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PICOSEC-Micromegas: Robustness measurements and study of different photocathode materials

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Abstract. Detectors with a time resolution of 20-30 ps and a reliable performance in high particles flux environments are necessary for an accurate vertex separation in future HEP experiments. The PICOSEC-Micromegas detector concept is a Micro-Pattern Gaseous Detector (MPGD) based solution addressing this particular challenge. The PICOSEC-Micromegas concept is based on a Micromegas detector coupled to a Cherenkov radiator and a photocathode. In this detector concept, all primary electrons are initiated in the photocathode and the time jitter fluctuations are reduced. Different resistive anode layers have been tested with the goal of preserving a stable detector operation in a high intensity pion beam. One important characteristic of a gaseous detector in a high flux environment is the ion backflow (IBF). That can cause damage to more fragile photocathode materials like CsI. Various types of photocathode materials have been tested in order to find a robust solution against IBF bombardment.

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1. Introduction

Tracking detectors with improved spatial resolution and timing performance are one solution to mitigate the pile-up effects that will occur in the future high luminosity colliders [1]. These future vertex detectors, located near the interaction point, have to withstand high particle fluxes and large irradiation doses for several years, while maintaining the initial performance. The PICOSEC-Micromegas is one possible concept to satisfy this task.

The PICOSEC-Micromegas detection concept aims at developing a Micromegas-based detector [3] with superior timing precision and robustness under a strong flux of ionising particles. The results obtained with the first prototype yielded a time resolution of 24 ps for Minimum Ionization Particles (MIP) of 150 GeV muons [2].

In this work, we report a progress in the detector design with a focus on the photocathode material. With this development we aim for a detector able to sustain high fluxes of ionising particles (such as pions) and retain its performance, initially limited by the ion back-flow (IBF) produced in the detector, throughout its operational lifetime. In Sec. 2, we describe the first prototype and the different developments in Micromegas readout and photocathode composition, followed by observations and IBF measurements in Sec. 3. The results for different alternative photocathode materials are presented in Sec. 4.

2. Detector description

The first prototype of the PICOSEC-Micromegas detection concept (figure 1) is a 1 cm-diameter detector composed of a 128 µm thick-gap bulk Micromegas, four 50 µm thick kapton rings to define the drift gap, a 3 mm-thick crystal (MgF_2) that works as Cherenkov radiator and a photocathode composed of a 5.5 nm-thick Chromium layer and a 18 nm-thick CsI film. Cherenkov photons are generated by relativistic charged particles passing through the crystal and simultaneously converted into electrons at the photocathode. These primary electrons are preamplified in the drift gap, partially traverse the Micromegas mesh, and are finally amplified in an avalanche in the Micromegas amplification gap. This first prototype was tested in laser and particle beam tests, and the main results were reported in [2]. A time resolution of 76 ps was measured for single photoelectrons, and 24 ps for 150 GeV muons with a mean number of 10.4 photoelectrons produced per muon. These results were obtained with a CsI photocathode.

However, a resistive detector design is necessary to operate the PICOSEC-Micromegas in a high flux environment with high electric fields. Two different resistive Micromegas designs have been successfully tested with the PICOSEC-Micromegas detection principle. One uses a resistive layer of different materials on top of the anode [4]. The actual resistivity is determined by the chosen material and its thickness. The second one uses a conductive copper layer that is coupled to ground by a resistor. This method is also known as the "floating strip" resistive Micromegas [5].

3. High Flux Beam Measurements

The resistive prototypes were tested using a high rate pion beam ($\approx 2{\cdot}10^6\,\frac{\text{pions}}{\text{spill}\cdot\text{cm}^2}$). Two different resistive layers with a resistivity of $10.4\,\mathrm{M\Omega/mm^2}$ and $37\,\mathrm{k\Omega/mm^2}$, as well as a "floating strip" anode with a $25\,\mathrm{M\Omega}$ coupling have been tested. All of them could operate under stable conditions for several hours to days, while taking data. After the long-term irradiation with pions, the detector was disassembled and the photocathode had to be replaced. The old photocathode was removed, and its degeneration was investigated under a microscope.

With the resistive layer, the electrons are attenuated to keep the current on the anode low. With each electron, a heavy positive ion cloud is formed in the gaseous volume. These heavy ions are accelerated by the electric field towards the photocathode. During the pion irradiation, a high ion flux is arriving at the photocathode. This heavy ion flux is called IBF [6]. The IBF is causing a degeneration of the photocathode. This can be seen for a CsI photocathode

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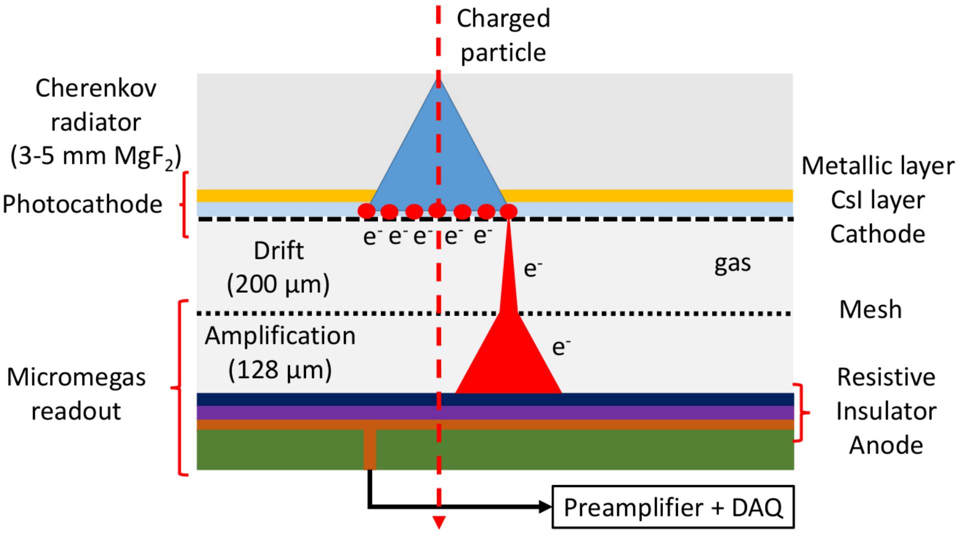

Figure 1. Sketch of the PICOSEC-Micromegas detector configuration tested with particle beams. The traversing of a charged particle through the Cherenkov radiator produces UV photons, which are then absorbed at the photocathode and partially converted to photoelectrons. Photoelectrons are subsequently preamplified and amplified in the drift and amplification gaps, and induce a signal which is measured between the anode and the mesh. The photocathode is composed of a metallic layer (either Chromium or Aluminium) to polarize the crystal and a CsI layer or other photocathode materials. These two amplification stages are filled with a gas mixture (80%Ne+10%C_2H_6+10%CF_4) at atmospheric pressure. The Micromegas readout could be "bulk" or "resistive", with two extra resistive and insulator layers over the anode in one of the configurations. The sketch is not drawn to scale.

in the microscope photograph in figure 2. A few specific patterns are visible in the picture. A negative image projection of the mesh and the location of the support pillars can be seen. Most ions are produced in avalanches inside the amplification region. Thus, the ions produced in the amplification region can only pass through the holes of the mesh to the photocathode. Those reaching the mesh itself are absorbed by it and are causing a current in the mesh. The ones not absorbed by the mesh are drifting up to the cathode and create a current in it. Those ions are irradiating the CsI and causing the pattern showing the grid of the mesh.

Another typical degeneration is the small white crack (labelled "spark" in figure 2). These small cracks appear when a spark is generated in the detector. A spark is produced when the field is too strong and plenty of electrons are produced at once, thus causing a strong current to flow between the cathode and the anode. The spark causes a discharge that is then followed by a voltage drop between the anode and the cathode. A voltage drop implies a gain drop and the detector is not efficient until the field has recovered from the spark. The time the detector needs to recover depends on the RC value of the detector stage. If too many subsequent sparks appear, the voltage supply fails due to the large current flow, and the detector cannot operate in stable condition. If the voltage supply does not fail, those sparks may create an even worse damage to the photocathode or to the mesh.

The microscope image of the imprint of the mesh shows that the IBF plays a serious role in the deterioration of (resistive) PICOSEC-Micromegas detectors in a high-flux environment. To investigate this issue, the currents at the anode and at the cathode are measured for different field settings during the data-taking. The ratio of the anode and cathode currents determines the IBF rate [6]. The measured values are shown in table 1 for different configurations.

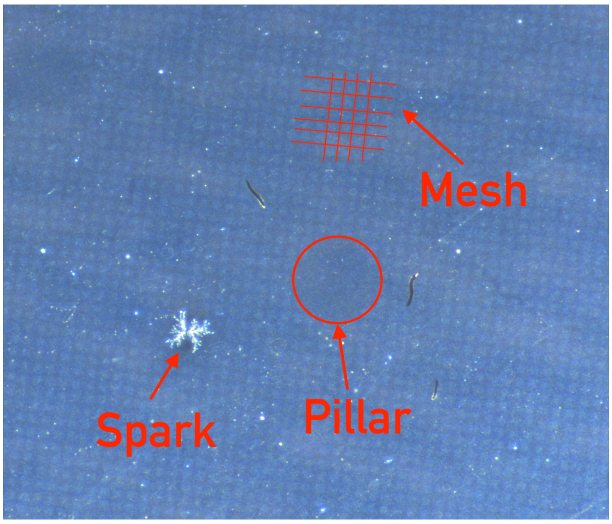

Figure 2. Photocathode degenerated by IBF after exposure to a high-intensity pion beam. A few effects of the exposure are shown in the photocathode (see text).

Table 1. Anode and cathode voltage settings are shown together with the measurements of the corresponding currents and the IBF in a high flux pion beam. The IBF of 63 % has been reached in unstable conditions at high electric fields.

U_{anode} (V)	U_{cathode} (V)	I_{anode} (nA)	I_{cathode} (nA)	IBF (%)
+450	-350	98.00	23.40	24
+450	-375	193.85	53.00	28
+450	-325	45.47	10.65	23
+425	-400	193.50	53.10	28
+425	-375	87.30	23.95	27
+425	-350	44.48	10.99	25
+400	-425	178.84	112.39	<u>63</u>
+400	-400	88.55	25.54	28
+400	-375	41.28	11.10	27
+400	-350	20.42	4.44	22

At stable conditions and various field settings, the IBF varies between 20 % and 30 %. When the electric field is stronger, the detector is operating in unstable conditions. At these fields, several sparks appear and the current in the voltage supply drops as it is not able to supply enough current to operate the detector. In unstable conditions, the current flows through the cathode and the IBF ratio is much larger (it reaches 63 % in table 1). This effect causes a deterioration of the photocathode that was observed.

There are several options to operate PICOSEC-Micromegas detectors in stable conditions at a higher particle flux. One is to reduce the electric field, however this results in a lower gain and worse time resolution. Another option is to use a resistive coating, not only on the anode but also on the mesh. These types of meshes are being developed and will be tested in future prototypes. An important aspect of future applications in high flux environments is the material of the photocathode. A more robust solution will be investigated in order to operate the detectors in stable conditions.

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4. Comparison of Different Photocathodes

The results of the PICOSEC-Micromegas detector equipped with different photocathodes are shown in table 2. Photocathodes based on CsI show a larger number of photoelectrons ($N_{p.e.}$) and a better time resolution when compared to other types. The higher number of photoelectrons are directly contributing to a better time resolution as

$$\sigma \propto \frac{1}{\sqrt{N_{p.e.}}}$$

where σ is the time resolution and $N_{p.e.}$ is the number of photoelectrons.

Different combinations of CsI thickness and metallic coatings were tested (No. 1-6, in table 1), showing values between 8 and 10 photoelectrons. No optimal metallic coating was found but CsI thicknesses between 10 and 20 µm (No. 1-3, in table 1) show better performances than a photocathode with thicker layers. We attribute the different number of photoelectrons for the same CsI thickness to the variable exposure time of each photocathode to air during its installation in the detector, which ranged between 2 and 5 minutes. For the other photocathode types, the 5 mm-thick MgF_2 crystal with a 10 nm-thick Aluminium layer (No. 12, in table 1), and the CsI-based photocathode with a MgF_2 protection layer (No. 8) have a number of photoelectrons of 2-3 and a time resolution around 50 ps, which makes them interesting for long-term applications.

Table 2. The thickness of the MgF_2 crystal and the type of photocathode, the mean number of photoelectrons ($N_{p.e.}$), the best time resolution achieved and the optimum operation point (anode and drift voltages) of the PICOSEC-Micromegas detectors measured in beam tests (except for photocathode with (*), where higher drift voltages have not been scanned). All samples have been tested in a "bulk" mesh Micromegas with a non resistive readout plane.

No.	MgF_2 (mm)	Photocathode	$N_{p.e.}$	Time Res. (ps)	Anode/Drift (V/V)
1	3	5.5 nm Cr + 18 nm CsI	10.4 ± 0.4	24.0 ± 0.3	+275/-475
2			9.0 ± 0.1	26.5 ± 0.3	+225/-525
3			9.9 ± 0.4	27.5 ± 0.3	+300/-450
4	3	5.5 nm Cr + 36 nm CsI (*)	6.43 ± 0.11	56.4 ± 0.7	+425/-350
5	3	3 nm Cr + 18 nm CsI (*)	8.41 ± 0.24	49.9 ± 0.5	+450/-350
6	3	6.5 nm Al + 18 nm CsI (*)	8.40 ± 0.24	47.7 ± 0.9	+450/-325
7	3	Cr + CsI + LiF	<1.0	87.7 ± 3.7	+250/-625
8	3	Cr + CsI + MgF_2	3.55 ± 0.08	45.6 ± 1.5	+250/-550
9	3	20 nm Cr (*)	0.66 ± 0.13	189.4 ± 5.3	+425/-425
10	3	6 nm Al	1.69 ± 0.02	71.4 ± 1.8	+275/-525
11	5	10 nm Cr (*)	2.15 ± 0.05	94.5 ± 0.9	+440/-360
12	5	10 nm Al	2.20 ± 0.05	57.0 ± 0.6	+325/-500

Furthermore, a scan over a wide range of operation points is shown in figure 3 for a metallic photocathode (No. 12, in table 1). The optimal operation point is at a drift voltage of 500 V, slightly higher than a CsI-based photocathode, because higher pre-amplification gains can be reached.

5. Conclusions

Different resistive PICOSEC-Micromegas have been operated in a high-flux pion beam. The electric fields have to be as high as possible to operate a PICOSEC-Micromeags with an optimal

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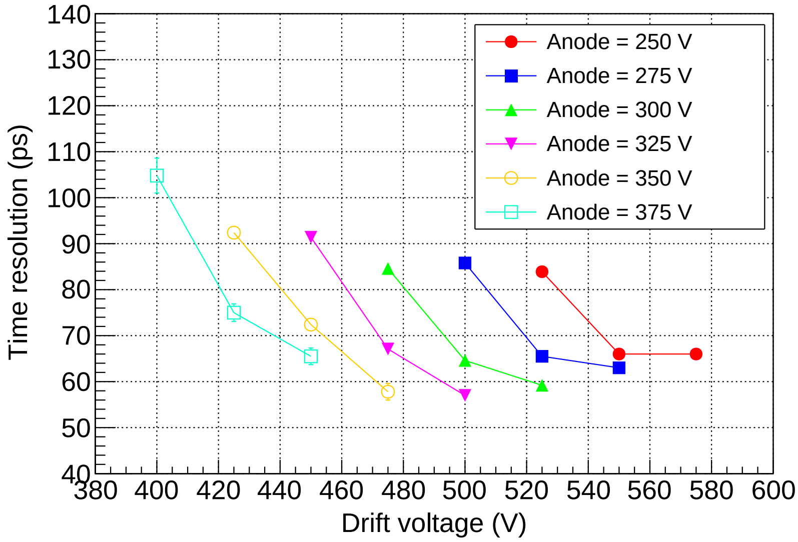

Figure 3. Dependence of the time resolution on the drift and anode voltages for a PICOSEC-Micromegas detector equipped with a bulk Micromegas readout coupled to a 5 mm MgF_2 crystal and a 10 nm-thick aluminum layer (No. 12, in table 1) irradiated by 150 GeV muons. For each curve at a given anode voltage, the maximum drift voltage corresponds to the maximum gain at which the detector can work in stable conditions. Statistical uncertainties are shown.

timing performance. Operating the detector in a high rate environment can cause severe damage to less robust photocathode materials like CsI. Alternative materials have been tested and further studies are needed to achieve a timing performance comparable to that measured with CsI samples. The most promising results were obtained using photocathodes coated with 10 nm Al and with MgF_2 protected CsI. These showed a time resolution of the order of $\approx$ 50 ps.

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