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. STAR is one of the two major detectors at RHIC. The STAR detector is shown in Fig.1 and its abbreviation stands for "Solenoidal Tracker At RHIC". The reconstruction of charged tracks in barrel region is done with Time Projection Chamber (TPC), Silicon Vertex Tracker (SVT), and Silicon Strip Detector (SSD). In the next sections we

- provide parameters of these detectors
- discuss problems with two drift detector alignment: SVT with respect to TPC
- impact of SSD on alignment
- new goals for Inner Silicon Detector (SVT and SSD) in context of charm and beauty physics
- introduce a figure of merit for Silicon detectors alignment precision
- present calibration and alignment methods and procedure
- show results, and
- make conclusions

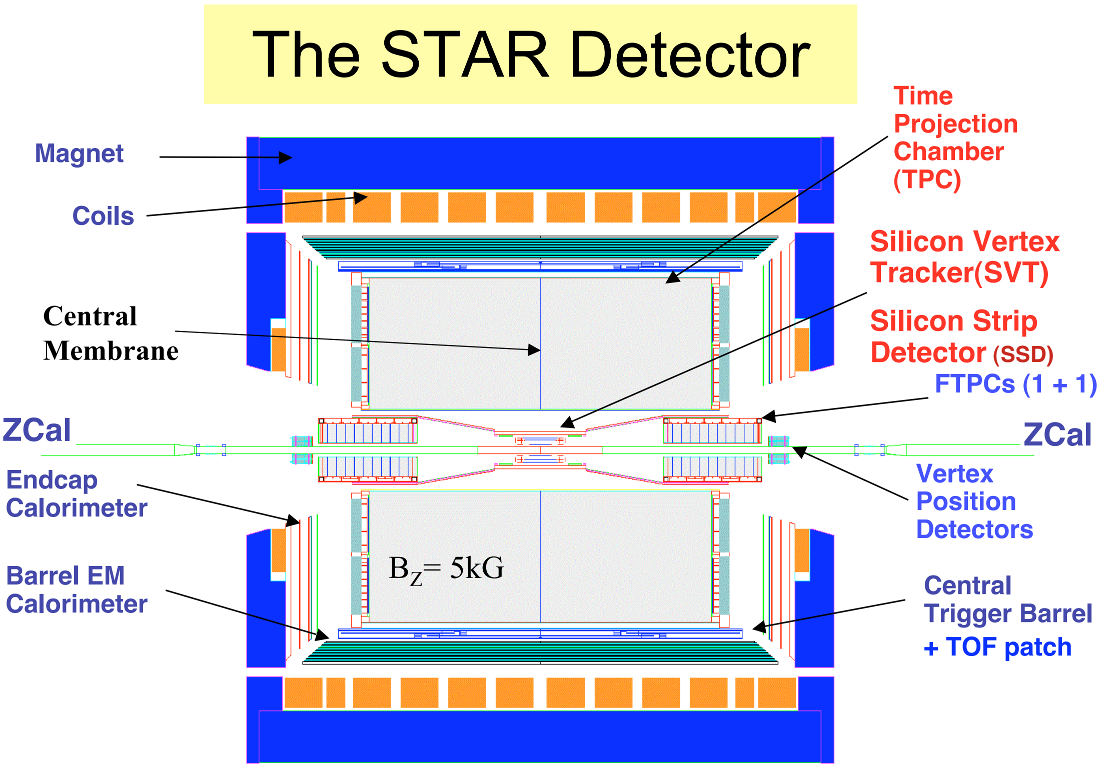

Figure 1. The STAR detector includes TPC and SVT/SSD for tracking in barrel region with 5 kG magnetic field.

2. STAR barrel track detectors

2.1. Time Projection Chamber

The TPC is the main STAR tracking detector[1], working in STAR from day one (Run I, FY 2000). The TPC is divided into halves by Central Membrane and contains 12 sectors in each half and each sector contains inner (13 pad rows) and outer (32 pad rows) sub sectors. Electrons produced by charged particles drift (in Z direction) from central membrane to end caps in almost parallel electric and magnetic fields where they are detected with 45 pad rows placed at radii in range [60,190] cm. Drift velocity is monitored by laser system[2] with precision $\approx 2 \times 10^{-4}$ providing systematic error in Z direction ≈ 400 μm at the maximum drift length ($\approx$2m).

Spatial resolutions:

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

Distortions due to non-perfect electric field and space charge collected in the TPC are monitored by DCA (distance of closest approach) of the track at the primary vertex and kept to the level better than $\approx 100\mu m$[3].

2.2. SVT- A 3 Layer Silicon Drift Detector

The SVT[4] shown in Fig.2 is the innermost tracking detector in STAR, with active elements at 6.5 to 15 cm radially from the interaction point. Two hybrids form a wafer, the wafers form a ladder, and the ladders are arranged in 3 barrels on two rigid clam-shells. The detector consists of 216 wafers in total. The SVT was primarily designed to do multi-strange particle physics. Electrons drift in $\rho\phi$ direction (perpendicular to TPC drift direction). Cathode strips are placed along Z (beam axis). The size of a virtual pixel is $\rho\phi \times Z = 250\ \mu m$ (time bin) $\times$ 250 μm (strip pitch). The intrinsic spatial resolution is (accounting for charge sharing): $\sigma_{\rho\phi} < 80\mu m$ 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 in STAR for Run II, and has been functional since Run III.

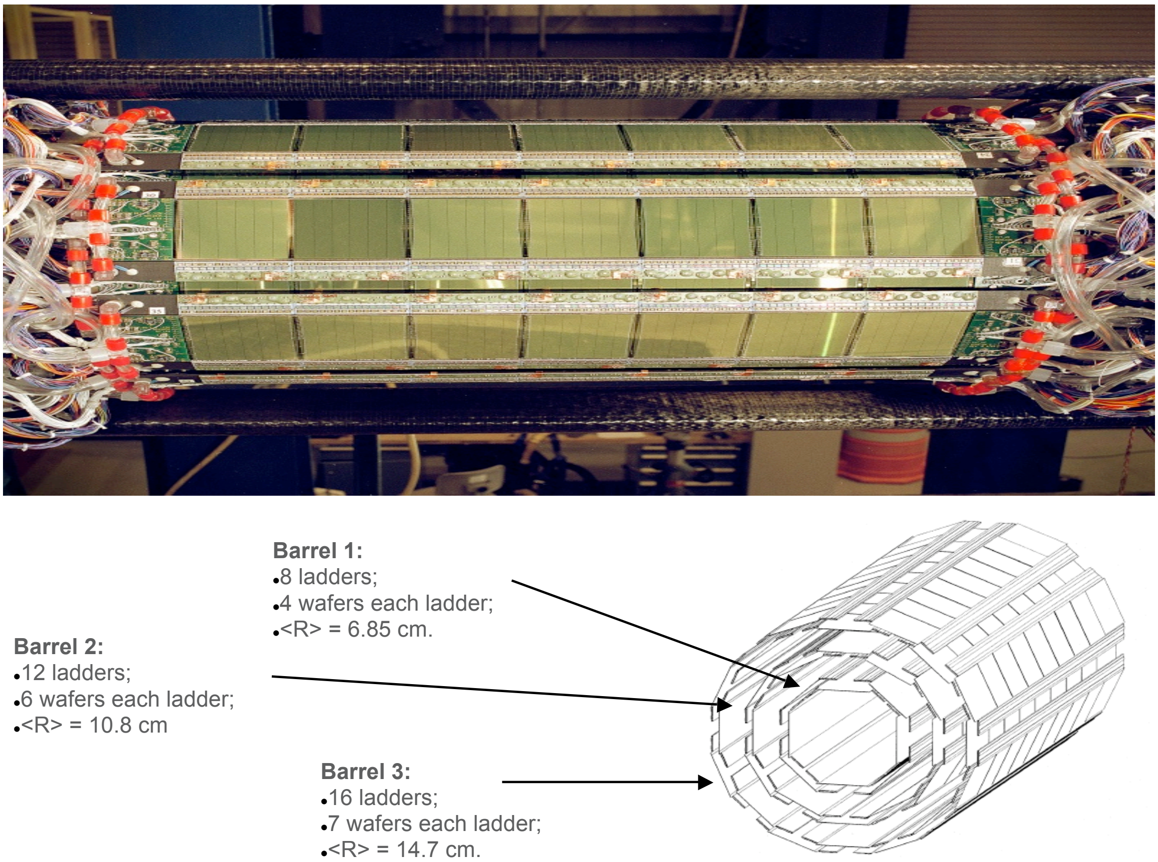

Figure 2. Silicon Drift Detector

2.3. SSD - A single layer of 2-side Silicon Strip Detector

The SSD[5] 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 $\approx$23 cm from the beam.

The SSD was installed in STAR for Run IV, and was fully functional in Run V. It has strip pitch: 95μm, strip length: 4cm, and stereo angle between p- and n-strips: 35mrad. Intrinsic resolution is better than $\approx$30 μm ($\rho\phi$)$\times$ 860 μm (Z). The SSD has a big advantage: non-drifting technology. Of course there is a Lorentz shift of holes and electrons in ($\rho\phi$) direction due to 5 kG magnetic field (with Lorentz $\Theta_{holes} = 4.4^o \rightarrow 4.4\mu m$ and $\Theta_{electrons} = 1.6^o \rightarrow 1.6\mu m$) which produces a sizable effect in Z direction ($\approx 200\mu m$) due to the stereo angle. But it is clear how to account for this effect.

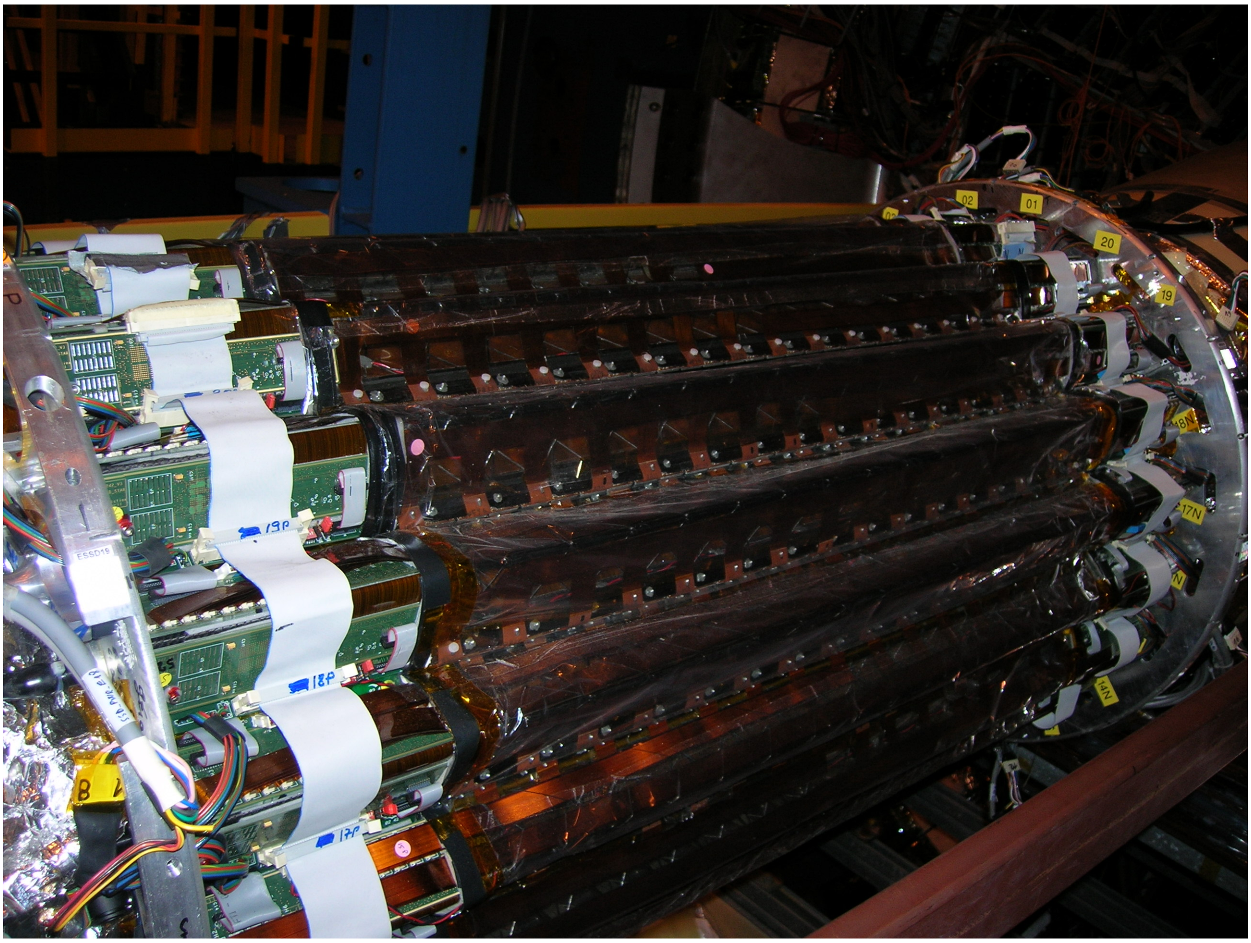

Figure 3. Silicon Strip Detector

3. Alignment and Calibration

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

Analysis of the first SVT data with respect to the TPC[6] has showed rather weak correlation between the data and SVT calibration and alignment done on test bench and clearly required re-calibration and re-alignment in situ. These re-calibration and alignment efforts for these two drifting detectors gave rather modest results: spatial resolution (including alignment) $\sigma_{\rho\phi} \approx \sigma_Z \approx 200\mu m$. However the achieved accuracy was not good enough to be used in heavy ion collision high track multiplicity environment due to a high ghosting level. We had to revisit this problem when the SSD came into the game.

3.2. New goals

The initial goal for the SVT was to measure Ξ and Ω particles, but this task has been largely accomplished with the TPC-only analysis. However there is much interest in direct charm measurements now. In Cu+Cu 200 GeV interactions (Run V) we have already observed ≈4 standard deviations of D0 signal. Thus it looks very attractive to set a worthy task to reduce background and enhance significance of the charm signal by a factor of ≈3-5 through use of the STAR inner silicon tracking system.A renewed effort started with SSD coming online. Alignment and drift velocity calibrations were re-visited to see if we are able to do some/any direct D-meson measurement and/or B-meson tagging.

3.3. Figures of merit for SVT/SSD precision

Pointing accuracy (aka impact parameter resolution, DCA resolution in bending XY ($\equiv \rho\phi$) plane: σ_{DCA} and resolution in non-bending plane: σ_Z) figure of merit for charm decay ($c\tau \approx 100\mu m$) registration with a vertex detector:

- $\sigma^2_{DCA} = \sigma^2_{vertex} + \sigma^2_{track} + \sigma^2_{MCS}$ (the same for non-bending plane)
- primary vertex resolution: $\sigma_{vertex} \approx 600\ \mu m/\sqrt{N_{goodtracks}}$, for central Au+Au collisions turns out to be better than 20 μm (for minimum biased events $\approx 100\mu m$),
- track pointing resolution: $\sigma_{track} \approx 2 \times \sigma_{XY}$ in our case, where σ_{XY} is intrinsic detector precision $\oplus$ alignment errors
- Multiple Coulomb Scattering (MCS): MCS $\approx 170\mu m$ / p(GeV/c) (from simple analytic estimations)

From the requirement that the track pointing resolution should be comparable with MCS @ 1 GeV/c it follows that detector resolution (including alignment) should be $\sigma_{XY} < 80\mu m$ and $\sigma_Z < 80\mu m$ for both bending and non-bending planes.

3.4. Methods

Methods can naturally be split into two parts:

- Calibration of SVT drift velocities on hybrid level, and
- Alignment of detectors assuming that wafer positions on ladder are frozen from survey data, i.e. 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, i.e. using 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 velocity per hybrid from 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 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. This is the sample which we are using for alignment

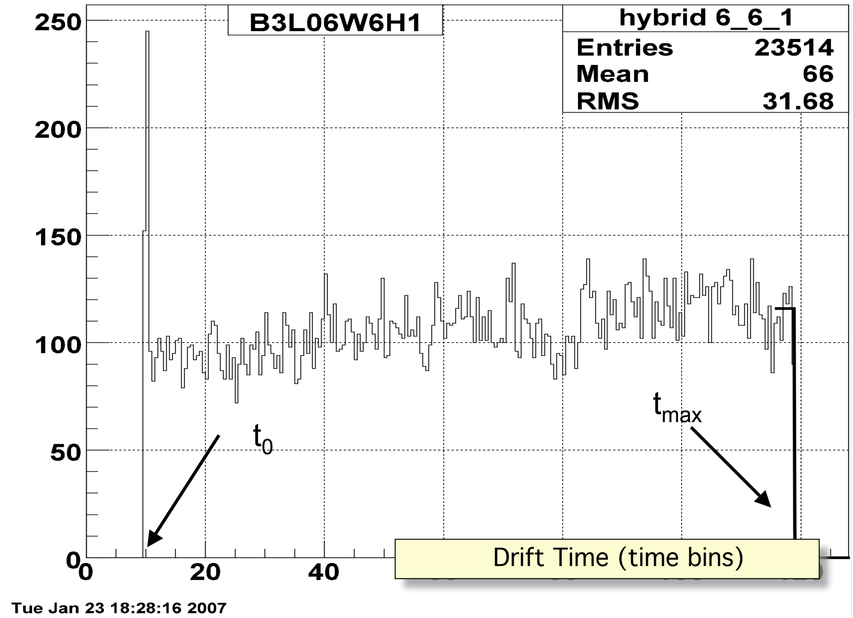

Figure 4. Drift time distribution used for average drift velocity estimation

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 (e.g. 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)
- Global alignment: $\vec{X}_{hit} - \vec{X} = \partial\vec{X}/\partial\vec{\Delta} \times \vec{\Delta} \equiv \mathbf{G} \times \vec{\Delta}$
- Local alignment[7]: $\vec{u_{hit}} - \vec{u} = \partial\vec{u}/\partial\vec{\delta} \times \vec{\delta} \equiv \mathbf{L} \times \vec{\delta}$
- Misalignment parameters have been calculated as slopes of straight line fits to histograms of the most probable deviations (X_{hit} - $\vec{X}$ or $\vec{u_{hit}} - \vec{u}$) versus the corresponding derivative matrix (G_{ij} or L_{ij}) component[8] (see examples in Figs. 5 and 6)
- For alignment we use good (with well defined parameters) tracks fitted with the primary vertex. Use of primary tracks significantly improves precision of track predictions in Silicon detectors and reduces influence of systematics
- Precision of the method is checked with simulation. Accuracy is $\approx$10 μm in a detector position and $\approx$0.1 mrad in its rotation
- There is a problem when a starting point is far from minimum because there are significant correlations among alignment parameters. To solve this problem as the starting point we use Least-Squares Fit with above derivatives to get first approximation for the parameters. The precision of this method is less than slopes method but it does provide a reasonable approximation to use slopes.

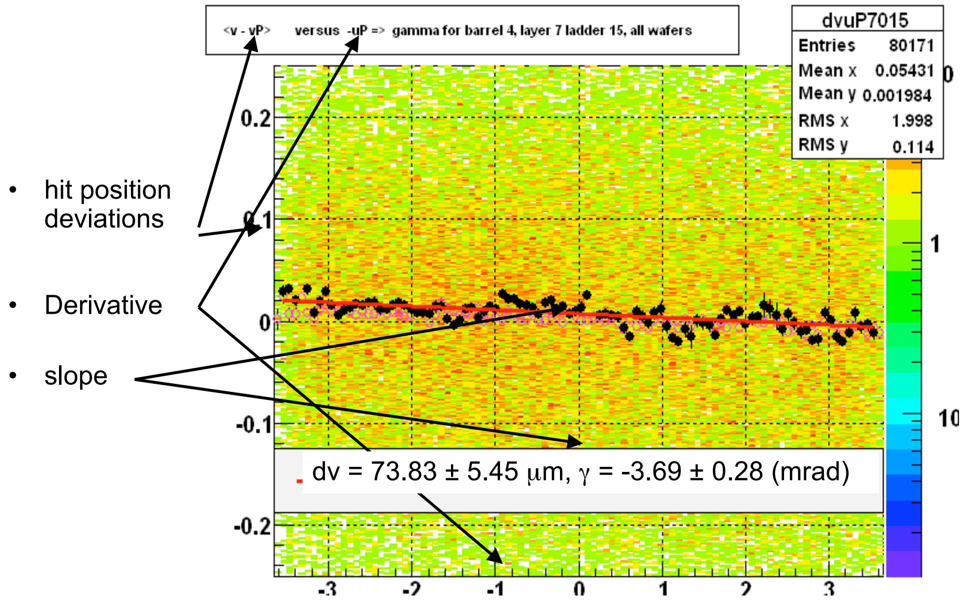

Figure 5. An other example of local alignment: γ (slope) is rotation around w ($\equiv$local Z) axis

3.4.3. Procedure includes 4 steps:

- Average SVT drift velocity: as the first approximation, average drift velocity for the SVT is obtained from charge step method for each hybrid.
- TPC-only tracks
  - Global alignment of SSD with respect to the TPC as whole
  - Global alignment of SSD sectors
  - Local alignment of SSD ladders. Individual Ladders showed translations up to $\approx 200\mu m$ and rotations (especially around y-axis) of up to $\approx$20mrad. After the SSD Ladder fine tuning, the majority of ladders had translational alignments calibrated to under $20\mu m$, and rotational alignment calibrated to within 0.5mrad, both of which were within errors of 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 have been re-fitted including extra dependence on drift distance and strip (up to 3rd degree Tchebyshev). This fit reduced hit residuals from $\approx$100 μm to $\approx$10 μm.
- TPC + SSD + SVT tracks
  - Check consistency
  - Reevaluate SVT and SSD hit errors

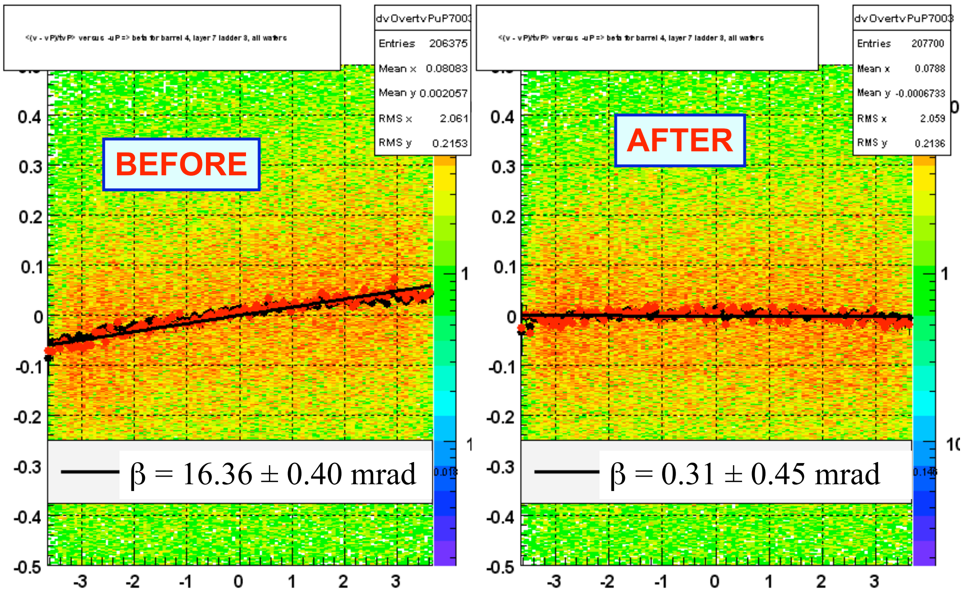

Figure 6. Example of correcting a SSD individual ladder rotation (β) around the v-axis (local Y). The lines represent the results of linear fit with slope parameters corresponding to the measurement misalignment (β). Shown are the slopes β measured **BEFORE** and **AFTER** applying correction.

4. Results

4.1. SVT/SSD resolutions after calibration/alignment

The quality of calibration/alignment procedure for Run V has been estimated from hit pull analysis on track fits, and the spatial resolution estimated by requirement to have pull standard deviation equal to 1 (averaged over 3 samples: 62 GeV Forward Magnetic Field, 200 GeV Reverse and Forward Magnetic Field). Results are as follows:

- SVT resolution: $\sigma_{\rho\phi} = 49 \pm 5\ \mu m$, and $\sigma_Z = 30 \pm 7\ \mu m$
- SSD resolution: $\sigma_{\rho\phi} = 30\ \mu m$ (set to design value since $\ll$ MCS), $\sigma_Z = 742 \pm 41\ \mu m$

4.2. DCA resolution

Pointing (DCA) resolution has been estimated as standard deviation of global track DCA with respect to the primary vertex and shown in Fig.7. With increasing numbers of fitted Silicon points it is improved by about an order of magnitude. The estimated DCA resolution at momentum 1 GeV/c is summarized in table 1. Contribution from tracking (constant term) is comparable with MCS @ 1 GeV/c. Thus we have reached our desired goal!

5. Conclusions

- Recent interest in charm physics has re-focused STAR's interest in its vertex detectors.

Table 1. DCA resolution versus no. of Silicon points in track fit

Number of Silicon Points fitted to track	σ_{XY}@1GeV/c (μm)	σ_Z @1GeV/c (μm)
• 0 - TPC-only	3350	1884
• 1 - TPC+SSD	967	993
• 2 - TPC+SSD+SVT	383	351
• 3 - TPC+SSD+SVT	296	232
• 4 - TPC+SSD+SVT	281	212

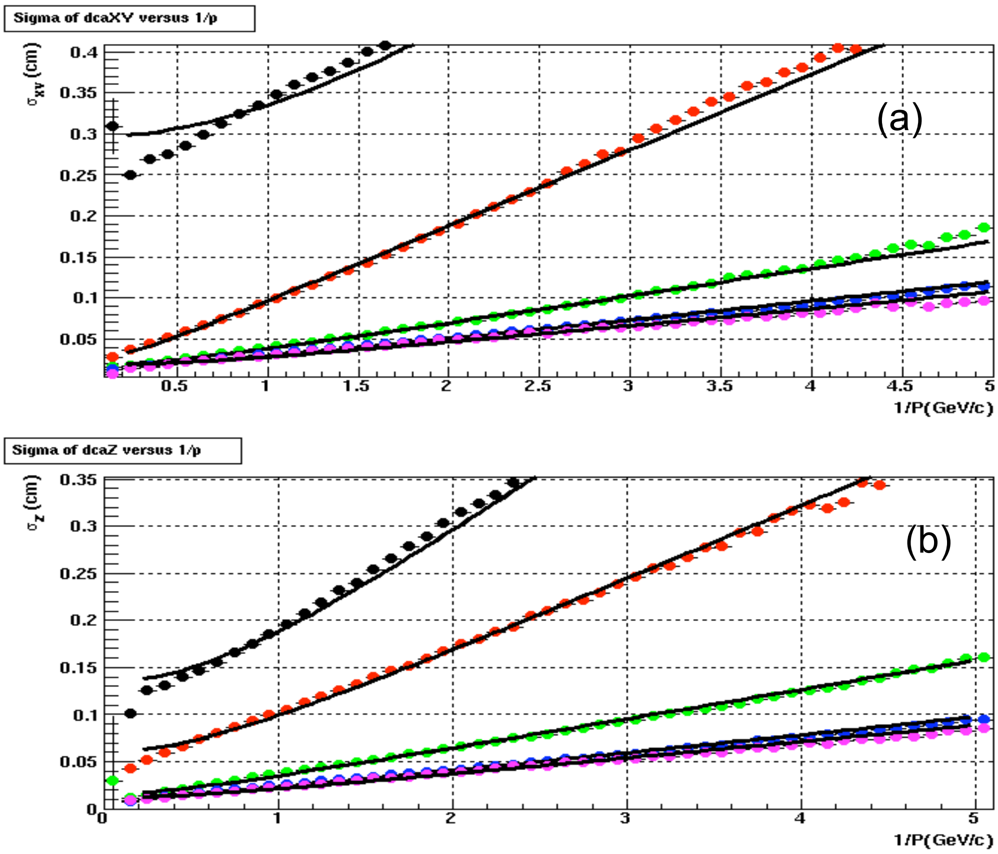

Figure 7. Pointing precision for global track with respect to the primary vertex in the bending (a) and non-bending (b) planes for tracks with various numbers of silicon hits (see table 1 for the corresponding markers).

- The presence of drift silicon (SVT) technology complicates the alignment task but also presence of non-drifting detectors (like SSD) improve the situation drastically.
- Our alignment approach and techniques were successful to overall shifts better than 20 μm which is sufficient for this device.
- Calibration/alignment procedure for Run V (Cu+Cu) has been completed, data has been re-processed, and data analyses are under way.

- Calibration/alignment procedure for Run VII (Au+Au 200 GeV) is under way.
- First physics checks (Run V) look fine. Silicon detectors:
  - improve momentum resolution for global tracks,
  - improve primary vertex resolution,
  - greatly improve track selection (based on DCA),
  - sharpen (multi-)strangeness physics, and
  - provide other non-physics side benefits: Use of the SVT and SSD as a high resolution microscope to undo TPC distortions and as a distortion monitor in high luminosity runs.
- STAR Silicon Vertex Tracker and Silicon Strip Detector are sharpening our physics.

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

6.1. Misalignment of the detector in Global Coordinate System (GCS)

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

$$\vec{X}_{hit} - \vec{X} = \partial\vec{X}/\partial\vec{\Delta} \equiv \mathbf{G} \times \vec{\Delta}\mathbf{G} =$$

$$\begin{pmatrix} -1 + j_x v_x & j_x v_y & j_x v_z & j_x(-v_y z + v_z y) & -z + j_x(v_x z - v_z x) & y + j_x(-v_x y + v_y x) \\ j_y v_x & -1 + j_y v_y & j_y v_z & z + j_y(-v_y z + v_z y) & j_y(v_x z - v_z x) & -x + j_y(-v_x y + v_y x) \\ j_z v_x & j_z v_y & -1 + j_z v_z & -y + j_z(-v_y z + v_z y) & x + j_z(v_x z - v_y x) & j_z(-v_x y + v_y x) \end{pmatrix} \vec{\Delta}$$

6.2. Misalignment of the detector in Local Coordinate System (LCS)

- $\vec{u} = (u, \, v, \, w \equiv 0)$ - track prediction in LCS on measurement plane
- $(t_u, \, t_v)$ - track direction tangents in Local Coordinate system (LCS) on measurement plane
- $\vec{u}_{hit} = (u_{hit}, \, v_{hit})$ - hit position in LCS on 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 axises, respectively

$$\vec{u}_{hit} - \vec{u} = \partial\vec{u}/\partial\vec{\delta} \equiv \mathbf{L} \cdot \vec{\delta} = \begin{pmatrix} -1 & 0 & t_u & t_u v & -t_u u & v \\ 0 & -1 & t_v & t_v v & -t_v u & -u \end{pmatrix} \vec{\delta} =$$

$$\begin{pmatrix} u_{hit} - u \\ v_{hit} - v \end{pmatrix} = \begin{pmatrix} -\delta_u + t_u(\delta_w + v\delta_\alpha - u\delta_\beta) + v\delta_\gamma \\ -\delta_v + t_v(\delta_w + v\delta_\alpha - u\delta_\beta) - u\delta_\gamma \end{pmatrix}$$

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