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Performances of an Active Target GEM-Based TPC for the AMADEUS Experiment

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Abstract

In this paper, we present the R & D activity on a new GEM-based Time Projection Chamber (GEM-TPC) detector for the inner region of the AMADEUS experiment, which is aiming to perform measurements of low-energy negative kaon interactions in nuclei at the DAΦNE e+ e− collider at LNF-INFN. A novel idea of using a GEM-TPC as a low mass target and detector at the same time comes motivated by the need of studying the low energy interactions of K− with nuclei in a complete way, tracking and identifying all of the produced particles. Even more, what makes the experimental proposal revolutionary is the possibility of using different gaseous targets without any other substantial intervention on the experimental setup, making it a flexible multipurpose device. This new detection technique applied to the nuclear physics requires the use of low-radiation length materials and very pure light gases such as Hydrogen, Deuterium, Helium-3, Helium-4, etc. In order to evaluate the GEM-TPC performances, a 10 × 10 cm^2 prototype with a drift gap of 15 cm has been realized. The detector was tested at the πM1 beam facility of the Paul Scherrer Institut (PSI) with low momentum pions and protons. Detection efficiency and spatial resolution, as a function of gas mixture, gas gain and ionazing particle, are reported and discussed.

Keywords

GEM, TPC, Tracking, Particle Identification

1. Introduction

An important, yet unsolved problem, in hadron physics is how the hadron masses and interactions change in the

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nuclear medium. This topic could be investigated by means of "in-medium hadron-mass spectroscopy", producing bound states of a hadron by which to extract the hadron-nucleus potential and the in-medium hadron masses. The AMADEUS (Antikaon Matter At DAΦNE Experiments with Unraveling Spectroscopy) experiment [1] [2] will study the low energy interactions of negative kaons with nucleons and nuclei. The dedicated AMADEUS setup will be implemented inside the KLOE [3] Drift Chamber (DC), in the free space between the beam pipe and the DC entrance wall. Currently, the main component of the experimental setup to be developed is an active target GEM-based [4] Time Projection Chamber [5] (GEM-TPC), which will act as low mass target and particles tracking detector at the same time.

A drawing of the dedicated AMADEUS setup surrounding the beam pipe within KLOE detector is given in **Figure 1**. The GEM-TPC will be 20 cm long with an inner diameter of 8 cm and an outer one of 40 cm.

The main requirements can be summarized as:

- a spatial resolution better than 300 µm in X − Y and 500 µm in Z with a magnetic field of 0.5 T;
- a detector material budget lower than 0.5% of X0;
- a rate capability of ~5 kHz/cm^2 [6].

Since most of the above requirements are fulfilled by a GEM-TPC, the R & D activity at the Laboratori Nazionali di Frascati (INFN) is mainly focused on the study of the detector performances with pure gas. A GEM-TPC prototype of 10 × 10 cm^2 with a drift gap of 15 cm has been realized and tested both in laboratory and at the Paul Scherrer Institute (PSI). In Section 2 preliminary simulation studies on an active hydrogen target GEM-TPC in the AMADEUS experiment are shown, while details of the prototype construction are described in Section 3. The detector performances obtained at the πM1 beam facility, in terms of detector efficiency and spatial resolution, are presented in Section 4.

2. Simulation for a Hydrogen GEM-TPC

Simulation studies have been performed with GEANT-4 [7] in order to investigate the use of an active target GEM-TPC in the AMADEUS experiment. The GEM-TPC is constrained to fit into the free volume between the DAΦNE beam-pipe and the KLOE drift chamber. In the GEANT-4 simulation we set the following conditions:

- the phase space of Φ mesons is populated according to the recently proposed scheme of crab-waist collisions for DAΦNE [8] [9];
- the charged particles undergo multiple scattering throughout the gas contained nside GEM-TPC, losing energy only by ionization;
- the GEM-TPC is filled with pure Hydrogen gas at standard condition (300 ◦ K, 1 atm);
- the particles move inside a magnetic field of B = 0.5 T.

As an example of this simulation study, we consider the K− p → K− p elastic scattering for a 127 MeV/c negative kaon, produced by the Φ decay, colliding with the gas target. The momentum of the scattered kaon ranges from ~40 MeV/c to 127 MeV/c and the proton momentum can be as high as ~165 MeV/c as shown in **Figure 2**: the kaons (blue line) with momentum larger than 100 MeV/c are emitted mainly at forward angles

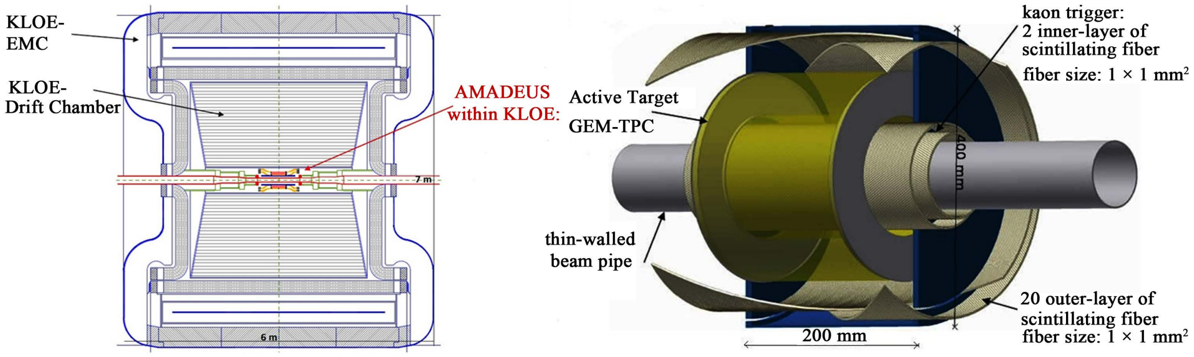

Figure 1. Cross-section of the KLOE detector including the AMADEUS inner setup inside the Drift Chamber (left) and the dedicated AMADEUS setup (right). From the beam pipe to the outer region: the Kaonic Trigger, the active target GEM-TPC.

along with protons (red line), otherwise for kaons with momentum lower than 100 MeV/c, protons and kaons are emitted principally backward. Therefore the use of an active target TPC-GEM will allow tracking the considered elastic scattering in both forward and backward directions.

We also evaluated the effect of the multiple Coulomb scattering when a 127 MeV/c kaon crosses the Hydrogen gas target. As shown in **Figure 3**, the angular distribution is described for both the x- and y-coordinates (transverse plane to the beam direction) by a Gaussian distribution with a $\sigma \sim 85$ µm, corresponding to a deflected kaon angle of less 1 mrad.

In **Table 1** are reported for completeness the primary ionization of the hydrogen gas and the gas mixtures used at the PSI, which are estimated with the GARFIELD [10] simulation tool. Garfield is a computer program for the detailed simulation of two-and three-dimensional gas detectors and it is interfaced to the Magboltz [11] and HEED [12] programs for the computation of electron transport properties in nearly arbitrary gas mixtures and to simulate ionization of gas molecules by particles traversing the detector, respectively.

3. The Amadeus GEM-TPC Prototype Production

The GEM-TPC construction has been performed in a class 1000 clean room. The detector is composed by three GEM foils glued on Fiberglass (FR4) frames, defining the gaps between GEM themselves, then sandwiched

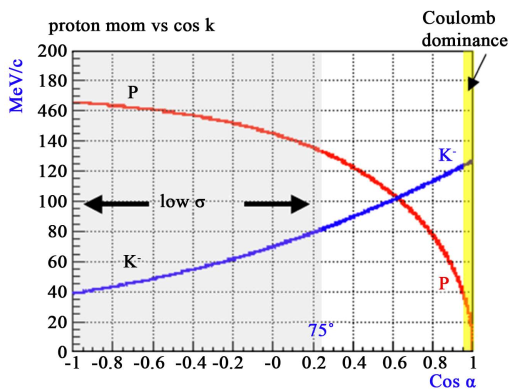

Figure 2. Kinematics of the K− p elastic scattering: the blue curve shows the momentum of the emitted kaon versus the cosine of the angle between the incident kaon direction and the emitted one. The red curve shows the kinematics of the associated proton.

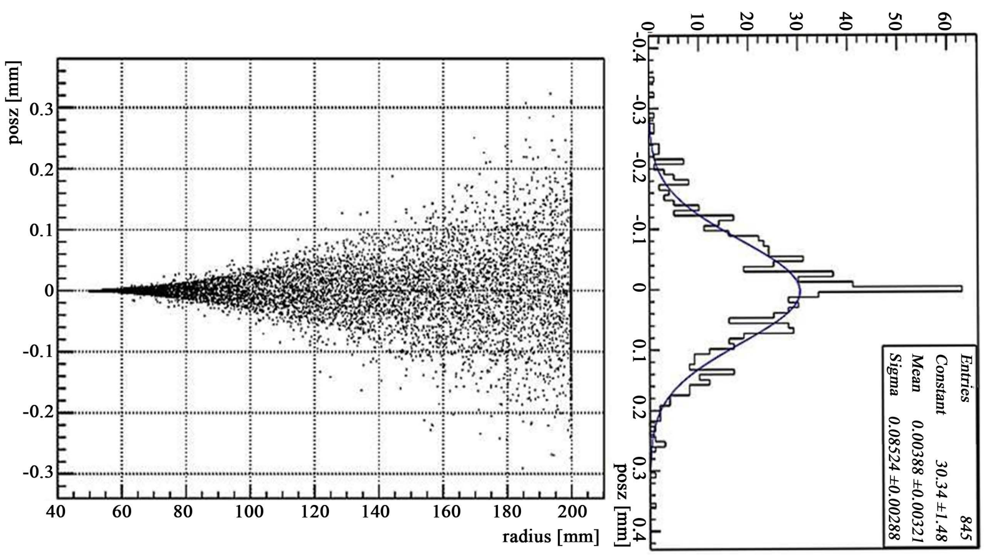

Figure 3. Multiple Coulomb scattering in the Hydrogen gas (left) and the relative angular distribution for an incident 127 MeV/c kaon (right).

Table 1. Primary ionization clusters (mean value) and electrons per cluster (most probable value) for a pure hydrogen gas and the gas mixture tested at PSI for different particle momentum.

		PSI		DAFNE
Gas Mixture		170 MeV/c Pion	440 MeV/c Proton	127 MeV/c Kaon
Hydrogen 100	clu/cm			78.0 ± 2.7
	e−/clu			1.73 ± 0.01
Helium 100	clu/cm	4.0 ± 0.7	12.1±1.1	31.1 ± 1.8
	e−/clu	2.05 ± 0.02	2.03 ± 0.01	2.21 ± 0.01
Ar/i-C4 H10 90/10	clu/cm	40.2 ± 2.0	122.2 ± 3.4	
	e− clu	2.05 ± 0.01	2.04 ± 0.01	

between a cathode and anode PCBs (**Figure 4**). The electric field uniformity in the drift volume is provided by a cylindrical field cage, which consists of two sets of copper strips (2.5 mm wide) on both sides of an insulating kapton foil (100 μm thick), where the outer strips cover the gaps between the inner strips. The potential on each ring is defined by a precision resistor chain located outside the gas volume. The cylindrical shape has been obtained by exploiting the vacuum bag technique [13] and rolling the copper-kapton foil onto machined polytetrafluorethylene (PTFE) cylinder that acts as mold. In this R & D phase, the prototype has been encapsulated inside a gas tight box, which has been equipped by two 14 × 12 cm^2 windows covered by 10 μm Mylar film, in order to reduce as much as possible the radiation length for a particle crossing the detector.

The detector gas tightness results to be lower than 2 mbar per day, corresponding to less than 100 ppmV of residual humidity with a gas flux of 100 cc/min.

4. GEM-TPC Measurements and Performances

4.1. Gas Gain Measurement

The effective gain of a triple-GEM detector has been measured for different gas mixtures and pure helium using a high intensity 5.9 keV X-ray tube. Gain value is obtained from the ratio of the pad current (with high voltage on the GEM foils) to the current on the first GEM (with no high voltage on the GEM foils). As shown in **Figure 5**, operational instability has been observed only for the pure helium gas at a gain greater than ~3 × 10^4 due to the absence of a quencher in the gas.

4.2. GEM-TPC Performances at the PSI Beam Facility

The performances of the GEM-TPC prototype have been studied at the πM1 beam facility of the Paul Scherrer Institut (PSI) without magnetic field. The πM1 beam is a quasi-continuous high-intensity secondary beam providing pions or protons. The study of the detection efficiency and spatial resolution has been performed with a beam rate of ~200 Hz.

The prototype readout is composed by 4 columns of 32 pads of 3 × 3 mm^2 each. Each pad is connected to a front-end board based on CARIOCA-GEM chip [14] with a discriminator threshold of ~2 fC. Six MDT layers have been used in the test as an external track reference. The spatial resolution reached by the external tracker was ~100 μm. The trigger of the setup has been generated by the coincidence of three scintillators S1⊗S3⊗S2, centred on the beam axis and covering an area of ~12 × 20 mm^2 (**Figure 6**). Moreover, another scintillator, about 5 m far from the S1, S2, S3 cross, has been acquired in order to perform a measurement of the particle momentum crossing the prototype by means of time of flight. The measured momentum resolution for pion and proton beams in the momentum range between 100 and 440 MeV/c was less then 1%. A schematic view of the

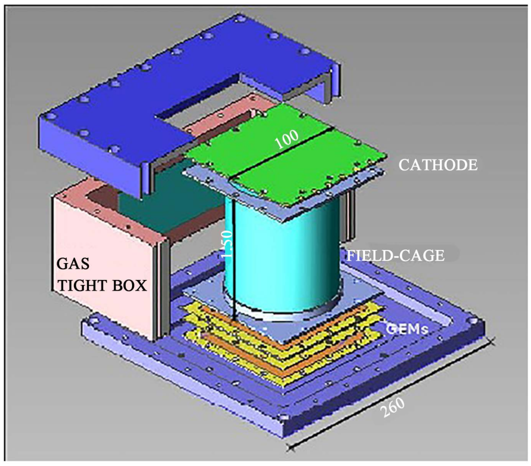

Figure 4. Exploded view of the GEM-TPC prototype.

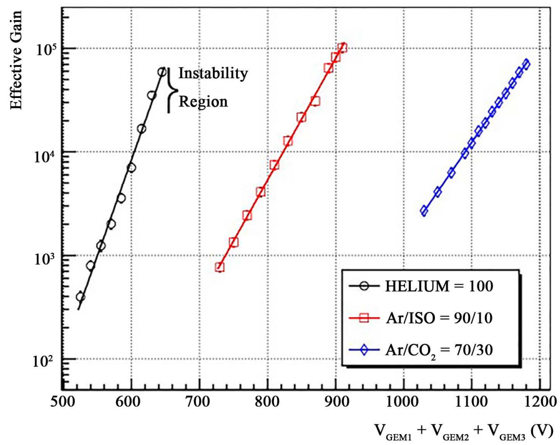

Figure 5. Effective gain as a function of the sum of the voltages applied on the three GEM foils for different gas mixtures and pure helium gas. The curve of the Ar/CO_2 = 70/30 gas mixture is reported for comparison.

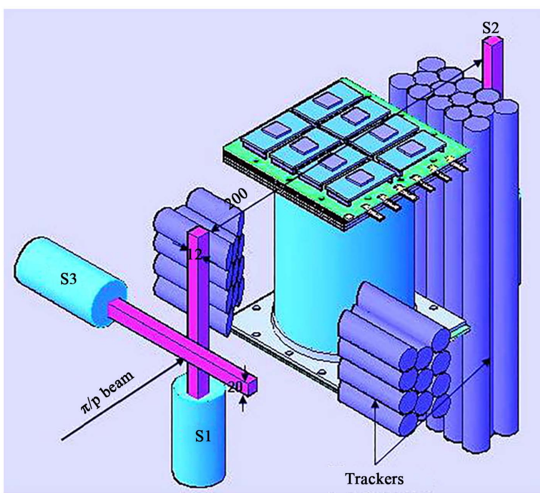

Figure 6. Schematic drawing of the experimental setup: the GEM-TPC prototype is located between the scintillators and the MDT layers used in the trigger and the external tracker, respectively.

Data Acquisition (DAQ) used for the measurement of the GEM-TPC performances is shown in **Figure 7**.

In the following, unless otherwise stated, the beam is directed perpendicular to the drift axis of the GEM-TPC prototype and 4 cm far from the first GEM foil.

4.2.1. Efficiency

The single pad row detection efficiency has been evaluated considering the fraction of the hits in a single pad row with respect to a track selected by the external tracker.

An example of the single pad efficiency for the full detector and for each row is shown **Figure 8**. It is worth noticing that most of the pads have a detection efficiency larger than 98% except for the first 16 channels of the first row and some channels of the fourth row that are dead. A not full detection efficiency in the first and last pads of each row is clearly evident. The reason of this effect will be discussed more in detail in Section 4.2.3 and therefore the first and the last two pads of each row have been not considered in the following.

The detection efficiency, averaged on the 28 considered pads, as a function of the gain for 440 MeV/c proton and 170 MeV/c pion beams crossing the detector filled with Ar/i-C4 H10 (90/10) gas mixture and pure helium gas, is shown in **Figure 9**. As expected, due to the primary ionization of the particle in the gases used in the

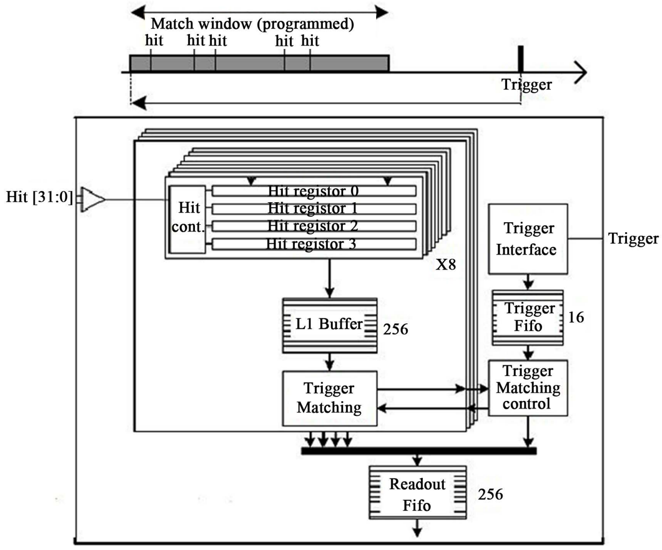

Figure 7. Sketch of the system used during the PSI beam test: hits storage occurred prior triggering, which has been properly delayed (top); the simplified Block Diagram of the Data Acquisition (DAQ) (bottom).

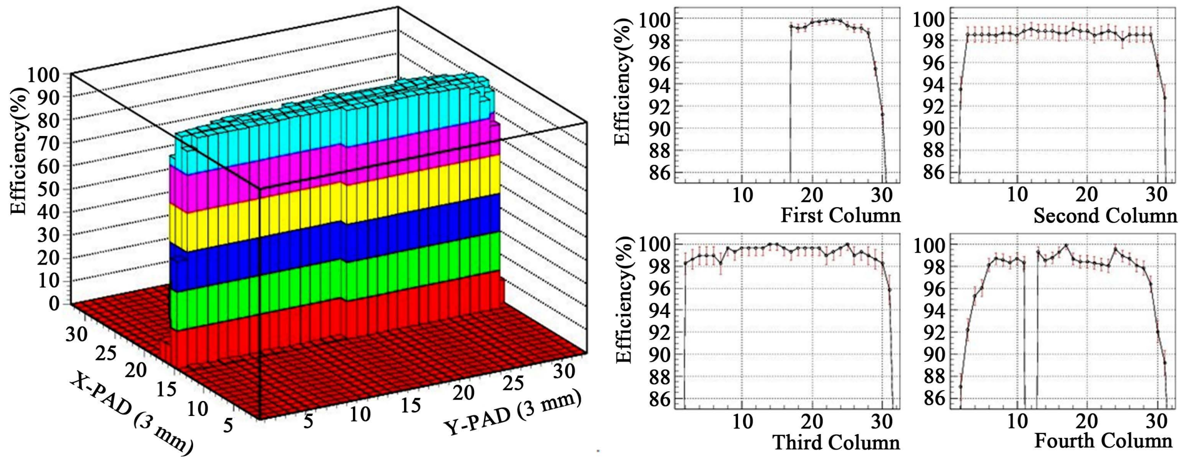

Figure 8. Single pad row efficiency for the full detector (left) and for each row (right) measured at the PSI beam facility. Each pad is ~3 × 3 mm^2.

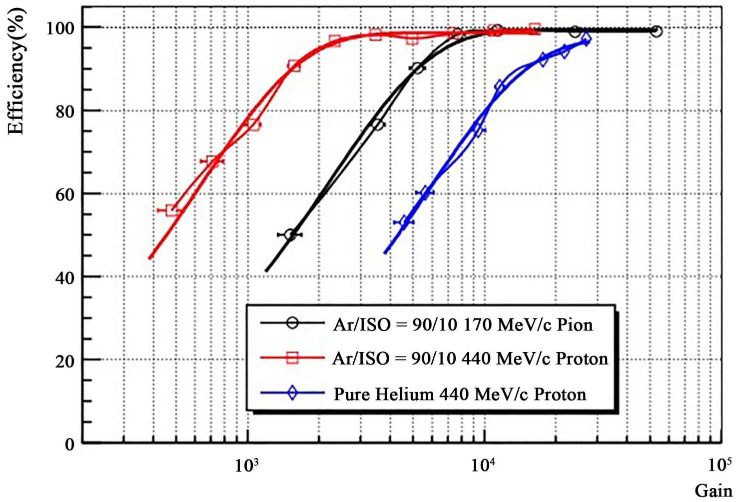

Figure 9. Detector efficiency as a function of the gain for 440 MeV/c proton and 170 MeV/c pion in Ar/i-C4 H10 gas mixture and pure helium measured at the PSI beam facility. The drift field is set to 0.4 kV/cm for all the measurements.

beam test, a full efficiency is reached with an isobutane-based gas mixture at lower gain, *i.e.* $\sim 3 \times 10^4$ for protons and $\sim 8 \times 10^4$ for pions, respectively, while for pure helium gas the maximum efficiency is ~97% before to reach the instability region. The points in **Figure 9** are fitted with a negative exponential function[1] in order to evaluate the gain at which the detector efficiency is 97%, 95% and 90%. These results have been plotted in **Figure 10** as function of the primary ionization (simulated by GARFIELD) for 440 MeV/c proton and 170 MeV/c in Ar/i-C4 H10 (90/10) gas mixture and 440 MeV/c proton in pure helium gas (see **Table 1**). A function $y = p0/x^{p1}$ has been used to fit the points of **Figure 10**[2] in order to estimate the gain, and accordingly the efficiency, for a 127 MeV/c kaon crossing the active target GEM-TPC filled with a pure helium or a pure hydrogen gases as foreseen in the AMADUES experiment. A suitable gain value of $\sim 8 \times 10^3$ or 4×10^3 for a helium or hydrogen gases (vertical dotted lines), respectively, will allow to reach a detection efficiency of ~95% and to operate the detector in stable condition.

4.2.2. Spatial Resolution

The spatial resolution has been evaluated by the residuals between the hit position in a single pad row (excluding it from the fit) and the track defined by the six MDT layers. The spatial resolution is then calculated as an average of the 28 considered pads:

$$\frac{1}{28}\sum_{i=1}^{28}\sqrt{\left(\sigma_{i-residual}^{2}-\sigma_{externaltracker}^{2}\right)}$$

Figure 11 shows that the behavior of the spatial resolution depends on the gain and the ionizing particle: the higher is the gain and the greater is the primary ionization produced by the particle crossing the detector, the higher is the spatial resolution. Moreover, the different level of the spatial resolution reached by the prototype at high gain can be explained by the different transverse diffusion of the tested gas, which are ~350 μm/cm and ~600 μm/cm at 0.4 kV/cm (provided by GARFIELD) for the Ar/i-C4 H10 gas mixture and the pure helium gas, respectively.

4.2.3. Edge Effect Due to the Field Cage

Low and/or not full detection efficiency has been measured on the edge of each pad rows as clearly visible in **Figure 8**. Such effects are due to different reasons:

• the length of each pad row is 102 mm while the effective diameter of the cylindrical field-cage is ~100 mm.

[1]Eff = 1 – e – G , where Eff and G are the detector efficiency and gain, respectively.

[2]G = ntot /nt , where ntot and nt are the number of secondary electrons inducing a signal on the readout and the number of primary electrons produced by a ionizing particle, respectively.

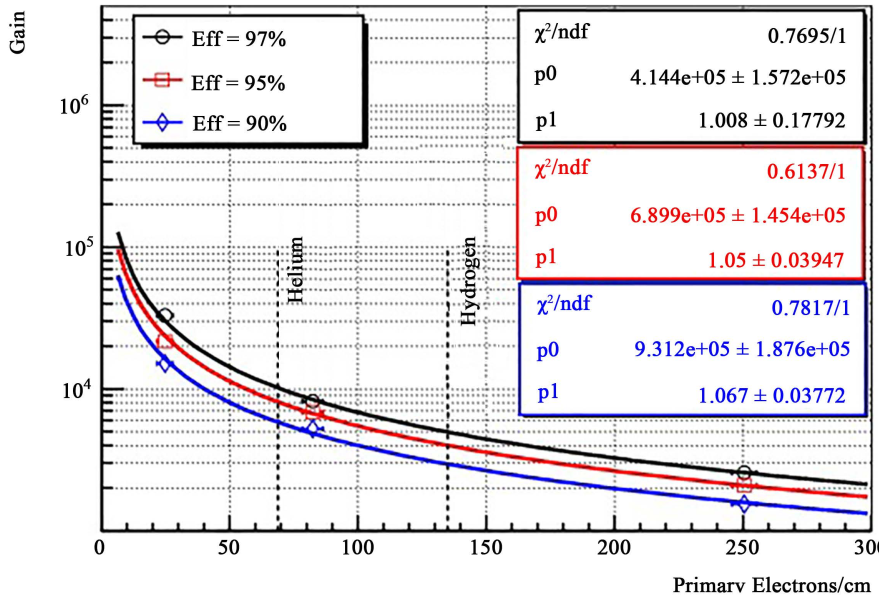

Figure 10. Gain (estimation from the previous fit) as a function of the primary electrons (simulated) for different value of the accepted detector efficiency measured at the PSI beam facility (97% black line; 95% red; 90% blue).

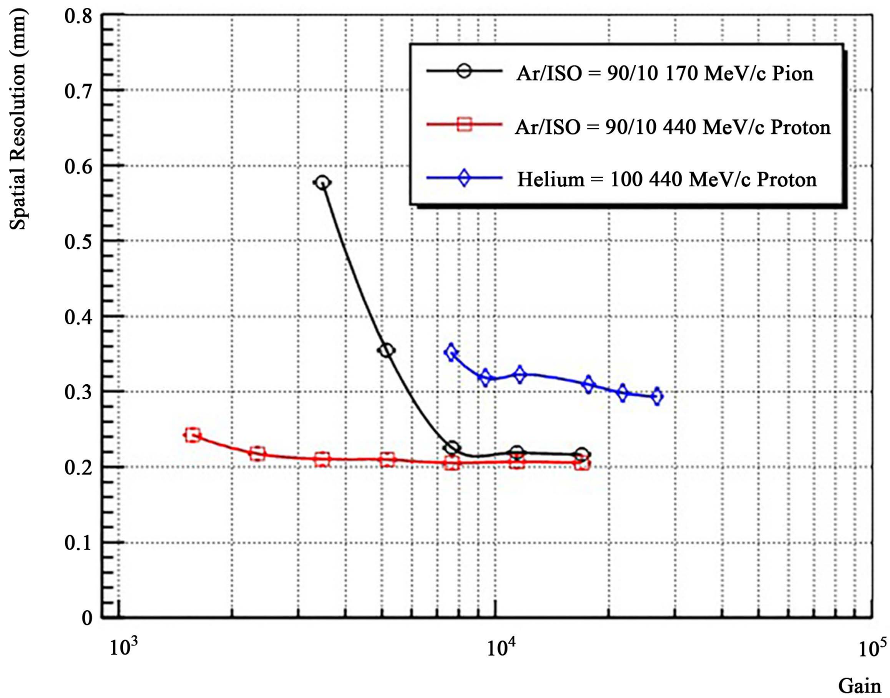

Figure 11. Spatial resolution as a function of the gas gain for proton of 440 MeV/c and pion of 170 MeV/c in Ar/i-C4 H10 gas mixture and pure helium measured at the PSI beam facility. The drift field is set to 0.4 kV/cm for all the measurements.

This means that the first and the last pad of each row collects about 2/3 of the charge with respect to the other pads of the row;

• electric distortion of the field in the drift gap mainly near the field-cage are notcompletely cured;

• the primary electrons produced in the drift gas and drifting toward the first GEM can be collected by the internal strips of the field-cage (**Figure 12**). In any case all these effects are fully reduced drifting away from the field-cage by ~5 mm.

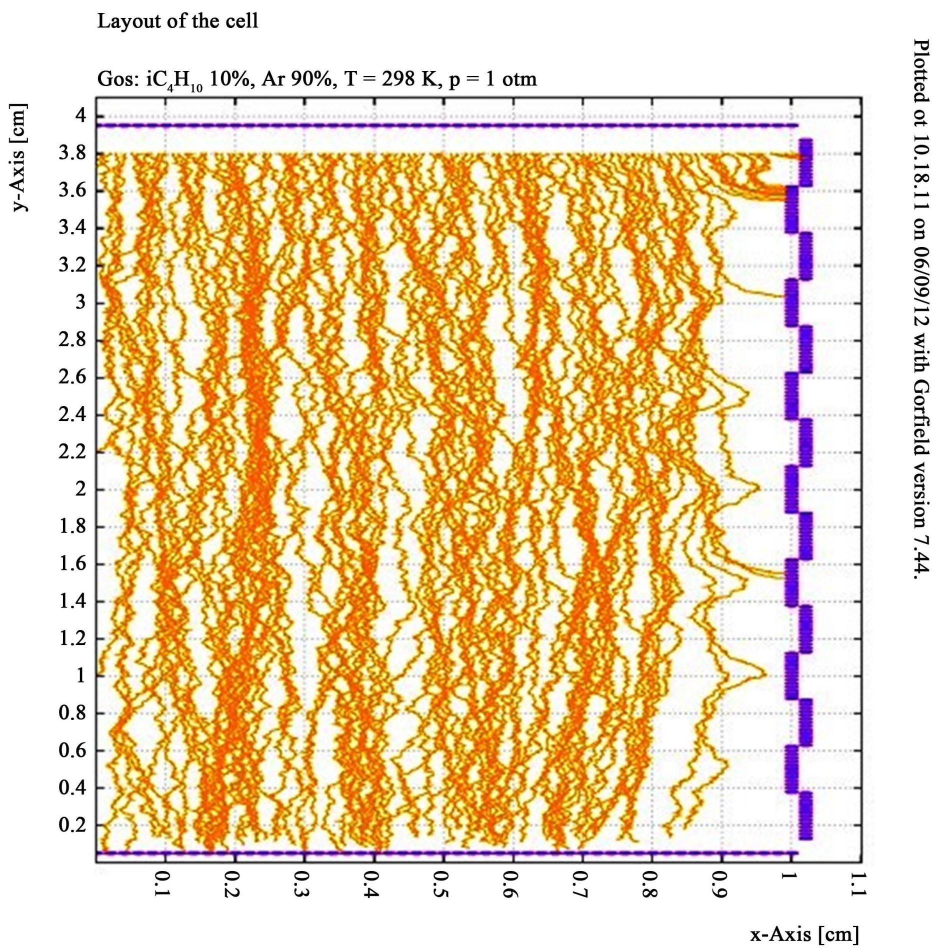

Figure 12. Garfield simulation of primary electrons motion in the drift gap.

5. Conclusions

The R & D activity on a new active target GEM-based TPC for the inner region of the AMADEUS setup has started at the Laboratori Nazionali di Frascati (INFN).

A GEM-TPC prototype with a drift gap of 15 cm has been successfully built and tested at the πM1 beam facility of the Paul Scherrer Institute with low momentum pion and proton beams.

The measurement of the detector performances, in terms of detection efficiency and spatial resolution, as a function of the gain and ionizing particle has been reported for an isobutane-based gas mixture and a pure helium gas. The detector performances have shown a detection efficiency of 99% and a spatial resolution of ~200 µm for Ar/i-C4 H10 = 90/10 gas mixture, while for a pure helium gas the detector performances have reached a 97% of efficiency and a ~250 µm of spatial resolution.

The achieved results could open the possibility to use such GEM-TPC filled with pure light gas as a low mass target and tracker detector at the same time in the AMADEUS environment.

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