Large-size triple GEM detectors for the CMS forward muon upgrade

C. Calabria* on behalf of the CMS GEM Collaboration

*Università di Bari and INFN Sezione di Bari, Bari, Italy

Abstract

The CMS collaboration considers upgrading the muon forward region which is particularly affected by the high-luminosity conditions at the LHC. The proposal involves Gas Electron Multiplier (GEM) chambers, which are able to handle the extreme particle rates expected in this region along with a high spatial resolution. This allows to combine tracking and triggering capabilities, which will improve the CMS muon High Level Trigger, the muon identification and the track reconstruction. Intense R&D has lead to the development of several GEM prototypes and associated detector electronics which were operated in several test beams. Strip cluster parameters, detection efficiency, and spatial resolution for charged particles are studied with position and high voltage scans and at different inclination angles. A first GEM station is foreseen to be already installed in LHC Phase-I to operate jointly together with the existing CSC detectors in the forward region. The resulting improved transverse momentum assignment and lower trigger fake rate will reduce the needed bandwidth and therefore allow to lower the trigger threshold resulting in an increased sensitivity in channels triggering on soft muons, such as H to tau’s with subsequent leptonic decays to muons. Further GEM detectors are proposed for LHC Phase-II to significantly increase the forward muon acceptance.

Keywords: LHC, CMS upgrade, Muon, GEM

1. Introduction

The CMS muon system[1] is designed to provide robust, redundant and fast identification of the muons traversing the system, in addition to trigger capabilities and momentum measurement. Precision measurements are provided by Drift Tubes (DT) in the barrel, covering acceptances up to $|\eta| < 1.2$ and Cathode Strip Chambers (CSC) in the endcaps covering $1.0 < |\eta| < 2.4$. Resistive Plate Chambers (RPC) cover the region up to $|\eta| < 1.6$. The region $|\eta| > 1.6$ is only instrumented with CSC. One of the main goals during the upgrade phases will be to restore the originally foreseen redundancy in the forward region beyond $|\eta| > 1.6$ based on modern, high-resolution and fast gas detectors capable of fully exploiting the increased LHC performance [2] and sustaining reliable operation for the next decades.

Such detectors have to satisfy a high rate capability, $O(MHz/cm^2)$, a good time resolution for triggering, and a good spatial resolution, $O(100 \, \mu m)$, for tracking. The current CMS RPC design is not able to sustain the high rates expected during the next phases of LHC. However, there are various solutions in the field of micro-pattern gaseous detectors (MPGDs), the gaseous electron multipliers (GEMs) [3].

2. The CMS GEM Project

The baseline of the CMS GEM project is the installation of 36 double-layered triple-GEM chambers in front of the ME1/1 station during the LHC second Long Shutdown (LS2), called the GE1/1 system [4, 5]. The chambers will provide full coverage in $\phi$ and $1.55 < |\eta| < 2.18$ in pseudo-rapidity. The odd-numbered GE1/1 chambers will be slightly larger to maximize coverage in $|\eta|$. The station 2 upgrade (GE2/1) consists of installing two rings of double-layered triple-GEM

*Corresponding author
Email address: cesare.calabria@ba.infn.it (C. Calabria)
chambers covering up to $1.6 < |\eta| < 2.45$ during the third Long Shutdown (LS3). Each GE2/1 chamber spans about 20 degrees in $\phi$. Finally, a muon near-tagger (ME0) with 18 six-layered triple-GEMs, with each chamber providing coverage of 20 degrees in $\phi$ and $2.0 < |\eta| < 3.0$ in pseudo-rapidity, behind the future shortened hadron calorimeter (after LS3). The geometry of both GE2/1 and ME0 is yet to be finalized. The geometry of the proposed GE1/1, GE2/1 and ME0 is sketched in Fig. 1 while their location in the present CMS Muon system is shown in Fig. 2.

The detectors will have to sustain a background rates up to $O(10^5 \text{kHz/cm}^2)$ at the instantaneous luminosity expected for Phase-II ($5 \times 10^{34} \text{Hz/cm}^2$), as can be seen from the simulation in Fig. 3 where the rates in each station is represented as a function of the distance from the beam-pipe. However the GEM detectors are designed to withstand up to $O(MHz/cm^2)$.

3. CMS GEM prototypes

In many years of R&D at CERN, we have made the production of large scale areas ($\sim 0.5 \text{m}^2$) cost-effective, enabling the design and testing of CMS-scale prototypes. Six GEM prototypes have been developed since 2009. The first large GEM prototype, GE1/1-I, had all components glued together, had spacers and 8 readout sectors. This number of spacers was increased to 24 in GE1/1-II. GE1/1-III was the first type to make use of the manual stretching technique (NS2), that thanks to o-rings and screws on a plastic (FR4) frame attached to the GEM foil allows to adjust the tension accordingly (Fig. 5). This technique introduce a new way to stretch the foils and assembly a chamber without spacer and glue, reducing assembly time and allowing a fast and easy repair of broken chambers. In addition, the distances of the drift, transfer and induction region were finalized. GE1/1-IV was the first prototype to be fully mechanically constructed and produced at various production sites around the world. The GE1/1-V have an optimized coverage in $\eta$ and $\phi$ and have short and long types. The final version GE1/1-VI will have the same features as the V prototype with an optimized coverage in $R$.

4. GE1/1 Detector Layout

The baseline detector is the GE1/1 chamber shown in Fig. 4. The triple-GEM has a trapezoidal shaped active area of $990 \times (220 - 455) \text{mm}^2$ with a $3/1/2/1 \text{mm}$ drift/transfer-1/transfer-2/induction field gap configuration. The bottom of the assembly is the Drift Board, which is a printed circuit board holding the drift electrode and the GEM voltage divider. The top of the as-

Figure 1: Layouts of the GE1/1 (top), GE2/1 (center) and ME0 (bottom) stations.

Figure 2: Transverse section of CMS showing the Muon system with DTs, CSCs and RPCs. The proposed GEM stations, GE1/1, GE2/1 and ME0 are given by the red boxes.
5. GEM project achievements

The GEM foils for the detector prototypes have so far all been produced at the CERN Surface Treatment Workshop using the photolithographic hole etching procedure. The recently introduced single-mask technique [7] is used for the production of the foils for the large-area detectors. For the assembly of the triple-GEM detectors themselves, a novel, cost effective NS2 (no-spacer, no-stretch) technique has been developed permitting the chambers to be assembled without the use of any glue nor spacers in the active detector volume [8]. With NS2 technology, one full-scale GE1/1 chamber can be assembled in about two hours only, which is to be compared to the one week that was needed for an assembly using the former glueing technique.

The performance of the CMS triple-GEMs has been evaluated both in the RD51 lab at CERN with x-ray sources and in many test beam campaigns with pion/muon beams at the CERN SPS [11] and more recently at FNAL. The chambers were operated mainly with a Ar:CO2:CF4 45:15:40 gas mixture. The readout was done using either digital TURBO/VFAT2-based front-end electronics [9] or the Scalable Readout System (SRS) [10] with an analog APV25 hybrid front-end. It was demonstrated that the detectors exhibit a broad
efficiency plateau with maximum efficiency above 98 % (Fig. 6 top). A time resolution of 4 ns was obtained during drift and induction field scans (Fig. 6 center). Spatial resolutions of the order of 270 µm were measured with a digital readout (Fig. 6 bottom), compatible with what one expects from the strip pitch; using analog readout, spatial resolutions below 110 µm were found. It was shown that the detector performance was not affected significantly in the presence of an external magnetic field similar to the one expected inside CMS. Gain measurements performed using an x-ray gun on a GE1/1 detector showed that the variation in gain remained below 15 % across the detector surface [8]. Finally, ongoing detector irradiation tests with a 137Cs source at the CERN GIF facility revealed no aging effects so far, after an accumulated dose of 7 mC/cm² [12].

6. Integration into CMS

A slice test will take place during the Year-End Technical Stop of 2016-2017. A small number of fully working GE1/1 chambers will be installed in both endcaps with a total coverage of 40 degrees each. In preparation of the slice test and the possible installation of the full GE1/1 station in the 2nd LHC Long Shutdown (2018-2019), most of the services and cabling needed for this station is being put in place in the CMS experimental area already now during the ongoing 1st LHC Long Shutdown (2013-2015). To finalize the super-chamber layout, two sets of GE1/1 super-chamber dummies were produced: a first set with preliminary chambers dimensions, and a second set produced according to the final, alternating long-short chamber geometry. The dummies did not contain any detectors, nor any electronics, however, the weight was similar to the real super-chambers. The space available for the GE1/1 super-chambers inside CMS is quite limited (about 100 mm). Moreover, the forward GE1/1 region is densely packed in terms of detector cabling and services. Apart from verifying the

Figure 5: Sketch explaining the new self-stretching technique (NS2).

Figure 6: GE1/1 prototype performance measured during test beams: efficiency vs. gain (top), time resolution with different gas mixtures (center), space resolution with digital readout (bottom).
dimensions of the chambers and the detector insertion procedure itself, also the positions of the connections for gas, cooling, electronics and detector powering need to be optimized. A first trial installation of the first set of dummies into one of the inner endcaps was successfully performed during the Summer of 2013. A second trial installation with the second set was done in March 2014.

7. Impact on the Muon Trigger

7.1. GEM-CSC Bending Angle

The expected increase of the LHC beam instantaneous luminosity from the design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ up to $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ in the Phase-II era will have a big impact on the Muon endcap system, in particular the high-$\eta$ region. Many more soft particles will scatter off elastically in the muon detectors and in particular in the iron return yokes. Low-$p_T$ muons are misinterpreted as high-$p_T$ muons by the CSC Track-Finder, resulting in a flattening of the trigger rate curve at high-$p_T$. To reduce the trigger rate, while maintaining high efficiency, one needs to install an additional muon detector that measures more precisely the bending angle in station 1 (since the $p_T$ measurement is driven by the internal chambers). The extra measurement points will also yield a higher efficiency, even at very high pile-up scenarios, and recover possible CSC failures. The installation of an additional muon detectors (GE1/1) in front of ME1/1 can improve the $p_T$ measurement, thanks to the increased "lever arm" between GEM and CSC stations. GE1/1-ME1/1 bending angle provides a clear separation between soft ($p_T \sim 5 \text{ GeV/c}$) and hard muons ($p_T > 20 \text{ GeV/c}$) as can be see in Fig. 7. Better separation is achieved for odd numbered chambers where the lever arm is maximum.

7.2. Trigger rate

The bending angle separation power exhibited by the combined system GEM+CSC can be exploited at L1 trigger. Combining the CSC and GEM informations it is possible to develop a combined local trigger that allows to maintain or reduce the $p_T$ thresholds applied at L1 to the muon candidate without efficiency loss thanks to the improved $p_T$ resolution. The GEM-CSC local trigger based on soft stub rejection recovers the trigger flattening at high $p_T$ due to multiple scattering and shows that a rate reduction of a factor 10 can be achieved in case of a single muon trigger, see Fig. 8 (Top). Considerably lower fake contributions reduce the trigger rate which allows to lower the trigger threshold. Bottom plot in Fig. 8 shows also the trigger rate reduction achievable in the the pseudo-rapidity region covered by GE1/1 when the thresholds is fixed at 20 GeV/c. For some physics channels a trigger threshold of about 15 GeV/c nearly doubles the sensitivity. With the lower rate achieved by the GEM+CSC system, such threshold could be taken into account also at high luminosity.

8. Conclusions and outlook

Over 5 years of R&D resulted in the validation of performance characteristics, assembly and quality control of triple-GEM detectors for the CMS Muon System upgrade that are now close to final. The present scope of the project proposes the installation of 3 new stations: GE1/1, GE2/1 in the presently vacant positions in front ME1/1 and ME2/1 and a near-tagger, ME0. Triple-GEM detectors installation in the CMS high eta region will restore the lack of redundancy and allow to improve the muon momentum resolution measuring more precisely the bending angle and thus helping to reduce the trigger rate in the high luminosity scenarios expected.
The bottom plot shows the ratio of tight 2 stubs with at least one 1 stub from ME1/1a unganging CSC Track-Finder track rates for at least 2 stubs (loose), at least 2 (top) and pseudo-rapidity (bottom) in the 2012 configuration with the GMT as a function of the L1 muon candidate transverse momentum.

Figure 8: Comparison of the trigger rates for the Global Muon Trigger (GMT) as a function of the L1 muon candidate transverse momentum (top) and pseudo-rapidity (bottom) in the 2012 configuration with the CSC Track-Finder track rates for at least 2 stubs (loose), at least 2 (top) and pseudo-rapidity (bottom). The bottom plot shows the ratio of tight/GMT (top) and tight/medium (bottom).

in the LHC Phase-II era. The CMS collaboration approved the installation during the 2016-2017 LHC Year End Technical Stop of a demonstrator system that will allow to perform a complete system validation in-situ, to gain operational experience with GEMs inside the CMS detector and to test the integration of the GEM+CSC system at trigger level. In the presently proposed schedule, the GE1/1 station installation is possible during the second LHC Long Shutdown in 2017-2018, while the installation of the other two stations (GE2/1 and ME0) is possible during the third LHC Long Shutdown (2023-2024).

Acknowledgments

We acknowledge the continuous technical support from the RD51 Collaboration and CERN for this project. We gratefully acknowledge support from FRSFNRS (Belgium), FWO-Flanders (Belgium), BSF-MES (Bulgaria), BMBF (Germany), DAE (India), DST (India), INFN (Italy), NRF (Korea), QNRF (Qatar), DOE (USA), and WSU (USA).

References