Overview of the Inner Silicon detector alignment procedure and techniques in the RHIC/STAR experiment.

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Abstract. The STAR experiment was primarily designed to detect signals of a possible phase transition in nuclear matter. Its layout, typical for a collider experiment, contains a large Time Projection Chamber (TPC) in a solenoid magnet, a set of four layers of combined silicon strip and silicon drift detectors for secondary vertex reconstruction, plus other detectors. In this presentation, we will report on recent global and individual detector element alignment as well as drift velocity calibration work performed on this STAR inner silicon tracking system. We will show how attention to details positively impacts the physics capabilities of STAR and explain the iterative procedure conducted to reach such results in low, medium and high track density and detector occupancy.

1. Introduction

The Relativistic Heavy Ion Collider (RHIC) is one of the main facilities of Brookhaven National Laboratory, and the Solenoidal Tracker at RHIC (STAR, shown in Fig.1) is one of its two major detector systems\cite{1}. The reconstruction of charged tracks in STAR’s central (mid-rapidity) region is done with a Time Projection Chamber (TPC), a Silicon Strip Detector (SSD), and a Silicon Vertex Tracker (SVT). In the next sections we present

- parameters of these detectors,
- problems with relative alignment of two drift detectors: the SVT with respect to the TPC,
- impact of the SSD on alignment,
- new goals for the silicon detectors (SSD and SVT) in the context of charm and beauty physics,
- a figure of merit for alignment precision of the silicon detectors,
- calibration and alignment methods and procedure,
- results, and
- conclusions
Figure 1. Tracking in the central region of the STAR detector uses the TPC, SSD, and SVT. Shown is a cross section of the cylindrical geometry, typically operated with a 5 kG solenoidal magnetic field.

2. STAR central tracking detectors

2.1. The TPC

Working since day one of the experiment, the TPC is the main STAR tracking detector[2]. The TPC is divided into halves by a central membrane and contains 12 sectors in each half. Each sector has inner and outer subsectors comprised of 13 and 32 rows of sensitive pads respectively. Electrons produced by charged particles drift (in the Z direction) from the central membrane to the end caps in almost parallel electric and magnetic fields, where they are detected by the pads placed at radii ranging from 60 to 190 cm (the beams collide nominally along the Z axis through the center of the detector). The TPC drift velocity is monitored by a laser system[3] with a precision of $\approx 2 \times 10^{-4}$, providing a systematic error in the Z direction of $\approx 400 \mu m$ at the maximum drift length ($\approx 2$ m).

Reconstruction of hits from the TPC pads gives spatial resolutions of:

- $\sigma_{\rho\phi} \approx 600 \mu m$ and $\sigma_Z \approx 1200 \mu m$ for inner subsectors and
- $\sigma_{\rho\phi} \approx 1200 \mu m$ and $\sigma_Z \approx 1600 \mu m$ for outer subsectors

Distortions due to a non-uniform electric field and space charge collected in the TPC are
monitored by the DCAs (distance of closest approach) of tracks at the primary (collision) vertex and are typically kept to a level better than $\approx 100 \, \mu m$.

### 2.2. The SVT - A 3 Layer Silicon Drift Detector

The SVT\cite{5} was designed primarily to aid multi-strange particle physics. Shown in Fig.2, it is the innermost tracking detector in STAR, with active elements ranging from 6.5 to 15 cm radially. Two silicon hybrids form a wafer, several wafers are lined up along a ladder, and the ladders are arranged in 3 barrels on two rigid clam-shells. The detector consists of 216 wafers in total. Electrons liberated in the silicon drift in the $\rho\phi$ direction (perpendicular to the drift direction of the TPC) to anode strips. The size of a virtual pixel is 250 $\mu m$ in $\rho\phi$ (time bins) $\times 250 \, \mu m$ in Z (the anode strip pitch). The intrinsic spatial resolution (accounting for charge sharing) is: $\sigma_{\rho\phi} < 80 \mu m$ and $\sigma_{Z} < 80 \mu m$. The detector is relatively thick ($\approx 1.5% \, X_0$ per layer), and is not very close to the beam. It was installed into STAR in 2001 for Run II, and has been functional since Run III.

**Figure 2. Silicon Drift Detector**

| Barrel 1: | 8 ladders; | 4 wafers each ladder; | $<R> = 6.85 \, cm.$ |
|-----------|-------------|-----------------------|---------------------|
| Barrel 2: | 12 ladders; | 6 wafers each ladder;  | $<R> = 10.8 \, cm.$ |
| Barrel 3: | 16 ladders; | 7 wafers each ladder;  | $<R> = 14.7 \, cm.$ |

### 2.3. The SSD - A Single Layer 2-Sided Silicon Strip Detector

The SSD\cite{6}, shown in Fig.3, wraps around the SVT as a fourth layer. Its primary purpose is to provide an intermediate, non-drifting point for track matching between the TPC and the SVT.
It consists of 20 ladders with 16 wafers each, mounted on 4 rigid sectors at ≈23 cm from the beam. The SSD was installed in STAR for Run IV, and was fully functional in Run V. The strips are 4 cm long and laid out at a 95 µm pitch, with a stereo angle between p- and n-side strips of 35 mrad. The intrinsic resolution is better than ≈30 µm (ρφ) × 860 µm (Z). The non-drifting technology of the SSD provides a big advantage for alignment calibration. Note that there is a Lorentz shift of holes and electrons transported through the silicon in the ρφ direction due to the 5 kG magnetic field (with Lorentz Θholes = 4.4° → 4.4µm and Θelectrons = 1.6° → 1.6µm) which produces a sizable effect in the Z direction (≈ 200µm) due to the stereo angle. But it is clear how to account for this effect.

Figure 3. Silicon Strip Detector

3. Alignment and Calibration

3.1. Alignment and Calibration of SVT with TPC for Run III-IV data

Calibration and alignment of the SVT was initially done on a test bench, but analysis of in situ data from the detector in the experiment showed that re-calibration and re-alignment were necessary[7]. These initial re-calibration and alignment efforts between these two drifting detectors gave rather modest performance results: spatial resolution σρφ ≈ σZ ≈ 200 µm. However the achieved accuracy was not good enough to be used in the heavy ion collision high track multiplicity environment due to a high ghosting level. Instead, many of the multi-strange physics goals (reconstructing Ξ and Ω particles) were accomplished with TPC-only analyses.

3.2. New physics goals

Recently, much interest has become focused on direct charm measurements. In 200 GeV Cu+Cu interactions (Run V) STAR has already observed ≈4 standard deviations of D0 signal. This, along with the availability of the SSD, motivated a revisitation of trying to obtain better spatial resolution from the SVT. The rest of this paper describes the effort involved to achieve the new end goals of reducing backgrounds and enhancing the significance of the charm signal by a factor of ≈3-5 through use of the STAR inner silicon tracking system. More specifically, this involved using the SSD in the alignment and drift velocity calibrations in order to achieve spatial resolutions sufficient to provide direct D-meson measurement, and perhaps B-meson tagging.
3.3. Figures of merit for SVT/SSD precision

We chose to use for the figures of merit various pointing accuracies (or impact parameter resolutions) of charm decay registration at the primary vertex. These accuracies are reported here as the DCA resolutions in the XY (≡ ρφ) plane (σ_{DCA}) and in the Z direction (σ_Z), where we have the following for each:

- \( \sigma_{DCA}^2 = \sigma_{vertex}^2 + \sigma_{track}^2 + \sigma_{MCS}^2 \)
- primary vertex resolution: \( \sigma_{vertex} \approx 600 \, \mu m/\sqrt{N_{goodtracks}} \), for central Au+Au collisions this turns out to be better than 20 \( \mu m \), and for minimum biased events \( \approx 100 \, \mu m \),
- track pointing resolution: \( \sigma_{track} \approx 2 \times \sigma_{XY} \) in our case, where \( \sigma_{XY} \) is intrinsic detector precision ± alignment errors
- multiple coulomb scattering (MCS): \( \sigma_{MCS}^2 \approx \frac{170}{p} \, \mu m/(GeV/c) \) (from simple analytic estimations)

In the context of the effort to realize the physics goals, we set as the primary goal of this calibration work the requirement that the track pointing resolution should be comparable with MCS at 1 GeV/c. It then follows that the detector resolutions (including alignment) should achieve \( \sigma_{XY} < 80 \, \mu m \) and \( \sigma_Z < 80 \, \mu m \).

3.4. Methods

Methods can naturally be split into two parts:

- calibration of SVT drift velocities on the hybrid level, and
- alignment of detectors assuming that wafer positions on ladders are frozen from survey data (i.e. a ladder is the lowest level degree of freedom) and ignoring possible twist effects, gravitational/stress sagging, etc.

The methods are interconnected and require an iterative procedure where we use average drift velocities to do alignment, then check and correct drift velocities, and iterate.

3.4.1. Average drift velocities

As the first approximation we are using average (constant) drift velocities per hybrid from a charge step method:

- clean up noisy strips
- from drift time distribution (an example of this distribution for a hybrid is shown in Fig.4) for each hybrid we have reasonably sharp cut offs (charge steps) at \( t_0 \) and \( t_{max} \)
- from these numbers and the total drift length (L) we can estimate average drift velocity as \( v_D = L/(t_{max} - t_0) \)
- these hybrids’ \( v_D \) should be correct on average per ladder and are used for subsequent alignment

3.4.2. Alignment

For small misalignments, we can assume a model where the hit position deviations from tracks are linearly proportional to the misalignments through derivatives of track projections to measurement planes with respect to misalignment parameters (i.e. the first order of a Taylor expansion). The derivatives take as a condition that both the track prediction and the hit stay on a measurement plane after applying the correction (see Appendix for details). We define:

- for global alignment: \( \vec{X}_{hit} - \vec{X} = \partial \vec{X}/\partial \vec{\Delta} \times \vec{\Delta} \equiv \vec{G} \times \vec{\Delta} \)
- for local alignment[8]: \( \vec{u}_{hit} - \vec{u} = \partial \vec{u}/\partial \vec{\delta} \times \vec{\delta} \equiv \vec{L} \times \vec{\delta} \)
Figure 4. An example drift time distribution used for average drift velocity estimation via the charge step method.

Misalignment parameters are then determined as the slopes of straight line fits to histograms of the most probable deviations ($X_{hit} \cdot \bar{X}$ or $u_{hit} \cdot \bar{u}$) versus the corresponding derivative matrix ($G_{ij}$ or $L_{ij}$) component[9] (see examples in Figs. 5 and 6). For alignment we use good (with well defined parameters) tracks fitted with the primary vertex. Use of such tracks significantly improves accuracy of track predictions in the silicon detectors and reduces the influence of systematics from other factors (e.g. distortions in the TPC). The accuracy of the method is checked with simulation, giving $\approx 10 \mu m$ in a detector’s translational position and $\approx 0.1 \text{ mrad}$ in its rotation.

However, there is a problem when a starting point is far from the minimum because there are significant correlations among alignment parameters. To solve this, we use as the starting point a least-squares fit with the above derivatives to get a first approximation for the parameters. The accuracy of this method is less than the slopes method, but it does provide a reasonable starting approximation from which to use slopes.

3.4.3. Procedure sequence: In practice, the calibration methods must be done in a sequence which can be categorized by the data utilized:

- SVT hit reconstruction
  - First approximation of average SVT drift velocities (obtained from the charge step method for each hybrid)
- TPC-only tracks
  - Global alignment of the SSD with respect to the TPC as whole
Figure 5. Another example of local alignment: $\gamma$ (slope) is the rotation around the w ($\equiv$local Z) axis

- Global alignment of the SSD sectors
- Local alignment of the SSD ladders (individual ladders showed translations of up to $\approx$200 $\mu$m and rotations (especially around the y-axis) of up to $\approx$20 mrad; after the SSD ladder fine tuning, the majority of ladders achieved translational alignments calibrated to under 20 $\mu$m, and rotational alignments calibrated to within 0.5 mrad, both of which were within errors of zero for the calibration method)

- TPC + SSD tracks
  - Global alignment of the SVT as whole
  - Global alignment of the SVT clam shells
  - Local alignment of the SVT ladders
  - Correction to the SVT drift velocities (the SVT drift velocities are re-fitted including extra dependences on drift distance and strip using a third degree Tchebyshev; the fit reduces hit residuals from $\approx$100 $\mu$m to $\approx$10 $\mu$m)

- TPC + SSD + SVT tracks
  - Check consistency
  - Reevaluate SVT and SSD hit errors

4. Results
4.1. SVT/SSD resolutions after calibration/alignment
The SVT and SSD hit errors after this calibration/alignment procedure are estimated using a hit pull analysis on track fits: the spatial resolution is determined by the requirement that the
standard deviation of pulls should be equal to one. Further, we average the results over three data samples acquired by STAR during Run V Cu+Cu collisions: 62 GeV collisions with one magnet polarity, and 200 GeV collisions for both polarities. The results demonstrate the quality of this work, and are as follows:

- SVT resolution: $\sigma_{\rho\phi} = 49 \pm 5 \text{ } \mu m$, and $\sigma_Z = 30 \pm 7 \text{ } \mu m$
- SSD resolution: $\sigma_{\rho\phi} = 30 \text{ } \mu m$ (set to the design value since $\sigma_{DCA}^2$ is dominated by $\sigma_{MCS}^2$), and $\sigma_Z = 742 \pm 41 \text{ } \mu m$

4.2. DCA resolutions

Pointing (DCA) resolutions are estimated as the standard deviations of the distribution of global track DCAs with respect to the primary vertex; they are shown in Fig.7. With increasing numbers of fitted silicon points, the resolutions improve by about an order of magnitude. The estimated DCA resolution at a momentum 1 GeV/c is summarized in table 1. The contribution from tracking (constant term) is comparable with that from MCS at 1 GeV/c, indicating that this effort has indeed achieved its basic goal.

5. Conclusions

Recent interest in charm physics has re-focused STAR’s interest in its vertex detectors. The presence of drift silicon technology (the SVT) complicates the alignment tasks, but the
Table 1. DCA resolution versus no. of Silicon points in track fit

| Number of Silicon Points fitted to track | \( \sigma_{XY} \) @1GeV/c (\( \mu m \)) | \( \sigma_{Z} \) @1GeV/c (\( \mu m \)) |
|------------------------------------------|------------------------------------------|------------------------------------------|
| 0 - TPC-only                             | 3327                                     | 2918                                     |
| 1 - TPC+SSD                              | 957                                      | 1528                                     |
| 2 - TPC+SSD+SVT                          | 382                                      | 540                                      |
| 3 - TPC+SSD+SVT                          | 296                                      | 383                                      |
| 4 - TPC+SSD+SVT                          | 280                                      | 344                                      |

Figure 7. Pointing precision for global track with respect to the primary vertex in the bending (a) and non-bending (b) planes for tracks with various numbers of silicon hits (see table 1 for the corresponding markers).

The lines represent fit by \( \sigma_{DCA} = \sqrt{A^2 + (B/P)^2} \).

The presence of additional non-drifting detectors (like the SSD) improves the situation drastically. Our alignment approach and techniques were successful in achieving overall detector position accuracy under 20 \( \mu m \), which is expected to be sufficient for serving the new physics goals.

The calibration/alignment procedure for Run V (Cu+Cu) has been completed, data has been re-processed, data analyses are under way, and first physics checks look fine. Also under way is a repeat effort of the calibration/alignment procedure for Run VII (Au+Au 200 GeV). Some of the benefits for STAR from these well-calibrated silicon detectors include:
• improved momentum resolution for global tracks,
• improved primary vertex resolution,
• greatly improved track selection (based on DCA),
• sharpened (multi-)strangeness physics, and
• other non-physics side benefits, such as use of the SVT and SSD as a high resolution microscope to monitor and help correct for TPC distortions.

The Silicon Vertex Tracker and Silicon Strip Detector are clearly sharpening STAR’s physics capabilities.

6. Appendix. Jacobian of measured hit position deviation from predicted track ones with respect to misalignment parameters.

6.1. Misalignment of the detector in the global coordinate system (GCS)
• \( \vec{j} = (j_x, j_y, j_z) \) - track direction cosines in GCS on the measurement plane
• \( \vec{X} = (x, y, z) \) - track prediction in GCS on the measurement plane
• \( \vec{X}_{hit} = (x_{hit}, y_{hit}, z_{hit}) \) - hit position in GCS on the measurement plane
• \( \vec{v} = (v_x, v_y, v_z) \) - direction of normal to the measurement plane in GCS
• \( \vec{\Delta} = (\Delta_x, \Delta_y, \Delta_z, \Delta_v, \Delta_\beta, \Delta_\gamma) \) - misalignment parameters: shift and rotation with respect to X,Y,Z axes, respectively

\[
\vec{X}_{hit} - \vec{X} = \partial \vec{X}/\partial \vec{\Delta} \equiv \mathbf{G} \times \vec{\Delta} = \\
\begin{pmatrix}
-1 + j_x v_x & j_x v_y & j_x v_z \\
-j_y v_x & -1 + j_y v_y & j_y v_z \\
-j_z v_x & j_z v_y & -1 + j_z v_z
\end{pmatrix}
\begin{pmatrix}
\Delta_x (-v_y z + v_z y) & -z + j_x (v_x z - v_z x) & y + j_x (-v_y y + v_x y) \\
\Delta_y (v_x z - v_z x) & -x + j_y (-v_x y + v_y y) & \Delta_v \\
\Delta_z (-v_y z + v_z y) & x + j_z (v_x z - v_y y) & j_z (-v_x y + v_y y)
\end{pmatrix}
\]

6.2. Misalignment of the detector in the local coordinate system (LCS)
• \( \vec{u} = (u, v, w \equiv 0) \) - track prediction in LCS on the measurement plane
• \( (t_u, t_v) \) - track direction tangents in LCS on the measurement plane
• \( \vec{u}_{hit} = (u_{hit}, v_{hit}) \) - hit position in LCS on the measurement plane
• \( \vec{\delta} = (\delta_u, \delta_v, \delta_w, \delta_\alpha, \delta_\beta, \delta_\gamma) \) - misalignment parameters shift and rotation with respect to local u,v,w axes, respectively

\[
\vec{u}_{hit} - \vec{u} = \partial \vec{u}/\partial \vec{\delta} \equiv \mathbf{L} \cdot \vec{\delta} = \\
\begin{pmatrix}
-1 & 0 & t_u \\
0 & -1 & t_v \\
-t_u & -t_v & u
\end{pmatrix}
\begin{pmatrix}
\delta_u \\
\delta_v \\
\delta_w + v \delta_\alpha - u \delta_\beta + u \delta_\gamma \\
-\delta_v + t_v (\delta_w + v \delta_\alpha - u \delta_\beta) - u \delta_\gamma
\end{pmatrix}
\]

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