The ALICE TPC in lead-lead collisions at Run 3: Space charge corrections

Matthias Kleiner
Goethe-Universität Frankfurt
RD51 Collaboration Meeting
December 4-8, 2023

ALICE Time Projection Chamber

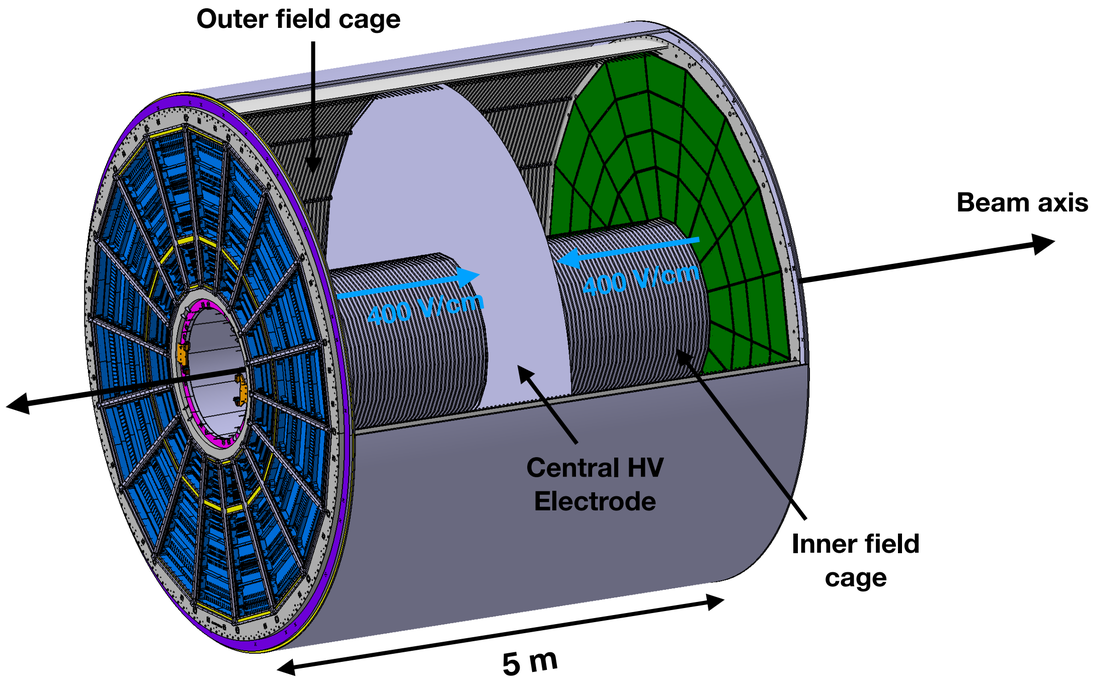
Main tracking and charged-particle identification (PID) detector

Properties

- Total length: 5m
- Radial dimension: $83.5\,\text{cm} < r < 254.5\,\text{cm}$
- Gas mixture: Ne-CO_2-N_2 (90-10-5)
- Central electrode and field cage
  - Uniform electric field 400 V/cm along beam (z) axis

Run 3 upgrade

- Run 1 and Run 2: Multi-Wire Proportional Chambers
  ➡ ~1 kHz Pb-Pb: triggered readout
- Run 3 (2022): Gas Electron Multipliers (GEM)
  ➡ 50 kHz Pb-Pb: continuous readout



Ion backflow (IBF)

Multiplication of primary electrons

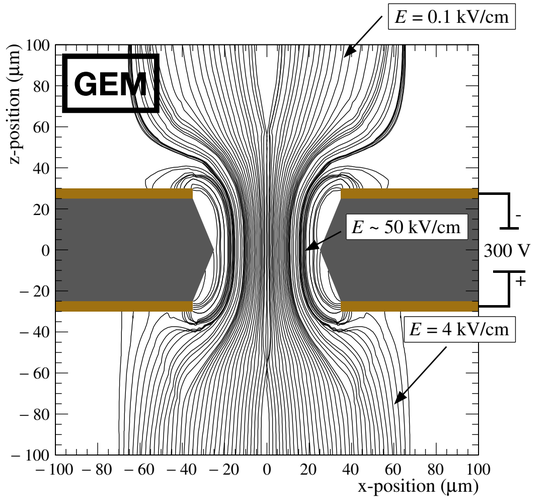
- Stacks of four Gas Electron Multipliers (GEM)

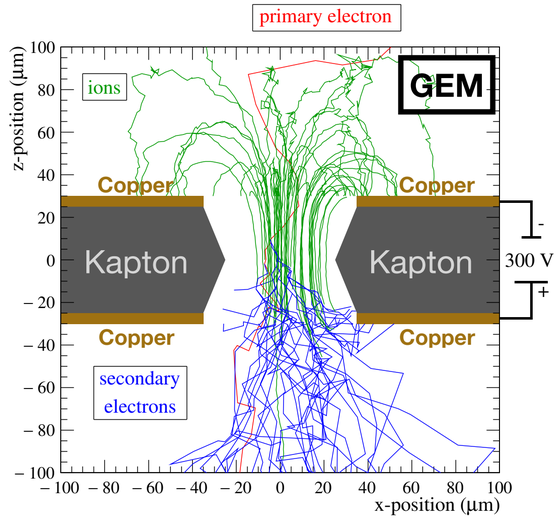
Ions from amplification enter drift volume

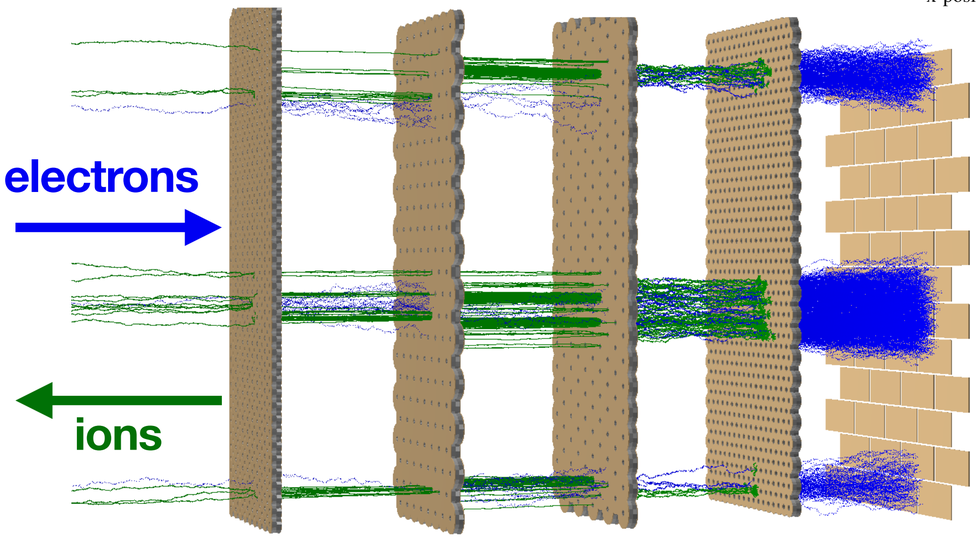
- Slow drift velocity compared to electrons
  - $T_{Electron} \approx 100\,\mu s$ vs $T_{Ion} \approx 200\,ms$
- Optimisation of $\langle IBF \rangle$ to ~1% (gain ~ 2000)
- Ions from *n* events piling up in the drift volume
  - e.g. 10.000 events for 50 kHz Pb-Pb
- $\varepsilon = IBF \cdot gain$

Space-charge density

- Depends on the interaction rate and collision type
- Local variations of ε
- Fluctuations
  - Number of events
  - Event multiplicity







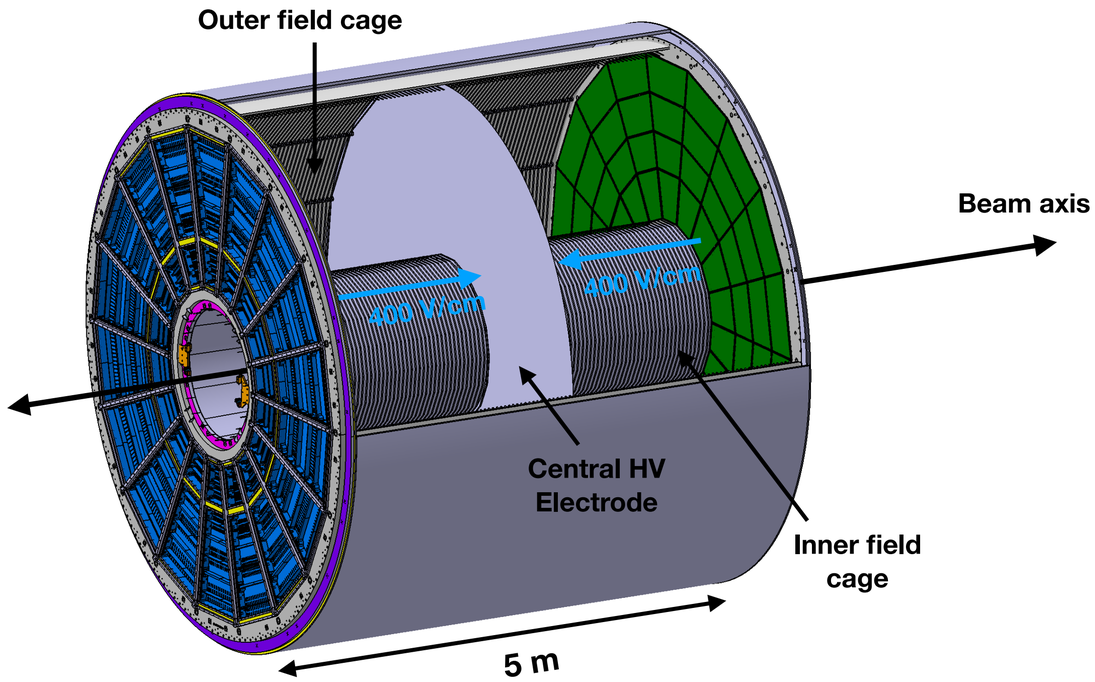
Overview of distortions

Distortions of drift electrons

- IR dependent
  - Space-charge from ion back flow and primary ionization
    - 10 ms
  - Inner field cage charging up
    - Charging up: $\mathcal{O}$(min)
    - Discharge: $\mathcal{O}$(10min), $\mathcal{O}$(s)
  - Distortions at higher rates for one IROC, B+ (A-side)
- Semi static
  - Charge up of GEM frames
- Static
  - Misalignment of electric and magnetic field
- Time dependent
  - V-shape distortions

➡ 50 kHz Pb-Pb: ~15 cm distortions

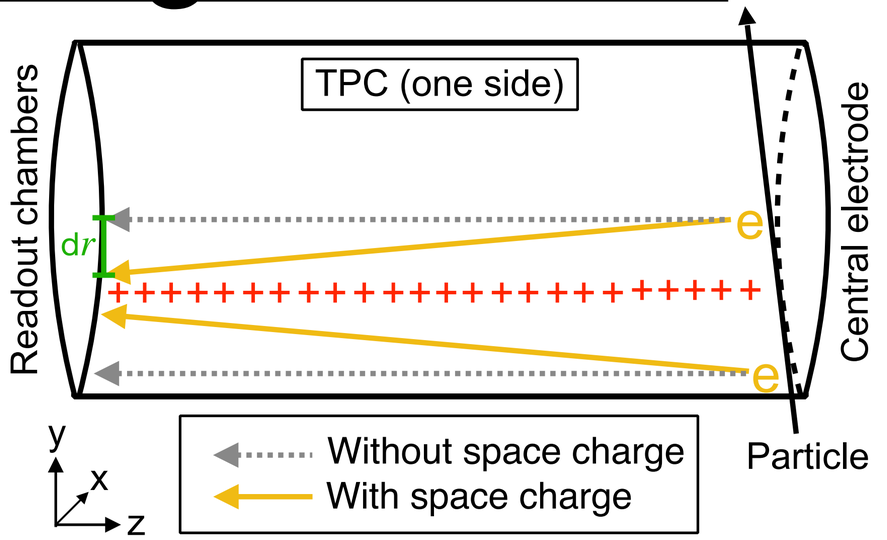
➡ 500 kHz pp: ~3 cm distortions

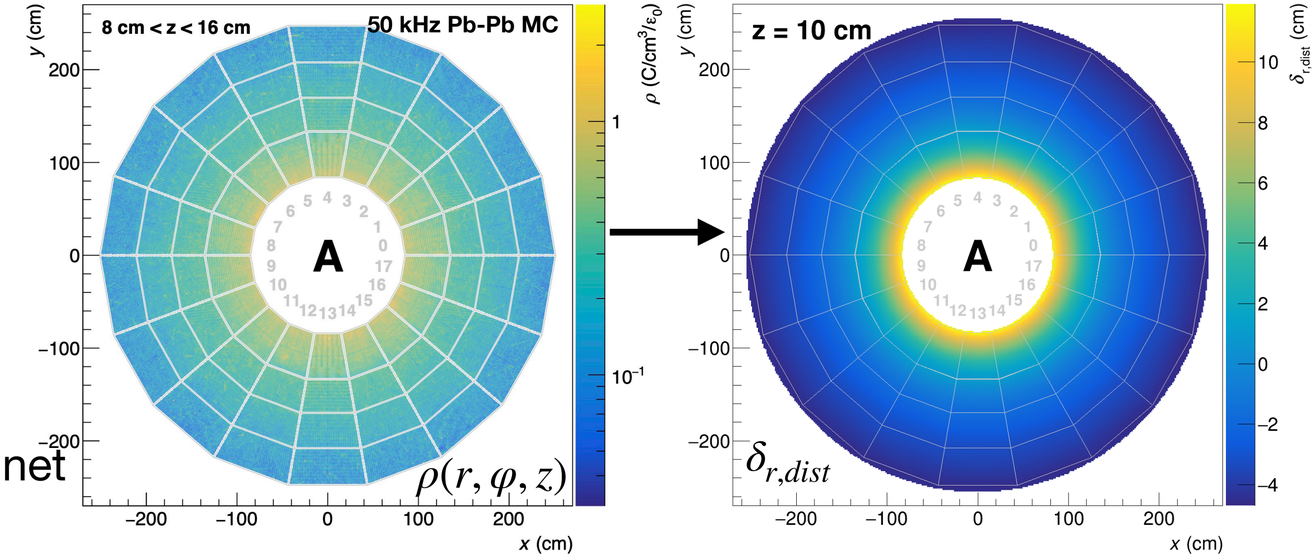


Electron movement through the gas

Langevin equation

- Equation of motion: $m\frac{\mathrm{d}\vec{u}}{\mathrm{d}t} = q\vec{E} + q\left[\vec{u}\times\vec{B}\right] - K\vec{u}$
- $\delta_r(r,\varphi,z) = c_0\int_{z_1}^{z_1+\Delta z}\frac{E_r}{E_z}\mathrm{d}z + c_1\int_{z_1}^{z_1+\Delta z}\frac{E_\varphi}{E_z}\mathrm{d}z - c_1\int_{z_1}^{z_1+\Delta z}\frac{B_\varphi}{B_z}\mathrm{d}z + c_2\int_{z_1}^{z_1+\Delta z}\frac{B_r}{B_z}\mathrm{d}z$
- $\delta_{r\varphi}(r,\varphi,z) = c_0\int_{z_1}^{z_1+\Delta z}\frac{E_\varphi}{E_z}\mathrm{d}z - c_1\int_{z_1}^{z_1+\Delta z}\frac{E_r}{E_z}\mathrm{d}z + c_2\int_{z_1}^{z_1+\Delta z}\frac{B_\varphi}{B_z}\mathrm{d}z + c_1\int_{z_1}^{z_1+\Delta z}\frac{B_r}{B_z}\mathrm{d}z$
- Integration of E and B fields along electron drift path
- Electric fields
  - Space-charge (ion backflow + primary ionisation)
    - Obtained by simulations (uncertainty IBF, MC)
    - Poisson equation: $\Delta\Phi(r,\varphi,z) = -\rho(r,\varphi,z)$
    - Electric fields: $\vec{E}(r,\varphi,z) = -\nabla\Phi(r,\varphi,z)$
  - Potential inhomogeneities
  - Misalignment of GEMs etc.
- Magnetic field components: Imperfections of L3 magnet





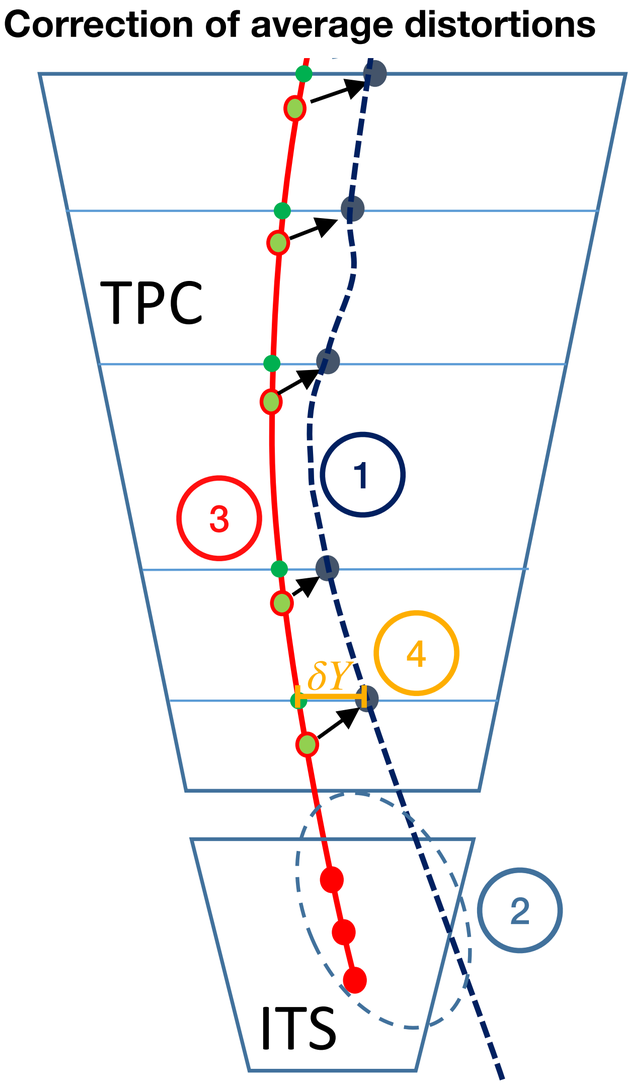
Data driven approach to extract corrections for distortions

Correction of average distortions

- Already performed during Run 2

Procedure

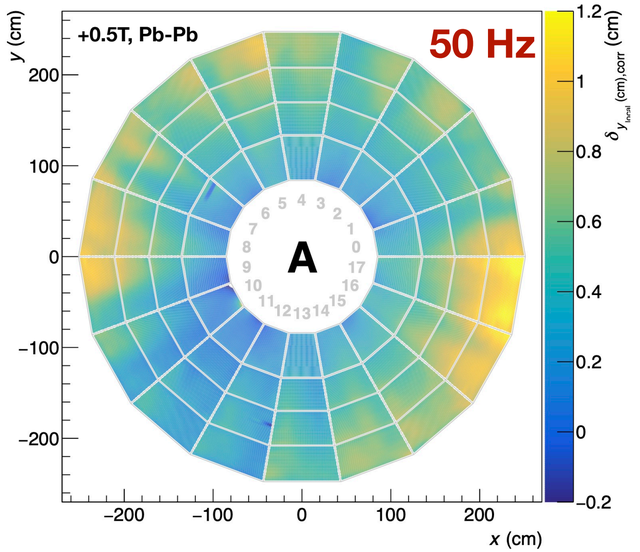
1. Reconstruction of distorted TPC track
   - Tracking with relaxed tolerances
2. Track matching with ITS track segments
3. Residuals between TPC clusters and reference ITS track
   - Measurement of $\delta Y, \delta Z$
   - Storage in 3D map
4. Collect data for full TPC volume $\left(\mathcal{O}(\text{min})\right)$
   - $\delta Y, \delta Z \rightarrow \Delta x, \Delta y, \Delta z$
5. Smooth parametrisation of extracted corrections

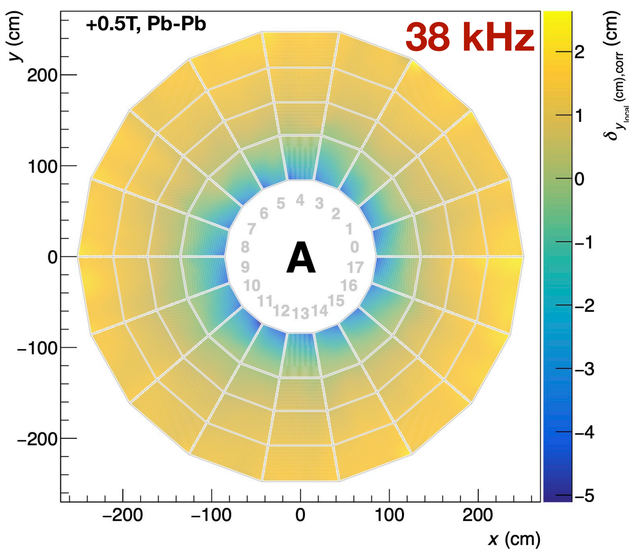


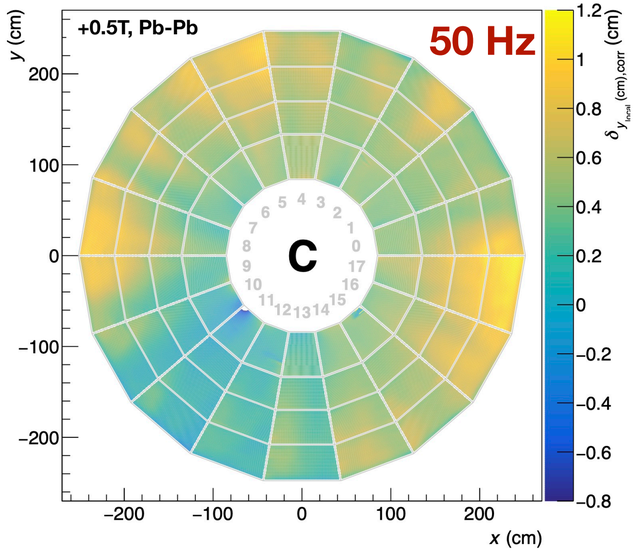
Extracted correction maps for distortions

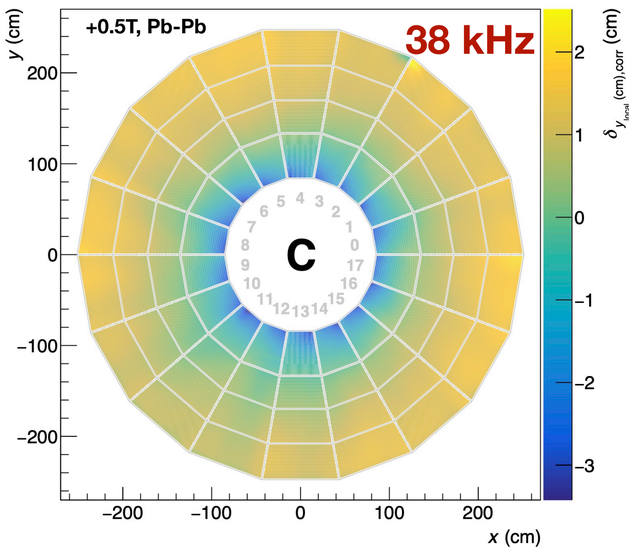
Extracted correction maps

- 50Hz (IR independent distortions)
  - ExB misalignment etc.
- 38kHz (IR dependent distortions)
  - Space-charge





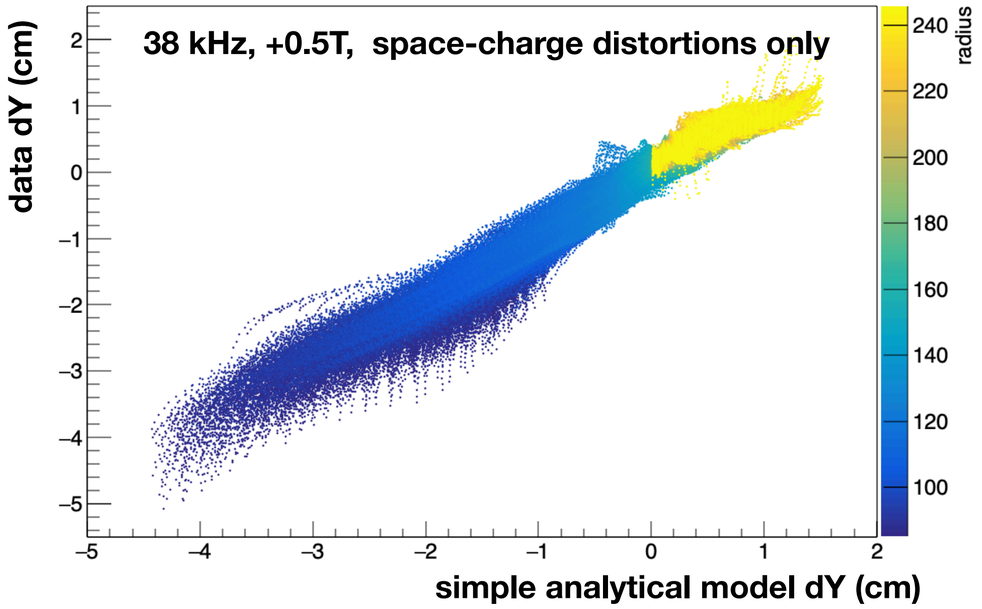


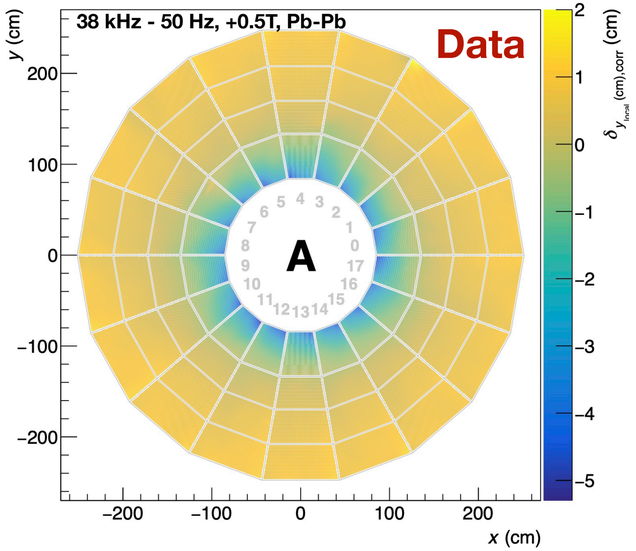


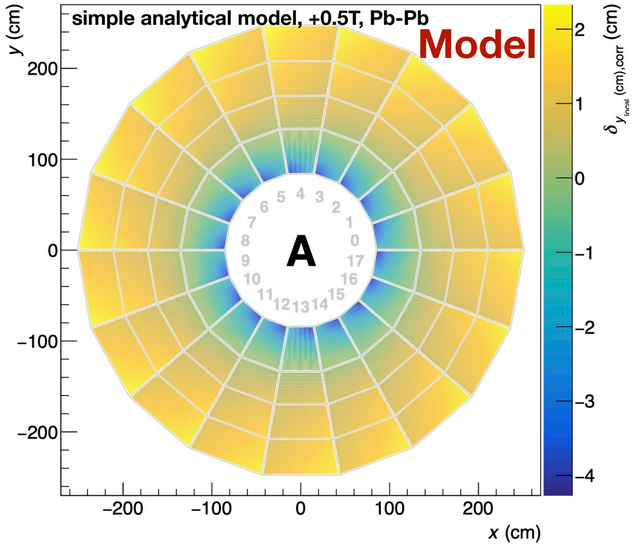
Extracted space-charge distortions vs analytical model

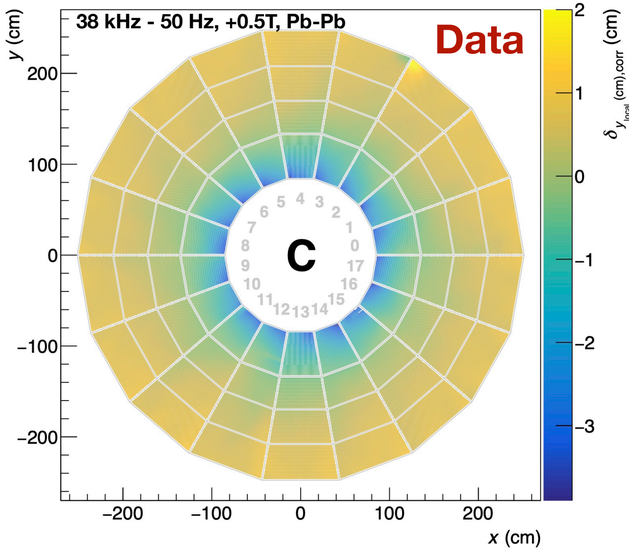
Extracted space-charge map

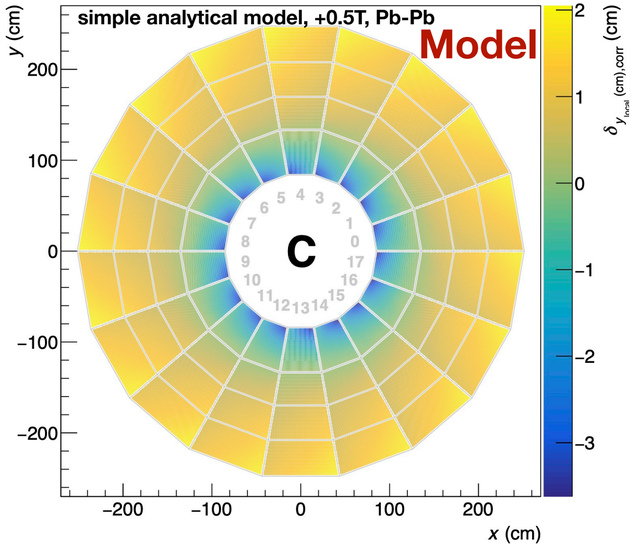
- Subtracting 50Hz map from 38kHz map
  - Space-charge
- Comparison with simple analytical model shows good agreement
  - No variation of IBF across chambers







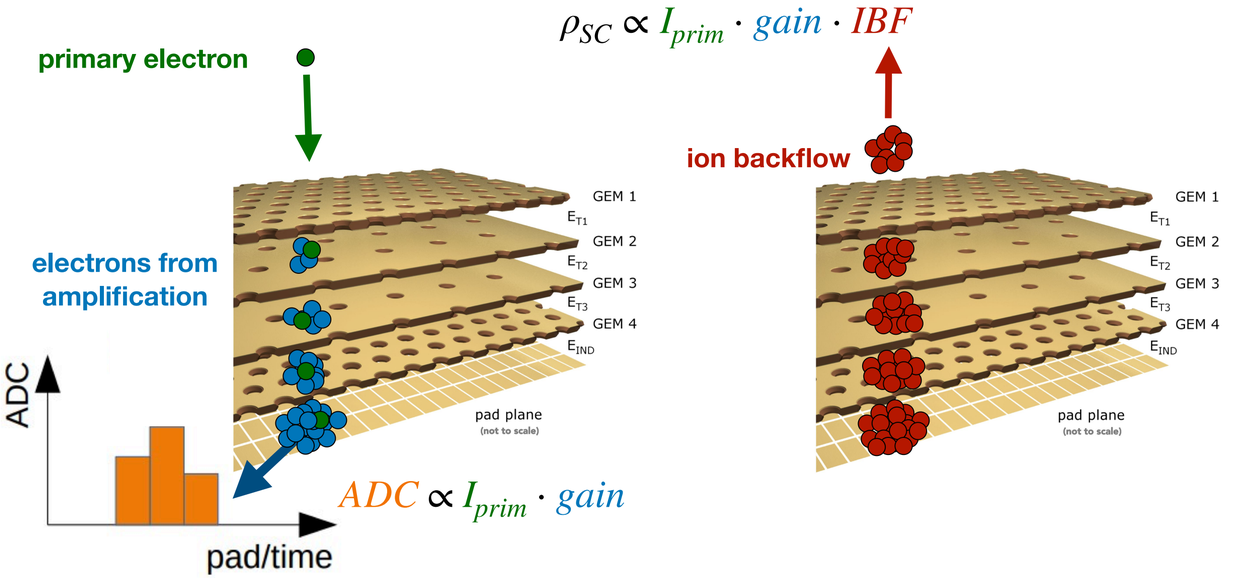




Time dependent space-charge variations

Integrated digital currents (IDCs)

- Integration of *ADC* values over ~1ms
- $ADC \propto I_{prim} \cdot gain$
- $\rho_{SC} \propto I_{prim} \cdot gain \cdot IBF$
- Estimate for space-charge density and density fluctuations



Time dependent space-charge variations

Integrated digital currents (IDCs)

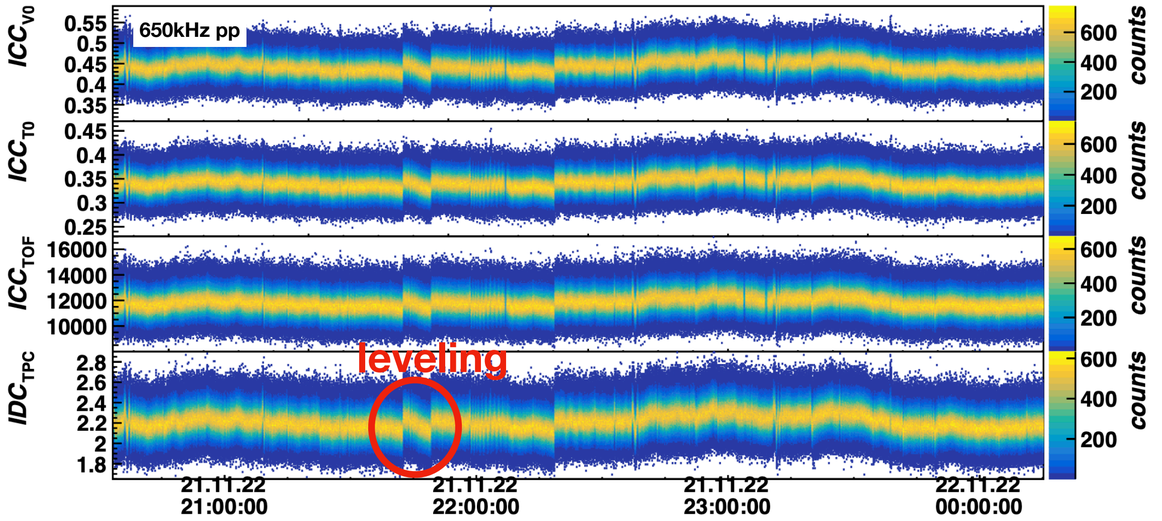
- Integration of *ADC* values over ~1ms
- $ADC \propto I_{prim} \cdot gain$
- $\rho_{SC} \propto I_{prim} \cdot gain \cdot IBF$
- Estimate for space-charge density and density fluctuations

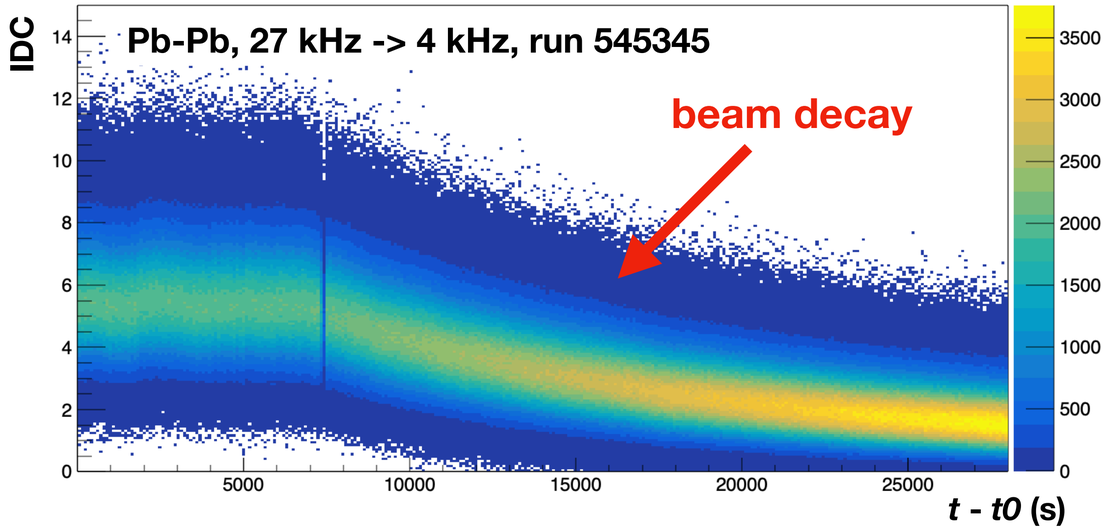
Integrated cluster currents (ICCs)

- TOF, FT0, FV0, FDD
- Integration of reconstructed clusters

Integrated currents

- Online processed
  - Storage in the CCDB (calibration database)
- Input for corrections
  - Beam decay, levelling, space-charge distortion fluctuations





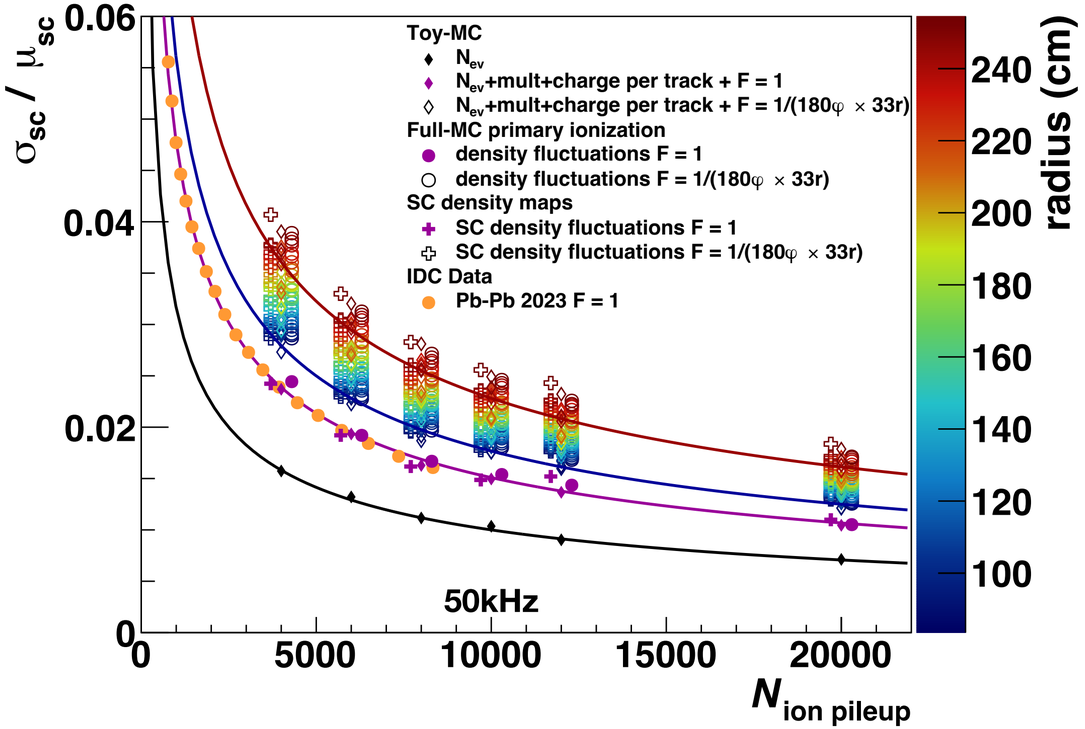
Space-charge density fluctuations

Space-charge density dependencies

1. Number of ion pile-up events (Poisson distribution)
2. Primary + secondary track multiplicity per event
3. Number of tracks for volume element
4. Energy loss per track

- Analytical formula agrees well with fluctuations from MC
- Fluctuations of ~2% expected at 50 kHz Pb-Pb

➡ Distortion fluctuations $\left(\mathcal{O}(\text{mm})\right)$

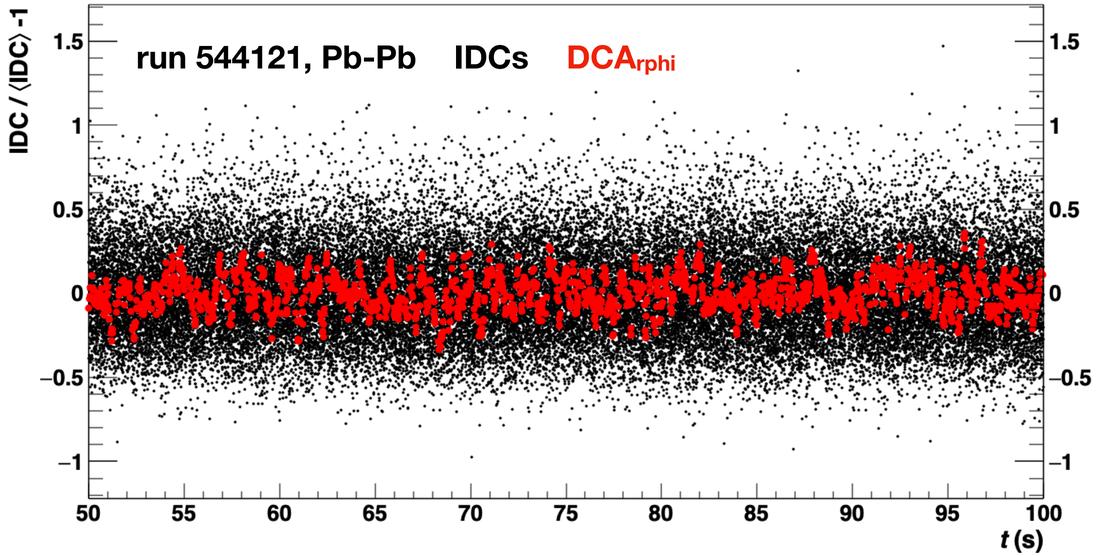


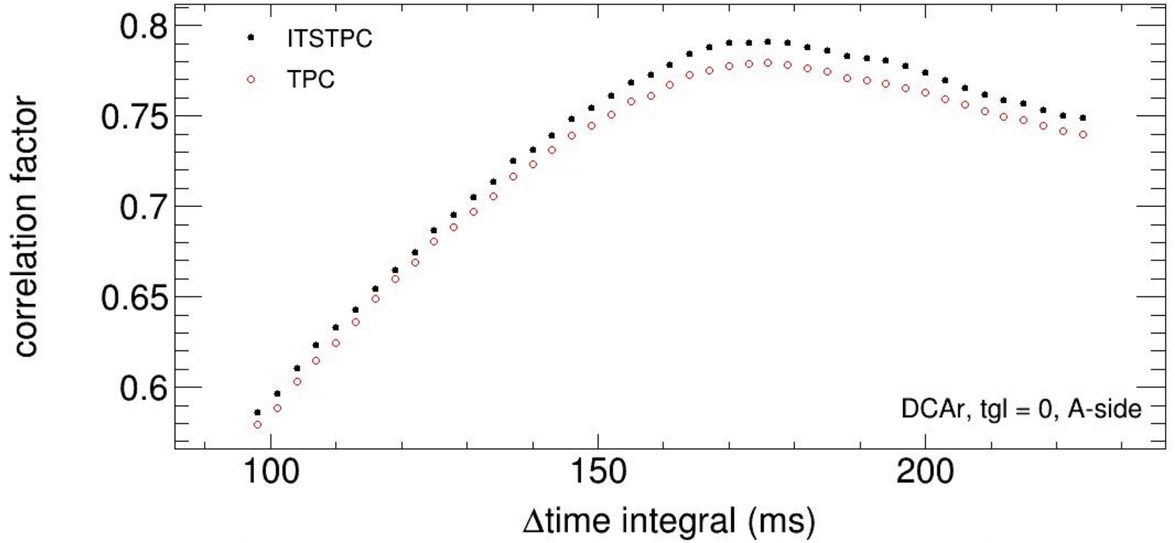
$$\frac{\sigma_{sc}}{\mu_{sc}} = \underbrace{\frac{1}{\sqrt{N^{ion}_{pileup}}}}_{1} \sqrt{1 + \underbrace{\left(\frac{\sigma_{N_{mult,prim}}}{\mu_{N_{mult,prim}}}\right)^2 + \left(\frac{\sigma_{N_{mult,relsec}}}{\mu_{N_{mult,relsec}}}\right)^2}_{2} + \frac{1}{\left(F_{prim}(r) \cdot \mu_{N_{mult,prim}} + F_{sec}(r) \cdot \mu_{N_{mult,sec}}\right)} \underbrace{\left[1 + \left(\frac{\sigma_{Q_{track,prim}}(r)}{\mu_{Q_{track,prim}}(r)}\right)^2 + \left(\frac{\sigma_{Q_{track,sec}}(r)}{\mu_{Q_{track,sec}}(r)}\right)^2\right]}_{3\ \ 4}}$$

Space-charge distortion fluctuations

DCA as a proxy of distortions and corrections

- Extrapolation of distorted TPC tracks to primary vertex
- Monitoring of distortions as a function of time (~3ms)
- Correlation of integrated IDCs in time windows with DCAs
  - Ions from last ion drift time contribute to space-charge
- Integration time with best correlation used for correction





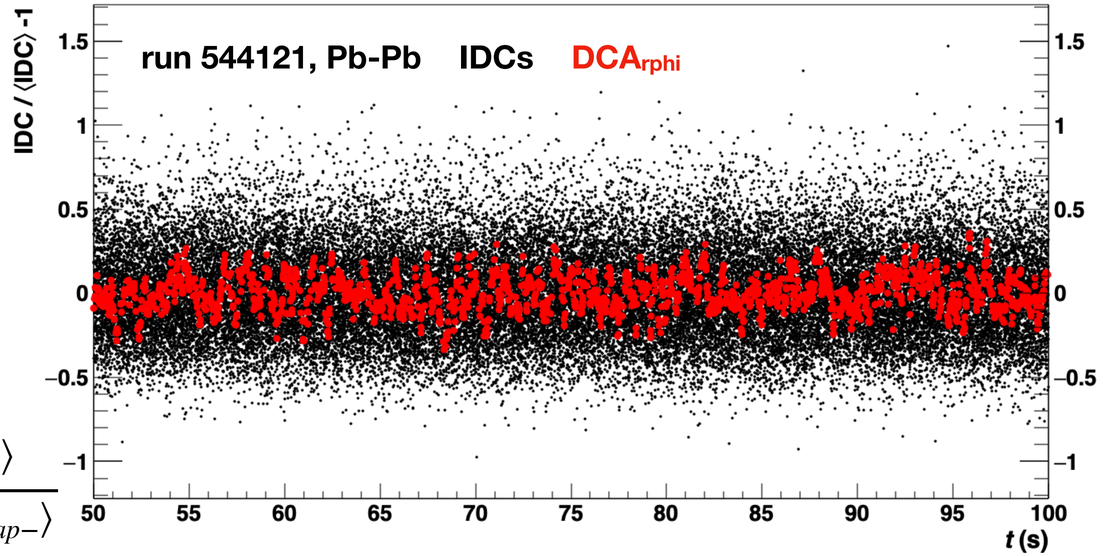
Space-charge distortion fluctuations correction

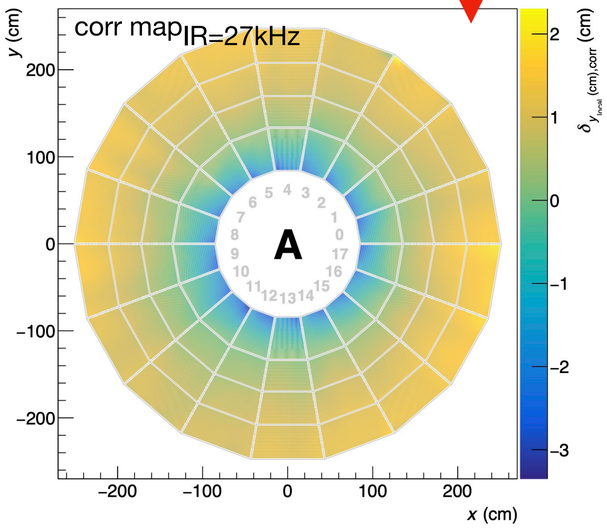
DCA as a proxy of distortions and corrections

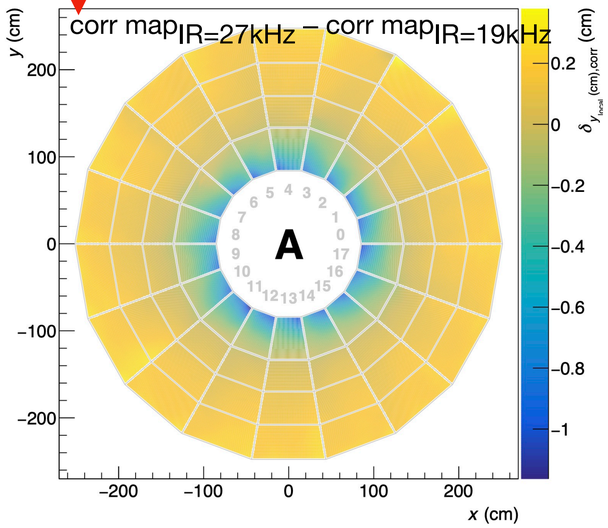
- Extrapolation of distorted TPC tracks to primary vertex
- Monitoring of distortions as a function of time (~3ms)
- Correlation of integrated IDCs in time windows with DCAs
  - Ions from last ion drift time contribute to space-charge
- Integration time with best correlation used for correction

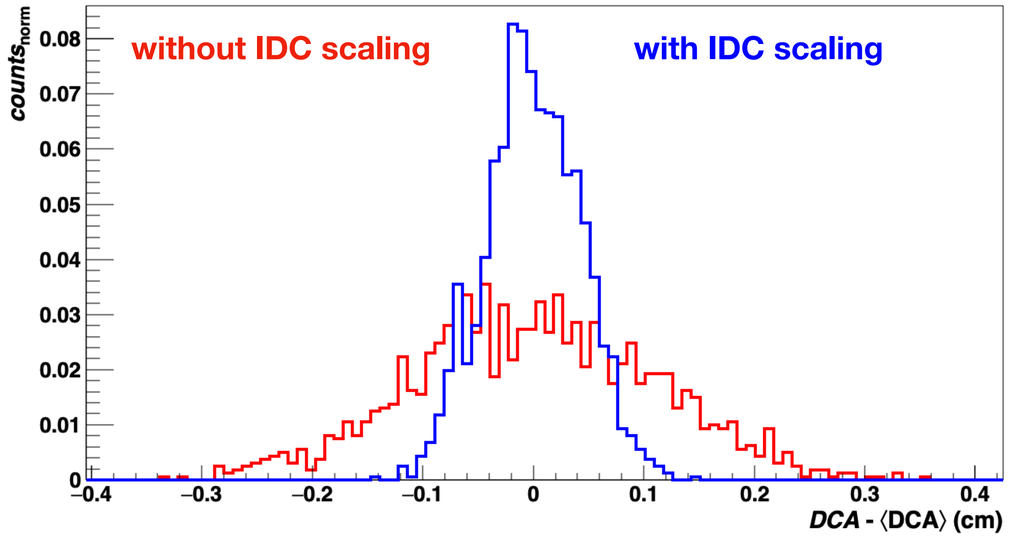
Scaling of space-charge distortion corrections

- $\text{corr map}(IR) = \text{corr map}_{IR} + \left(\text{corr map}_{IR+} - \text{corr map}_{IR-}\right) \cdot \dfrac{IDC(t) - \langle IDC_{map}\rangle}{\langle IDC_{map+}\rangle - \langle IDC_{map-}\rangle}$





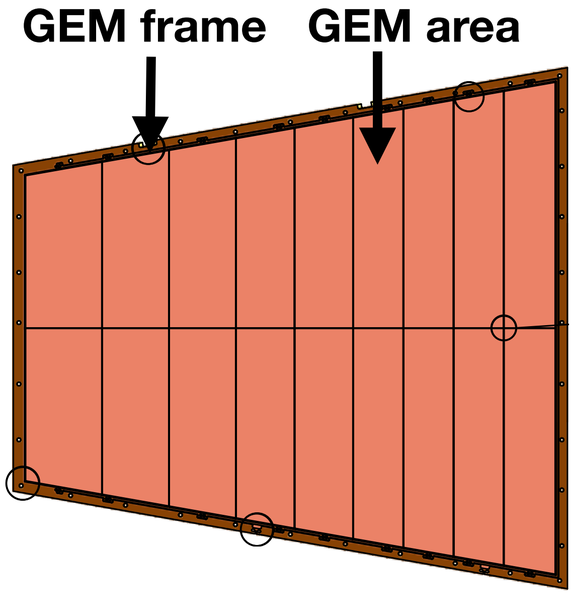


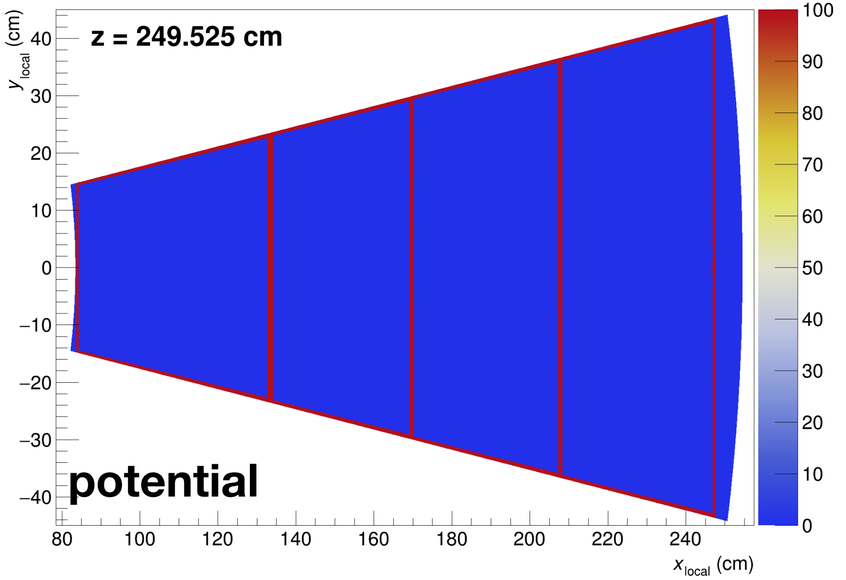


Further distortions: Charge-up of GEM frames

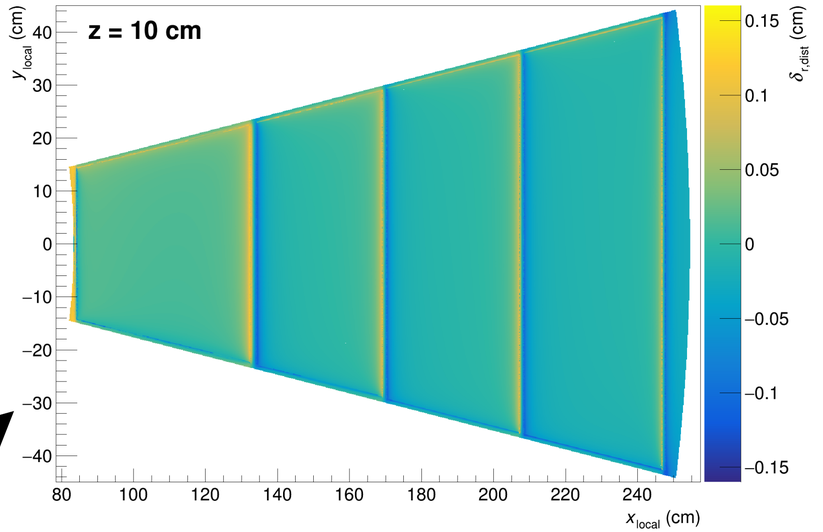
GEM frame

- Potential difference between GEM frame (insulator) and GEM1
- Time until charged-up depends on IR and the past IR
- Distortions at boundaries of the GEM frame
  - Steep gradient

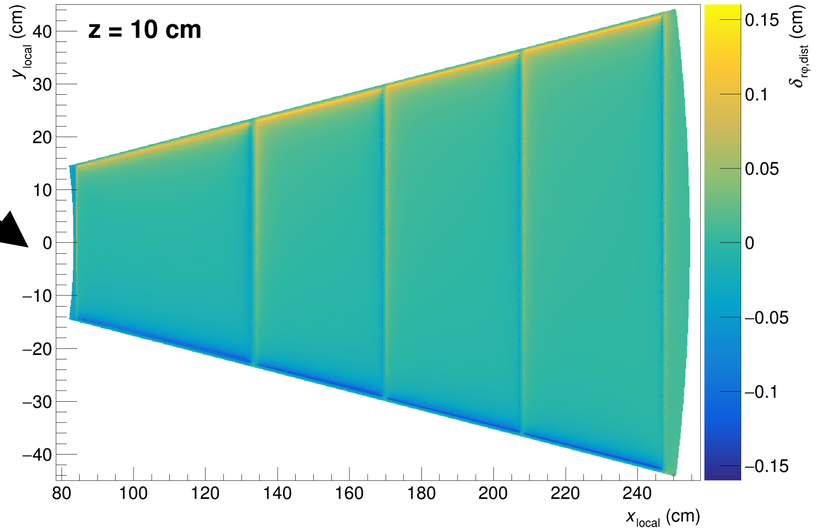




δ_r



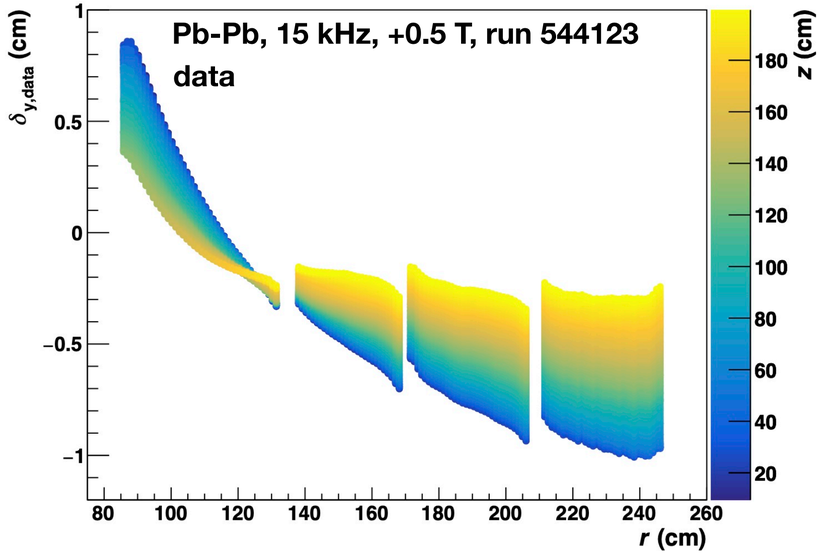
$\delta_{r\varphi}$

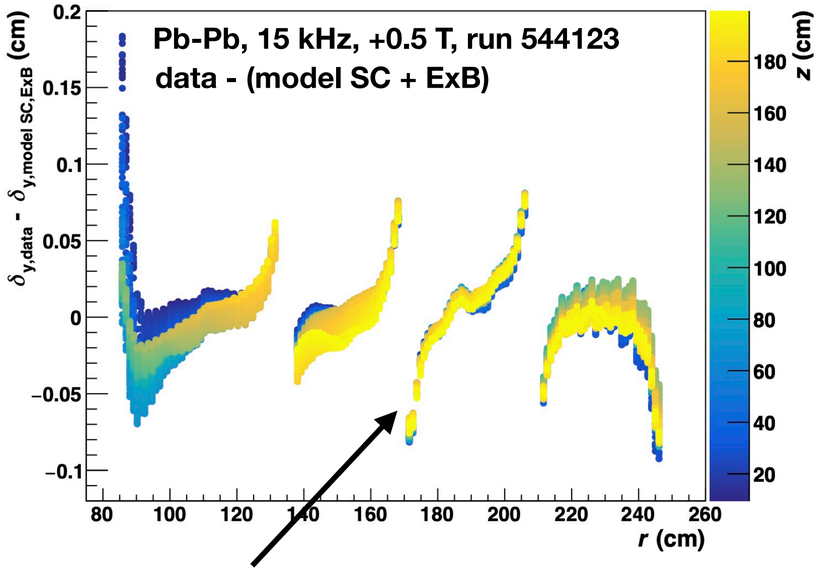


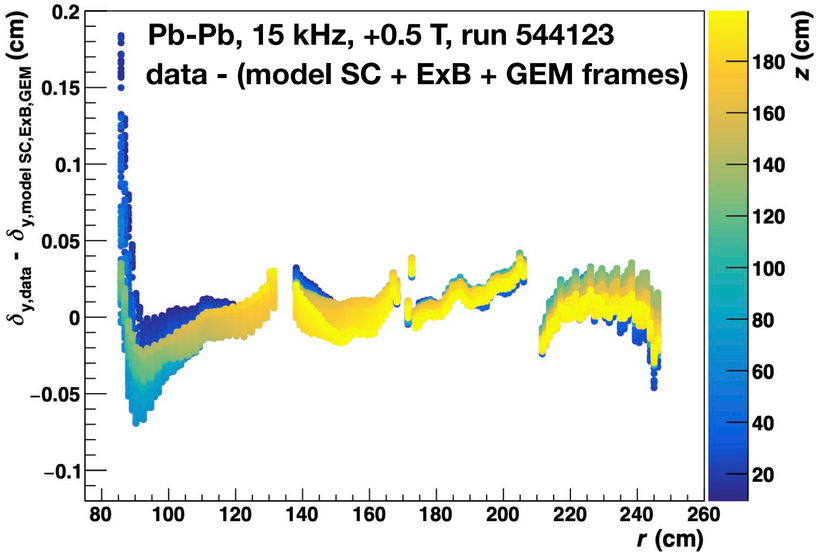
Charge-up of GEM frames

GEM frame

- Potential difference between GEM frame (insulator) and GEM1
- Time until charged-up depends on IR and the past IR
- Distortions at boundaries of the GEM frame
  - Steep gradient
- Accurate description with analytical models







Distortions due to charging of GEM frames

Summary

Space-charge distortions

- 50 kHz Pb-Pb: ~15 cm distortions
- 500 kHz pp: ~3 cm distortions
- Correction with data driven ITS-TPC map
- Space-charge density fluctuations and LHC beam variations
  - Scaling of space-charge correction map with IDCs

- Further sources of distortions near GEM frames
  - Charging of frames
  - Steep gradient distortions