Reconstruction in ALICE and calibration of TPC space-charge distortions in Run 3

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The Ninth Annual Conference on Large Hadron Collider Physics (LHCP2021)
June 7, 2021
ALICE Time Projection Chamber (TPC)

Insertion of the TPC after the upgrade during LS2

Fri plenary talk:
Upgrades for ALICE by C. Lippmann
Goals and challenges

Record large Pb-Pb minimum bias sample

Continuous readout at 50 kHz interaction rate in Pb-Pb collisions

- No triggers or event rejection
- Processing of time frames (TF, 10 - 20 ms) instead of events
- Events overlapping in TPC

GPU processing and data compression

- 50 times more events and data to be processed and stored

TPC calibration and tracking

- Calibration of space-charge distortions
- Tracking with continuous readout and space-charge distortions

Talks by D. Rohr: LHCP2020, vCHEP2021

TPC tracks of overlapping events (different colors)
Time frame of 2 ms at 50 kHz Pb-Pb collisions
Data processing in Run 3

First Level Processors (FLPs)
- Calibration, processing and collection of data from detectors

Event Processing Nodes (EPNs)
- **Synchronous processing** during beam and data recording
  - TPC tracking (~99 % of computing time) fully running on GPUs
- **Asynchronous processing** when EPN resources are available, e.g. no beam, pp collisions
  - TPC processing, ITS and TRD tracking on GPUs (~80 % of processing)
  - Goal to perform full barrel tracking on GPUs (~95 % of the total processing) in the future
TPC calibration

Pedestal, Noise, Pulser

Gain and dE/dx

- Pad-wise gain calibration
- $p$, $T$, high-voltage dependence
- Track topology
- Track-based residual calibration

Electron drift velocity

Distortions due to space charge and other effects

- Average space-charge distortion correction
- Correction of space-charge distortion fluctuations
- Static distortions and distortions due to charge-up effects
TPC upgrade

Readout chambers based on GEMs replaced MWPCs + gating grid

No dedicated mechanism to prevent ion backflow (IBF)

- Suppression to below 1% by a combination of four GEMs and optimized high-voltage settings

Continuous readout at 50 kHz Pb-Pb

- Gating grid implied rate limitation to ~3 kHz

Significant amount of space charge piling up inside the drift volume

- Non-uniform space-charge density $\rho_{sc}$
  - Large space-charge distortions ($dr$, $dr\phi$, $dz$) of measured space points
  - Space-charge density and distortion fluctuations

Simulation Pb-Pb 50 kHz
Integral over $\phi$

Simulation Pb-Pb 50 kHz
$\phi$ average

Integral over $z$
Space-charge density and distortion fluctuations

Dependencies of the space-charge density

- Ion backflow x gain = $\varepsilon$
- 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 $\sigma_{SC}/\mu_{SC}$ of ~2 % at 50 kHz Pb-Pb

- Distortion fluctuations of O(mm - cm) in $r$ and $r\phi$
- Relevant time scales: 5 - 10 ms

$$\frac{\sigma_{SC}}{\mu_{SC}} = \frac{1}{\sqrt{N_{\text{ion pileup}}}} \sqrt{1 + \left( \frac{\sigma_{N_{\text{mult,prim}}}}{\mu_{N_{\text{mult,prim}}}} \right)^2 + \left( \frac{\sigma_{N_{\text{mult,sec}}}}{\mu_{N_{\text{mult,sec}}}} \right)^2}$$

1D fluctuations

3D fluctuations
# Space-charge distortion calibration

| **Synchronous reconstruction** | **Asynchronous reconstruction** |
|--------------------------------|---------------------------------|
| **Correction of average distortions** | **Correction of average distortions** |
| • Stored correction maps from previous calibration intervals | • Correction map extracted from data itself |
| **1D→3D distortion-fluctuation correction** | **Distortion-fluctuation correction** |
| | • 1D→3D for pp  
| | • 3D→3D for Pb-Pb |
| **Precision: O(mm)** | **Precision: 200 μm** |
| • Tracking | • Intrinsic track resolution of the TPC  
| • Track matching to external detectors |
Correction of average space-charge distortions

Distorted TPC track fitted with relaxed tolerances

Matching to ITS and TRD+TOF track segments

Residuals between distorted TPC clusters and ITS-TRD-TOF track refit

- TPC volume divided into small voxels

Statistics / calibration interval length for required precision ($O(50 \, \mu m)$) depending on voxel size

- $O(\text{min})$
- Space-charge distortion fluctuations relevant on much shorter time scales

Calibration of other effects like static $E$-field distortions, $ExB$, electron drift velocity and misalignment included
Correction of space-charge distortion fluctuations

Update interval of 5 - 10 ms for distortion-fluctuation correction

- Insufficient statistics for ITS-TRD-TOF reference method
  ➔ Data-driven machine learning (ML) algorithms and convolutional neural networks (CNN)
    - Space-charge density ➔ 3D fluctuation corrections

Dependencies of distortion fluctuations

- Space-charge density fluctuations
  ➔ Integrated digital currents (IDCs)
- Mean space-charge density
  ➔ Derivative of average corrections w.r.t. IDCs
Integrated digital currents (IDCs)

Estimator for the space-charge density fluctuations $\rho_{SC} - <\rho_{SC}>$

Charge (ADCs) on each pad integrated over ~1 ms

- Relation to the space-charge density
  - Local $\varepsilon$
  - Drift-field distortions for ions
  - Ion drift time

3D IDCs $(r, \varphi, t)$

- 3-dimensional $(r, \varphi, z)$ information about space-charge density fluctuations

1D IDCs $(t)$

- Information about fluctuations in time $(z)$ direction
Estimators of mean space-charge density

Average space-charge corrections

• Contributions affecting the space-charge density
  - Local $\varepsilon$ variations
  - Ion drift distortions
  - Ion drift velocity

• Additional contributions from other sources
  - Static distortions
  - Charge-up effects

→ Non-linear system

Derivative of average corrections w.r.t IDCs

• Single dependence on the change of the space-charge density
• Challenge: extraction for calibration intervals using ITS-TRD-TOF method
  - Fourier transform of 1D IDC fluctuations for time windows ~ ion drift time O(200 ms)
  - Distributions of Fourier coefficients $c_k$
  - Extraction of average corrections for percentiles $P_i$ defined by $c_k$ intervals
  - Numerical derivative using average corrections from 2 or more percentiles
Data-driven ML algorithms and CNNs

1D→3D distortion-fluctuation correction

- 1D IDCs (Fourier coefficients) + derivative of avg. corr. → 3D corrections
- Boosted Decision Trees (BDTs) or simple dense networks
- Correction of
  - 1D distortion fluctuations
  - Global properties of distortion fluctuations
- Precision expected to be sufficient for pp collisions

3D→3D distortion-fluctuation correction

- 3D IDCs + derivative of avg. corr. → 3D corrections
- Convolutional neural network: U-Net
- Correction of 3D distortion fluctuations
- Preliminary studies
  - Predictions dominated by global properties instead of local properties of space-charge distortion fluctuations
  - 1D→3D correction as pre-filter

\[
\text{RMSE and } \mu \text{ (cm)}
\]

\[
dr_{\text{pred}} - dr_{\text{true}} \text{ (cm) of trained models (U-Net)}
\]

\[
0.05 < \int_{r, \psi, z} \frac{<d\rho>_{SC} - \rho_{SC}}{<d\rho>_{SC}} < 0.07
\]

\[
0.00 < z < 5.00 \text{ cm, 20 epochs}
\]
Summary

Continuous readout at 50 kHz of Pb-Pb collisions

- Synchronous and asynchronous processing on the EPN farm
  - Utilization of GPUs for dominant part of the processing

TPC space-charge distortion calibration

- Most challenging calibration task
- Average distortion correction using ITS-TRD-TOF reference track method in time intervals $O(\text{min})$
- Correction of space-charge distortion fluctuations in time intervals $O(5-10 \text{ ms})$
  - IDCs as proxy for space-charge density fluctuations
  - Derivative of average corrections w.r.t. IDCs extracted from data
  - Data-driven ML algorithms and CNNs
    - 1D$\rightarrow$3D correction using BDTs or simple dense networks
    - 3D$\rightarrow$3D correction using a CNN
Backup
ALICE detectors in Run 3

Central barrel tracking
- **ITS** (7 layers)
- **TPC** (152 pad rows)
- **TRD** (6 layers)
- **TOF** (1 layer)

Calorimeters
- **EMCal**, **PHOS**, **DCal**

Forward detectors
- **MFT**, **MCH**, **MID**, **ZDC**

Fast Interaction Trigger (FIT)
- **FT0**, **FV0**, **FDD**

Others
- **HMPID**
Space-charge density and distortion fluctuations

Dependencies of the space-charge density

- Ion backflow x gain = $\varepsilon$
- Number of ion pile-up events within one full ion drift time
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Relative space-charge density fluctuations $\sigma_{SC}/\mu_{SC}$ of ~2 % at 50 kHz Pb-Pb

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1D fluctuations

3D fluctuations
Data-driven approach

Fourier transform of 1D IDCs for time windows ~ ion drift time $O(200\ ms)$
- Set of Fourier coefficients $c_k$ for each window
  - Assumption: Gaussian white noise vectors
  - Gaussian distributions with same finite width

Numerical derivative of average corrections w.r.t. IDCs
- Collection of windows with coefficients (e.g. 0th) within defined percentiles
  - Similar space-charge density fluctuations
  - Combined statistics from several windows
- ITS-TRD-TOF method to extract average corrections for given percentiles
- Numerical derivative using two or more average correction maps

Extended fully data-driven approach
- Linear decomposition of corrections
  - Derivatives of corrections for $n$ frequencies
  - $n$ Fourier coefficients

\[
I(t) = \langle I(t) \rangle + \Delta I(t)
\]
\[
I(t) = \langle I(t) \rangle + \sum_{k=0}^{N} c_k \Phi_k(t)
\]
\[
\frac{\partial \Delta_k}{\partial c_k} = \langle \Delta \rangle_{k,Q=0.8} - \langle \Delta \rangle_{k,Q=0.2}
\]
\[
\frac{\langle c_k \rangle_{Q=0.8} - \langle c_k \rangle_{Q=0.2}}{Q}
\]
\[
\Delta(t) = \sum_{k} c_k \frac{\partial \Delta_k(t)}{\partial c_k} \Phi_k(t)
\]
1D→3D distortion-fluctuation correction

Boosted Decision Trees (BDTs) or simple dense networks

- **Feature variables**
  - Position r, φ, z
  - n Fourier coefficients of 1D IDC fluctuations
    - Significantly less parameters than independent raw 1D IDC values
    - Importance of frequencies k expected to decrease with 1/k as IDC fluctuations are integrated over the drift length
  - Derivative of average corrections

- **Output variables**
  - dr, dφ, dz

Correction of:

- **1D fluctuations**
- **global properties of fluctuations imposed by boundary conditions**
  - Fixed TPC boundaries
  - Asymmetric profile of space-charge density

Precision expected to be sufficient for pp collisions

- Smaller space-charge distortions or much higher interaction rates (200 kHz to 1 MHz) than in Pb-Pb
3D→3D distortion-fluctuation correction

Convolutional Neural Network: U-Net

- Classification of each pixel
- Propagation of local information and context

Prediction of full fluctuation corrections ($dr$, $d\phi$, $dz$) using 3D IDC fluctuations and derivative of average corrections as input

Preliminary studies performed using space-charge density fluctuations and average space-charge density from simulation

- Systematic dependence of the mean and RMS of the predictions on the distance to the TPC boundaries
- Predictions of local fluctuations dominated by global properties imposed by boundary conditions
  - Network focused on learning boundary conditions instead of local fluctuations
  ➔ 1D→3D correction required as pre-filter to reduce the magnitude of global effects
Preliminary results

Evaluation

- Mean ($\mu$) and RMSE of the difference between predicted and true distortion fluctuations ($dr_{\text{pred}} - dr_{\text{true}}$)
- Multi-dimensional analysis in TPC phase space
  - r, $\varphi$, z, relative density fluctuations, ...

Variation of

- grid size: 90 x 17 x 17, 180 x 33 x 33
- number of training samples: 5k, 10k, 18k

Different training statistics required for different grid sizes

- Increasing number of training samples from 10k to 18k
  - Indications of overtraining for 90 x 17 x 17
  - Network still undertrained for 180 x 33 x 33

Systematic dependence of the predicted results on the TPC radius

- Effect of space-charge density fluctuations on the distortion fluctuations strongly depends on the distance from the TPC boundaries
Interpretation of the preliminary U-Net performance

Unit test

- Response of the U-Net to a local space-charge density fluctuation
- Narrow line charge fluctuation at fixed $r, \phi$

Scale and shape of the prediction dominated by global (long range) dependencies

- Training time spent on learning broken assumptions of the U-Net instead of local effects
  - Asymmetric boundary conditions
  - Continuity along $\phi$-direction
  - Broken translational invariance
- Inability to predict local fluctuations at the current stage of the development
Boundary and charge-up effects

Sources

- Finite granularity of field cage strips
- Dead zones between ROCs and GEM stacks
- Misalignment, e.g. between ROCs and CE
- Local charge-up effects

Consequences

- Sharp gradients of distortions close to the boundaries
  - Smeared out by average distortions and fluctuations
- Kinematic and QA variables affected by residual miscalibration

Calibration

- Analytical model or data driven templates
- Partial rescaling to account for time dependent changes (e.g. IR)
- Model based on local distortions / corrections
  - Commutativity of distortions from different effects only valid locally
Calibration of the ion drift time

Ion drift time a priori unknown

- Function of gas composition, $p$, $T$, $E$
- Microscopic ion movement in a gas substantially different from electrons
  - Velocity and direction after collisions with gas atoms
  - Drifting ion species not well-defined
    - Y. Kalkan et al 2015 JINST 10 P07004
  ➔ Separate calibration required on time scales $O(h)$
- Unavailable from hardware measurements

Possible calibration procedure using space-charge distortion calibration data

- Robust tracking variable after average distortion correction
  - $DCA$ fluctuations as a function of $\eta$, $\phi$, $q/p_T$
- Correlation of $DCA$ fluctuations to 0D $IDC$ fluctuations
  - Variation of the 0D $IDC$ integration time
    - Ion drift time $\pm \Delta t$ around the nominal value
  - Biggest correlation and smallest dispersion expected for the correct ion drift time