A continuous read-out TPC for the ALICE upgrade

C. Lippmann[a,1], for the ALICE TPC collaboration

[a] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstrasse 1, 64291 Darmstadt, Germany*

Abstract

The largest gaseous Time Projection Chamber (TPC) in the world, the ALICE TPC, will be upgraded based on Micro Pattern Gas Detector technology during the second long shutdown of the CERN Large Hadron Collider in 2018/19. The upgraded detector will operate continuously without the use of a triggered gating grid. It will thus be able to read all minimum bias Pb–Pb events that the LHC will deliver at the anticipated peak interaction rate of 50 kHz for the high luminosity heavy-ion era. New read-out electronics will send the continuous data stream to a new online farm at rates up to 1 TByte/s.

A fractional ion feedback of below 1 % is required to keep distortions due to space charge in the TPC drift volume at a tolerable level. The new read-out chambers will consist of quadruple stacks of Gas Electron Multipliers (GEM), combining GEM foils with different hole pitch. Other key requirements such as energy resolution and operational stability have to be met as well. A careful optimisation of the performance in terms of all these parameters was achieved during an extensive R&D program. A working point well within the design specifications was identified with an ion backflow of 0.63 %, a local energy resolution of 11.3 % (sigma) and a discharge probability comparable to that of standard triple GEM detectors.

Keywords: Time Projection Chamber, Tracking detectors, GEM, Micro-Pattern Gas Detectors, continuous read-out
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1. Introduction

ALICE is the dedicated heavy-ion experiment at the CERN Large Hadron Collider (LHC). The lead-ion campaigns of Run 1 and Run 2 will conclude the initial LHC heavy-ion programme with an integrated luminosity of 1 nb^{-1}. A significant increase of the LHC luminosity for heavy ions is expected after the Long Shutdown 2 (LS2) of the LHC, leading to collision rates of about 50 kHz. Under these conditions, for Run 3 an integrated luminosity of 10 nb^{-1} is within reach. This would imply a substantial enhancement of the sensitivity to a number of rare probes, in particular at low p_{T}, that are key observables for the characterization of strongly interacting matter at high temperature. Such measurements require that the experiment records a large sample of events. The ALICE strategy therefore foresees to read out all Pb–Pb interactions [1].

2. The ALICE TPC

The ALICE Time Projection Chamber (TPC) is the largest detector of its type, with an overall active volume of about 90 m^3. The TPC employs a cylindrical field cage with a central high voltage electrode and a read-out plane on each endplate. It covers full azimuth and provides charged-particle tracking over a wide transverse momentum range. The read-out planes currently consist of 72 MWPC-based read-out chambers, with a total of about 550,000 read-out cathode pads. The operating gas mixture is Ne-CO_2 (90-10) or Ar-CO_2 (90-10) [2].

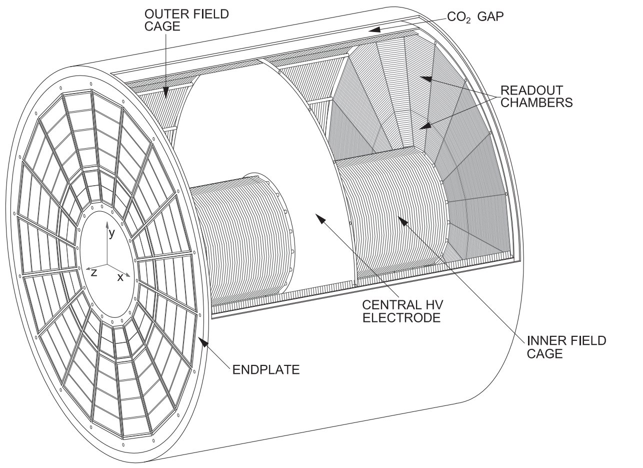

Figure 1: Schematic view of the ALICE TPC. The current MWPC-based read-out chambers will be replaced by 4 GEM stacks.

The current MWPC read-out chambers are operated with an active Gating Grid (GG) which, in the presence of a trigger, switches to transparent mode to allow the ionization electrons to pass into the amplification region. After the maximum drift time of 100 μs the GG wires are biased with an alternating voltage that renders the grid opaque to electrons and ions. This protects the amplification region against unwanted ionization from the drift region, and prevents back-drifting ions from the amplification region to enter the drift volume. In particular, the latter would lead to significant space-charge accumulation and drift-field distortions. However, the GG system implies a principal rate limitation of the present TPC to a few kHz.

Email address: C.Lippmann@gsi.de (for the ALICE TPC collaboration)

The given restriction due to the GG operation matched well the typical Pb–Pb collision rates seen in Run 1 in 2010 and 2011 (up to 3.5 kHz). In Run 3 however, the maximum drift time of electrons in the TPC (100 μs) together with the average event spacing at 50 kHz (20 μs) will lead to an average event pileup (tracks from different events overlapping in the TPC drift volume) of 5. A triggered operation would lead to inacceptable loss of data. Thus, in Run 3 the TPC will have to be operated continuously and the backflow of ions needs to be minimized without the use of a GG.

3. The ALICE TPC Upgrade

The endplates of the existing field cage will be equipped with new read-out chambers based on quadruple stacks of Gas Electron Multipliers (GEMs) [3]. Fig. 2 shows a schematic drawing of such a detector [4]. GEM detectors are the prime candidate (hybrid double GEM plus Micromegas detectors have been considered as well [5]) as they offer the possibility to reduce the backflow of ions into the TPC drift volume without the use of a gating grid. Moreover, GEMs feature high rate capability and the absence of an ion tail to the induced signals as seen in wire chambers.

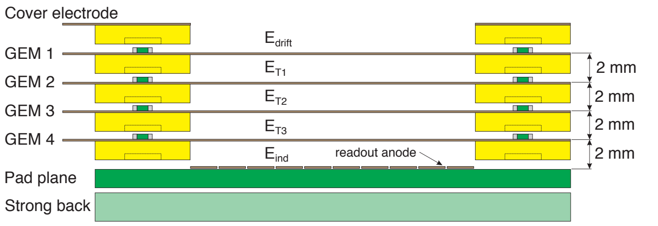

Figure 2: Schematic exploded cross section of the GEM stack. Each GEM foil is glued onto a 2 mm thick support frame defining the gap. The drift field E_{drift}, transfer fields $E_{\mathrm{T}i}$ and induction field E_{ind} are shown as well.

To achieve the required Signal-to-Noise ratio the GEM stacks will have to operate at an effective gain $G_{\mathrm{eff}} = 2000$. In order to keep the resulting drift field distortions at this gain within a tolerable level, an upper limit for the fractional ion backflow of 1 % has been set. In this case, for each electron entering the amplification region at maximum $\varepsilon = 20$ ions will drift back into the TPC drift volume. At the same time, the local energy resolution of the read-out chambers must not exceed $\sigma(^{55}\mathrm{Fe}) = 12\,\%$ at 5.9 keV in order to retain the performance of the existing system in terms of dE/dx resolution.

The upgraded TPC will be operated with a Ne-CO_2-N_2 (90-10-5) gas mixture. This choice is mainly driven by the higher ion mobility in neon as compared to argon, which also leads to less accumulation of ions in the TPC drift volume.

4. Ion backflow optimisation

The ion backflow is defined as IBF $= (1+\varepsilon)/G_{\mathrm{eff}}$. Comprehensive R&D studies starting in 2012 have shown that conventional triple GEM stacks using standard geometry foils do not have sufficient ion blocking. Better performance was achieved with a quadruple S-LP-LP-S GEM system in which the foils in layers 1 and 4 have a standard hole pitch (S, 140 μm), whereas the foils in layers 2 and 3 have a hole pitch that is two times larger (LP, 280 μm).

Special voltage settings are applied to reduce the IBF. Ions are blocked efficiently by the asymmetric transfer fields (high E_{T1} and E_{T2} and low E_{T3}). An increasing sequence of gas gains down the GEM stack (with the highest gain in GEM 4) helps to further reduce the IBF since ions created in GEM 3 and GEM 4 are blocked more efficiently.

The optimization of the GEM system in terms of IBF inevitably affects also the efficiency for electron transmission and thus the energy resolution of the detector. Therefore, a combined optimization with respect to both ion backflow and energy resolution is mandatory. Fig. 3 shows the correlation between IBF and energy resolution at 5.9 keV in a S-LP-LP-S GEM in Ne-CO_2-N_2 and for various voltage settings. The voltage on GEM 1 increases between 225 and 315 V from left to right for a given value of the voltage on GEM 2. The voltages on GEM 3 and GEM 4 are adjusted to achieve a total effective gain of 2000, while keeping their ratio fixed.

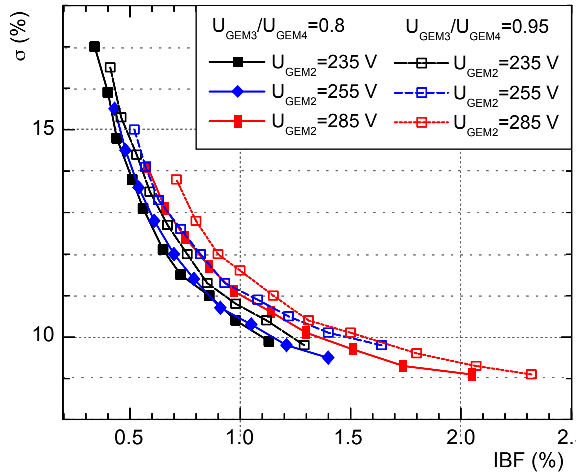

Figure 3: Correlation between IBF and energy resolution at 5.9 keV in a quadruple S-LP-LP-S GEM in Ne-CO_2-N_2 for various voltage settings.

A suitable working point with an IBF of 0.63 % at a local energy resolution $\sigma(^{55}\mathrm{Fe}) = 11.3\,\%$ at 5.9 keV exists. Typical voltage settings are summarized in Tab. 1.

Drift Field		= 0.4 kV/cm
ΔU_{GEM1}	$= U_{\mathrm{1top}} - U_{\mathrm{1bot}}$	= 270 V
Transfer Field 1 (E_{T1})	$= (U_{\mathrm{1bot}} - U_{\mathrm{2top}})/0.2\,\mathrm{cm}$	= 4.0 kV/cm
ΔU_{GEM2}	$= U_{\mathrm{2top}} - U_{\mathrm{2bot}}$	= 250 V
Transfer Field 2 (E_{T2})	$= (U_{\mathrm{2bot}} - U_{\mathrm{3top}})/0.2\,\mathrm{cm}$	= 2.0 kV/cm
ΔU_{GEM3}	$= U_{\mathrm{3top}} - U_{\mathrm{3bot}}$	= 270 V
Transfer Field 3 (E_{T3})	$= (U_{\mathrm{3bot}} - U_{\mathrm{4top}})/0.2\,\mathrm{cm}$	= 0.1 kV/cm
ΔU_{GEM4}	$= U_{\mathrm{4top}} - U_{\mathrm{4bot}}$	= 340 V
Induction Field (E_{ind})	$= U_{\mathrm{4bot}}/0.2\,\mathrm{cm}$	= 4.0 kV/cm

Table 1: Typical high voltage settings for IBF $< 1\,\%$ in a quadruple GEM in Ne-CO_2-N_2 at an effective gain of 2000. Note the high transfer field in the 1st and 2nd gap, whereas E_{T3} is very low.

5. Large-size prototypes

Full size prototypes have been constructed and tested in beam. Fig. 4 shows the four stacks of GEM foils needed to equip one full sector of the ALICE TPC. Each sector consists of an Inner Read Out Chamber (IROC, one GEM stack) and an Outer Read Out Chamber (OROC, 3 GEM stacks). An IROC prototype has been operated in beam tests to measure the particle identification performance and discharge behavior with hadrons (see below). The first OROC prototype was constructed in 2014/15 and is the largest GEM detector built to this point.

Figure 4: To equip one full sector of the ALICE TPC (IROC and OROC) four GEM stacks are needed.

5.1. Particle identification measurements at the CERN PS

A full-size IROC prototype equipped with the baseline S-LP-LP-S GEM configuration was built and tested at the T10 beam line of the CERN Proton Synchrotron (PS) in the fall of 2014. The detector was operated with the baseline gas mixture Ne-CO_2-N_2 (90-10-5). The read-out electronics for this test (10 front-end cards corresponding to about 1200 read-out channels) was borrowed from the Linear Collider TPC collaboration. It covers a 6 to 7 cm wide corridor over the full length of the detector to allow for a systematic measurement of the dE/dx performance with beam particles. The read-out system has an RMS noise of about 600 electrons. A zero suppression threshold of 2 ADC counts was used, corresponding to about 2000 electrons (12 mV/fC conversion gain).

To discriminate electrons from pions, a Cherenkov counter was used. Moreover, the ambient temperature and pressure were monitored. This information was read out through a classic CAMAC system.

Main focus of the data taking at the PS and the subsequent analysis was on the study of the particle identification performance of the detector via the measurement of dE/dx. The energy loss dE/dx is determined using the total charge Q_i^{tot} of the ionization clusters reconstructed on the rows of anode pads ($i \in \{0..62\}$) that the track crosses. We use the truncated mean of the 70 % lowest Q_i^{tot} values. Typical energy loss spectra are shown in Fig. 5.

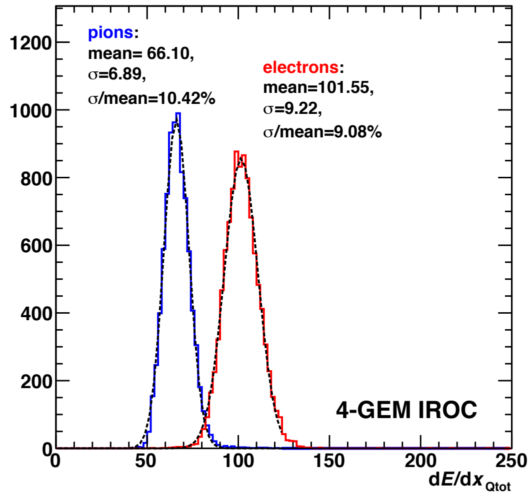

Figure 5: dE/dx distributions of pions (blue) and electrons (red) at an effective gain of 2000 [5].

These measurements verified that the 4 GEM technology offers a dE/dx performance that is compatible with the requirements of the ALICE upgrade physics programme. The results are also in very good agreement with simulations.

5.2. Discharge studies at the CERN SPS

The discharge behaviour of the IROC prototype (again with the baseline gas mixture) was evaluated in a test beam at the CERN Super Proton Synchrotron (SPS). We assume that mainly particles that cross the GEM foils are relevant for the discharge behaviour. The discharge probability for such events was measured using showers of hadrons produced by a high-intensity secondary pion beam with a momentum of 150 GeV/c impinging on a 30 to 40 cm thick iron converter. The average beam intensity was about 6×10^6 particles per spill (~ 5 s). During the two-week RD51 test beam campaign in 2014, a total of 36 h of dedicated data taking was allocated for the ALICE TPC tests.

The particle flux into the IROC chamber was calibrated by recording the current at the anode pad plane (without iron absorber) as a function of the counts measured in the beam scintillators. The IROC anode current was recorded continuously. The integral of the chamber current over the whole beam period gives the total number of accumulated particles: $(4.7 \pm 0.2) \times 10^{11}$.

The discharge performance of the 4 GEM IROC is similar to standard triple GEMs. The odd voltage settings required for IBF minimization are compensated by the addition of the 4th GEM foil.

In summary, for a typical yearly heavy-ion run at 50 kHz we estimate about 650 discharges for the whole TPC, or 5 for each of the 144 GEM stacks. This is not likely to cause any damage to the detectors [5].

6. Front-end electronics and read-out

The minimization of the ion space-charge density in the TPC drift volume requires the operation of the read-out chambers at the lowest possible gas gain. Together with the required Signal-to-Noise ratio this leads to a requirement of low front-end noise. For the current TPC a system noise of 670 electrons (ENC) has been achieved, which is taken as requirement for the upgraded detector. A new 32 channel Front-End ASIC SAMPA (see Fig. 6) [6] is being developped. It features continuous sampling at 10 bit and 10 MHz, read-out through serial electrical links and digital filters for baseline correction (to correct for the common mode effect in the read-out chambers) and zero suppression. Moreover, it offers different, programmable conversion gains and peaking times.

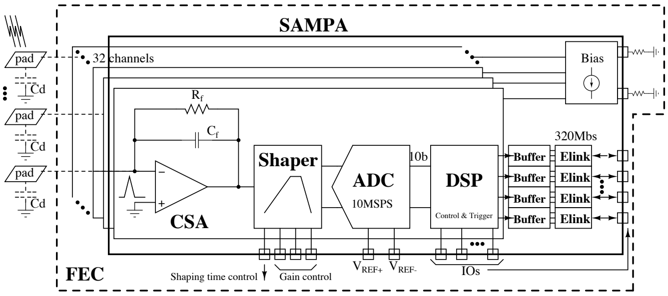

Figure 6: Schematic of the SAMPA ASIC for the GEM TPC read-out.

The read-out of the data from the SAMPA chips is based on the radiation hard, CERN–developed GBT and Versatile Link components [7]. The average expected data output from the TPC to the online farm for 50 kHz PbPb collisions is 1 TByte/s.

7. Space-charge calibration

Even with the required IBF of 1 % considerable space-charge build-up is expected in the drift volume of the TPC. For 50 kHz Pb–Pb collisions ions from on average 8000 events pile up inside the drift volume (the ion drift time for the full drift distance of 2.5 m is 160 ms). Distortions on the cm level are expected in certain parts of the drift volume. These distortions must be correctable without deterioration of the online reconstruction efficiency and of the final momentum resolution of the detector. A two-stage calibration and reconstruction scheme is envisaged to achieve this performance [4].

The influence of the space-charge distortions on the matching efficiency of the tracks to the silicon Inner Tracking System and on the transverse momentum resolution (see Fig. 7) have been studied. The performance is retained even if an IBF value of twice the design value (2 %, $\varepsilon = 40$) is assumed.

Also the increase of the track density in the drift volume of the TPC (due to event pileup) is not found to have a large impact on the reconstruction performance. The track matching efficiency and transverse momentum resolution deteriorate only for interaction rates > 100 kHz, twice the design value.

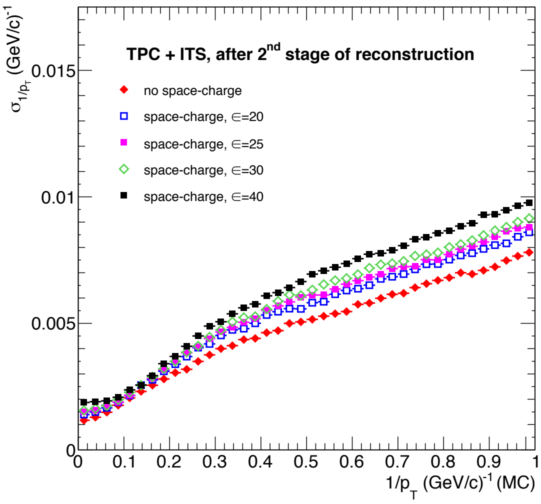

Figure 7: Transverse momentum resolution for TPC tracks combined with tracklets in the silicon Inner Tracking System (left) for different space-charge densities without distortions and with residual distortions after the second reconstruction stage.

8. Summary and conclusions

A major upgrade of the ALICE experiment will be realised in 2018/19. In order to allow inspection of all Pb–Pb collisions at the full expected LHC HI luminosity of 50 kHz the TPC will be upgraded with read-out chambers based on a novel scheme with quadruple GEM stacks combining foils with different hole pitch. The data from the GEM stacks will be read continuously using new front-end electronics and a radiation-hard optical link set. The requirements for the GEM system in terms of ion backflow, energy resolution and stability against discharges have been met in prototype tests.

References

[1] ALICE Collaboration, Upgrade of the ALICE Experiment: Letter Of Intent, CERN-LHCC-2012-012 / LHCC-I-022, 2012, http://cds.cern.ch/record/1475243/.

[2] J. Alme et al, The ALICE TPC, a Large 3-Dimensional Tracking Device with Fast Read-out for Ultra-high Multiplicity Events, Nucl. Instrum. Meth A622 (2010) 316–367.

[3] F. Sauli, GEM: A new concept for electron amplification in gas detectors, Nucl. Instrum. Meth. A386 (1997) 531–534.

[4] ALICE Collaboration, Technical Design Report for the Upgrade of the ALICE Time Projection Chamber, CERN-LHCC-2013-020, 2013, http://cds.cern.ch/record/1622286.

[5] ALICE Collaboration, Addendum to the Technical Design Report for the Upgrade of the ALICE Time Projection Chamber, CERN-LHCC-2015-002, ALICE-TDR-016-ADD-1, 2015, https://cds.cern.ch/record/1984329.

[6] ALICE Collaboration, Upgrade of the ALICE Readout & Trigger System, Technical Design Report, CERN-LHCC-2013-019, ALICE-TDR-015, 2013, https://cds.cern.ch/record/1603472.

[7] F. Vasey et al, The Versatile Link common project: feasibility report, JINST 7 C01075, 2012, http://iopscience.iop.org/1748-0221/7/01/C01075/.