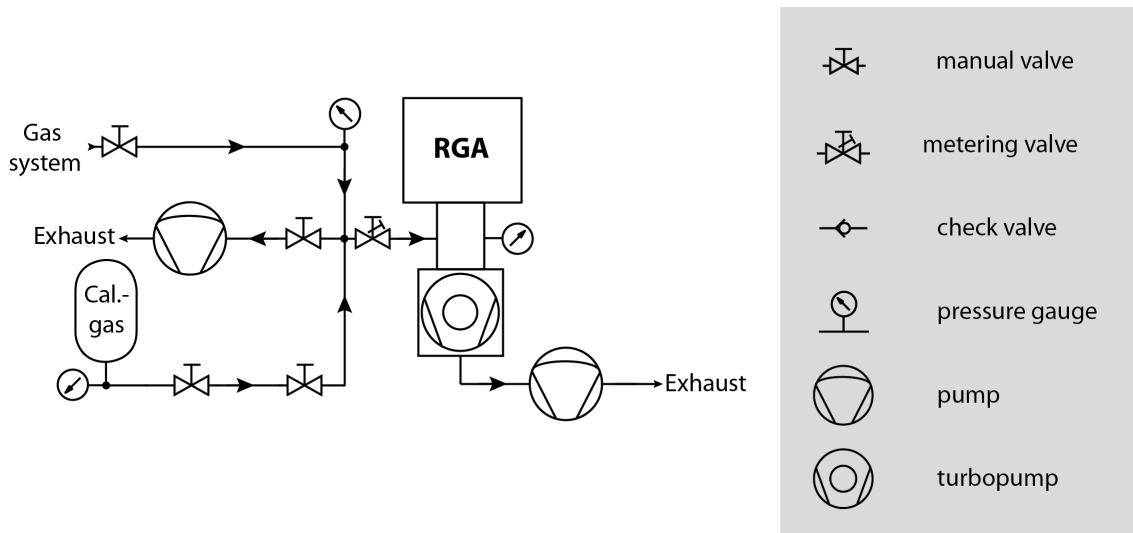


Figure 4.5: Scheme of the RGA setup for the measurements of the ratio between the main gas mixture components.

The setup for the gas analysis (see Figure 4.5) is designed in such way that a small gas sample could be at any time extracted from the closed gas system during

operation condition. Therefore, the RGA measurement setup is connected to the closed gas system via a manual two-way valve (see Figures 4.2 and 4.5). A second inlet gas line is connected via two manual valves to a small calibration gas bottle. The calibration gases were gas mixtures of Ar/CO₂ and Ne/CO₂ with a well defined ratio. A small pump is connected to an additional exhaust line, which is needed to evacuate the gas-inlet lines and to pump out gas samples from previous measurements.

The RGA was connected to a turbo pump, which evacuated the RGA gas volume to a pressure between 10^{-9} - 10^{-7} mbar. Between the setup tubing and the RGA inlet a fine metering valve was installed. Therefore it was possible to generate a controllable gas flow between the setup tubing and the RGA gas inlet, which increased the pressure in the RGA inlet volume by approximately one order of magnitude during the measurements. Figure 4.6 shows a picture of the setup as it was implemented during the tests at GSI.

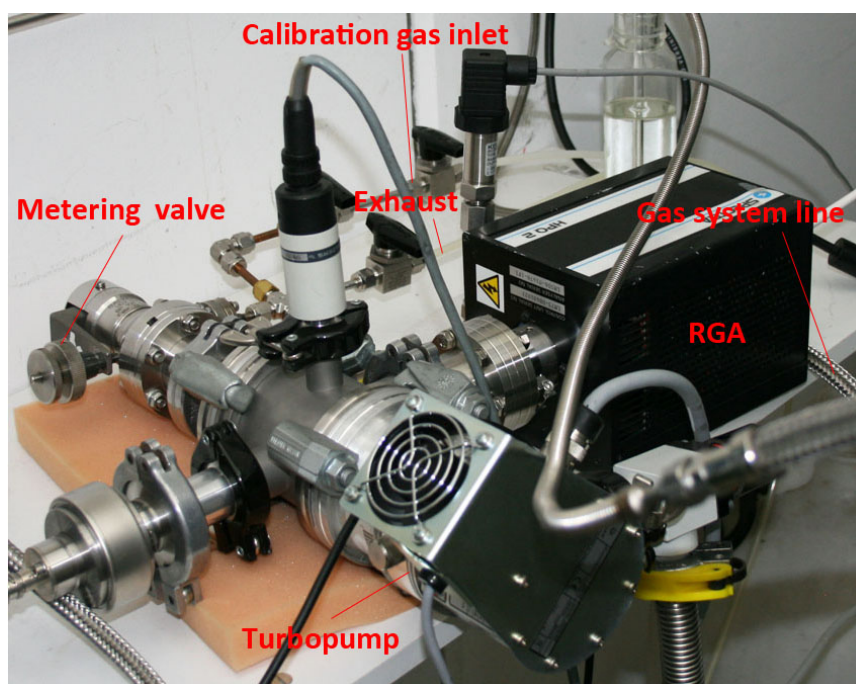


Figure 4.6: Picture of the RGA setup for the measurements of the ratio of the main gas mixture components as it was installed at GSI.

4.2 Gas Mixing

The "Mixing" module for the GEM-TPC tests should be able to mix two different gas mixtures Ar/CO₂ and Ne/CO₂ with an absolute accuracy of 0.1% of the CO₂ fraction. The module has three connections for the three gases Ne, Ar and CO₂. The gas lines of Ar and Ne are connected to two inlets of a manual three-way valve, which can be alternately connected to the valve outlet. Thus, the change of the gas mixture components from Ar and Ne can be easily done. Inside the module only two different gas lines were installed, which are connected to the gas outlet of the three-way valve and the CO₂ inlet. Each line has a SLA5850 mass flow controller from Brooks [46]. This two MFCs regulate the gas flows of the two gas mixture components and ensure the correct mixing ratio. The maximal flow for the Ar respectively Ne MFC is 1 ℓ /min and for the CO₂ MFC 0.2 ℓ /min at STP. The accuracy of the MFCs is 1% of the rate for gas flows in the range of 20% - 100% of the MFC full scale and 0.2% of the full scale for a gas flow below 20%. The outlets of the two MFCs are connected and the gas components are mixed at this point.

The MFCs need some time before a stable gas flow is established, wherefore the output line of the MFCs is at the beginning connected to an exhaust line until the gas flow in both MFCs is stable. After the stabilization, the exhaust line is closed and the gas line to the buffer volume is opened. In order to seal off the different gas lines from each other, each line is equipped with a normally-closed pneumatic-valve. Figure 4.7 shows a top view of the "Mixing" module.



Figure 4.7: Top view of the "Mixing" module. In the bottom left corner, the two MFCs can be seen (left: Ar/Ne MFC, right: CO₂ MFC).

Besides the main gas lines for Ar respectively Ne and CO₂ a third line for a purging gas is build in the "Mixing" module. This line was used for the purging of the GEM-TPC with N₂, e.g. after a longer system shutdown, or for the reactivation of a second purification cartridge with an Ar/H₂ gas mixture during the operation of the first one (see Section 4.3). Because the gas flow does not have to be as accurate as for the main gas lines, the gas flow controller is only a manual flow controller from Newport Electronics. In order to automatize the purging procedure, two normally-closed pneumatic-valves were installed in the gas line. The first valve seals off the purging from the main gas line and the second valve disrupts the gas line to the purging cartridge.

However, the purging gas line was not tested, because so far only one purification cartridge was build and tested and therefore a reactivation during normal operation of the closed gas system was not possible. Also during longer GEM-TPC test breaks, the large prototype was disconnected from the gas system and directly connected to a N₂ bottle.

The most important devices of the "Mixing" module are the two MFCs for both gas mixture components. The SLA5850 MFC uses the thermal mass flow measurement principle. A restrictor inside the MFC separates the total gas flow into two stream. Stream *A* flows straight through the restrictor and stream *B* through the flow sensor. At the far side of the restrictor both stream are united again.

The flow sensor consists of a narrow, thin walled stainless-steel tube with a heating element at midpoint of the tube [46]. Upstream and downstream of this element temperature sensors are installed. The heater element is supplied with constant power. If no gas flows through the sensor tube, the measured temperature at both temperature elements is equal. Flowing gas on the other hand carries the heat from the upstream to the downstream element, which causes a temperature difference ΔT between the two temperature sensors. The difference is directly proportional to the gas mass flow. But the temperature difference depends also on the specific heat capacity c_p of the specific gas. This is shown in equation 4.1, where ΔT is the temperature difference of the two temperature sensors, A a constant, P the heater power, c_p the specific heat capacity and m the mass flow.

$$\Delta T = A * P * c_p * m \quad (4.1)$$

Because of this relation and the N₂ calibration of the MFCs, we had to recalibrate the MFCs for our detector gases Ar, Ne and CO₂. For the calibration of the two MFCs the accuracy of the total gas flow was not as important as the accuracy of the mixing ratio of Ar/CO₂ respectively Ne/CO₂. The absolute deviation of the set CO₂ fraction from the designated fraction should not exceed 0.1%.

First calibration attempts, where the gas flow through a single MFC was measured at fixed set points (see Section 5.3.2), showed that this accuracy could not be achieved

by an independent calibration of the MFCs. Hence, we developed a calibration process, where we could calibrate both MFCs at the same time. For this process we used the RGA setup as it was described in section 4.1.3.

On account of the maximum gas flow of the MFCs ($1\text{ }\ell/\text{min}$ for Ar/Ne and $0.2\text{ }\ell/\text{min}$ for CO_2), the MFC set points were calculated for Ar/ CO_2 and Ne/ CO_2 gas mixtures with a ratio of 90:10 and a total gas flow of $60\text{ }\ell/\text{h}$. The gas mixtures were then measured with the RGA and with respect to the results the set point of the Ar/Ne MFC was adjusted, while the set point for the CO_2 MFC was unchanged. After the final MFC set points were found, several RGA measurements were made to check the CO_2 fraction within the gas mixture. Figure 4.8 shows the results of these measurements. The blue points in the top graph and the green points in the bottom graph of figure 4.8 refer to the single test measurements for Ar/ CO_2 and Ne/ CO_2 gas mixtures. The solid red lines in both graphs represent the mean of the measurements for each gas mixture and the dashed red lines the error of the mean values. With this step by step calibration an absolute deviation below 0.1% from the designated CO_2 fraction of 10% for both gas mixtures Ar/ CO_2 and Ne/ CO_2 could be achieved.

On the other side, the gas flow of the gas mixing MFCs can not be changed without loss of accuracy. However, because the gas flow through the large GEM-TPC prototype is defined by the MFC in the "Flow control" module, while the MFCs in the "Mixing" module only regulates the gas flow into the buffer volume of the closed gas system (see Figure 4.2), the regulations of the gas mixture ratio and the total gas flow through the GEM-TPC are disentangled. Therefore, the GEM-TPC gas flow can be easily changed without impact on the gas mixture ratio.

For future detector tests it was discussed to use a gas mixture of three gases. The "Mixing" module and the slow control software could be easily adapted, but the combined MFC calibration procedure for the gas mixture ratio will be more difficult for three components than for two. While one MFC has to be held at a fixed set point, two other MFCs had to be adjusted at the same time until the desired gas mixture ratio is reached. Although it is possible to calibrate three MFCs in such a way, it is a more difficult procedure.

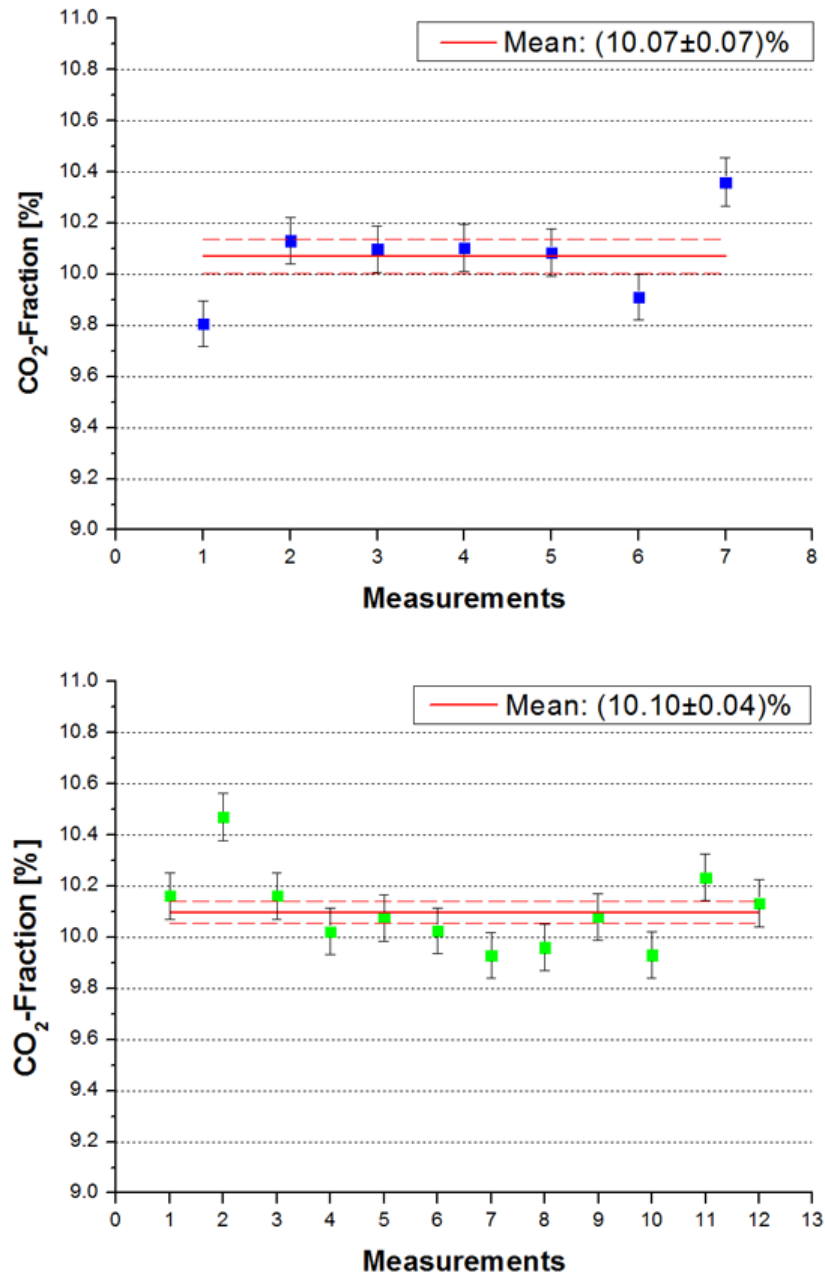


Figure 4.8: Results of the mass flow controller calibration for the gas mixtures Ar/CO₂ (top) and Ne/CO₂ (bottom). The designated CO₂ fraction for both gas mixtures was 10%. The blue points in the top graph and the green points in the bottom graph correspond to the single measurements. The solid red lines in both graphs represent the mean value and the dashed red lines the standard deviation of the mean value.

4.3 Gas Purification

It is important for gaseous detectors as the GEM-TPC, that gas impurities, which disturb the detector performance, are kept as low as possible. The main gas impurities for the GEM-TPC are oxygen and water vapour. For open gas systems the constant gas change in the detector volume with fresh gas from the gas reservoir is often sufficient to reduce the oxygen and water vapour content to an acceptable level. However, for closed gas systems, where the gas in the whole gas system will not be continuously changed, the amount of oxygen and water can not be reduced without a gas purification.

We decided to build for the GEM-TPC the same purification system as it is used in the ALICE-TPC [47] and the LHCb outer tracker [48] gas systems. The system uses the chemisorption procedure for oxygen, which is often used for oxygen extraction from gases. Activated copper binds the oxygen contained in the gas by a chemical reaction where copper and oxygen forms copper oxide.



The activated copper has a limited capacity for oxygen adsorption due to the chemical reaction. Therefore it has to be regularly cleaned. By purging of the purification volume with a gas mixture of hydrogen and a carrier gas while heating the purifier at the same time, the copper will be regenerated. The hydrogen reacts with the oxygen bound in copper dioxide and forms water vapour.



The water vapour is then removed from the purifier by the carrier gas. The continuous operation of this purifier can only be achieved by the usage of two purification cartridges. One cartridge cleans the gas while the other one regenerates.

For the water vapour adsorption, the adsorption power of molecular sieves was used. Molecular sieves are materials with pores of precise and uniform size in the range of the size of gas molecules. Gas or liquid molecules which are small enough to pass through the pores are adsorbed from the sieve while larger molecules pass the sieve unresisted. We used a molecular sieve with a pore size of 3 Å for water adsorption.

4.3.1 Purification cartridge tests

For the first tests we build only one purification cartridge. The cartridge consists of a stainless steel cylinder with a diameter of 38 mm and a length of 500 mm. A 6 mm stainless steel tube with a length of 15-20 cm was welded on each face side of the cylinder. The ends of the tubes were connected to manual two-way valves to be able to encapsulate the purification cartridge. The cylinder is wrapped in

a heating mat with a maximal temperature of 450°C . The heating mat assures a uniform heating distribution over the whole purification cylinder. For safety reasons the heating mat is embedded in glass fiber material as heat insulation. The heat insulation is surrounded by a metal mesh which is grounded. Figure 4.9 shows a picture of the whole purification cartridge.



Figure 4.9: Picture of the purification cartridge at GSI.

The heating module for the purification cartridge is shown in figure 4.10. It is designed in such a way, that the heating mats of two purification cartridges can be connected at the same time. The temperature is regulated with a PID-controller.

First tests of the closed gas system with included gas purification system showed an unexpected effect on the gas mixture. We observed a major decrease of the CO_2 fraction in the gas mixture from 10% to approximately below 1%. In order to identify the origin of this effect, we separated the activated copper from the molecular sieve and build two new purification cartridges each containing only one sort of gas purifier. Additionally, we build a setup for the gas purification tests, which was designed as closed gas cycle (see Figure 4.11). The test gas was Ferromix 18, which is a Ar/CO_2 gas mixture with a CO_2 fraction of 18%.

The gas flow through the test setup was regulated with a SLA5850 mass flow controller which was connected to a Brooks Model 0254 control unit [49]. This



Figure 4.10: Picture of the heating module for the purification cartridge. The PID controller with a setpoint of 200°C can be seen on the left side.

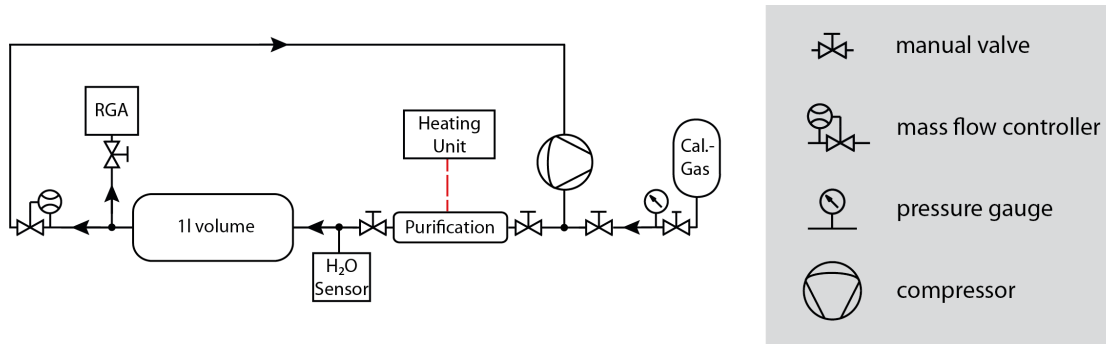


Figure 4.11: Scheme of the setup for the test measurements of the gas purification cartridges.

device is a multi channel process control instrument which allows the controlling of the MFC without computer.

For this test the gas flow was set to 1.5 ℓ /min. A small buffer volume of 1 ℓ was implemented right before the MFC, which compensated gas losses due to possible leaks in the test setup. In order to get a circulation of the gas in the test setup a pump of the same type as in the GEM-TPC closed gas system was used.

Between the buffer volume and the MFC the RGA setup was connected (see Section 4.1.3), which was used for the measurement of the CO_2 fraction of the gas mixture. The calibration gas was Ferromix 18.

The oxygen content level in the test setup had to be also determined by the RGA measurements, because an oxygen sensor was not available during the test measurements of the activated copper purification cartridge. Because an absolute determination of the oxygen level is not possible with the RGA system, the ratio of Ar and O_2 was determined. The RGA was not sensitive enough to measure the oxygen content in the test setup in the ppm region, thus the oxygen level in the gas line had to be artificial increased to a range, where the RGA could measure the ratio between Ar

and O_2 . Due to a controllable leak downstream of the MFC and the under pressure in the gas line section between MFC and compressor, a controlled contamination of the gas system with air was possible.

For the measurement of the water vapour content in the system during the test measurements of the molecular sieve purification cartridge a water vapour sensor was installed between the test cartridge and the buffer volume. The sensor was of the same type as the sensor, which is used in the closed gas system (see Section 4.5.2) but had a measurement range of 0-1000 ppm.

Because the efficiency of the oxygen binding to the activated copper depends strongly on the temperature of the activated copper, test measurements with different temperatures were made. Effects on the adsorption efficiency of the molecular sieve due to temperature changes were also studied.

Before the test cartridges were build in the test setup, they had to be activated for the first time. Therefore, the activated copper cartridge was heated to a temperature of 250°C and purged with an Ar/H_2 mixture (90:10) for eight hours. Before it was implemented into the test setup, the cartridge was evacuated during the night following the purging. During the evacuation, the heating was stopped. For the activation the molecular sieve cartridge, it was heated to 150°C , purged for twelve hours with pure Ar , and afterwards evacuated for approximately three hours at room temperature.

The results of the test measurements of the activated copper purification cartridge are displayed in figure 4.12. The top graph shows the mass 32 to mass 40 ratio in the RGA measurements which corresponds to the oxygen to argon ratio in the gas system. The relative errors of the measurements are below 1%. Thus, the error bars are smaller than the symbols in the graph. The blue squares represent the measurements at room temperature and the red points at a cartridge temperature of 160°C . Both sets of measurement were made within the same measurement run. During the first twelve hours, where the cartridge temperature was kept at room temperature, no visible change in the M_{32}/M_{40} ratio was observed. After 23 hours the cartridge temperature was changed to 160°C . Shortly after this change the M_{32}/M_{40} ratio decreased clearly. The green triangles represent the results for a second measurement run, where the cartridge temperature was set to 160°C from the beginning. Already a few minutes after the contamination of the system with the same amount of air as for the first measurement run a drop in the oxygen level was observable. The bottom graph of figure 4.12 shows the CO_2 fraction in the gas system for the same measurements. It can be seen, that the CO_2 fraction is not affected by the gas purification through activated copper at different cartridge temperatures.

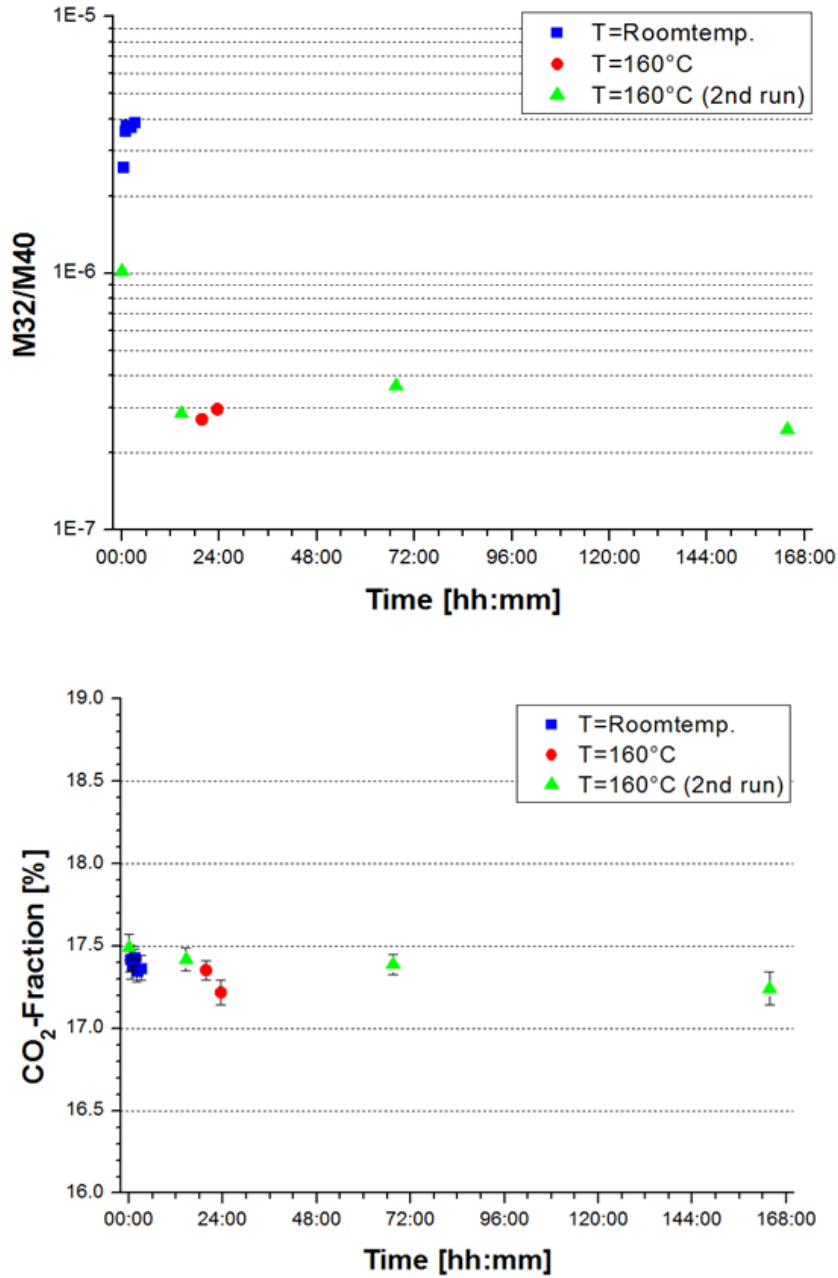


Figure 4.12: On the top graph the trend of the M32/M40 (O₂/Ar) ratio in the gas purification test setup is shown. The bottom graph shows the CO₂ fraction in the test setup for the same time. The blue squares show the measurements at room temperature, the red points at 160°C and the green triangles a second measurement series at 160°C.

Figure 4.13 shows the results of the test measurements of the molecular sieve purification test cartridge. The blue squares represent the measurements at room temperature and the red points the measurements for a cartridge temperature of 75°C. On the top graph the H₂O level in the gas system can be seen. The errors of the measurements are given by the systematic error of the water sensor (5 ppm + 20% of the measured value). It can be seen, that a temperature difference of the purification cartridge does not affect the adsorption of the water vapour in the gas system. The bottom graph shows the CO₂ fraction in the gas system. The relative error of the measurements is 1%. The graph shows that the CO₂ fraction is highly affected by the gas purification through the molecular sieve independent of the cartridge temperature, especially at the first few hours.

The results show initially observed decrease of the CO₂ fraction in the gas mixture is caused by the molecular sieve. For further development of the closed gas system, other solutions for the H₂O purification of the detector gas are in consideration and has to be tested, e.g. activated charcoal.

During the first performance test of the whole GEM-TPC closed gas system a purification cartridge without molecular sieve was used.

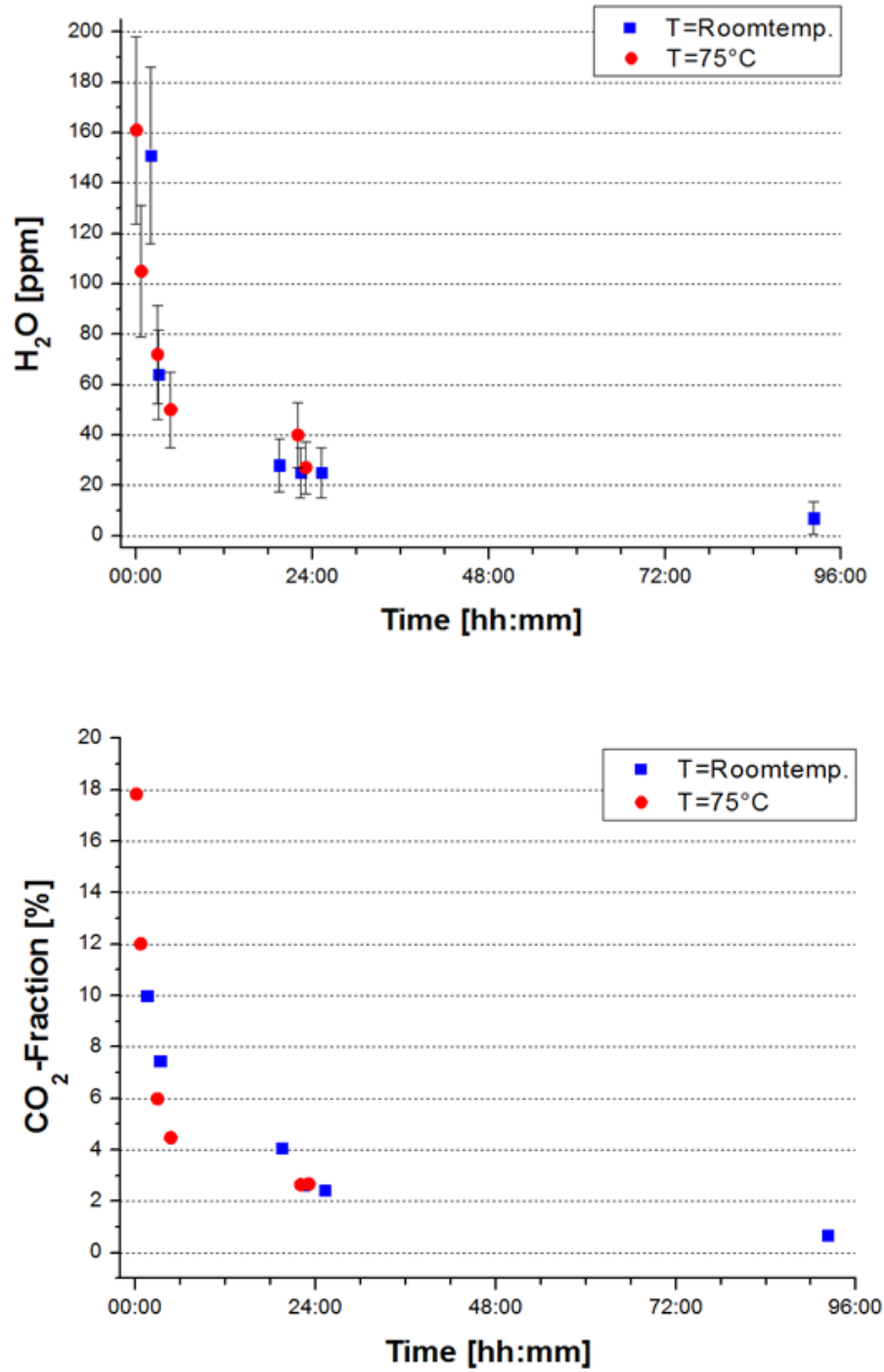


Figure 4.13: On the top graph the H₂O content in the gas purification test setup is shown. The bottom graph shows the CO₂ fraction in the test setup for the same time. The blue squares show the measurements at room temperature and the red points at 75°C.

4.4 Slow Control

The conceptional idea for the slow control of the GEM-TPC closed gas system is based on a stand-alone system. It was designed as failsafe solution which is independent from generally used computer networks. The main device is a Compact Reconfigurable I/O (cRIO) from National Instruments. This is a front-end real-time embedded system, which consists of a real-time controller, a chassis with an integrated FPGA and several easily exchangeable I/O modules.

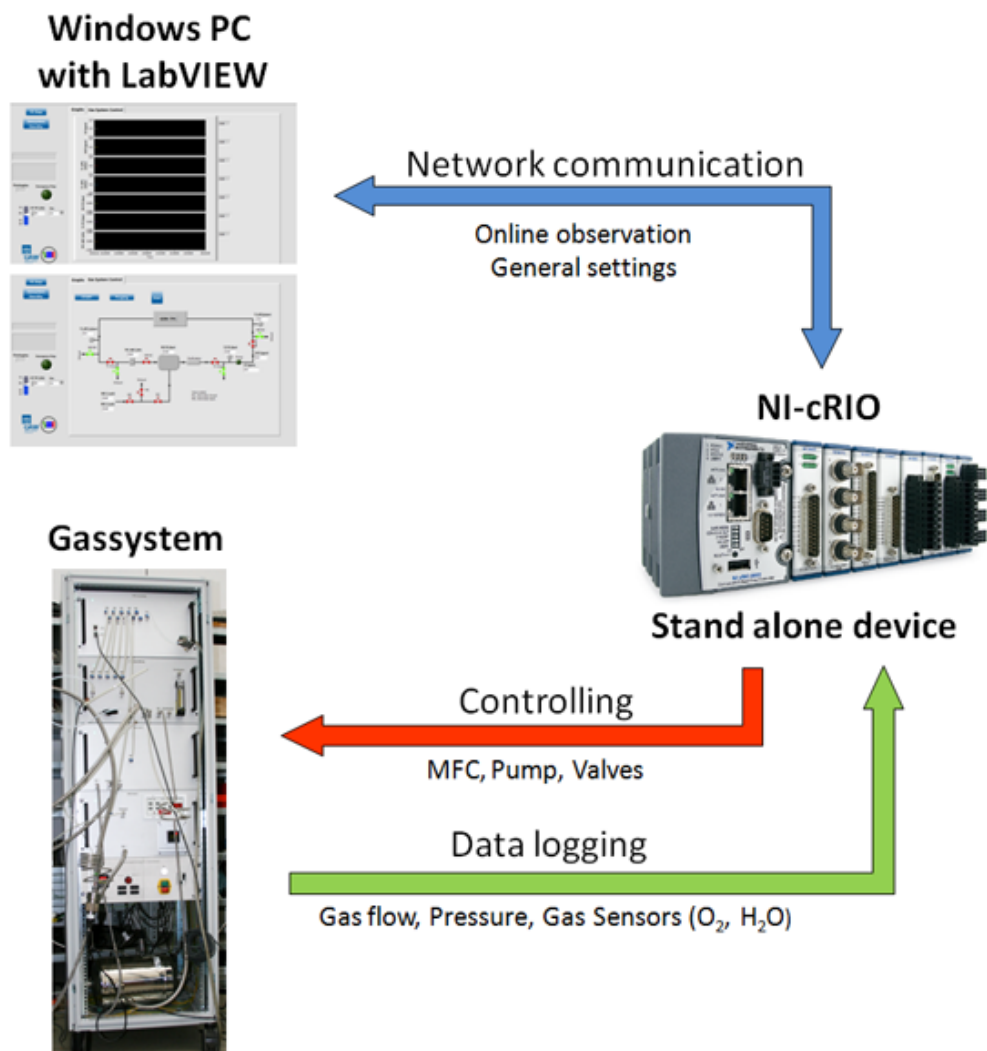


Figure 4.14: Schematic overview of the slow control system.

The cRIO reads out the gas system parameters like gas flow, pressure, oxygen and water vapour levels. The data is automatically logged on the hard disk of the real-time controller and can be easily downloaded on a backup storage. The cRIO also

provides the set points for the MFCs and controls the compressor and the valves. It can be connected via network to a PC with a LabVIEW application, which makes it possible for an user to observe the gas system parameters and operational status online. The user is also able to set new MFC setpoints and change the operation mode (closed, purging, standby) of the system via the LabVIEW application of the PC. Figure 4.14 shows a schematic overview of the slow control system.

4.4.1 cRIO-module

The cRIO-module consists of the cRIO, the power supply for the whole gas system and several two-way magnetic valves for the compressed air distribution to the pneumatic valves (see Figure 4.15).

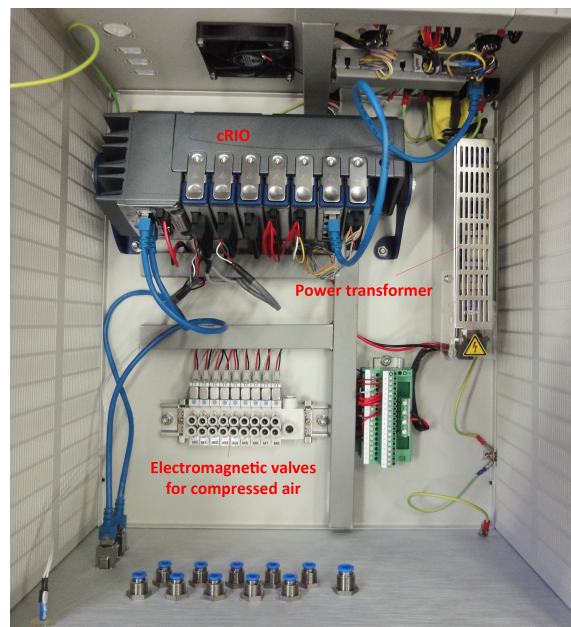


Figure 4.15: Top view of the cRIO-module. The cRIO can be seen in the upper half of the picture.

The cRIO was equipped with seven I/O modules. For the control of the gas system only six modules were needed, while the seventh module was installed as backup. A NI-9265 current output module provides the set point signals for the gas system MFCs. The MFCs measurement signals are read by a NI-9203 current input module. The output signals of the pressure gauges, oxygen sensor, and water vapour sensor are read out with a NI-9205 voltage input module. The signal of the "Flow control" module pressure gauge is read out with a NI-9237 high speed bridge/strain module. The electromagnetic two-way valves for compressed air in the cRIO-module and the electromagnetic three-way valves in the other gas system modules are controlled with

two NI-9485 relay modules. A list of the used cRIO I/O modules with their main specifications is given in table 4.1.

cRIO I/O Modules

NI-9265 4-channel, 20 mA, 100kS/s per channel, 16-Bit analog output
NI-9203 8-channel, ± 20 mA, 200kS/s, 16-Bit analog input
NI-9205 32-channel, ± 10 V, 250kS/s, 16-Bit analog input
NI-9285 8-channel, ± 60 VDC, 750 mA SSR C Series
NI-9237 4-channel High speed bridge/strain

Table 4.1: List of the cRIO modules used in the GEM-TPC closed gas system.

Except for the electromagnetic three-way valves, all valves in the closed gas system are pneumatic. The compressed air is distributed via a block of several two-way magnetic-valves from SMC. These are installed in the controller module right in front of the cRIO (see Figure 4.15). The magnetic valve block has only one input line for the compressed air and several output lines, which are independently actuated by the magnetic valves.

The module itself is powered by a standard 230 V power supply. Inside the module a power transformer is installed, which provides the low voltage of 24 V for the cRIO, the magnetic valves inside the "cRIO" module and the gas system components in the other modules. The electric power is distributed to the other gas system modules via three especially designed power connectors on the module backside. Besides the power connectors three connectors for the signal exchange between the "cRIO" module and the other gas system modules are installed.

On the front plate of the "cRIO" module several connectors for compressed air and an Ethernet connector for the network connection of the cRIO are mounted (see Figure 4.15).

4.4.2 Slow control software

The slow control software is realized with the graphical programming language LabVIEW from National Instruments. The software consists of two LabVIEW applications, which run on the cRIO and one PC. The communication between cRIO and Windows PC is automatically established after the start of the PC application. The slow control software can run on any PC which is connected to the same network as the cRIO.

The cRIO application comprehends the controlling and data logging routines for the gas system. One data file of logged gas system parameters contains the data of 24 hours, in order to keep the size of one file small. The operation variables like MFC set points, detector gas mixture or operation mode are logged within the cRIO software environment and can be overwritten with new values set on the PC

application. If the network connection between PC and cRIO is interrupted, the cRIO continues operation with the last given set point values. All necessary software routines for each operation mode of the gas system are logged on the cRIO and will be automatically executed, if an appropriate command is given at the PC application.

The data, logged by the cRIO, is also forwarded to the PC application, which displays the data for online observation during operation of the gas system.

The "Graph" display (see Figure 4.16) shows several graphs, where the trend of the gas system parameters during the last four hours can be observed. Next to each graph a numerical display shows the actual value of the corresponding parameter.

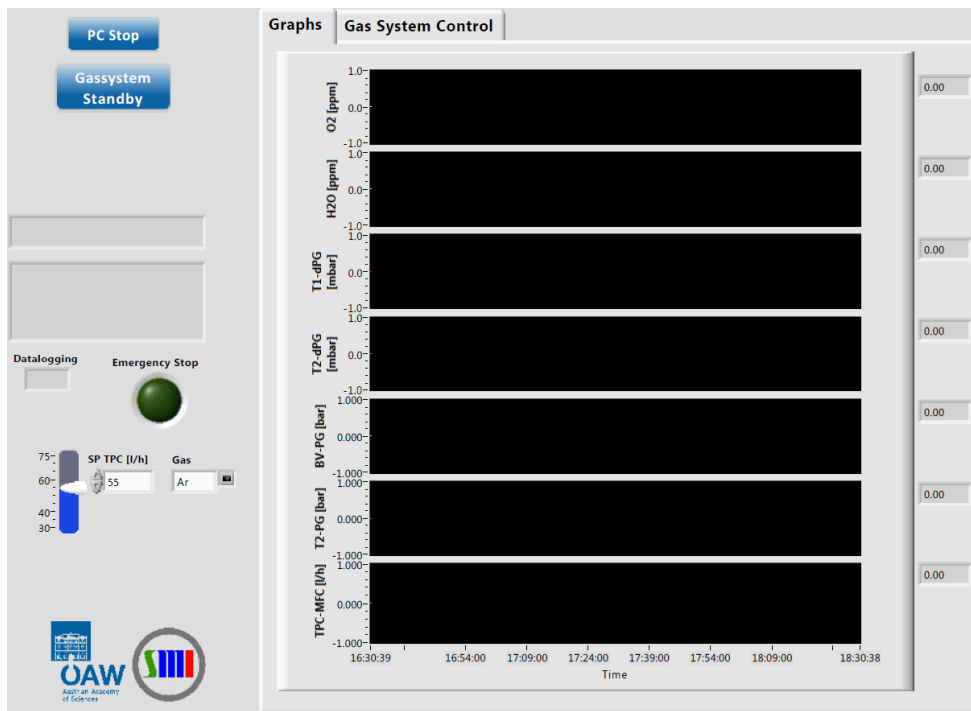


Figure 4.16: Screenshot of the "Graph" display of the LabVIEW application.

The "Gas System Control" display (see Figure 4.17) shows a scheme of the closed gas system. The gas system control devices (e.g. Pressure gauges or MFCs) are shown with numerical displays at their positions in the gas system. The gas system valves are displayed as standard valve symbols. Active valves are marked green while closed valves are red. Also, the operation condition (On/Off) of the compressor in the "Pressure control" module is visualized by a LED on the display. Due to this display arrangement problems in the gas system can be easily identified. Three buttons are arranged above the gas system scheme on the "Gas System Control" tab. With the "Start" button the gas system can be awakened from a standby mode. Anytime during normal operation of the gas system, it can switch to purging mode by pressing the "Purging" button. The purging mode can be ended pressing the "End" button

and the gas system returns into normal operation. The software protocols for the step by step switching between the gas system modes are automatically executed by the cRIO application.

On the left side of the application display another two buttons are placed. With the "PC Stop" button the PC application can be stopped while the cRIO application continues operation. With the "Gassystem Standby" button, the whole gas system can be shut down and send into the standby mode. The gas flow of the "Flow control" module MFC can be regulated with the slide bar below the "Emergency Stop" LED. Next to the slide bar the used main gas component (Ar or Ne) has to be chosen at the PC application, in order to properly set the MFC set point values for the "Mixing" module for each gas mixture (Ar/CO₂ or Ne/CO₂).

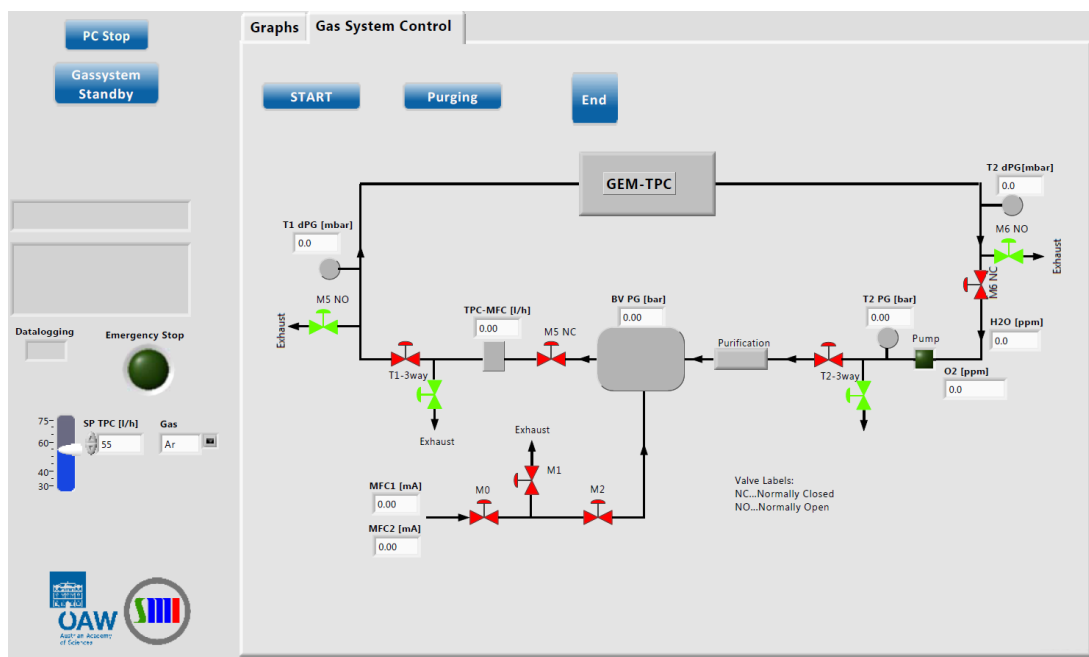


Figure 4.17: Screenshot of the "Gas System Control" display of the LabVIEW application.

4.4.3 Safety Features

The biggest safety risk for the GEM-TPC related to the gas system is an excessive pressure difference between inner and outer chamber wall. This pressure difference could cause distortions of the drift chamber walls. Therefore, several safety features had to be implemented in the gas system to ensure the safety of the GEM-TPC. The safety routine was designed in such a way, that after a possible activation the closed gas system shuts immediately down and returns to the standby mode while the detector is sealed off from the rest of the gas system. In the standby mode the GEM-TPC is sealed off from the gas system by the pneumatic valves in the "Flow control" and "Pressure control" modules and the MFCs and compressor are shut down. From this mode, the gas system can be easily reactivated after an emergency shut down.

The valves of the gas system has a standard position if no electrical power is available. Because the pressured air supply to the pneumatic two-way valves is controlled by the electromagnetic valves in the "cRIO" module (see Section 4.4.1), the valves return to their standard position normally open (NO) or normally closed (NC) at a power blackout. The electromagnetic three-way valves are opened to the exhaust line. Therefore, the detector is also protected during a power blackout.

There could be many reasons for a pressure change in the gas system, but the effects are always verified by the differential pressure gauges in the "Flow control" and "Pressure control" modules. Therefore, some overpressure limits are set in the slow control software for these pressure gauges. The limits for the "Flow control" module pressure gauge are 5 mbar and 25 mbar. The limits for the "Pressure control" module pressure gauge are -5 mbar and 15 mbar. If the measured pressures exceed the limits, an emergency shut down is immediately carried out.

During the first tests of the closed gas system, a few emergency scenarios were simulated, where the safety features of the gas system could be tested. These scenarios included a simulation of a power blackout, a rising of the pressure up- and/or downstream of the GME-TPC and a falling of the pressure downstream of the GEM-TPC. The results showed, that in all cases the emergency shut down worked and the system returned into the standby mode as expected.

For an upcoming upgrade of the GEM-TPC gas system several extensions of the safety system are in preparation. In the next step a purging gas will be connected to the exhaust line of the "Flow control" module to provide a purging of the detector also during an emergency shut down of the gas system. These should prevent the contamination of the detector. Therefore an additional safety device has to be installed in the gas line, which does not depend on electric power or pressured air, in order to operate also during an electric blackout. Two additional exhaust lines sealed off by mechanical safety valves from Air Liquide Austria (see Figure 4.18) will be therefore installed upstream and downstream of the GEM-TPC as close as possible to the detector. The mechanism of the valves is rather simple. The valve orifice is closed with a little plate which is hold in position with a spring. The orifice



Figure 4.18: Picture of the mechanical safety valve.

opens, if the pressure difference between both sides of the plate exceed a limit. The pressure limits depend on the strength of the spring and are set to 15 mbar for the valve upstream of the GEM-TPC and -5 mbar for the downstream valve. The valves do not only ensure the detector safety during an electric blackout, they also extend the safety system during normal operation of the gas system near the detector.

Another important point is the communication with the GEM-TPC high voltage system. The risk of sparking in the detector region rises if the gas flow through the detector is interrupted. Therefore, the high voltage has to be shut down after an emergency stop of the gas system. The communication could be established via a voltage signal provided by the gas system and read out by the HV system. The HV system can only be turned on, if the signal from the gas system is set, or has to be ramped down, if the signal is lost because of an emergency shut down of the gas system.

4.5 Gas system performance test

The first closed gas system setup was tested within the GEM-TPC gas supply lines of the FOPI experiment at GSI but without the large prototype. The goal of this test was to study the performance of the different gas system features like gas mixture stability, gas purity and safety. In order not to damage the large GEM-TPC prototype during this test, it was replaced by a pressure vessel with a volume of 4 ℓ (see Figure 4.19).



Figure 4.19: Picture of the GEM-TPC dummy volume used during the first tests of the closed gas system.

The main focus of these tests were on the pressure and gas mixture stability of the gas system and the measurement of the oxygen level. Because of the observed CO_2 adsorption effect of the molecular sieve during the first purification system tests, the purification cartridge for this test contained only activated copper and the stability of the CO_2 fraction of the gas mixture was measured. In order to see even small changes in the gas mixture a premixed Ar/CO_2 gas mixture with an mole ratio 90:10 was used during the test measurements. A picture of the test setup can be seen in figure 4.3.

4.5.1 Pressure stability

Figure 4.20 shows the differential pressure in the gas system during the test. The blue line shows the overpressure measured by the differential pressure gauge in the "Flow control" module and the red line shows the overpressure measured by the differential pressure gauge in the "Pressure control" module. The uncertainty of the measurements is mainly given by the systematic error of the differential pressure gauge, which is $\pm 0.2\%$ of the fullscale. This corresponds to an error of ± 0.2 mbar.

The graph shows that a pressure stability below ± 0.5 mbar could be achieved during normal operation. While the overpressure in the "Pressure control" module is fixed to 5 mbar, the pressure in the "Flow control" module reaches a plateau at

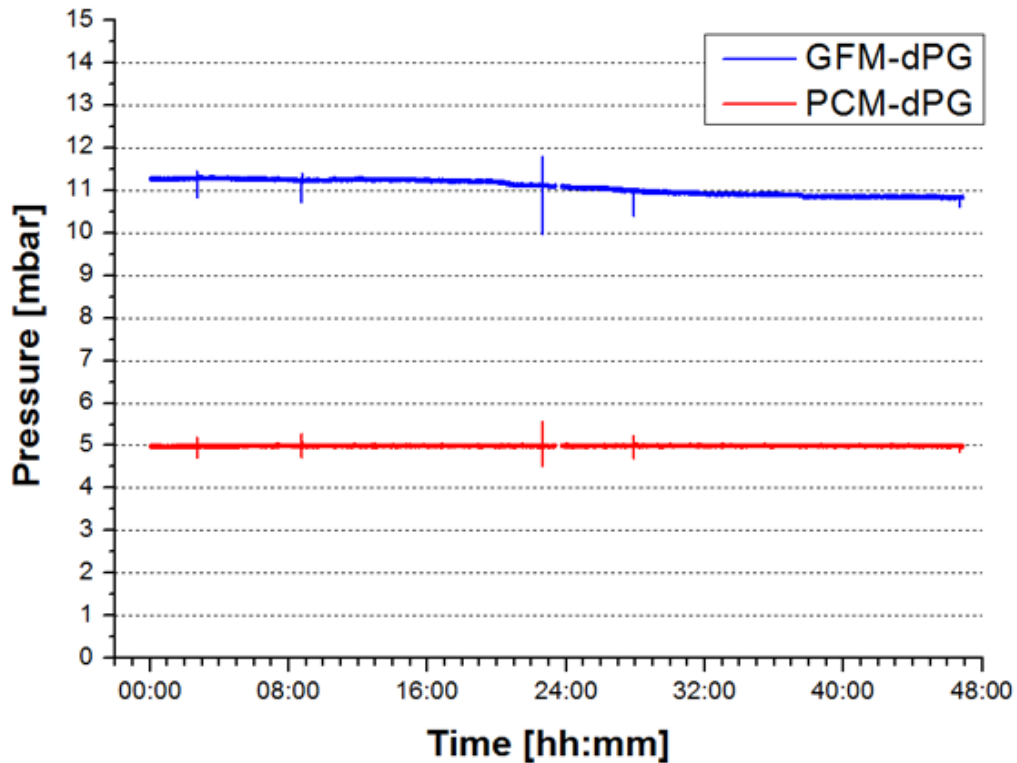


Figure 4.20: The graph shows the pressure stability of the closed gas system over 48 hours. The red line shows the measurements of the differential pressure gauge in the "Pressure control" module (PCM-dPG). The blue line shows the results of the differential pressure gauge in the "Flow control" module (GFM-dPG).

11 mbar, which is far below the pressure tolerance of the GEM-TPC of maximal 50 mbar overpressure.

During the first minutes of the gas system start-up temporary oscillation of the pressure inside the gas system occurs before it is stabilized by the pressure control system. The transient oscillation was analyzed towards maximal amplitude of the oscillation and time till pressure stabilization. Figure 4.21 shows the pressure deviation in both differential pressure gauges during the first minutes after the activation of the compressor in the course of the gas system start-up. The blue line corresponds to the overpressure in the "Flow control" module and the red line to the overpressure in the "Pressure control" module. The measurements show that the pressure could be stabilized by the pressure control system already after approximately three minutes after the activation of the compressor. Even during the temporary oscillation the pressure in the "Pressure control" module does not exceed ± 0.5 mbar. The only exception is the first peak with a deviance of approximately 3.5 mbar above the nominal set point of 5 mbar. After the first deflection of the pressure to nearly

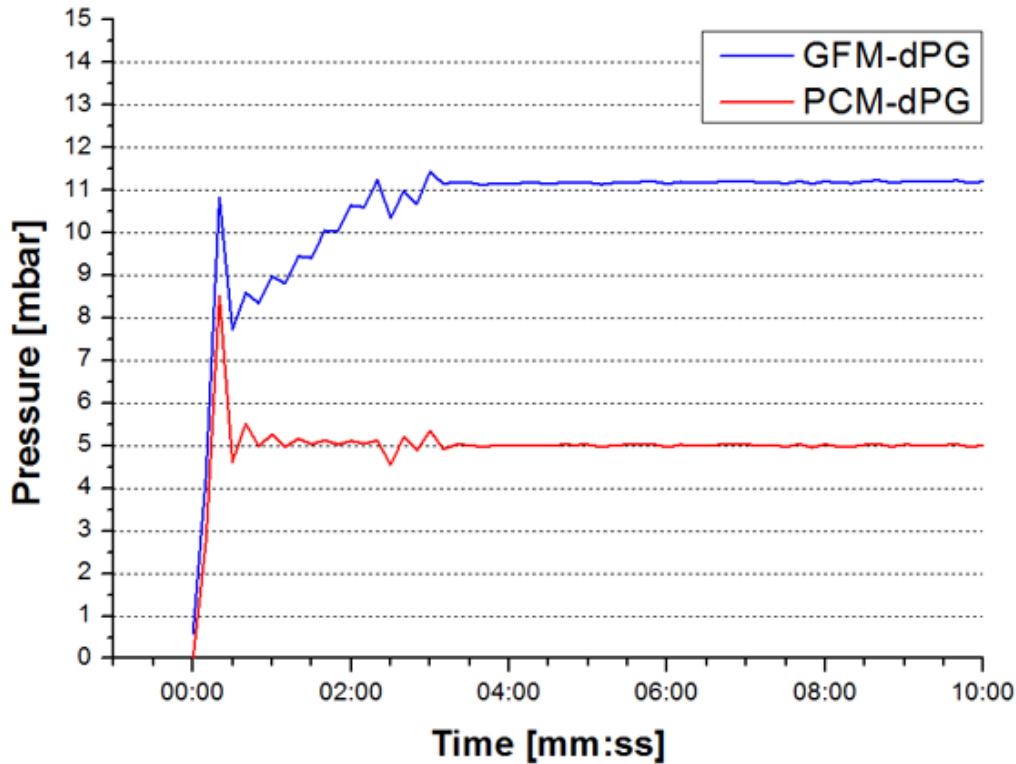


Figure 4.21: The graph shows the transient oscillation of the pressure during the start-up of the closed gas system. The red line shows the measurements of the differential pressure gauge in the "Pressure control" module. The blue line shows the results of the differential pressure gauge in the "Flow control" module.

11 mbar overpressure in the "Flow control" module, it dropped to 8 mbar before it slowly rose again. The pressure reached a plateau at 11 mbar after three minutes after the compressor activation.

The results showed, that a stable pressure level in the gas system could be achieved after a relative short transient oscillation period of only a few minutes. Furthermore, with the pressure stability of below ± 0.5 mbar during the normal operation, the aspired goal of ± 1 mbar could be exceeded. Also the maximal amplitude of the oscillation during the start-up is well below the pressure tolerance level of the large prototype.

4.5.2 Oxygen content

In order to get rid of the majority of the impurities in the whole setup and to fill it with the test gas mixture, the gas lines were purged over one night with Ar/CO₂ before the purification cartridge was implemented and the gas system was closed. Due to the purging, the oxygen level in the gas system was already at 5 ppm before the start of the test.

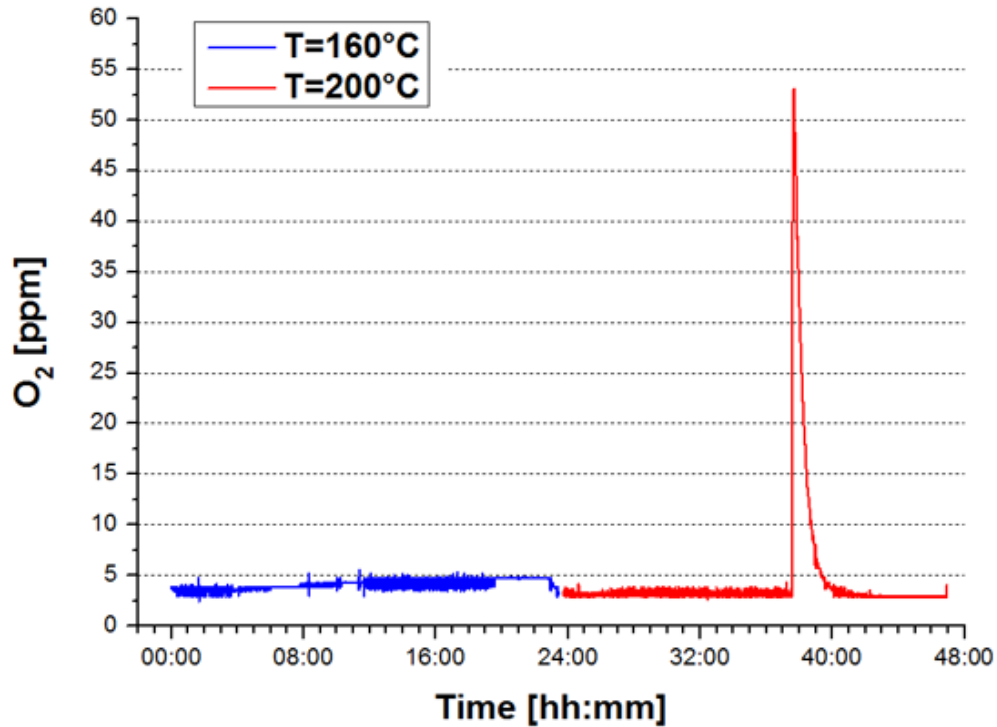


Figure 4.22: The graph shows the oxygen content in the closed gas system over 48 hours. The blue line shows the results for a purification cartridge temperature of 160°C and the red line the results for a temperature of 200°C.

Figure 4.22 shows the oxygen content in the gas system during the test. The blue line shows the measurement results for a purification cartridge temperature of 160°C and the red line the results for a temperature of 200°C. It can be seen that the oxygen level stayed below 5 ppm for both temperatures. After approximately 37 hours of operation the oxygen level rose above 50 ppm before it fell again below 5 ppm after another two hours.

Figure 4.23 shows the pressure trend in the buffer volume during the test. As it can be seen, the pressure in the buffer volume slowly decreased until the refill procedure started after approximately 37 hours of operation, which concurred with the time of the oxygen level increase.

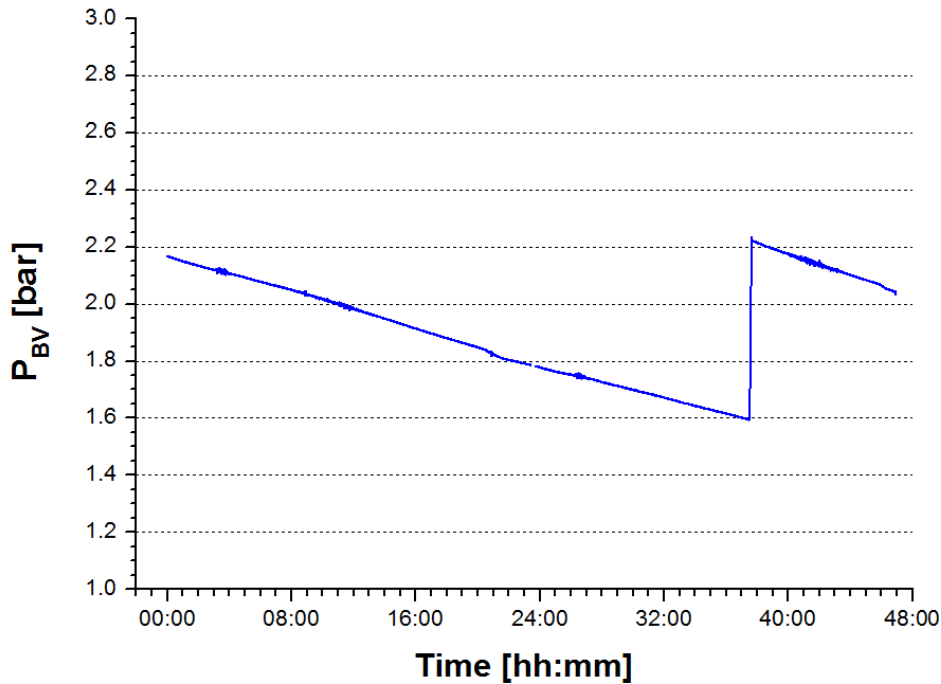


Figure 4.23: The graph shows the pressure trend of the closed gas system buffer volume over 48 hours.

An increase of the oxygen level during the refilling of the gas system with fresh gas was expected. During normal operation, the gas mixing system is in standby mode, which means that the gas flow in this part of the gas system is stopped. Therefore, the gas lines of the "Mixing" module are not purged and could be contaminated with air during the standby time. Additionally, during the start up of the "Mixing" module for the refilling of the buffer volume with fresh gas, the output lines of the MFCs are connected to the exhaust line until both MFC gas flows are stabilized. This could also lead to contamination of the gas mixing lines. Because the pressure in the buffer volume continuously decreased, due to possible leaks, until the minimal pressure limit was reached, the slow control system automatically started to fill the buffer volume with fresh gas from the "Mixing" module and thus the impurities reached the closed gas system.

For an upcoming upgrade of the gas system a continuous pumping of the gas mixing system during the standby time is foreseen. Furthermore, the gas lines will be purged for a longer time, before the connection to the buffer volume is established. Thus, the contamination in the "Mixing" module can be avoided.

Nevertheless, the test showed that the oxygen content in the closed gas system could be easily kept below 5 ppm, which is considerably below the designated level of 10 ppm.

4.5.3 Gas mixture stability

As already mentioned before a premixed Ar/CO₂ gas mixture with an mole ratio of 90:10 was used for the gas system test. Therefore, only the possible change of the CO₂ fraction during the test time was examined. For that purpose the RGA setup for gas mixture determination was used for these measurements. Figure 4.24 shows the results of the CO₂ fraction measurements, where a change of gas mixture CO₂ fraction can not be seen. The result shows, that the gas mixture stability can be assured over a longer operational time.

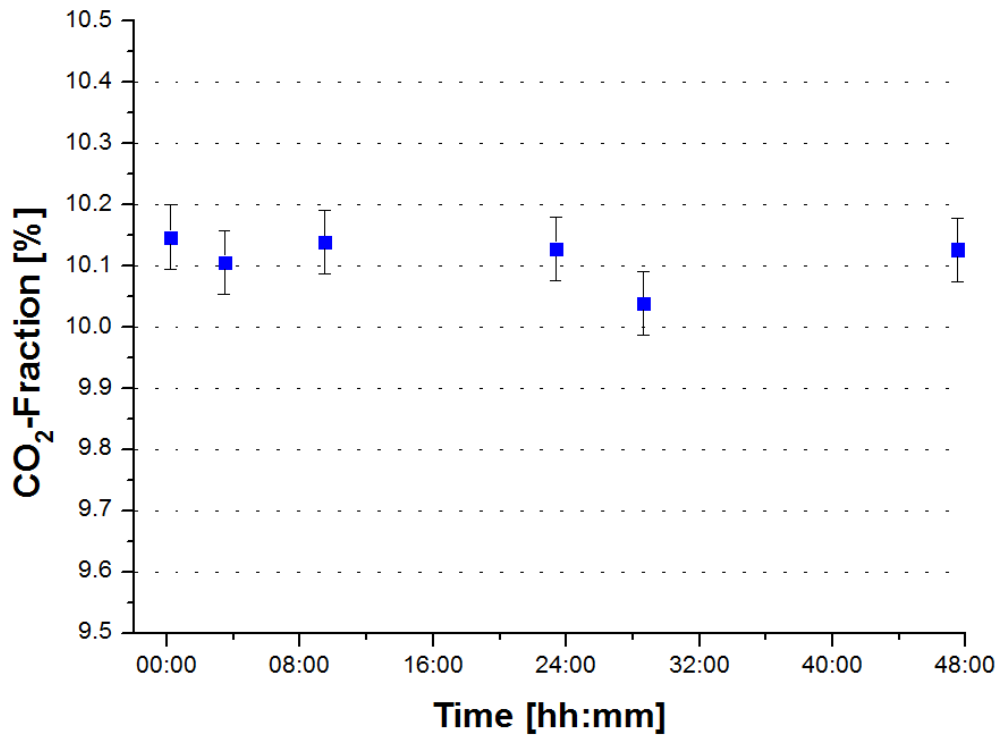


Figure 4.24: The graph shows the CO₂ fraction of the closed gas system over 48 hours.

5 FOPI experiment S339

As already mentioned in the introduction, the large GEM-TPC prototype was installed inside the FOPI detector system for tests and also during an experiment on strangeness production in π^- -induced reactions (FOPI experiment S339). The following chapter will first give an overview of the FOPI detector system, afterwards the physics motivation of the experiment S339 will be discussed and the experimental described.

5.1 FOPI detector system

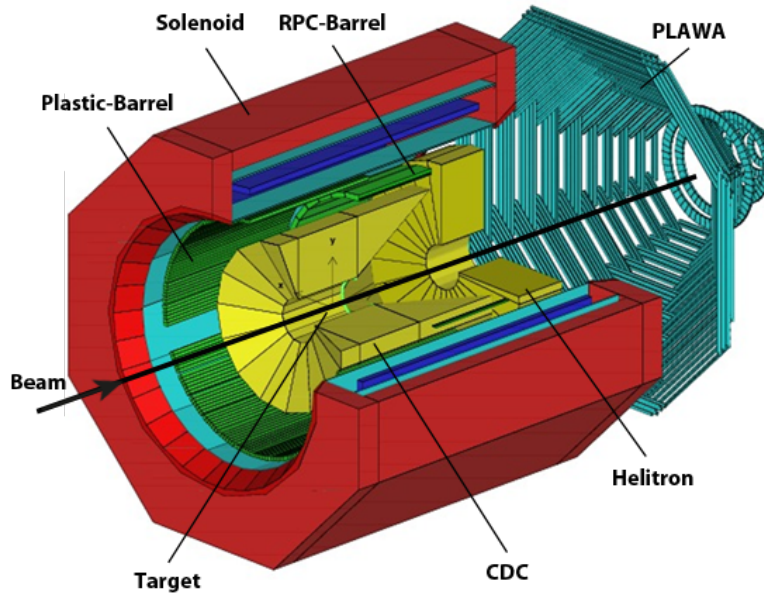


Figure 5.1: Scheme of the FOPI spectrometer.

FOPI has been designed as a fixed-target heavy ion experiment with a large angular acceptance. It was built to study the properties of hot and dense nuclear matter formed by heavy ion collisions covering the complete beam energy range

(0.1 - 2 A·GeV) of the Heavy Ion Synchrotron SIS at GSI, Darmstadt, Germany [50]. FOPI is a modular detector system, which consists of two drift chambers and several scintillator detectors [28] covering nearly the full 4π solid angle. It allows the identification of charged particles like light mesons ($\pi^\pm$, $K^\pm$), hydrogen (p, d, ^3H), helium isotopes (^3He , ^4He) and heavier fragments.

The detector system components are the Central Drift Chamber (CDC), the Plastic- and MMRPC-Barrel (Multi-strip Multi-gap Resistive-Plate Counter), the HELITRON drift chamber, the Forward Plastic Wall (PLAWA) and a superconducting solenoid (see Figure 5.1). Figure 5.2 shows a picture of the FOPI system.

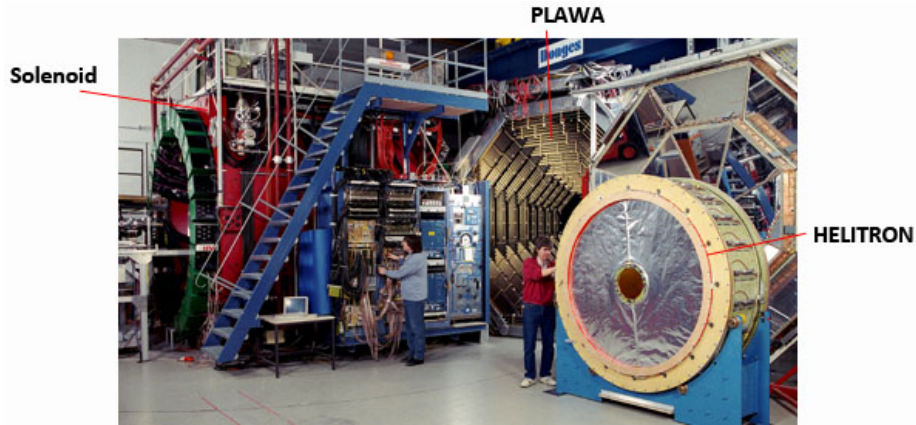


Figure 5.2: Picture of the FOPI spectrometer at the installation of the HELITRON.

- **Start System:** The start system consists of the start counter and a veto counter. The start counter measures the number of beam particles and provides the start time for the FOPI sub-detectors. For the S339 experiment it was placed 2.5 m upstream of the nominal FOPI target position. It consists of one $4 \times 6 \text{ cm}^2$ big scintillator bar with a thickness of 1 cm. The scintillator is read out on both sides by photomultipliers.

The veto counter is in anti-coincidence with the start counter to reject beam particles, which are not focused on the target. It is built of a ring-shaped 5 mm thick single layer scintillator, which is read out by Silicon Photomultipliers (SiPMs) [51]. It was installed in front of the target in order to detect beam particles aloof the beam axis.

- **CDC:** The CDC measures the specific mean energy loss dE/dx as well as the momentum of a particle, which can be used for particle identification and its mass determination via the Bethe-Bloch equation (1.3). It is a jet type drift chamber which covers the full azimuthal angle. The polar angle acceptances of all detector parts during the experiment can be seen in table 5.1. The CDC has a cylindrical geometry with conical end-caps on both sides. The

maximum length in beam direction is 2 m and the inner and outer radii are 20 cm respectively 80 cm. The detector is divided into 16 sectors each with 60 sense and 60 potential wires, which are aligned parallel to the beam axis. The wire length varies between 86 cm and 190 cm depending on their radial position. The hit resolution in the xy -plane is around $300\text{ }\mu\text{m}$ whereas in z -direction it is several cm . As chamber gas typically a gas mixture of Ar, Isobutene and Methane (88:10:2) is used.

- **RPC-Barrel:** The RPC-Barrel can determine the time-of-flight (ToF) of a particle with a time resolution of $\sigma \leq 70\text{ ps}$ [52]. With the track momentum information of the CDC, enhanced PID via improved mass determination is possible. A single RPC counter consists of a double-sided printed-circuit board (PCB) with sixteen 900 mm long and 1.64 mm broad anode stripes with 0.9 mm gaps between. The anode is sandwiched between two stacks of alternating 1.1 mm and 0.55 mm thick glass plates with four gaps defined by $220\text{ }\mu\text{m}$ spacers. The outermost glass plates serve as cathodes. Five counters are mounted together in a partially overlapping layer in a carbon-fiber box as an so called Super Module (SM). The total RPC-Barrel consists of 30 SMs mounted around the CDC in a distance of 94 cm from the beam axis [52], leaving only space for the mechanical support structure of the CDC. The position of the charged particle hit in transverse direction is given by the fired stripe, while the position in beam direction can be measured by the difference of the signal times measured at both ends of the stripe.
- **Plastic-Barrel:** The Plastic-Barrel is a second ToF detector, which surrounds the CDC at a radius of 111 cm from the beam line. It consists of 180 individual, parallel to the beam axis aligned detectors. Each detector consists of a $150 \times 4 \times 3\text{ cm}^3$ plastic scintillator bar. Except for two 11° wide holes for the CDC mechanical support the full azimuthal angle is covered. The scintillator bars are readout on both sides with 2" photomultipliers. Due to the space limitations the signals from one end cap are guided via approximately 90 cm long light-guides to the PMTs. The time resolution of the Plastic-Barrel varies between 140-300 ps depending on the position and the amount of primary light [28].
- **Superconducting Solenoid:** The Superconducting Solenoid surrounds the Plastic- and RPC-Barrel and the Helitron (see Figure 5.1). The diameter of the magnet is 2.4 m and the length 3.3 m. With the maximum current of 720 A a 0.6 T magnetic field with a homogeneity of $\pm 1.5\%$ can be achieved in the central volume.
- **HELITRON:** A second drift chamber, the HELITRON, is installed in forward direction with a polar angle range of 7° to 30° regarding to the nominal target

position. The track reconstruction and PID methods are similar to the CDC. The material budget in the detection area of the drift chamber is reduced by the bicycle wheel like design, where the inner cylinder structures is held by the radially installed cathode frames. The HELITRON consists of 24 sectors each with 54 sense and 53 potential wires. The wires of one sector are aligned in a plane parallel to the beam axis and, where the wire direction is radially, perpendicular to the the beam axis. The chamber gas is the same gas mixture as for the CDC.

- **Plastic Wall:** The Forward Plastic Wall [53] is installed downstream the HELITRON drift chamber. It measures the deposited energy as well as the ToF, thus provides charge and velocity information. The combination of HELITRON and PLAWA allows a PID in forward direction similar to matched CDC/Barrel tracks. The PLAWA consists of 512 scintillator bars with a cross-sectional area of $1.8 \times 2.4 \text{ cm}^2$ and a length between 45 cm and 165 cm. The total number of bars are divided into 8 radial sectors each with 64 scintillator bars. The scintillators are on both ends read out via light guides by 1" phototubes. The light guides and tubes of one sector are behind the crossing area of two neighboring sectors. The time resolution varies between 80 ps for a scintillator bar length of 50 cm and 120 ps for 165 cm [53].

Table 5.1 shows a list of the polar angle acceptances of the different FOPI detector parts and the GEM-TPC with respect to the actual target position during the S339 experiment.

Detector	Polar angle acceptance
GEM-TPC	$9^\circ - 172^\circ$
CDC	$18^\circ - 122^\circ$
Barrel	$57^\circ - 125^\circ$
RPC	$32^\circ - 59^\circ$
HELITRON	$5^\circ - 29^\circ$
PLAWA	$6^\circ - 26^\circ$

Table 5.1: Polar angle acceptances of the different FOPI detectors regarding to the target position during the S339 experiment.

For the S339 experiment the FOPI detector system was upgraded with the large GEM-TPC prototype as inner tracker. Due to this upgrade an improvement of the tracking and the particle identification capabilities of the whole detector system were expected.

The FOPI spectrometer is with approximately 20 years rather old and therefore has some drawbacks compared to modern detector system like $\bar{\text{P}}\text{ANDA}$. One drawback is the rather low hit resolution of the drift chambers, which lower the track separation

capabilities for events with higher track density. Most tracking detector systems have also a vertex detector or at least an inner tracker with a high resolution, which can determine track vertices with an accuracy up to a few μm . FOPI had no detector near the target system, which could undertake this task with a satisfying accuracy. The situation was particular bad in forward direction, where the first detector is the HELITRON with a distance of more than 150 cm from the nominal target position. Thus a vertex determination for particle tracks in forward direction was not possible. The CDC could in principle determine track vertices with an accuracy of a few mm in the xy plane, but, due to its low z resolution, the vertex resolution in beam direction is worse by one order of magnitude. The GEM-TPC as inner tracker could overcome these drawbacks. With the GEM-TPC track position informations with a high resolution near the target can be achieved. Thus the vertexing capabilities for high polar angles (CDC) is improved and for low polar angles (HELITRON) vertex determination is possible in the first place. The track separation capabilities should be also enhanced. In addition, it is expected, that the momentum and therefore the mass resolution of the whole detector system will improve.

5.2 Physics motivation

The goal of the FOPI experiment S339 in June, 2011 was the study of strangeness properties and propagation in normal nuclear matter. The pion (π^-) induced in-medium $\phi(1020)$ resonance production by its decay into charged kaons (K^+K^-) was therefore explored [29].

The low-energy Quantum Chromo Dynamic (QCD) ground state (vacuum) hosts strong condensates of quark-antiquark pairs and gluons. The ground state expectation value of the scalar quark density, or quark condensate $\langle q\bar{q} \rangle$, represents a parameter for the spontaneous breaking of the chiral symmetry [54]. The $\langle q\bar{q} \rangle$ behavior is expected to depend on temperature T and density ρ of the medium [55]. Low-energy QCD models predict already at normal nuclear matter density a considerable decrease of the expectation value of $\langle q\bar{q} \rangle$ [54]. This could modify the hadron properties when embedded into nuclear matter, which can lead to a change of the lifetime and/or mass of the particle, and hence in a change of 'the absorption and/or production cross sections [29]. For the study of these effects at normal nuclear matter density, the in-medium strangeness production of π^- induced reactions is an appropriate tool.

Within the context of the study of in-medium hadron properties, the $\phi(1020)$ vector meson resonance is of special interest. $\phi(1020)$ is a pure $s\bar{s}$ state with a mass of 1019.5 MeV/ c^2 and a total width in vacuum of 4.26 MeV (46.9 fm). In its mass range, no significant overlaps with other resonances occur. The ϕ -meson decays preferably into kaons (see Table 5.2), whereas only the charged kaon channel is relevant for FOPI. With these features the ϕ -meson is a promising candidate for the study of strangeness and anti-strangeness in nuclear matter.

Decay channels	B.R.	p_{decay} [MeV/c]
K^+K^-	0.492	127
$K_L^0 K_S^0$	0.340	110

Table 5.2: Preferred $\phi(1020)$ decay channels with their branching ratios and decay momenta.

For the in nuclear matter embedded ϕ -meson, ref.[56] predicts a change of its spectral function. The modifications include an in-medium life time of less than 5 fm/c. Due to the short life time, low momenta ϕ -mesons have a reasonable decay probability inside the target nucleus. Reactions induced by π^- with momenta close to the ϕ production threshold of 1.56 GeV/c are suitable to achieve these experimental conditions, e.g. a ϕ -meson with a momentum of 1.56 GeV/c and a life time of 5 fm/c decays after approximately 4 fm, which is within the size of a nucleus.

Interesting results in the context of in-medium hadron properties could be achieved by several different experiments like LEPS [57], the KEK E325 Collaboration [58, 59] or ANKE at COSY [60]. An overview of the experimental status in the context of hadron properties in the nuclear medium is given in ref. [55].

However, the overall knowledge of the in-medium ϕ -meson properties is still incomplete. Additional information can be achieved with attenuation measurements [57, 61, 62], in which the nuclear transparency ratio

$$T_A = \frac{\sigma_{\pi^- A \rightarrow \phi X}}{A \sigma_{\pi^- N \rightarrow \phi X}} \quad (5.1)$$

is the measured quantity. T_A is defined as the cross section of the ϕ production at the nucleus A relative to the elementary cross section times A . The nuclear transparency ratio T_A is a parameter for the decrease of the meson flux due to inelastic processes in nuclei and its A dependency corresponds to the ϕ -nucleus potential absorption term [62]. Hence, T_A is a measure of the probability, that the ϕ -meson escapes the nucleus.

However, T_A was introduced for photo induced reactions and can not be adopted for the S339 experiment, since π^- induced production of a ϕ -meson on a neutron is not possible. Therefore, T_Z is used (see (5.2)) in place of T_A .

$$T_Z = \left(\frac{6}{Z}\right)^\alpha \frac{\sigma_{\pi^- Z \rightarrow \phi X}}{\sigma_{\pi^- C \rightarrow \phi X}}. \quad (5.2)$$

Instead of the elementary cross section the ϕ production cross section at ^{12}C nuclei will be used as reference, which was measured in the course of the S339 experiment. The ^{12}C nucleus is suited as reference nucleus since, due to its small size, the in-medium effects are expected to be small and due to the equal neutron and proton number no isospin effects appear. The Z scaling factor α of the cross section in (5.2)

will be determined by simultaneously measured inclusive K^0 and/or Λ production cross sections.

It is expected, that the transparency ratio T_Z decreases with increasing nuclear mass, because of the possible in-medium effects suffered by the ϕ -meson and due to the rescattering of the ϕ -meson decay products in matter. For example, a BUU-Simulation of the transparency ratio T_A for antikaons as a function of the targets nucleus mass was done for photo production (see Figure 5.3) [62]. The graph shows clearly the decrease of T_A with increasing mass number A .

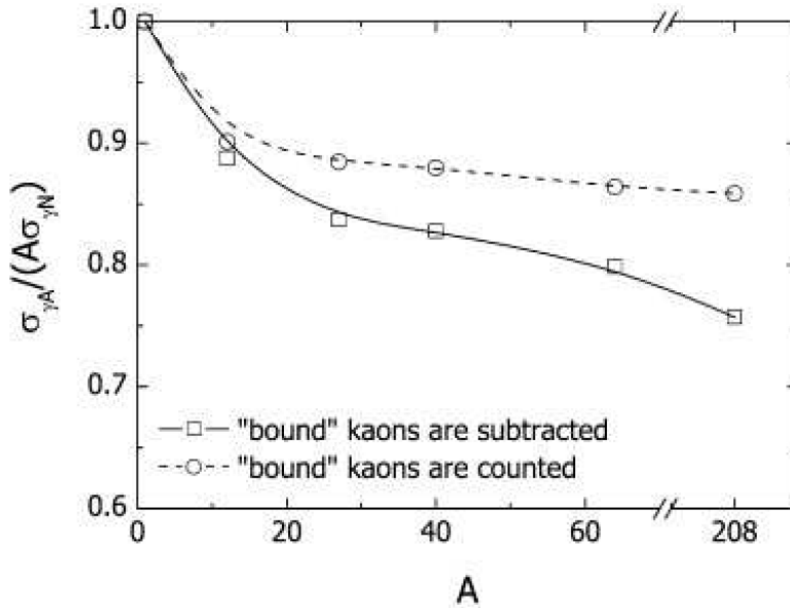


Figure 5.3: BUU-Simulation of the transparency ratio T_A for antikaons as function of the target nucleus mass for photo production [62]. (full line) T_A with subtracted negative energy anti kaons (corresponds to measurable $\bar{K}_s$), (dashed line) total antikaon yield.

The interaction of the ϕ -meson decay products K^+K^- with the nuclear medium has also an impact on the study of the ϕ properties in matter. Because of the rather large cross section, the strange quark containing K^- is particularly affected by strong in-medium effects [63, 64]. Therefore, the simultaneous determination of the K^- yield as a function of the target mass A can show some interesting aspects of its in-medium properties.

Furthermore, elder measurements of $\pi^- + p$ reactions showed comparable production cross sections for ϕX and K^+K^-X in the relevant beam momentum range [65]. This implies, that K^+K^- pairs are also directly produced, which can be distinguished from the ϕ resonant K^+K^- pairs by their invariant mass. Therefore, a determination of the directly produced K^- -yield as a function of the target mass can be done similar to the ϕ -yield.

The FOPI detector system can detect and identify the charged kaons emitted from the π^- induced reaction in the relevant momentum range due to the mean energy loss and momentum measurements of the drift chambers (CDC, HELITRON) and the ToF measurements of the scintillator detectors (Barrel, RPC, PLAWA). The large GEM-TPC prototype was used as central tracking detector. It was expected, that the overall PID capabilities of the FOPI spectrometer is improved due to the GEM-TPC upgrade, which is important for a better determination of the charged kaons.

At a π^- momentum of 1.7 GeV/c the total cross section of the $\pi^- + p$ reaction is about 35 mb and for $\pi^- + p \rightarrow$ strange particles about 1 mb. A list of the most prominent background processes, at a π^- momentum of 1.7 GeV/c, for the measurements of K^+ and K^- with at least one charged kaon in the final state can be seen in table 5.3. A more detailed list can be found in [65]. The beam momentum is tuned in such way, that it is close to the ϕ -meson threshold. Therefore, the occurrence of a K^+K^- pair in the final state is a very clean signature for ϕ -meson production..

Decay channels	cross section [μb]
$\Sigma^- K^+$	200
$\Lambda \pi^- K^+$	100
$\Sigma^- \pi^0 K^+$	10
$\Sigma^0 \pi^- K^+$	10
$p K^0 K^-$	few

Table 5.3: List of most prominent background processes with at least one charged kaon in the final state [29].

5.3 Experimental Setup for S339

5.3.1 Beam and target properties

The pion beam was produced by the GSI-SIS accelerator. It can provide a bunched pion beam in a momentum range of 0.6 - 2.8 GeV/c, with the maximum beam intensity at 1.1 GeV/c beam momentum [66]. The pions were produced via the reaction of a 1.923 AGeV nitrogen primary beam on a cylindrical beryllium production target (10 - 12 cm length and 6 - 8 mm diameter). The production rate was $5 - 6 \cdot 10^{10}$ /spill in front of the beryllium target. The momentum of the secondary π^- beam was 1.7 GeV/c (ϕ threshold: 1.56 GeV/c). Due to the long transport distance of 89 m from the production target to the FOPI cave and the beam line momentum acceptance, the number of π^- reaching the FOPI start counter per spill was 29 000 in 3.22 s, which corresponds to a π^- rate of approximately $9\,000\text{ s}^{-1}$ [67].

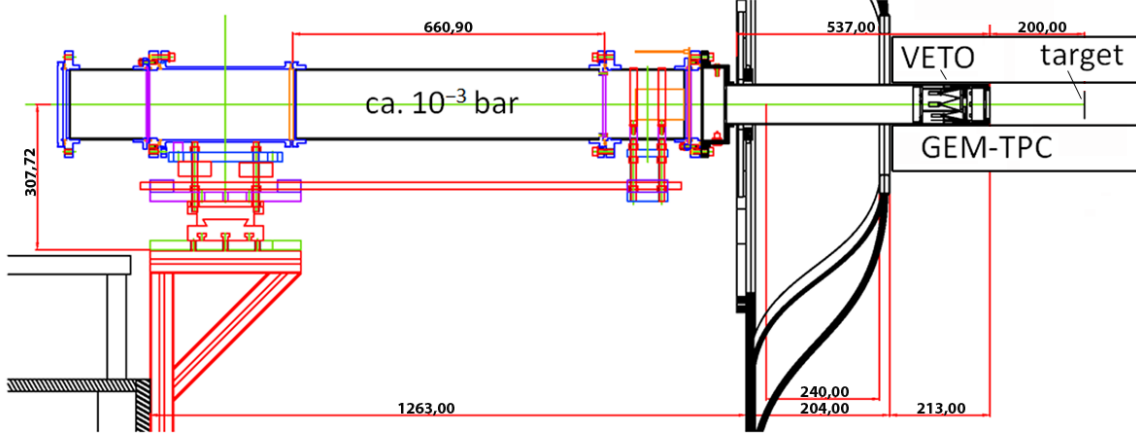


Figure 5.4: Schematical view of the beam line near the target position (Dimensions in mm) [67].

In order to determine the mass dependency of the ϕ -meson in-medium properties three solid targets with different Z where measured. Carbon ($Z = 6$), copper ($Z = 29$) and lead ($Z = 82$) targets were used, which have a surface area of $45 \times 45 \text{ mm}^2$ and a thickness of 10 mm for carbon, and 5 mm for copper and lead. The target was positioned inside the GEM-TPC inner hole right behind the FOPI veto counter. A schematical view of the target position is shown in figure 5.4.

5.3.2 The S339 experimental setup

The GEM-TPC was installed inside the CDC. Figure 5.5 shows a schematic drawing of the detector setup with the GEM-TPC inside the FOPI detector system. The solenoid magnet is not shown in this scheme. Figure 5.6 shows the large prototype with the installed cooling ring and the GEM-TPC readout electronics (see Chapter 2) inside the CDC.

For the experiment two different data acquisition (DAQ) systems of FOPI and the GEM-TPC were used. The FOPI DAQ is designed as a Multi Branch System (MBS) and the data is read out via VME. Because the VME based readout could not handle the amount of GEM-TPC data (40 MB/s), a modified version of the COMPASS readout [68] was used for the large prototype. The trigger signal of the FOPI main trigger was also used for the GEM-TPC Trigger Control System module (TCS), which sends trigger signals to the GeSiCa (see Section 2.3) readout modules. To get a synchronization of the data of the different detectors, the MBS event header time-stamps were communicated to the GeSiCa modules. The GEM-TPC data were send via S-Link protocol [68] to the event builder, which merged the data with the FOPI data stream.

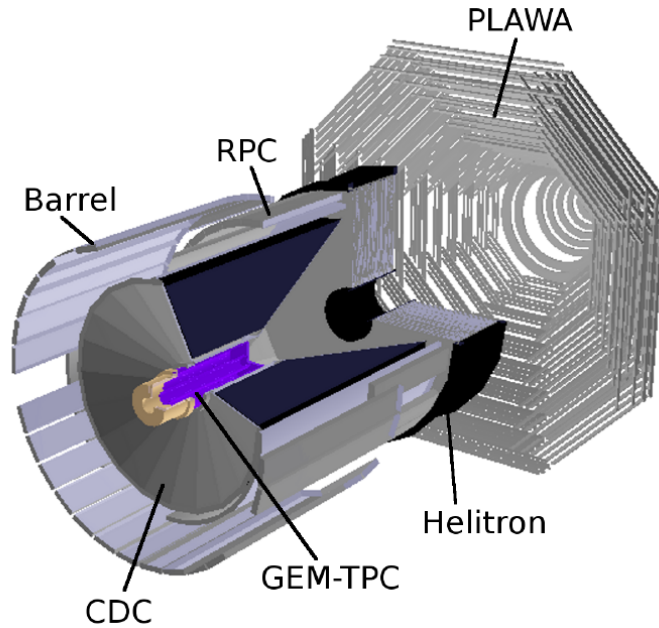


Figure 5.5: Scheme of the FOPI spectrometer with the large GEM-TPC prototype.

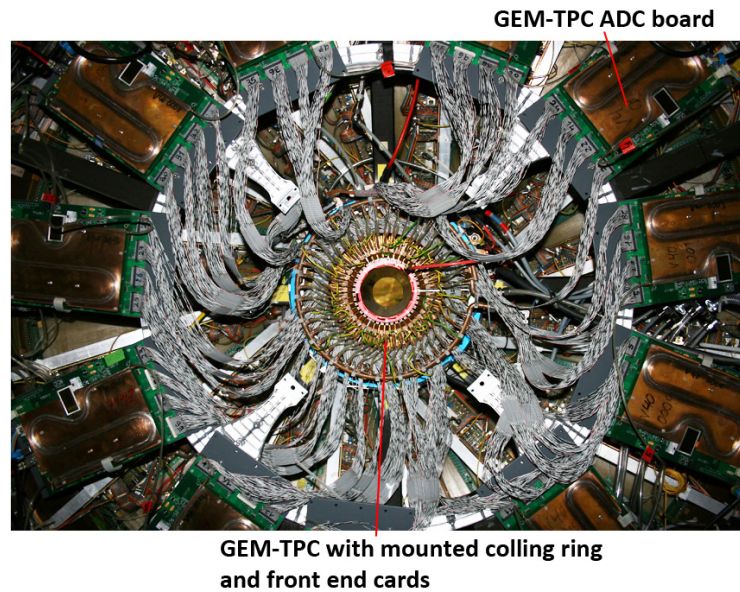


Figure 5.6: Front view of the GEM-TPC inside the FOPI system in beam direction. In the center, the GEM-TPC with mounted cooling ring and front end cards can be seen. Circular around GEM-TPC the ADC boards for the GEM-TPC data acquisition are mounted. Behind the ADC boards is the CDC of FOPI.

At the time of the FOPI experiment S339, some components of the closed gas system for the GEM-TPC were still under construction or in test phase. Therefore an open gas system, as an intermediate solution, was developed.

5.3.3 GEM-TPC open gas system

The advantage of the open gas system is its simpler design compared to a closed gas system. Due to the constant fresh gas supply from the gas bottles, a gas purification system is not needed. In addition, a gas circulation compressor is not necessary, because the gas flow through the GEM-TPC is achieved by the overpressure in the gas bottles. A scheme of the developed open gas system for the S339 experiment is shown in figure 5.8.

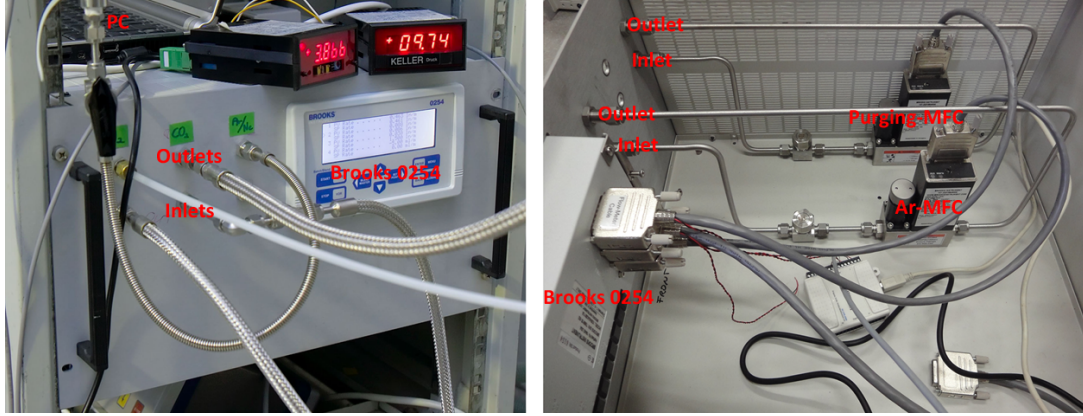


Figure 5.7: Picture of the gas mixing unit for the open gas system. (left) Front plate of the module with gas in- and outlets and the display of the Brooks model 0254. (right) Top view of the gas mixing unit with two mounted MFCs.

The GEM-TPC gas for the experiment was an Ar/CO₂ gas mixture with a CO₂ fraction of 10%. The gas flow was set to 45 l/h and a constant overpressure of 18 mbar was kept in the chamber. The main part of the open gas system was the gas mixing unit (see Figure 5.7). Three Brooks SLA5850 mass flow controllers [46] were built in a 19"-rack. The maximum gas flow of the MFC for Ar was 5 l/min and for CO₂ 1 l/min. The third MFC with a maximum gas flow of 5 l/min was foreseen for a purging gas. The MFCs were controlled with a Brooks model 0254 control unit [49], where the gas flow set points for the MFC could be manually set.

Downstream of the gas mixing unit the gas line "Node" was installed. Each of the four branches could be manually sealed off with a two-way valve. Therefore it was possible to secure the GEM-TPC during the start-up of the MFCs while the gas mixing unit was connected to an exhaust line. It also allowed an easy switching between the gas mixture and the purging gas. One gas line lead to the GEM-TPC gas supply line into the FOPI cave, where the GEM-TPC was connected. Right after

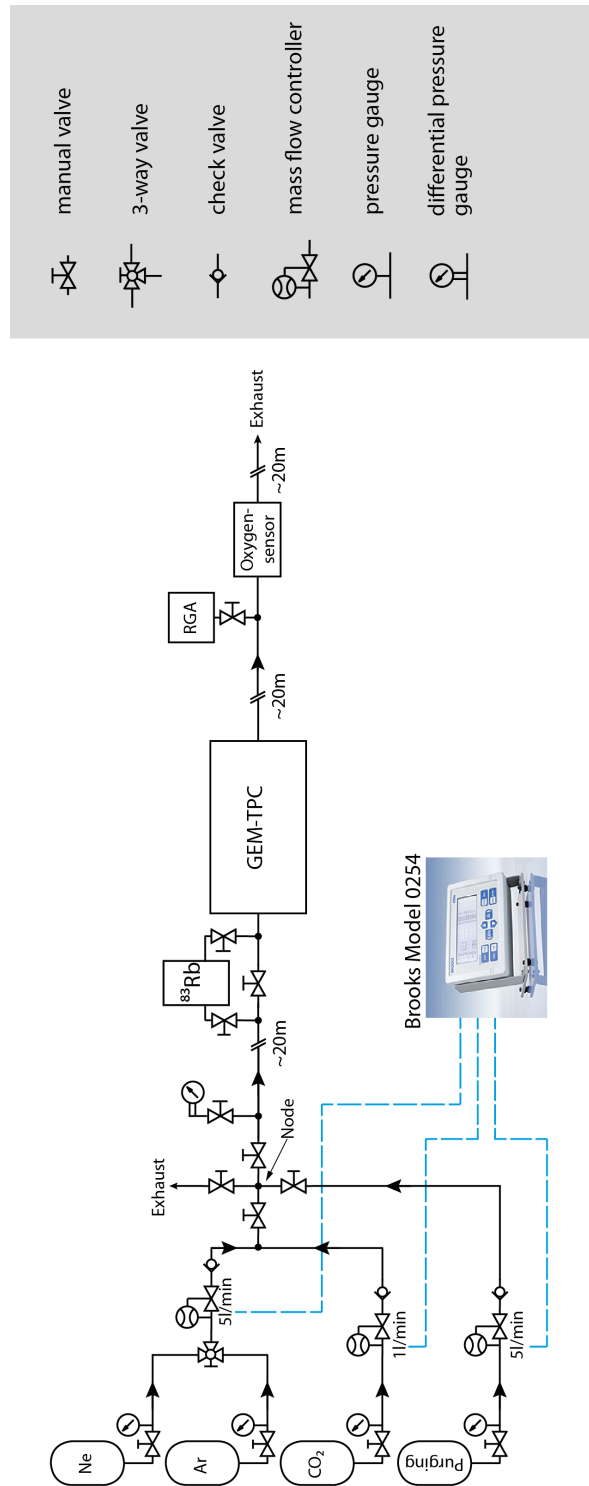


Figure 5.8: Scheme of the GEM-TPC open gas system for the FOPI experiment S339.

the "Node" a gas line side-branch to a differential pressure gauge was installed. With this pressure gauge the overpressure in the gas system could be observed during the experiment. The ^{83}Rb calibration container (see Section 2.5) was implemented in the gas line right before the GEM-TPC. Downstream of the GEM-TPC exhaust line the RGA measurement setup (see Section 4.1.3) and the oxygen sensor (see Section 4.1.2) were mounted before the gas line ended into an exhaust.

The MFCs of the gas mixing unit were only calibrated for N_2 . Thus they had to be recalibrated for Ar and CO_2 . Other than for the MFC calibration for the closed gas system (see Section 4.2), the MFC gas flows were calibrated independently from each other. The calibration procedure allowed the determination of the MFC gas flow as a function of the pressure change in a well defined gas volume.

$$F = \frac{\Delta p \cdot V}{p_0 \cdot t} \quad (5.3)$$

F is the gas flow through the MFC in ℓ/min , Δp the pressure change in the gas volume, p_0 the room pressure and t the time. The measuring principle of the MFC gas flow was rather simple. The gas volume was filled with the calibration gas to a fixed pressure of approximately 8 bar inside the volume. After the filling was finished, the calibration gas bottle was sealed off and the MFC was connected to the gas volume. The MFC was set to a fixed gas flow set point and generated therefore a well defined leak in the setup. While the gas flow through the MFC, the pressure decreased in the volume during a well defined time.

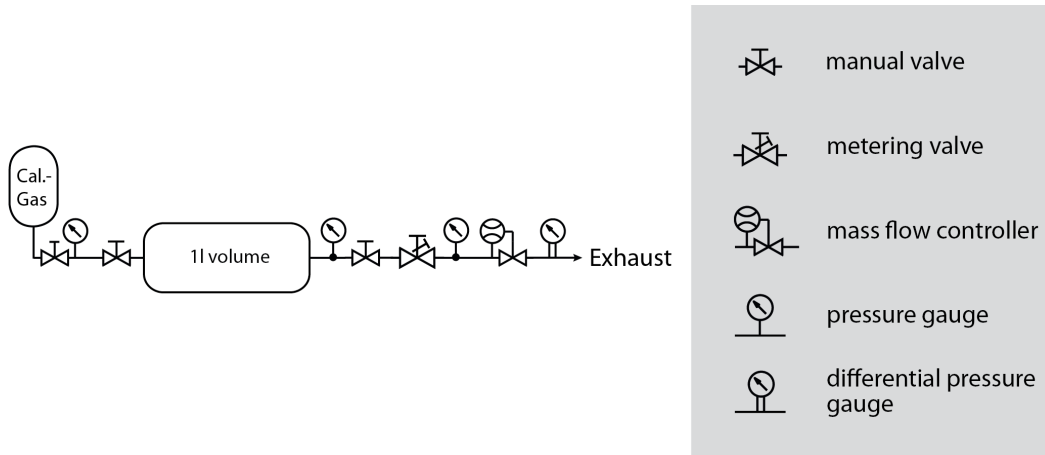


Figure 5.9: Scheme of the MFC calibration assembly for the GEM-TPC open gas system.

Figure 5.9 shows scheme of the calibration assembly. The gas volume was a 1 ℓ pressure vessel. The vessel could be sealed off from both sides with two manual two-way valves. Between the pressure vessel outlet and the two-way valve a pressure gauge with a measurement range of 0-10 bar was installed. The next device in the

gas line was a metering valve, which regulated the inlet pressure of the MFC. Another pressure gauge was mounted between the metering valve and the MFC in order to control the MFC input pressure. The MFC outlet was connected to an exhaust and the gas flow set points were set via the Brooks Model 0254.

The analog output of the vessel pressure gauge was connected to a NI-USB-6009 ADC which was itself connected to a PC with a small LabVIEW application. The calibration measurements were made for different gas flow set points of the MFC. Therefore the correlation between MFC gas flow set points and the calculated gas flow could be determined (see Figure 5.10).

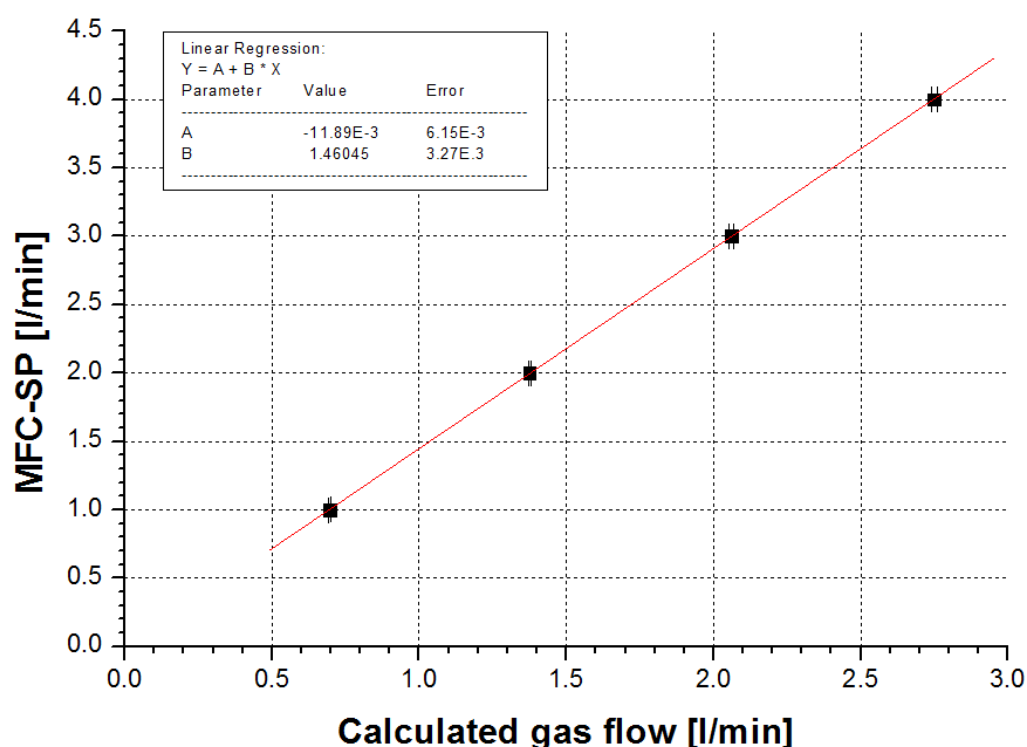


Figure 5.10: Correlation between the MFC gas flow set points and the calculated gas flow for Ar.

The results of the RGA measurements (see Figure 5.11) during the experiment showed, that the required accuracy of $\pm 0.1\%$ for the deviation from the designated CO_2 fraction in the gas mixture of 10% was not fully achieved with the gas mixing unit of the open gas system. The solid red line in figure 5.11 shows the mean of the CO_2 fraction of $(9.83 \pm 0.02)\%$.

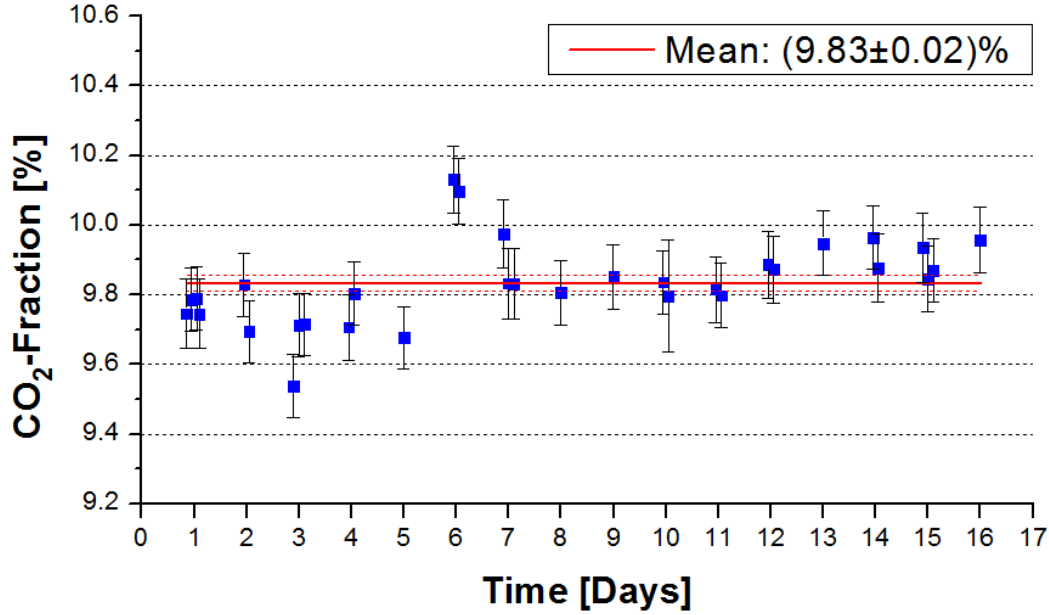


Figure 5.11: The graph shows the CO₂ fraction of the GEM-TPC open gas system during the FOPI experiment S339. The blue squares show the single measurements, the solid red line the mean of these measurements and the dashed red lines the standard deviation.

The large deviation from the designated CO₂ fraction of 10% could have several reasons. One reason could be the dependence of the systematic error of the MFCs on the maximum gas flow range of the MFCs, which is 300 ℓ/h for the Ar and 60 ℓ/h for CO₂. The error is $\pm 0.5\%$ of the full scale for each MFC, which corresponds to a systematic error of the total gas flow of the open gas system of about $\pm 1.53 \ell/h$. By comparison, the systematic error of the total gas flow of the closed gas system "Mixing" module could be decreased to $\pm 0.31 \ell/h$ by the usage of MFCs with a maximum gas flow range of 60 ℓ/h for Ar and 12 ℓ/h for CO₂ (see Section 4.2).

Furthermore, small adjustments of the set point have bigger effects on MFCS with higher measurement range, because the signal range of the analog output of the MFCs are equal (4-20 mA), while the corresponding gas flow ranges are different.

In addition, the MFCs were calibrated independently from each other in order to get a more accurate gas flow for each MFC. But the uncertainties in the gas flows of both MFCs could add up in such way, that the uncertainty of the gas mixture ratio is increased.

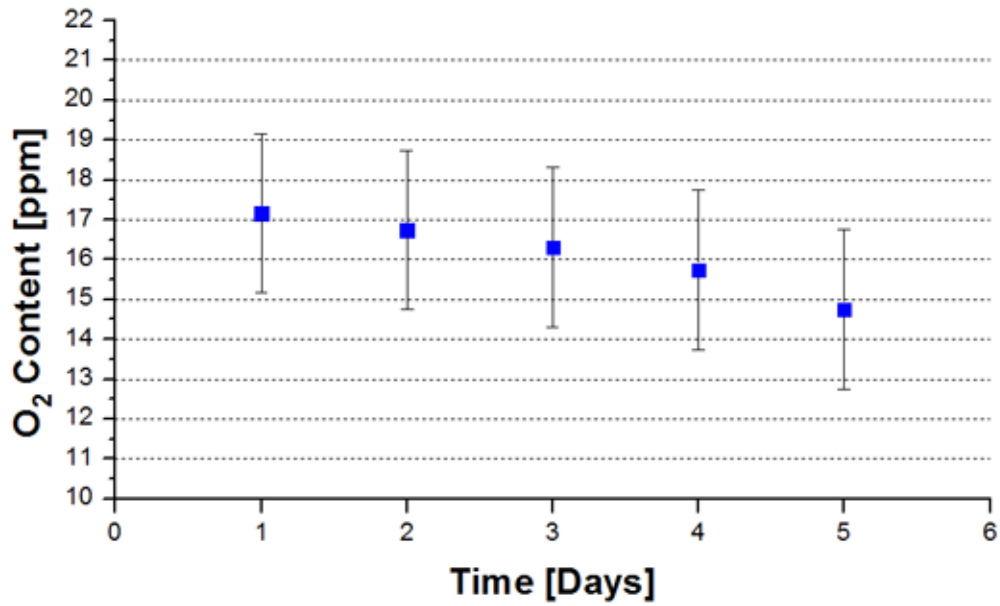


Figure 5.12: The graph shows the oxygen content of the GEM-TPC open gas system during the last five days of the S339 experiment.

Figure 5.12 shows the oxygen content in the GEM-TPC open gas system during the experiment. The graph shows that an oxygen content below 20 ppm after approximately two weeks of operation could be achieved without any gas purification in the system. It also shows, that the oxygen level still decreases after this time. This allows the assumption, that an even lower oxygen level could be achieved.

6 Data Analysis

The data of the FOPI experiment S339 is divided into two parts. One for the GEM-TPC and one for the FOPI spectrometer, which includes the data of all FOPI detectors. The FOPI raw data were processed with the FOPI standard procedure, which is based on old CERN software packages (e.g. Fortran, PAW), including track finding, track fitting and PID. The output of the standard analysis was written to root-files to be able to process it with ROOT, C++. The GEM-TPC raw data were preprocessed independently including clustering, track finding, track fitting and PID with ROOT.

This work was done by colleagues from the Technical University in Munich and SMI¹ and is still under development. Only a part of the whole data were processed so far. Thus, the analysis presented here could be done only for a part of the data set with the carbon target (see Section 5.3.1).

The informations from the GEM-TPC data were now added to the FOPI data, which should improve the results of the FOPI standard analysis.

The data in both data sets were saved in such way, that each detected event could be non ambiguously identified. The raw data sets were subdivided in several run-files. Each run-file contains the data of several spills, which are themselves divided into the data of each spill event. Therefore each event is marked with an non ambiguous stamp containing the run, spill and event numbers.

In this context a specific problem is the matching of tracklets from the GEM-TPC with the tracklets from other detectors for each event. A tracklet is a part of a full particle track, which was measured by one detector (e.g. GEM-TPC or HELITRON). Within this work a data processing method was developed, which matches the GEM-TPC track data with the data from the HELITRON. The method generates particle tracks through the detector system in forward direction by the combination of the single detector tracklets. The challenge of the combined track generation was to find the tracklets of the GEM-TPC and the HELITRON, which belong to the trajectory of the same particle.

In the FOPI standard analysis, possible PLAWA hits are already combined with the corresponding HELITRON tracklet. Thus, the GEM-TPC tracklets had only to be matched with the HELITRON tracklets.

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6.1 Particle trajectory simulations

Despite outer influences like magnetic fields, electric fields and energy loss in detector materials, a particle trajectory will be mainly determined by the initial momentum and position of the particle. Momentum information for the single tracklets were available from the individual track fits of each detector. However, track fits do not always converge, such that momentum information can be missing. Therefore I avoided this information as selection parameters for the track matching. Anyway, the track direction can be also determined by the polar angle Θ and azimuthal angle ϕ of the track, which can be used as track matching parameters.

Simple simulations show the characteristics of charged particle trajectories inside the FOPI spectrometer. The trajectories were determined by the solution of the equation of motion of a charged particle inside an in z -direction homogeneous magnetic field with a strength of 0.6 T.

$$m \cdot \vec{a} = q \cdot \vec{v} \cdot \vec{B}. \quad (6.1)$$

m is the particle mass, $\vec{a}$ the initial acceleration of the particle, q the particle charge, $\vec{v}$ the initial particle speed and $\vec{B}$ the magnetic field.

The magnetic field of the superconducting solenoid is not homogeneous over the whole FOPI spectrometer detection area. Figure 6.1 shows the dependency of the strength of the magnetic field components in longitudinal and transversal direction as a function of the z position. The axis of these figures are chosen in such a way, that the zero point corresponds with the center of the magnet and not with the nominal target position.

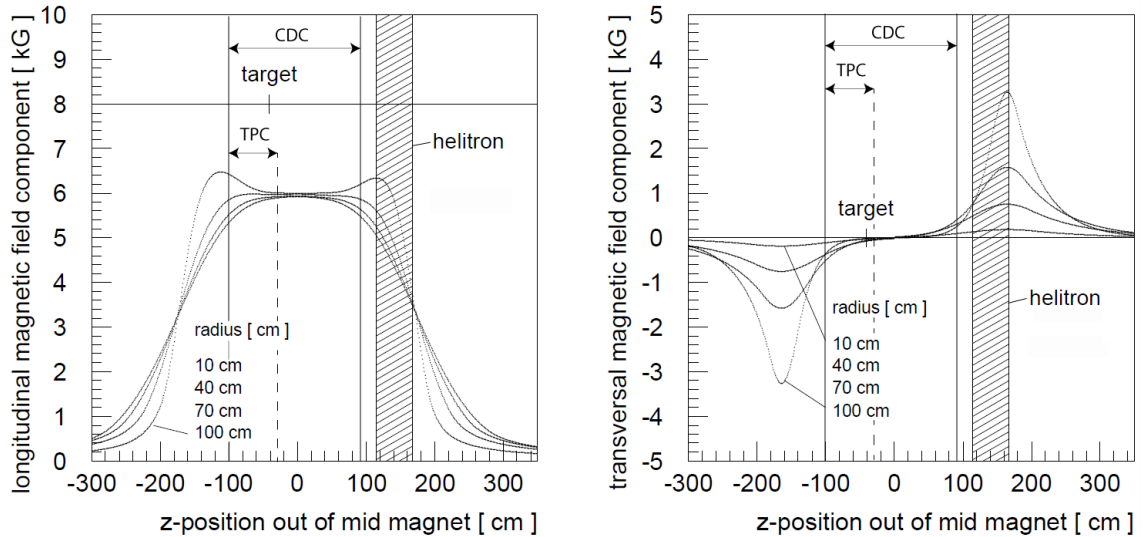


Figure 6.1: The left graph shows the longitudinal and the right graph the transversal component of the FOPI magnetic field as a function of the position in z direction. [69].

Although the field is nearly homogeneous in the GEM-TPC and CDC region downstream of the nominal target position, a considerable change of the magnetic field can be seen in the HELITRON region. In the simulations of the particle trajectories the inhomogeneity of the magnetic field was included by a scaling of the longitudinal magnetic field component from 0.6 T down to 0.4 T in the HELITRON region. The change of the transversal component was not considered as well as the energy loss of the particles through due to the interaction with the detector materials.

The simulations were done for positive charged particles with different initial momenta (0.15, 0.4, 1 GeV/c) and polar angles Θ (10° , 30° , 50°). Figures 6.2, 6.3 and 6.4 show the results of these simulations. The trajectories of negative charged particles like π^- and K^- differ from positive charged particles only by the rotation direction.

The topmost graph in figure 6.2 shows the particle trajectory in the rz -plane, where r is the distance from the beam axis and z the beam direction. The right graph shows the xy -plane and the other graphs the xz - and xy -plane. The angle between the z or beam axis and the particle track in the rz -plane corresponds to the polar angle Θ . The angle ranges from 0° to 180° , where 0° is in beam direction. The azimuthal angle ϕ is the angle between x -axis and track position in the xy -representation and ranges from 0° to 360° , where 0° is in x -direction.

In the rz -representation one can see, that the particle tracks are, independent of their momentum and initial polar angle, in good approximation, straight lines in the GEM-TPC region. The simulations show, that the direction of the particle trajectory changes with increasing distance from the nominal vertex position. The strength of the particle deflection due to the magnetic field depends on the initial polar angle and momentum. It can be seen in the rz -graph, that the particle trajectories of particles with higher momenta have still the same direction in the HELITRON and CDC regions as in the GEM-TPC region, independent from their initial polar angle. In contrast, the trajectories of low momenta particles show partly considerable changes of their directions, depending on their initial polar angles.

From the equation of motion (6.1) the correlation

$$q \cdot p \cdot \Delta\phi \cong \text{const} \quad (6.2)$$

can be drawn, where q is the sign of the particle charge (-1, 1), p the particle momentum and $\Delta\phi$ the change of the azimuthal angle between GEM-TPC and HELITRON. This basic equation shows, that $\Delta\phi$ strongly depends on the particle momentum and that it increases with decreasing momentum. It implies, that also for very high particle momenta a deflection of the particle trajectory in the xy -plane can be expected. The xy -graph of figure 6.2 shows the change of the azimuthal angle ϕ of the particle trajectories over the whole detection region. Only track parts of the particle trajectories are shown, where the particle traverse the GEM-TPC or HELITRON detection volume.

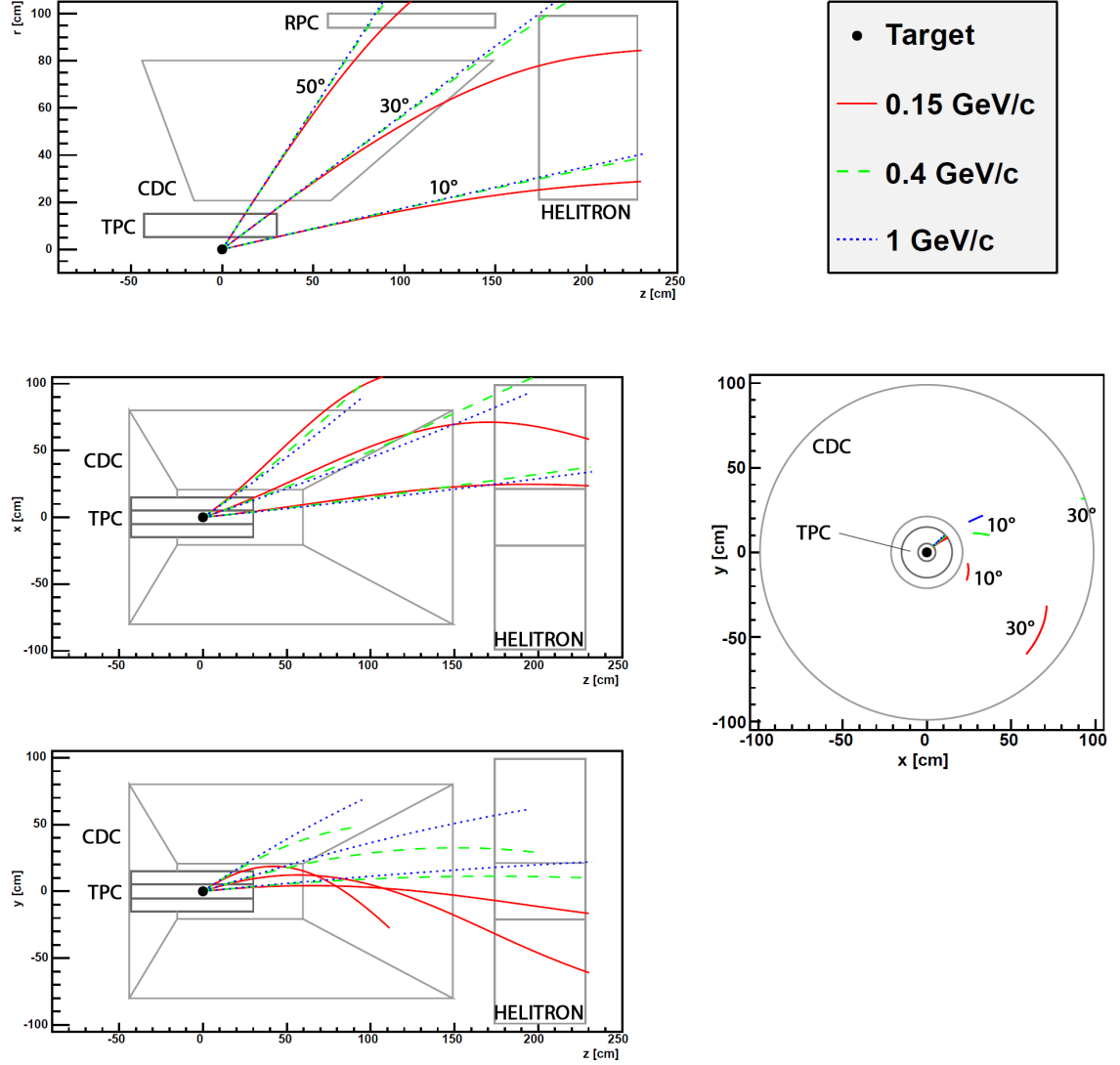


Figure 6.2: Simulations of particle trajectories with different initial momenta (0.15, 0.4, 1 GeV/c) and polar angles Θ (10° , 30° , 50°) inside the FOPI spectrometer. The topmost picture shows the trajectories in the rz -plane, where z is the beam direction and r the distance to the beam axis. The graphs below show the trajectories in the xz - and yz -planes. On the right picture these parts of the particle trajectories in the xy -plane can be seen, where the particles traverse the GEM-TPC and HELITRON detection area.

The xy -graph shows, that the tracks are approximately straight lines in the GEM-TPC region. Also the HELITRON track parts can be on its own considered as straight lines, but they are rotated with respect to the nominal vertex position. As expected all particle tracks showed a change of the angle ϕ between the GEM-TPC and HELITRON track parts depending on the particle momenta. While the changes are rather small for high momentum tracks, the difference between GEM-TPC and HELITRON tracks are rather large for low momentum.

Therefore, the determination of the HELITRON track angle ϕ with respect to the nominal vertex position can only be an approximation for the position of the track center in the xy -plane. However, with a pre-selection of possible track matches due to a comparison of the Θ angles, the track azimuthal angle ϕ can be used as second matching parameter.

Figure 6.3 shows simulated particle trajectories in the rz -plane with the same initial polar angle Θ of 30° but different momenta (150, 200, 300, 400, 500 MeV/c). It can be seen, that for particle momenta of 300 MeV/c or higher the trajectories are approximately straight over the whole detection area, while lower momenta particles feel a greater deflection.

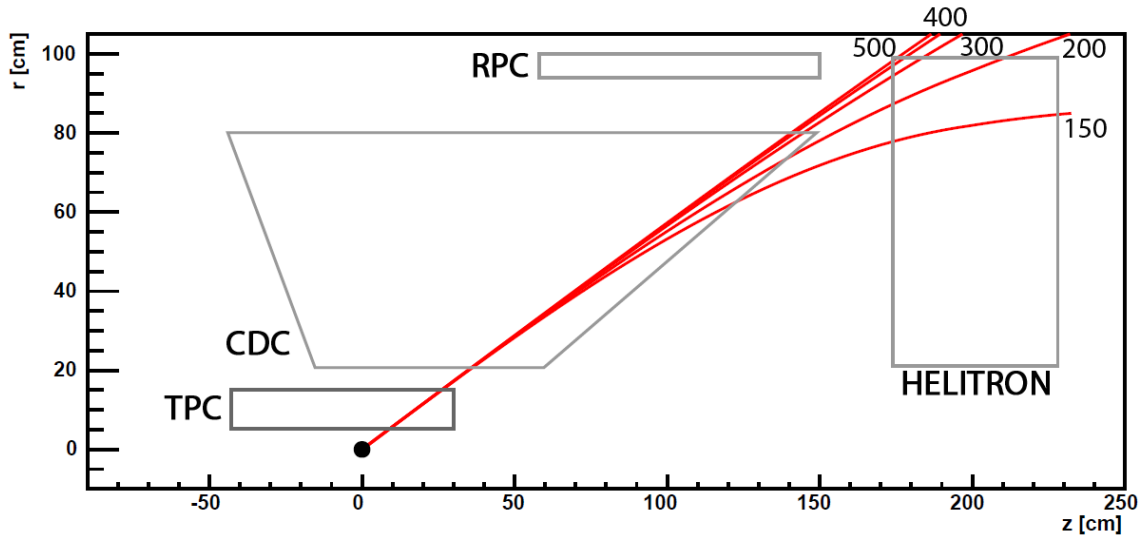


Figure 6.3: rz -representation of the simulations of particle trajectories with an initial polar angle of 30° and different momenta (150, 200, 300, 400, 500 MeV/c).

The rz -representation in figure 6.2 also shows, that the deflection strength of low momenta particles depends strongly on the initial polar angle. For a particle with a momentum of 150 MeV/c and an initial polar angle of 30° , the polar angle difference between the GEM-TPC tracklet and the HELITRON tracklet amount to 22° and the Θ change in the HELITRON region with respect to the nominal vertex position is 4° . In comparison, the polar angle difference for a particle with an initial angle of

10° is only 4° between the two detectors.

Therefore it can be concluded, that in the rz -plane the deflection of the trajectories of low momenta particles with high initial polar angle is strongest. However, also for these particles, the polar angle change over the HELITRON region with respect to the nominal target position is rather small and thus also these tracks can be considered as nearly straight in the HELITRON.

Due to the strong dependency of the particle trajectories on the initial polar angle, also low momenta particles with an initial polar angle higher than the maximal polar angle acceptance of the HELITRON (see Table 5.1) can be detected in the HELITRON. In order to get informations about the maximum initial polar angle of low momenta particles, which can be still detected with the HELITRON, trajectories of particles with a momentum of $150 \text{ MeV}/c$ and different initial polar angles were simulated. Figure 6.4 shows the results of these simulations, where the initial polar angle was varied in 5° steps from 30° up to 50° . The simulations show, that the maximum polar angle of low momenta particles of $150 \text{ GeV}/c$ detectable with the HELITRON is in the region between 35° and 40° , which is well above the estimated polar angle acceptance.

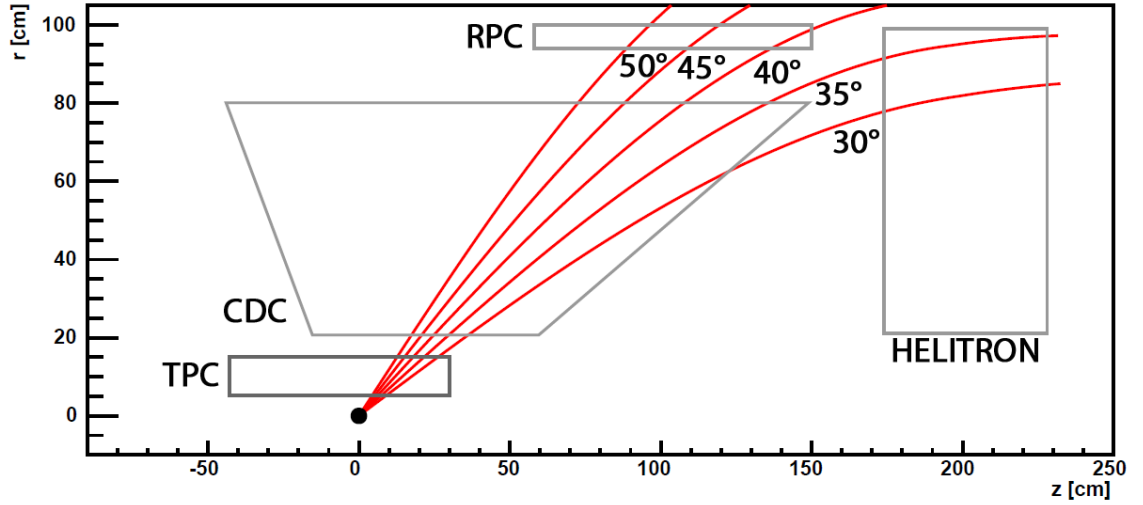


Figure 6.4: rz -representation of particle trajectory simulations with a momentum of $150 \text{ MeV}/c$ and different initial polar angles Θ (30° , 35° , 40° , 45° , 50°).

6.2 GEM-TPC/HELITRON track matching

In order to use the polar and azimuthal track angles as parameters for the matching of GEM-TPC and HELITRON tracklets, Θ and ϕ had to be determined for each tracklet. This can be done by the calculation of Θ and ϕ of the track hits. A track

hit is a hit point measured in the detector volume, which could be assigned to a tracklet. Generally, for each track hit the polar angle Θ and the azimuthal angle ϕ can be determined with respect to the nominal vertex position. For straight tracklets originating from the nominal vertex position, the Θ and ϕ angles are approximately equal for all track hits and the average angles for the tracklet can be calculated.

In order to compute the true angles Θ and ϕ for the GEM-TPC tracklets without using the nominal vertex position, they were determined by means of track hit pairs. The angles Θ and ϕ between two track hits were calculated for each possible hit pair and the mean of all hit pair angles was determined (see (6.3)). This kind of calculation is only valid for straight tracklets, but, in view of the simulation results, this is here a good approximation.

$$\Theta_{TPC} = \frac{1}{n} \sum_{i=1}^{N-1} \sum_{j=i+1}^N \text{acos} \left(\frac{z_j - z_i}{\Delta r_{ij}} \right) \quad , \quad \phi_{TPC} = \text{atan} \left(\frac{\bar{y}}{\bar{x}} \right) \quad (6.3)$$

n is the number of possible track hit pairs, N the number of GEM-TPC track hits and r_i is

$$\Delta r_{ij} = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2 + (z_j - z_i)^2}. \quad (6.4)$$

$\bar{x}$ and $\bar{y}$ can be calculated for the GEM-TPC with

$$\bar{x} = \frac{1}{n} \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{x_j - x_i}{\Delta r_{ij}} \quad \text{and} \quad \bar{y} = \frac{1}{n} \sum_{i=1}^{N-1} \sum_{j=i+1}^N \frac{y_j - y_i}{\Delta r_{ij}}. \quad (6.5)$$

Due to this method, the angles of GEM-TPC tracklets of particles, which were not emitted from the nominal target position, could be calculated properly. This is relevant for the determination of secondary vertices and particle tracks with the origin upstream of the target.

This kind of calculation is for the GEM-TPC possible, because of the very exact track hit determination. Due to the large uncertainty in radial direction of the HELITRON track hits, the assignment of the hits to the individual tracks is not as accurate as for the GEM-TPC. Thus, a calculation of the track angles via track hit pairs as for the GEM-TPC tracklets is not reliable. Therefore, the Θ and ϕ angles of the HELITRON track hits were calculated with respect to the nominal target position (see (6.6)). The true angles Θ and ϕ of the HELITRON tracklets are the angles relative to the true vertex of the particle track. Since the true vertex is not known we use the nominal target position as reference point for the angle calculation. Since the possible displacement of the true vertex relative to the nominal vertex are small compared to the distance of the HELITRON from the target, this approximation has only small impact on the resulting angles.

$$\Theta_{Helitron} = \frac{1}{N} \sum_{i=1}^N \text{acos} \left(\frac{z_i}{r_i} \right) \quad , \quad \phi_{Helitron} = \text{atan} \left(\frac{\bar{y}}{\bar{x}} \right) \quad (6.6)$$

N is the number of HELITRON track hits. $\bar{x}$ and $\bar{y}$ can be calculated with

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N \frac{x_i}{r_i} \quad , \quad \bar{y} = \frac{1}{N} \sum_{i=1}^N \frac{y_i}{r_i}. \quad (6.7)$$

With this set of Θ and ϕ angle pairs for the GEM-TPC and the HELITRON tracklets, the difference of the polar and azimuthal angles $\Delta\Theta$ and $\Delta\phi$ can now be determined with

$$\Delta\Theta = \Theta_{TPC} - \Theta_{Helitron} \quad , \quad \Delta\phi = \phi_{TPC} - \phi_{Helitron}. \quad (6.8)$$

For the track matching, the $\Delta\Theta$ and $\Delta\phi$ of all available GEM-TPC/HELITRON tracklet pairs were computed and the $\Delta\Theta$ and $\Delta\phi$ distributions were determined. For the $\Delta\Theta$ -distribution plot in figure 6.5 not all track pairs were used. Because of the different polar angle acceptances of both detectors (see Table 5.1), the matching of a HELITRON tracklet with a GEM-TPC tracklet with a polar angle far above the maximal polar angle acceptance of the HELITRON does not make sense. With respect to the simulation results of figure 6.4 and in order not to lose tracks of very low momenta particles, the polar angle limit for considered GEM-TPC tracklets was set to 45° .

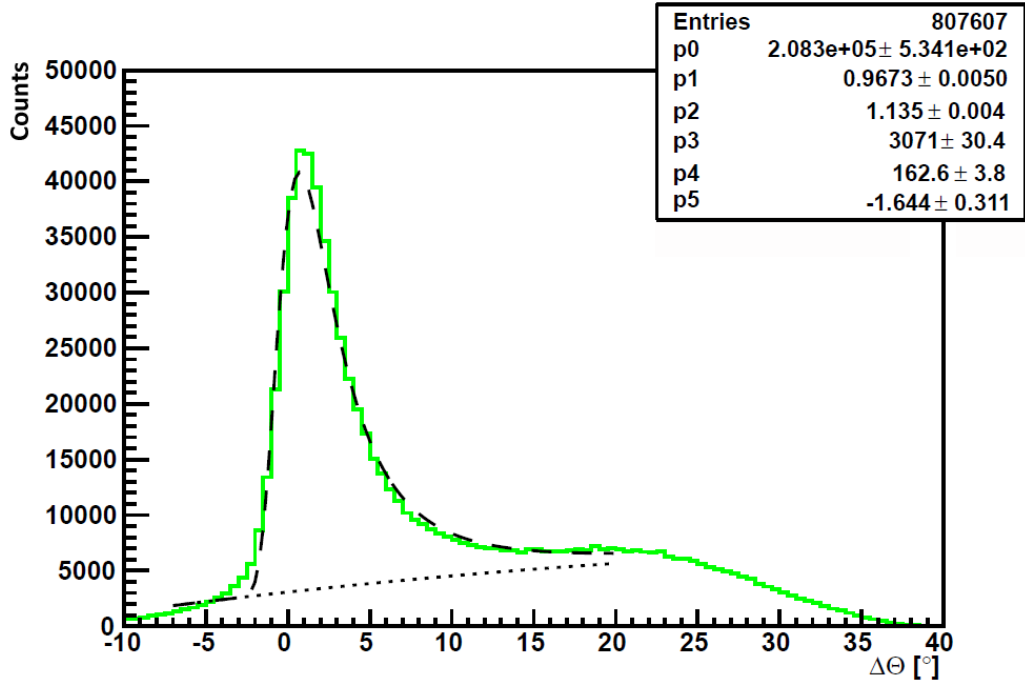


Figure 6.5: Histogram of $\Delta\Theta$ of the GEM-TPC/Helitron tracklet pairs. $p0 - p2$ corresponds to the function parameters of the Landau-distribution and $p3 - p5$ to the Polynomial distribution parameters.

The $\Delta\Theta$ -distribution was approximated with a combined Landau-Polynomial

(2nd order) - distribution function, as an attempt to approximate the observed distribution as the sum of good track combinations (Landau distribution) and false track combinations (Polynomial). The dashed line corresponds to the combined function and the dotted line represents the polynomial part, which is considered to correspond to false combinations.

The graph shows a clear peak at very low $\Delta\Theta$ angles. This confirms the simulation results, that the polar angle of a particle track changes only slightly over a the distance between GEM-TPC and HELITRON. The tail to higher $\Delta\Theta$ results mainly from the different polar angle acceptances of the two detectors, as mentioned above. However, the simulation results showed, that the tracklet pairs of combined tracks with a very low momentum and, with respect to the HELITRON polar acceptance, high initial Θ could have a rather high $\Delta\Theta$.

Figure 6.6 shows the integrated number of good match - candidates as a function of $\Delta\Theta$ with respect to the total number of match - candidates over the whole $\Delta\Theta$ - plot range in figure 6.5. The numbers were obtained by the integration of the Landau - function within the appropriate $\Delta\Theta$ - limits. The lower limit was fixed to -7° and the upper limit was varied from 0° to 20° . It can be seen, that nearly 90% of the match - candidates are expected to have a $\Delta\Theta$ below 10° .

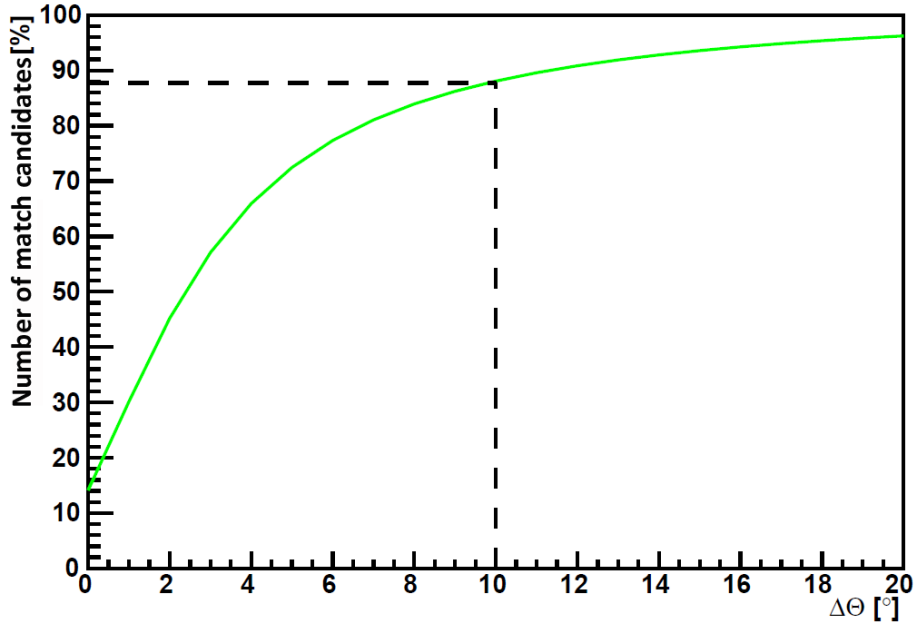


Figure 6.6: Integrated number of good matched track combinations as a function of the upper limit of $\Delta\Theta$ in respect to the total number of good track combinations.

Figure 6.7 shows the plot of $\Delta\Theta$ as a function of the HELITRON track momentum times the charge sign. It shows, that the $\Delta\Theta$ of the majority of the matched tracklet pairs does not exceed 10° even for low momenta. Although the simulations showed,

that higher values are possible for low momenta particles with a high initial polar angle, the upper $\Delta\Theta$ cut limit is set to 10° . This limit was chosen, because, with respect to the results shown in figure 6.6, already at this level a large fraction of the good track combinations are included while the number of false combinations is heavily suppressed. Also, as the simulation results have shown, only low momenta particles with an additional high initial polar angle have such high $\Delta\Theta$ that they are dismissed by the chosen cut. Particles with the same momentum but a lower initial polar angle are still within these limits. The $\Delta\Theta$ cut limits are also listed in table 6.1.

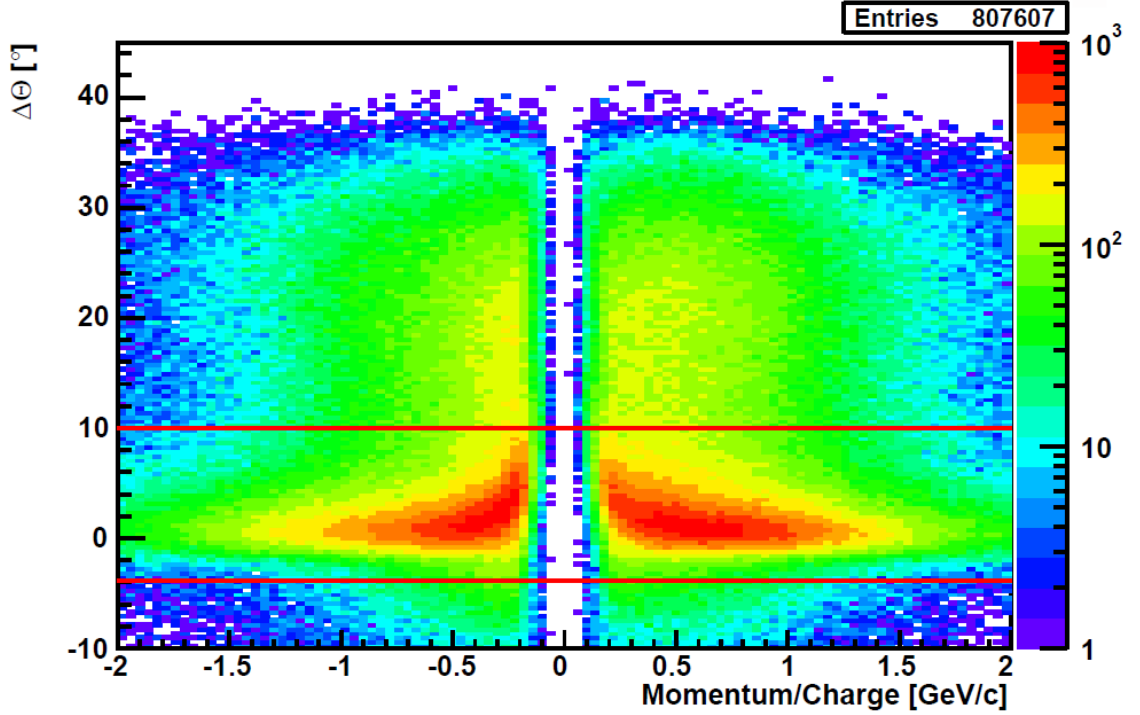


Figure 6.7: $\Delta\Theta$ as a function of the HELITRON tracklet momentum times charge sign. The red lines correspond to the final set $\Delta\Theta$ -cut limits ($-4^\circ < \Delta\Theta < 10^\circ$).

Cut limits
$-4^\circ < \Delta\Theta < 10^\circ$
$0^\circ < \Delta\phi < 60^\circ$

Table 6.1: Cut limits of the track matching parameters $\Delta\Theta$ and $|\Delta\phi|$ for the tracklet pair selection.

For the $\Delta\phi$ distribution the absolute value of the difference between ϕ_{TPC} and $\phi_{Helitron}$ was calculated, because of the right-hand or left-hand rotation of differently charged particles in the magnetic field. Figure 6.8 shows the distribution plot of $|\Delta\phi|$.

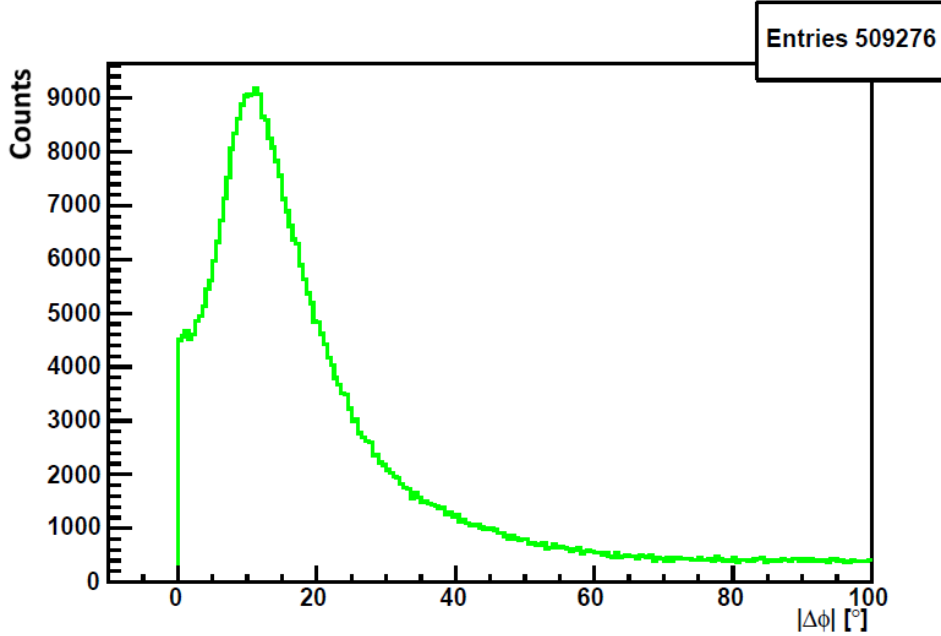


Figure 6.8: Histogram of the $|\Delta\phi|$ distribution of the GEM-TPC/Helitron tracklet pairs with applied $\Delta\Theta$ -cut limits ($-4^\circ < \Delta\Theta < 10^\circ$).

The simulation results showed already, that not only low momentum but also high momentum particles feel a deflection of their trajectory in the xy -plane. This leads to the higher peak position in the $|\Delta\Theta|$ distribution plot, compared to the $\Delta\Theta$ distribution plot in figure 6.5. There only for low momentum particles a considerable deflection could be recognized. Also the long tail to higher $|\Delta\phi|$ can be explained by the strong momentum dependency of $\Delta\phi$. In order to further study the momentum dependency of $|\Delta\phi|$, figure 6.9 shows $|\Delta\phi|$ as a function of the HELITRON tracklet momentum times the charge sign. The red lines correspond to the $|\Delta\phi|$ final cut limits listed in table 6.1.

It can be seen, that the long tail of the $|\Delta\phi|$ -distribution plot in figure 6.8 is mainly given by tracks with low momenta. Therefore, the upper cut limit for $|\Delta\phi|$ had to be chosen very carefully, in order not to unintentionally reject low momenta particles. Thus, the range of the $|\Delta\phi|$ -cut limits were set rather wide for the first data analysis.

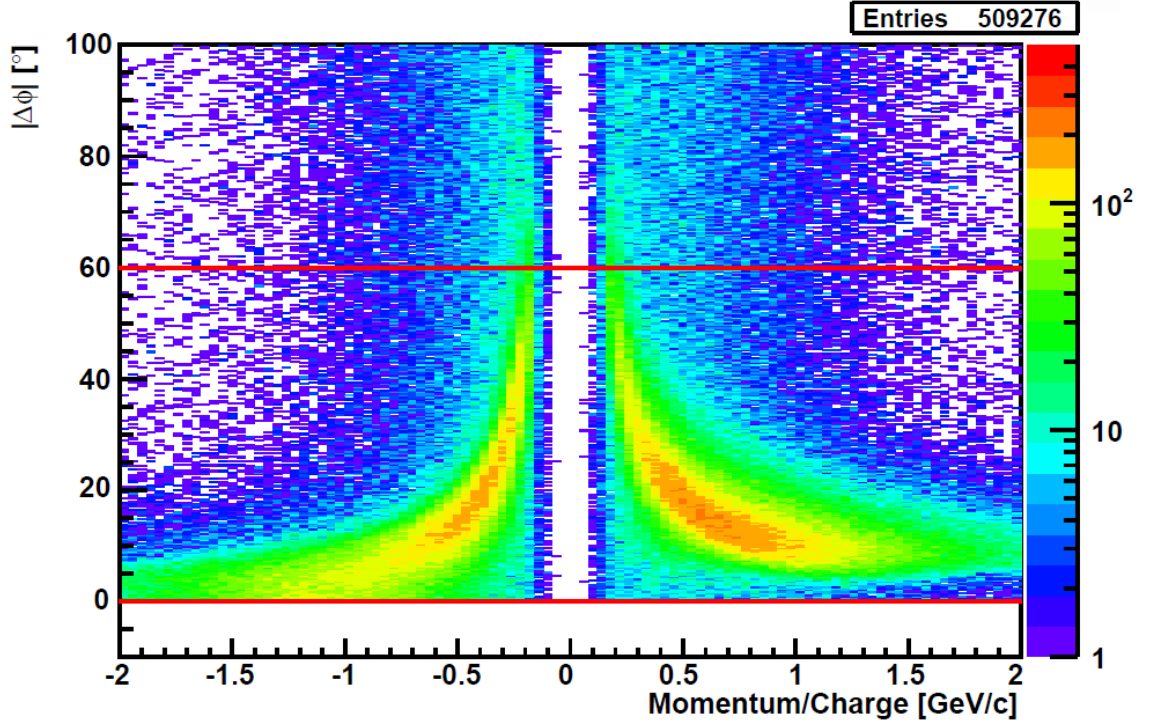


Figure 6.9: $|\Delta\phi|$ as a function of the HELITRON tracklet momentum times charge sign.

The results showed, that the comparison of the polar and azimuthal angles Θ and ϕ of the GEM-TPC and HELITRON tracklets are a good tool for the determination of possible candidates for combined tracks. However, a final assignment of the GEM-TPC and HELITRON tracklets to a combined track of a particle with just the angle information of the tracklets is not always possible. Sometimes tracklets of one detector are matched with more than one tracklet of the other detector, if the track pair combinations have a $\Delta\Theta$ and a $|\Delta\phi|$ which lies within the cut limits. In order to overcome this problem an additional parameter had to be introduced in the data processing routine, which selected the best track matching candidates.

For the final selection of the good match candidates the fitting results of the combined tracks are used. A filter was implemented in the data processing routine, which ranked the combined tracks of an event based on the quality of the track fit. The reduced χ^2 of the track fits was used as quality parameter. If a tracklet of one detector (GEM-TPC or HELITRON) was used for multiple match candidates, the combined track was selected, whose fit had the lowest reduced χ^2 . The fitting provides also information about the direction and magnitude of the momentum of the combined tracks, which is used for the results shown in section 6.3.

The toolkit used for the track fitting was the C++ based GENFIT [70], which is the standard track fitting tool for $\bar{\text{P}}\text{ANDA}$ and Belle-II. With its interchangeable fitting algorithm modules, GENFIT is adaptable to a wide range of experiments. For

this experiment, the GENFIT framework contains a Kalman filter [71].

Figure 6.10 shows the tracks of an example event with a combined GEM-TPC/HELITRON track fit. The red point corresponds to the nominal target position, the blue points are the hits of a CDC track, the gray points near the target are GEM-TPC track hits, the brown points are the HELITRON track hits, the green point is the PLAWA hit and the green line corresponds to the result of the combined track fit.

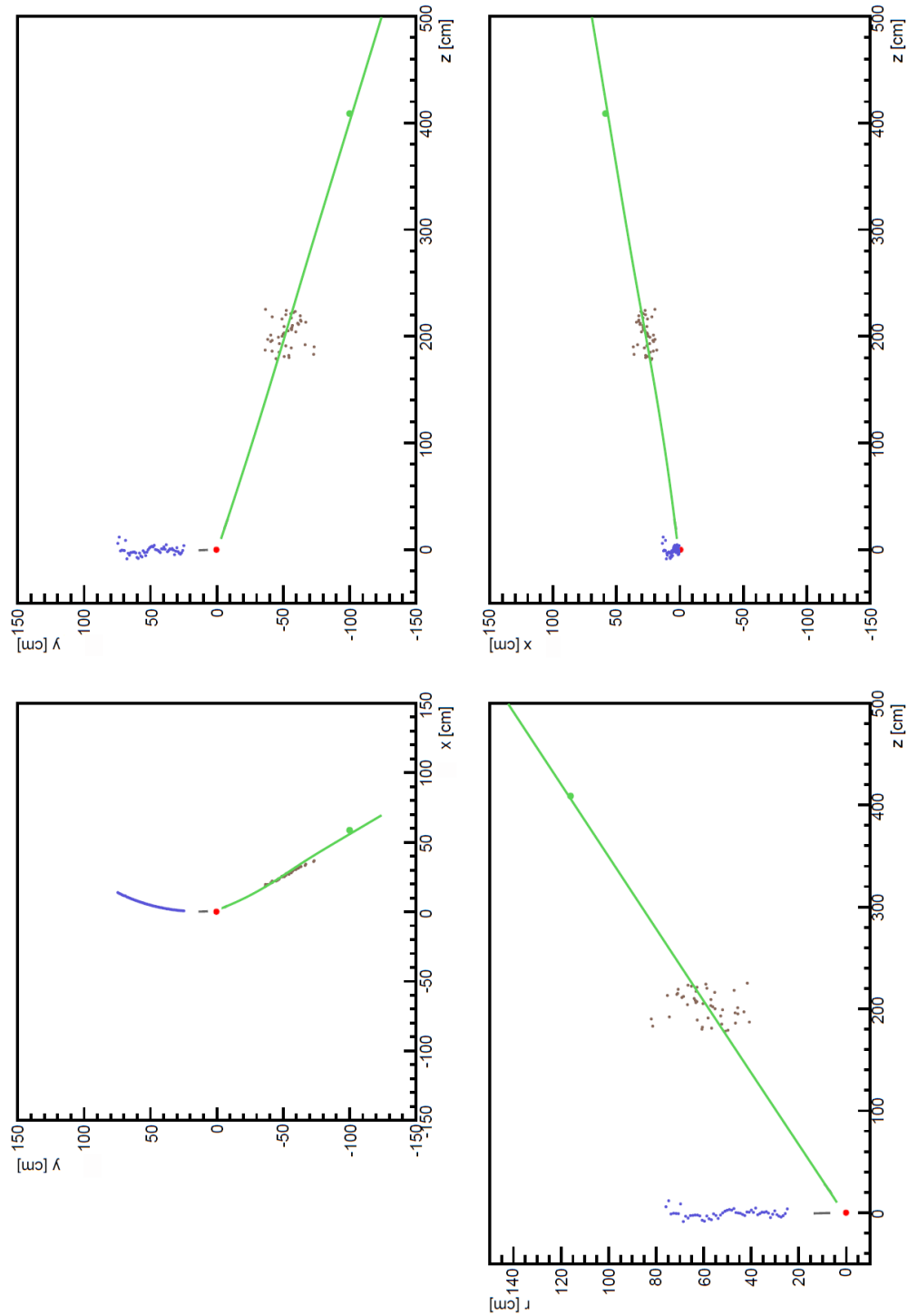


Figure 6.10: Plots of an event with a combined GEM-TPC/HELITRON track fit: (top left) xy -graph, (top right) zy -graph, (bottom left) zr -graph, (bottom right) zx -graph. (red point...nominal vertex position, grey points...GEM-TPC hit points, blue points...CDC hit points, brown points...HELITRON hit points, green point...PLAWA hit point, green line...matched track fit)

6.3 Results

This section shows preliminary results of momentum and mass resolution and vertex determination in forward direction for the matched GEM-TPC/HELITRON track data in comparison to the HELITRON data.

For the analysis of the data of former FOPI experiments, only HELITRON tracks with an associated PLAWA hit were used. Therefore, in all following plots, which apply to the data from the HELITRON, only tracks with an associated PLAWA hit were used.

6.3.1 Vertex determination

The biggest achievement for the data analysis due to the GEM-TPC upgrade of the FOPI spectrometer is the possibility of the vertex determination in forward direction. Because of the great distance between the HELITRON and the target position, vertexing in forward direction was in former FOPI experiments not possible. The particle tracks were assumed to originate at the nominal target position. Because of the GEM-TPC, additional track position information near the target could be obtained for particles emitted in forward direction. In order to determine the vertex distribution, the combined track fits were extrapolated in backward direction and the points of closest approach (POCA) to the nominal vertex position were determined.

This kind of determining the vertex distribution is only approximately correct, because the POCA position depends on the nominal vertex position. A more accurate way of determining the vertex distribution is the calculation of the crossing points of two or more tracks, which are emitted from the same reaction point. Due to this procedure not only the true main vertex can be better defined also secondary vertices can be determined. However, a lot of statistics is needed for this kind of vertex determination, because events have to be found with at least two tracks coming from the same point. Therefore, a combined determination with HELITRON and CDC track data will have to be performed.

Figure 6.11 shows the POCA distribution of the tracks in x , y and z direction. The red lines in the z -distribution plot corresponds to the carbon target thickness of 10 mm at the nominal target position.

The width of the distributions are not only determined by the statistical distribution but also by the size of the interaction region. This means, that the plotted distributions are a convolution of the target volume ($45 \times 45 \times 10 \text{ mm}^3$) times the beam profile times the vertex resolution. Although the target volume is well known, the exact vertex resolution can not be easily extracted without an independent measurement of the beam profile. However, the z -distribution plot indicates a vertex resolution in mm range or better. Furthermore, only very short peak-tails can be seen in all three distribution, although no additional cuts were applied. This implies, that the majority of the matched GEM-TPC/HELITRON tracks have their origin

in the target volume.

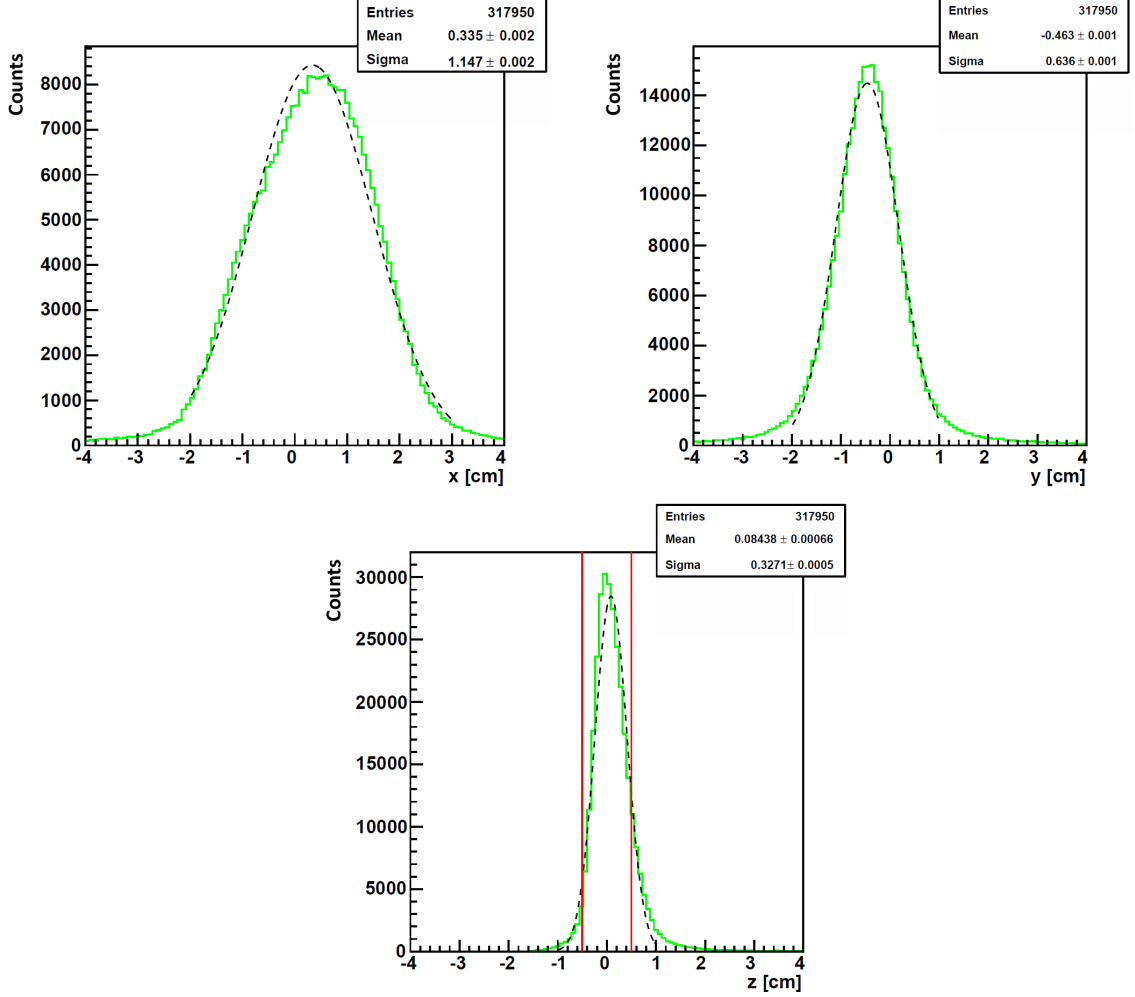


Figure 6.11: Plots of the POCA distributions with approximated Gauss-fits: (top left) x - direction, (top right) y - direction, (bottom) z - direction.

6.3.2 Momentum resolution

Because of the relation between the particle momentum and the mean energy loss dE/dx , the particle and its mass can be identified using the Bethe-Bloch equation (1.3). If additional information about the particle velocity v is available (e.g. ToF measurement of the PLAWA), the particle mass can also be determined with the help of the relativistic relation

$$p = \frac{m \cdot v}{\sqrt{1 - \frac{v^2}{c^2}}}, \quad (6.9)$$

between the particle momentum p and velocity v . For both options a good momentum resolution is important for PID.

Two dimensional plots of the mean energy loss dE/dx or the particle velocity v as a function of the momentum were studied. In order to distinguish between differently charged particles in these plots, the absolute value of the momentum is multiplied with the elementary charge $(-1,1)$ of the particles.

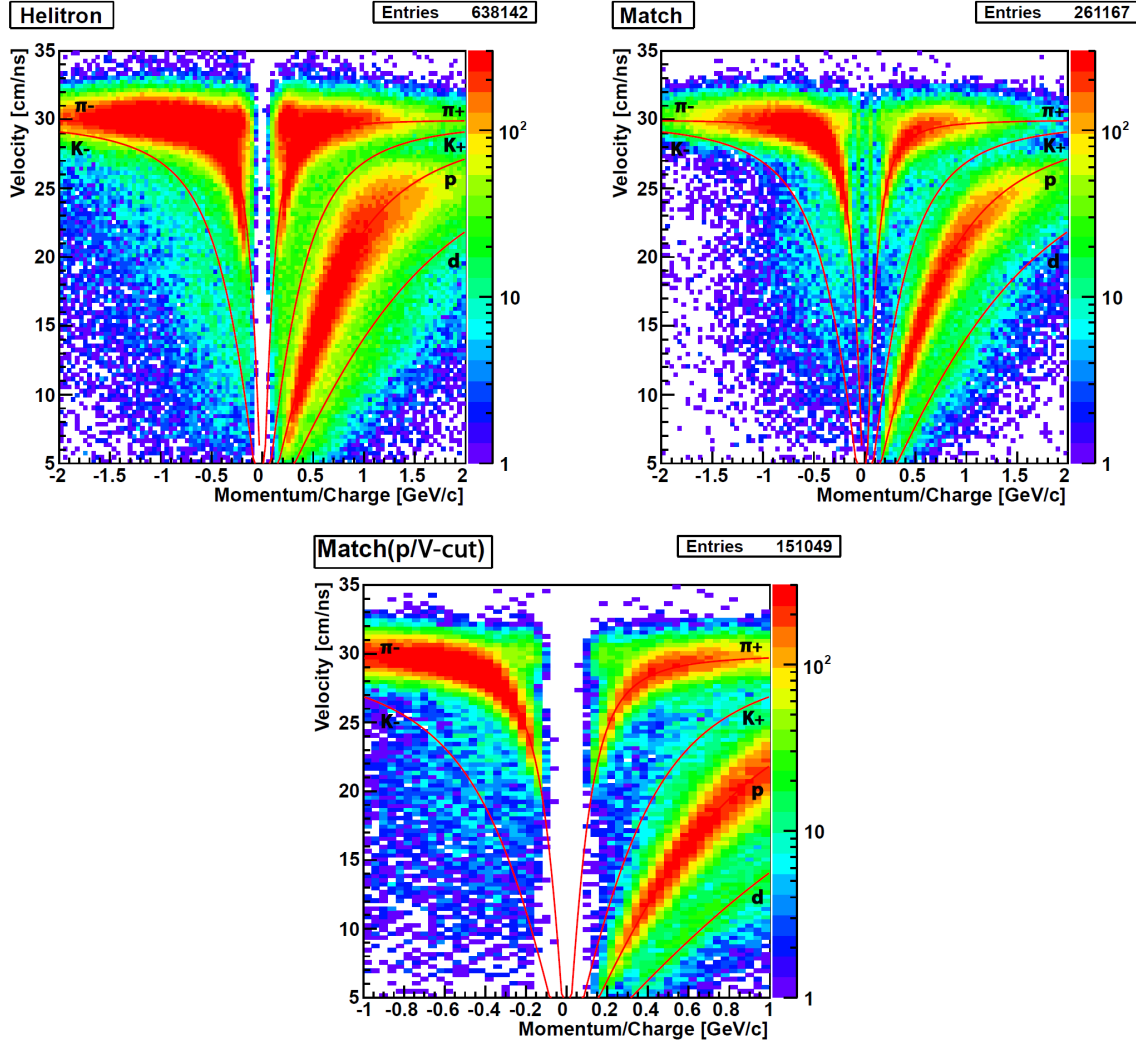


Figure 6.12: Particle velocity v versus momentum p times charge sign: (top left) HELITRON tracklets, (top right) matched tracks, (bottom) matched tracks with p and vertex cut.

Figure 6.12 shows three graphs, where the particle velocity v is plotted against the momentum p . The red lines indicate the regions where the entries of the corresponding particle should theoretically be in the pv -plane. The velocity information is

provided by the data of the PLAWA detector. Therefore, for these plots only tracks with an associated PLAWA hit could be used. The top left graph shows results using only HELITRON information, the top right results from the matched GEM-TPC/HELITRON tracks and the bottom graph results from the matched tracks, where a momentum and vertex cut was applied. A more detailed discussion about the cuts is given in section 6.4. The momentum information of the "Helitron" plot was obtained from the HELITRON tracklets, while for the other two plots the momentum information was achieved from the combined track fits.

The comparison of the "Match" plot with the "Helitron" plot shows, that with matched GEM-TPC/HELITRON tracks protons and π^+ can be better separated, because of the narrower peaks, and the K^+ background is therefore reduced. Additionally π^- can be better defined.

In addition, the comparison of the "Helitron" plot entries with the "Match" plot entries of both figures shows that approximately 40% of the HELITRON tracklets with an associated PLAWA hit could be matched with GEM-TPC tracklets. This number do not describe a track matching efficiency, because not all HELITRON tracklets have a matchable GEM-TPC track, e.g. in an event cluster without GEM-TPC tracklets.

During the HELITRON raw data processing a momentum threshold of approximately 100 MeV/c was set, thus no track signals can be seen in this region in the "Helitron" plot. For the combined track fits no such threshold was set, thus also entries with a momentum below 100 GeV/c can be seen in the "Match" plot. In the "Match(p/V-cut)" plot these tracks are again cut off due to the applied vertex cut.

Figure 6.13 shows some dE/dx versus $p \cdot q(-1,1)$ plots with different data inputs. For these plots the same data sets as for the plots in figure 6.12 were used. Because a mean energy loss information of the GEM-TPC tracklet was not yet available, the dE/dx measured by the HELITRON was used for all plots. The momentum information was again obtained for the "Helitron" plot from the HELITRON tracklets, while for the other two plots the information from the combined track fit was used.

Both figures demonstrate qualitative improvement of the momentum resolution, but are not suited to quantify the effect. In order to get a better understanding of the results an additional analysis of the mass distribution with different data inputs were made.

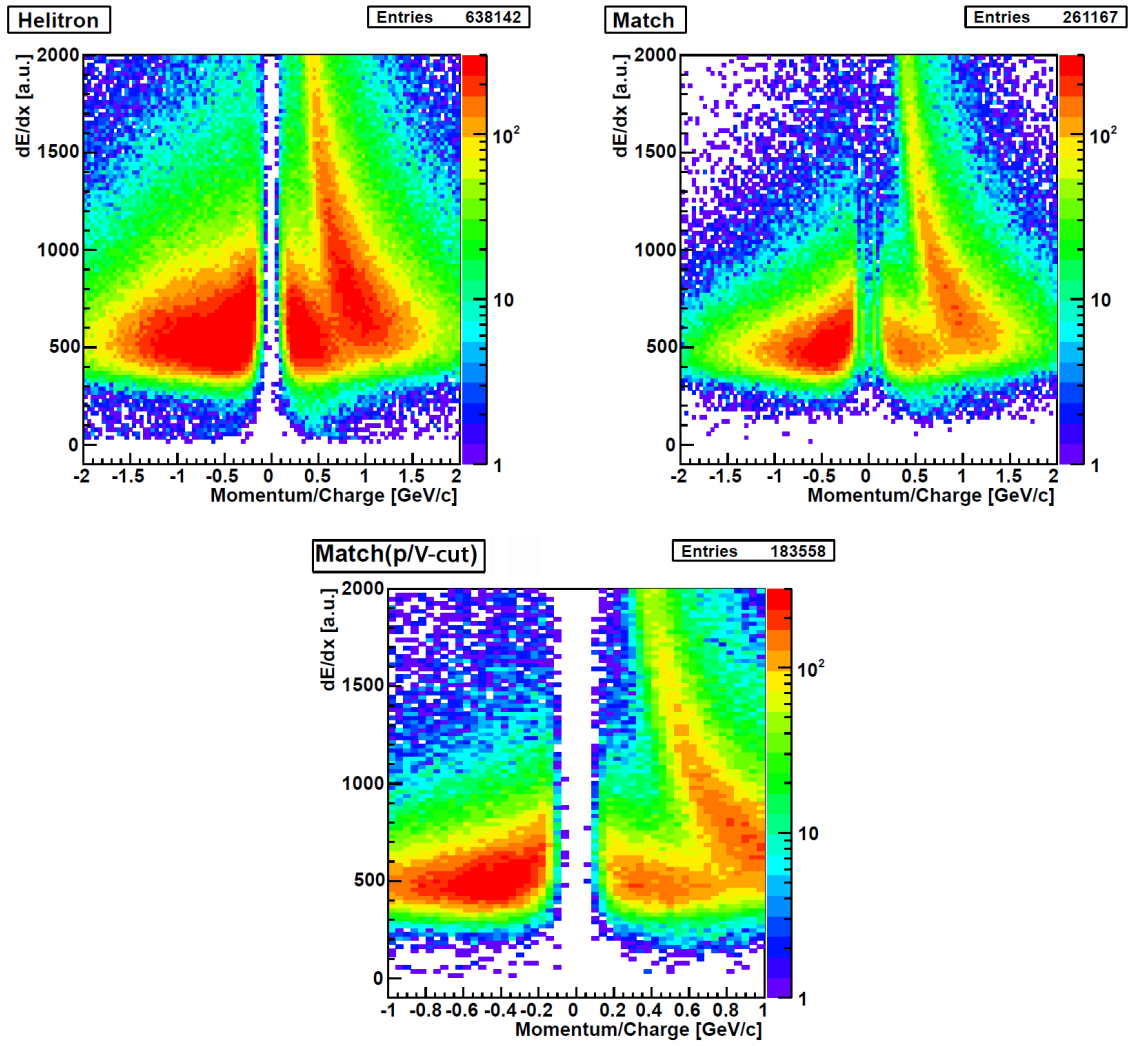


Figure 6.13: Mean energy loss dE/dx versus momentum p times charge sign: (top left) HELITRON tracklets, (top right) matched tracks, (bottom) matched tracks with p and vertex cut.

6.3.3 Mass resolution

The mass of the particles were calculated using the relation (6.9). The momentum information was obtained either from the HELITRON or the combined track fits, depending on the mass distribution plot. The velocity was provided by the associated PLAWA hit. In order to be able to distinguish between differently charged particles in the mass distribution plots, the calculated mass was multiplied with the elementary charge (-1,1) of the particles. Figure 6.14 shows the mass distribution plots for the HELITRON (red line), matched tracks (green line) and matched tracks with momentum and vertex cuts (blue line). The mass distribution plots correspond to the "Helitron", "Match" and "Match(p/V-cut)" plots in figures 6.13 and 6.12. Because of the different statistics of each plot and in order to facilitate comparison, a second graph is shown on the right side of figure 6.14, where the distributions are normalized according to their integrated signal events (in the range from -1 to 2.5 GeV/c²).

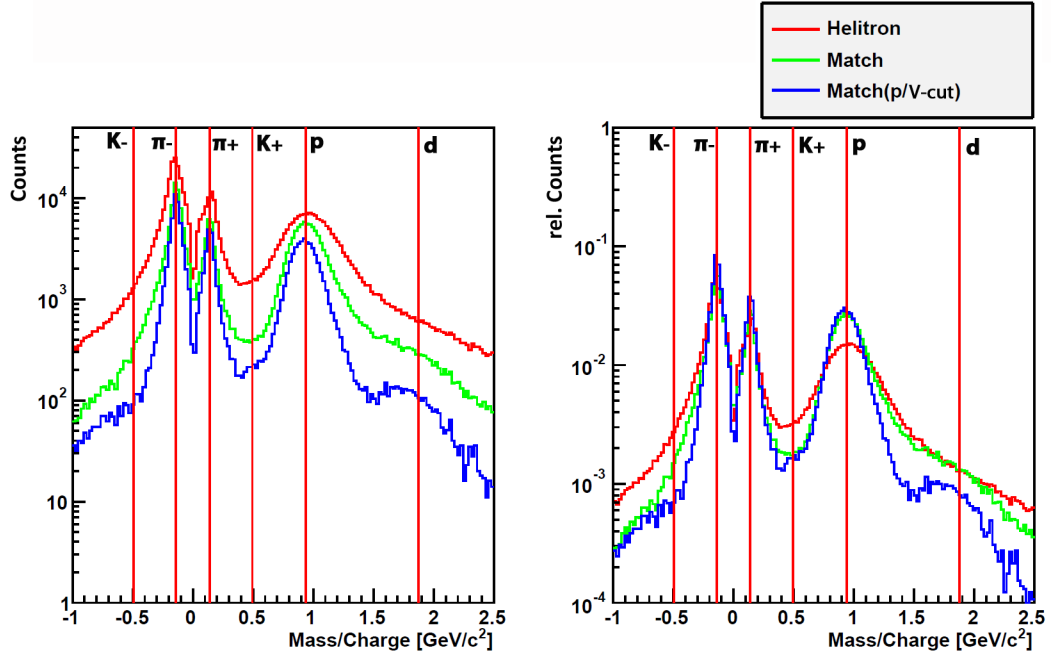


Figure 6.14: (left) Mass distribution plots, (right) Normalized mass distribution plots.

In the mass distribution plots, the improvement of the mass resolution due to the matched GEM-TPC/HELITRON track matching can be clearly seen. Both graphs show, that the signal to background ratio could be, due to the track matching, significantly improved over the whole mass range. As mentioned before, for the blue plot some additional cuts were applied on the matched track data. The cuts include an upper limit of 1 GeV for the track momentum and a restriction of the POCA. A more detailed discussion about the cuts, and why especially these were chosen, is given in section 6.4. However, with these cuts, the overall signal to noise ratio could be

further improved. The "Match(p/V-cut)" plot shows a structure in the region of the deuteron mass and a bump can be recognized on the lower proton tail in the region of the K^+ mass. The improvements of the mass resolution can be quantitatively expressed. Gauss-fits of the prominent π^- , π^+ and p peaks were made. The results of this fits are summarized in table 6.2, where the peak positions are listed, and table 6.3, which gives an overview about the peak widths.

Plot	π^- [MeV/c ²]	π^+ [MeV/c ²]	p [MeV/c ²]
Helitron	-146.2 ± 0.2	136.0 ± 0.3	963.7 ± 0.9
Match	-137.7 ± 0.2	135.5 ± 0.4	951.1 ± 0.6
Match(p/V-cut)	-138.3 ± 0.2	137.6 ± 0.4	932.1 ± 0.6
nominal mass	-139.6	139.6	938.3

Table 6.2: Positions of π^- , π^+ and p mass peaks for different plots.

Plot	π^- [MeV/c ²]	π^+ [MeV/c ²]	p [MeV/c ²]
Helitron	62.4 ± 0.2	69.1 ± 0.3	218.0 ± 1.2
Match	54.1 ± 0.2	57.7 ± 0.4	153.1 ± 0.7
Match(p/V-cut)	48.4 ± 0.2	49.5 ± 0.4	128.5 ± 0.7

Table 6.3: Widths (σ) of π^- , π^+ and p mass peaks for different plots.

The fitting results show, that the positions of the π^- , π^+ and p peaks could be determined more precisely. But more important, the peak widths could be considerably reduced. In case of the p -peak, the peak width is reduced by almost a factor two. This results implies, that the mass resolution of the FOPI spectrometer could be significantly improved in forward direction for the S339 experiment due to the upgrade with the GEM-TPC.

6.4 Cuts

In the course of the first data analysis, the influence of different cut parameters was explored. The goal was to investigate the influence of the different data cuts on the mass distribution of the combined GEM-TPC/HELITRON tracks, in order to further enhance the already improved signal to noise ratio and to uncover hidden structures. For a better comparison of the results only normalized mass distribution plots are shown in this section.

6.4.1 Momentum cut

The first investigated cut was the momentum cut. For this cut, the track momenta were restricted by upper limits of 0.75 GeV/c and 1 GeV/c. Since these thresholds can be also applied on the HELITRON only data, the effect on HELITRON and matched track data can be compared. Figure 6.15 shows the plots of the uncut HELITRON and matched track mass distributions as well as the result of the on both distributions applied momentum cut. The graphs show the mass plots with a momentum cut at $p < 0.75$ GeV/c (left) and $p < 1$ GeV/c (right).

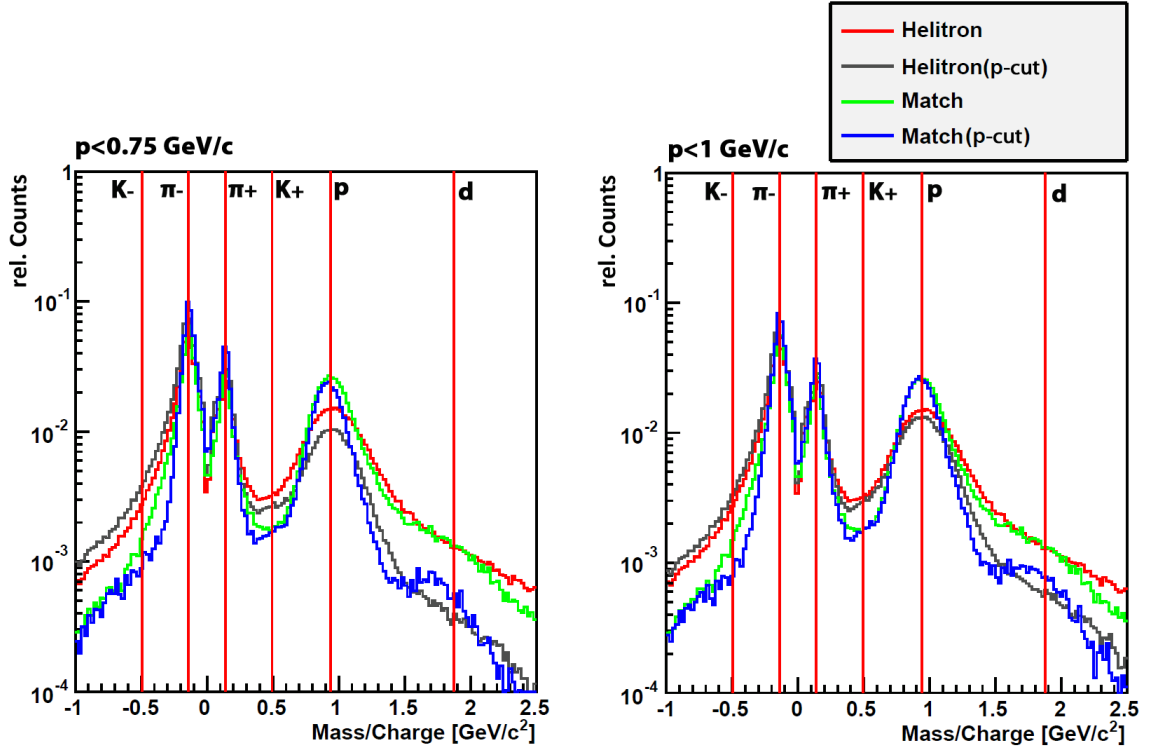


Figure 6.15: Mass distribution plots with applied momentum cut: $p < 0.75$ GeV/c (left) and $p < 1$ GeV/c (right).

As it can be seen in both graphs, the momentum cuts have indeed a considerable impact on the results, though the effect on the HELITRON data is rather limited. In the "Helitron(p-cut)" plots it can be seen, that the level in the K^- region rises, compared to the "Helitron" plots, while the π^- peak level of cut and uncut HELITRON data is equal. This indicates, that the signal to noise ratio is not improved in these mass regions for the HELITRON data. The π^+ peak level of the HELITRON data seems to be unaffected by the momentum cut. Interesting is the decrease in the K^+ region in both graphs. Yet a possible improvement in this mass region is reduced by the simultaneous reduction of the p peak level. This implies, that the decrease in the K^+ and also in the d region is mainly caused by a statistical reduction in the expanded p mass region due to the momentum cut. The plot of the momentum cut HELITRON data indicates, that the momentum threshold cut just reduces the total statistics over the whole mass range without significant improvements for the signal to noise ratio.

For the matched tracks the situation is different. The "Match(p-cut)" plots in both graphs clearly show, that the signal to noise ratio of the matched track data is improved by the momentum cuts:

- **d -region:** Especially at large masses the background was effectively suppressed. In the d mass region the level could be in such a way reduced, that a structure can be recognized.
- **K^+ -region:** The momentum cut effect on the K^+ region is ambivalent. On the one hand the level could not be decreased in both graphs, but on the other hand a small structure can now be recognized in the K^+ mass region. This could be a consequence of a small reduction of the π^+ peak width.
- **K^- -region:** A level decrease can be also recognized in the K^- mass region, which could, similar to the K^+ mass region, a consequence of the narrower π^- peak width.

6.4.2 Vertex cut

Due to the additional vertex information of the combined GEM-TPC/HELITRON tracks in forward direction, a vertex cut could be applied for the first time in forward direction for the matched track data. For the vertex cut the limits for the tracks were set by means of the POCA-distribution plots (see Section 6.3.1). For each direction (x, y, z), the POCA of each track has to be within the limits

$$\begin{aligned}\bar{x} - t \cdot \sigma_x &\leq x \leq \bar{x} + t \cdot \sigma_x & , \\ \bar{y} - t \cdot \sigma_y &\leq y \leq \bar{y} + t \cdot \sigma_y & , \\ \bar{z} - t \cdot \sigma_z &\leq z \leq \bar{z} + t \cdot \sigma_z & .\end{aligned}\tag{6.10}$$

$\bar{x}$, $\bar{y}$ and $\bar{z}$ are the mean and σ_x , σ_y and σ_z the standard deviation of the respective POCA-distribution plots of figure 6.11. t is a freely chosen parameter. Figure 6.16 show the mass plots of HELITRON, uncut matched tracks and matched tracks with different vertex cuts. The left graph shows the vertex cut mass plot with $t = 0.5$, while the parameter for the right graph are set to $t = 2$.

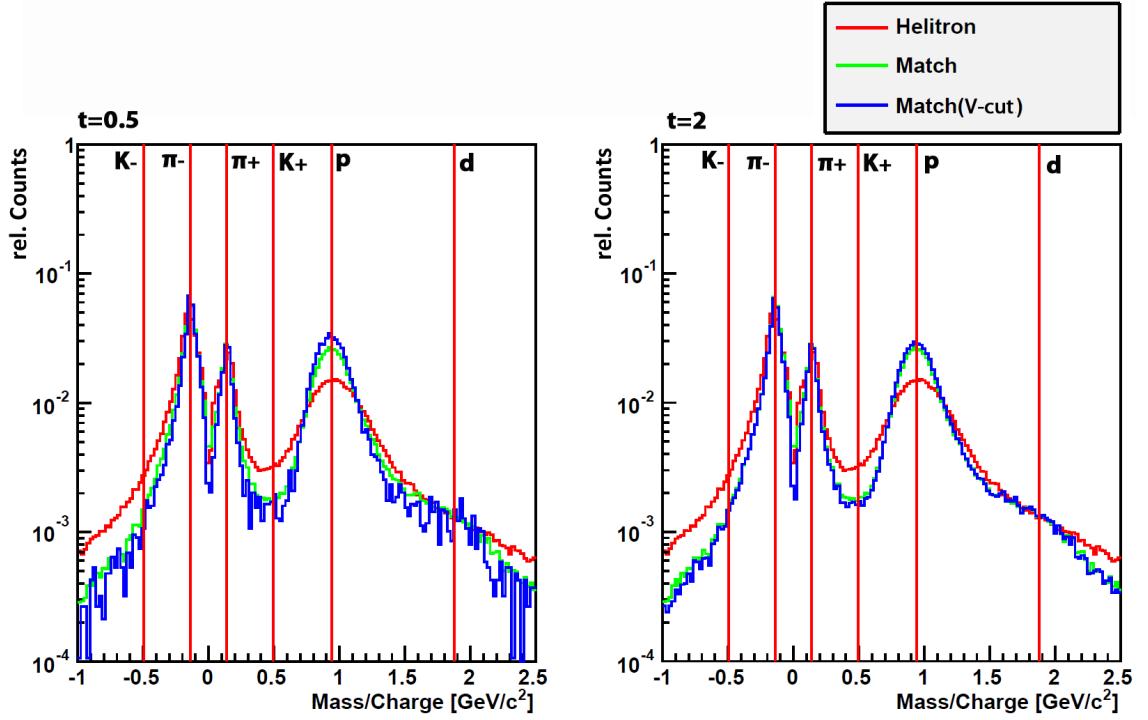


Figure 6.16: Mass distribution plots with applied vertex cut: $t = 0.5$ (left) and $t = 2$ (right)

The effect of the vertex cut is, independent of cutting grade, rather modest. A clear visible improvement can only be recognized in the mass region between the π^- and π^+ peaks, where a considerable reduction of the background level was achieved. This corresponds with the loss of the low momenta ($p < 100 \text{ MeV}/c$) tracks in the "Match(p/V-cut)" plots of figures 6.12 and 6.13. In the mass regions of K^+ and d an effect of the POCA cut could only be seen with a harder ($t = 0.5$) vertex cut.

The rather modest impact of the vertex cut can be explained by the results of the POCA-distribution plots (see Figure 6.11). Due to the short tails in all three distribution, it can be inferred, that the matched GEM-TPC/HELITRON tracks of almost all particles have their origin in the target volume. Therefore, a vertex cut on the mass plots effects the whole mass region.

In order not to loose too much statistics and with respect to the results of figure 6.16, a rather soft ($t = 2$) vertex cut was applied on the "Match(p/V-cut)" mass distribution plot shown in figure 6.14.

6.4.3 Quality Cuts

In addition to the momentum and vertex cuts, other cut options were tested, which should improve the input quality of the matched track data.

The first quality cut parameter is the reduced χ^2 of the combined GEM-TPC/HELITRON track fits (see Section 6.2). The χ^2 -distribution of all matched track fits was evaluated and plotted in figure 6.17. With respect to the results of χ^2 -distribution plot the threshold was set to $\chi^2 < 2$ for all mass distribution plots of the combined GEM-TPC/HELITRON tracks shown in this work.

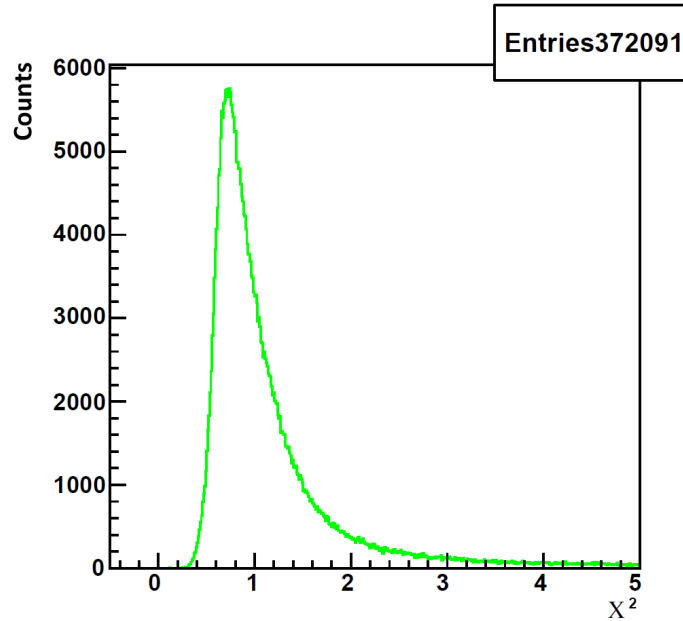


Figure 6.17: Reduced χ^2 -distribution of matched track fits.

For the other cut options some geometrical considerations were involved. It was assumed, that GEM-TPC tracklets of particles, originated from the nominal target position, are shorter at lower polar angles due to the geometrical alignment of target and GEM-TPC. This can be derived from the rz -plane plot in figure 6.2, where the geometrical alignment of the target and the active volumes of GEM-TPC and HELITRON is sketched.

A shorter GEM-TPC tracklet means, that the track hit number is decreased. This could lead to a reduced track quality. In order to see a possible polar angle dependency of the track hit number, the polar angle Θ of a tracklet was plotted as a function of the track hit number for both (GEM-TPC, HELITRON) detectors (see Figure 6.18).

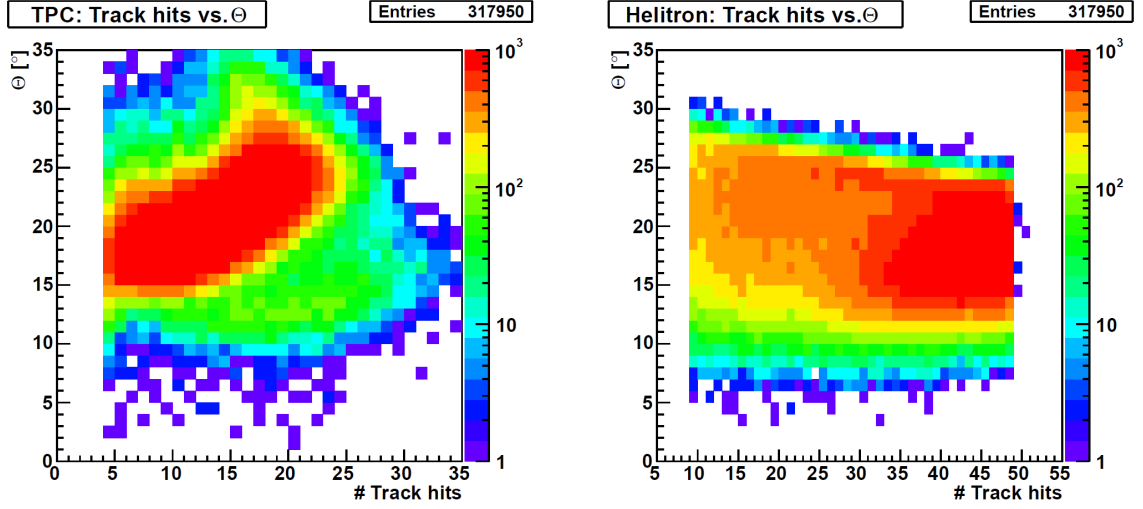


Figure 6.18: Plot of tracklet polar angle Θ against track hit number N for GEM-TPC (left) and HELITRON (right).

It can be seen, that in case of the GEM-TPC the track hit number N depends on the polar angle Θ of the GEM-TPC tracklet in forward direction. As expected, the track hit number increases with rising angle. While the angle dependency is less pronounced in the HELITRON, it can be seen, that there are tendential more hits at low Θ . This can be also explained by the geometrical alignment of target and HELITRON. It can be derived from the rz -plane plot in figure 6.2, that particles with a higher initial polar angle Θ do not traverse the full active area in z -direction (e.g. see simulated particles with $p = 0.4 \text{ GeV}/c$ and $\Theta = 30^\circ$ in figure 6.2). The number of track hits in the HELITRON is given by the number of hit wires, which are aligned parallel in z -direction. This leads to a reduction of the track hit number for HELITRON tracklets at large polar angles

With these results, mass distribution cuts for the combined GEM-TPC/HELITRON track data were tested, which have the GEM-TPC track hit number and the tracklet Θ angle as parameters. Figure 6.19 shows the mass distribution plots with applied track hit cut of $N > 10$ for the left graph and $N > 7$ for the right graph. The graphs show, that these cuts have almost no visible effects on the mass plots. Figure 6.20 shows mass distribution plots with applied polar angle cuts of the GEM-TPC tracklets of $\Theta > 20^\circ$ (left graph) and $\Theta > 15^\circ$ (right graph).

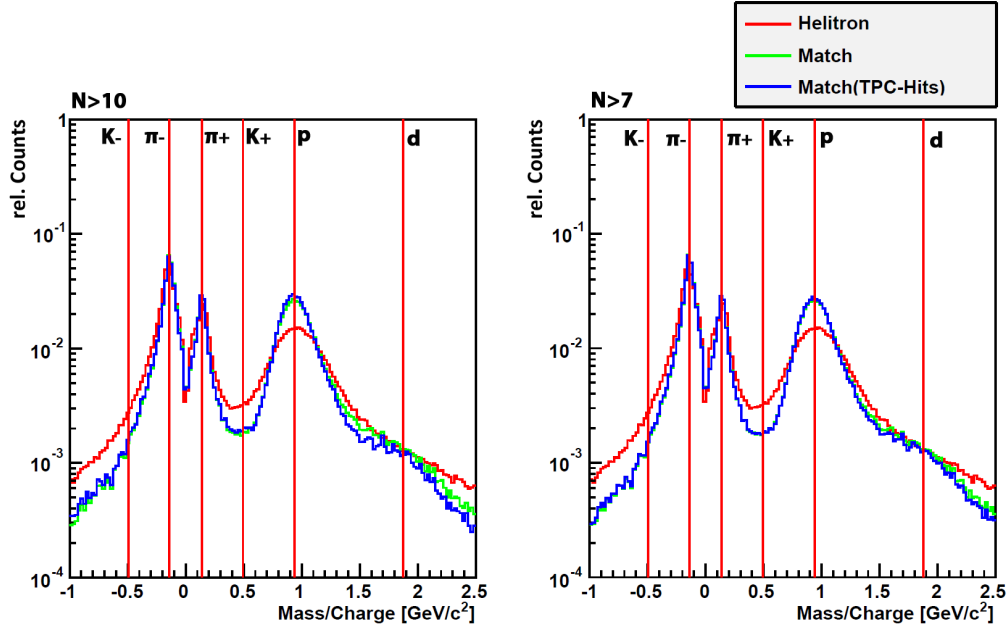


Figure 6.19: Mass distribution plots with applied GEM-TPC track hit cut: $N > 10$ (left) and $N > 7$ (right)

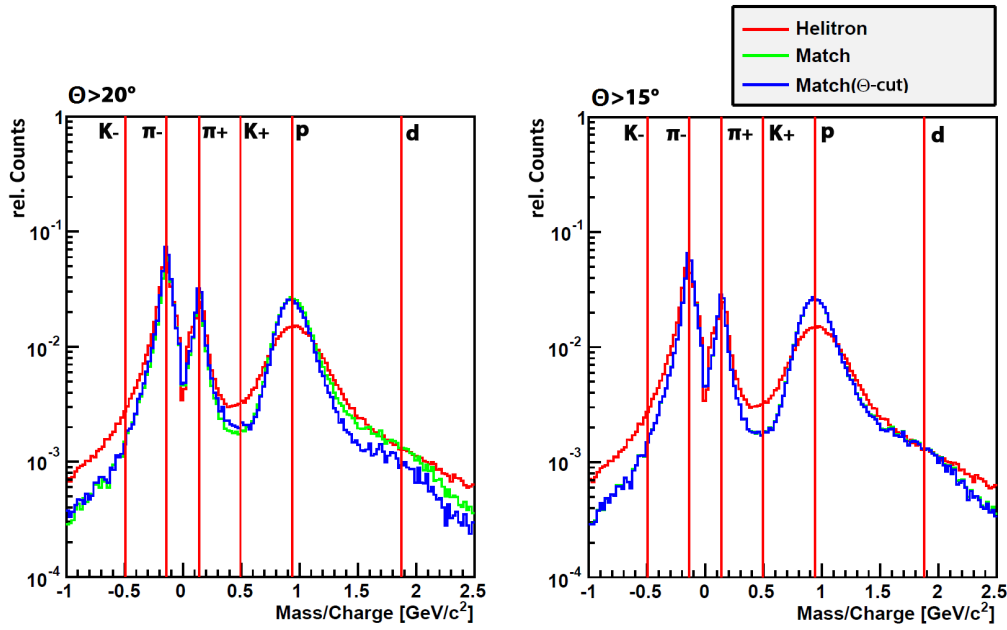


Figure 6.20: Mass distribution plots with applied polar angle Θ cut: $\Theta > 20^\circ$ (left) and $\Theta > 15^\circ$ (right)

In figure 6.20 it can be seen, that the lower Θ cut of 15° on the right graph shows no effect on the matched track data. With the harder Θ cut of 20° on the left graph, some small effects can be recognized in the deuterium and K^+ mass regions. While the background level in the deuterium region could be reduced, the level in the K^+ increases which indicates a worsening of the signal to noise ratio in this region.

The mass plots of the different applied cuts, show that not all cut options are sensible. While the GEM-TPC track hit and track polar angle cuts showed nearly no effects, the momentum and vertex cuts improved the data considerable. On those grounds only these two cuts, besides the χ^2 cut of the combined track fits, were applied on the "Match(p/V-cut)" mass distribution plots shown in figure 6.14.

However, cut optimization is a tedious work. At first an optimization quantity has to be defined, which should be a measure for the quality of the cuts. The optimization quantity could consist of different parameters. The signal to noise ratio seems to be a good choice. A second option could be the ratios between peak heights and widths of the three prominent mass peaks of π^- , π^+ and p , which give information about the mass resolution.

The second step would be to find the optimum combination of the cuts and their limits. The effects of the cuts on the results are diverse. Some show large, others rather small effects. The cuts can also have different impacts on different mass regions and some cuts have even a negative effect on the result. Therefore, the cuts have to be systematically varied in order to find the final set of cuts, which optimize the optimization quantity. In order to get the final results, the work on the cut optimization has to be done.

7 Conclusion and Outlook

In the course of this work the large GEM-TPC prototype was introduced. The technical development of a closed gas supply system was discussed in more detail. The physical requirements on the detector gas were also described, because it was an important input for the technical realization of the gas system. The main gas system components like pressure and gas flow controller, gas mixer, gas purifier and the gas system safety features were discussed in detail. The results of the first gas system performance tests are presented, which showed that the technical and physical requirements on gas mixture stability and oxygen purification of the detector gas could be fulfilled. The demands on the gas pressure stability inside the gas system even exceeded the initial expectations. Also the satisfying performance of the system safety features during the first tests showed, that the safety of the large prototype can be assured during an experimental operation of the detector.

But the development of the gas supply system for the GEM-TPC is still not finished. For example, a communication between GEM-TPC closed gas and high voltage supply system will be established. Thus, the high voltage of the large prototype will be automatically ramped down at an emergency shut down of the gas system.

A further development of the gas system will be the upgrade with a water vapour purification system. Furthermore, the extension of the gas mixing system to a third gas will enlarge the operational properties of the whole gas system.

The principle design of the closed gas system allows an easy accommodation of its features (e.g. higher gas flow) to different requirements. Thereby, it is on its own a prototype for closed gas supply systems, which can also be used for other gaseous detectors.

Within the framework of this thesis, the first steps of a combined data analysis of the large GEM-TPC prototype and the FOPI detector system in forward direction of the experiment S339 could be completed and the results are presented. A data processing method was developed, which successfully combines the by the GEM-TPC and the HELITRON independently detected track parts of a particle. With the limits on the polar and azimuthal angle differences of GEM-TPC and HELITRON tracks, appropriate selection parameters were found for the FOPI track matching in forward direction. Yet the study of the momentum dependence of $\Delta\Theta$ and $\Delta\phi$ showed, that the cut limits can still be optimized. The idea is to use after all the momentum information of the HELITRON track parts, to configure the cut limits in such a way, that a better suppression of wrongly matched tracks can be achieved.

Due to the GEM-TPC upgrade a significant progress in PID was achieved for FOPI in forward direction. With the help of the GEM-TPC track information near the target position the determination of the main vertex in forward direction was possible for the first time. Further efforts are in progress, which will in addition allow the identification of secondary vertices of tracks in forward direction. This will facilitate the determination of intermediate meson states like ϕ or Λ , which will be another big step in order to study the in-medium properties of hadrons with FOPI. The long term goal in the course of vertexing with FOPI will be of course the corporate vertex determination of the whole FOPI spectrometer with the GEM-TPC.

Although the vertex determination in forward direction is the highlight of the combined data analysis of GEM-TPC and HELITRON, the PID potential in forward direction could be also optimized in other areas. A significant improvement of the mass resolution of FOPI in forward direction was achieved due to the track matching of GEM-TPC and HELITRON. The results illustrated a considerable reduction of the background level in the mass regions of K^- and K^+ , which is a significant progress for the detection of K^- and K^+ in the course of the study of the in-medium kaon and ϕ meson properties within the S339 experiment.

In order to exploit the full potential of the experimental data, a detailed study on the data cut optimization is in progress.

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