Space-Point Calibration in the ALICE TPC

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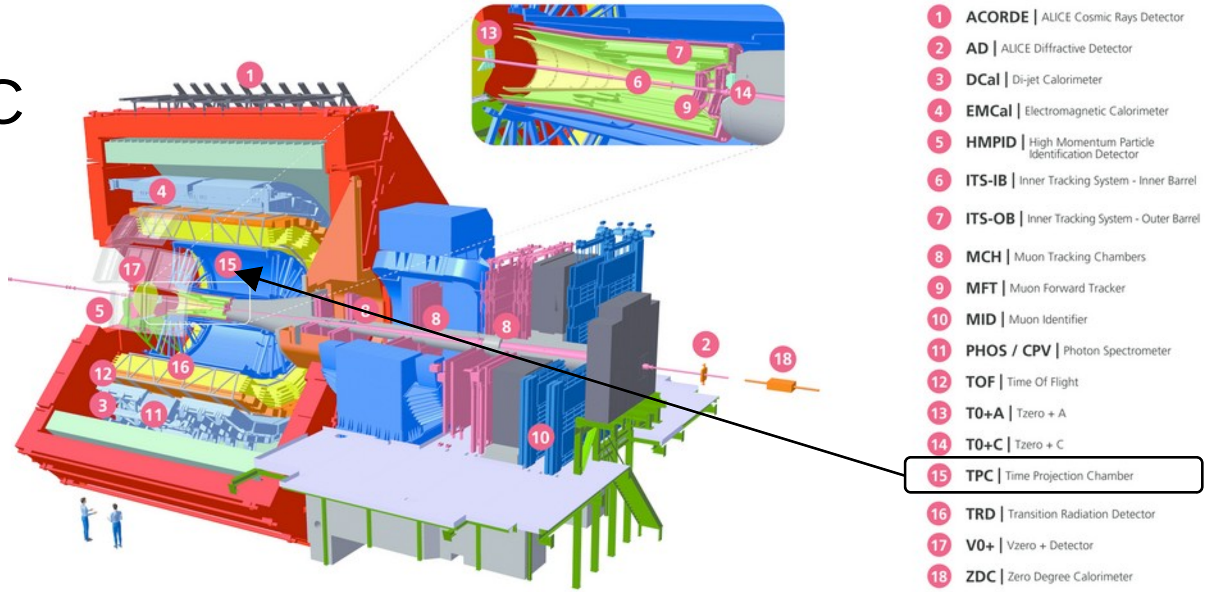
- The ALICE and its TPC – technical overview
- Space-point distortion contributions
- Distortion corrections

ALICE and its TPC

Technical overview

The ALICE Detector system

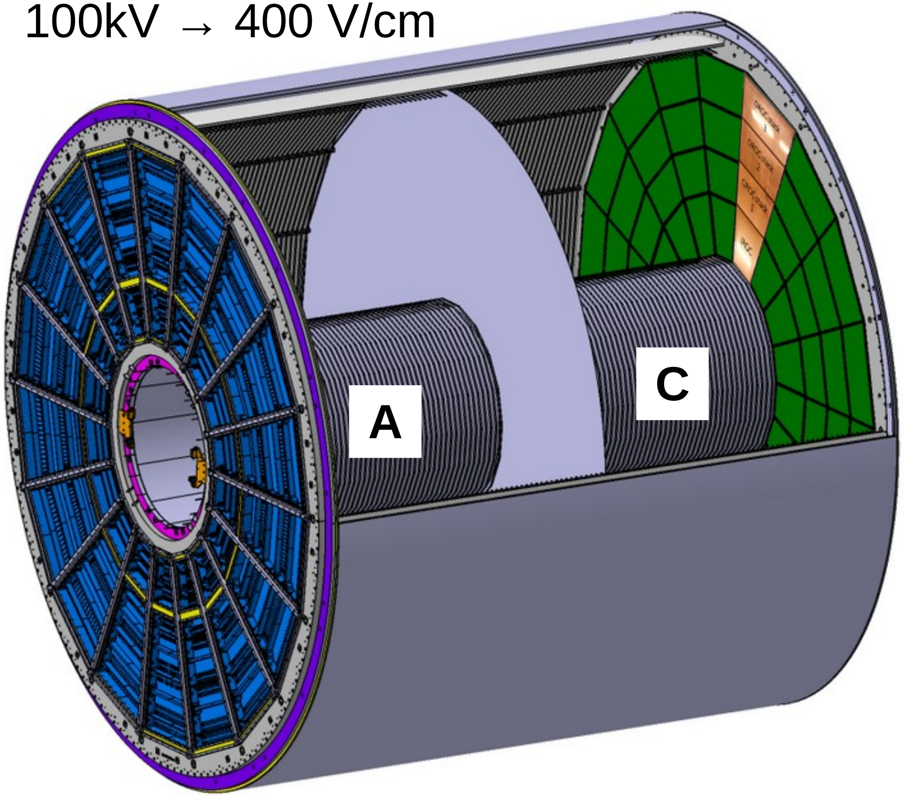
- Dedicated heavy-ion experiment at CERN LHC
- Running conditions
  - 50kHz Pb-Pb
  - Up to 5MHz pp, default 0.5-1MHz
- Main detector for particle identification and track reconstruction
  - Large-volume TPC



The ALICE TPC

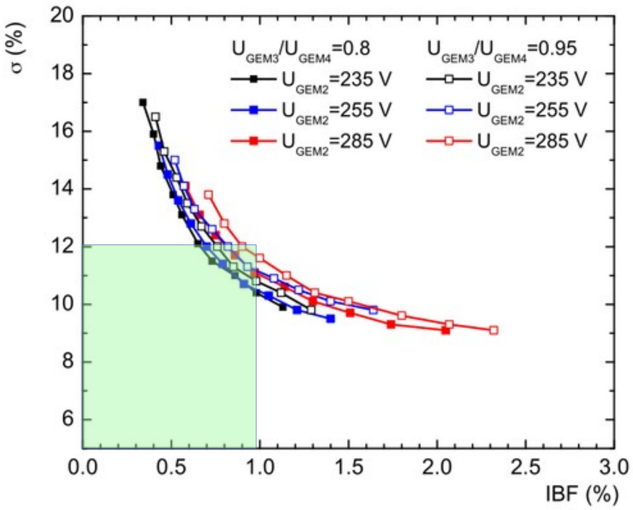
- Large volume TPC (~90m^3)
- Gas: Ne-CO_2-N_2 (90-10-5)
- Drift voltage: 100kV, 94µs drift time
- Two read-out halves, divided by central HV electrode
- 18 readout sectors in azimuthal direction
- Each sector divided into an inner and out readout chamber (IROC / OROC)

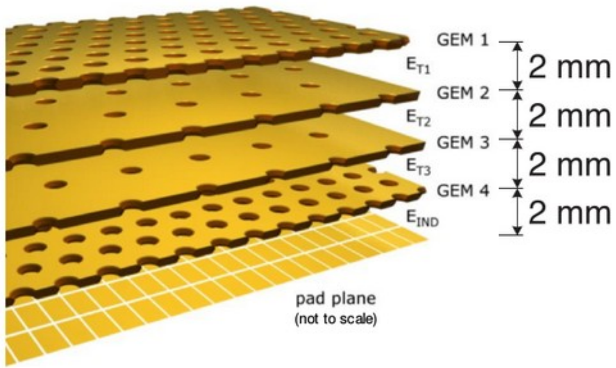
Central HV electrode (CE)
100kV → 400 V/cm



Readout technology

- Readout technology:
  Gas Electron Multipliers (GEMs)
  - Continuous readout
  - Good local energy resolution
  - Moderate Ion back flow
  - High operational stability
- Optimized operational point
  - Pitch layout S-LP-LP-S
  - HV settings





Space-point distortion contributions

- Static distortions
- Charge-up effect
- Space-charge

Space-point distortions

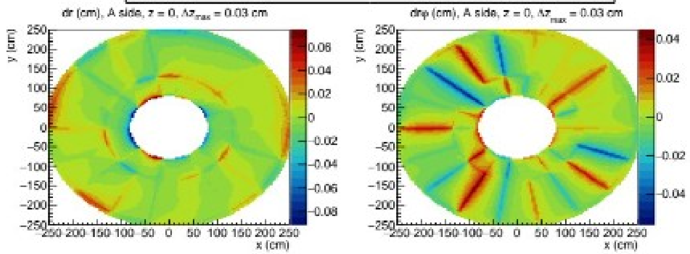
Static distortions and charge-up

- Static distortions
  - Misalignment between readout chambers and central electrode
  - Misalignment of nominal B- and E-fields due to imperfections

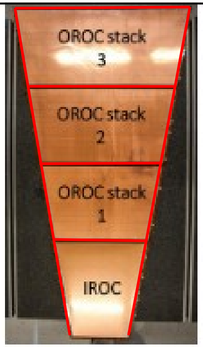
    ➔ Constant in time for given detector configuration
- Charge-up effects
  - Non-conducting surfaces of GEM frames
  - Inner field cage close to the central electrode on the C side

    ➔ Time constants O(mins), scaling with load

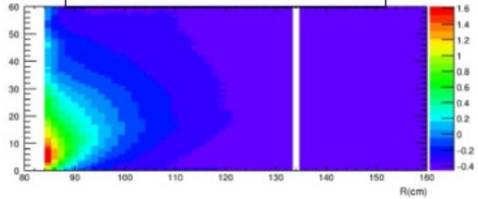
Misalignment between ROCs and CE



Readout sector



Charge-up effect at C side CE

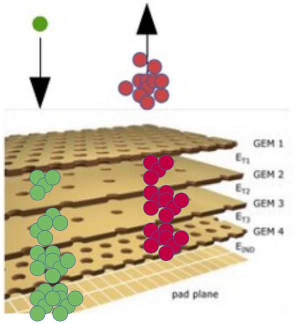


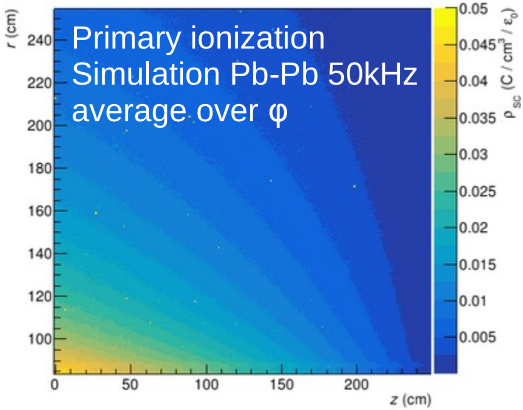
Space-point distortion contributions

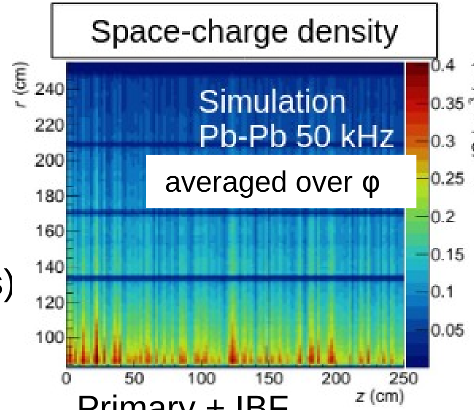
Space-charge

- Ions from amplification stage drift back to the drift volume (~1%)
  - Back drifting ions per primary electron:
    ε = IBF * gain (2000) = 20
- Slow ion drift (~200ms for full drift)
  - Ions from large number of events piling up (~10000 events @ Pb-Pb 50kHz)
  - Large space charge
  - Large average distortions (O(5-10cm))
  - Intrinsic resolution at inner wall ~200μm
- Realistic simulation
  - full detector description (Geant4)
  - Measured relative gain map
  - Measured relative IBF map (with production HV settings)
  - Caveat: linear electron and ion transport

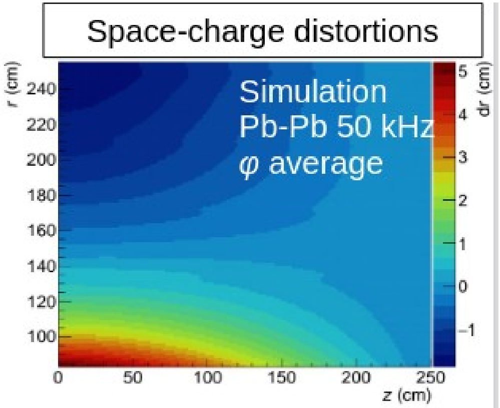
$$\rho_{ion} \sim I_{prim} * \varepsilon \sim Q * \varepsilon$$







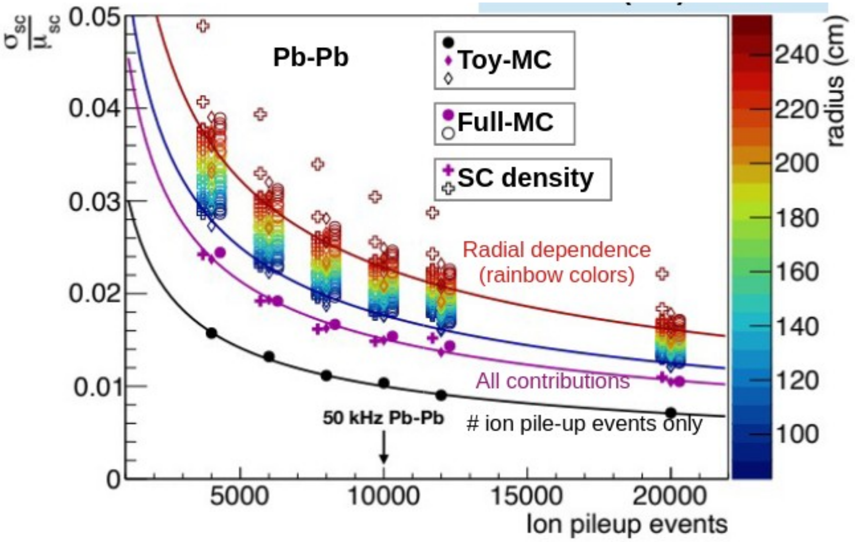
Primary + IBF



Space-point distortion contributions

Space-charge fluctuations

- Fluctuations driven by
  - Ion backflow x gain = ε
  - Number of ion pile-up events within one full ion drift time
  - Particle flux (primary, secondary particles) from collisions
  - Ionization deposited by single particles
- Relative space-charge density fluctuations σ_{SC}/μ_{SC} of ~2 % at 50 kHz Pb-Pb
  - Distortion fluctuations of O(mm - cm) in r and rφ
  - Relevant time scales: 5 - 10 ms
- **Direct measure for density fluctuation required**



$$\frac{\sigma_{sc}}{\mu_{sc}} = \frac{1}{\sqrt{N^{ion}_{pileup}}}\sqrt{1+\left(\frac{\sigma_{N_{mult,prim}}}{\mu_{N_{mult,prim}}}\right)^2+\left(\frac{\sigma_{N_{mult,relsec}}}{\mu_{N_{mult,relsec}}}\right)^2+\frac{1}{\left(F_{prim}(r)\cdot\mu_{N_{mult,prim}}+F_{sec}(r)\cdot\mu_{N_{mult,sec}}\right)}\left[1+\left(\frac{\sigma_{Q_{track,prim}}(r)}{\mu_{Q_{track,prim}}(r)}\right)^2+\left(\frac{\sigma_{Q_{track,sec}}(r)}{\mu_{Q_{track,sec}}(r)}\right)^2\right]}$$

1D fluctuations

3D fluctuations

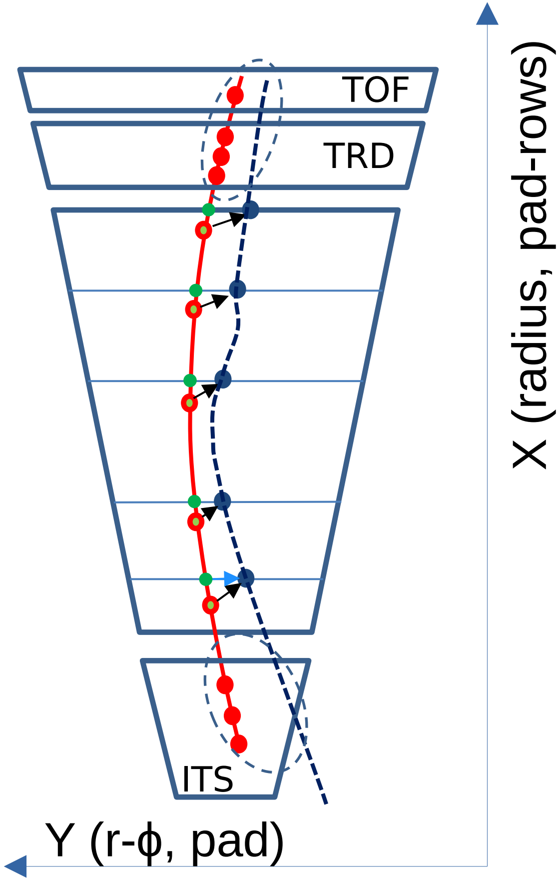
Distortion corrections

- Long term average
- Short-term average corrections
- Fluctuation corrections

Distortion corrections

Long term average – apparent distortions

- **Main input**: **direct measure of distortions**
- Reconstruct TPC tracks with relaxed tolerances (applying “default distortion map” if available)
- Match to ITS and TRD/TOF with relaxed tolerances
- Refit ITS-TRD-TOF part and interpolate to TPC as a **reference** of the **true track position** at every pad-row
- Collect **δY**, δZ differences between **distorted clusters** and **reference** points in sub-volumes (voxels) of TPC



Distortion corrections

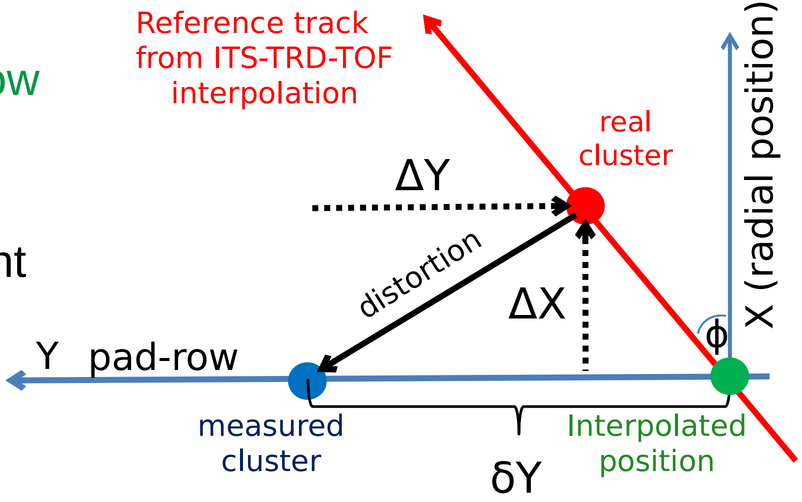
Long term average – real distortions

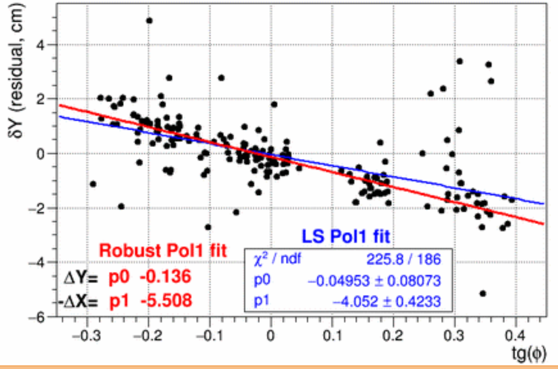
- We measure Y distortion δY as a difference between reference (ITS-TRD/TOF) track intersection with pad-row and measured cluster
  - → Strong bias due to the X distortions
- Same TPC region (voxel) is probed by tracks at different inclinations ϕ wrt pad row
- Deconvolute real ΔX and ΔY distortions using δY dependence on tg(ϕ) then extract Z distortion

$$\delta Y = \Delta Y - \Delta X \, tg(\varphi)$$

$$\delta Z = \Delta Z - \Delta X \, tg(\lambda)$$

- Keep residual information for each data taking window (time frame – TF = 10ms)
- Integration over longer time intervals ~1 min (Pb-Pb) and <~10 min (pp): "long term average map" $M_{L,ref}$



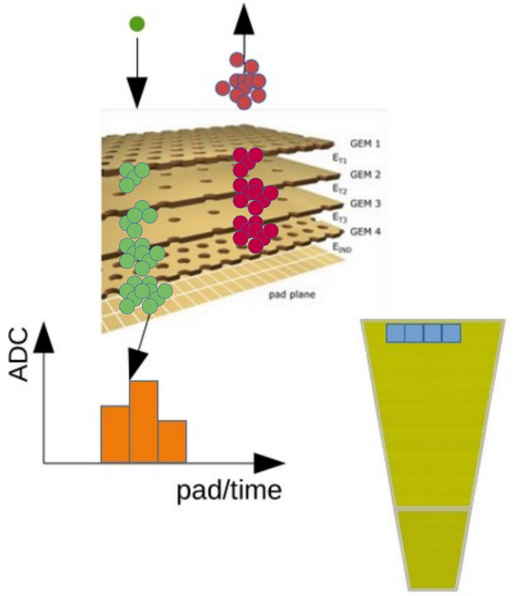


Space-charge distortion calibration

Fluctuation measure – Integrated Digital Currents

- **Main input: direct measure of fluctuations**
- Space-charge density related to ADC currents via IBF (ε = gain * IBF)
  - Assume gain and IBF constant on short time scales
- Integrated Digital Currents - IDCs
  - Integrated ADC values over 1ms inside the readout uni (CRU), pad-by-pad, injected in data stream
  - Factorisation and averaging to minimize data volume at maximum information content

$\rho_{ion} \sim I_{prim} * \varepsilon \sim Q * \varepsilon$



$IDC = Q \sim I_{prim} * gain$

Space-charge distortion calibration

Integrated Digital Currents – Factorisation

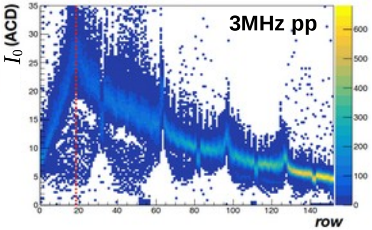
Factorisation: $I(r, \varphi, t) = I_0(r, \varphi) \cdot I_1(t) \cdot \Delta I(r, \varphi, t)$

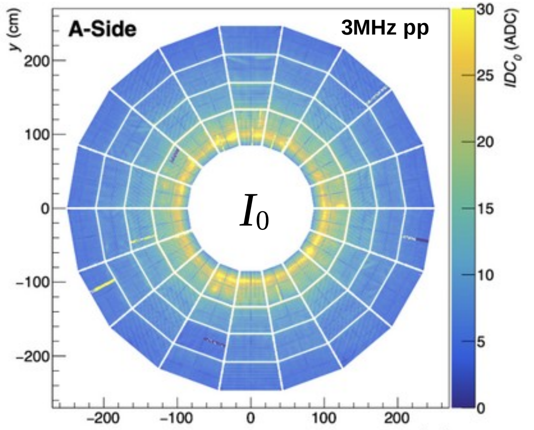
$I_0(r, \varphi) = \langle I(r, \varphi, t) \rangle_{t=1000TFs}$: average IDCs

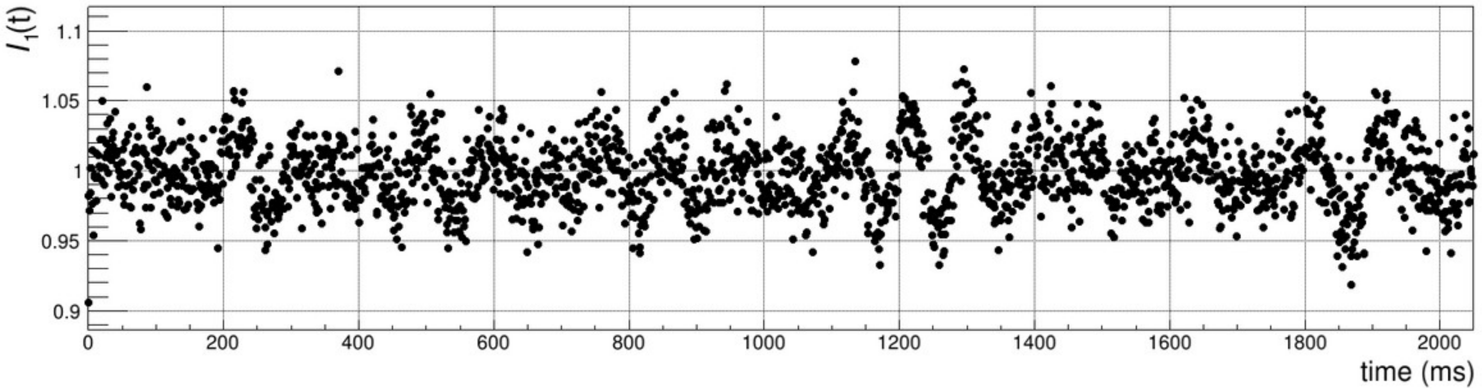
$I_1(t) = \langle I(r, \varphi, t)/I_0(r, \varphi) \rangle_{r,\varphi}$: 1D-fluctuations

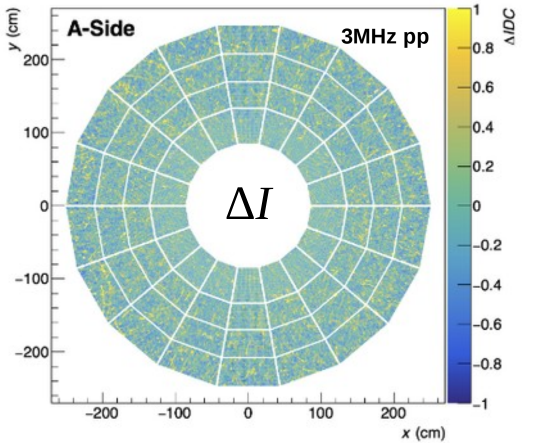
$\Delta I(r, \varphi, t) = I(r, \varphi, t) / \left(I_0(r, \varphi) \cdot I_1(t) \right)$: 3D fluctuations

Radial projection of I_0





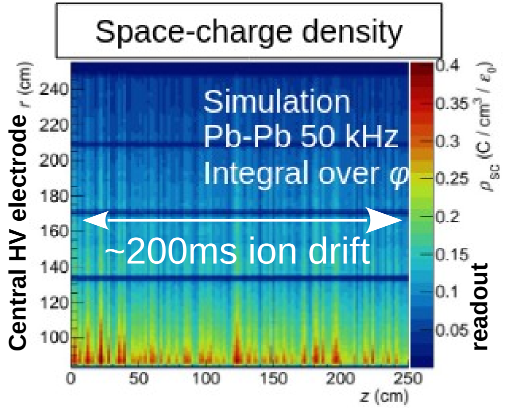


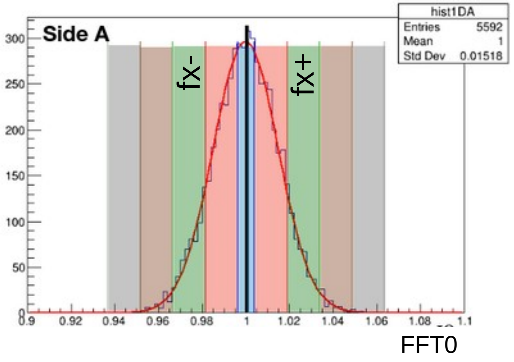


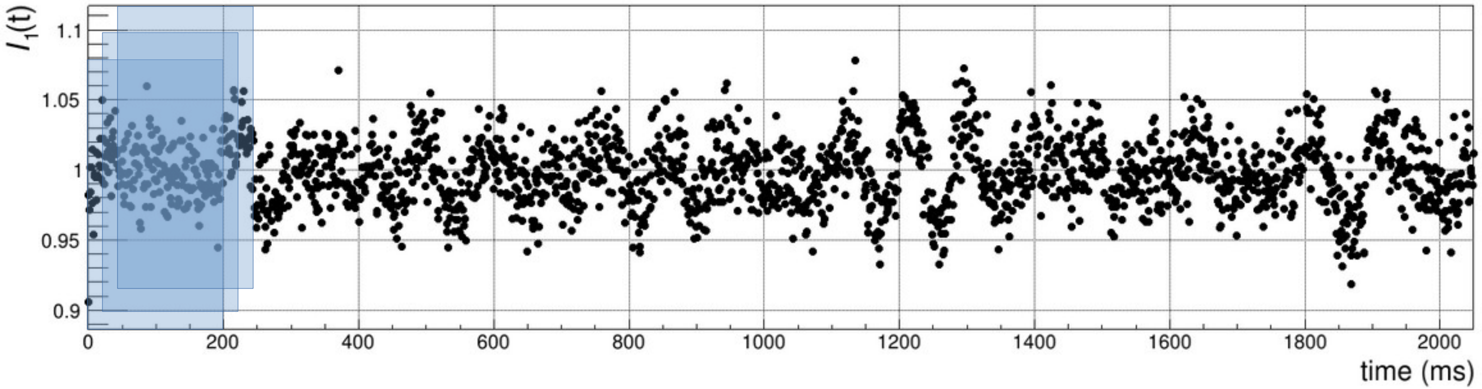
Space-charge distortion calibration

Integrated Digital Currents – FFT + 1D classification

- Do FFT decomposition of time intervals reflecting on ion drift (~200ms)
  - Classification of 1D (z) fluctuations
  - Ion drift time required!
- Perform this for "time frame" of 10ms
  (relevant time scale for fluctuations = data taking window)
- Select time frames of certain classes (e.g. window in FFT0 class) and build the average map for the selected time frames: $M_{L,fx+-}$





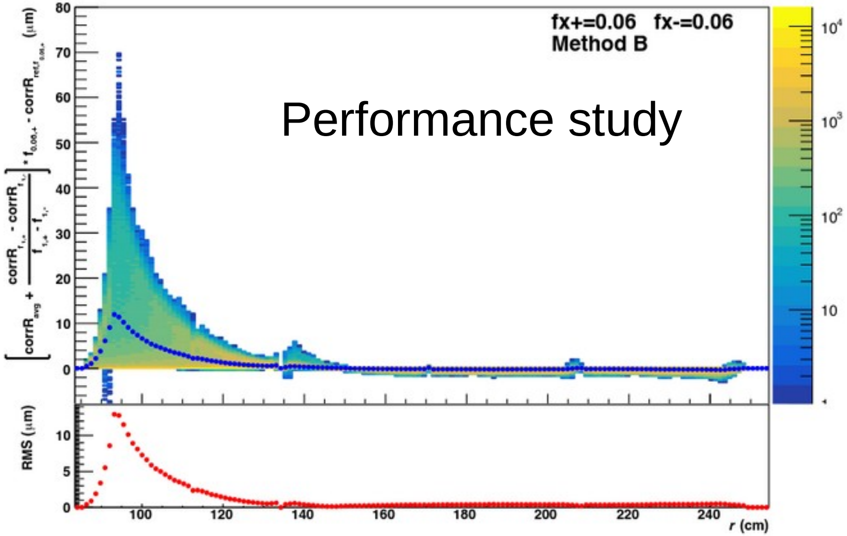


Space-charge distortion calibration

Reconstruction procedure

- Perform scaling using local derivatives
- $M_{\mathrm{corr}} = M_{L,ref} + \Delta M_{L,fx+-} / \Delta\mathrm{FFT0}(I_{1,\mathrm{ref}}) * \mathrm{FFT0}(I_{1,\mathrm{now}})$
  - Alternatively ML using more FFT coefficients
- $M_{L,ref}$: long-term average map
  (or offset from linear fit)
- $\Delta M_{L,fx+-} / \Delta\mathrm{FFT0}(I_{1,\mathrm{ref}})$:
  map from local derivatives

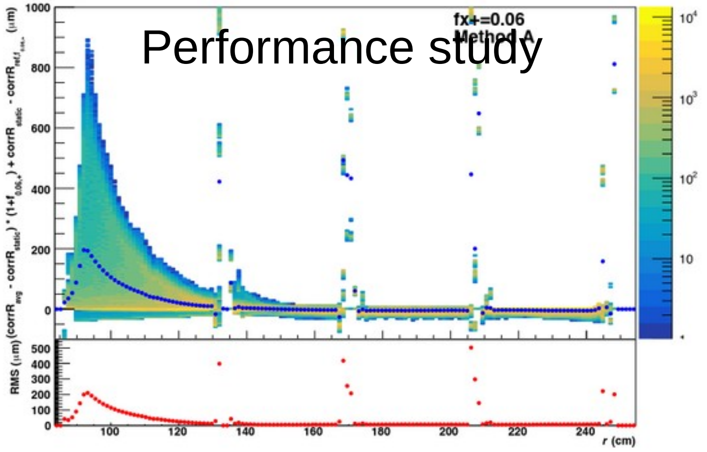
Performance study



Space-charge distortion calibration

Reconstruction procedure – simplistic approach

- Perform scaling using absolute map
- $M_{\mathrm{corr}} = M_{\mathrm{static}} + (M_{L,ref} - M_{\mathrm{static}}) * L_{\mathrm{now}} / L_{\mathrm{ref}}$
- M_{static}: long-term average map, measured at low luminosity
- $M_{L,ref}$: long-term average map measured at high (reference) luminosity
- Caveat: different scaling of static, charge-up and space-charge distortions!



Space-charge distortion calibration

Further plans

- Distortion fluctuations corrections
  - Step 0: Linear regression of fluctuation corrections as a function of derivatives and coefficients for ~10 FFT coefficients, 1D = delta of IDCs
  - Step 1: Use of ML (Random Forest, BDT) to correct residuals wrt step 0
  - Step 2: Use of CNN to further correct for the 3D case
    - Will depend on the size of the fluctuations and on the performance after Step 0 and Step 1

Summary

Summary

- Different types of distortions present in the TPC (static, charge-up, space-chare)
  - Different scaling over time and detector load to be taken into account
- Large distortions due to space-charge expected O(5-10cm)
  - Correction down to intrinsic tracking precision envisaged O(few 100um)
- Two main ingredients for distortion corrections
  - Direct measure of distortions via interpolation from external detector points
  - Measure of fluctuations using continuously integrated digital currents on the pad plane (IDCs)
- Different procedures foreseen for corrections
  - Scaling of absolute distortion map
  - Scaling of local derivative distortion map
  - Linear regression / ML using derivative map and 1D FFT coefficients of IDCs
  - ML using NDim IDC fluctuation information

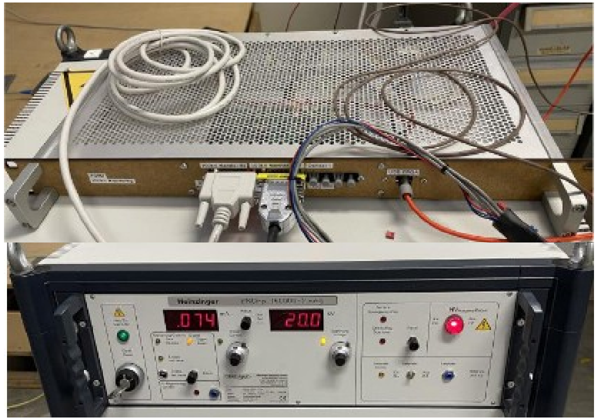
Backup

References

- The upgrade of the ALICE TPC with GEMs and continuous readout arXiv:2012.09518v2
- Reconstruction in ALICE and calibration of TPC space-charge distortions in Run 3 arXiv:2109.12000v2
- Space-point calibration of the ALICE TPC with track residuals arXiv:2003.03174
- Upgrade of the ALICE Time Projection Chamber (Technical design report) CERN Document Server

Space-charge distortion calibration

Ingredients – Ion drift time



- Required for FFT of $I_1(t)$ (1D IDCs)
- Hardware solution
  - Fast readout of CE power supply
  - Correlation currents from CE PS with
    - 1D IDCs, or
    - CE laser signal, or
    - Beam dump sigature
- Software solution
  - Uses numerical derivatives of measured residuals wrt. 1D IDC FFT coefficients (same concept as advanced lumi correction)
  - Conceptually proven in toy studies