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An innovative Micro Strip Gas Detector for low energy cosmic rays detection

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The development of new instruments for low-energy atoms is becoming of considerable interest in various research fields, such as the direct detection of dark matter, micro-dosimetry, the study of the atmospheres of the Solar System bodies, as well as in the direct measurement of low-energy cosmic rays. In the last few years, our working group, at INFN Pisa Laboratory, has been involved in the development of a gas detector based on a Micromegas device working in a low-pressure regime. Within the micro pattern gas detector family, the intrinsic characteristics of the Micromegas device represent the most promising features for constructing a new detector to be operated as an imaging device gas chamber. The main goal of the experimental activity was the development of an electrode configuration optimizing the instrument performance for atoms in the energy range of 1-100 keV, with good energy and angular resolution in a single compact instrument. The dependence of the gain, the energy resolution from the amplification field, gas pressure, and drift field have been deeply investigated, both with x-rays sources and ionized helium beams. Here a summary of a measurements campaign devoted to a technical characterization of a Micromegas bulk filled with a gas mixture maintained at low pressure is presented.

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1. Introduction

Our project concerns the design of a gas detector that measures the energy of ionizing radiation, identifies its direction, and can distinguish different atomic species based on a three-dimensional reconstruction of the track itself. The class of Micro Pattern Gas Detectors (MPGD) seems to be the most promising among the family of gas detectors commonly used in high-energy physics (HEP). Using these instruments, it is possible to measure the energy released by the ionizing particle in the active volume and simultaneously reconstruct its position in two dimensions using front-end electronics connected to anodic strips. In addition, a three-dimensional reconstruction of the event is possible by measuring the arrival time of the electric charges as in a micro time projection chamber. For our purposes, the low-pressure operation of the detector is a key feature. In fact, the low-energy atoms travel a few tenths of a micron in a gas mixture maintained at normal temperature pressure (NTP), while lowering the gas pressure increases the mean free path of the particle itself, allowing a much better reconstruction of the event.

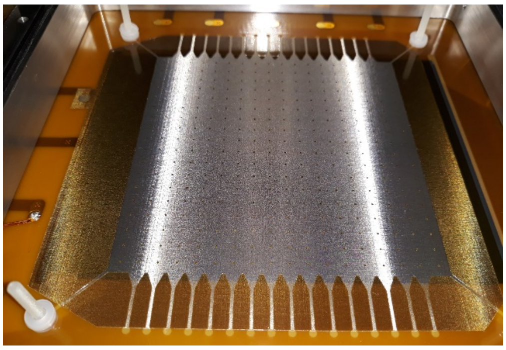

Figure 1: the bulk 128 μm MM detector initially employed for the R&D detector.

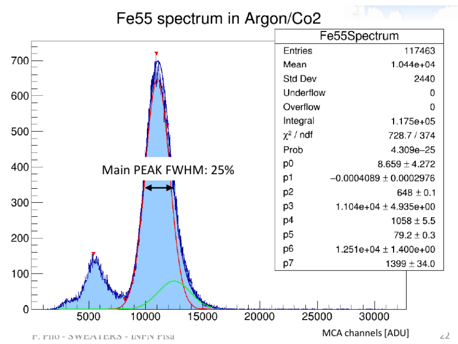

Figure 2: ^{55}Fe X-rays spectrum in Ar:CO2 93:7 gas mixture using the detector mesh electrode output for the energy measurements.

2. Starting from a standard Bulk Micromegas

Within the MPGD family, Micromegas (MicroMEsh GAseous Structure, shortened to MM), used in the most advanced LHC experiments[1], have intrinsic properties allowing operation with low-pressure gas mixtures. A standard kit from the CERN RD51 collaboration has been used in the first phase of our studies. The kit consists of 128 μm avalanche gap "bulk" Micromegas with an active area of 10x10 cm^2, equipped with a 250 μm pitch XY stripe plane for reading the signal below the anode, hereafter referred to as MMBulk128umXY (see figure 1). The "bulk" technology[2] guarantees an excellent uniformity of amplification over the whole surface of the detector as well as a very high robustness against mechanical stress. In addition, the anodic plane has been realized with a diamond-like carbon (DLC) deposition to increase the instrument's high-rate detection capability. The MMBulk128umXY has been characterized using ^{55}Fe X-rays (widely used as a standard active source for MPGD characterizing performances) at atmospheric pressure. The detector response has been studied for different values of electric fields (drift and avalanche), gas pressure, and gas mixture composition, measuring the most relevant parameters such as: gain as a function of the electric field in the avalanche volume; primary charge collection efficiency as a function of drift volume electric field; the energy resolution. The best particle energy measurement performance is obtained by collecting the signal at the central electrode (called "mesh") with a dedicated charge preamplifier (see figure 2). Since the Micromegas is produced as a sort of standard kit for particle detection, our measurements, collected under NTP conditions, have been validated with many works on the same topic available in the literature. In addition, our experience, shared with many colleagues in the MPGD R&D community, could represent the reference feature set for all other experimental measurement campaigns.

3. Low-Pressure characterization

After validation of the detector at the NTP, it was equipped with a first version of a low-pressure mechanical frame and an ad hoc gas distribution system for the continuous flow of an ultra-pure gas mixture to the active volume. The mechanical frame has been designed to ensure very low leakage rates, reducing atmospheric oxygen and moisture contamination to less than 0.1‰ at low pressures. Its design is such that the MM kit prepared at the CERN laboratory can be easily installed without modification of the printed circuit board (PCB) layout. The MM units tested have a square cross-section and only a small number of screws are used to secure the frame. This makes it difficult to keep the gas volume tight.

Several features have been implemented to improve the sealing of the Micromegas. A reinforcing

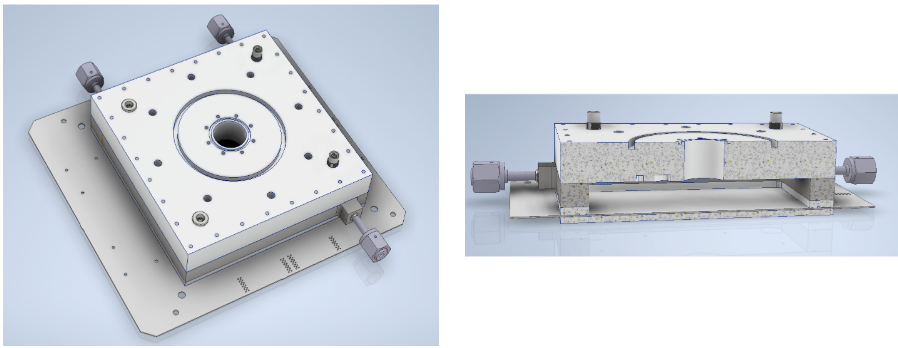

Figure 3: MMBulk192umXY mechanical support frame with X-ray source and Ion beam interface. In the right picture a section of the assembly where the two frames are clearly visible.

plate has been bonded to the back of the PCB. The side frame consists of two parts. The lower part is a thin aluminum frame that is bonded to the top layer of the PCB. This improves the flatness of the surface and then the sealing between the Micromegas and the side frame itself. The upper part is made of stainless steel with welded tubes and connectors for gas distribution. An indium wire gasket has been inserted between the two components of the side frame and between the side frame and the top cover. This is a well-known technique used in the ultra-high vacuum environment. Our tests have shown that the indium wire seal is much better than the polymer O-ring seal. Swagelok VCR valves were installed on the gas inlet and gas outlet to completely isolate the detector from the gas system and evaluate its performance under static conditions.

Figure 3 shows the 3D drawings of the new MM bulk frame. The top cover serves as the interface between the detector and the X-ray source collimator and the ion beam vacuum tubes. The leak rate of the fully assembled detector is estimated to be less than $0.9 \cdot 10^{-5}$ mbar l/s. A gas flow of only 40 cc/min allows to keep the oxygen contamination below the 0.01% level, which is considered the reference level [3] for best performance. Our reference gas mixture is Ar-CO2 with the composition rate of 93%:7%, widely used in the Mmm detectors for the LHC experiments.

The only way to achieve high detector performance is to continuously monitor all relevant parameters which affect the performance of the detector. The most important of these are the gas pressure and temperature in the gas cell, the high voltage channel currents, the mesh current, and the detection rate.

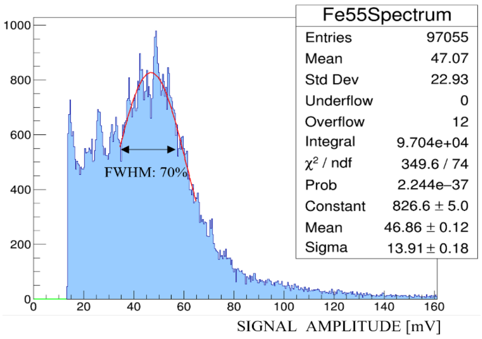

Figure 4: MMBulk128umXY characterization at 100 mbar with ^{55}Fe X-rays (drift volume height of 5 mm). An energy resolution (FWHM) of 70% has been measured using a gaussian fit of the main peak.

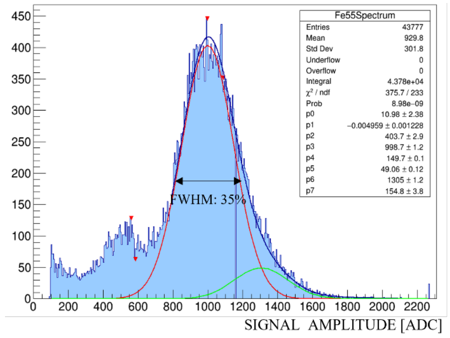

Figure 5: MMBulk192umXY characterization at 100 mbar with ^{55}Fe X-rays (drift volume height of 20 mm). The 3 keV Argon escape peak is clearly visible; the energy resolution is around 35% (FWHM), half of the resolution obtained with the MMBulk128umXY.

For all these reasons, a slow monitor system has been designed and developed. This system is highly flexible, collecting data from many sensors and DAQ systems, storing them in a dedicated database connected to web dashboards, allowing the user to interrogate, visualize and receive alerts from the system. Remote control of many subsystems allows the user to precisely adjust the working condition, test different working conditions, or reproduce a particular setup to evaluate, for example, the long-term stability of the detector.

By implementing all the tools described above, it has been possible to perform a precise characterization of the MMBulk128umXY. This measurement campaign demonstrated the feasibility of a particle detector operating at low pressure. However, the measured performance at 100 mbar did not meet our requirements for gain, energy resolution (see figure 4), and long-term stability.

4. Enhanced performance with increased avalanche gap

Both simulation and experimental data suggest that a larger avalanche gap results in higher amplification factors, increasing the working interval in terms of the avalanche electric field before reaching discharge conditions.

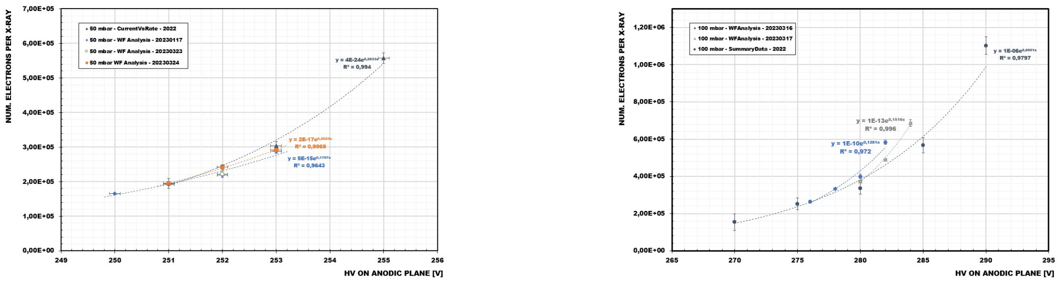

Figure 6: Number of electrons per ^{5}5Fe X-ray at 50 mbar (left) and 100 mbar (right). The MMBulk192umXY performance are unchanged after about one-year operational time.

The current limits of bulk technology allow an MM avalanche gap of up to 192 µm. A standard CERN bulk Micromegas with a 192 μm avalanche gap and a 400 μm pitch XY strip readout plane (designated MMBulk192umXY) has been fully characterized with X-rays up to 30 mbar. Compared to the 128 µm avalanche gap model, the performance at 100 mbar is significantly improved, while for the first time operation at 50 mbar and below has been demonstrated (see figures 4 and 5 for a comparison of the ^{55}Fe spectrum). The MMBulk192umXY detector has been tested for more than a year, with only a few interruptions due to setup adjustments, frame upgrades, installation of the ion beam interface, etc. The performance of the instrument has remained essentially unchanged (see figure 6), demonstrating the great robustness of the instrument and the efficiency of the support system in reducing any external contamination.

5. Results from the ionized atoms test beams

The atom detection capability of the MM detector has been verified using ion sources with energy up to 5 KeV and at a rate up to 400 - 500 Hz. A special test beam has been set up: the detector is directly connected to the ion beam vacuum tube, without an entrance window, and the atoms enter the drift volume through a small diameter (5-10 μm) pinhole glued in the center of the cathode plane. This solution allows maintaining the correct pressure difference between the MM gas cell (where the pressure is kept in the 50-150 mbar range) and the beam pipe (where a vacuum better than 10^{-5} mbar is required to keep the energy spectrum of the accelerated ions unchanged).
Preliminary analysis of the experimental data confirms good energy linearity down to 1.5 keV. The energy resolution is in agreement with our estimates. Figure 6 shows the ion energy distribution measured by the MMBulk192umXY (using the mesh readout chain) for a beam in the energy range of 2.5 to 5 keV. Since the initial ion beam energy distribution has a width of tens of eV, the final measured FWHM (compatible with our simulations) is mainly due to electron production fluctuations in the avalanche process inside the MM. The energy released by a particle in a medium is the result of three interrelated processes: ionization, scintillation, and heat, essentially due to the motion of nuclei and electrons. According to the literature [4], low-energy atoms in gas lose a significant fraction of their kinetic energy in non-ionizing processes: this fraction is not visible in MM and can cause a non-linear response of our detector. Therefore, a very accurate estimation of the absolute energy scale is required, using X-ray sources as reference calibration. In addition,

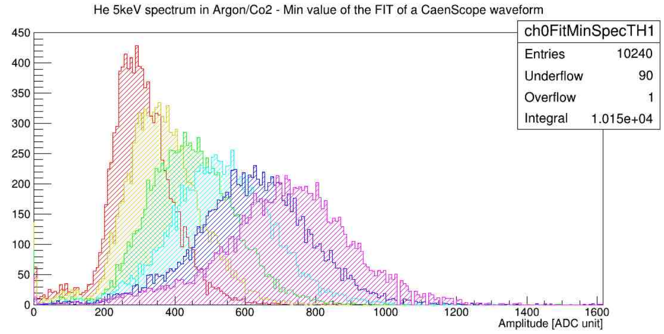

Figure 7: He spectra in MMBulk129umXY at 100 mbar. Beam energies: 2.5 (red coloured distribution), 3, 3.5, 4, 4.5, 5 KeV (magenta).

detector tracking capabilities can be tested using ion sources. Beam test setups are equipped with high-precision positioning systems to move and rotate the detector under test to simulate tilted particle entry into the gas cell. Detailed data analysis and studies on energy resolution linearity and absolute energy scale are ongoing.

6. Detector simulation

Packages commonly used in high energy physics and developed at CERN have been used: Garfield for microscopic tracking in an electric field and Geant for geometrical description and interaction of particles with materials. Geant can track particles down to energies of the order of 1 MeV, while our project requires the use and detection of particles down to ∼1 keV. Therefore we used the additional packages Degrad and SRIM. The simulation is divided into two parts corresponding to the two parts of the detector: the drift region and the avalanche region. The first part describes the primary gas ionization and the electron drift. It can simulate X-ray interactions with Degrad and ion interactions with SRIM and Garfield. The simulation of the first part allows to estimate the total primary ionization charge, the ion track length, the drift velocity, and the lateral and longitudinal electron diffusion.

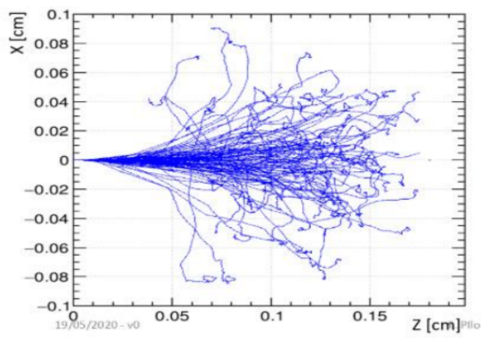

Figure 8: Event display of a 100keV ionised Helium in pure Argon at NTP.

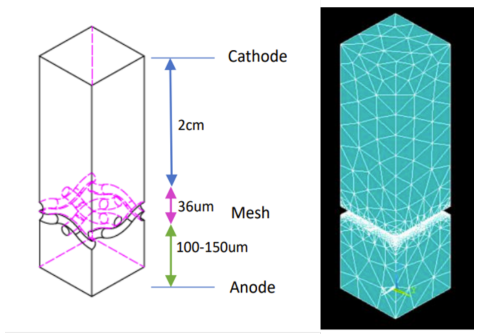

Figure 9: Ansys mesh model used for very accurate electric fields estimation near the mesh.

The figure 8 shows simulated ion tracks in the drift region. The interacting particles are 100 keV helium in pure argon at NTP, entering at x=0, z=0, with the direction parallel to the z-axis. The second part describes the electron avalanches in the amplification volume and the charge collection on the readout electrodes. The detailed electric field simulation requires the ANSYS package (in figure 9 the finite element analysis describing the MM mesh volume). The simulation of the second part allows the calculation of the detector charge amplification, the mesh transparency, and the amount of charge collected by the tracking electrodes below the anodic plane. The first attempts to reproduce the experimental measurements failed. The mesh transparency for electrons crossing from the drift to the avalanche region at low pressure was underestimated by the simulation. This resulted in an underestimation of the number of electrons entering the avalanche volume, and then the number of electrons produced for each avalanche was much lower than the values obtained from experimental tests. The avalanche size did not have the correct dependence on the electric field strength. An effective solution was to apply a major modification directly to the Garfield

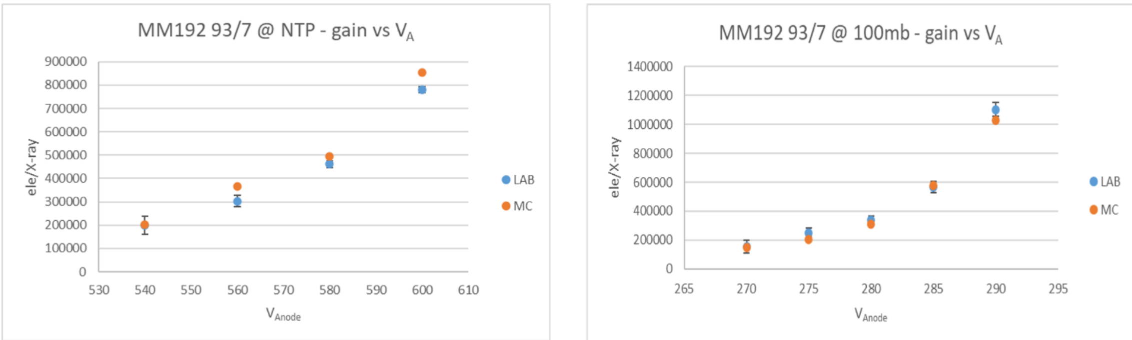

Figure 10: MMBulk192umXY number of electrons generated by an ^{55}Fe X-ray interaction in Ar:CO2 (7%): experimental data and EDSIM estimates shown very good agreement both for NTP (left plot) and 100 mbar/20°C (right) operating conditions.

code, which had been well-tested at NTP but was still unable to model the physical process at low pressure. The figure 10 shows a comparison between the simulated number of electrons produced for a ^{55}Fe X-ray and the experimental measurements at gas pressures of 100 and 1000 mbar. Both data are well fitted by an exponential. The discrepancy between the two data sets is within ± 5 % for all avalanche electric field values.

7. Current status and future perspectives

According to our experimental data and simulation, the MM technology has the potential to increase its performance at low gas pressure by changing the height of the avalanche gap. It is possible to exceed the 192 µm gap limit by abandoning bulk technology and suspending the mesh over support frames of precisely calibrated thickness. This requires a design solution that ensures a uniform height of the avalanche gap over the entire active area of the detector. This parameter is directly related to the uniformity of the electric field in the avalanche region, which in turn provides uniform charge amplification factors and detector response.
A new gas cell has been designed in collaboration with CERN engineers and two samples have been produced at CERN. Based on the design of our reference mechanical support frame, some

modifications were introduced to maintain or improve the flatness of the MM PCB. A first planarity check on one of the freestanding grids confirmed planarity at the 30 μm level in the central area (40 x 40 mm^2) of the detector. The many configurations of the new instrument will allow the detector's performance to be further enhanced. The test campaign is currently underway.

Acknowledgments

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