ROBUSTNESS TEST OF A SYSTEM OF MSGC+GEM DETECTORS AT THE CYCLOTRON FACILITY OF THE PAUL SCHERRER INSTITUTE

M. Ageron\textsuperscript{a}, A. Albert\textsuperscript{e}, T. Barvich\textsuperscript{c}, W. Beaumont\textsuperscript{i}, T. Beckers\textsuperscript{i}, K. Bernier\textsuperscript{h}, P. Blüm\textsuperscript{c}, O. Bouhali\textsuperscript{i,1}, I. Boulogne\textsuperscript{f}, D. Bouvet\textsuperscript{a}, J.M. Brom\textsuperscript{g}, F. Charles\textsuperscript{e}, J. Coffin\textsuperscript{g}, D. Contardo\textsuperscript{a}, E. Daubie\textsuperscript{f,2}, F. Didierjean\textsuperscript{g}, M. Erdmann\textsuperscript{c}, G. De Lentdecker\textsuperscript{j,3}, O. Devroede\textsuperscript{k}, J. De Troy\textsuperscript{i}, J.P. Ernenwein\textsuperscript{e}, M. Fahrer\textsuperscript{c}, G. Flügge\textsuperscript{d}, J.C. Fontaine\textsuperscript{e}, W. Geist\textsuperscript{g}, U. Goerlach\textsuperscript{g}, M. Gottschalk\textsuperscript{d}, J.M. Helleboid\textsuperscript{g}, D. Huss\textsuperscript{e}, F. Iacopi\textsuperscript{k}, K. Kärcher\textsuperscript{c}, F. Kühn\textsuperscript{c}, P. Juillot\textsuperscript{g}, A. Lounis\textsuperscript{g}, C. Maazouzi\textsuperscript{g}, D. Macke\textsuperscript{d}, C. Martin\textsuperscript{a}, L. Mirabito\textsuperscript{a}, S. Moreau\textsuperscript{g}, T. Müller\textsuperscript{c}, D. Neuberger\textsuperscript{c}, A. Nowack\textsuperscript{d}, S. Perries\textsuperscript{a}, I. Ripp-Baudot\textsuperscript{g}, F. Röderer\textsuperscript{c}, R. Schulte\textsuperscript{d}, L. Shekhtman\textsuperscript{b}, H.J. Simonis\textsuperscript{c}, W. Struczinski\textsuperscript{d}, A. Tatarinov\textsuperscript{b}, W.H. Thümmel\textsuperscript{c}, F. Udo\textsuperscript{k}, W. Van Doninck\textsuperscript{k,4}, C. Van Dyck\textsuperscript{i}, C. Vander Velde\textsuperscript{j}, P. Vanlaer\textsuperscript{j,5}, L. Van Lancker\textsuperscript{k}, T. Weiler\textsuperscript{c}, A. Zander\textsuperscript{d}, A. Zghiche\textsuperscript{g}, V. Zhukov\textsuperscript{j,6}

\textsuperscript{a}Institut de Physique Nucléaire, Lyon, France
\textsuperscript{b}Budker Institute for Nuclear Physics, SB RAS, Novosibirsk, Russia
\textsuperscript{c}Institut für Experimentelle Kernphysik, Universität Karlsruhe (TH), Karlsruhe, Germany
\textsuperscript{d}RWTH, III. Physikalisches Institut B, Aachen, Germany
\textsuperscript{e}G.R.P.H.E. - Université de Haute Alsace, Mulhouse, France
\textsuperscript{f}Université de Mons - Hainaut, Mons, Belgium
\textsuperscript{g}Institut de Recherches Subatomiques, IN2P3-CNRS-ULP, Strasbourg, France
\textsuperscript{h}Université Catholique de Louvain, Louvain-La-Neuve, Belgium
\textsuperscript{i}Universiteit Antwerpen (UIA), Antwerpen, Belgium
\textsuperscript{j}Université Libre de Bruxelles, Brussels, Belgium

Preprint submitted to Elsevier Preprint 21 June 2000
Abstract

A system of detector modules consisting of a large size Gas Electron Multiplier (GEM), coupled to Micro Strip Gas Counters (MSGC), has been exposed to a pion beam at the Paul Scherrer Institute Cyclotron facility. As part of a CMS tracker milestone, the aim of this test was to investigate the robustness of such detectors when exposed to experimental conditions close to what is expected at the Large Hadron Collider (LHC) of CERN. Eighteen detector modules have been operated at voltage settings corresponding to a 98 % detection efficiency for Minimum Ionizing Particles during a period of five weeks. Sparking rates and strip losses have been monitored throughout the exposure. An operation margin of at least a factor of three w.r.t. the required gas gain has been demonstrated.

1 Introduction

Micro Strip Gas Counters (MSGC) have been considered to equip the outermost layers (total surface > 200 m²) of the central tracking system of the Compact Muon Solenoid experiment (CMS) (1) at the Large Hadron Collider (LHC) under construction at CERN. Experimental results from similar detectors exposed to an intense pion beam of relatively low energy (350 MeV/c) or to alpha sources showed destructive sparking behaviour, questioning the robustness of such detectors in LHC like conditions (2). Triggered by these observations, a milestone test of a large system of CMS MSGC detectors of final design was set up in accordance with the requirements of the LHC committee. This beam test was run in the πM1 pion beam at the cyclotron facility of the Paul Scherrer Institute (PSI) in Villigen (CH) at the end of 1999 in an exposure that lasted for five weeks. The results of this milestone test of the forward - backward MSGC + GEM system are reported in this paper. Initially the definition of the milestone test is given. The detectors, their assembly and commissioning prior to the exposure at PSI are described next. After reviewing the experimental set-up and running conditions, the results of the milestone test as well as of the exploration of operation margins are then given.

1 Presently at NIKHEF, Amsterdam, Netherlands
2 Scientific Collaborator, FNRS, Belgium
3 Supported by FRIA, Belgium
4 Research Director FWO, Vlaanderen
5 Chargé de Recherches au FNRS, Belgium
6 Supported by FNRS, on leave of absence, MSU, Moscow
In its simplest version, an MSGC detector consists of a glass substrate of 300 μm thickness on which a regular pattern of alternating anode and cathode strips is deposited by a photolithography procedure. Anode widths typically range from 7 to 10 μm, while cathode strips are much wider, about 90 μm. Anode pitches ranging from 180 to 400 μm have been produced and tested, whereas strip lengths up to 27 cm have been manufactured. A metallised drift electrode placed about 3 mm above the substrate encloses the gas volume and completes the sensor.

A possible drawback of the MSGC technology has been reported by the GDD group at CERN and the Hera-B Collaboration, showing that sparks may develop between anodes and cathodes in the presence of Highly Ionizing Particles (HIP) (2; 3). Such sparks can damage and eventually interrupt the anode strips. First observed with α particles, this behaviour was confirmed in the low energy pion beam at PSI where the experimental conditions are close to those expected at the LHC. Triggered by this observation, the groups involved in the MSGC project of the CMS tracker, in agreement with the LHC committee referees, have defined milestone tests to demonstrate the robustness of the MSGC detectors developed within CMS.

For the end cap parts of the CMS MSGC tracker, the same solution as for Hera-B has been adopted. A Gas Electron Multiplier (GEM) (4) has been added in the drift region, 3 mm below the drift electrode and 2 mm above the MSGC substrate (5). Such an arrangement is schematically illustrated in figure 1. The gas amplification taking place both in the GEM holes and near the anode strips of the MSGC, a two-stage gas amplification is thus obtained which was shown to substantially improve the robustness of the detector in the presence of HIPs (6).

For the barrel part, a different solution has been developed to avoid damaging sparks. The cathode edges have been passivated by a narrow (6 μm) strip of polyimide. This lithographic step, called “advanced passivation”, has shown to postpone the onset of sparking due to the reduction of the electric field at the cathode edges where sparks are initiated (7).

The milestones have been defined by imposing a ceiling on the number of interrupted anode strips, such that less than 10% of the strips would be lost after 10 years of operation at the LHC (5×10⁷ seconds) at full luminosity. Since the interruption of a single anode does not lead to a loss of detection efficiency because the ionization charge is collected by the neighbouring anodes, this ceiling would imply that in 5% of the detector area the spatial resolution is somewhat degraded, typically from 35 μm to about 60 μm (8).
For the barrel milestone, a minimum of 25 MSGC detectors had to be exposed for 360 hours with a ceiling of 33 interrupted anodes. For the forward milestone, 24 MSGC substrates exposed to the beam were allowed a maximal strip loss of 32 anodes.

In the present paper, the results of the end cap milestone will be described, the barrel milestone results are given elsewhere (9).

3 The forward milestone detectors, assembly and commissioning

The forward multi-substrate detector modules developed for CMS consist of four wedge shaped MSGC substrates glued side by side on a common Peek frame, yielding a detector with the shape of a sector of an annulus and a single gas volume (10). Neighbouring substrates are aligned such that the anode pitch across the boundary between substrates is twice the pitch elsewhere on the substrates. With such an assembly it was shown that no detection efficiency loss occurs between adjacent substrates (8).

For the milestone at PSI, modules of the second innermost detection ring have been produced. Each MSGC substrate of trapezoidal shape had 512 anode strips of 7 µm width at a pitch of 200 µm at the long base. The strip length was 10 cm. Three different companies produced substrates for the milestone on DESAG glass D263 of 300 µm thickness. Contrary to the barrel substrates, no coating and no passivation was applied. In all cases, the strip metallization was gold, produced by the lift-off technique at IMT (CH), with direct gold wet etching at OPTIMASK (F) and with electroless plating at IMEC (B).

A total of 91 MSGC substrates have been delivered by these three companies. Out of the total production, 72 substrates have been used to build 18 detector modules containing four MSGC substrates each.

Seventeen modules have been equipped with a GEM foil produced at CERN. These large GEM foils in one piece (50 × 15 cm²) had their copper electrodes segmented into 4 sections matching the MSGC substrates. One detector module was equipped with a GEM foil produced by Würth Elektronik GmbH (D) without such segmentation.

Prior to the assembly, every substrate was cut to the required shape and dimensions using a diamond scriber. Because of the multi-substrate assembly, the cut is performed parallel to the edge cathode strips at a distance of only 20 µm. Every anode strip of each substrate was probed to measure its capacitance. This procedure allows to register anode interruptions and short circuits present in the artwork. In the 72 substrates used for the 18 detector modules,
less than 1% of strips were affected by such lithographic defects. Before gluing, the substrates are rinsed in isopropyl alcohol and subsequently in deionised water in an ultrasonic bath. The module assembly proceeds using precision gibs for substrate alignment under a 3D measuring device or using an optical fiber system allowing to reach a positioning accuracy of less than 5 µm.

Before assembly, every GEM foil was tested in dry atmosphere at a potential difference of 500 V between the electrodes. Afterwards, the foil is stretched and glued together with the gold plated Ferrozell drift plane and two frames of 3 mm (defining the drift region) and 2 mm (defining the transfer gap). This assembled cover is then aligned and glued over the substrates already glued to the support frame.

For the milestone detectors, only the two central MSGC substrates have been equipped with ceramic hybrids holding four PREMUX preamplifier chips (11) of 128 channels each. Wire bonding of the anode strips to the preamplifier chips via a pitch-adapter is performed after the closing of the gas volume. The anodes of the edge substrates of the modules were bonded to a grounded bus. All cathode strips, grouped in blocks of 16, were connected to the high voltage supply via a 10 MΩ bias resistor. High voltage was supplied to the four substrates from the same side as the readout. The GEM electrodes were powered separately via a 5 MΩ resistor and an RC filter. Figure 2 shows an assembled forward milestone detector. Two finalized detector modules were then mounted back-to-back on a central aluminum support plate designed to fit in the bench holding the detectors in the beam.

Gas supply enters the module below the GEM foil and exits above it in the drift region. The detectors mounted on the same support plate are put in serial gas flow. Before leaving to PSI all detector modules have been brought to nominal voltages, typically -500 V on cathodes and 380 V across the GEM, and tested with cosmic muons and a 90Sr source. Maps of alive strips have been recorded. The timescale for the assembly and commissioning process described above amounted to only 2.5 months.

4 The experimental set-up at PSI and the running conditions

Nine support plates with two detector modules each were installed on the bench in the πM1 pion beam of momentum 350 MeV/c at the cyclotron facility of PSI. The forward milestone detectors were sandwiched between two boxes, each containing 16 barrel milestone MSGCs as shown in figure 3. The gas mixture used was Ne/DME 2/3 and was fed in parallel to the nine pairs of modules with a flush rate of 1 l/h, yielding two gas renewals per hour.
The trigger system consisted in a series of scintillation counters that also provided a measurement of the particle rates. At full intensity the rate at the exit of the collimators, reaches up to 10 kHz/mm² depending on the primary current in the machine. This rate exceeds the one expected at the LHC in the innermost layers of the MSGC tracker, at a radius of 0.7 m. The beam profile is rather wide and the rate drops by about a factor of two outside an area of about 10 × 10 cm². Along the set-up with a length of 2.5 m, the rate drops by about a factor two due to the beam divergence. At the location of the forward milestone detectors, the particle rate in high intensity was above 4 kHz/mm², which is close to the anticipated LHC conditions, and covers the two central substrates of the modules.

The five weeks period of exposure time has been subdivided in four phases: the setting-up period of about one week, the hardening phase of one week where “infant mortality” of weak strips or electronic channels was allowed to occur. The milestone period proper, lasting for 376 hours of high intensity exposure, and finally the last week which was devoted to the investigation of operation margins.

During the setting-up phase, detectors were brought to the “working point”, defined as voltage settings at which the signal to noise ratio (SNR) is such as to guarantee 98 % detection efficiency for Minimum Ionizing Particles (MIP) with the final readout electronics (APV) foreseen in CMS (1). This minimal SNR has been measured in particle beams at CERN (12), but has also been determined during low intensity running at PSI itself. To this end, two detectors in the middle of the string of forward detectors were used. Tracking was performed through seven detection planes, three upstream and four downstream of the central modules for which a cathode voltage scan of the MSGC substrates was performed. A track was accepted if the tracking planes recorded seven aligned hits. A hit is defined by a cluster charge exceeding 3.4 times the RMS value of the cluster noise. Figure 4 shows the resulting efficiency plateau as a function of the SNR. Throughout this paper the SNR is defined as the maximum probability of the Landau charge distribution of the largest cluster detected in the module for a given scintillator trigger, divided by the quadratic mean of the noise for all strips belonging to the cluster. A 98 % detection efficiency is reached at a SNR value of 17, confirming the results obtained elsewhere (12). For the milestone test the PREMUX front-end chip was used (11). Taking into account the ballistic deficit and the extra noise that the deconvolution of the signal will bring once the final APV chip is used, the minimal SNR with PREMUX has to be increased by a factor 2.2 to guarantee 98% MIP detection efficiency at the LHC. The forward milestone has therefore been run at voltage settings yielding a SNR of 37 or more, measured during the low intensity periods which were typically taken twice per 24 hours. During the high intensity runs, as the cluster with the highest SNR is always chosen, an apparent SNR of substantially larger value is observed. This is due
to several particles recorded by the detectors at every trigger, above 7.

Throughout the entire test period, the spark rate and the strip loss have been monitored. Streamers and possible sparks were recorded via current excursions registered by picoamperemeters connected to the detector electrodes. Figure 5 shows a typical example of a discharge of one group of 16 strips where the charge (\( \sim 34-37 \) nC) corresponds to the energy stored in the capacitance of one cathode group. To monitor the strip loss, three methods have been exploited:

- investigation of the RMS value of the noise determined from the daily pedestal runs. Interrupted anode strips have a reduced capacitance and hence a reduced noise.
- monitoring of the beam profiles.
- injection of a signal that capacitively coupled to the readout channels.

A strip was considered as interrupted if confirmed by all three methods. As an example, figure 6 illustrates the search using the RMS method: the loss of anode strip number 111 during the milestone exposure can be clearly seen, whereas strip number 363 was missing already before the exposure.

5 Results from the hardening and milestone phases

To illustrate the tracking capability of the MSGC set-up installed at PSI, figures 7 and 8 show for a given trigger the cluster charge (height of the towers) as a function of the strip number, in the 2\( \times \)16 barrel MSGCs with vertical strips as well as in the 18 forward MSGC+GEM modules with close to horizontal strips during low and high intensity exposure, respectively. The triggered particle track is clearly seen at low intensity. At high intensity several other tracks are added, not necessarily in time with the trigger. A projection of these events is shown in figures 9 and 10 displaying the module number as a function of the strip number; the density of points is proportional to the signal charge. Notice the presence of HIPs with large cluster charge, and the small amount of noise hits in the low intensity plots.

During the hardening phase that lasted for one week, the detector modules experienced high intensity exposure for the first time. For the MSGC+GEM detector modules of the forward milestone, a given SNR can be attained with several different combinations of the voltage settings on the different electrodes. Tuning of the voltage as to obtain a SNR value around 40, was performed such that the sparking rate in high intensity was minimized. The two stages of gas amplification were tuned such that each of them remained safely below critical operation. For all the detector modules the voltages to reach a SNR around 40 were in the following ranges:
negative voltage on the cathodes: 420-490 V  
voltage difference on the GEM electrodes: 320-410 V  
transfer field strength: 3.5-4.5 kV/cm  
drift field strength: 3.5-5 kV/cm.

In the course of this tuning of voltages, the spark rate and the anode interruptions were continuously monitored and guided the optimization procedure. During the voltage tunings, short excursions into unstable regimes sometimes occurred. It is therefore difficult to disentangle strip loss due to these excursions from infant mortality of weak strips. In total, 41 strips out of the 18000 exposed, were lost during the setting-up and hardening period, whereas one short circuit developed (group of 16 cathodes) in one substrate. The highest strip loss in a single substrate amounts to 9 anodes. At the end of the hardening period, voltage settings were not changed by more than a few percent throughout the 376 hours of high intensity running in the milestone period. All detector modules, except the one equipped with IMEC substrates, were found adequate to participate to the milestone. The IMEC detector showed instabilities at rather low voltages due to the bad quality of the gold plating and was discarded from further analysis. In addition, one more substrate, that showed the highest strip loss during the hardening phase was not considered for participating in the milestone period: inspection of the “road sheets” of this substrate revealed that the cutting on one edge was performed inside the metallisation, leaving metallised chips on the artwork. This substrate would have been discarded before module assembly. Its strip loss can not be considered as statistical in nature and should thus not be extrapolated to LHC conditions.

The stability of the detector operation is depicted in plots of the SNR versus the date, both for low and high intensity periods. The corresponding spark rate is also given for the 2 MSGC substrates illuminated by the beam. Figure 11 shows such a plot for a detector module with an average spark rate of $10^{-4}$ Hz, characteristic for the majority of the detector modules. The spark rate at the working point varied for all detectors between $10^{-5}$ Hz and $10^{-3}$ Hz. For the 33 MSGC substrates, 24 strips out of the 16896 exposed were lost during the milestone period. The history of strip loss throughout the milestone period is depicted in figure 12 showing the cumulated number of lost anodes as a function of the date for the 33 substrates of the forward detector modules considered during the robustness test. The milestone ceiling is also shown and clearly the slope of the actual strip loss remains well below this ceiling.
During the last week of exposure, the voltages on the different electrodes have been increased to operate the detector modules at higher gain. Spark rate and strip loss have been monitored throughout. Figure 13 illustrates the behaviour of a detector module during the margin period. For 50 hours, all detectors were operated above the working point gas gain without noticeable increase in the spark rates. Towards the end of the period, all detectors reached a SNR up to 3 times the required gas gain and were operated for about 12 hours without substantial instabilities. It was found that to increase the SNR, the potential difference on the GEM foil could be increased without producing instabilities and strip loss. The total amount of strips lost during the operation with an increased potential difference on the GEM foil is 11 for all the detectors.

7 Summary and conclusions

Within the framework of the development of the MSGC sensors for the central tracking system of CMS, a milestone has been set to test the robustness of these detectors when exposed to LHC like conditions. For the forward-backward part, a multi-substrate detector module equipped with a large size GEM foil has been designed corresponding to the next to innermost detector ring. Eighteen such detector modules have been built, representing more than 1 m² or about 1 % of the required final forward MSGC tracker surface. During a 5 weeks exposure to a high intensity pion beam of momentum 350 MeV/c, none of the shortcomings reported for similar detectors have been detected. The rate of sparks induced by HIPs was modest and the resulting loss of anode strips remained well below the imposed ceiling when running the detectors at their working point for operation at the LHC. Extrapolation to 10 years of exposure at the LHC indicates that the anticipated strip loss would result in a slight worsening of the spatial resolution for less than 4 % of the area covered. It was also shown that all the detector modules could safely be operated up to 3 times the required gas gain before instabilities set in. The successful completion of this milestone undoubtedly proves that such detectors are appropriate for safe long-term operation at the LHC and that they fulfill all the requirements for the outer layers of the CMS central tracker. In view of the large scale of this test, 72 MSGC substrates assembled, and considering the short time scale in which the detectors have been built and commissioned, all observations confirm the readiness of such sensors for mass production.
8 Acknowledgements

We wish to express our thanks to A. Gandi, J.-C. Labbe and R. De Oliveira for their contribution. Their efficient manufacturing of the GEM foils was essential to the success of the milestone.

We are also deeply indebted to the CERN-CMS group, in particular J. Martin, R. Hammarström, P. Siegrist and P. Mattig. Without their help and continuous support, the milestone could not have taken place.

We would like to acknowledge the assistance of the whole staff of the Paul Scherrer Institute. This work would not have been possible without their skill and experience in the beam operations.

References

   B. Boimsta et al., Nuclear Physics B 61B (1998)
[9] R. Bellazzini et al. to be published
Fig. 1. Scheme of the principle of a MSGC+GEM detector.
Fig. 2. Forward multi-substrate MSGC+GEM detector module mounted on the support plate with electronic readout and power supply boards.
Fig. 3. Photo of the bench of the barrel + forward milestone test at PSI. The 18 forward detector modules are sandwiched between 2 boxes with 16 barrel MSGCs each.
Fig. 4. Efficiency versus SNR for two forward MSGC+GEM detectors as measured during low intensity runs at PSI.
Fig. 5. Cathode current as a function of time showing the discharge of a cathode group.
Fig. 6. RMS of the noise versus the strip number (ADC counts) before the milestone period (a), after it (b) and ratio of both RMS (c).
Fig. 7. Cluster charge recorded for one trigger at low intensity in the $2 \times 16$ barrel MSGCs and the 18 forward MSGC + GEM modules as a function of the strip number.
Fig. 8. Cluster charge recorded for one trigger at high intensity in the $2 \times 16$ barrel MSGCs and the 18 forward MSGC + GEM modules as a function of the strip number.
Fig. 9. Same event at low intensity as in Figure 7.
Fig. 10. Same event at high intensity as in Figure 8.
Fig. 11. History plot: (a) spark rate and (b) SNR as a function of date for a given module during the milestone period.
Fig. 12. The number of lost anodes versus the date during the milestone period. The dashed line corresponds to the milestone ceiling.
Fig. 13. Sparkrate and SNR of a detector module as a function of date during the margins period.