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ABSTRACT: Resistive-anode micromegas detectors have been in development for several years, in an effort to solve the problem of sparks when working at high flux and high ionizing radiation like in the HL-LHC (up to ten times the luminosity of the LHC). They have been chosen as one of the technologies that will be used in the ATLAS New Small Wheel project (forward muon system). An ageing study is mandatory to assess their capabilities to handle the HL-LHC environment on a long-term period. A prototype has been exposed to several types of irradiation (X-rays, cold neutrons, $^{60}$Co gammas and alphas) above the equivalent charge produced in the detector in five HL-LHC running years without showing any degradation of the performance in terms of gain and energy resolution, and with the characterization of the tracking performance in terms of efficiency and spatial resolution, verifying non degradation on the exposed resistive micromegas.

KEYWORDS: Performance of High Energy Physics Detectors; Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Large detector systems for particle and astroparticle physics; Particle tracking detectors (Gaseous detectors)

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1 Introduction

High amplification gains are required in Micro-Pattern Gaseous Detectors (MPGD) in order to achieve a comfortable signal to noise ratio, therefore improving the performance of detectors in terms of spatial resolution and efficiency. The gain applied allows to observe signals from gas ionizing interactions which produce primary electrons in the detector conversion region. The dense electron avalanches achieved at high gains entail the risk of producing a discharge at the cathode of the detector when the critical electron density of $\sim 10^7 - 10^8$ electrons per avalanche is reached (related to the Raether limit [1]).

Discharges might affect the detector response in different ways;

- *reducing its operating lifetime* due to intense currents produced in short periods of time, heating and melting the materials at the affected regions,
- *damaging the readout electronics* which have to support huge current loads,
- *increasing the detector dead-time* resulting from a discharge of the cathode.\(^1\)

It was first observed in RPC-type detectors that the introduction of a high impedance resistive coating at the anode limits the detector current, constraining the spark process to the streamer phase during a time interval of at least some microseconds.\(^2\) Thus it reduces the total amount of charge released [2]. Furthermore, the limited discharge current affects the field locally, thus reducing the dead-time of the detector which remains operative in non-affected regions.

\(^1\)In this case, the amplification field is lost during a relatively long period of time due to the time required by the high voltage power supply to restore the charges, leading to an unavoidable detector dead-time

\(^2\)The field is required to be lost for at least few microseconds allowing the high density electron and ion clouds to be evacuated before recovering field sparking conditions in the affected region.
Micromegas detectors were introduced in 1996 [3] as a good candidate for high particle flux environments, and spark studies with detectors based on micromegas technology were also carried out [4, 5]. Recently, additional efforts have pushed the development of resistive strip micromegas detectors in order to further increase its robustness in high particle flux environments by limiting spark discharges in the same way as it was done for RPCs. In particular, the MAMMA collaboration [6] is developing large area micromegas detectors and introduced the resistive coating technique [7] for the upgrade of the HL-LHC.3

The existing Micromegas technology [8] allowed the MAMMA collaboration to investigate detector prototypes with different resistive coating topologies [9]. This new type of detectors will be installed in ATLAS at the New Small Wheel project. Thus, it should be proved to be long term radiation resistant. The introduction of a new technology made of new materials adds some uncertainties of operation during long periods of time in intense particle flux environments. The results that we report here represent the first ageing tests with this type of detectors using different types of highly ionizing radiations.

2 Ageing of resistive micromegas detectors

An ageing study of resistive-anode detectors is mandatory to assess their capability to handle the rate and level of radiation required for the HL-LHC. For this study, two new identical micromegas prototypes (named R17) were used, lent by the MAMMA collaboration and built at the CERN workshop.

These detectors are based on a resistive strips technology [9] with a 2-dimensional readout. The X and Y readout strips are in copper. The top Y strips have been covered by a 60 µm thick insulating coverlay. The 35 µm thick resistive strips are placed on top of this layer parallel to the X strips (see figure 1 (Left)).

Both resistive and copper strips have a pitch of 250 µm and a width of 150 µm. The resistivity along the strips and boundary resistance value was measured during the fabrication process. The first detector, R17a, showed a linear resistivity4 of 45–50 MΩ cm−1, and a boundary resistance of 80–140 MΩ. The resistivity obtained for the second detector, R17b, was comparable with a linear resistivity of 35–40 MΩ cm−1 and a boundary resistance of 60–100 MΩ.

A first characterization in Ar+CO2 mixtures5 showed that the gain behaved as expected, and the results obtained with both detectors, R17a and R17b, were comparable. figure 1 (Right) shows the gain curves in these mixtures.

Ageing tests took place at different CEA-Saclay facilities, one prototype (R17b) was kept unexposed as a reference and the other (R17a) was exposed to different types of radiations including X-rays, cold neutrons, high energetic gammas, and alphas. These tests will be described in the following sections.

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3High Luminosity Large Hadron Collider (luminosity will be increased by at least a factor 5 reaching up to \(L = 5 \times 10^{34} \text{cm}^{-2}\text{sr}^{-1}\))

4The linear resistivity was measured during the fabrication process (before mesh integration) and the range of values we provide represent the fluctuation between different strips inside the same detector.

5The mixture used during ageing periods described in the text was always Ar + 10% CO2, and Ar + 7% CO2 for the test beam performance.
Figure 1. (Left) R17 micromegas detector schematic, including a typical 128 $\mu$m amplification gap on top of resistive strips which are isolated from the X-Y copper readout strips through coverlay. (Right) Gain curves of each detector for two different gas mixtures, argon as main component.

![R17 Micromegas Detector Schematic](image1)

Figure 2. (Left) X-ray generator cage where detector R17a was placed during irradiation. (Middle) The prototype can be seen together with the metallic mask on top, containing the squared aperture mentioned in the text. An additional small hole (which was closed during the irradiation tests) perfored in the mask could be used for calibrations at a non-exposed region. (Right) The 9-hole mask used to monitor the gain profile.

![X-ray Generator Cage and Masks](image2)

2.1 X-ray exposure

The prototype under test was placed inside a cage with a high intensity X-ray generator (see figure 2 (Left)). The X-ray generator consists of an electron gun with an accelerating power of a few tens of kV and electron currents up to 20 mA, which points to a metallic cathode producing X-rays, the energy of which depends on the cathode material (in our case copper with a fluorescence peak at 8 keV).

In order to study the response to a long exposure at a specific region of the detector, a mask was prepared by using an aluminum plate with a 4 cm$^2$ hole aperture. The plate was placed on top, using the chamber screws as reference allowed us to fix it always in the same position$^6$ at every use (see figure 2 (Middle)).

The radiation exposure tests aim to accumulate an amount of charge comparable to the values that will be integrated during the lifetime of the HL-LHC. The estimation of the total charge produced at the HL-LHC in the muon chambers of ATLAS is based on the energy deposit $E_{MIP}$ of a Minimum Ionizing Particle (MIP) in a 0.5 cm micromegas conversion gap. In our gas mixture $E_{MIP} = 1.25$ keV. Considering the detector gain $G$, the charge produced by each incident particle

$^6$The mask can be rotated by 180 degrees allowing two different positions.
Figure 3. Mesh current evolution (red curve) for a period of 21 days and an integrated charge of 918 mC. The gain control measurements with the non-exposed detector are also plotted (black circles).

at the HL-LHC

\[ Q_{\text{MIP}} = \frac{E_{\text{MIP}}}{W_i} q_e G \]

where \( W_i = 26.7 \text{ eV} \) is the mean ionization energy of the gas. Taking into account a nominal gain of 5,000, the charge produced per MIP yields \( Q_{\text{MIP}} = 37.4 \text{ fC} \).

Assuming the expected rate at the HL-LHC future muon chambers will be 10 kHz/cm\(^2\), the total charge generated in 5 years of operation (200 days/year) will be 32.3 mC/cm\(^2\). The flux produced at the X-ray generator will accumulate an amount of charge well above this value for an exposure of a few days.

The detector has been exposed for more than 20 days with a gain of 5,000 and a gas flow of one renewal per hour. The irradiation took place in two different operating conditions, with and without grounding the readout strips, in order to compare the effects on the current in different conditions (further details can be found at references [10, 11]). The current remained stable (see figure 3), proving the detector gain was not affected on the whole irradiation period, which corresponds to 21.3 days of exposure and an integrated charge of 918 mC, that is 5 years of HL-LHC with a safety factor above 7.

The gain of both detectors was measured using a \(^{55}\text{Fe}\) source at different positions, before and after exposure. We used a dedicated 9-hole mask (see figure 2) which covers the full active area of the detector in one of its axis.

These measurements took place before the ageing period (26-Sep-2011), when the grounding connectors were removed (8-Oct-2011) and after the exposure (19-Oct-2011). The relative gain at each position for these three sets of measurements is plotted in figure 4 and shows that the gain profile in both detectors is compatible with previous measurements. Moreover, the exposed detector region does not show any significant difference in relative gain compared to the other, non-exposed regions. The X-rays irradiation had therefore no effect on the detector response.

2.2 Neutron exposure

Neutron irradiation took place at the Orphée reactor in CEA-Saclay. The reactor, which operates only for research purposes, is connected to different lines which guide different fluxes of cold
Figure 4. Gain measurements as a function of position before, during (connectors changed, details can be found at reference [10]), and after the irradiation period for the exposed detector R17a (Left) and non-exposed detector R17b (Right). The exposed region is indicated for the irradiated detector.

Figure 5. A schematic top-view of the Orphée reactor where the various cold neutron lines can be seen. The detector was installed at the cavity G32 marked in the schematic and the 3D-model by a circle. A picture of the detector as it was installed inside the cavity is also shown.

neutrons produced in the reactor (see figure 5). The line where the detector was installed provides a neutron beam of about $8 \times 10^8 \text{cm}^{-2}\text{s}^{-1}$, with energies in the range of 5–10 meV within an area of a few cm$^2$.

The first irradiation lasted for a short period of 5 minutes, during which the detector materials activation reached levels that saturated the acquisition of mesh signals. The activation was observed during several hours, the rate being above 1 kHz after 8 hours. Figure 6 (Left) shows the measured spectra when the beam was active (ON) and once the beam was shutdown after different periods of time; few minutes (206 kHz), 3 hours (35 kHz), 7 hours (21 kHz) and 22 hours (881 Hz). The 6 keV X-rays from the $^{55}$Fe source were almost imperceptible over the background after this period (see figure 6 (Right)).

Therefore, the gain could not be monitored due to the activation of the detector materials during the neutron irradiation tests. Different irradiation periods were scheduled with an increased time exposure (see figure 7). The mesh current remained stable and at the same level in each of these periods.
Figure 6. (Left) Spectra from deactivation during and after a 5 minute neutron irradiation period. (Right) $^{55}$Fe calibration over background due to the activation of the detector.

Figure 7. Mesh current during the different neutron irradiation periods. The drift voltage was modified during the 5 hour period. Thus, it proves the mesh current dependency with the mesh electron transmission when the neutron beam was active (related to the micromegas field ratios [17]).

The expected neutron flux at the CSC (Cathode Strip Chamber) in ATLAS is about $3 \times 10^4$ cm$^{-2}$s$^{-1}$. The total exposure time of the prototype R17a was more than 40 hours, accumulating a total amount of neutron flux which is equivalent to 5 years of operation of the HL-LHC with a safety factor well above 10.

Before and after the neutron tests the gain was monitored using the same 9-hole mask used for the tests described in the previous section. The gain profile is compatible and the performance of the detector shows no degradation with respect to the measurements before neutron irradiation (see figure 8).

2.3 Gamma exposure

After proving that the detector R17a was operating properly it was installed at the COCASE [12] gamma facility, which provides a high activity $^{60}$Co source, of about 500 mGy/h, emitting gammas at 1.17 MeV and 1.33 MeV (see figure 9).

The highest activity for gammas at the muon spectrometer is recorded in the forward CSC region [13], with a flux which is below $1.8 \times 10^4$ cm$^{-2}$s$^{-1}$. For 5 years of running HL-LHC, we consider a factor 5 in luminosity increase, with a safety factor 3 the integrated gamma flux results to be $2.3 \times 10^{13}$ cm$^{-2}$. 

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Figure 8. (Left) Measured gain profile before and after neutron irradiation (error-bars are proportional to the energy resolution). (Right) $^{55}$Fe spectra for some of the gain measurements given in the left plot.

Figure 9. (Left) A picture of the detector installed at COCASE. (Right) A schematic of a $^{60}$Co source gamma decay channels.

The source was calibrated for the last time in summer 2005 resulting in an activity of 630 GBq. Considering the half-life of the $^{60}$Co to be 5.27 years, and our measurement being taken 6.5 years after, we estimated the actual decay rate to be 268 GBq. The detector was placed at 50 cm from the source receiving an equivalent flux of $1.7 \times 10^7 \text{ cm}^{-2}\text{s}^{-1}$ which should be uniformly distributed in the active area of the detector. Thus, time required to reach the expected gamma flux integrated for 5 years of HL-LHC would be of 16 days in COCASE.

The detector was irradiated during 480 hours between March,22$^{nd}$ and April,11$^{th}$ 2011. The integrated charge during this period was 1.48 C at a mean mesh current of 858 nA. Figure 10 shows the evolution of the mesh current which fluctuates around the mean value within 5%, variation which can be perfectly attributed to environmental effects (i.e. pressure and humidity variations$^7$

$^7$The COCASE facility is kept at constant temperature
Figure 10. Mesh current evolution during the gamma irradiation period with a zoomed plot inside showing humidity measurements taken at the COCASE facility.

Figure 11. (Left) The 9-hole mask normalized gain profile before and after gamma irradiation (error-bars are proportional to the main $^{55}$Fe peak energy resolution). (Right) Mesh signal amplitude for different conversion-amplification field ratios at each of the mask holes.

are also typically within 5%).

Gain control measurements were taken before and after exposure by using the 9-hole mask. The gain profile before and after exposure shows a reasonable reproducibility (see figure 11 (Left)). Moreover, the mesh signal amplitude was measured at different field ratios (see figure 11 (Right)), these curves resemble the typical electron transmission curves measured with a different micromegas technology [17].

2.4 Alpha exposure

Additional tests, similar to the ones described in [14], were carried out by using an $^{241}$Am source emitting alphas at 5.5 MeV. The source was placed inside the detector chamber, just on top of the metallic mesh defining the drift field (see figure 12 (Left)). A first alpha measurement took place at low gain (around 100), allowing to determine the alpha decay rate observed by the detector (see figure 12 (Right)).
Considering that the estimated number of primaries produced by an $^{241}$Am alpha will be between 30,000 and 60,000 for a 0.5 cm conversion gap in Ar+10%CO$_2$, gains above 3,000 will exceed the Raether limit [1] producing a spark almost on every alpha. Therefore, the gain was increased well above this value to about $G = 7,000$. The alpha source stayed inside for a period of 66 hours leading to a mesh current above 100 nA. After the alpha irradiation (which was localized at the center of the detector) the gain profile of the detector remained the same as it is observed by using the gain profile measurement (see figure 13).

3 Beam test performance after irradiation

After the completion of the above described exposures, the R17a and R17b prototypes were installed in the H6 CERN-SPS beam line. The beam consists of positively charged pions at 120 GeV/c in spills of about 10 s every 48 s. The beam intensity was typically $5 \times 10^4$/spill over an area of 20 mm x 10 mm. The DAQ recorded around 800 events per spill.

The intention of this last test was to determine any hint of ageing of the R17a by comparing the spatial resolution (SR) and efficiency obtained with respect to the reference detectors. The R17a and R17b were installed in the existing micromegas telescope line, as shown in figure 14. The micromegas telescope (Tmm2, Tmm3, Tmm5, Tmm6) is used as reference for the track reconstruction of the beam. The detectors under test were placed 2 m downstream of Tmm6.
Figure 14. Test bench setup used at the CERN pion beam facility. Beam is coming from the left and goes through reference telescope detectors Tmm\(_n\). The line is shared with other detectors which were under test at the same time and have been excluded in this drawing for simplicity. Our resistive prototypes were placed behind the telescope.

Figure 15. Relative cluster position alignment with fitted tracks. We show, before and after the alignment, the residuals of the two telescope detectors Tmm3 and Tmm6, together with the residuals of one of the resistive detectors under test, R17a.

The intrinsic SR of the telescope is around 60–70 \(\mu\)m. Given that our detectors were far away from the telescope we decided to include them inside the beam track definition. Figure 15 shows the alignment of telescope detectors with the R17a detector. In this case, we obtain an increased value for the SR of the telescope (Tmm) detectors coming from intrinsic errors on the track definition, due to multiple scattering and extrapolation.

The data were taken within two weeks at the end of October 2012. Three different regions were exposed to the beam in order to compare zones which received different types of radiations, as described in section 2. The regions exposed to the beam correspond to the two X-ray irradiation mask positions (left and right at about 2.5 cm from the center) and the center of the detector. We took data at each of these regions for several values of the amplification field by varying the mesh voltage. We performed several scan repetitions in these regions by applying increasing and decreasing voltage sequences. Figure 16 shows the SR at each measurement as a function of the run number, revealing the different mesh voltage scans performed. Run numbers below 8127 correspond to the left zone (in this region measurements were taken only at high detector gain). Run numbers between 8140 and 8208 correspond to the center region and run numbers above 8215 correspond to the right zone. A full scan, from low to high gains, was performed for these two last regions. The highest values for the SR observed in the plot correspond to the lowest gain values, and vice versa.
Figure 16. SR of R17a and R17b (two lower panels) and SR of one of the telescope detectors during the full beam test period.

Figure 17. Comparison of the SR of R17a and R17b in center (Left) and left (Right) regions as a function of the absolute gain.

The improved spatial resolution for higher gains emphasizes the importance of charge statistics to obtain an accurate cluster position in the detector. Figure 17 shows the averaged SR as a function of the mesh voltage pointing to an optimum SR at about 550 V, which corresponds to gains slightly above 10,000 for the gas used at the beam tests (Ar+7%CO$_2$).

The setup used is not optimized to observe SR differences between both resistive detectors. However, it is still good enough to describe the improvement of the spatial resolution as a function of the gain, observed in both detectors (see figure 17). Moreover, no differences are observed between the SR obtained in zones with different irradiation natures. Considering that the SR we obtained is dominated by the detector with degraded (or worst) SR, the absolute values obtained are comparable to the telescope detectors.

Finally, the resistive detector efficiencies were determined as the probability to detect one charge cluster when a track is found in each of the four telescope detectors. Figure 18 shows the detection efficiency of both detectors as a function of the absolute gain. In this case, the measurements do not fully match. However, both detectors reach efficiencies of about 99.5% for the highest values of the gain. It is also remarkable that the (irradiated) R17a detector reaches these values for

\footnote{The resistive detectors SR is dominated by the detector with the highest SR value [18]. This is due to the fact that the resistive detectors were placed far away from the telescope.}
4 Conclusions

A 2D-readout resistive strip detector was tested to different intense irradiation sources: X-rays, high energy gammas, neutrons and alphas. For each radiation type, the total charge or interactions produced during the ageing process was well above the expected levels at the HL-LHC for 5 years of operation with an additional safety factor. In addition we investigated the performance of these detectors at the CERN pion beam test facility. The results obtained are comparable to those obtained with a non-irradiated detector of same construction. We did not observe any degradation.

The intense irradiation of R17a prototype did not harm seriously the performance of the detector in terms of efficiency and SR which were found to be compatible with the reference telescope. We present it as a definitive proof that irradiations of different nature, which will be present at the HL-LHC, do not affect this new technology. The values obtained for the spatial resolution and detection efficiency are reasonably good considering that the setup was not designed to minimize the error on the track definition.

We have proven the robustness of the detector technology to a high level of radiation and of different nature in a relative short period of time, requiring the accumulated charge to be above the values that would be integrated in the final setup installation in the New Small Wheel at the HL-LHC. We consider this as an important step towards the consolidation of this technology for high-rate environments in long periods of time.

However, future tests should include longer period ageing at the nominal rate of the HL-LHC. In the tests reported here, we cannot provide a lower limit on the mean lifetime of these detectors by the possibility of formation of radicals which require long term polymerization processes (as described in [16]). A future test in this direction would be complementary to our measurements.

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\(^9\)R17a detector showed higher gains at lower voltages along all the ageing irradiation tests.
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