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Stability studies on triple-GEM detectors for the GEM upgrade of the ALICE TPC

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The ALICE experiment at CERN is planning a major upgrade of its main central tracking device, the Time Projection Chamber (TPC), for the upcoming RUN 3 at LHC, beyond 2019. The present TPC uses gated Multi-Wire Proportional Chambers (MWPCs) with pad readout to amplify and read out the signal. A gating grid is necessary to prevent the ions created in the amplification process, near the anode, to flow back into the drift volume, which would eventually lead to distortions of the reconstructed tracks (space-charge effect). Unfortunately, this also limits the TPC readout rate to around 1 kHz, whereas for RUN 3 Pb-Pb collision rates of 50 kHz are expected. We are therefore planning to substitute the MWPCs with Gas Electron Multiplier (GEM) detectors, which combine a comparable spatial and momentum resolution with an intrinsic suppression of the ion back-flow, allowing to operate in a continuous, trigger-less readout mode.

A common issue with micro-pattern gaseous detectors is stability against discharges, that are thought to be triggered by events with high local charge-density. We will present the results of the stability tests carried out with a prototype of an Inner ReadOut Chamber (IROC) with large GEM foils, built at TUM. We tested the IROC with highly ionizing heavy particles - namely low energy alphas and protons - using the Maier-Leibnitz-Laboratorium tandem accelerator, at TUM. The results indicates that the detector can sustain the high current densities foreseen in the LHC RUN3 environment, even though a real LHC beam test is still needed. We will also present a parallel R&D program on smaller prototypes which aims to understand the influence of gas mixture and field configuration on discharges inside multi-GEMs detectors.

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1. Introduction

The TPC is the main charged particle ID and tracking device of ALICE (see [1] for a detailed description). The read-out chambers currently employ MPWC technology with a gating grid, used to reduce the back-drifting of ions. This latter sets an overall intrinsic dead time of $\sim 300\ \mu$s limits the TPC to a maximum operating rate of ~ 3.5 kHz in p-p collisions. For Pb-Pb collisions, because of the higher multiplicities, the constraints are even more severe, down to ~ 300 Hz. Operating without the gating grid would result in unbearable space-charge effects in the drift volume (i.e. distortions in reconstructed tracks). The LHC RUN 3 (beyond 2019) will reach luminosities of $\mathscr{L}_{\mathrm{int}} = 10\ \mathrm{nb}^{-1}$, or 50 kHz minimum bias Pb-Pb collisions. It is thus clear that a major upgrade of the TPC, both of the read-out chambers and electronics, is required to exploit the high statistics that the LHC can provide [3]. The main idea behind the upgrade is thus to substitute the MWPC-based readout chambers and to operate in a continuous, trigger-less readout mode, i.e. without gating. The proposed technology, which combine a comparable spatial and momentum resolution with an intrinsic suppression of the ion back-flow, is the Gas Electron Multiplier (GEM) [4].

However, GEMs showed to be more problematic in terms of stability. The reasons is connected to the high charge densities that could be reached inside a GEM-hole and the relatively small distances of the electrodes. Contrary to wire chambers, the formation of a propagating streamer most likely results in an electrical breakdown, as the ionization channel connects the two copper layers and a temporary short is formed. In particular, the ALICE GEM-TPC would need to sustain the extreme conditions foreseen for RUN 3. With a safety factor of 10, which takes into account the contribution of highly ionizing particles, background, secondaries, etc., a maximum current density of ~ 10 nA/cm^{2}s is expected[1] [2].

2. Stability tests of the GEM-IROC prototype

We tested a prototype of the TPC Inner Read-Out Chamber (IROC) equipped with a triple GEM-stack, built with the alubody and the pad-plane of the standard MWPC-based IROC (for a detailed description, see [2]). The detector was placed inside a small drift chamber (test box).

The goal was to measure the discharge probability (discharge per incoming particle) of the GEM-IROC prototype under beam conditions. The tests were carried out at the Maier-Leibnitz-Laboratorium (MLL), located at the TU-München campus, in Garching (Germany). We used a beam of low-energy (20 MeV) protons, which deposit a high charge density along their tracks, allowing to get even above the LHC conditions in terms of current flowing across the GEMs. To achieve a uniform irradiation over the detector, the beam was orientated parallel to the GEM-foils, across the two mylar windows on the sides of the test box (see fig.1). The gas mixture was $Ne/CO_2/N_2$ (90/10/5). The voltage was supplied to the GEM-foils through a voltage divider.

A dedicated study was then carried out with Geant4 to simulate the energy deposition and straggling of the protons in the the detector. In $Ne/CO_2/N_2$ (90/10/5) and a gain of 2000, assuming no secondary electrons pile-up at the rates of the experiment (10-258 kHz), we expect a current density at the GEM-foils of ~ 4.05 pC/cm^2 (see [11] for a comprehensive description).

[1] This value is of course an average over the operation period; single rare events, e.g. the decay of an activated nuclei at the edge of the chamber, are expected to induce higher, even if instantaneous and local, charge densities.

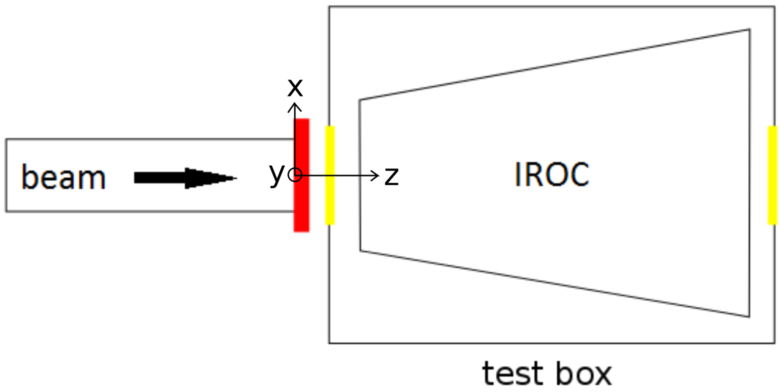

Figure 1: Schematic view of the experiment. In red, the window at the end of the beam line, in yellow the windows of the test box.

A discharge consists of a propagating streamer connecting the two copper layers of a GEM-foil, across one or more GEM-holes, which then has two unambiguous signatures: a voltage drop across the foil, because of the temporary short (i.e. a rise in the current supplied by the power supply) and a huge release of charge - for one sector, up to $\sim$2 μC - which induces a big signal on the pad-plane. The read-out that was developed allowed to monitor both. It was also important to keep constant track of the beam conditions, to disentangle possible discharges from fluctuations in the proton rate or from bunches of multiple protons. Therefore we recorded event-by-event the energy spectrum of the beam and the number of discharges. For a detailed description, see [11].

2.1 Results

The detector was powered with the optimal voltage configuration for IBF suppression, operating at a gain of 2000, foreseen for real TPC operations. The proton rate was set at 10 kHz, which corresponds to an expected current density of 40.5 nA/cm^2, of the same order of magnitude of what expected at LHC in 50 kHz Pb-Pb collisions ($\sim$ 10 nA/cm^2) [2], during RUN 3.

Starting from 2000, the gain was increased, scaling the potential U_{tot} supplied to the resistor chain[2] in steps of $\Delta U/U_{\text{tot}} = 5\%$, and then recording for $\sim$ 16 min long runs. The proton rate was kept constant at 10 kHz. Above $g \sim 10^4$, the pre-amplifier was saturated by standard signals of protons, making impossible to discriminate discharges from the pad-plane signals. The discharges were then detected only from the over-currents measured by the power supply. We observed discharges above $g = 4.3 \times 10^4$ (expected current density $\sim$ 91 nA/cm^2), see fig.2.

The final test was performed increasing the beam intensity at a fixed gain of 2000. The limits of the read-out were again reached, as pile-up started to dominate in the signal processing. The extrapolation of the real proton rate was based on an independent measurement of the beam intensity, using a Faraday cup placed right after the accelerator. The rate was increased step by step,

[2]This means to change the transfer fields as well. However, while the amplification on GEMs can be increased by one order of magnitude with $\sim +10\ \Delta U$, the proprieties associated to the transfer fields, which correspondingly change by $\sim 10\ \Delta U/2\text{ mm} = 0.05$ kV/cm, are less affected.

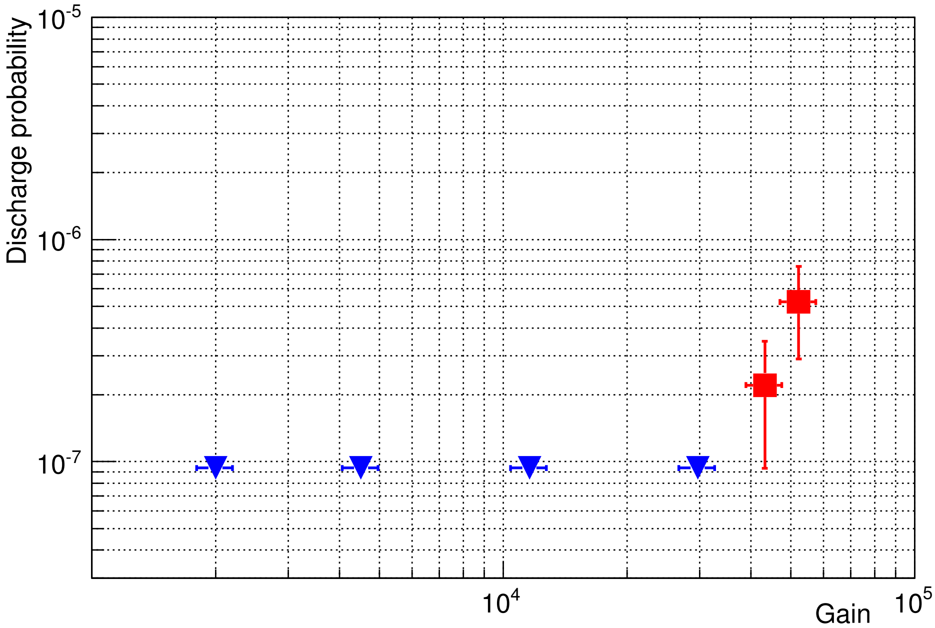

Figure 2: Discharge probability as a function of gain, recording trips of the power supply, in "IBF" HV settings. Blue points are lower limits, red points established values (see text).

until 258 ± 8 kHz (expected current density $\sim 1045 \pm 32$ nA/cm^2). No discharges were recorded, allowing to set lower limits on discharge probability ($< 3.9 \times 10^{-8}$) at the nominal gain of 2000.

Within the limits of the beam intensity and of the statistics that was collected, the detector was stable. No discharges were observed up to very high gains, $\sim$ 10 times higher than what is foreseen to be used in ALICE, and current densities $\sim$ 100 times higher than those expected in 50 kHz Pb-Pb collisions during RUN 3.

3. Discharge studies

The IROC's settings (gas mixture, voltages on GEMs, transfer and induction fields) used at the MLL were chosen to fulfil the requirements that are most crucial for the TPC, mainly the IBF suppression, while no systematic study of their influence on stability was ever performed. Since the mechanisms involved in the formation of discharges in GEMs are still known only to a limited extent, it is not easy to foresee how these parameters could affect stability. There is only one study [10] ever published on discharge probability of GEM detectors, performed in Ar/CO_2 (70/30). With neon-based mixtures, on the contrary, there is only a limited experience in real applications and no dedicated studies of their stability[3].

For these reasons, a dedicated study was carried out using a smaller triple-GEM detector, with a low rate (0.5 Hz) gaseous ^{222}Rn alpha source; since the GEM-foils and the HV settings used had

[3]Considering, more in general, Micro-Pattern Gas Detectors (MPGDs), some observations were made [8] concerning the differences between argon and neon in Micromegas [9] detectors, concluding that with the latter higher gains could be reached before the appearance of discharges.

the same characteristics of those of the IROC, this measurements are expected to provide direct insight on its limits. For a detailed description of the detector, see [11].

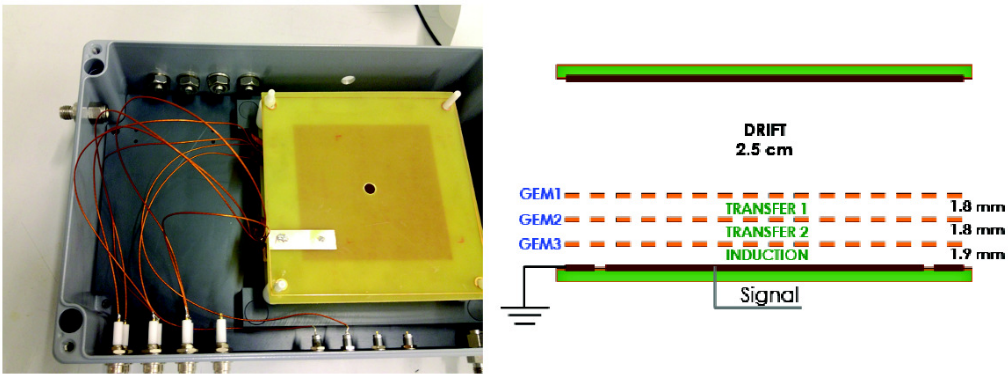

Figure 3: Left: top view of the small triple-GEM detector. Right: sketch of the GEM-stack used in the measurements.

3.1 HV settings effects

The effects of different HV settings on the discharge probability were studied in the gas mixture Ne/CO_2/N_2 (90/10/5). Our phase space ranged between a configuration optimal for stability ("standard" settings) and one optimal for ion back-flow suppression ("IBF" settings). The main differences between the two are the order of amplification, set by the voltage applied on GEMs, and the low transfer field above GEM3 (E_{t2}). To disentangle the contribution of these two parameters to discharge formations, a series of measurements with intermediate settings ("reversed" and "low-E_{t2}") was carried out. The specifications of the different HV settings at gain 2000 are reported in tab.1.

	standard	**IBF**	**reversed**	**low-E_{t2}**
ΔUGEM1 (V)	284	227	213	318
E_{t1} (kV/cm)	2.6	3.0	2.6	3.0
ΔUGEM2 (V)	260	278	260	278
E_{t2} (kV/cm)	2.6	0.1	2.6	0.1
ΔUGEM3 (V)	227	318	298	227
E_{ind} (kV/cm)	2.6	3.0	2.6	3.0

Table 1: Different triple-GEM HV settings, gain 2000 in Ne/CO_2/N_2 (90/10/5).

The results are shown in fig.4. Both amplification order and low transfer field have a considerable effect on stability, that translates into a difference of more than one order of magnitude, for a fixed effective gain, of the discharge probability, which sum up to the "IBF" HV settings values. These measurements shows that the voltages and the electric fields in the GEMs can actually be much more crucial for stability than the choice of the gas mixture. The gas choice fixes the total primary charge density on the GEMs, which cannot then explain the differences observed. What is indeed connected to the HV configuration, and can differ even at a fixed effective gain, is the *real* charge flowing through the GEM-holes. This depends on the collection and extraction efficiencies of each GEM, which in turn are set by the electric fields and the ΔUGEMs. Moreover, the charge sharing among different GEM-holes on GEM2 and GEM3, which reduces the GEM-hole charge density, can also be affected by the HV settings.

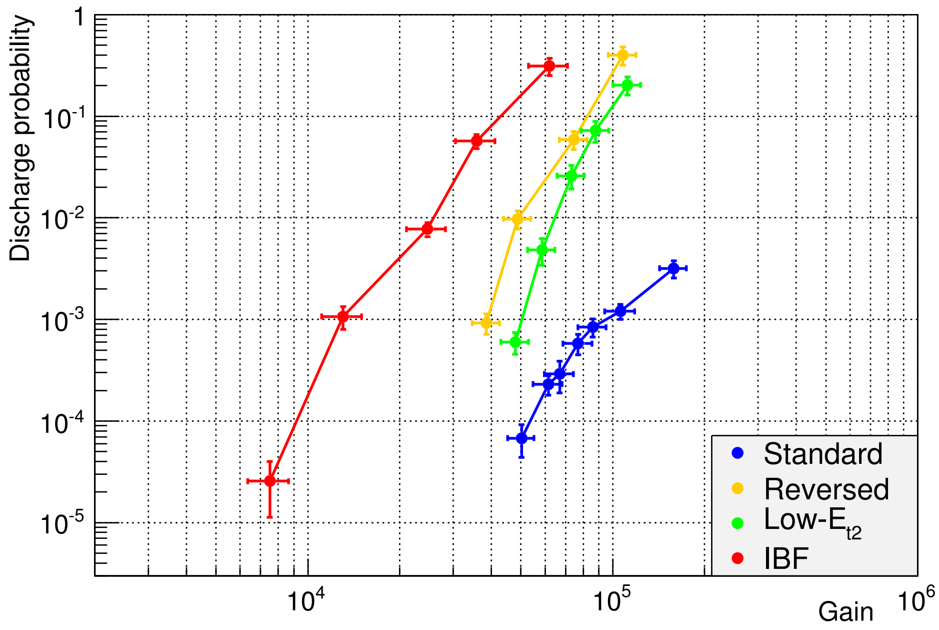

Figure 4: Discharge probability in Ne/CO_2/N_2 (90/10/5), with different HV settings. Lines are to guide the eye.

3.2 Gas effects

We also studied the contribution of the different gas mixtures on the discharge probability. The results are shown in fig.5, together with the measurement from [10], performed with a similar detector and with a gaseous ^{222}Rn source. Considering the slightly different HV settings and the different ambient conditions (pressure, temperature, oxygen and water content), the agreement is rather good. For the other gases, no previous measurements were published.

The results clearly show a consistent effect, of order of magnitudes, that small fractions of quenching gases (CO_2, N_2) introduce in terms of discharge probability. Considering the same effective gain, i.e. same charge flowing across the GEMS, neither the differences in primary ionization or diffusion, which reduces the charge density at the GEM-holes, are enough to explain the differences observed. The results suggest that other mechanisms may play a bigger role in discharge formation, for example absorption of photons from atomic de-excitation or electronic capture (photon feedback suppression), for which quenchers are thought for. It also seems that the curves roughly follow a power-law dependence (straight lines in log-log scale), with a similar slope

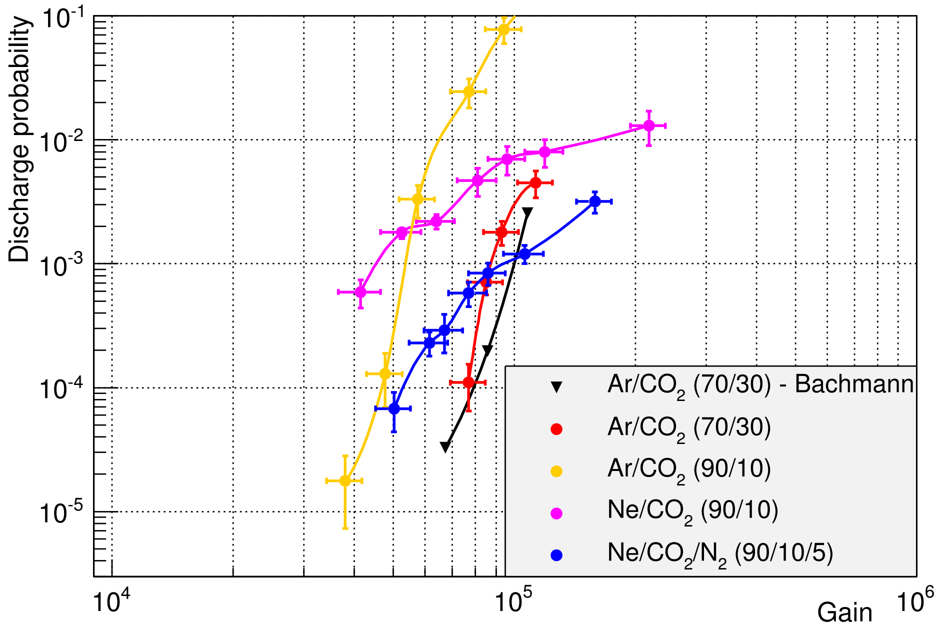

Figure 5: Discharge probability as a function of gain in argon-based gas mixtures, with "standard" HV settings, compared with measurements from [10] (Bachmann et al.). Lines are to guide the eye.

between mixtures with same noble gas, even in the case of the neon, where a different quencher is added. This suggests that the slope is mainly set by the noble gas, i.e. by the primary ionization density, while the fraction of quenching gas only introduces an offset. A deviation from this behaviour is observed above $g > 10^5$. The effective gain was measured with a low-energy ^{55}Fe γ-source, which induce $\sim 10^3$ times less ionization electrons than the α-particles; for the latter, at this high gains, the detector is being operated close to the Raether limit, where deviations from the proportionality in the amplification of the GEMs have been observed [5] [6]. The main mechanism involved is thought to be the space charge effect in the GEM-holes, that locally reduces the electric field [7]; the smaller effective gain in the case of the α-particles could then explain the measurements. Because of the low rate of the ^{222}Rn source, it could not be used to measure the gain, and thus confirm this interpretation.

4. Conclusions

We hereby presented the results of an extensive study on stability of triple-GEM detectors, carried out in the framework of the GEM upgrade of the ALICE TPC, foreseen for LHC RUN 3.

A prototype of the ALICE TPC IROC has been successfully tested in a dedicated beam test with low energy protons, which allowed to set safety margins both in rate and particle rate for beam operations. Assuming that the crucial parameter responsible for discharges is the primary ionization density in the detector and, conversely, the current density flowing through the GEM-foils, the conditions foreseen for the LHC RUN 3 have been reproduced and overtaken. Further stability tests at the LHC are nevertheless needed.

The parallel R&D project on a smaller prototype allowed us to investigate the effects of the detector's settings on spark formation. The results showed that there is indeed a strong dependency both on the order of amplification across the GEM-stack and on the transfer fields between GEMs. In particular, the settings optimal for ion back-flow suppression have been observed to involve a consistent worsening of detector's stability. This in turn suggests that the proprieties of the amplification process across the GEM (absolute gain, collection and extraction efficiency, charge sharing among different GEM-holes) have a great influence on the detector's stability and need to be finely optimized. The choice of the gas mixture was studied as well. A strong dependence of the discharge probability was observed with respect to the quenching gases used in the mixture: small differences in their amounts can improve the performances of the detector by orders of magnitude. This result opens to the possibility to greatly improve GEM detectors stability already with a careful choice of the gas mixtures.

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