СООБЩЕНИЯ
ОБЪЕДИНЕННОГО
ИНСТИТУТА
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

99-60

E10-99-60

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STAR/SVT ALIGNMENT
WITHIN A FINITE MAGNETIC FIELD

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1999

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Геометрическая калибровка детектора STAR/SVT
в магнитном поле

Представлены результаты разработки части математического обеспечения для STAR/SVT детектора, которая предназначена для определения относительных положений кремниевого вершинного детектора и времяпроекционной камеры, и геометрической калибровки компонент SVT. Разработанные процедуры дополняют процедуру локальной геометрической калибровки SVT, описанную в сообщении STAR-коллаборации (STAR Note 356). Алгоритмы калибровки основаны на использовании реконструированных треков частиц в обоих (SVT и TPC) детекторах в событиях, произошедших при номинальной напряженности магнитного поля. Описываются как математическая сторона проблемы, так и исследование возможностей предлагаемых алгоритмов. Результаты исследований говорят о возможности успешного применения разработанных методов как для относительной SVT-TPC калибровки, так и для определения положения составных частей внутри вершинного детектора.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна, 1999

Barannikova O.Yu. et al. E10-99-60
STAR/SVT Alignment within a Finite Magnetic Field

We report on the development of SVT (Silicon Vertex Tracker) software for the purpose of the SVT and TPC (Time Projective Chamber) relative alignment as well as the internal alignment of the SVT components. The alignment procedure described in this document complements the internal SVT alignment procedure discussed in Star Note 356. It involves track reconstruction in both the Star TPC and SVT for the calibration of the SVT geometry in the presence of a finite magnetic field. This new software has been integrated under the package SAL already running under STAF. Both the implementation and the performance of the alignment algorithm are described. We find that the current software implementation in SAL should enable a very satisfactory internal SVT alignment as well as an excellent SVT to TPC relative alignment.

The investigation has been performed at the Laboratory of High Energies, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna, 1999

1 Introduction

By the very nature of the mechanical support cone of the SVT, it will be impossible to obtain, on hardware installation, a perfect positioning of the SVT detector and its 216 wafer components in their designed positions and orientations. One expects that the actual positions and orientations may deviate by few tens of microns and tens of milli-radians respectively from the nominal positions/orientations. Moreover, given the detector location within the TPC, a detailed and accurate detector position survey will also be difficult. A measurement of the actual wafer positions and orientations after the STAR SVT detector is rolled into its data data-taking position should thus be derived from data taken with the detector in-situ. We envision the full SVT alignment can be done in three stages. The first stage consists of a preliminary local alignment without magnetic field. The second stage involves the global SVT alignment relative to the TPC whereas the third and last stage provides for final or fine tuning of the detectors relative and absolute positions within the TPC and the magnet. The first stage of the analysis is discussed in detail in Star Note 365[2]. In this note, we assume the first stage of the analysis is satisfactorily completed and proceed to discuss the last two stages only of the alignment procedure. The software described in this note is written in C++ and integrated to the already existing SVT software package SAL (SVT ALignment package) running under the Star shell analysis framework STAF.

The last two stages of the SVT alignment involve track reconstruction in a magnetic field. One wishes to establish with good accuracy the relative position of the SVT and the TPC as well as their orientation relative to the Star Magnet solenoidal field. The track driven alignment reconstruction procedure is based on the assumption that the magnetic field is sufficiently uniform so one can assume it is purely longitudinal with no significant transverse component. Trajectory of particles with sufficiently high momentum should then be well described, on the average, with a simple helicoidal track model. The use of such a track model and the availability of a large number of tracks in each Au+Au collision should, in principle, enable an excellent set of external constraints for the determination of the detector alignment parameters. In practice, one must recognize that the SVT detector consists of only three layers, and that with three points (from the three layers) one cannot unambiguously determine both the particle trajectories and the detector wafer positions and orientations. It is thus necessary to obtain the track parameters from a reliable external source. The procedure developed in this work consists in finding the accurate and precise relative position and orientation of the SVT and TPC (second alignment stage) so one can use, in the last stage, the TPC track data to determine the the helicoidal track parameters (magnetic rigity, curvature, etc) in order to constrain the SVT alignment.

2 Alignment Method

The alignment proceeds on the basis of reconstructed tracks extracted from Au+Au central events for a finite set of events. Strictly speaking, the events need not be central or of any particular range of centrality. It is intuitively clear however that, provided they can be tracked, events of high track multiplicity should enable a more accurate and faster alignment. The alignment procedure described in this work has so far beenlimited to a small set of central events. This restriction arise mainly because of various resource limitations in the generation of the faked events. In the future, we expect such limitations to disappear and one should be able to use an arbitrarily large number of events to conduct simulations or perform the actual alignment procedure.

The alignment of the SVT in a non zero magnetic field requires, as stated in the introduction, knowledge of the track parameters based on the TPC track reconstruction. One must then reconstruct the tracks in both the TPC and the SVT and match the SVT tracks to TPC tracks in order to determine their kinematic parameters. The track reconstruction are realized with the "stk_track" and "tptrack" packages for the SVT and TPC respectively[1, 3]. The track parameters used as an input to the alignment package use the nominal table format of the "stk_track" and "tptrack" packages. In addition, one also needs an estimate of the main vertex of each event to begin the alignment procedure. The vertex position is determined with the special module. One uses as input to the alignment package the global vertex table.

2.1 Geometrical Conventions

We first consider the global alignment task. The problem consists in determining the position of the SVT relative to the TPC, and finding the orientation of the SVT relative to the TPC and the solenoidal field. One should point out that the actual position of the origin of the coordinate system is somewhat immaterial and unimportant. However, in so far as one use a simple helicoidal track model and express the longitudinal motion (i.e. the motion along the field) strictly in function of the "z" coordinate, the choice of longitudinal axis does bear an impact on the track reconstruction quality and will be considered below in more detail.

The origin of the SVT coordinate system is chosen as the geometrical center of the SVT. The axes of the SVT reference frame are chosen such that 'z" is along the beam direction,"x" is in the horizontal plane pointing outward from the center of the RHIC ring, and "y" is such that it forms a right-handed (x, y, z) triplet. Likewise one expresses position measurements in the TPC coordinate frame relative to the geometrical center of the TPC and along three axes x, y, and z chosen with the same definition. The position of the TPC origin is expressed relative to the SVT origin by means of three translations "ΔX", "ΔY", "ΔZ" along the "x", "y", and "z" axes respectively. The relative orientation of the TPC and SVT coordinate frame is expressed with three rotation angles α, β, γ.

Next, we consider the geometrical convention for the local alignment. The local alignment of the SVT wafers requires a transformation of the hit positions measured in the local coordinate frame of the various wafers to the global SVT reference frame. We define local reference frames for each wafer as follows . The origin of the frame is chosen as the geometrical center of the wafer. "x" is chosen to be the drift direction, "y" is measured along the wafer anode direction, and "z" is normal to the wafer and points radially outward from the SVT. The nominal position of the ith wafers (i=1,:,216) in the SVT global coordinate frame is $\mathbf{W_{o,i}}$, and the orientation of the local frame relative to the global frame is given by a set of euler angles $\theta_\mathbf{i}$. In principle, the actual position and orientation of the wafers differs very little from their nominal position. The difference can thus be expressed in the reference frame of each wafer as a set of three translations $(\Delta x, \Delta y, \Delta z)$, and a set of three rotation angles (α, β, γ). These three angles measure rotations around the "z", "x", and "y" axis respectively.

Both alignment tasks require a good matching quality. A relative shift of the SVT and TPC as small as $\pm 1mm$ (and maybe more) can lead to the loss of a considerable number of tracks and in turn to a substantial degradation of the alignment accuracy. Both detectors should report the same event vertex position and the same track parameters for a given particle. Since the SVT vertex and angular resolutions are expected to be superior to that of the TPC, one should use the vertex and orientation data of the SVT as reference and make sure the SVT reported vertex and track positions lie inside the TPC positions/errors. Since in both tasks the alignment is taken according to various comparisons and calculations, one must insure that these actions are consistent. We assume that using the information about vertices obtained separately from the SVT and TPC (i.e. the average difference between the vertices $\vec{V_s}$ and $\vec{V_t}$), accumulated over a large sample of events, reflects the spacial translation of the two systems relative to each other with sufficient accuracy (tens of microns). So we assume that residual misalignments do not essentially affect the correct TPC to SVT track matching.

The relative alignment procedure is a statistical process based on a very large number of tracks and independent events (collisions). One proceeds to analyze a large number of events and calculate, for each event, the SVT $(\vec{V_s})$ and TPC primary vertex positions $(\vec{V_t})$ as well as the tracks three director cosines measured by the SVT $(\hat{e}_s)$, and by the TPC $(\hat{e}_t)$.

We assume the magnetic field is perfectly uniform in the fiducial volume of the Detector and that particle energy losses due to multiple scattering can be neglected. Because geometrical calibration package for magnetic field 'on' implies the usage of information obtained from processing TPC data, the input data of SAL-package is correlated with the output of TPC tracking package, i.e. with data in tptrack table format.

TPC tracking team supposes to use the following helix parametrization [3]:

The trajectory of a particle in a static uniform magnetic field with a field vector parallel to the z-axis is a helix with an axis along the field lines. The helix can be parametrized as follows:

$$x(s) = x_0 + R_H \left[cos \left(\Phi_0 + \frac{hscos\lambda}{R_H} \right) - cos\Phi_0 \right],$$

$$y(s) = y_0 + R_H \left[sin \left(\Phi_0 + \frac{hssin\lambda}{R_H} \right) - cos\Phi_0 \right],$$

$$z(s) = z_0 + ssin\lambda$$

where: - s is the path length along the helix. It increases when moving in the direction of the particle's momentum vector.

- (x_0, y_0, z_0) are the coordinates of the starting point of the helix. This is where $s = s_0 = 0$.

- λ is the slope of the helix, also referred to as the dip angle. This is equal to the $arcsin\frac{dz}{ds}$, where $-\pi/2 < \lambda <= \pi/2$.

- R_H is the radius of the helix. This is given by expression:

$$R_H = \frac{P cos\lambda}{|qBk|} = \frac{1}{\left(\frac{1}{p_t}\right) \times 0.001499}$$

with the standard STAR magnetic field.
- k is the conversion factor. If the radius is in units of centimeters, the magnetic field is in units of kiloGauss, and the momentum is in units of GeV, $k = 0.00003$.
- B is the value of the magnetic filed parallel to the z-axis.
- q is the charge of the particle.
- h is the sense of rotation of the projected helix in the xy plane. This is equal to $sign(qB) = sign(dy/ds)$.
- y is the azimuthal angle of the momentum.
- z is the polar axis parallel to the helix axis.
- Φ_0 is the azimuthal angle of the starting point of the helix in cylindrical coordinates with respect to the helix axis. This is equivalent to $\Phi 0 = Y - h\pi/2$.
- Y is arctan(dy/dz)s=0. This is the azimuthal angle of the track direction at the starting point of the helix.

(For more detaliled description of the helix parameters, see [4].)

The circle fit used in TPC tracking returns the center of the fitted circle as the coordinates (xc, yc) along with the value of Rh. The linear fit returns the values of z_0 and $tan(\lambda)$. In order to calculate the parameters to be placed into the tptrack table, the starting point of the helix was determined. In order to facilitate track matching to the SVT, it is logical to select a point closest to the SVT. Therefore, the azimuthal angle in the helix coordinate system for the point closest to the TPC inner field cage is evaluated as follows:

$$\Phi_0 = arctan(\frac{y_1 - y_c}{x_1 - x_c})$$

where $(x1, y1)$ are the coordinates of the closest TPC point. A point on the fitted track is selected by evaluating:

$$x_0 = x_c + R_H cos\Phi_0, \quad and \quad y_0 = y_c + R_H sin\Phi_0.$$

The elements used in the tptrack table are then evaluated:

$$r_0 = \sqrt{x_0^2 + y_0^2}, \quad \phi_0 = arctan\left(\frac{y_0}{x_0}\right), \quad \psi = \Phi_0 + \frac{h\pi}{2},$$

$$p_t = R_H \times |qBk|, \quad p_z = p_t tan\lambda, \quad and \ p = \sqrt{p_t^2 + p_z^2}.$$

Using this information it is easy to get all the necessary parameters of the simple helicoidal representation used in SAL-package for geometrical calibration. This representation of particle trajectories is used as follows:

$$\begin{aligned} R_{Hi}^2 &= (x - x_{ci})^2 + (y - y_{ci})^2, & (1) \\ z &= z_{0i} + L\, tg(\psi_i). & (2) \end{aligned}$$

The motion is represented as a perfect circle in the transverse plane and as a straight line in the $zvs\psi_i$ plane.
- R_{Hi} is the radius of the circle corresponding to the ith track (radius of the helix),
- (x_{ci}, y_{ci}) is its origin,
- z_{0i} is the z-coordinate of a helix point closest to the beam axis.
- L is the trajectory path length measured between z_{0i} and the point (x, y, z),
- ψ_i is an angle reflecting the particle motion in the transverse plane. It, too, is measured from the closest Helix point to the beam axis.

One has by construction:

$$tg(\psi_i) = \frac{\vec{P_i} \cdot \hat{z}}{\sqrt{(\vec{P_i} \cdot \hat{x})^2 + (\vec{P_i} \cdot \hat{y})^2}}, \qquad (3)$$

Quite evidently, the model, as expressed above, is strictly valid only if the direction of the "z" axis strictly coincides with the direction of the solenoidal field. One thus expects poor track chi-square fits until the SVT alignment is properly completed.

The alignment is achieved through the minimization of a global alignment functional defined as follows:

$$G = \sum_{\alpha=1}^{N_{events}} \frac{\sum_{i=1}^{N_t} \sum_{j=1}^{3} (A_{i,j}^2 + B_{i,j}^2)}{N_t}, \tag{4}$$

where

$$A_{i,j} = \sqrt{(x_j - x_{ci})^2 + (y_j - y_{ci})^2} - R_{Hi}$$

- corresponds to the distance between SVT hit and helix in the ortogonal to beam plane.

$$B_{i,j} = z_j - z_{0i} - tan(\psi_i)L$$

corresponds to the distance between hit and helix along z direction.

The path L is calculated by means of the cosine theorem, as illustrated in Fig. 1.

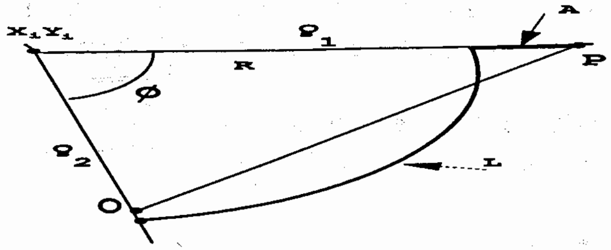

Figure 1: Definition of the track length.

$$L = \phi R_{Hi} = acos(\varrho_1^2 + \varrho_2^2 - \frac{x_j^2 + y_j^2}{2\varrho_1\varrho_2})R_i \tag{5}$$

where

$$\varrho_1 = R_i + A_{i,j}, \quad \varrho_2 = \sqrt{x_{ci}^2 + y_{ci}^2}$$

The functional G is constructed in such a way that large functional values reflect poor alignment and small values good alignment. It is minimized by operating a steepest gradient descent search in the space of detector positional and angular parameters (which is described in [2] in more detail).

For each iteration of this method all the parameters are recalculated according to the corresponding partial derivative values.

The steepest descent procedure is iterated while the track χ^2 and the global alignment functional keep decreasing. The track χ^2 is calculated using:

$$\chi^2 = \sum_{i=1}^{3} \frac{A_{i,j}^2 + B_{i,j}^2}{\sigma_i^2}. \tag{6}$$

In this expression, σ_i represents the estimated error on the track parameter. It is determined via an average procedure as follows. Using HIJING events, we propagated the tracks with GSTAR and determined the average track deviation, $\sigma_{avg,i}$ due to MCS on each SVT layer.

Tracks had momenta ranging from < 100 MeV/c to a few GeV/c. The average deviation obtained with GSTAR amounts to a value of $81.3\mu m$ and is used in the calculation of Eq. 3.

The alignment procedure is interrupted when the variation of alignment parameters leads to no significant improvement of the tracks χ^2, i.e.when χ^2 reaches a stable minimum.

Indeed, the procedure is interrupted when common iteration step reaches some fixed critical value (because the steps and weight values for parameter category are selected in such a way that the difference of their influence on χ^2 is minimized, it is enough to watch just the common iteration step). The critical value of the iteration step is chosen so that the influence of the strongest parameter becomes commensurable with χ^2 definition error.

3 Results

We have studied the performance of both stages of the alignment separately in oder to optimize and evaluate each stage separately. The results of relative and local alignments represented in sections 4.1 and 4.2 respectively.

3.1 SVT - TPC relative alignment

To study capabilities of the alignment procedure we simulated translations of the whole SVT in the range $\pm 100 \mu m$, and rotationsin the range of ±10 mili-radian. The effect of rotational misalignment can be particularly dramatic. For example, an azimuthalmisalignment of ±5 milli-radians corresponds to a positional shift of $\pm 300 \mu m$, $\pm 700 \mu m$ for wafers on the first and third layers respectively. Given such a large positional shift of the third layer, the SVT-TPC track matching may be significantly affected and a large number of tracks may not be reconstructed at all. The alignment procedure then relies on a small fraction of the tracks and can be potentially quite biased. It thus becomes necessary to divide alignment procedure described above into two steps. In a first step, we perform a preliminary alignment of rotational parameters only. When such a preliminary alignment is completed, the same steepest descent algorithm is used while including both translational and rotational alignment parameters simultaneously.

A very good reconstruction accuracy is obtained for global parameter definition (see Fig. 2). Such success can be attributed to the relatively small number parameters and large number of track, because for the global alignment task all tracks from all treated events are used for parameters definition simultaneously. To obtain distributions of parameters errors represented in Fig. 2 we simulated 100 different sets of misalignment parameters, and restore the geometry using 10 Monte Carlo simulated events for every set.

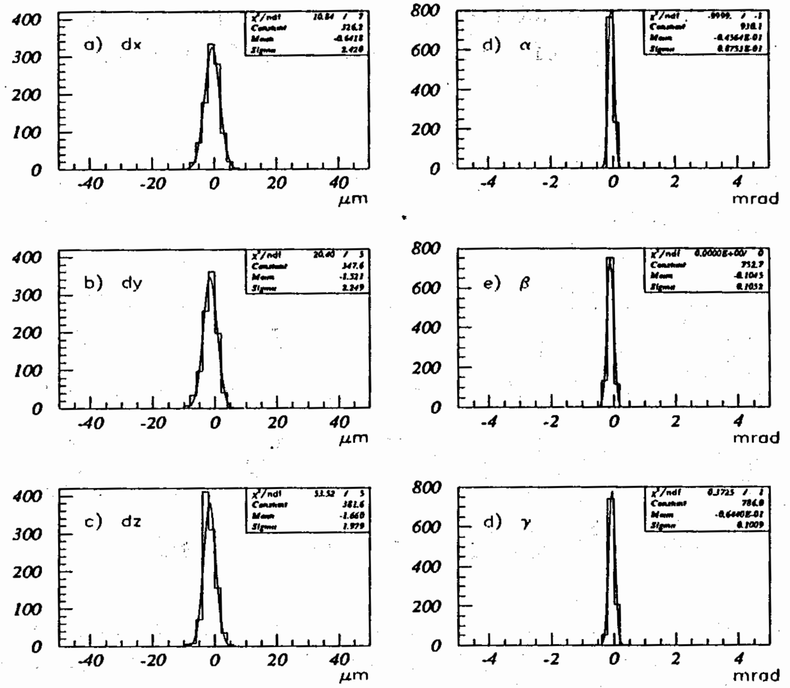

Figure 2: Precision of the whole SVT position determination $(B > 0)$.

The figure (Fig. 3) show the same results: the mean value and the shape of functional distribution are practically the same for ideal geometry and after geometry calibration. Because the functional was composed in such a way that its minimum corresponds to ideal geometry , and thus to correct coordinate recalculation, similarity of these two distributions means that the hit global coordinate calculations are done correctly. So the global alignment procedure realized in SAL - package (based on TPC data) allows to get alignment parameter estimation, which restores the relative position of SVT and TPC detectors with high precision.

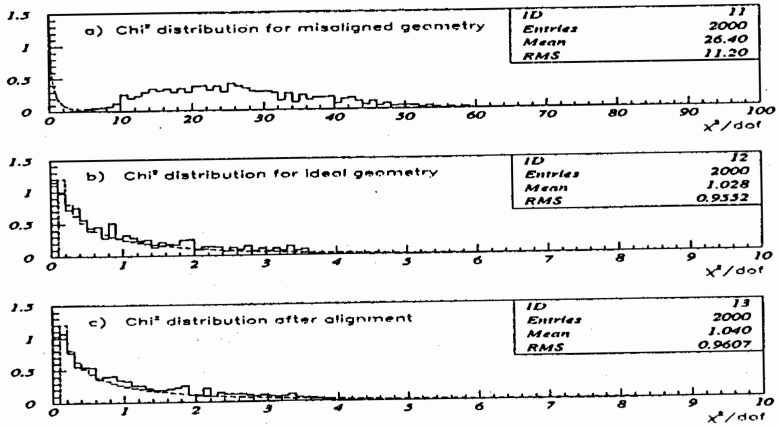

Figure 3: Tracks χ^2 distribution for simulated SVT related to TPC misalignment geometry (*a*), ideal geometry (*b*) и reconstructed geometry (*c*). Doshed line show the theoretical curve.

3.2 Local alignment within magnetic field

To evaluate local alignment quality in conditions of magnetic field 'ON' we used the same two criteria : the comparison of χ^2 distributions (before and after calibration) with the ideal one; and the investigation of parameter error distributions. For SVT local alignment procedure without magnetic field we obtained the following parameter definition errors for the set of 10 GSTAR events (table 1, see [2])

We expected that using the track momentum information from the TPC improves the accuracy of the wafer position determination. Because the precision of momentum definition in TPC is very high, track parameters can be defined more accurately than in case of using only SVT hit coordinates(like in case of local SVT alignment without magnetic field, for this task SVT wafer

Table 1: Precision of the wafers position determination ($B = 0$)

σ_x	σ_y	σ_z	σ_α	σ_β	σ_γ
11.8	8.0	12.9	0.5	1.0	1.2
μm			*mrad*		

misalignment directly influences track parameter definition.

But after first tests (the results of which are shown on Fig. 4) it's not happened. During minimization functional reached the stable minimum, close to the functional value for ideal geometry (the difference between the mean values was less than 5% , in comparison with 11% for magnetic field 'off'). That means that SVT points the helices, parametrized by TPC data. So we expected that parameter definition errors would be sufficiently lower than that represented in table 1. The errors obtained in the first tests are shown in table 2:

Table 2: First results of the wafers position determination ($B > 0$)

σ_x	σ_y	σ_z	σ_α	σ_β	σ_γ
33.9	12.2	36.2	0.9	1.1	1.8
μm			*mrad*		

The rotation parameters errors are practically the same as for the local alignment without magnetic field, and translation parameters errors are about 3 time larger than for 1-st alignment stage (see [2]).

Another unexpected result was that the X, Y and Z parameter errors we obtained distinguishconsiderably as it easy to see from table2. But investigation of the different parameters category influence on the functional behavior has shown that these accuracies should be practically equal.

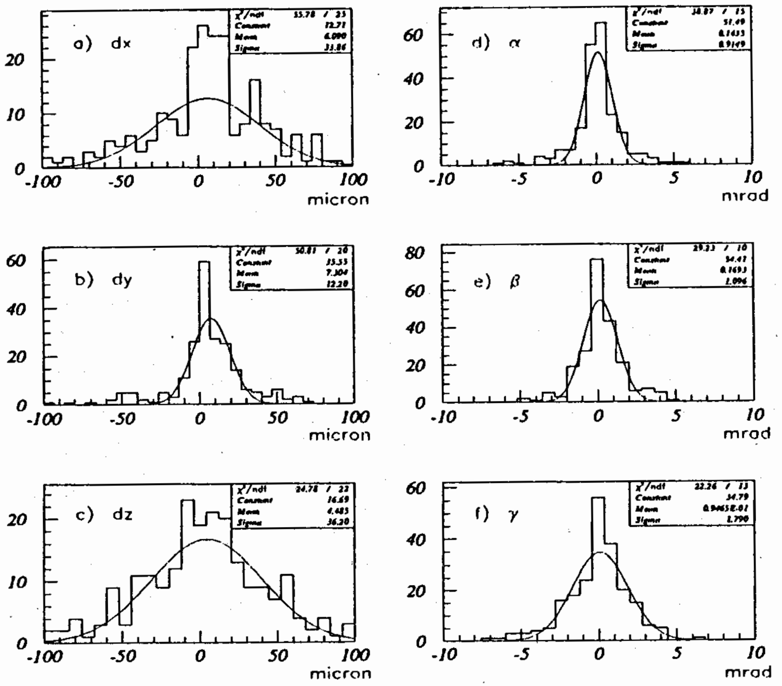

Figure 4: Distributions of the alignment parameters errors ($B = 0$) obtained after first tests.

The further studies showed the existence of a correlation between dz and dx parameters for wafers, which are placed far from vertex (see Fig. 5). This correlation completely disappears if one treats the events origin from vertices, arranged exactly under wafer (see Fig. 6).

Therefore for improving of the precision of misalignment parameters definition one needs to consider events with vertices which placed in the range of $\pm 9cm$ along Z-axis instead of those in the range of $\pm 3cm$ as we had for 1-st stage citelocal. In case of wide vertex region the correlation problem is practically solved and errors become smaller (see Fig. 7).

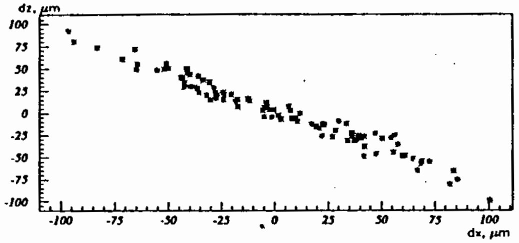

Figure 5: $\Delta z \Delta x$ correlation for waffers, which are placed far from detector center.

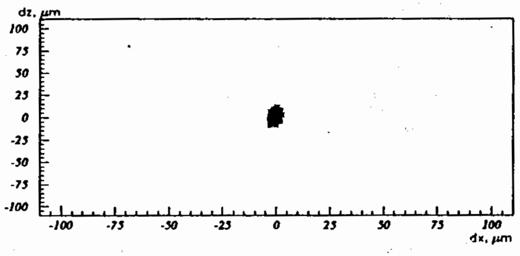

Figure 6: $\Delta z \Delta x$ distribution for data set with vertecies placed in the region $\pm 9cm$.

Nevertheless for the 1-st and last wafers from the 2-nd layer, and for the two first and two last wafers from the 3-rd layer the correlation between dx and dz parameters is still an unsolved problem. However for these wafers the alignment can still be done. dz and dx parameters can just compensate each other, which also leads to good functional minima. In Fig. 8,*a* one can see, that the presence of misalignment causes to significant increasing of a tracks residue. But after alignment (Fig. 8,*b*) the average value and shape of χ^2 distribution is very similar with χ^2 distribution for the ideal geometry (showed by dashed line in the same figure). The distinguish between average χ^2 values is less then 1%. The existence of such correlation don't prevent to carry out a good matching.

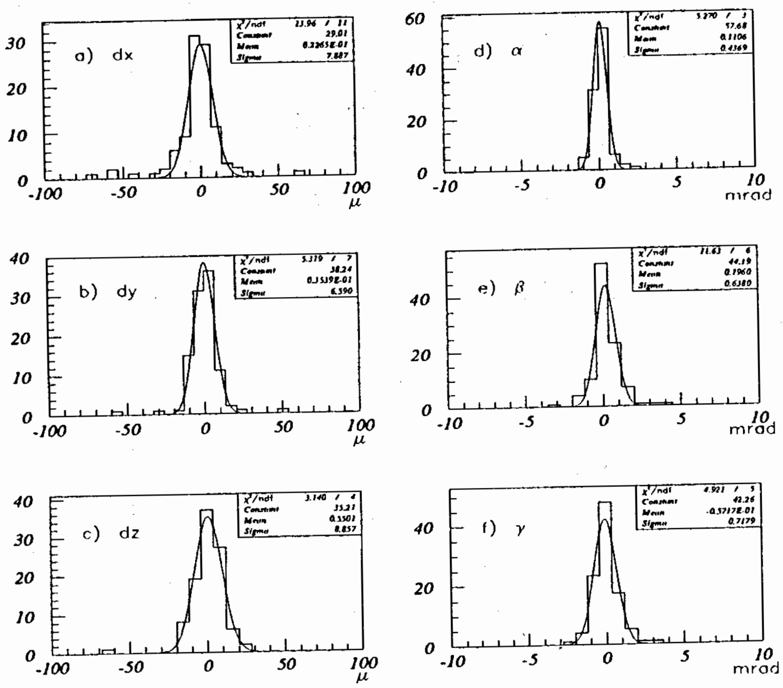

Figure 7: Parameter definition erorrs for local alignment.

4 Conclusion

Detector geometry calibration is an important part of preliminary stage of any experiment data treatment in elementary particle physics, because wrong transformation of data read out from detectors to some common global coordinate system may lead to significant errors even with very high resolution detectors.

The worked out alignment package is supposed to be used for definition of relative positioning of wafers within SVT as well as for definition of the whole SVT position relative to TPC. The precision study of the suggested algorithms was done with the GSTAR simulated events. The obtained results show a good per-

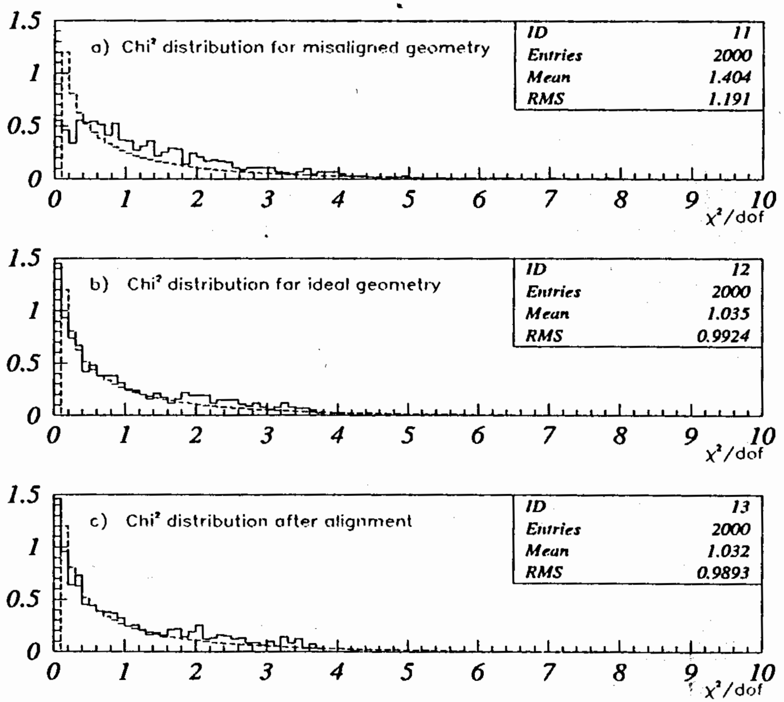

Figure 8: Tracks χ^2 distribution for misaligned geometry (*a*), ideal geometry (*b*) and reconstructed geometry (*c*). The doshed line show the theoretical curve.

Table 3: Precision of the detectors position determination ($B > 0$)

DETECTOR	σ_x	σ_y	σ_z	σ_α	σ_β	σ_γ
WAFERS	7.9	6.6	8.9	0.4	0.6	0.7
SVT	2.4	2.2	2.0	0.1	0.1	0.1
	μm			$mrad$		

spective of using these algorithms in real data treatment. The values of the sensitive to misalignment functional obtained in minimization differ form the ideal ones by less than 1% for the local alignment and less than 0.6% for global one. The obtained errors of geometry position definition for wafers (see table 3) as well as for the whole SVT are sufficiently lower than the resolution of the SDD itself.

References

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[2] SVT Internal Alignment Package, Starnote-0356, 1998.

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Received by Publishing Department
on March 12, 1999.