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ALIGNMENT OF DETECTORS AT CERES/NA45

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Introduction

In this note the problem of alignment (accurate positioning) of Silicon Drift Detectors (SDD) within Silicon Vertex Telescope (SVT) system and alignment influence on the matching quality at the CERES experiment is addressed. It is well known that most of measurements are significantly affected by misalignment caused by numerous physical effects (thermal expansion, misplacing and stress during insertion, magnetic field effects, etc.). Until the present time there exited the system of heuristical geometry corrections. This system fitted for data ensemble of 1995 could not be applied for ensemble of 1996. This was the reason for working out of the represented alignment algorithm.

The CERES experiment at the CERN Super Proton Synchrotron (SPS) studies the electron-positron pairs produced in hadron-nucleus and nucleus-nucleus collisions. The target of CERES is composed of eight Au disks of $25\mu m$ thickness and $600\mu m$ width that are equidistantly spaced along the beam direction by $3mm$ each. The central part of the vertex and track reconstruction facility in the experiment are the Silicon Drift Detectors situated about $9cm$ behind target. The alignment procedure is to be data driven; i.e. one will use data collected from the detector at known magnetic field settings to provide constraints for the determination of the SDD alignment parameters.

We are dealing here with two sets of hits from each SDD's. The target and SDD doublet are located in a low magnetic field region and the particle trajectories are straight lines connecting the corresponding hits in SDD-1 and SDD-2. We also use the distances between the right target disk and both SDD's and between neighboring target disks, but these values were used as the parameters and the algorithm itself doesn't take into account the possible misalignment of the detectors. At the last part of our note we also use the set of hits from the PAD-chamber and the distance between the first SDD and PADC.

1 Mathematical Formulation of the Problem

Taking the SDD as a rigid object, the misalignment breaks down into two categories: 3 translation parameters (along coordinate axes) and 3 rotation parameters (around corresponding axes). If (x_{i1}, y_{i1}), $i_1 = 1, ..., n_1$ (x_{i2}, y_{i2}), $i_2 = 1, ..., n_2$ - points from SDD-1 and SDD-2, Δx, Δy, Δz - shift along the corresponding coordinate axes and α, β, γ - the angles of SDD rotation in xy, xz and yz-planes correspondingly then in the case of misalignment the point coordinates can be written as following (we suppose angles are sufficiently small, so $\sin\alpha \approx \alpha, \cos\alpha \approx 1$ and any product of two parameters vanishes):

$$\begin{aligned} x' &= x + \Delta x + y\alpha, \\ y' &= y + \Delta y - x\alpha, \\ z' &= z + \Delta z + x\beta + y\gamma. \end{aligned} \tag{1}$$

It is easy to demonstrate the impossibility of reconstructing all 12 parameters (6 for every SDD) using the data only from two SDD's without some additional information from other parts of the detector. So we can obtain the exact position of only one SDD with respect to another one.

It was suggested to minimize the following functional in order to get the exact parameter values:

$$F = F(\Delta x, \Delta y, \Delta z, \alpha, \beta, \gamma) = W_1 F_1 + W_2 F_2, \tag{2}$$

where

$$F_1 = \sum\{(z_v - z_{ND})^2 + x_v^2 + y_v^2\} \tag{3}$$

corresponds to the distance between found vertex coordinates and the nearest target disk. Here x_v, y_v, z_v - calculated vertex coordinates, z_{ND} is z-coordinate of the nearest target disk.

$$F_2 = L(x_v, y_v, z_v) / \sum \omega_i \tag{4}$$

corresponds to the width of the track beam in the vertex point. W_1, W_2 - weights determined by the influence of the misalignment parameters on F_1 and F_2.

Both functionals, discussed before, are constructed in such a way that large functional values reflect on a poor alignment and small values state for a good alignment.

The F_2 includes values that are used in the SDD vertex reconstruction robust algorithm [1], minimizing the following functional:

$$L(x_v, y_v, z_v) = \sum \omega_i e_i^2,$$

where

$$e_i^2 = \{\Delta X_{v,i1} - \frac{\Delta Z_{i2,v}}{\Delta Z_{i2,v}} \Delta X_{i2,i1}\}^2 + \{\Delta Y_{v,i1} - \frac{\Delta Z_{i2,v}}{\Delta Z_{i2,v}} \Delta Y_{i2,i1}\}^2.$$

Here we define:

$$\Delta X_{i,j} = x_i - x_j$$

$$\Delta Y_{i,j} = y_i - y_j$$

$$\Delta Z_{i,j} = z_i - z_j$$

We use suboptimal weight functions [1]:

$$\omega_i^{(k)} = \begin{cases} (1 - (e_i^k / c_T * \hat{\sigma}^{(k-1)}))^2)^2, & \text{if} \quad |e_i^{(k)}| \le c_T * \hat{\sigma}^{(k-1)}, \\ 0 & \text{otherwise} \end{cases}$$

with

$$\hat{\sigma}^{(k)^2} = \sum \omega_i^{(k)} (e_i^{(k)})^2 / \sum \omega_i^{(k)}$$

and a carefully tuned Tukey's constant c_T.

The minimization (1) was achieved by operating a steepest gradient descent search in the space of parameters analogously to [2].

During every iteration for each of the necessary alignment parameters the partial derivatives are calculated as follows

$$\frac{\partial F}{\partial \mu_i} = \frac{F(\mu_i + \delta\mu_i) - F(\mu_i - \delta\mu_i)}{2\delta\mu_i}, \tag{5}$$

where μ_i is one of the alignment parameters, $\delta\mu_i$ is the step size which is selected separately for each parameters category correspondingly to their physical sense.

During each iteration all derivatives have been calculated, the values of all parameters are recalculated in accordance with the corresponding derivatives. The changes are normalized according to the maximum of all derivatives. So, for each iteration j :

$$\mu_i^j = \mu_i^{j-1} - \frac{\partial F}{\partial \mu_i} \frac{\delta\mu_i st^j W_i}{max(\frac{\partial F}{\partial \mu_i})},$$

where st^j is a common iteration step, W_i is an individual parameter weight, which is selected separately for each parameter category by means of investigation of parameter influence on the functional behavior.

Next, the functional value is calculated using the new geometry obtained after this recalculation. If this new functional value is less than it was before, the alignment procedure is continued. In the opposite case the iteration step is reduced.

The alignment parameters are varied with a steepest descent algorithm to find the parameter values which minimize the track residues.

The procedure is interrupted when the variation of alignment parameters leads to no significant decreasing of the functional value, i.e. when F reaches a stable minimum. At that point, the SDD parameters (positions, and orientations) are calculated, written out and saved. The alignment procedure is completed.

2 Results

2.1 Calculations with model data

To estimate proposed algorithm quality we used the model data for this part of CERES experiment setup. As the result of the simulation eight narrow peaks for found vertices, corresponding to z-coordinates of the target disks can be obtained. Evidently, if we have a misalignment of SDD's, the vertex reconstruction precision becomes much worse. We simulated this situation by the random choice the misalignment parameters in boundaries $\pm 100 \mu m$ for the shifts and $\pm 10 mrad$ for rotation parameters. After the alignment procedure we obtain almost the same peaks as in the ideal case.

Fig.1 shows the vertex reconstruction errors in all 3 cases which have been discussed before. Here we have histograms for subtraction of vertex z-coordinates taken from model data and the found ones (thus vertex reconstruction errors for all target disks can be seen as one peak around zero). This distribution, fitted by Gauss, for

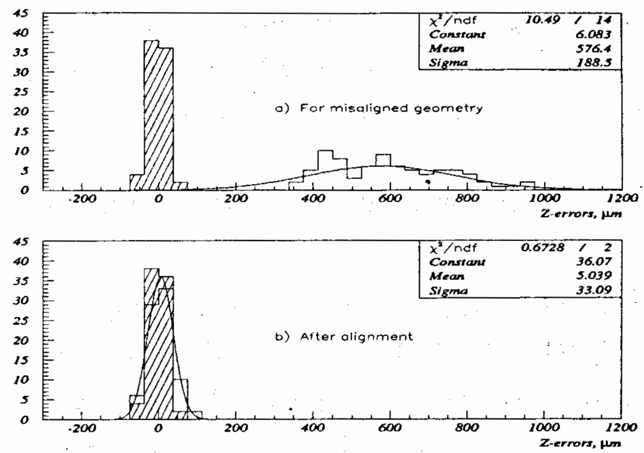

Figure 1: Vertex reconstruction errors for the model data with simulated misalignment(a) and after alignment(b); hatched histograms - the same ones in ideal case.

the case of the simulated misalignment is shown in Fig.1 (a) and then after the alignment procedure in Fig.1 (b); hatched histograms show the vertex reconstruction errors for the ideal case (pure model data). The standard deviation for these distributions in the ideal case and after the alignment are $21\mu m$ and $33\mu m$ correspondingly, whereas in case of misalignment this value is $189\mu m$. It is very important that the misalignment presence influences not only this distribution width but also its mean value. As it can be seen, the mean value of distribution in Fig.1 (a) is non-zero, that means the impossibility of obtaining the real distance between neighboring target disks in that case.

If the functional value is normalized in the ideal case to 1, then after applying the alignment algorithm we would obtain exactly the same result, but for situation as in Fig.1 (a) it becomes about 20 times bigger.

2.2 Calculations with data 1995 - 1996. Comparative study.

Our alignment method was applied for experimental data taken at the CERES in 1995 - 1996. For this purpose we use data after correction. Usage of this approach for data without such correction will be discussed later. The Fig.2 presents vertex reconstruction errors for data 1995. There are histograms for subtractions of the found vertex z-coordinate and z-coordinate of the nearest target disk. These distributions are well fitted by Gauss and the standard deviation for data before alignment (Fig.2 (a)) is 247 μm and after alignment (Fig.2 (b)) - 244 μm. This sufficiently small difference between standard deviation values is connected to potential of the vertex reconstruction method itself. It is more important to obtain the mean value equal to zero after the alignment (before alignment it is equal to -196 μm), since that gives possibility to obtain the real distances between neighboring target disks using found misalignment parameter values. For data 1996 practically the same pictures are obtained. The mean values of the functional value distribution become about 2 times less after the alignment for both data ensembles.

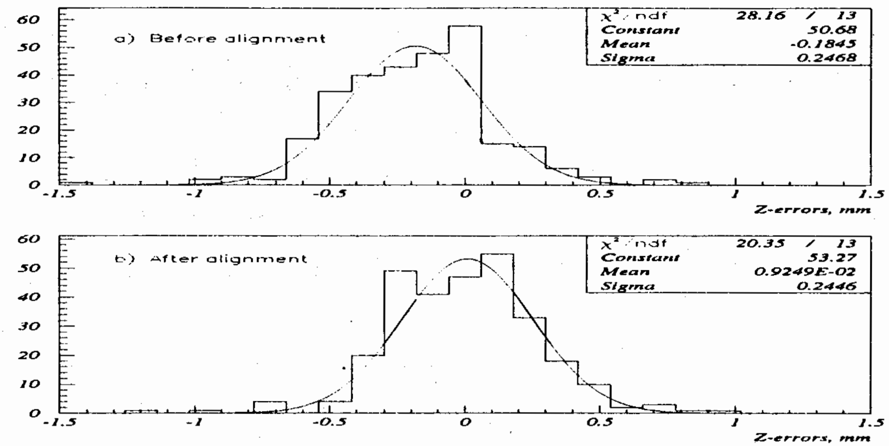

Figure 2: Vertex reconstruction errors for the data of 1995 before alignment(a) and after it(b)

To be sure in the quality of our results we made a comparative study of various methods and approaches. Thus besides of the proposed algorithm, we applied also the MINUIT software [3] (one of the standard general purpose packages for minimization). By means of this package almost the same result (parameters and functional values) was obtained, but using MINUIT for this task is very difficult. The problem is not only complicated profile of the functional (1) and presence of many local minima, but also large correlations between parameters. The MINUIT work in this case strongly depends on the parameter boundaries ant initial point initialization. But even after good choice of these values the program code, using MINUIT, works more than 10 times slower, than the proposed algorithm.

Besides we use two different approaches for the minimization of the functional (1): for all events together and for "event-by-event" minimization. Table 1 presents results of both approaches: for the proposed algorithm and for the minimization results by means of MINUIT. The first column includes values of the functional, the second one contains standard deviation values for the vertex errors. It is obvious that in our case "event-by-event" approach is worse, because we have sufficiently more "bad" events. As it was mentioned above, computing time for finding misalignment parameters using MINUIT is more than 10 times longer.

DATA	$F(\Delta x, \Delta y, \Delta z, \alpha, \beta, \gamma)$	$\sigma_z(\mu m)$
Without Alignment	2.11	255
Proposed Algorithm	1.01	245
Proposed Algorithm for ev-by-ev	1.08	245
MINUIT	1.10	255
MINUIT for ev-by-ev	1.12	250

Table 1: Vertex reconstruction errors for the data of 1995 before alignment(a) and after it(b)

For the accurate estimation of the proposed alignment method and parameter errors computation we chose randomly the initial values of misalignment parameters in limits of $\pm 70\mu m$ for the shifts and $\pm 10 mrad$ for rotations and repeated this procedure 100 times. Fig.3 presents the results. As one can see they are well fitted by Gauss distributions for all 6 parameters and their standard deviations can be used as estimation for their statistical errors. The shapes of these distributions and the steady values of the estimated misalignment parameters prove the independence of the result from the initial points within chosen boundaries. Therefore one can apply this approach for the real data measurements without any preliminary corrections. The same procedure was repeated for the "event-by-event" approach. The MINUIT can not compute these errors because the error matrix is not positively defined. Table 2 presents the found correction values obtained with the help of different approaches for data 1995 and the their error estimations for each of misalignment parameters (the mean square deviation for parameter distribution are not shown for MINUIT, because its error matrix is not defined positively). Found correction values obtained by different approaches are similar (in the error range). However, mean square deviation errors for proposed algorithm are much less than those for other approaches.

The same work was performed for the data 1996 and the similar results obtained for ensembles using the ex-

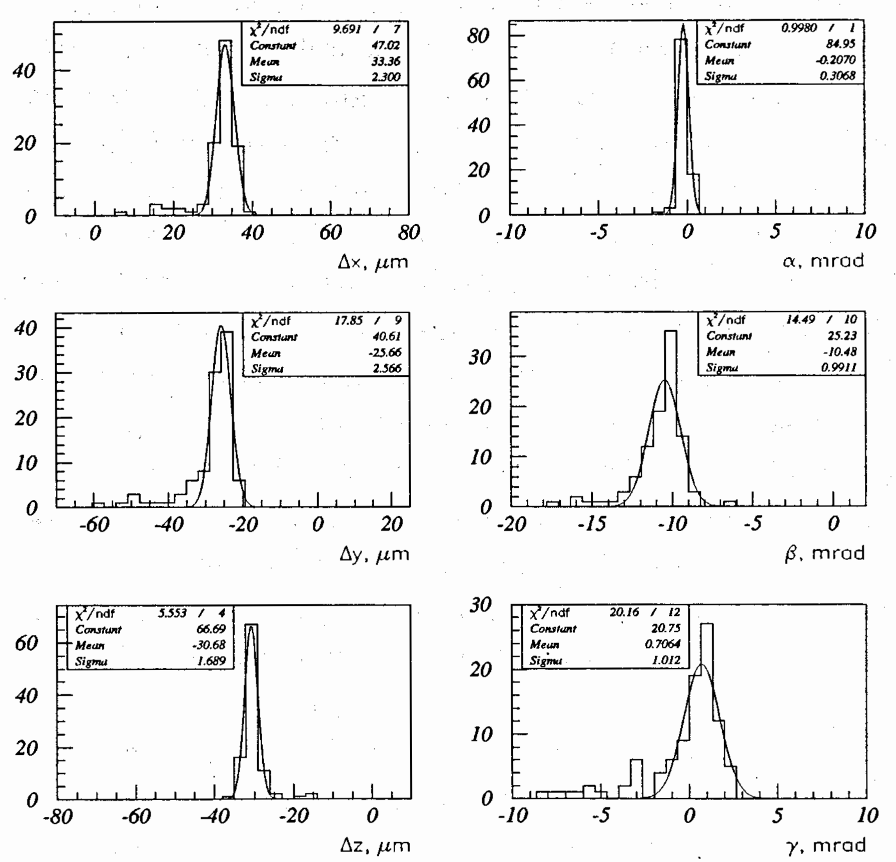

Figure 3: Distributions of misalignment parameter errors for data of 1995

isting conventional corrections which was obtained by means of heuristical program and manual tuning of SDD position [4]. Of course, it is more important to obtain the misalignment parameter values from raw data without any preliminary corrections. Table 3 presents functional values and standard deviations of reconstructed vertex z-coordinate errors before and after the alignment

for both of these cases (in the first line of the table the initial point was given taking into account existing corrections and in the second line - without them).

Parameters	Propos.Alg.	Propos.Alg. ev.-by-ev.	MINUIT ev.-by-ev.
$\Delta x(\mu m)$	33.4 ± 2.3	38.1 ± 17.7	38.0
$\Delta y(\mu m)$	-25.7 ± 2.6	-7.3 ± 18.4	-11.1
$\Delta z(\mu m)$	-30.7 ± 1.7	-22.6 ± 29.2	-20.05
$\alpha(mrad)$	-0.2 ± 0.3	-0.8 ± 2.0	1.4
$\beta(mrad)$	-10.5 ± 0.99	-6.5 ± 4.7	-7.7
$\gamma(mrad)$	0.7 ± 1.01	1.1 ± 5.1	4.6

Table 2: The found correction values obtained with different alignment approaches for data 1995

It can be seen, that the application of our algorithm for data 1996 without preliminary corrections substantially improves the functional value as well as the σ_Z. This procedure gives sufficiently good values for shift parameters and for α angle. Values of the found β and γ are connected with the tilt existence for both SDD's [4] (they have identical angles). For the considered problem we can obtain misalignment parameters only for the one SDD with respect to another.

However, this situation can be corrected by means of the alignment with the help of data from other detectors

	before alignment		after alignment	
Data	F	$\sigma_Z(\mu m)$	F	$\sigma_Z(\mu m)$
existing corrections	1.57	293	1.00	277
without corrections	52.41	353	1.54	277

Table 3: The values of functional and vertex z-resolution for data 1996

of experimental setup, for example, PAD-chamber (or TPC in future).

3 Alignment and matching quality

Evidently, the knowledge of the misalignment parameter values can help to improve the vertex telescope and PAD-chamber tracks matching quality, but for this purpose we have to do the next step, i.e. the alignment using data from other parts of the experimental setup. Suppose Δx, Δy, Δz - shifts along the corresponding coordinate axes of the entire vertex telescope with respect to PAD-chamber and α, β, γ are angles of its rotation in xy, xz, yz-planes correspondingly and (x_{i3}, y_{i3}), $i_3 = 1, ..., n_3$ are points from PAD-chamber. Then in the case of a misalignment the point coordinates on both SDD's can be written according to (1). It was proposed to minimize the following functional:

$$\Phi = \sum\{(x_{i3} - x_{found})^2 + (y_{i3} - y_{found})^2\}, \qquad (6)$$

where x_{found} and y_{found} are coordinates found on PAD-chamber as the intersection point of the reconstructed track with it. For the tracks reconstruction both SDD's and the found vertex are used. At first, track segments are reconstructed using the SDD-2 hits and the vertex. For each track segment the predicted hit position in SDD-1 is calculated and compared to the actual hits in a restricted region given by the corresponding parameters of the setup. Then if a match to SDD-1 is found, the φ and θ (azimuthal and polar angles of the track) are calculated as the mean values of both contributing hits within a prescribed limit. After this procedure the found track is propagated through a PADC and presence of hits within φ and θ boundaries is verified. The best of those hits are taken to contribute to the functional (6).

To apply the described minimization with PADC data a supplementary study of weights and steps was needed. The results are present next.

3.1 Calculations with model data

As the first stage, this approach is executed for the model data, where PAD-chamber points are generated as the intersection of the straight line, going through the corresponding SDD's points in the accordance with experimental setup geometry. Then the misalignment is simulated by means of the random choice of the shifts values in limits of $\pm 1cm$ and rotation parameters in limits of $\pm 10mrad$.

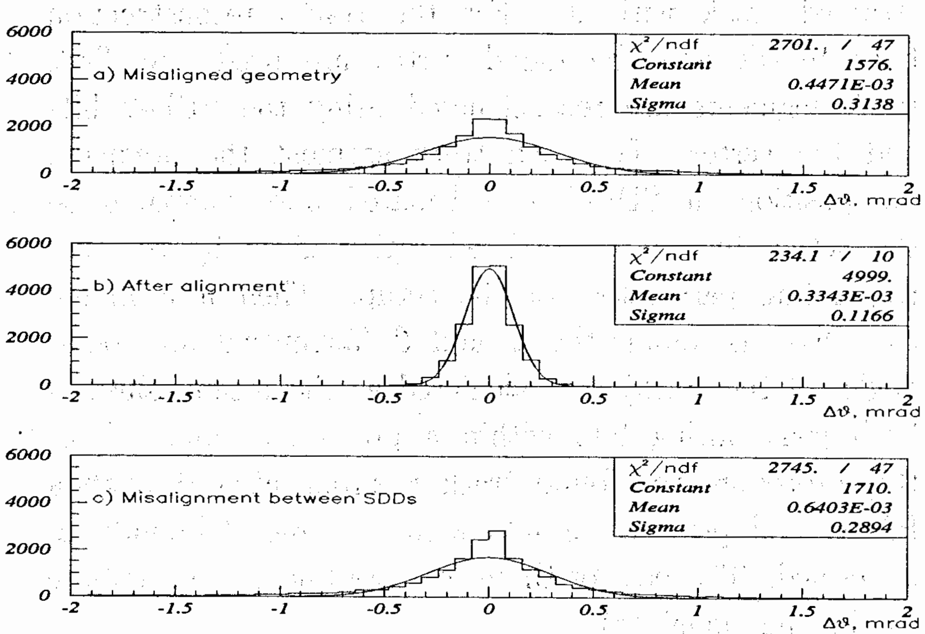

Figure 4: Distributions of $\Delta\theta$ in case of misalignment of entire SVT and PAD-camber (a), after alignment (b) and in case of misalignment within SVT (c)

The Fig.4 presents this procedure results. There is the distribution of $\Delta\theta$ (angles between the ideal and found tracks) in the case of the misalignment presence for the whole silicon vertex telescope and PAD-chamber (Fig.4 (a)) and then after the alignment (Fig.4 (b)). Fig.4 (c) presents the $\Delta\theta$ distribution in the case of the SDD misalignment within SVT. Here the misalignment

parameter values are simulated in limits of $\pm 20\mu m$ and $\pm 3mrad$ for the shifts and rotations correspondingly that corresponds to the values found for experimental data. This situation can not be improved without preliminary alignment of SDD's within SVT.

3.2 Calculation with experimental data

This approach is applied for the experimental data of 1996 without magnetic field. As a result 6 parameters of the SDD misalignment within SVT and 6 parameters of the whole SVT misalignment including PAD-chamber was obtained. We would like to note, that all these values can be obtained very fast without any preliminary corrections. Moreover, after the study of parameter weights and steps this procedure can be executed just only once for the concrete geometrical configuration of this part of the experimental setup.

Nevertheless, we can say that the corrections, existing at the present time, are good enough and the obtained set of parameters improves matching quality and functional values only by 2%, obtained parameters set gives better distributions of vertex reconstruction coordinate errors. Fig.5 presents these distributions for both parameter sets. As one can see, all mean values of these distribution become much closer to zero.

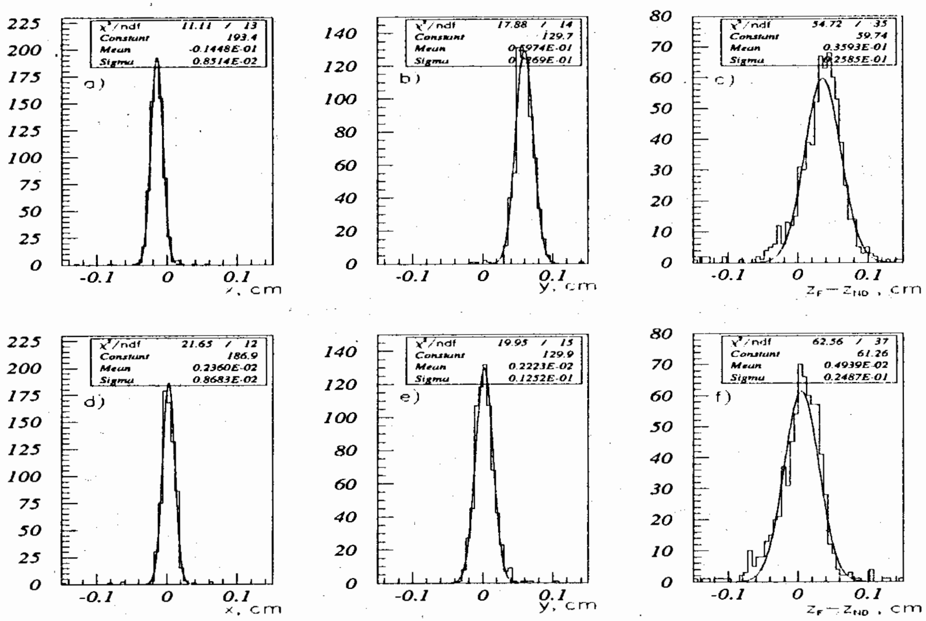

Figure 5: Reconstructed x-coordinates (a) and y-coordinates (b) of the vertices and z-coordinate reconstruction errors (c) in case of existing correction and corresponding distributions (d), (e), (f) in case of obtained parameter values.

4 Conclusion

The fast algorithm for determination of the misalignment parameters of SDD within SVT and of the entire SVT with respect to PAD-chamber is proposed and approved for the simulated data and for data ensembles of 1995 and 1996. The results show good precision of the parameters obtained. The advantage of this algorithm is its insensitivity to the choice of initial values of parameters. This approach allows to find misalignment parameters without using standard general purpose packages for

minimization, that makes it considerably less time consuming. In future this approach can be applied for the alignment with data obtained from TPC.

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Агакишиев Г. и др. E10-98-277
Геометрическая калибровка детекторов
для эксперимента CERES/NA45

Работа посвящена проблеме точного позиционирования кремниевых дрейфовых камер (SDD) внутри вершинного телескопа и исследованию влияния геометрической разбалансировки детекторов в телескопе на качество сшивания треков в эксперименте CERES/NA45. Предложены быстрые алгоритмы геометрической калибровки SDD внутри вершинного телескопа и определения относительного положения всего телескопа и PAD-камеры. Алгоритмы опробованы на модели, соответствующей реальным данным, и данных 1995, 1996 годов. Результаты говорят о хорошей точности используемых методов, что позволит использовать их в будущем для геометрической калибровки по данным, полученным в CERES/NA45 с использованием времяпроекционной камеры.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Agakishiev H. et al. E10-98-277
Alignment of Detectors at CERES/NA45

This note is addressed to the problem of alignment (accurate positioning) of Silicon Drift Detectors (SDD) within Silicon Vertex Telescope (SVT) system and alignment influence on the matching quality at CERES. The fast algorithm for determination of the misalignment parameters of SDD within SVT and entire SVT with respect to PAD-chamber was proposed and approved for the model data and data ensembles of 1995 and 1996. The results show good precision of obtained parameters. In the future this approach can be applied for the alignment with data obtained from TPC.

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

Communication of the Joint Institute for Nuclear Research. Dubna, 1998