Development of Micro-Pattern Gas Detectors for the Upgrade of the Muon System of the CMS Experiment at the Large Hadron Collider

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Abstract.
After the discovery of the long awaited Higgs boson in 2012, the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) and its two general purpose experiments (ATLAS and CMS) are preparing to break new grounds in High Energy Physics (HEP). The international HEP collaboration has established a rigorous research program of exploring new physics at the high energy frontiers. The program includes substantial increase in the luminosity of the LHC putting detectors into a completely new and unprecedented harsh environment. In order to maintain their excellent performance, an upgrade of the existing detectors is mandatory. In this work we will describe ongoing efforts for the upgrade of the CMS muon detection system, in particular the addition of detection layers based on the Gas Electron Multiplier (GEM) technology. We will summarize the past 5-year R&D program and the future installation and operation plans.

1. Introduction
The Large Hadron Collider has been built to shed light on several fundamental questions in particle physics. The Compact Muon Solenoid (CMS) experiment [1] is one of its two general purpose experiments designed and built to detect and reconstruct particles produced during LHC collisions. With the discovery of the Higgs boson [2, 3], the international collaboration has established a rigorous research program involving precise measurements of the Higgs properties and searches for new physics. This requires a large increase in the LHC luminosity which puts stringent requirements on the detectors. In order to maintain its excellent performance, CMS is undergoing a series of upgrades of its components, among them its muon system. This latter is a critical component of CMS due to the strong role of new physics channels involving muon particles in the final state. The CMS muon system is composed of three detector technologies: Resistive Plate Chambers (RPC), Drift Tubes (DT) and Cathode Strip Chambers (CSC). Until now the redundancy of the CMS muon system could not yet be established in the pseudorapidity region $\eta > 1.6$ (figure 1). In the past 5 years the muon collaboration has conducted an extensive R&D program to recover this redundancy, extend the capabilities of the forward region to cope with the future increase in the LHC luminosity and enhance the trigger and reconstruction performance.

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2. The forward muon system upgrade

The forward region will be instrumented with additional layers of a new technology based on GEM [4] detectors. The GEM is an amplification stage consisting of a 50 μm thick polymer foil, metal coated on each side, and perforated regularly by a high density of holes (figure 2 left). In our application, the hole diameter is 70 μm, and the hole spacing is 140 μm. With a suitable voltage of a few hundreds of volts, applied between the two metal coated sides of the GEM, a high electric field of up to 100 kV/cm is reached inside the holes (figure 2 right). When a charged particle crosses the detector, it ionizes gas molecules inside the detector active volume, creating pairs of electrons and positive ions. Thanks to the electric field inside the detector, electrons will drift towards the positive anode creating a signal that can be measured by appropriate readout electronics. The detector gain can be further enhanced by inserting three GEM foils inside the same gas volume known as triple-GEM detector (figure 3). The triple-GEM was proposed by the collaboration to equip the region of 1.55 < η < 2.18. These detectors have to fulfill several requirements: uniform response, high detection efficiency, good spatial and time resolution [5].

The collaboration has designed, built and operated large-area of triple-GEM chambers [5]. These trapezoidal chambers, denoted as GE1/1, have an active area of 990 \times (220-455) \text{mm}^2 each, and are sectorized in η partitions to cover 18° each in the azimuthal direction and provide radial readout with strips pointing towards the beam pipe (figure 4). Two chambers are mounted face-to-face to form a double detection layer referred to as “superchamber”. The standard gas mixture consists of either Ar/CO$_2$ or Ar/CO$_2$/CF$_4$. The readout electronics are based on a binary technology VFAT [5, 6].

3. Performance results

In the past five years several GE1/1 prototypes were built in laboratories and tested with charged particles at CERN [7] and Fermilab [8]. Below we summarize the results from these efforts.

3.1. Detection efficiency and spatial resolution

Figure 5 shows the detection efficiency as a function of the electric field applied to the GE1/1 chamber. Three regions of the chamber are reported. An efficiency of 97-98% per chamber is achieved. With 97% efficiency per chamber, a superchamber will have 99% efficiency if the signals of its two face-to-face chambers are combined as a logical ”OR”. Figure 6 shows the
distribution of the residual between the particle coordinate measured by the GE1/1 chamber and that extrapolated from an external reference detector. The width of this distribution, after adequate corrections, gives the spatial resolution of the GE1/1 detector. A spatial resolution of 268 µm is achieved which is well within the required accuracy [5].

Figure 5. Detection efficiency as a function of the electric field in the GE1/1 chamber [5]. Three different areas of the chamber are reported.

3.2. Time resolution
A key parameter to match the CMS trigger requirement is the time resolution of the detector. Figure 7 shows the time resolution as a function of the electric field for both Ar/CO₂ and Ar/CO₂/CF₄. The difference in the time resolution between both gas mixtures is due to the difference in electron drift velocity between both gases. Nevertheless, in each case at least 8 ns time resolution is obtained which largely matches the CMS trigger requirements in this region for an LHC bunch crossing of 25 ns.

3.3. Uniformity response
Due to the unprecedented large area of GEM foils used in GE1/1, a uniformity of response across the whole chamber needs to be ensured. The collaboration has optimized the assembly procedure to fulfill this requirement and prevent any deformation of the GE1/1 or its components. Figure 8
shows the relative gain obtained from a uniformity study across the full chamber area. The observed gain variations are within the range set by the collaboration.

**Figure 7.** Time resolution as a function of the electric field in a GE1/1 for two different gas mixtures.

**Figure 8.** Gain uniformity scan across a full GE1/1 chamber. The gain variations are within the acceptable limit set by the collaboration.

### 4. Summary and future upgrades

Thanks to the excellent performance achieved during its R&D program, the GE1/1 project has been approved by the collaboration. In total 36 superchambers will be installed in the LHC Long Shutdown (LS2) in 2018. As a preparation for this milestone, 5 GE1/1 chambers have been recently installed successfully in CMS.

Moving forward, the collaboration has embarked in an R&D program for two additional upgrades. The first one, referred to as GE2/1, consists of installing two rings of double layered triple-GEM chambers covering the region of $1.6 < \eta < 2.45$ (figure 1) and planned for the LHC Long Shutdown (LS3) in 2024. The second one, called ME0, consists of additional layers to extend the coverage to $2.0 < \eta < 3.0$. (figure 1).

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