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Correcting for distortions due to ionization in the STAR TPC

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Abstract

Physics goals of the STAR Experiment at RHIC in recent (and future) years drive the need to operate the STAR TPC at ever higher luminosities, leading to increased ionization levels in the TPC gas. The resulting ionic space charge introduces field distortions in the detector which impact tracking performance. Further complications arise from ionic charge leakage into the main TPC volume from the high gain anode region. STAR has implemented corrections for these distortions based on measures of luminosity, which we present here. Additionally, we highlight a novel approach to applying the corrections on an event-by-event basis applicable in conditions of rapidly varying ionization sources.

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Keywords: Calibration; Space charge; Time projection chamber

1. Introduction

The time projection chamber (TPC) used by the STAR experiment at RHIC has several potential sources of field distortions [1]. While most of these sources are static, the buildup of slow-drifting positively charged ions in the gas volume generated from standard operation of the TPC varies with the quantity of charged particles traversing the TPC, and thereby both the luminosity of the collider and the multiplicity of charged particles emitted by the collisions. The variations in this "space charge" can occur on time scales down to what it takes the ions to drift the length of the chamber, which is approximately one half second for the STAR TPC.

2. Space charge distortions

Modeling the distortions due to space charge is a straightforward process beginning with a postulation of the typical three-dimensional distribution of ionization in the TPC. The nearest measure we have of this in STAR is a record of the distribution of electron clusters reaching the TPC endcap averaged over many events using a so-called "zero-bias" trigger (which is random with respect to collision times, removing any biases related to the definition of a collision). This measure integrates out any drift-direction dependencies, but compares well in radial dependence (approximately as inverse radius squared) for $\sqrt{s_{NN}} = 200\,\text{GeV}$ Au + Au collisions to a simulation using the HIJET event generator [2]. The simulation indicates a uniform distribution of charge in the drift direction.

We use the HIJET charge distribution integrated along the distance from the endcap to any point in space (representing the effect of continual collision contributions) in conjunction with the boundary conditions of grounded surfaces surrounding the TPC gas volume to solve for the electrical potential due to space charge. Since an analytical solution is not possible we use a numerical relaxation to solve for the potential on a grid in two dimensions with assumed azimuthal symmetry and interpolate. An electric field is obtained from the potential and is treated as a

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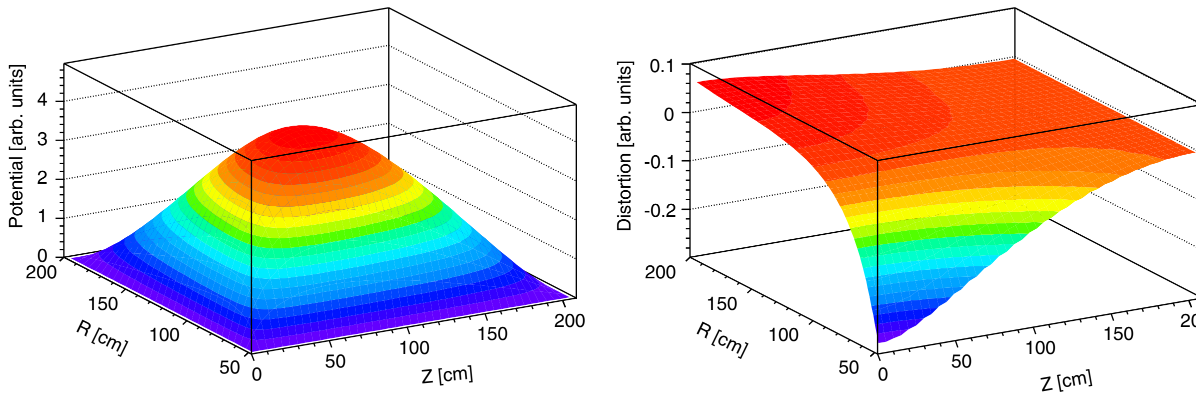

Fig. 1. Simulated shape of the potential due to space charge in the TPC (left) and the azimuthal distortions of electron clusters (right) caused by drifting through that potential as a function of radius R and drift Z. The cathode is at $Z=0$, and electron clusters drift to the endcaps at high Z.

perturbation on top of the normal drift field. The distortions to the measured positions of electron clusters are then calculated by integrating the effects of this perturbing field (which depend on operating conditions of the chamber) along the path from a point in the TPC to the endcap where the clusters are measured [1]. The amplitude of this distortion is directly proportional to the quantity of space charge (ρ_{SC}) present. In practice, we calibrate the average charge density over the volume of the chamber: $\langle\rho_{SC}/\varepsilon_0\rangle$.

Since the Lorentz force on the drifting electron clusters is proportional to the cross product of the electric and magnetic field vectors, which are aligned along the drift direction in STAR, the principle distortion of consequence is azimuthal, Fig. 1. This distortion has the effect of rotating reconstructed tracks in the transverse plane about a point midway along their path through the TPC.

3. Space charge corrections

Knowledge of ρ_{SC} is sufficient to subtract the calculated distortions from the measured electron cluster positions to obtain their approximate original, undistorted positions. In the absence of direct measures of ρ_{SC}, a measure of the distortion to tracks (fit from distorted clusters) may suffice to indirectly determine ρ_{SC}. Simulation shows that for any given distorted primary particle track, its signed distance of closest approach to the collision vertex (sDCA, where the sign indicates whether the momentum vector in the transverse plane at the point of closest approach is directed clockwise or counter-clockwise about the vertex) is approximately linearly proportional to space charge, and we can obtain $C^{sim}_{track} = \rho^{sim}_{SC}/\mathrm{sDCA}^{sim}_{track}$, where C^{sim}_{track} depends on the locations of points on the track. Each real track can then be used to derive an observed space charge:

$$\rho^{obs}_{SC} = C^{sim}_{track}\cdot \mathrm{sDCA}^{obs}_{track} = \rho^{sim}_{SC}\cdot(\mathrm{sDCA}^{obs}_{track}/\mathrm{sDCA}^{sim}_{track}).$$

For this analysis, we use only TPC tracks with at least 25 points out of a maximum 45, pseudorapidity within ± 1, and transverse momentum between $0.3-2.0\,\mathrm{GeV}/c$. To understand the scale of this distortion, it is worthwhile to note that some recorded events exhibited beyond 1 cm offsets in $\langle\mathrm{sDCA}\rangle$, the mean of their $\mathrm{sDCA}^{obs}_{track}$ distributions.

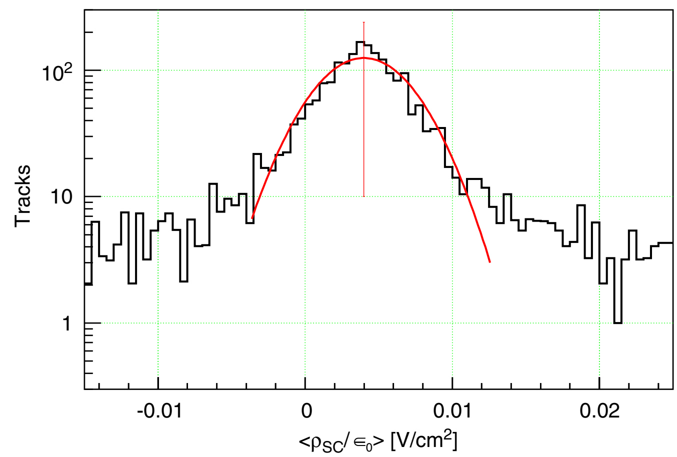

Fig. 2. Observed space charge density (averaged over the volume of the TPC) determined from individual tracks in a single high-multiplicity event. The mean of a Gaussian peak (formed from primaries) is fit to extract ρ^{obs}_{SC} for that event.

A distribution of ρ^{obs}_{SC} values from any given collision event will include a background from secondaries which naturally do not point to the collision vertex, and will be smeared by the intrinsic resolution of the TPC to measure sDCA. As seen in the distribution from a single very high-multiplicity event in Fig. 2, the centroid of a peak formed by primaries provides a means to determine ρ^{obs}_{SC} more accurately.

To be effective, the value of ρ_{SC} used to correct the distortions must be updated on time scales shorter than the fluctuations caused by collider operating conditions. Between 2000 and 2003, trigger rates recorded every 30 s measured these fluctuations with sufficient resolution [3]. Along with a significant luminosity increase in 2004, however, these fluctuations were observed in the systematic behavior of sDCA distributions on sub-second time scales.

An event-by-event (E-by-E) method using only ρ_{SC}^{obs} from individually recorded events suffers from insufficient statistics to get a good measure in most events. To compensate, we can take advantage of the fact that ρ_{SC} fluctuations cannot occur on time scales much shorter than the drift time of ions in the TPC. We do this by building a running sum of ρ_{SC}^{obs} from each event and previous events downweighted appropriately by their age. Because we measure ρ_{SC}^{obs} from events which have already been corrected with some value ρ_{SC}^{used}, we set the new value to be $\rho_{SC}^{new} = \rho_{SC}^{used} + \rho_{SC}^{obs}$. This method is self-correcting in that even if the conversion factors C_{track}^{sim} are not perfect, ρ_{SC} will quickly converge to a value which brings the sDCA distributions to peak at zero.

The weaknesses in this technique include events at the start of data files for which there are no previous events, sizable time gaps between some events, and series of low-multiplicity events for which insufficient statistics are obtained within short time scales. The first problem is solved by performing a prepass on the first few events in each file to determine a viable initial $\rho_{SC}^{prepass}$, which is then used in the production pass until the E-by-E method becomes applicable. The latter issues are handled by falling back to $\rho_{SC}^{prepass}$ for such events until the E-by-E method can again be useful. Backgrounds which introduce charge distributions different from the HIJET model can also degrade performance.

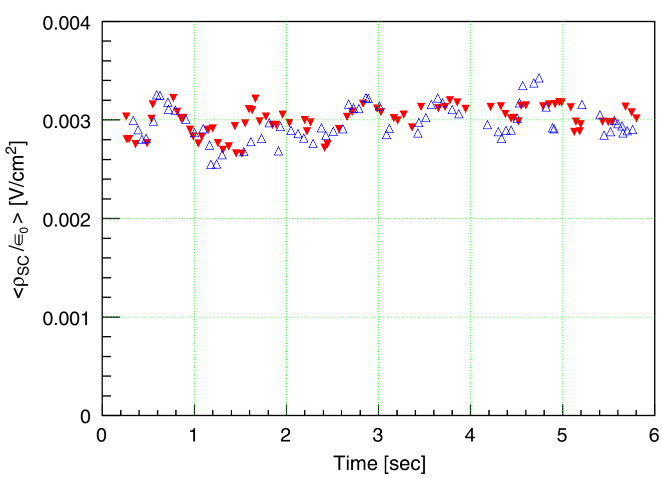

Fig. 3. Observed volume-averaged space charge density measured and used in the E-by-E method for two selections of independent but concurrent events versus time.

Fig. 3 demonstrates that the fluctuations in ρ_{SC} determined by the E-by-E method are not artificial. In two independent but concurrent sets of events, similar behaviors can be seen on sub-second time scales, while differences illustrate the uncertainty on $\langle \rho_{SC}/\varepsilon_0 \rangle$ in the method of about 0.0001 V/cm^2.

4. Ion leakage around the gated grid

The STAR TPC was designed with a gated grid to prevent ions created in the high gain region around the anode wires from leaking into the TPC main volume and drifting across to the cathode. A discontinuity observed in the residuals of TPC cluster positions from reconstructed tracks, Fig. 4, reveals that a thin sheet of charge is leaking around the edge of this grid at the gap between inner and outer readout wire chambers of the TPC.

Again, we can model the distortions from this charge in the same manner as the space charge, providing a map of cluster position corrections whose magnitude is proportional to the amount of leaked charge (ρ_{leak}). These distortions similarly affect sDCA, and ρ_{leak} was found to scale with collision rates in the same manner as ρ_{SC}. A calibration was performed to find the ratio (D) between ρ_{leak} and ρ_{SC} which removed the residual discontinuities while simultaneously zeroing sDCA in a sample of events. And the E-by-E correction was modified to track the two distortions together:

$$(\rho_{SC}^{obs} + \rho_{leak}^{obs}) = (\rho_{SC}^{sim} + \rho_{leak}^{sim}) \cdot (\mathrm{sDCA}_{track}^{obs}/\mathrm{sDCA}_{track}^{sim}),$$
$$\rho_{leak} \equiv D \cdot \rho_{SC}.$$

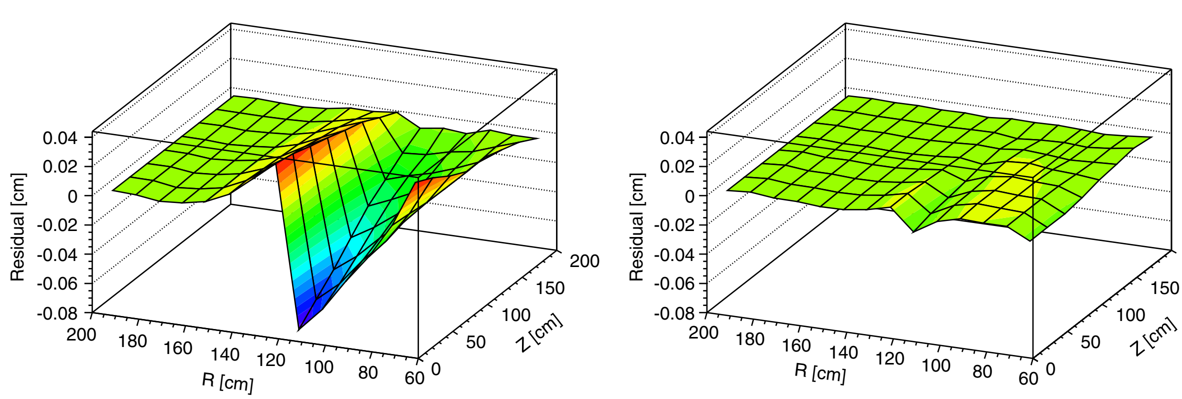

Fig. 4. Residuals of TPC tracks over R and Z in a selection of events acquired during high luminosity before (left) and after (right) leakage distortion corrections. The gap between inner and outer wire chambers is at $R \approx 122$ cm.

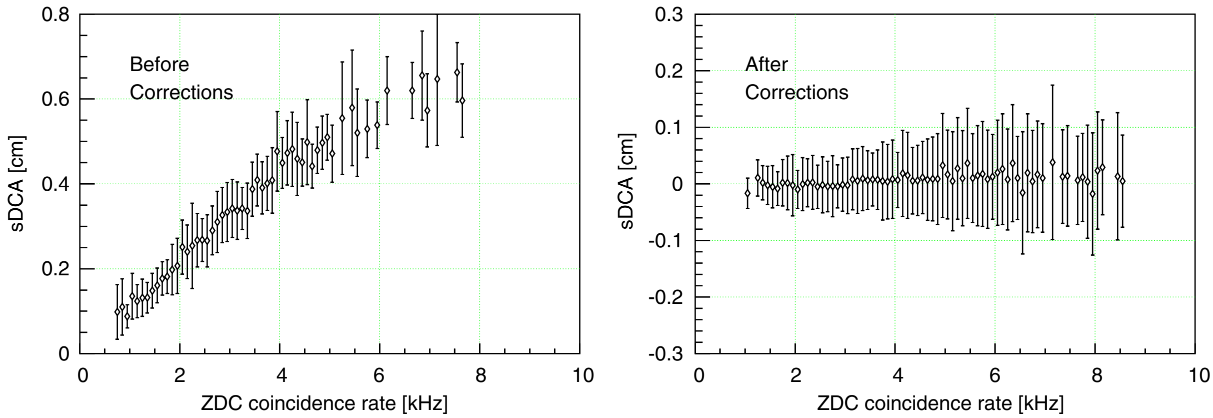

Fig. 5. Distributions of ⟨sDCA⟩ (error bars are the spread (RMS), diamonds the mean) versus luminosity (represented by the rate of zero degree calorimeter (ZDC) coincidences [3]) for $\sqrt{s_{NN}} = 200$ GeV AuAu collisions. The luminosity dependence of ionization distortions on ⟨sDCA⟩ is evident from a small subset of the data before corrections (left). A larger subset with applied corrections (right) demonstrates performance of the ionization distortion corrections.

5. Summary

We have identified and corrected for distortions due to ion charge buildup in the STAR TPC. With the onset of significant short time scale fluctuations in the sources of the ions which were not monitored with fine time granularity during data acquisition, we have developed a technique to determine and adjust for the fluctuations during reconstruction on an event-by-event basis. Performance of the corrections can be assessed by examining the distribution of ⟨sDCA⟩ as a function of luminosity, shown in Fig. 5. Here, we see that the spread in ⟨sDCA⟩ is contained to within approximately 1 mm at all luminosities, and the mean is kept to within a few hundred microns of zero. In 2005, online monitoring with one second granularity was implemented and will provide further assessment of the technique's success.

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