Performance of GE1/1 Chambers for the CMS Muon Endcap Upgrade


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Abstract

The high-luminosity phase of the Large Hadron Collider (HL-LHC) will result in particle backgrounds ten times higher than its current value. In order to fully exploit the highly-demanding operating conditions during HL-LHC, the Compact Muon Solenoid (CMS) Collaboration has proposed the use of Gas Electron Multiplier (GEM) detector technology. The technology will be integrated into the innermost region of the forward muon spectrometer of the CMS as the additional muon station in the form of GE1/1. The primary purpose of this auxiliary station is to help in muon reconstruction and to control level-1 muon trigger rates in the pseudo-rapidity region of $1.6 < |\eta| < 2.2$. The new station will be embellished with specific trapezoidal shaped GEM detectors known as GE1/1 chambers. The design of these chambers is finalized, and the installation is foreseen during the Long Shutdown phase two (LS-2) starting at the beginning of 2019. Several full size prototypes were built and operated successfully in various beam tests at CERN. We describe the performance measurements such as gain, efficiency, and timing resolution of such chambers after years of R&D and summarize their behavior in different gas compositions as a function of the voltage fed to the HV divider chain that feeds the different electrodes.

Key Words – CMS, GEM, High Luminosity LHC
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1 Introduction

The upgrade of the LHC to center-of-mass energy of 14 TeV will smoothly bring the luminosity \( L \) up to or above \( 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \) resulting in the High Luminosity phase of the LHC (HL-LHC). The increase in the collision rate will affect the operational conditions in HL-LHC due to increase in pileup and radiation background. It will also pose a challenge to maintain an efficient and reliable trigger particularly in the region \( |\eta| > 1.6 \). Additionally, the high-radiation background may speed-up the aging of the current muon system and may cause performance losses, dead regions and the degradation of the efficient online event selection due to bandwidth limitations.

The CMS Collaboration is, therefore, preparing for the upgrade of current muon system scheduled in 2019 to perpetuate its high level of performance. A quadrant of the CMS muon system where both present detectors and the proposed extensions are shown in Figure 1. In the \( 1.6 < |\eta| < 2.4 \) forward end-cap region, currently only Cathode Strip Chambers (CSC’s) are installed. To enhance muon trigger and reconstruction capabilities, the large-area GEM detectors [1, 3] would be installed in this region. These detectors are playing a significant role in the instrumentation of particle physics experiments and are known to have very high performances such as spatial resolution better than 70 \( \mu \text{m} \), rate capability on the order of MHz/cm\(^2\) and high tolerance to radiation in strong radiation background environments. The integration of these new detectors together with the existing CSC system would highly improve the muon trigger momentum resolution due to an increase in the lever arm for the measurement of the muon bending angle. In particular, the new station to be installed is GE1/1 \(^1\), which would be equipped with a specific type of GEM detectors named as GE1/1 chambers.

Therefore, we present the performance studies such gain, efficiency, timing resolution and discharge probability of GEM GE1/1 chambers and further describe their behavior for standard CMS operating conditions. The document is structured as follows: the first two sections describe the preliminary details such as the design of GE1/1 chambers and the CMS GEM upgrade. Third to seventh sections describe the performance studies, which is followed by the summary in which the recommended operating conditions of the GE1/1 chambers for CMS are provided.

\(^1\)In "GE1/1", the "G" stands for GEM and the "E" for Endcap; the first "1" corresponds to the first muon station and the second "1" to the first, innermost ring of the station.
2 Impact of GE1/1 upgrade on the CMS

The introduction of the new station known as GE1/1 will cover the pseudorapidity region $1.6 < |\eta| < 2.2$ of the CMS [3] and is to complement the current CSC system. These new chambers are based on GEM technology and can operate at very high rates with good performance. The GE1/1 station will extend the path length and will provide additional hits that will help to refine the stub reconstruction and improve the momentum resolution. With the new station installed, muon direction will be measured using hit positions in the adjacent GEM GE1/1 and CSC ME1/1 chambers. The good position resolution of both the detectors and an increased lever arm formed by the two detectors will allow excellent directional measurement.

FLUKA simulation studies at $L = 5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, are used to assess the capability of this new technology to cope with background fluxes expected in the high $\eta$ region [3]. The background rate is estimated by convoluting the fluxes mentioned above with the chamber sensitivities to background computed through standalone Geant4 simulations. The resulting rate is found to be of the order of 1 kHz/cm$^2$, orders of magnitude below the rate capability of the chambers, whose gain is stable up to 100 MHz/cm$^2$.

Therefore, introducing GE1/1 muon station into CMS, consists in reducing the level-1 (L1) muon trigger rates as shown in Figure 2. The muon lever-arm between the adjacent CSCs and the GEMs will allow determining the muon $pT$ by measuring the bending angle due to the magnetic field in the first muon station alone. This $pT$ measurement, independent from the one based on the muon bending through the whole detector will allow the maintenance of a low
Figure 2: Trigger rate reduction with the deployment of muon direction measurement using GEM GE1/1 and CSC ME1/1 chambers [3].

momentum threshold. It would be crucial for a broad spectrum of physics processes whose signatures are characterized by the presence of low $p_T$ muons in the final state. Few examples, ranging from new physics searches to the measurements in the Higgs sector in standard model like Higgs decaying via $\tau\tau \rightarrow \mu + X$, two-Higgs doublet model extended with scaler singlet (2HDM + S) Higgs production $pp \rightarrow h \rightarrow aa \rightarrow \mu\mu bb$, and super-symmetry stop production [3].

3 GE1/1 detector design

After several years of R&D program, many versions of GE1/1 chambers (Figure 3) have been built so far by improving their design in each release. Figure 4 shows a development of the GE1/1 chambers since 2010, when the CMS collaboration proposed their use in muon end-cap region of the CMS detector. The latest version is generation-X with its final design shown in Figure 3. The structure consists of a trapezoidal shaped drift board, three GEM foils stacked together within frames, a readout board and an external gas frame. Three trapezoidal GEM foils are sandwiched in between drift and readout boards in a particular triple-GEM module with a gap configuration of 3/1/2/1 mm to ensure the best timing resolution. However, the mechanical constraints in the GE1/1 station, allow the use of two versions of chambers to have maximum detection coverage, the long GE1/1-L with a length of 128.5 cm and the short GE1/1-S of 113.5 cm. The technical details about long and short versions, their construction and layout can be found in [2]. Further, the two identical GE1/1 detectors are combined to form a ‘super-chamber’
(Figure 3 for illustration) to obtain two detection planes and thus maximize the detection efficiency and the redundancy of the GE1/1 layer.

A GEM [1] is a 50 $\mu$m thick copper-clad polymer (Kapton or Apical NP) foil chemically perforated by a high density of microscopic holes. The copper-clad is on both sides of the foil with a thickness of 5 $\mu$m. The holes in the foil are pierced with double cones with outer diameters of 70 $\mu$m and the inner diameter of 50 $\mu$m with a pitch of 140 $\mu$m. Each hole acts as a signal amplifier, and three foils are cascaded to form a detector known as triple GEM to obtain a measurable signal.

The large area GEM foils needed for CMS are produced at the CERN PCB workshop using a single-mask production technique [4]. The surfaces of GEM foils oriented towards the readout board are a single continuous conductor whereas the GEM foil surfaces facing towards the drift board are segmented into sectors with the area of each sector about 100 cm$^2$. This segmentation limits the energy of discharges preventing the structure from damage which
otherwise could be large enough in extreme cases to generate a short leaving the entire structure dead (more details in Section 7). Further, with such a design and considering a worst-case scenario, a discharge may only render unusable a particular HV segment.

The drift board is a trapezoidal-shaped printed circuit board (PCB) holding the drift electrode. The board has an active area coated with a copper layer and lies within the active gas volume. The readout board is also trapezoidal-shaped PCB with the inner side of the board featuring 3072 trapezoidal readout strips oriented radially along the longer sides of the detector. All the readout strips are connected through metalized vias to the outer side of the board where traces are routed from the vias to readout pads in partitions of $8 \times 3$ partitions in $(\eta, \phi)$ (Figure 6). Each $\eta$-partition has 384 strips comprised of three 128-strip sectors in $\phi$. Drift, readout boards and external frame define the gas volume with gas tightness ensured by the O-ring placed in the groove of the outer frame [2].

4 Gain Measurements

4.0.1 Test Setup

The detector under test is powered using a programmable high voltage (HV) power supply (CAEN N1470) that allows controlling the current limit ($I_{\text{set}}$), the steps to ramp up and down the voltage, the maximum voltage, and the trip time. The power supply delivers a current up to 1 mA with a monitoring resolution of about 50 nA in order to identify unusual current fluctuations. The measurements are performed by irradiating the detector using mini AMPTEK X-ray Silver (Ag) target source. The detector is irradiated within the closed copper chamber, the design of which is shown in Figure 5, to protect the radiation exposure to human beings.

The detector output (from a sector $(\eta, \phi) = (5, 2)$ as in Figure 6) is read out by using a charge sensitive pre-amplifier (ORTEC 142PC) whose output is sent to an amplifier plus shaper (ORTEC 474) unit followed by a discriminator. The resulting digital pulses from discriminator (Lecroy 623A) are fed to a scaler unit, and the rate plateau is obtained by ramping up the detector slowly using HV source. Even though X-ray photons interaction rate is of the order of the kHz; the primary current is very small and is very challenging to measure it directly from the drift electrode usually powered at high voltage and is prone to noise. The primary current is, therefore, obtained by multiplying rate count ($R$) with number of primary electrons ($n_{e^-}$) per X-ray
**Figure 5:** Design of the setup used for gain measurements with X-ray tube and the GE1/1 detector inside the copper chamber. The copper chamber is completely closed when the detector is exposed to X-rays.

Photon and by elementary charge ($e^-$) induced in the drift gap by the X-ray source. The output current is measured using pico-ammeter connected to Keithley Electrometer Model 6487, and the data is recorded with a Labview program via a General Purpose Interface Bus (GPIB).

### 4.0.2 Results

The chamber is connected to the gas system and flushed with the standard gas mixtures at the flow rate of 5 liters per hour (5 L/hr), and left to flush for at least 5 hours before taking the actual measurement. Two test gas mixtures, Ar/CO$_2$ and Ar/CO$_2$/CF$_4$ in proportion 70/30 and of 45/15/40, respectively, are used. The choice of using CF$_4$ quencher in the latter case is driven by its good timing characteristics [9] and the fact that it is non-flammable, non-corrosive for metals and is safer with respect to other hydrocarbons like methane.

The effective gas gain is measured by exposing the detector to an X-ray source with a silver target for generating X-rays. The incident X-rays consist of silver $K_\alpha$ and $K_\beta$ peaks (centered around the energy of 22 and 25 keV) over an electron bremsstrahlung continuum background. The X-ray photons are absorbed by the copper atoms of the drift electrode which in turn, emits copper X-ray photons of 8 keV energy while returning to the ground state. The X-ray photons emitted by the copper are then converted by photoelectric effect in the active gas volume. The resulting spectrum is thus a convolution of the energies of the incident X-rays photons interacting in the active gas.
volume of the detector, the bremsstrahlung continuum background, and a small fraction of unconverted silver $K_{\alpha}$ and $K_{\beta}$ lines. The gain is then measured in each gas composition by comparing the primary current $I_p$ induced in the drift gap by the X-ray source, and the amplified output current ($I_o$) induced on the readout board.

One such measurement of rate and gain for the sixth generation GE1/1-VI detector is shown in Figure 6 for the gas mixture of Ar/CO$_2$/CF$_4$.

![Figure 6: (left) Map of the readout board showing 24 ($\eta$, $\phi$) sectors of GE1/1 chambers, and (right) Gain and rate measurements of sixth generation chamber (GE1/1-VI) while reading a particular ($\eta$, $\phi$) = (5, 2) sector.](image)

The gain of various other chambers are also estimated, the result of one such a case where a fourth generation GE1/1-IV has been considered is presented in Figure 7 for the gas mixtures Ar/CO$_2$ and Ar/CO$_2$/CF$_4$. It is observed that the gain for GE1/1-IV is higher in Ar/CO$_2$ compared to Ar/CO$_2$/CF$_4$, and is due to electron absorption by CF$_4$ quencher.

Further, the gain measurements are also performed on fourth and sixth generation detectors (GE1/1-IV and GE1/1-VI) for the gas composition of Ar/CO$_2$/CF$_4$. The results are compared and are presented in Figure 7. The results show that the gain is higher for sixth generation GE1/1-VI compared to the fourth generation GE1/1-IV and is attributed to GEM foil orientation. Since GE1/1 detector uses single-mask GEM foils, which are asymmetrically bi-conical in shape compared to symmetrically biconical holes in double-mask foils. The holes with the narrow opening facing the incident radiation (source), which is also now CMS preferred orientation, show higher gain compared to the case when a wider opening of the holes face the incident radiation [7, 8].
Figure 7: (left) Gain of fourth generation GE1/1-IV detector for the gas mixtures Ar/CO$_2$ (70/30) and Ar/CO$_2$/CF$_4$ (45/15/40), and (right) Observed gain of fourth GE1/1-IV and sixth generation GE1/1-VI detectors for Ar/CO$_2$/CF$_4$ (45/15/40). Points represent the data and the solid lines as a fit to the observed data.

5 Efficiency and Timing Measurements

5.1 Beam Facility

The CERN’s Northern Area Experimental Halls (EHs) located at Preveissin site host Super Proton Synchrotron (SPS), a circular particle accelerator and a multi-purpose facility designed to deliver primary ion and attenuated proton beams. This facility is also meant to provide a wide spectrum of secondary and tertiary particle beams of varying and flexible composition (hadrons and leptons) to fixed-target experiments. Before being injected into the LHC main accelerator, the protons beams with 115 billion protons are bunched together (up to 2,808 bunches) . These protons are then prepared by a series of accelerator systems that successively increase their energy. The 50-MeV protons from the the linear particle accelerator are generated, which feeds the Proton Synchrotron Booster (PSB). The PSB accelerates these protons upto 1.4 GeV before they are injected into the Proton Synchrotron (PS). The PS accelerated these protons upto an energy of 26 GeV and injects them into the Super Proton Synchrotron (SPS), the later increases their energy further to 450 GeV before they are at last injected into the LHC ring. For testing prototype detector, the beam is extracted from the SPS and splitted into several channels called as H2, H4, H6, H8, etc. to feed more than one test facility simultaneously.
Figure 8: Schematic of the beam test set-up showing the direction of muon beam, triggering Scintillators (photo multiplier tubes (PMTs)) (in dark grey colour), 10 cm × 10 cm tracking GEMs (in yellow) and GE1/1 chambers (in green) [15].

5.2 Tracking Telescope

The conceived experimental beam-test setup used a similar tracking telescope as developed by RD51 Collaboration [5]. The tracker consists of three organic plastic scintillators S1, S2 and S3, three 10 cm × 10 cm GEM detectors and a movable aluminum structure (Figure 9). The scintillators are used to provide the trigger and, the GEM detectors featuring a strip-based two-dimensional readout plane acts as a tracking system. The movable structure provides the support to the entire tracking as well as to triggering system and also enables the translations in \( \phi \) and \( \eta \) directions to allow the beam alignment with different GE1/1 readout sectors. The test beam setups used in various earlier test campaigns can be found in [5, 6, 10].

Figure 9: (left) Design of the tracking telescope showing three triggering scintillators (in grey colour), 10 cm × 10 cm tracking GEMs (in yellow colour), (middle) movable aluminum stand holding actual GE1/1 chambers in front of the tracking telescope during H4 beam test campaign, and (right) one of the earliest (December 2014) beam test setup at CERN SPS.
5.3 Readout Electronics

Application Specific Integrated Chip (ASIC) VFAT2 [11, 12], a digital front end chip (Figure 10 (left)) originally developed by TOTEM Collaboration [13] is used to read the signal from the GEM chambers. The chip is controlled by TURBO cards, a stand-alone portable control and data acquisition (DAQ) platform developed by TOTEM Test Platforms (TTPs) [14] for front-end VFAT2. Each TURBO card can accommodate up to 8 VFAT chips, and each VFAT2 chip provides a binary output with a variable latency for the position information and a fixed latency output, called SBIT, for the timing information. The TURBO boards are controlled through Labview.

5.4 Results

H4 beamline has been used for the measurements of efficiency and timing resolution of GE1/1 detectors. A secondary beam consisting of pions and their decay products is produced after striking the primary beam on existing Beryllium target. Muon beams of 150 GeV energy are then selected by closing the collimators as they represent minimum ionizing particles (MIPs) at this energy and pass through the collimators while pions are stopped. The GE1/1 chambers are aligned perpendicular to the direction of the muon beam and placed in front of the tracking telescope as shown in Figure 8 (also in Figure 9). Further, chambers are shielded with aluminum and copper-clad foils to reduce the noise level below the expected signals. The beam particles are selected by analog pulses from three scintillators S1, S2, and S3 placed in coincidence and are converted into digital form by using discriminators. The digitized signals are sent to three comparators connected to AND port, the output of which is used as a trigger to master TURBO card. The output from the master TURBO card acts as an input to the slave TURBO card and both the cards received additional inputs from the VFAT2 chips connected to the tracker and GE1/1 chambers.

Out of the 24 ($\eta, \phi$) sectors in GE1/1 chamber, the output from the particular test sector ($\eta, \phi = (5, 2)$) has been sent to the shaper of the VFAT2 and then compared to a customizable threshold used to optimize the process of data acquisition in noisy environments. The beam trajectories are reconstructed from the hit information from the tracking telescope. The beam profile from GE1/1 is obtained from the information collected from TURBO controlled VFAT2 chips and using the track reconstruction algorithm.
5.4.1 Efficiency

The efficiency which represents the probability to record an event when a particle crosses the detector has been estimated by recording the total number of triggers $N$ generated by the coincidence of the three scintillators and number of hits $N_1$, generated by a test region. However, due to the possible misalignment of the test region and particle scattering, the number of hits $N_2$ are also observed from neighboring regions. The efficiency is therefore calculated by removing these additional hits from the total number of triggers and has been calculated by equation 1:

$$\varepsilon = \frac{N_1}{N - N_2}$$

The efficiency of the GE1/1 chambers is measured for the gas mixtures Ar/CO$_2$ (70/30) and Ar/CO$_2$/CF$_4$ (45/15/40) as a function of drift bias. An average efficiency plateau of over 98% is reached at lower voltages for Ar/CO$_2$ gas mixture compared to Ar/CO$_2$/CF$_4$ corresponding to effective gains of $\sim$10$^4$ as shown in Figure 10.

5.4.2 Timing

Timing resolution of GE1/1 detector is an essential parameter as it ensures that it can act as a fast triggering system in CMS and hence can identify correct bunch crossing. It has been estimated as the standard deviation of time distribution of the recorded events with the time reference being the particular instance when the particles cross the drift volume of GE1/1 chambers. The trigger signals from the coincidence of the three scintillators
are sent to the common stop input of a Time to Digital Converter (TDC) unit (CAEN V775), and the latency output from the detector under test is also sent to one of the inputs of the same TDC. For each event, the time difference between the two digital signals is determined. The time resolution is then obtained from the width of the resulting distribution.

**Figure 11:** (left) The timing resolution for Ar/CO$_2$ (70/30) and Ar/CO$_2$/CF$_4$ (45/15/40) gases as a function of gain. The fit equations from Figure 10 (right) are used to obtain new data points by interpolation, the solid lines merely connect the points and (right) rate capability of a GE1/1-IV chamber, the Figure is also merged with a rate capability of a 10 cm × 10 cm test detector. The shaded portion 'CMS Region' is the expected particle flux region of the CMS during HL-LHC.

However, there are fluctuations in the period between a reference time and the detection of the signal due to the variations in the distance between the primary cluster formed in the drift region and the first GEM from one event to another. After crossing first GEM foil, the charges follow the same path length till they are detected at the readout board. The time resolution is degraded by the diffusion of the charges in the gaps between the GEM foils and this degradation, however, is improved by the addition of component gas with low diffusion coefficient such as CF$_4$. The estimated results are depicted in Figure 10 and correspond to GE1/1-IV for gas compositions Ar/CO$_2$ and Ar/CO$_2$/CF$_4$. The timing resolution primarily depends upon the drift voltage at a constant value of transfer and induction fields. However, GE1/1 chambers are powered using a divider chain allowing all the fields to vary simultaneously. Therefore, it is very difficult to make any conclusive statement for the timing improvement of Ar/CO$_2$/CF$_4$ with respect to Ar/CO$_2$ mixture in the present case. Therefore, results are expressed as a function of gain (Figure 11) and are obtained by fitting timing data in Figure 10 (right). The plot shows that there is an improvement of ∼ 24% by adding CF$_4$ component in Ar/CO$_2$. The CMS Region in the plot, defines the timing resolution of GE1/1 detectors when they will be operating in the CMS.
6 Rate Capability

The flux in the CMS end-caps is not expected to exceed 10 kHz/cm\(^2\). Therefore, rate capability of GE1/1 chambers is measured by varying the flux of X-ray photons at the starting gain equal to the expected CMS operational gain of the chambers (\(\sim 7 \times 10^3\)) \cite{3}. In a separate campaign, rate capability is measured for a 10 cm \(\times\) 10 cm test detector with 2/2/2/2 mm gap configuration at a starting gain of \(\sim 1.5 \times 10^4\) in Ar/CO\(_2\) (70/30) \cite{7, 16}. In each case, the chambers are irradiated with a very intense X-ray source, and the amplified current is measured using a pico-ammeter connected to the anode of the detector. The incident particle flux is varied by using copper attenuators, and the effective gain is measured (Figure 11 (right)). It is found that the effective gain remains stable up to \(10^5\) kHz/cm\(^2\). Therefore, we consider rate capability of \(10^5\) kHz/cm\(^2\), a constant factor in the present note.

7 Discharge probability

The GE1/1 detectors are to be operated at sufficiently high gains (\(\sim 10^4\)) to ensure the maximum detection efficiency while maintaining the timing performance. However, in case of intense particle fluxes or densely ionizing trails, operating a detector at high gains increases the probability of producing discharges which could damage the detectors. Discharges initiate when the charge exceeds Raether limit \cite{18}, resulting in the variations in the local electric field. The local perturbation of the electric field can afterwards transform the avalanche into a streamer which propagates through both the directions of GEM electrodes and hence provokes the electrical breakdown of the gas. The three amplification stages, however, in GE1/1 chamber are slightly set to different gains by applying different voltages across the foils. The voltage across first GEM foil is 3\% higher than on second GEM foil which itself is 5\% higher than third foil. This configuration reduces the probability of discharge significantly because of the gain sharing between three amplification stages, and also because these layers are independent of the readout plane which considerably diminishes the propagation of a streamer before further amplification. The particular design, in turn, reduces their probability of inducing large signals on the readout board and reduces the chances of possible damage to detector and electronics.

Furthermore, the design of GEM foils is such that the electrodes facing the drift plane are divided into several sectors with each sector having an area nearly equal to 100 cm\(^2\). Each sector is mounted with 10 M\(\Omega\) protection resistor, and in the extreme case of a discharge, the current flowing through
the resistance will induce a voltage drop across it. This design, in turn, will limit the available charge, and the maximum energy of the discharges and hence helps to reduce the propagation of the discharges. CMS has adopted the sectorization of the GEM foils, the use of protection resistors to limit the energy available in case of a discharge, and the asymmetric distribution of charge-amplifying electric fields over the three GEM foils after following the recommendations in [17].

The discharge probability is estimated for third generation GE1/1 [3] and separately for a 10 cm × 10 cm test detector with the similar gap configuration as GE1/1 [16]. In each case, gain is set to extremely high values ranging from 4 to 6 × 10^5 (Figure 12) and the detector is irradiated by densely ionizing α-particles from 241Am source. The actual discharge probability is then calculated by extrapolating its behavior against the drift potential (V). However, the alpha particle from the 241Am source, produces nearly hundred times more primaries than a MIP and hence, the discharge probability is divided by this factor and is observed to be less than 10^{-11} for MIPs in standard CMS operating conditions (Figure 13) as shown in Figure 12.

8 Summary and Outlook

Different GE1/1 generations are tested for gain, efficiency, timing resolution, and discharge probability for the gas composition Ar/CO₂ and Ar/CO₂/CF₄. Gain measurements show that the detector can be operated smoothly
up to a gain of about $10^5$ with a discharge probability of less than $10^{-11}$ under CMS operating conditions and with a rate capability up to $10^6$ Hz. The performance of the chamber in beam tests show an efficiency of 98% or better obtained across the active area and timing resolution nearly equal to 5 ns. The observed data is fitted with various equations and the results are presented in the Table 1. By using these fit equations, the pseudo data points are calculated using the technique of interpolation. The new data points describe the observed data very well and have been plotted in the Figure 13 and Figure 14, respectively. These master plots are obtained using the data from GE1/1-IV or earlier releases and describe the gain, discharge probability, efficiency, and timing resolution for Ar/CO$_2$ and Ar/CO$_2$/CF$_4$ gasses, respectively. The results are also compared for the timing resolution of Ar/CO$_2$ with its corresponding value for Ar/CO$_2$/CF$_4$. For a given value of gain, resolution for Ar/CO$_2$/CF$_4$ appears to be $\sim 23\%$ ns better than the corresponding value for Ar/CO$_2$. In other words, by adding CF$_4$ to Ar/CO$_2$, timing performance of the detector is improved. It also allows the detector to operate at the lower gains, hence reducing the discharge probability. Further, these parameters are optimized and accordingly under efficient, standard CMS, and extrapolated regions are defined. The CMS Region is the most important region for CMS Collaboration as it descibles the operational conditions of GE1/1 chambers while they will be in operation in CMS.

### Table 1: The fit equations and the value of constants obtained by fitting gain, efficiency, timing resolution and discharge probability data for the gas compositions Ar/CO$_2$ and Ar/CO$_2$/CF$_4$.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Property</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>Fit Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar/CO$_2$</td>
<td>Gain</td>
<td>270.88</td>
<td>-22.72</td>
<td>0.007</td>
<td>$G = a \cdot \exp(b + cV)$</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>0.983</td>
<td>2885.12</td>
<td>62.59</td>
<td>$\varepsilon = a / 1 + \exp(V - b)/c$</td>
</tr>
<tr>
<td></td>
<td>Timing Resolution</td>
<td>58.45</td>
<td>2446.34</td>
<td>441.4</td>
<td>$R = a / 1 + \exp(V - b)/c$</td>
</tr>
<tr>
<td></td>
<td>Discharge Probability</td>
<td>1.002 $\times 10^{-14}$</td>
<td>0</td>
<td>0.013</td>
<td>DP = a * $\exp(b + cV)$</td>
</tr>
<tr>
<td>Ar/CO$_2$/CF$_4$</td>
<td>Gain</td>
<td>4346.63</td>
<td>-26.27</td>
<td>0.0068</td>
<td>$G = a \cdot \exp(b + cV)$</td>
</tr>
<tr>
<td></td>
<td>Efficiency</td>
<td>0.99</td>
<td>3502.37</td>
<td>50.78</td>
<td>$\varepsilon = a / 1 + \exp(V - b)/c$</td>
</tr>
<tr>
<td></td>
<td>Timing Resolution</td>
<td>39.24</td>
<td>3146.77</td>
<td>428.09</td>
<td>$R = a / 1 + \exp(V - b)/c$</td>
</tr>
<tr>
<td></td>
<td>Discharge Probability</td>
<td>1.79 $\times 10^{-28}$</td>
<td>0</td>
<td>0.009</td>
<td>DP = a * $\exp(b + cV)$</td>
</tr>
</tbody>
</table>
Figure 13: Master plot of GE1/1 detectors showing the gain (green), discharge probability (black), efficiency (red) and timing resolution (blue) for the gas composition Ar/CO₂ (70/30) as a function of drift voltage. The axes and corresponding data are represented by the unique color code in the plot. Also, the plot shows the shaded region which is the recommended operational region of the chambers during their use in CMS.

Figure 14: Master plot of GE1/1 detectors showing the gain (green), discharge probability (black), efficiency (red) and timing resolution (blue) for the gas composition Ar/CO₂CF₄ (45/15/40) as a function of drift voltage. The axes and corresponding data are represented by the unique color code in the plot. Also, the plot shows the shaded region which is the recommended operational region of the chambers during their use in CMS.
Acknowledgements

We gratefully acknowledge the support from FRS-FNRS (Belgium), FWO-Flanders (Belgium), BSF-MES (Bulgaria), BMBF (Germany), DAE (India), DST (India), INFN (Italy), NRF (Korea), LAS (Lithuania), QNRF (Qatar), and DOE (USA) and the RD51 collaboration.

A Expected GE1/1 HV operating conditions for Ar/CO₂ gas

<table>
<thead>
<tr>
<th>Drift Voltage (V)</th>
<th>Gain</th>
<th>Efficiency</th>
<th>Resolution (ns)</th>
<th>Rate Capability (kHz/cm²)</th>
<th>Discharge Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2900</td>
<td>1.02×10²</td>
<td>0.54</td>
<td>17.42</td>
<td>10⁵</td>
<td>2.36×10⁻¹⁷</td>
</tr>
<tr>
<td>3000</td>
<td>2.17×10²</td>
<td>0.84</td>
<td>14.54</td>
<td>10⁵</td>
<td>8.68×10⁻¹⁷</td>
</tr>
<tr>
<td>3100</td>
<td>4.60×10²</td>
<td>0.95</td>
<td>12.04</td>
<td>10⁵</td>
<td>3.18×10⁻¹⁶</td>
</tr>
<tr>
<td>3200</td>
<td>9.74×10²</td>
<td>0.97</td>
<td>9.912</td>
<td>10⁵</td>
<td>1.16×10⁻¹⁵</td>
</tr>
<tr>
<td>3300</td>
<td>2.06×10³</td>
<td>0.98</td>
<td>8.109</td>
<td>10⁵</td>
<td>4.28×10⁻¹⁵</td>
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<tr>
<td>3400</td>
<td>4.36×10³</td>
<td>0.98</td>
<td>6.60</td>
<td>10⁵</td>
<td>1.57×10⁻¹⁴</td>
</tr>
<tr>
<td>3500</td>
<td>9.24×10³</td>
<td>0.98</td>
<td>5.35</td>
<td>10⁵</td>
<td>5.77×10⁻¹⁴</td>
</tr>
<tr>
<td>3600</td>
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<td>0.98</td>
<td>4.32</td>
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<td>2.11×10⁻¹³</td>
</tr>
<tr>
<td>3700</td>
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<td>3.48</td>
<td>10⁵</td>
<td>7.77×10⁻¹³</td>
</tr>
<tr>
<td>3800</td>
<td>8.76×10⁴</td>
<td>0.98</td>
<td>2.80</td>
<td>10⁵</td>
<td>2.85×10⁻¹²</td>
</tr>
<tr>
<td>3900</td>
<td>1.85×10⁵</td>
<td>0.98</td>
<td>2.25</td>
<td>10⁵</td>
<td>1.00×10⁻¹¹</td>
</tr>
<tr>
<td>4000</td>
<td>3.93×10⁵</td>
<td>0.98</td>
<td>1.80</td>
<td>10⁵</td>
<td>3.84×10⁻¹¹</td>
</tr>
<tr>
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<td>0.98</td>
<td>1.44</td>
<td>10⁵</td>
<td>1.40×10⁻¹⁰</td>
</tr>
</tbody>
</table>

Table 2: The gain, efficiency, rate capability and discharge probability as a function of drift voltage for GE1/1 chambers corresponding to Ar/CO₂ gas. The green region are the recommended working points while as light gray is under efficient region. The red region is merely an extrapolation and would be strongly avoided becasue of steep rise in discharge probability.
B Expected GE1/1 HV operating conditions for Ar/CO$_2$/CF$_4$ gas

<table>
<thead>
<tr>
<th>Drift Voltage (V)</th>
<th>Gain</th>
<th>Efficiency</th>
<th>Resolution (ns)</th>
<th>Rate Capability (kHz/cm$^2$)</th>
<th>Discharge Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2900</td>
<td>0.62×10$^4$</td>
<td>0.00</td>
<td>24.67</td>
<td>10$^5$</td>
<td>3.87×10$^{-19}$</td>
</tr>
<tr>
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<td>1.22×10$^4$</td>
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<td>10$^5$</td>
<td>9.52×10$^{-19}$</td>
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<tr>
<td>3100</td>
<td>2.41×10$^4$</td>
<td>0.00</td>
<td>20.21</td>
<td>10$^5$</td>
<td>2.34×10$^{-18}$</td>
</tr>
<tr>
<td>3200</td>
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<td>0.00</td>
<td>17.93</td>
<td>10$^5$</td>
<td>5.76×10$^{-18}$</td>
</tr>
<tr>
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<td>10$^5$</td>
<td>1.41×10$^{-17}$</td>
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<tr>
<td>3400</td>
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<td>0.11</td>
<td>13.55</td>
<td>10$^5$</td>
<td>3.48×10$^{-17}$</td>
</tr>
<tr>
<td>3500</td>
<td>3.66×10$^5$</td>
<td>0.48</td>
<td>11.56</td>
<td>10$^5$</td>
<td>8.57×10$^{-17}$</td>
</tr>
<tr>
<td>3600</td>
<td>7.23×10$^5$</td>
<td>0.86</td>
<td>9.75</td>
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<td>2.10×10$^{-16}$</td>
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<tr>
<td>3700</td>
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<td>8.14</td>
<td>10$^3$</td>
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<tr>
<td>3800</td>
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<td>6.73</td>
<td>10$^5$</td>
<td>1.27×10$^{-15}$</td>
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<tr>
<td>3900</td>
<td>5.56×10$^6$</td>
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<td>10$^5$</td>
<td>3.13×10$^{-15}$</td>
</tr>
<tr>
<td>4000</td>
<td>1.09×10$^7$</td>
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<td>5.51</td>
<td>10$^5$</td>
<td>7.71×10$^{-15}$</td>
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<tr>
<td>4100</td>
<td>2.16×10$^7$</td>
<td>0.98</td>
<td>3.66</td>
<td>10$^3$</td>
<td>1.89×10$^{-14}$</td>
</tr>
</tbody>
</table>

Table 3: The gain, efficiency, rate capability and discharge probability as a function of drift voltage for GE1/1 chambers corresponding to Ar/CO$_2$/CF$_4$ gas. The green region are the recommended working points while as light gray is under efficient region. The red region is merely an extrapolation and would be strongly avoided because of steep rise in discharge probability.

References


