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Performance of the ALICE Time Projection Chamber

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Abstract

The Time Projection Chamber of the ALICE experiment is a large 3-dimensional tracking device for ultra-high multiplicity events. It has been operated successfully at the Large Hadron Collider at CERN, recording collisions of protons (since November 2009) and of heavy-ions (lead nuclei, in November 2010). We describe the detector and the calibration procedures necessary to guarantee an optimal data quality. We report on the performance, in particular of tracking and particle identification, and on readout speed. Finally, we summarize the challenges in the design and the experience in operating the Time Projection Chamber under the extreme conditions of heavy-ion collisions at the LHC.

Keywords: ALICE, TPC, particle identification, tracking, LHC, heavy-ion collisions, calibration

1. Ultrarelativistic heavy ion collisions at the LHC

The basic idea of ultrarelativistic heavy ion (HI) collisions is to compress a large amount of energy in a very small volume. A "fireball" of hot matter will be produced, with a temperature of the order 10^{12} K. This is equal to 10^5 times the temperature at the center of the sun, and is believed to have been the temperature of the universe about 10 μs after the Big Bang. Quantum-Chromodynamics predicts that a state of deconfined quarks and gluons is generated in such collisions (the so called Quark-Gluon Plasma, QGP). In order to find out how this new kind of matter behaves, the largest available stable nuclei (Pb ions) are accelerated at the Large Hadron Collider (LHC) at CERN in Geneva to the highest possible center-of-mass energy per nucleon of $\sqrt{s_{\mathrm{NN}}} = 5.5$ TeV (currently 2.76 TeV). A comprehensive HI programme at the LHC focuses on the study of these collisions: one month of beam time per year is devoted to ions, with ALICE (A Large Ion Collider Experiment [1]) being the dedicated HI experiment.

2. The ALICE experiment at the LHC

The basic idea of a dedicated HI experiment is to use the hadrons, electrons, muons and photons, that are produced in the collisions, as probes of the QGP [2]. As a consequence, ALICE has not only precise tracking capabilities over a large momentum range ($100\,\mathrm{MeV}/c < p < 100\,\mathrm{GeV}/c$), but also excellent particle identification (PID). As compared to proton-proton (pp) collisions the luminosity is rather low (10^{27} Hz/cm^2). With a cross section of 8 barn

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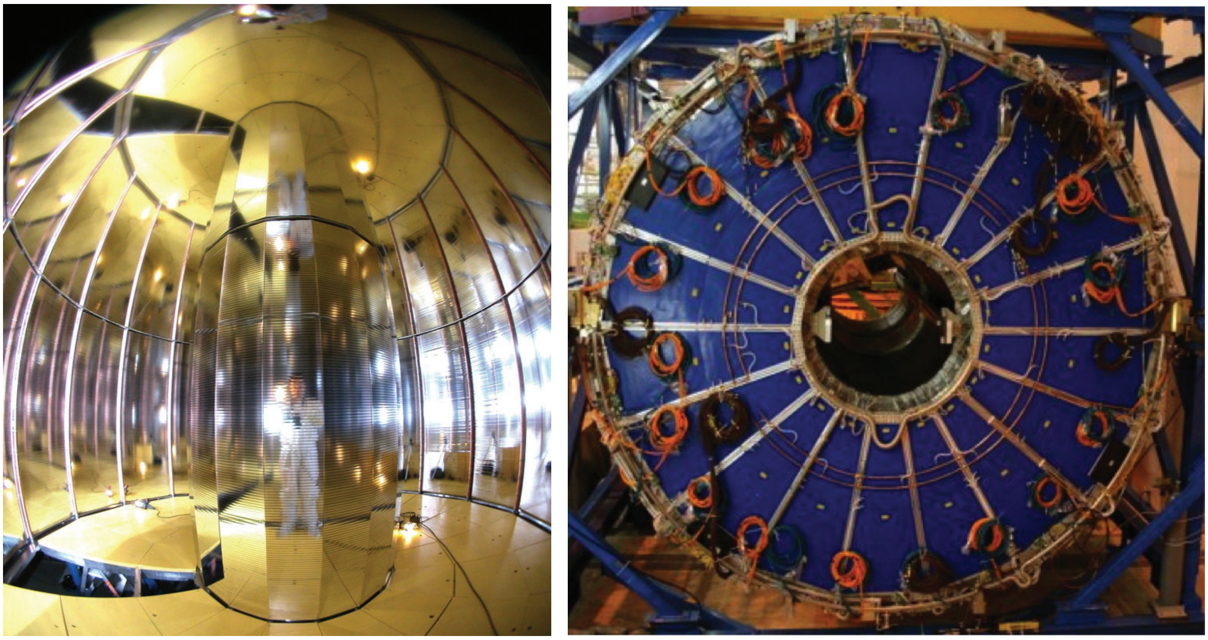

Figure 1: Left: Fish-eye view of the TPC field cage during assemply. The central high voltage electrode is located at the top of the image and reflects like a mirror. Right: The two endplates of the TPC are divided into 18 sectors holding two readout chambers (ROC) each. The ROCs and front-end electronics are hidden behind the blue covers.

this gives an interaction rate (minimum bias) of 8 kHz. However, the corresponding charged particle multiplicities are extraordinary: in central Pb–Pb collisions a charged particle multiplicity per unit of pseudo-rapidity[2] η of $dN_{ch}/d\eta = 1600$ was observed at $\sqrt{s_{\rm NN}} = 2.76\,\rm TeV$ [3].

3. TPCs are perfect tools in heavy-ion collisions

In general, Time Projection Chambers (TPCs) are perfect detectors for high multiplicity environments like HI collisions and to resolve particle jets. This is because TPCs provide a large volume which may be sampled with very high granularity and which is filled with a light detecting medium (a gas). Pattern recognition is very robust due to the continuous track model. Finally there is low multiple scattering due to the large radiation length, since the active material is gaseous. On top of the tracking information there is also the possibility to use the measured signal amplitudes to estimate the specific ionization. This is generally known as dE/dx measurement and can provide very powerful PID, especially in the low energy region ($p \leq 1\,\rm GeV/\it c$), where the ionization is $\propto 1/\beta^2$, and where the particles are well separated. For many gas mixtures one makes use of the fact that the transverse diffusion of the drifting electrons is largely reduced if $\omega\tau > 1$ and for a configuration with the magnetic and electric fields aligned. At a given magnetic field, the plasma frequency ω and the mean time between two collisions τ can be tuned over a wide range by proper choice of the gas mixture. The maximum possible trigger rate is limited by the electron drift time (typically tens of µs). This matches well the rather moderate HI luminosities offered by the LHC. Consequently, a TPC was chosen as the main tracking and PID device of ALICE.

4. Description of the ALICE TPC

The ALICE TPC [4] (see Fig. 1) has 5 m diameter and 5 m length, divided into two halves by an aluminised mylar foil acting as the central drift electrode. It has an active volume of $\sim 92\,\rm m^3$ and is filled with a gas mixture based on Ne with an admixture of around 10% CO_2. This gas mixture has a rather small $\omega\tau$ of 0.32, so that the mentioned effect of the magnetic field on the diffusion is negligible. However, it has very low diffusion to start with ("cold gas"). Due to the low Z of Ne, multiple scattering (total material budget is 3% X_0 around pseudo-rapidity $\eta = 0$) and primary

[2]ALICE was optimized for charged particle densities of up to $dN_{ch}/d\eta = 8000$.

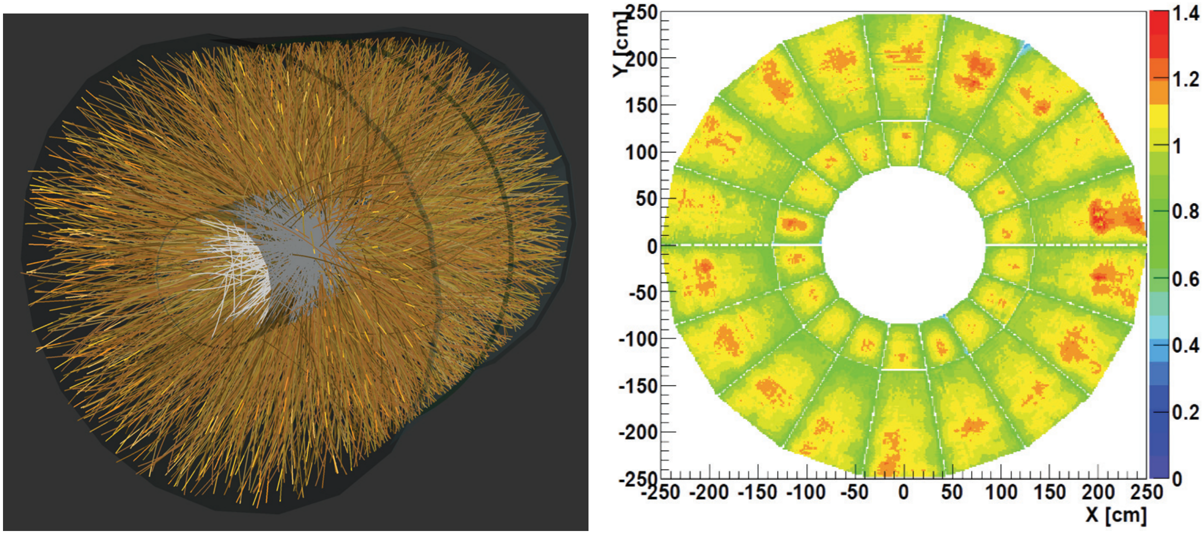

Figure 2: Left: 3D view of the tracks reconstructed from a central Pb–Pb collision in the TPC. Right: Relative variation of the gain per readout pad for the ROCs on one side (C side) of the TPC. The data is extracted from the decay spectrum of radioactive ^{83}Kr in the TPC gas mixture.

ionization are both low. The latter minimizes the space charge in the drift volume. The electron drift time for the full drift length of 250 cm is around 92 μs. Since the drift velocity for this gas mixture is not saturated any change in temperature, pressure or gas composition immediately reflects in a change of the drift velocity. As a consequence the temperature has to be well homogenized (variations on the level 10^{-4} in the gas volume) and precise drift velocity calibration is fundamental.

The readout chambers (ROCs) are Multi Wire Proportional Chambers with cathode pad readout and a gated wire grid to block the passage of drifting charges when the TPC is untriggered. The field cage, ROCs and gas system are very leak tight (1 ppm O_2). For stability of operation 50 ppm of water vapor are added to the gas mixture.

The TPC has 557 568 readout pads and front-end electronics (FEE) channels. Each channel can be sampled into up to 1023 time bins, which means that the active volume is sampled in 557 million voxels. The PreAmplifier ShAper (PASA) chips with 12 mV/fC gain and a shaping time of 190 ns (FWHM) feed the signals into the digital ALTRO [5] chip with 10 bit digitization, 10 MHz sampling, two baseline restoration circuits, tail cancellation, zero suppression with glitch filter and multi event buffering (MEB). The mean noise measured on the detector is ~ 0.7 ADC (700 e^-), much better than the design value of 1000 e^-. The signal processing in the ALTRO is designed to remove systematic baseline shifts due to the pile-up of the ion tails of the electronic signals from the ROCs even at the highest charged particle multiplicities.

The TPC field cage was assembled at CERN during the years 2002 to 2004. The ROC and electronics installations were finished in 2005 and 2006, respecively. The fully integrated TPC was then installed inside the ALICE solenoid magnet in 2007. Commissioning and calibration activities took place in the years 2007 to 2009, before data taking with LHC beams started at the end of 2009. While the LHC delivers pp collisions, the TPC is in continuous data taking mode. In November 2010 the first Pb–Pb collisions were delivered. A central Pb–Pb collision recorded with the TPC is shown in the left panel of Fig. 2.

5. Calibration: gain, drift velocity and field distortions

The precision of the tracking and PID information from the TPC depends crucially on a precise calibration of the ROC and FEE gain and of the electron drift properties. For the gain calibration a short-lived radioactive isotope (^{83}Kr) is injected into the TPC gas mixture about once per year. The decay produces an electron spectrum in the keV range and can be used for a precise gain determination for each pad to within 1%. The resulting gain map for one side of the TPC is shown in the right panel of Fig. 2.

Three dimensional coordinate measurements require precise knowledge of the electron drift properties inside the TPC volume. Sources for drift distortions are inhomogenieties of the magnetic field, misalignment of electric and magnetic fields ($E \times B$-effect, see left panel of Fig. 3), field cage imperfections (see right panel of Fig. 3) and space

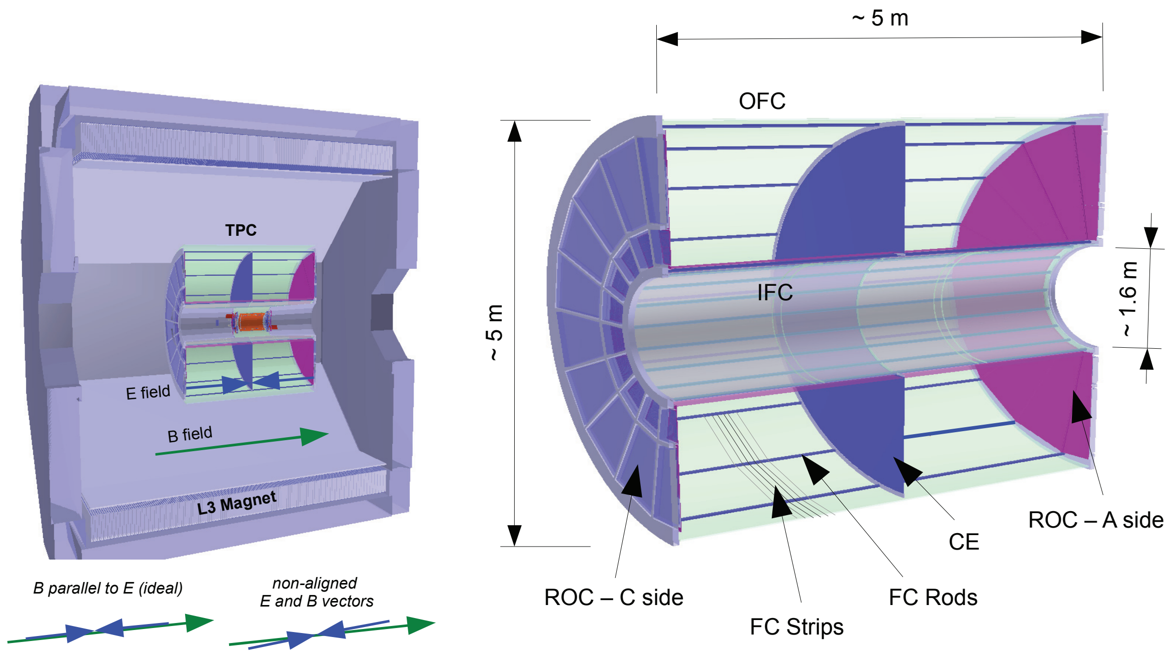

Figure 3: Left: Schematic image of the TPC inside the ALICE L3 solenoid magnet, indicating the possibility of slight misalignments between the electric drift field inside the TPC and the magnetic field. Right: Schematic image of the TPC field cage. It consists of the Inner and Outer Field Cage (IFC and OFC), the Central Electrode (CE), the ROCs and the voltage divider strips, which are held by several field cage rods. Imperfections in the field cage (like shifts or rotations of individual components) may lead to a deflection of the drifting electrons from the ideal trajectory.

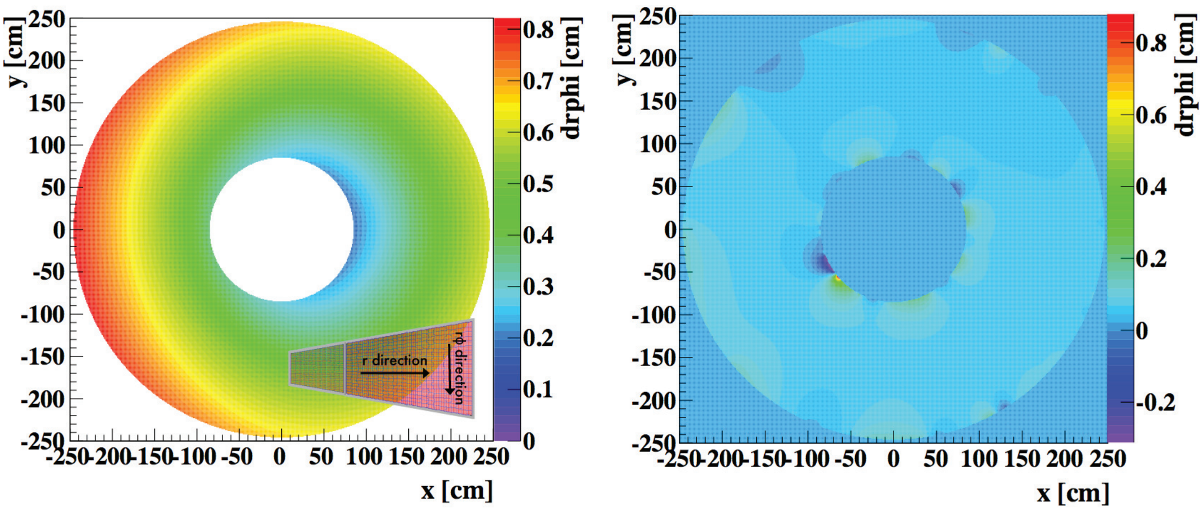

Figure 4: Both panels show the $r\phi$-component (as shown in the inlay) of the drift distortions at a fixed position along the drift direction (close to the CE, $z = 1$ cm) on one side (A side) of the TPC. Left: The effect of misalignment (as shown in the left panel of Fig. 3) and inhomogenieties of the magnetic field. Right: Distortions due to field cage imperfections. The maximum distortion is localised close to the IFC. All distortions can be corrected using the shown calibration data.

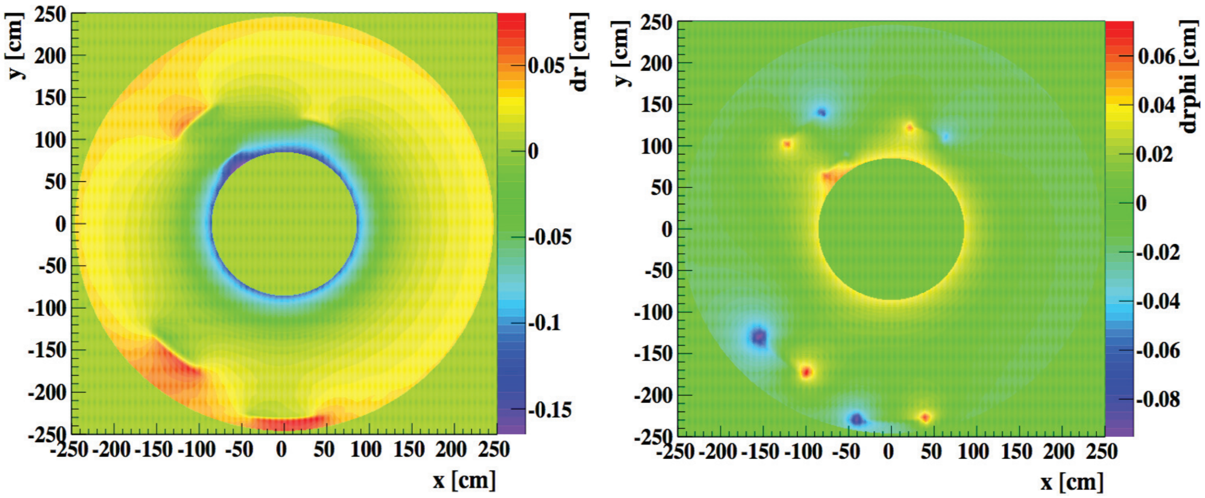

Figure 5: Two components (δr and $\delta r\phi$) of the expected space charge distortions at a fixed position along the drift direction close to the CE (z = 1 cm) at one side of the TPC (A side). The data is based on an expected charge density for Pb–Pb collisions with an interaction rate of 8 kHz and a minimum bias multiplicity (top 80%) of $dN_{ch}/d\eta = 950$. Some leaking gating grid wires are added as an additional source of space charge.

charge inside the drift volume. All of these effects can be adequately calibrated (corrected). Two examples are shown in Fig. 4. The maximum distortions are up to $\delta r = 10$ mm and $\delta r\phi = 8$ mm (these are local coordinates in each TPC sector, see the inlay in the left panel of Fig. 4) and may be very localized. Fig. 5 shows the expected distortions due to space charge in the drift volume of the TPC during high luminosity HI running. Such distortions are caused by the slowly drifting ions from primary ionization in the gas volume, as well as by possible leakage of the ROCs gating grid wires. So far no such distortions are visible in the pp and Pb–Pb collisions recorded. However, some effect is expected once the maximum Pb–Pb luminosity is reached. The resulting charge distribution $\rho(r, z)$ is azimutally symmetric in a first order approximation, whereas it follows $1/r^2$ in the radial direction. In the drift direction it increases linearly with z with a maximum close to the CE, because of the random distribution of collisions in time. The slope of this increase is defined by the interaction rate, the ion mobility and the average multiplicity of individual events. The maximum expected distortions are $\delta r = 5$ mm and $\delta r\phi = 0.8$ mm (both shown in Fig. 5). All mentioned effects can be corrected by calibration procedures based on the distortion maps shown exemplary here.

Furthermore, laser tracks are used for drift velocity calibration and for alignment. Not only the laser tracks themselves are used as input. Scattered photons extract photoelectrons from the aluminized surface of the CE. These arrive at the ROCs after traveling the same, precise distance (2.5 m) for all readout pads and produce a substantial signal, creating a very powerful input for drift velocity calibration. Finally, as a further input for drift velocity calibration an external drift velocity monitor is used.

Also particle tracks are used for calibration purposes. Cosmic particles are useful for alignment. Tracks from collisions play an important role during physics data taking for the time-dependent calibration of gain changes, e.g. due to pressure changes, and for drift velocity calibration. Here the matching of TPC tracks to hits in the Inner Tracking System (ITS) of ALICE is used.

6. Tracking performance

A low material budget and a rather low magnetic field (0.5 T) are the requirements to optimize the ALICE detector for tracking and particle identification down to very low momenta ($p \geq 100$ MeV/c). Inside the TPC, the track of a particle with momentum above a few hundred MeV/c consists of up to 159 clusters. This number is given by the maximum number of pad rows the particle can cross. The space point resolution for such a cluster along the pad row direction (local $r\phi$ coordinate) as a function of the track inclination angle is shown in the left panel of Fig. 6. In a global tracking procedure the TPC tracks are combined with hits in the ITS. A transverse momentum resolution of $\sigma(p_t)/p_t = 20\%$ at $p_t = 100$ GeV/c was achieved in HI collisions (see right panel in Fig. 6) with the calibration available at the time of the conference (summer 2011). This has to be compared with the values expected from simulations: $\sigma(p_t)/p_t = 5\%$.

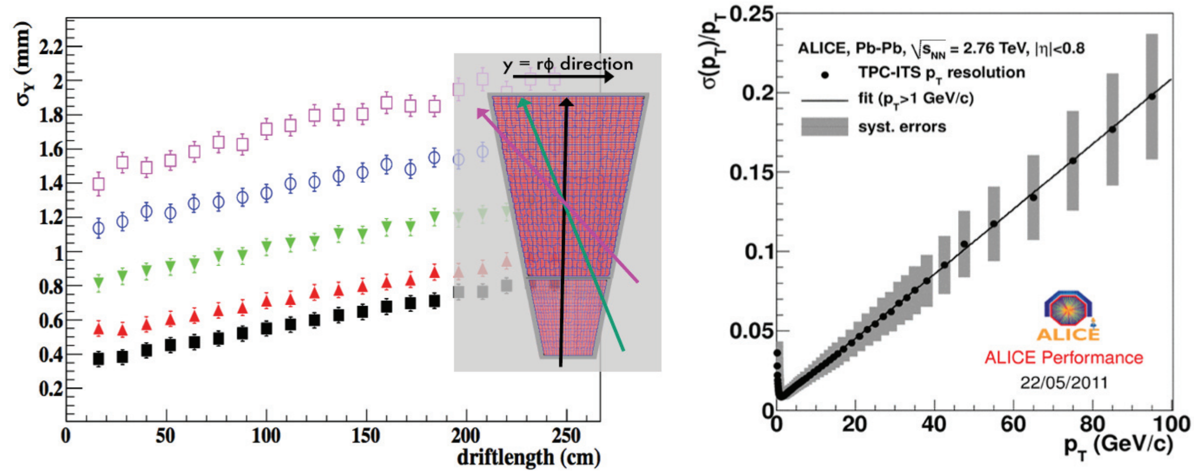

Figure 6: Left: Space point resolution of the TPC. This value depends on the drift length (due to diffusion) and on the inclination angle (as shown in the inlay). The data sample analyzed was collected with a cosmic trigger in the year 2009 and shows a space point resolution of 400 to 800 μm for tracks that are crossing the pad rows almost perpendicularly as high-p_t tracks do. Right: Transverse momentum resolution in the central rapidity region ($|\eta| < 0.8$) for TPC tracks combined with hits in the ALICE Inner Tracking System (ITS). The current status yields a resolution of $\sigma(p_t)/p_t = 20\%$ at $p_t = 100\,\mathrm{GeV}/c$.

As work is ongoing to improve the tracking performance, the expected performance is within reach for the year 2011. By combining the global tracks also with tracklets in the six layers of the Transition Radiation Detector (TRD) that surrounds the TPC, a resolution of $\sigma(p_t)/p_t = 3.5\%$ at $100\,\mathrm{GeV}/c$ can ultimately be reached [6].

7. Particle identification performance

The ionization produced by each track is sampled on up to 159 pad rows in the TPC and a truncated mean is used for the calculation of the PID signal. The left panel of Fig. 7 shows the ionization signals of charged particle tracks in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$. The different characteristic bands for various particles including deuterons are clearly visible. The use of a 10 bit ADC provides a dynamic range which is sufficient to examine ionization signals of up to 26 times that of a minimum ionizing particle. In order to achieve PID in a certain momentum region, histograms are filled and fitted with multiple Gaussians. An example is shown in the right panel of Fig. 7. For a given momentum region one can derive the particle yields, which represent the probabilities for the particle to be a kaon, proton, pion or electron. One can also extract the resolution of the ionization signal ("energy resolution" $\sigma_{dE/dx}$), which is proportional to the ionization signal itself: for the TPC it is $\sigma_{dE/dx} = 5\%$ for tracks with the maximum number of samples (requirement was 5.5% [6]). The dependence on the number of samples N_{cl} is shown in the left panel of Fig. 8. In heavy-ion collisions the energy resolution degrades slightly to an average of about 5.3%. For the highest multiplicity events it falls off to 6%. The degradation is explained by overlapping signals from neighboring tracks, which have to be removed, thus reducing the number of usable samples N_{cl}. Part of the deterioration is also explained by baseline fluctuations in the electronics due to large hit densities in single channels. These fluctuations can in principle be removed using the tail cancellation and baseline correction features available in the ALTRO chip, but this feature was not yet enabled in 2010.

The TPC in combination with the ALICE Time-Of-Flight detector is also very well set up for the detection of rare stable particles, e.g. light anti- or hyper-nuclei. Four anti-alpha candidates created in Pb–Pb collisions were found in the data collected in November 2011 (see right panel of Fig. 8).

8. Readout speed

Proton collisions at the LHC are recorded in ALICE at interaction rates that depend on the physics observables of interest. An interaction rate of 10 kHz is optimal for large cross section observables while having almost no event pile-up in the TPC. Due to the drift time (~92 μs) collision events from subsequent bunch crossings in the LHC start to overlap in the TPC drift volume at higher interaction rates. Up to 200 kHz is used for maximizing signatures of rare processes at an acceptable event pile-up. The event size and thus the readout time depend strongly on the pile-up and

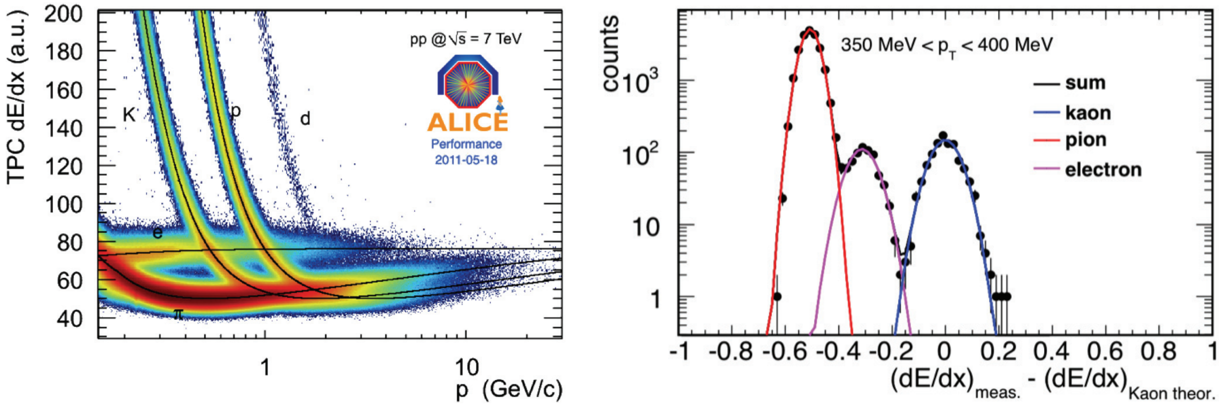

Figure 7: Left: Ionization signal measured in the TPC with tracks from pp collisions. Especially in the low momentum region at a few hundred MeV/c kaons and protons and also deuterons can be reliably identified. Right: A histogram of the ionization signal in a momentum window of 50 MeV/c width in the $1/\beta^2$ region of the Bethe-Bloch curve. The data can be fitted well by a sum of three Gaussians representing the yields of kaons, pion and electrons. Protons are completely separated in this momentum slice and are not shown in the plot.

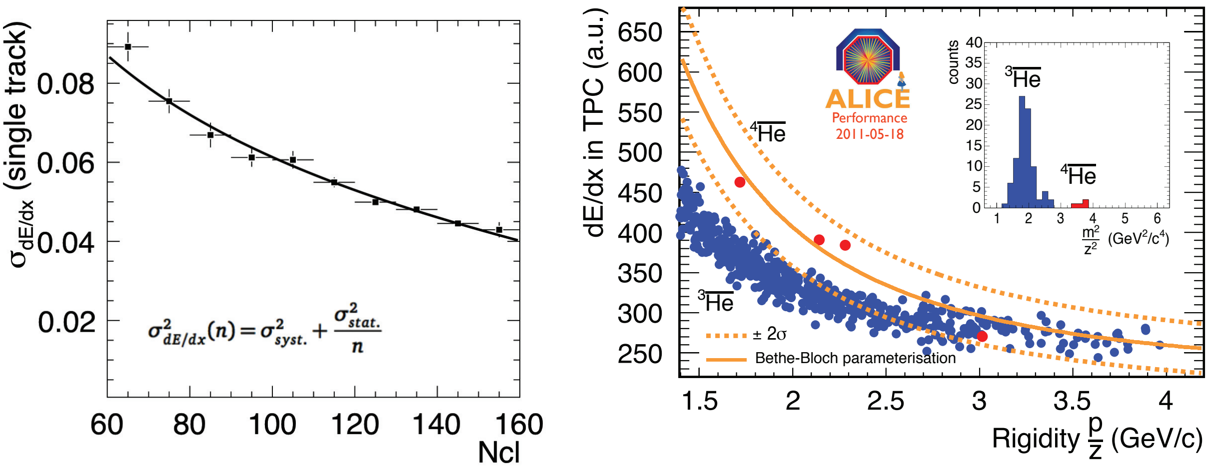

Figure 8: Left: Dependence of the resolution in the ionization signal ($\sigma_{dE/dx}$) on the number of samples N_{cl} available for sampling the ionization along a given track. The maximum number is given by the number of pad rows in a TPC sector (159). Right: Four anti-^{4}He candidates found in the data recorded in HI collisions in November 2010. They were identified by combining the specific ionization in the TPC with the Time-Of-Flight information from a separate detector.

thus on the collision rate. The event size of one pp event from the TPC is 380 kBytes (6 MBytes), while the readout time is 0.5 ms (1.1 ms) without pile-up (with about 16 overlapping events at 150 kHz).

In HI collisions the TPC readout time depends strongly on the centrality of the recorded HI event. The most central events have a size of 80 MBytes and require 4 ms to be read out. The latter number however depends strongly on the mixture of triggers used in the data taking. In order to not miss any interesting event, the Multi Event Buffer (MEB) of the ALTRO digital chip is used. The MEB is particularly useful in the case where the trigger rate is similar to the inverse of the readout time[3], e.g. for a trigger on central Pb–Pb collisions at 250 Hz.

9. Summary: Challenges and experience at ultra-high multiplicities

The high multiplicity that was expected in HI collisions at the LHC was the key ingredient for most design parameters of the ALICE TPC. Its implications on the detector performance are twofold: on the one hand it has an impact on the performance (accuracy of tracking and PID); on the other hand the operational stability may be affected. Overlapping tracks lead to cluster pile-up which potentially reduces the number of samples available for the calculation

[3]The times between two triggers are exponentially distributed with a mean τ. 63% of the triggers arrive with times shorter than τ and will be missed without a MEB. The MEB "derandomises" these events; they are shortly buffered and then sent during larger gaps between two triggers.

of the ionization signals used for PID. This effect was minimized by choosing a gas mixture with low diffusion and by minimizing the pad size. As a result an energy resolution of 6% is reached for the most central HI collisions. This excellent performance is also due to the precise gain calibration using radioactive isotopes in the gas mixture. Distortions due to space charge are minimized by a drift gas mixture with low Z and thus low primary ionization. A physical model of the remaining distortions allows their correction and permits the best possible performance. Finally, baseline fluctuations due to the overlap (in time) of the long ion tail signals of different tracks may be removed online by the digital processing in the ALTRO chips.

The operational stability may be compromised by ageing problems, but none were observed so far in >4 pb^{-1} (~9 μb^{-1}) collected with pp collisions (Pb–Pb collisions). The occurence of high voltage trips[4] and of damage to Front-End Electronics may also impact on the operational stability. As the luminosity increased, such events have occured and work is currently focussed on resolving these issues, mainly by reducing the energy released in possible discharges and by modification of the high voltage distribution.

Appendix A. The ALICE TPC collaboration

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Bibliography

[1] The ALICE Collaboration, K. Aamodt et al. (ALICE Collaboration), *The ALICE experiment at the CERN LHC*, JINST 3, S08002 (2008).
[2] F. Carminati et al. (ALICE Collaboration), *ALICE: Physics performance report, volume I*, J. Phys. G 30 (2004) 1517-1763.
[3] K. Aamodt et al. (ALICE Collaboration), *Charged-particle multiplicity density at mid-rapidity in central Pb–Pb collisions at* $\sqrt{s_{NN}}$ = 2.76 *TeV*, Phys. Rev. Lett. 105, 252301 (2010), arXiv:1011.3916 [physics.nucl-ex].
[4] J. Alme et al. (ALICE TPC Collaboration), *The ALICE TPC, a large 3-dimensional tracking device with fast readout for ultra-high multiplicity events*, Nucl. Instr. and Meth. A 622 (2010) 316-367; arXiv:1001.1950v1 [physics.ins-det].
[5] R. Esteve Bosch et al., *The ALTRO chip: a 16-channel A/D converter and digital processor for gas detectors*, IEEE Trans. Nucl. Sci. 50 No. 6 (2003) 2460-2469.
[6] B. Alessandro et al. (ALICE Collaboration), *ALICE: Physics performance report, volume II*, J. Phys. G 32 (2006) 1295-2040.

[4] A high voltage trip is a controlled ramp down of the high voltage when the power supply detects a current exceeding a predefined threshold.