Development of GEM-based Read-Out Chambers for the upgrade of the ALICE TPC

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ABSTRACT: ALICE at the LHC at CERN is planning a major upgrade of the central barrel detectors, including the TPC, to cope with an increase of the LHC luminosity after 2018. A prototype of an ALICE TPC Inner Read-Out Chamber (IROC) was equipped with three large-size Gas Electron Multiplier (GEM) foils as amplification stage to demonstrate the feasibility of replacing the current readout by Multi-Wire Proportional Chambers (MWPC) with such technology. The GEM IROC was installed within a test field cage with a drift length of 115 mm and commissioned with radioactive sources. The $dE/dx$ resolution of the prototype was evaluated in a test beam campaign at the CERN PS and is comparable to the resolution of the MWPC IROC. Stability under LHC conditions was tested during the ALICE p-Pb beam time, when the prototype was mounted underneath LHC beam pipe, close to the interaction point.

KEYWORDS: Time projection Chambers (TPC); Micropattern gaseous detectors (MSGC, GEM, THGEM, RETHGEM, MHSP, MICROPIC, MICROMEGAS, InGrid, etc); Heavy-ion detectors; Particle tracking detectors (Gaseous detectors)

1For the ALICE TPC Collaboration.
1 ALICE TPC upgrade

A significant increase of the LHC luminosity is expected after the second long shutdown (LS2) in 2018, leading to minimum bias Pb-Pb interaction rates of about 50kHz. At this rate, a pile-up of about five events (on average) is expected in the drift volume of the Time Projection Chamber.
Figure 1. a) Layout of a prototype GEM foil. The top side is segmented into 18 sectors; b) layout of the support frame.

(TPC) at any given time [1]. This implies replacement of the existing MWPC-based readout chambers of the TPC by continuously operated GEM (Gas Electron Multiplier) detectors to overcome the rate limitations imposed by the present gated readout scheme.

2 GEM Inner Readout Chamber prototype

A full-size prototype of a TPC Inner Readout Chamber (IROC) equipped with a triple GEM readout stage has been built. The goal was to study stages of GEM integration on a large-size chamber body and to validate the \( \frac{dE}{dx} \) capabilities of a GEM-based TPC. Moreover, issues of operational stability were studied under LHC running conditions.

2.1 GEM foils

Four large area GEM foils have been produced at CERN using the single-mask technique [3]. They have trapezoidal shape with dimensions given by the size of the aluminium frame of the readout chamber (see section 2.3). The top side of the trapezoidal foil is segmented into 18 individually powered sectors with an area of \( \sim 100 \text{cm}^2 \) each (see figure 1a). The gap between sectors is 400 \( \mu \text{m} \), the same as the thickness of the spacer grid of the mounting frames (see section 2.2). An additional 100 \( \mu \text{m} \) of copper between sector boundary and GEM holes is added on each side of the gap to account for possible misalignments during the production of the foil. The measured diameter of the inner (polyimide film or Kapton) holes varies between 40 and 50 \( \mu \text{m} \). The outer (copper) holes have a diameter of 70 – 80 \( \mu \text{m} \). The variations of the hole sizes may come from the etching process and are within reasonable limits. The pitch of 140 \( \mu \text{m} \) is constant over the foils since it is given by the printed mask. The HV distribution trace runs along three sides of the foil. It consists of a 2 mm
copper path and connection flaps. Sectors are powered in parallel via loading resistors soldered directly on the foil between the distribution path and a sector (see section 2.4.1). The bottom (not segmented) side of the foil is connected directly to the HV, therefore no distribution path is needed.

The GEM foils are tested before and after framing in order to validate them for the final assembly. Our quality assurance (QA) tests consist of optical and high voltage tests described below.

2.1.1 Optical check

The optical test allows to check the hole size uniformity across the GEM active area and to record any mechanical defects on the foils in order to identify possible correlations with electrical instabilities which could appear later, during the detector operation. Large-size defects on the copper or Kapton layers may increase the probability of electrical breakdown. Big mechanical defects, like cuts, may result in short circuits between top and bottom side of a foil.

The overall quality of the GEM foils used with the prototype is relatively poor mainly due to the short time scale available for their production. All defects found on the foils were photographed for the report and discussed with the producer. Since no delay was possible at the time of the prototype production, it was decided to use the available GEM foils. No critical defects were found. As critical, we consider for example: i) alignment errors, ii) pieces of copper sticking out from the foil, which would cause the direct electrical connection between the top and bottom sides of the foil.

2.1.2 HV test

A HV test is performed at each step of the detector assembly. The aim of HV test is to check if the foils are stable under high voltages, measure leakage currents of sectors, identify sectors with short circuits and find correlations between stability under HV and defects observed in the foil sectors.

All foils are tested before and after framing. Sectors with high leakage current measured during the first HV check usually improve after the framing procedure. Experience shows that heating the foil for curing the epoxy glue improves HV stability of the foil (perhaps because the water absorbed in the hygroscopic Kapton is evaporated). Sectors, which have high leakage current even after framing the foil, are cured by ramping them up with high current limits (up to 1 µA) to let the high current burn or evaporate the cause of the high \( I_{\text{leak}} \) (high-ohmic short).

Before assembling the detector, all sectors in all four foils were stable and had low and acceptable leakage currents. During the HV tests the approximate positions of the observed sparks were noted but no significant correlation was found between these spots and large defects observed in the first QA step.

2.2 Supporting frames

The foils are glued on 2 mm thick fiberglass (G10) frames (see figure 1b) and then mounted in a stack. The frames contain a 400 µm thick spacer grid to prevent the foils to approach each other due to electrostatic forces even in the case the tension is lost. Each grid is aligned with the sector boundaries, so no additional dead area is introduced. When the stack is mounted, the loading resistors fit into grooves milled in the bottom side of the frame placed above. Framed foils, therefore, lie flat on top of each other.
2.3 Detector assembly

The prototype is assembled on a spare IROC of the ALICE TPC [2]. It is a trapezoidal chamber with dimensions $497 \times (292-467) \text{mm}^2$. The chamber, after removing the wires, was equipped with three GEM foils. The mechanical structure of the chamber consists of four main components: the GEM stack, the pad plane (5504 pads of $4 \times 7.5 \text{mm}^2$), made of a multi-layer Printed Circuit Board (PCB), an additional 3 mm Stesalit insulation plate and an aluminum frame (alubody).

2.3.1 Gluing the foils

Before gluing onto the supporting frames, the foils are stretched on a pneumatic stretching tool with a tension of 10 N/cm. Once the foil is stretched, it is positioned on its frame and aligned with metal pins. A heavy aluminum plate (milled in a way to prevent it from touching the active area of the foil) is used to press the foil onto the frame. The epoxy glue used is ARALDITE 2011 [4]. The full assembly is kept for 24 hours under a hood heated up to 60°C. After gluing, the raw material surrounding the GEM foil is cut off (see figure 2a) and the framed foil is tested under high voltage.

Figure 2. a) Framed GEM foil; b) HV connection to a GEM sector through the loading resistors; c) Exploded view of the IROC prototype; d) chamber mounted in the test box.
Figure 3. Schematic exploded cross section of the GEM stack. The gaps between subsequent GEM foils are 2 mm, whereas distance between the last GEM and the pad plane is 4 mm. The designations of the GEM foils and electric fields used in this contribution are also given. $E_{\text{drift}}$ corresponds to the drift field, $E_{\text{tr}}$ denote the transfer fields between GEM foils, and $E_{\text{ind}}$ the induction field between the third GEM and the pad plane.

2.3.2 Mounting the GEM stack

After the HV check of the framed foils, the loading resistors are soldered (see figure 2b) and three foils are mounted in a stack on the alubody of the chamber (unsectorized side facing the pad plane) — see figure 2c. The foils in a stack are screwed to the alubody with nylon screws, thus each foil can be easily exchanged at any time if needed. On the corners, alignment pins are used to keep all the frames in the same position with the precision of $\lesssim 100\,\mu\text{m}$. The distance between subsequent foils is 2 mm, given by the thickness of the supporting frames. An additional frame is mounted between the bottom foil (GEM3) and a pad-plane in order to increase the induction gap from 2 to 4 mm to enhance spreading of the electron cloud over the readout pads (see figure 3). HV is applied to the foils via Kapton wires soldered to the HV flaps on each foil.

2.3.3 Test box with a field cage

The chamber is mounted in a test box (see figure 2d), which contains a drift cathode and a rectangular field cage with outer dimensions of $57 \times 61\,\text{cm}^2$. The drift electrode is made of 50 $\mu\text{m}$ aluminized Kapton foil. The field cage has 8 field-defining strips with a pitch of 15 mm. A 1 M$\Omega$ resistor is connected between each of the strips.

The drift distance to the first GEM is 10.6 cm. The last strip of the field cage is located 1 mm below the position of that foil (see figure 4). Therefore, the potential of the last strip, which is grounded via a 3.33 M$\Omega$ resistor, is adjusted by applying a voltage in order to match the drift field at the top electrode of GEM1 (top foil in a stack). Two walls of the test box, closest to the parallel sides of the chamber, were machined to install mylar windows for beam and radioactive source measurements.

2.4 High Voltage supply

2.4.1 System overview

The detector is powered using an ISEG EHS 8060n 8-channel 6 kV high voltage module for the three GEM foils and the last strip voltage of the field cage, and by an ISEG HPn300 30 kV module for the drift electrode. The system features high precision current measurements on each HV chan-
Figure 4. Cross section of test box with field cage and mounted IROC. The position of the first foil in the GEM stack is marked by a red line and labeled.

Figure 5. Schematics of the HV distribution of the prototype, showing the loading and grounding resistors.

nel (resolution 1 nA), adjustable ramp speeds and full remote control, which allows for global shut-down in case any channel trips. The powering scheme of the GEM-stack is displayed in figure 5.

Loading resistors ($R_L$) are installed for each sector of the top side of each foil. In addition, each HV channel is grounded through grounding resistors ($R_G$). Placing loading resistors on the top side of the foil assures that in case of discharge across a foil, the voltage drop occurs only on the top side, whereas the bottom side stays at its nominal potential. This helps prevent the propagation of the discharge to the next foil or to the pad plane and readout electronics. Moreover, in case of occasional sparks, the loading resistors limit the current supplied by the power supply before it trips. It also decreases the current flowing through the sector in case of a short circuit between top and bottom sides of the foil. The values of $R_L$ were chosen keeping in mind the current densities expected in the future Pb-Pb collisions at 50 kHz at a gain of 2000, which is roughly $5\text{nA/cm}^2$ (500 nA per GEM sector). Such a current may result in a significant potential drop across a large loading resistor, thus reducing the gain. Therefore 10 MΩ resistors were chosen for GEM1 and GEM2, whereas for GEM3 $R_L = 1 \text{M}\Omega$. High resistors to ground for each channel are chosen to assure safe discharge of the GEM foils after a HV trip. This scheme will result in a constant DC current to ground which must not exceed the current limit of each channel. On the other hand, in
case of a resistive connection or short circuit across a foil in one or several sectors, the rest of the sectors should remain fully operational. Therefore, the value of $R_G$ on the top side should be high enough to allow for additional current flowing through the shortened sectors (without exceeding HV supply current limit), whereas the resistor to ground for the bottom side should be as low as possible in order to avoid reverse currents into the HV supply.

Another constraint on values of grounding resistor in the HV distribution is given by the transient behaviour of the system in case of a sudden shutdown of the HV power supply, so called HV trip. It occurs whenever a current flowing in the circuit exceeds a value of the current limit set in the power supply. This may happen, for example, in case of a discharge in a GEM sector or low resistance connection between top and bottom electrode of a GEM foil. When the HV power supply trips, foil discharges, i.e. full charge collected in the foils must flow to the ground. The time constant $RC$ for (dis-)charging the foil is given by the full capacitance of the foil and the sum of loading and grounding resistances. Because of the parasitic capacitance present in the circuit (e.g. cables) the time constants for discharging the top and the bottom sides of the foil may differ. In case the time constant is higher for the top side of the foil than for the bottom one, the potential of the top electrode may decrease to zero slower than the bottom one. This would result in a sudden increase of the potential difference between the electrodes which may lead to breakdown or even damage of the foil.

The simplified example described above shows the importance of a proper choice of all electronic elements in the HV circuit used for powering the GEM stack. The final choice of the grounding resistors was done after performing a set of transient SPICE simulations and measurements of the discharge decay times. For the measurements the GEM foil was replaced by PCB with equivalent capacitors and resistors corresponding to the GEM assembly. The voltage difference across both sides of the equivalent GEM was recorded on an oscilloscope.

The values of the grounding resistors are $5\,\text{M}\Omega$, $5\,\text{M}\Omega$, $3.33\,\text{M}\Omega$ for the top side of GEM1, GEM2, GEM3, and $10\,\text{M}\Omega$, $10\,\text{M}\Omega$, $3.33\,\text{M}\Omega$ for the bottom sides, respectively. This configuration allows to run the detector with several shortened sectors in GEM1 or GEM2 and up to 2 shortened sectors in GEM3, using the HV settings described in the next paragraph.

The choice of 6 independent HV supplies was motivated by the required flexibility for applying different HV settings. On the other hand, such a powering scheme results in the extra complication of important parasitic capacitances and resistances that affect the way the system behaves in case of a large discharge, and in the large time constant introduced by the necessary grounding resistors.

Although all elements of the HV distribution were carefully chosen to avoid large fields in case of a HV trip, the reaction time of the HV power supply to a trip condition (100 ms in our present case) and the delay with which the rest of the channels are tripped may lead to exactly that. The tripping of the various channels of one stack must be synchronous enough so the voltage across each foil and the transfer and induction fields never increase.

The use of a passive voltage divider to power the whole stack with one single HV channel avoids the problems associated with grounding resistors — which are no longer needed — and delay times for the power supply. Also the time constants for discharging the foils after HV trips are expected to be at least an order of magnitude lower. Even though one loses the flexibility in applying different HV settings, this option is the default for the HV supply of the final detector, where the settings are known and unlikely to be changed.
Table 1. Standard and ion backflow high voltage settings for a gain of ∼2000 in Ne-CO\(_2\) (90-10).

|                      | Standard | IBF |
|----------------------|----------|-----|
| Drift Field          | 0.4kV/cm | 0.4kV/cm |
| \(\Delta U_{\text{GEM1}}\) | 276V     | 225V   |
| Transfer Field 1     | 2.57kV/cm | 3.8kV/cm |
| \(\Delta U_{\text{GEM2}}\) | 252V     | 235V   |
| Transfer Field 2     | 2.57kV/cm | 0.60kV/cm |
| \(\Delta U_{\text{GEM3}}\) | 221V     | 285V   |
| Induction Field      | 2.57kV/cm | 3.8kV/cm |

2.4.2 HV settings for the prototype

The nominal drift field of the ALICE TPC, \(E_{\text{drift}} = 400\) V/cm, is also applied to the prototype. Concerning voltages on the subsequent GEMs, two groups of HV settings are used: the so-called “standard” settings, typically used for triple GEM structures, and so-called “ion backflow” (IBF) settings, where the field configurations are aimed at minimizing the ion backflow. Each setting can be scaled in order to vary the total gain. Both are defined in table 1.

The standard settings are taken over from the COMPASS experiment [5] where GEM detectors are operated in Ar-CO\(_2\) (70-30). In Ne-CO\(_2\) (90-10) however, since the amplification in this mixture starts at lower electric fields, a scaling factor (SF) between 69 – 73 %, resulting in gains between 2000 and 6000 (see section 3), is applied. The standard settings are optimized for maximum stability according to the principles of stable operation described in [6]. The highest amplification takes place in the first GEM and decreases in subsequent stages. These settings however are not optimized for minimum ion backflow. In the case of the ion backflow configuration, where the voltages were optimised in the lab, only the GEM voltages (\(\Delta U_{\text{GEMi}}\)) were scaled with factors of 100, 103, 105 and 107 %. In addition 4 different values of Transfer Field 2 (\(E_{T2}\)) were used: 200, 400, 600 and 800 V/cm. Combining different values of SF and \(E_{T2}\) all together 16 ion backflow settings were tested. The value of the ion backflow for these settings, in Ne-CO\(_2\) (90-10), varies between 3 % and 6.5 %[7]. The approximate gains for all 16 combinations of ion backflow settings vary between 1000 and 6000 [8]. The highest amplification in this configuration occurs in GEM3.

3 Commissioning with \(^{55}\)Fe source

The prototype in the test box was tested in the lab with Ar-CO\(_2\) (90-10) and Ne-CO\(_2\) (90-10) gas mixtures, with standard HV settings, and irradiated with a \(^{55}\)Fe X-ray source.

For the commissioning of the detector, \(\sim 250\) pads (\(\sim 75\) cm\(^2\)) were connected to a charge sensitive preamplifier and the signal was digitized with a multi-channel analyzer for measuring the X-ray spectrum. A picoammeter is used to measure the gain by measuring the current in the pad plane taking into account the rate of X-rays.

Figure 6a shows the energy spectrum of \(^{55}\)Fe obtained in Ar-CO\(_2\) (90-10) at 86 % of the standard settings, which corresponds to a gain of around 6000. Figure 6b shows the spectrum obtained in Ne-CO\(_2\) (90-10) at 75 % of the standard settings, which corresponds to a gain of around 11000. The energy resolution of the main peak for both measurements is FWHM \(\approx\) 25 %.

Figure 7 shows the measured effective gain of the chamber for both gas mixtures.
Figure 6. $^{55}$Fe spectra obtained in Ar-CO$_2$ (90-10) (left panel) and Ne-CO$_2$ (90-10) (right panel).

Figure 7. Effective gain of the chamber as a function of HV, expressed in terms of the scaling factor of the standard settings.

4  $dE/dx$ resolution evaluation at CERN PS

4.1  Experimental set-up

The $dE/dx$ performance of the IROC prototype has been evaluated in a test beam at the Proton Synchrotron (PS) at CERN.

The prototype was installed in the PS East Area experimental hall (T10 beam line). The beam is derived from the 24 GeV/$c$ primary PS beam. The T10 beam is a secondary beam that delivers secondary particles up to 7 GeV/$c$ in the cycles with a flat top of about 400 ms, with uniform time distribution [9]. The following beam settings were taken:

- 1 GeV/$c$, 2 GeV/$c$, 3 GeV/$c$ negative particles ($e^-$, $\pi^-$),
- 1 GeV/$c$, 6 GeV/$c$ positive particles ($e^+$, $\pi^+$, $p$).
For each type of beam, both standard and ion backflow high voltage settings are used for powering the GEMs (see section 2.4.2). The drift field is 400 V/cm and the gas mixture Ne-CO$_2$ (90-10) as in the current TPC.

Together with the IROC prototype, other detectors were used during this test beam:

- 2 scintillator detectors for triggering,
- Beam Cherenkov Counter (BCC) for particle identification (PID),
- Pb-glass calorimeter for PID.

The additional detectors for PID have to be used since no identification is possible with IROC only (no momentum measurements). The photography of the test area is shown in figure 8.

4.2 Front-end electronics in the PS test beam

The prototype is equipped with 10 front-end cards (see figure 9a). The readout electronics has been borrowed from the LCTPC (Linear Collider TPC) collaboration. About 1200 electronic channels based on the PCA16 / ALTRO chips [10, 11] are used in the IROC test beam at the PS. The system integration with ALICE hardware and analysis software is straightforward since all electronics after the ALTRO, i.e. the whole readout, is the same as in ALICE. Ten front-end cards are reading out the signals from 16 to 18 pads on all 64 pad rows. The width of readout region is 6–7 cm (see figure 9b).
4.2.1 System performance

The system has an RMS noise of around 600 electrons (ENC). This is the total noise composed of amplifier noise, common mode noise (from the board and surroundings) and the effect of finite ADC scale. Whereas the total noise has implications on the charge resolution, the sensitivity must also be considered which is translated to thresholds being applied in zero suppression mode. The threshold depends on the amplifier noise, pickup noise and the stability of the baseline (on long and short time scales) at the ADC. The ALTRO makes corrections for baseline variations based on digitized measurements of the baseline. Pick-up noise may vary from channel to channel. The zero suppression threshold is 2 ADC counts, corresponding to about 1200 electrons (120 ns peaking time and 12 mV/fC conversion gain). The beam test at the PS uses 20MHz sampling frequency.

4.2.2 Data acquisition system

The front-end cards are read out using the current ALICE TPC readout system [2]: two ALICE TPC Readout Control Units (RCU) send the data to a Local Data Concentrator PC, which contains the receiving ReadOut Receiver Card (RORC) and runs the ALICE data acquisition system DATE [2]. The corresponding trigger logic is steered by a Local Trigger Unit (LTU) and a Busy Box [2]. Data transfer and trigger communication are based on optical links. The beam detectors, scintillators, Cherenkov counter and Pb-Glass detector, are read out through a classic CAMAC system into a PC running a LabView acquisition system. Signals are transmitted through copper cables. In order to synchronize the events in both systems, a busy logic is implemented in the CAMAC system which incorporates the busy status of both systems. Thus, the CAMAC system leads the acquisition. The two data streams are subsequently merged into a single data file based on the proper synchronization of the trigger and an event tag. This allows online visualization of the detector response to different particles species, as selected by the beam detectors.
Figure 10. Truncated (5–75%) energy loss distributions for electrons and pions with 1 GeV/c momentum measured with the IROC GEM prototype at a gain of $5 \times 10^3$.

The average DAQ rate was 500 events/spill (where the spill length was 0.5 s), whereas the beam rate during the experiment was on average of 2000 particles/spill.

4.3 $dE/dx$ measurements

For the measurement of the $dE/dx$ resolution only events with isolated tracks are selected. Additional cuts are applied on the number of clusters per track and the cluster drift time. The gain equalization is done using electron tracks. Since individual runs are rather short, no correction for pressure and temperature variations is applied. For the $dE/dx$ measurements a step length is given by the pad-row size (7.5 mm) and the truncated mean method is used to symmetrise energy loss distribution. For the analysis presented in this subsection, the truncation interval 5–75% was chosen.

An example $dE/dx$ spectrum of 1 GeV/c electrons and pions recorded at a gain of about 5000 is shown in figure 10.

The $dE/dx$ distributions are fitted with a Gaussian function to obtain the mean value ($\langle dE/dx \rangle$) and the width of the distribution $\sigma(dE/dx)$. The relative resolution, defined as

$$\frac{\sigma(dE/dx)}{\langle dE/dx \rangle},$$

is derived for pions and electrons for different momenta and HV settings. Figure 11 shows the results obtained in this analysis for 1 GeV/c electrons and pions. A resolution of 10% (10.5%) is obtained for electron (pion) tracks with a most probable value of 60 samples. All ion backflow settings yield similar $dE/dx$ resolution at a given beam momentum and particle type. No significant dependence on the gas gain is observed within the range under study. The results for the standard settings are slightly lower than those for the ion backflow settings.
Figure 11. The relative $dE/dx$ resolution measured for different HV settings for electrons (left) and pions (right) with 1 GeV/$c$ momentum. In the standard settings (grey curve) the gain ranges from 2000 to 6000; in the ion backflow settings (colourful curves) the gain spans between 1000 and 6000 (see section 2.4.2 for more details).

Figure 12. Separation power between pions end electrons with 1 GeV/$c$ momentum measured for different HV settings. In the standard settings (grey curve) the gain ranges from 2000 to 6000; in the ion backflow settings (colourful curves) the gain spans between 1000 and 6000 (see section 2.4.2 for more details).

The corresponding separation power, defined as

$$S_{AB} = \frac{2 |\langle dE/dx \rangle^A - \langle dE/dx \rangle^B|}{\sigma (dE/dx)^A + \sigma (dE/dx)^B}$$

(4.2)

for two particle types A and B, is shown in figure 12, for electrons and pions at 1 GeV/$c$ for different HV settings.

The $dE/dx$ resolution observed in the GEM IROC is compatible with the MWPC IROCs one. These findings corroborate that the $dE/dx$ resolution of the upgraded TPC will be preserved.
4.4 Detector stability

During 6 days of the PS test beam a total of 8 HV trips occurred, most probably initiated by discharges in the GEM foils. No increase of the current in any of the HV channels was recorded before the trips.

All trips occurred while running the detector with ion backflow settings. The trips might be related to the absolute voltage on the GEM1 top electrode ($U_{\text{GEM1T}}$). The value of $U_{\text{GEM1T}}$ for any of the ion backflow configuration is always higher than the corresponding value for even the highest standard settings. In addition, the HV channel of this electrode showed overcurrent status after each HV trip. Moreover, the poor quality of the GEM foils, reported in section 2.1.1, should be taken into account. This might lead to the observed instabilities in GEM, since the gain across GEM1 at ion backflow settings is rather low (see table 1). Defects coming from the etching process, like for example sharp tips of copper, may increase a corona discharge probability which could result in HV trips observed during the beam time.

5 Stability under LHC conditions

5.1 Experimental set-up

The second test beam with the GEM IROC prototype was performed at the ALICE cavern during the 2013 LHC p-Pb period at $\sqrt{s} = 3.5$ TeV. The goal of the experiment was to evaluate the stability of the detector operation under LHC conditions. The prototype was installed underneath the LHC beam pipe (see figure 13), $\sim 10$ m from the interaction point. Gas lines were pulled from the TPC, operated with Ne-CO$_2$ (90-10), to the prototype, such a part of the gas flow was diverted to it. The readout plane was positioned perpendicular to the beam direction, such that the particles produced in the p-Pb interactions were crossing the drift electrode towards the GEM stack.

The prototype was positioned at the rapidity $\eta \approx 2.6$, where the approximate charged-particle multiplicity is $\sim 25$ in p-Pb. At 200kHz interaction rate the total particle rate reaches 5 MHz per
rapidity unit at the position of the prototype. This number is of the same order of magnitude as the rate of about 20 MHz per rapidity unit expected after the luminosity upgrade of the LHC.

Signals from 700 pads (total area \(\sim 211 \text{cm}^2\)) connected together were read out at the oscilloscope before and after amplification with spectroscopy electronics. The shaped signals were saved with a low trigger rate, \(< 10\text{Hz}\) in order to save all signals with the highest amplitudes from the detector (high energy tail of the spectrum). The main aim of the experiment was to measure the HV trip rate for different high voltage settings and to find correlations with the recorded amplitude spectra.

5.2 Detector stability

All together 21 HV trips occurred during the duration of the period (21 days). Most of the trips happened while running with ion backflow settings. The overcurrent flag in the HV channel supplying the GEM1 top electrode was set in all trips. This again suggests a strong correlation with the absolute values of the voltages applied to the top most GEM electrode. No significant correlation was found between the trips and the beam conditions (rate, Pb-beam direction), although most of the trips happened while beams were present and stable. In particular, no correlations were found with instabilities of ALICE detectors.

As a consequence of the trips, 7 resistive connections between GEM electrodes developed during this period in different sectors. The values of resistances were decreasing with the subsequent HV trips showing that the development of an electrical connection between the top and the bottom side of the foil is a continuous process. After the first connections appeared, the chamber was operated only at the lowest ion backflow settings, but the trip rate persisted. After the second low-resistive connection in GEM3 developed, the ion backflow settings had to be modified since the HV supply configuration allowed only for 1 short (with zero resistance) in this foil. To protect the power supply from sinking the current, the GEM3 voltage had to be reduced, since no modification of loading or grounding resistors was possible. To keep the overall gain at the same value (\(\sim 1000\)), the voltages across GEM1 and GEM2 were increased. At the end of the campaign, the power supply tripped even in the absence of radiation.

Figure 14 shows a typical amplitude spectrum recorded at a gain \(< 900\). As described before, the oscilloscope trigger was adjusted to record only the highest signals. The signal spectrum ends at amplitudes around 5 V. The last signal recorded before the trip, indicated in the figure, is 5 – 10 times larger than the typical one, and it could correspond to a spark, to a large energy deposit created by a highly ionizing particle, or to the induction of the rapidly decreasing voltages during the trip.

5.3 Detector inspection after the test beams

After the test beams the prototype was disassembled to search for evidence of shorts or damage in the affected sectors. All holes with low-resistive connection have been identified. Measured resistance of those connections varied in a range of 50 – 6000 k\(\Omega\). In all cases a brownish area on the Cu-clad around the hole was visible, which indicates a discharge damage. Also, black-coloured material was found inside the problematic holes, which probably corresponds to carbonized Kapton, dust or other material which was possibly burned during the discharges. A microscope picture showing a hole with low-resistive connection is shown in figure 15.
The approximate positions of the damaged holes with respect to the position of the beam pipe are shown in figure 16. All low-resistive connections in holes happened in parts of the sectors close to the beam pipe. In case of GEM2 and GEM3 foils, they developed at nearly the same position. Moreover, spatially correlated connections in GEM2 and GEM3 occurred within very short time intervals. This suggests that they were initiated by the same incident, i.e. a single discharge propagates from one foil to the next.

Also, to be noticed that 5 out of 7 low-resistive connections appeared in sectors which experienced discharges during the HV tests before gluing the foils. Only 7 sectors (out of 72) did not fulfil QA requirements at this stage, which makes the observed correlation more significant. Although most of the problematic sectors stabilized after the gluing procedure (including all sectors where later shorts developed) the problems during the beam operation and the trips during the QA procedure may have the same origin. Furthermore, no correlations were found between shortened sectors and mechanical defects on the foils. Nevertheless, the facts point to the important role of the quality assurance in the validation of the GEM foils before assembly in the readout chambers.
5.4 Discharge probability studies

The relatively high discharge rate observed during the operation of the prototype during those tests is mainly attributed to the poor quality of the foils used to build the detector, and not to the exceptionality of the environment to which it was exposed. Indeed, it should be pointed out that GEM-based detectors are successfully operated in several particle physics experiments like COMPASS [5], PHENIX [12] or STAR [13], and in the LHC experiments LHCb [14] and TOTEM [15], who do not report problems with increased sparking rate or other stability issues. The TOTEM experiment did experience problems at the beginning of the operation with beams, and some detectors had to be exchanged. Since then, the operation has been smooth. Efforts to understand the reason for the faulty modules are under way. On the other hand, LHCb, who reports the absence in their HV system of a proper tripping mechanism in case of overcurrents, recommends to limit the gain in the first GEM.

So far, the only comprehensive discharge studies in the gas electron multiplier were reported in [6] and concern mainly Ar-based gas mixtures. Similar measurements in Ne-based mixtures are therefore to be performed in order to optimize the set of parameters for stable operation of the GEM readout chambers. Strong correlations between trips and the potentials applied to the GEM electrodes show the importance of a further optimization of the HV settings for both ion backflow and discharge probability minimization.

The addition of nitrogen to the Ne-CO₂ mixture will alleviate the instability issue. Nitrogen provides better quenching for neon and allows for higher fields without amplification in transfer and induction gaps. Also, an additional GEM foil in a stack allows for further sharing of the charge amplification between the foils, thus lowering the potential difference across any foil.

6 Summary and outlook

A full-size prototype of an Inner Readout Chamber with GEM amplification for the ALICE TPC upgrade has been built, commissioned and tested during a test beam campaign. A triple GEM stack was mounted as an amplification stage instead of the currently used wire planes. The dE/dx performance has been evaluated at the CERN PS. The observed dE/dx resolution is comparable to the one of the MWPC readout chambers. The experience from the LHC in-beam operation shows a
significant correlation between the stability of the detector and both the HV settings applied to the stack and the observations during the quality assurance procedure. It is clear that for the long-term and efficient operation of the upgraded TPC stable conditions for operating the GEM foils must be assured. The R&D for the ALICE TPC upgrade continues and includes among others: i) new powering scheme of the detector, ii) further optimisation of the HV settings for ion backflow and discharge probability minimisation.

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