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High rate capability studies of triple-GEM detectors for the ME0 upgrade of the CMS Muon Spectrometer

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Abstract. The high-luminosity LHC (HL-LHC) upgrade is presenting new challenges for particle detector technologies. In the CMS Muon System gaseous detectors, the increase in luminosity will produce a particle background ten times higher than at the LHC. To cope with the high rate environment and maintain current performance, the triple-Gas Electron Multiplier technology is a promising candidate for high-rate capable detectors for the CMS-ME0 upgrade project in the innermost region of the forward Muon Spectrometer of the CMS experiment. An intense R&D and prototyping phase is currently ongoing to prove that such technology meets the stringent performance requirements of highly efficient particle detection in the harsh background environment expected in the innermost ME0 region. Here we describe the recent rate capability studies of triple-GEM detectors operated with an Ar/CO_2 (70/30) gas mixture at an effective gas gain of 2×10^4 by using a high intensity 22 keV X-ray generator. Moreover, we present a novel foils design based on double-sided segmented GEM-foils, high voltage power distribution, and filtering, which the collaboration adopted for realization of the latter projects, and their impact on the performance of the detector in the light of new rate capability studies, with a summary of the ongoing R&D activities.

1. Introduction

The ME0 station of the CMS experiment is planned to be installed for the CMS Muon Spectrometer upgrade to cope with the increased pileup in the high-luminosity LHC upgrade and to extend the CMS muon system coverage to include the previously untracked pseudorapidity region of $2.4 < |\eta| < 2.8$ (Fig. 1). The Triple-GEM technology, chosen for the instrumentation of the ME0 station, is considered to be one of the most consolidated in the field of micro-pattern gaseous detectors, with its good space and time resolutions (up to $\sim 150\,\mu\text{m}$ and $\sim 8\,\text{ns}$, respectively) [1] and excellent rate capability, verified with X-rays up to $100\,\text{MHz/mm}^2$ on irradiated areas of several mm^2 [2]. The background particle flux expected for the ME0 detectors in the CMS environment during LHC operations, initially estimated to be lower than $50\,\text{kHz/cm}^2$ [3], has been updated after a more precise redesign of the CMS detector geometry to a maximum value of $150\,\text{kHz/cm}^2$ in the highest pseudorapidity region, with an exponential drop with decreasing η (Fig. 2). While this value may seem lower than the highest flux sustainable with GEM technology, the CMS triple-GEM detectors have undergone a heavy redesign to allow safe operation in the CMS harsh radiation environment, with the inclusion of protection resistors to ensure proper mitigation against the effects of self-sustained discharges and their propagation towards the readout board [4].

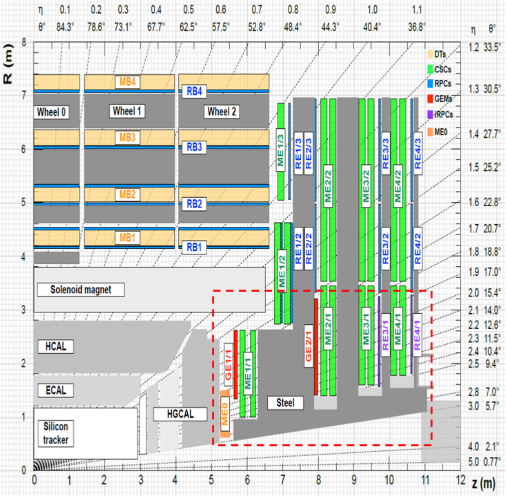

Figure 1. A quadrant of the CMS Muon Spectrometer, showing the locations of new forward muon detectors for HL-LHC Phase 2 contained within the dashed box.

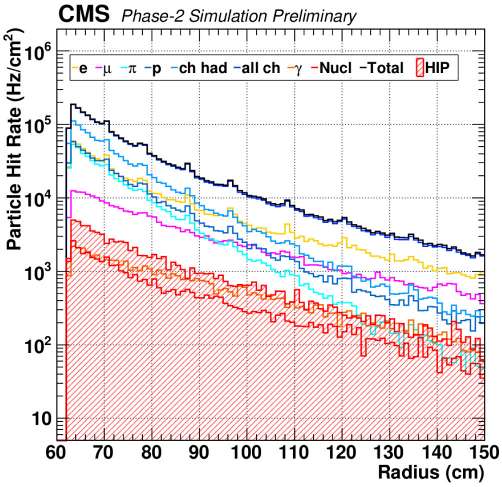

Figure 2. GEANT4 simulated background hit rate in the CMS ME0 pseudorapidity region for a ME0-like detector as a function of the distance from the LHC beam line.

As a consequence of the inclusion of protection circuits, the rate capability of the CMS triple-GEM detectors is limited by the voltage drops on the protection resistors due to the currents induced on the detector electrodes by the motions of electrons and ions in the gas. This effect requires a new take on the triple-GEM rate capability problem with a novel approach focused on high integral hit rates, obtained by irradiating the entire detector surface at moderate particle fluxes. The rate capability measurement is described in the following sections together with mitigation strategies.

2. Experimental setup and Measurement

We performed rate capability measurements on a triple-GEM detector of $10 \times 10\,\mathrm{cm}^2$ active area with a $1\,\mathrm{M\Omega}$ protection resistors on the electrode of each GEM-foil oriented towards the drift board and $100\,\mathrm{k\Omega}$ protection resistors on the electrode of each GEM-foil oriented towards the readout board. The detector was operated with Ar/CO_2 (70/30) gas mixture at an effective gas gain of 2×10^4 and was irradiated simultaneously by two silver-target X-ray generators at increasing fluxes; within a single measurement, the distance of the source from the detector was gradually decreased to span a wider range of particle rates from 200 kHz to 20 MHz. To avoid the relatively low saturation limits of traditional laboratory counting electronics due to the effects of pile-up pulses, the particle hit rate on the prototype was estimated by measuring the anode current with an ammeter of 1 pA current resolution as a function of the X-ray generator operating power (Fig. 3). The following parametric function was used for parameterizing the experimental anode current density (J_{measured}) to extrapolate the expected (real) anode current density (J_{expected}):

$$\mathrm{J_{measured}} = \frac{\mathrm{J_{expected}}}{1 + \mathrm{k} \times \mathrm{J_{expected}}} = \frac{\mathrm{A} \times \mathrm{I_{X-ray}} + \mathrm{B}}{1 + \mathrm{k} \times (\mathrm{A} \times \mathrm{I_{X-ray}} + \mathrm{B})}. \tag{1}$$

The expected particle hit rate (Fig. 4) on the detector was calculated from the expected anode current density by inversion of the effective gas gain equation:

$$\mathrm{R_{expected}} = \frac{\mathrm{J_{expected}}}{\mathrm{n_p} \times \mathrm{q_e} \times \mathrm{G_{measured}}}, \tag{2}$$

where $\mathrm{n_p}$ is the average number of primary electrons created by the X-ray photons in the detector per event, $\mathrm{q_e}$ is the electron charge, and $\mathrm{G} = 2 \times 10^4$ is the effective gas gain of the detector.

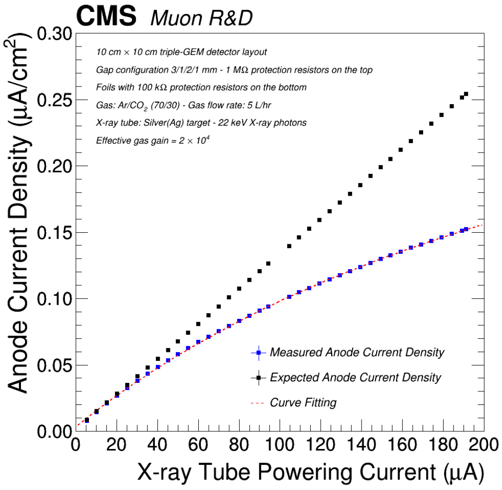

Figure 3. The anode current density of the $10 \times 10\,\mathrm{cm}^2$ detector prototype as a function of the X-ray tube powering current.

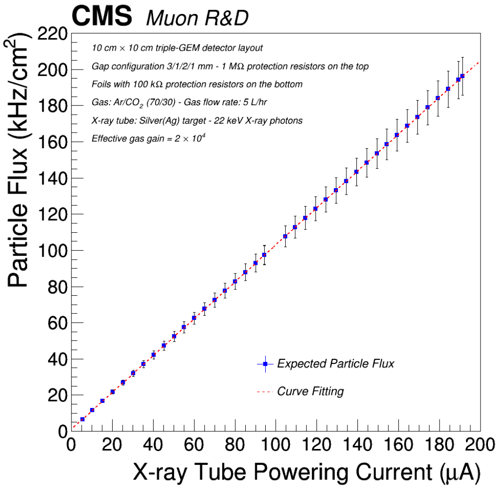

Figure 4. The particle hit rate of the $10 \times 10\,\mathrm{cm}^2$ detector prototype as a function of the X-ray tube powering current.

Two independent rate capability measurements were performed. In the first calculation method, the gas gain drop was obtained by extrapolation from the measured detector anode current, while in the second calculation method the gas gain under irradiation was measured at the effective bias voltages on the GEM-electrodes under irradiation, corrected for the ohmic voltage drop caused by the avalanche charges (Fig. 5). After the rate capability measurement, a compensation measurement was performed to determine the new bias voltage at which the detector should be powered, at a fixed irradiation rate, to recover the original nominal gas gain of 2×10^4, while maintaining the nominal gap fields. The measurement was carried out iteratively by increasing the applied voltage on each GEM-foil until the effective voltage on each electrode was equal to the desired voltage corresponding to the nominal gas gain (Fig. 6).

3. Results and Discussion

The results of the rate capability measurements obtained with the first and second calculation methods described in section 2 are in agreement with each other within the measurement statistical uncertainty, proving that the only perceptible gain drop in the explored rate interval is due to the already discussed ohmic effect. Because the the total current flowing through the protection resistors is not dependent on the irradiated area, the gas gain drop is expressed as a

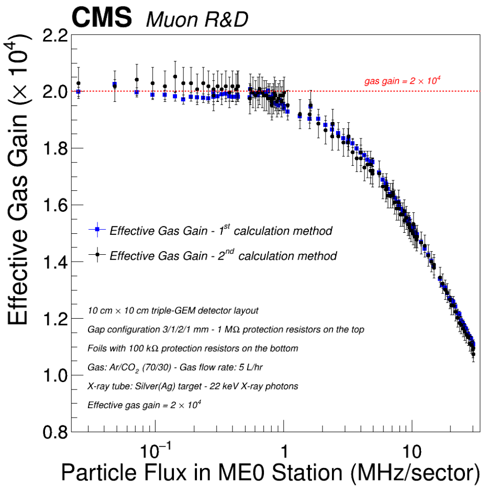

Figure 5. Effective gas gain drop of the irradiated detector prototype comparing the two measurement techniques.

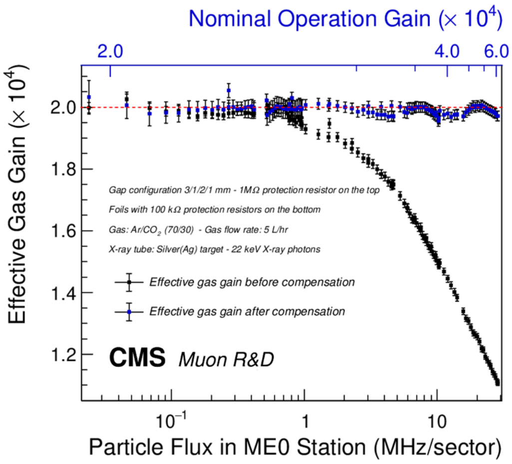

Figure 6. Effective gas gain drop of the irradiated detector prototype and recovered effective gas gain as a function of the particle hit rate.

function of the total hit rate on the detector instead of the particle flux. The highest gas gain drop observed in the laboratory measurements was 40% of the expected gas gain; compensation measurements show that it is possible to recover the original gas gain by operating the detector at higher nominal gains. Design strategies could be adopted to limit the overvoltages to be applied to operate the GEM detectors in the CMS environment at full efficiency; a redesign of the ME0 GEM-foil segmentation is discussed in the following section.

4. Radial Segmentation of the GEM-foils

Previous designs of the CMS triple-GEM detectors involved a GEM-foil segmentation along the longitudinal direction with respect to the beam line, resulting in non-uniform gas gain drops in different sectors along the η direction due to the exponentially decreasing background flux shape in the radial direction. Instead, the newly adopted solution consists of dividing each GEM elctrode in fine sectors along the azimuthal direction with respect to the LHC beam line (Fig. 7). Each sector is powered separately, to limit the total current flowing through each protection resistor and then the sector-by-sector gas gain drop is minimized. Simulations that include a radial segmentation with 40 sectors show the average rate per high voltage sector in the CMS background can be contained to 1.5 MHz, while the gas gain drop can be minimized to about 10% of the expected gas gain of about 2×10^4.

5. Conclusion

A new approach to the rate capability problem of triple-GEM detectors has been applied for the high-rate environment expected for the innermost muon station of the CMS endcaps for the high-luminosity upgrade. The rate capability of large-area triple-GEM detectors has been shown to be limited by the protection circuits applied to the detectors and to be independent of the irradiated area at fixed hit rate. The measured gas gain drops can be as high as 40% of the expected effective gas gain, which can be recovered by applying overvoltages to the detector electrodes. The mitigation strategy chosen for the CMS ME0 detectors, which involves a radial segmentation of the ME0 GEM-foils with respect to the beam line, is expected to reduce the gas gain loss during CMS operations to 10%. Studies are currently underway comparing the effect

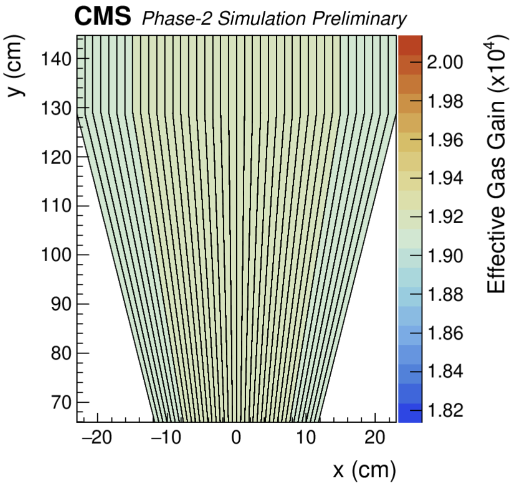

Figure 7. Design of the adopted azimuthal segmentation for the ME0 detectors, showing the expected gas gain under irradiation in the CMS environment.

of different choices of protection resistors and resistive high voltage filters.

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