RESULTS ON THE DELPHI MICROVERTEX ALIGNMENT FROM A PRECISE 3-D MAPPING

A. Andreazza, P. Biffi, C. Meroni, A. Stocchi*
INFN and Università di Milano, Italy

Abstract

The DELPHI microvertex has been carefully aligned for the 1990 period of data taking at LEP e^+e^- collider using a multistep procedure. The first two steps are presented. Method and results of a precise mapping of the microvertex before the insertion in the DELPHI apparatus using a 3-D measurement machine are described in detail. Secondly procedure and results of an alignment algorithm using the interaction tracks are presented.

(To be submitted to NIM)

*) *Present Address: Laboratoire de l'Accélérateur Linéaire (LAL) ORSAY-FRANCE*

1 Introduction

A silicon microstrip detector has been conceived and realized in the DELPHI experiment at LEP e^+e^- collider, in order to achieve a very high precision on the localization of the interaction point and of the secondary vertices [1]. It has been fully operational since the beginning of 1990 data-taking.

Two different views of the microvertex are shown in figure A. It consists of two independent half shells, each composed of two concentric layers located at radii of 9 and 11 cm. Each layer consists of 12 four-detector long modules with nearly 10% overlap in ϕ between the modules themselves. The $25\text{ }\mu\text{m}$ pitch strips are parallel to the beam direction and each second strip is readout by analog VLSI chips. The inner layer detectors contain 256 readout strips and the outer layer ones contain 320 readout strip.

The microvertex measures the $R\Phi$ coordinate with an intrinsic resolution of $8\text{ }\mu\text{m}$, covering the polar angle $43^\circ < \theta < 137^\circ$. In order to fully exploit the very high performances of microvertex the relative position of all the 192 detectors and the global microvertex position in the DELPHI apparatus have to be precisely known. The goal can be achieved in three subsequent steps:

- having a structure mechanically stable and machined with high precision;
- precisely mapping the detector after the assembly;
- using the interaction tracks to align the detector, once it has been inserted into the DELPHI apparatus.

The error associated to a microvertex hit being the sum of the spreads of its intrinsic resolution σ_{int} and of alignment error σ_{align} the procedure has to be precise enough to satisfy

$$\sigma_{align} \simeq \sigma_{int} \quad (1)$$

The mechanical structure has already been described in detail [2]. In the following we will focus on the mapping and alignment procedure.

2 The mapping

The spatial mapping of microvertex is performed using a 3-D measurement center (Galaxy of POLI ¹). It consists of a mechanical arm that can slide along the 3 orthogonal axes and supports a measuring head. All the supporting elements and the measure table are in granite to provide a high degree stability. In our configuration a programmable head has been used. It drives a synthetic ruby stylus mounted on a touching probe which is triggered by a small strength (~ 10 gr). All the measurements are computer assisted and are performed in a semi-automated way [3].

On polished surfaces we have an accuracy of $\sigma = 1 \mu\text{m}$ for a single point, while for the distance between two points the reachable accuracy is given by the formula:

$$\sigma (\mu\text{m}) = 3 (\mu\text{m}) + \frac{d (\mu\text{m})}{2 \cdot 10^5} \quad (2)$$

Before the mounting all the modules are measured under a microscope equipped with a long range xy table to record the position of the strips with respect to fiducial marks (two cylinders of 5.5 mm diameter at the opposite sides of the module) [4]. Due to the fact that up to now the 3-D measurement system in our configuration cannot see the strips, the cylinders give the possibility to link the module measurement in 2 dimensions with the position measured in space after the mounting. The precision of microscope measurement is $9 \mu\text{m}$ along the strip direction and $4 \mu\text{m}$ along the perpendicular direction, while the precision in determining the position of the reference cylinders is $5 \mu\text{m}$.

During the 3-D measurement, each half shell is independently measured and the relevant informations recorded. The detectors are parametrized as geometrical planes. To reduce the error coming from the fact that all the measured objects are far from being perfect planes and cylinders (see below), each half shell is measured at least 3 times. To minimize variations induced by small drifts both of the POLI reference system and of the half shell position, the measurements are overlapped using a transformation:

$$\mathbf{x}' = \mathbf{R}\mathbf{x} + \mathbf{T} \quad (3)$$

¹POLI S.p.A., Varallo Sesia, Italy

The rotation matrix and the translation are determined using a χ^2 minimization over all the detector plane equation of the quantities²:

$$\|n_1 - Rn_2\| \quad (4)$$

$$d_1 - d_2 - (Rn_2) \cdot T \quad (5)$$

and the detector plane equation is written as $n \cdot x + d = 0$. As can be noticed from table A the difference between two measurements can be of the order of several microns. From the complete set of measurements the actual shape of the microvertex has been reconstructed with good accuracy [5]. We define a *local frame* of the module, with the z axis directed towards the strips direction and the y axis oriented as the external normal. In this frame the microvertex measures the x coordinate. The orientation of the detector relative to this local frame can be described using the angle between the module and the detector itself in the yz plane (angle θ) and in the xy plane (angle ϕ). The precisions reached on these parameters are:

$$\sigma_\theta = 0.06 \text{ mrad}$$

$$\sigma_\phi = 0.15 \text{ mrad}$$

$$\sigma_d = 7 \text{ } \mu\text{m}$$

The difference between σ_θ and σ_ϕ is related to the different geometrical dimensions of our detectors (6 cm along z times 2.5 or 3.2 cm along x).

The most impressive difference with respect to the ideal description was the curved shape shown by the modules. In fig. A the θ angles between each module and its detectors are shown. As it can be seen angles up to 5 mrad have been measured. This picture outline the importance of an accurate and complete mapping of the microvertex. Later on we will quote the alignment precision we would have achieved if the ideal microvertex description had been considered adequate. No systematic effects are visible in ϕ angles and these angles are usually less than 1 mrad.

The next step is to determine the position on space of the strips connecting the 3-D Poli measurements with the strip microscope measurements. As already mentioned, the possibility of this link relies on the reference cylinders measured by both the systems.

²Due to the "barrel like" VD geometry the fit has little sensitivity to T_z , therefore this parameter is calculated using the centers of the reference cylinders.

In table A the errors contributing to σ_{align} are listed. The first two errors are directly derived from the microscope performances. The third one is the precision we can reach on the cylinder center position on space. The module aplanarity error is coming from the assumption that the points measured by the microscope lay on the plane. The link procedure between optical and mechanical measurements introduces an error due to small modifications of the modules in the mounting and to the two different ways of measuring the cylinder center. Our best estimation for this error is $10\text{ }\mu\text{m}$. Propagating all the error sources the microvertex mapping precision on $R\Phi$ is $15\text{ }\mu\text{m}$.

As the dominant error come from the link procedure between optical and 3-dimensional measurements, in order to improve our resolution we are performing a feasibility study of an upgrade of our machine with an optical sensor system for a direct visual inspection of the strips.

3 Microvertex alignment using tracks

The goal of this procedure is, once the detector is inserted in the DELPHI apparatus, to align the microvertex itself with respect to the other tracking detectors in the barrel region [6].

The two separate half-shells composing the MicroVertex have to be independently aligned with respect to DELPHI. We have to stress that the procedure defined does not affect the relative positions of the detectors themselves, but it consists of a global χ^2 minimization at the half shell level. Following this procedure, if the distortions due to the insertion and systematics coming from the track reconstruction in central tracking are not too important, we should reach the $15\text{ }\mu\text{m}$ precision we quoted for the 3-D mapping and then it should be possible to include microvertex information in the track fit.

A possibility to improve a mapping precision relies on alignment procedures that re-arrange the relative positions of the detectors [7].

3.1 The alignment algorithm

The alignment procedure using tracks we developed is a canonical method and has been already described in detail [8]. If a trajectory is reconstructed irrespective of the detector to be aligned then it can be extrapolated to

the detector reference surface. The residue between the extrapolate point x_{ext} and the reconstructed one x_{meas} has a functional dependence on the geometrical misalignment and the track parameters.

As an example for our detector, a simple case corresponding to a Δy misalignment of two modules in the local reference frame is shown in fig. A.

The χ^2 to be minimized can be written

$$\sum_i \frac{(y_i - \sum_{j=1}^n w_{i,j} p_j)^2}{\sigma_i^2} \quad \begin{array}{l} i = 1, \dots \text{number of hits} \\ j = 1, \dots \text{number of parameters} \end{array} \quad (6)$$

where y is the residue defined as $x_{meas} - x_{ext}$, w the weights depending on the track parameters, and p are the parameters to be determined. The error on y , σ , is dominated by the extrapolation error. The way in which the functional form of the residue is built up is described in the Appendix A. Two observations have to be done:

1. the functional form of the residue is a very general one, namely is valid in any reference system;
2. for VD geometry the residue has a very weak dependence from z translation, therefore the half-shell position will be considered determined by 5 parameters.

3.2 The procedure

As we have already said the aim of the above described method is the alignment of the two separate half-shells in the DELPHI reference frame. Due to the non perfect knowledge of the constraints induced on microvertex once inserted in DELPHI, its position could be shifted of some mm and rotated of some mrad with respect to the nominal one. It suggests, at least for the beginning, to use the events with the simplest topology, to be sure that the association of the measured points to tracks is not affected by alignment problems. The natural candidates are the muons coming from $Z^0 \rightarrow \mu^+ \mu^-$.

Before the alignment procedure the residue distribution versus the module number (vs. ϕ with 15° modularity) shows a clear sinusoidal-like shape due to a relative misalignment of the two microvertex half shells with respect to the DELPHI central tracking detectors (fig. Aa). Applying iteratively our algorithm the residue distribution versus the module number becomes

flat. The final distribution shown in fig. Ab has been obtained after few iterations, when the parameter values are definitively stabilized around zero. The errors obtained in the canonical way from the χ^2 minimization (6) are underestimated because the pull function $x_{meas} - x_{est}/\sigma_{est}$ which should follow a normal distribution, has a $\sigma = 2.3$ (fig. A). In order to give an idea of the applied corrections, the misalignment parameters at the first and at the last iteration together with the correlation coefficients are indicated in tables A-A. The errors are rescaled taking into account the above estimated correction factor.

A very important characteristic of the alignment algorithm is its convergence time. In figure A we show the behaviour of the different parameters (the 2 translations and the 3 rotations) as a function of the numbers of degrees of freedom used for the χ^2 minimization. It can be seen that to have a stable convergence of all the 5 parameters 3000 degrees of freedom (i.e. 3000 tracks) are needed. This is about the statistic of $Z^0 \rightarrow \mu^+\mu^-$ we have collected during the whole 1990 data-taking. It should also be noticed that after a thousand tracks the oscillation of the parameters lay within $50 \mu\text{m}$ for the 2 translations and 0.5 mrad for the 3 rotations. Hence, after a first re-alignment using 1000 $Z^0 \rightarrow \mu^+\mu^-$ events, it should be possible to use events with more complicate topologies allowing to reach the needed statistics very quickly.

3.3 The Results

In order to quote the microvertex resolution reached with this procedure and the extrapolation error this resolution allow to reach when the microvertex is included in the track fit, we will use three estimators.

The first one can be figured by the relative alignment of one module with respect to the corresponding one on the other layer. In fig. A we plot the residue distribution on the outer layer obtained extrapolating tracks with a hit in the inner layer. This distribution has a width given by

$$\sigma_{residue}^2 = 2\sigma_{int}^2 + 2\sigma_{align}^2 + (d \cdot \sigma_\phi)^2 \quad (7)$$

Being $\sigma_{int} = 8 \mu\text{m}$ [9], the distance between the two layers $d = 2 \text{ cm}$, assuming the extrapolation error of momentum direction at the microvertex surface approximatively $\sigma_\phi \approx 0.5 \text{ mrad}$, and using $\sigma_{residue} = 31.5 \mu\text{m}$ derived

from fig. A, we have:

$$\sigma_{align} = 19.5 \mu\text{m} \quad (8)$$

The second estimator makes use of overlapping regions between modules, looking at the relative alignment of one detector with respect to the neighboring ones (fig. A). In this case, being $d=2$ mm, the resolution we can extract does not depend from the extrapolation error. In this case, having $\sigma_{residue} = 29.3 \mu\text{m}$ we obtain:

$$\sigma_{align} = 19 \mu\text{m} \quad (9)$$

A similar result can be obtained using the missing distance. The missing distance is the algebraic sum of the impact parameter of the two muon tracks with respect to the beam spot center. This quantity, in practice, does not depend nor from the beam position nor from the beam dimension, but only from the extrapolation error to the vertex. The missing distance distribution, computed using only the microvertex informations for the $R\Phi$ coordinate is shown in figure A. The relation between extrapolation error and missing distance is

$$\sigma_{miss} = \sqrt{2}\sigma_{ext} \quad (10)$$

From the distribution in fig. A being $\sigma_{miss} = 198 \mu\text{m}$ we find:

$$\sigma_{ext} = 140 \mu\text{m} \quad (11)$$

The formula that links the extrapolation error to the errors on the two measured points is given by:

$$\sigma_{ext} = \sqrt{(n+1)^2\sigma_1^2 + n^2\sigma_2^2} \quad (12)$$

where $n = R_1/(R_2 - R_1)$, R_1 and R_2 are the distances of the points from the interaction vertex and σ_1 , σ_2 are the global errors of measurements at R_1 and R_2 respectively. In our case, $R_1 = 9$ cm, $R_2 = 11$ cm, $\sigma_1 \approx \sigma_2 = \sqrt{\sigma_{int}^2 + \sigma_{align}^2}$ and from (12) it can be obtained:

$$\sqrt{\sigma_{int}^2 + \sigma_{align}^2} = \frac{1}{7}\sigma_{ext} = 20 \mu\text{m} \quad (13)$$

Deconvoluting the $8 \mu\text{m}$ intrinsic error, we have:

$$\sigma_{align} = 18 \mu\text{m} \quad (14)$$

We can then conclude that, at the end of the procedure of the half shells alignment using interation tracks, the alignment error we have reached is:

$$\sigma_{align} \approx 18 \mu\text{m} \quad (15)$$

well compatible with the $15 \mu\text{m}$ mapping precision. Using the information of the aligned microvertex together with the DELPHI central tracking, the missing distance distribution shown in fig. A is obtained. From the fit to that distribution $\sigma_{miss} = 141 \mu\text{m}$ which gives an extrapolation error:

$$\sigma_{ext} \approx 100 \mu\text{m}$$

In order to stress once more the importance of an accurate mapping we quote the alignment error reacheable when the same alignment procedure is applied using to the ideal geometrical description of microvertex. In figure A the missing distance distribution obtained using the ideal microvertex is shown. From this distribution we obtain:

$$\sigma_{align} \approx 40 \mu\text{m}$$

to be compared with the $18 \mu\text{m}$ obtained with a mapped microvertex.

4 Conclusion

In this paper we have described two steps of the procedure used for the DELPHI microvertex alignment: the 3-D mapping and the alignment with respect to the other DELPHI barrel tracking detectors using interation tracks.

By means of this procedure a resolution of about $18 \mu\text{m}$ on microvertex alignment has been reached. This result has to be compared with the $40 \mu\text{m}$ we would have obtained without performing any mapping procedure. Nevertheless this alignment precision is still dominant over the intrinsic microvertex resolution. Then this $18 \mu\text{m}$ resolution should be considered as a necessary intermediate step toward the $\sigma_{align} \sim \sigma_{int}$ condition. To improve this resolution other methods have been developed and successfully applied by the DELPHI Microvertex group [7].

The mapping resolution could be further increased by means of a more suitable procedure. In this direction an optical 3-D measurement system is at present under study for looking directly at the strips. This new set-up should reduce the systematic errors due to the link of optical and 3-D measurements that can be held responsible of at least half of the global mapping error.

Acknowledgements

We would like to thank all our colleagues of Milano Group for their generous and precious support, and our colleagues of Microvertex group for the continuous and useful discussions.

A Functional Dependence of Residue from the Misalignment Parameters

In this appendix we define what we call the misalignment parameters and we describe the computation of the χ^2 weights used in (6).

In Section 2, we defined the local reference system of the modules. This frame is very useful because:

- the quantity measured by microvertex is exactly the x coordinate;
- the knowledge of the transformation from the local frame to the DELPHI one is completely equivalent to the knowledge of the position of the detector.

The starting point is a nominal transformation from the local frame to the DELPHI one:

$$\mathbf{x}_{DELPHI} = \mathbf{R}'\mathbf{x}_{local} + \mathbf{T}' \quad (16)$$

The rotation-translation to map the nominal transformation into the real one is

$$\mathbf{x}_{DELPHI} = \mathbf{R}(\mathbf{R}'\mathbf{x}_{local} + \mathbf{T}') + \mathbf{T} \quad (17)$$

$\mathbf{R}$ has been parametrized using the three rotation angles around the coordinate axes. In the small angle approximation it can be written:

$$\mathbf{R}\mathbf{x} = (1 + \mathcal{E})\mathbf{x} = \mathbf{x} - \boldsymbol{\epsilon} \wedge \mathbf{x} \quad (18)$$

where $\mathcal{E}$ is the matrix:

$$\begin{pmatrix} 0 & \epsilon_z & -\epsilon_y \\ -\epsilon_z & 0 & \epsilon_x \\ \epsilon_y & -\epsilon_x & 0 \end{pmatrix}$$

The quantity used to recover R and T is the difference between the measured value of x_{loc} and the one obtained by the extrapolation of the track into the module plane:

$$residue = x_{loc, meas} - x_{loc, ext} \quad (19)$$

The extrapolated point r_{ext} will be the intersection of a track with the nominal detector plane of equation $n \cdot x + d = 0$. The measured point r_{meas} is the intersection of the same track with the real detector plane, which, at first order, is described by equation:

$$(Rn) \cdot x + d - n \cdot T \quad (20)$$

If we approximate the track near the detector surface as a straight line, we find the relation:

$$r_{meas} = r_{ext} - \frac{p}{n \cdot p} ((\mathcal{E}n) \cdot r_{ext} - n \cdot T') \quad (21)$$

where p is the track momentum. Transforming in the local reference frame, we obtain, at first order:

$$r_{loc \ ext} = R'^{-1} (r_{ext} - T') \quad (22)$$

$$r_{loc \ meas} = R'^{-1} ((1 - \mathcal{E}) r_{meas} - T - T') \quad (23)$$

for the extrapolated and measured value of r_{loc} . Substituting (21) in (23) we can find the expression for the *three dimensional* residue:

$$r_{loc \ meas} - r_{loc \ ext} = R'^{-1} \left(-\mathcal{E} r_{ext} - \frac{p}{n \cdot p} ((\mathcal{E}n) \cdot r_{ext} + n \cdot T) \right) \quad (24)$$

Taking the x component:

$$x_{meas} - x_{ext} = T \cdot \left(-a + n \frac{p \cdot a}{p \cdot n} \right) + \epsilon \cdot \left(\left(-a + n \frac{p \cdot a}{p \cdot n} \right) \wedge r_{ext} \right) \quad (25)$$

where a is the local x versor, corresponding to the first row of R'^{-1} . In equation (25) the residue depends on six parameters: the vectors ϵ and T . The weight relative to T_x is proportional to a_x and n_x . In our geometry they are three orders of magnitude lower than the other components, therefore this method is not enough sensitive to this parameter. If the χ^2 method is applied to a module, all calculations can be made in the module local reference frame, so that equation (25) can be simplified substituting in it:

$$a = (1, 0, 0)$$

$$n = (0, 1, 0)$$

References

- [1] DELPHI Collaboration, *The DELPHI Detector at LEP*, CERN-PPE/90-128, Submitted to Nucl. Instr. and Meth.
DELPHI Vertex Detector, Addendum to the Technical Proposal DELPHI 86-86 GEN-52
H. Dijkstra, Nucl. Instr. and Meth. A289 (1990)400
- [2] H. Dijkstra, Nucl. Instr. and Meth. A277 (1989)154
- [3] P. Biffi and N. Redaelli, in preparation
- [4] G. Mællum, Internal Report
M. Karlsson, Internal Report
- [5] A. Andreazza, Thesis, Milano 1991
- [6] C. Troncon, *Some ideas and estimates for the software alignment of the Microvertex detector*, DELPHI 87-34 PROG-76 TRAK-47
- [7] V. Chabaud, Minutes of DELPHI Microvertex Meetings 1990
G. Wormser, Minutes of DELPHI Microvertex Meetings 1990
R. McNulty, Transparencies presented at DELPHI Microvertex Meetings, 30 October 1990 and 22 January 1991
- [8] M. Caccia and A. Stocchi, *The DELPHI Vertex Detector Alignment: a Pedagogical Statistical Exercise* INFN/AE-90/16
- [9] V. Chabaud, Transparencies presented at DELPHI Microvertex Meeting, 22 January 1991

Parameters of the transformation						
Measure from $\Rightarrow$ to	T_x μm	T_y μm	T_z μm	ϵ_x mrad	ϵ_y mrad	ϵ_z mrad
$B_1 \Rightarrow B_2$	3 ± 4	-2 ± 4	20 ± 3	0.03 ± 0.16	0.02 ± 0.16	0.01 ± 0.08
$B_1 \Rightarrow B_3$	46 ± 4	-9 ± 4	36 ± 9	0.04 ± 0.13	-0.02 ± 0.16	-0.03 ± 0.07
$D_1 \Rightarrow D_2$	5 ± 4	38 ± 4	-17 ± 6	0.01 ± 0.14	0.03 ± 0.14	0.06 ± 0.06
$D_1 \Rightarrow D_3$	12 ± 3	35 ± 3	-20 ± 6	0.02 ± 0.17	-0.01 ± 0.17	0.04 ± 0.08

Table 1: Transformation between different measurements. B and D are half shell labels and the reference measurements are called B_1 and D_1

Error source	Contribution to σ_{align} μm
Intrinsic microscope error	2
Microscope position of reference cylinders	5
3D position of reference cylinders	8
Modules aplanarity	6
Link procedure microscope-3D	10
Total	15

Table 2: Different contributions to σ_{align} .

	half-shell B	half-shell D
$\Delta x \text{ } \mu\text{m}$	-621.3 ± 4.6	-1045.1 ± 3.9
$\Delta y \text{ } \mu\text{m}$	-1788.8 ± 9.9	-2206.6 ± 8.8
$\epsilon_x \text{ mrad}$	0.55 ± 0.08	-0.77 ± 0.07
$\epsilon_y \text{ mrad}$	1.52 ± 0.08	2.83 ± 0.07
$\epsilon_z \text{ mrad}$	0.27 ± 0.07	-0.22 ± 0.06

Table 3: Misalignment parameters at the first iteration of the alignment procedure

	half-shell B	half-shell D
$\Delta x \text{ } \mu\text{m}$	-5.6 ± 4.6	-1.4 ± 4.2
$\Delta y \text{ } \mu\text{m}$	-0.9 ± 10.1	-4.2 ± 9.0
$\epsilon_x \text{ mrad}$	0.06 ± 0.08	-0.11 ± 0.07
$\epsilon_y \text{ mrad}$	-0.13 ± 0.08	-0.06 ± 0.07
$\epsilon_z \text{ mrad}$	-0.05 ± 0.07	0.00 ± 0.06

Table 4: Misalignment parameters at the last iteration of the alignment procedure

	Half-shell B					Half-shell D				
	Δx	Δy	ϵ_x	ϵ_y	ϵ_z	Δx	Δy	ϵ_x	ϵ_y	ϵ_z
Δx	-	0.01	-0.01	0.00	-0.01	-	0.06	0.01	-0.17	-0.01
Δy	0.01	-	0.02	-0.09	-0.89	0.06	-	0.10	-0.02	0.88
ϵ_x	-0.01	0.02	-	0.02	0.00	0.01	0.10	-	-0.12	0.02
ϵ_y	0.00	-0.09	0.02	-	0.10	-0.17	-0.02	-0.12	-	-0.01
ϵ_z	-0.01	-0.89	0.00	0.10	-	-0.01	0.88	0.02	-0.01	-

Table 5: Correlation coefficients of the misalignment parameters.

Figure Caption

Figure 1

Microvertex view (a) $R\Phi$ view (b) view

Figure 2

The residue due to a Δy misalignment, seen in the module local reference frame

Figure 3

The typical shape of a module as measured at the POLI machine.

Figure 4

Angles in yz plane between the detectors and the modules.

Figure 5

Residue distribution vs. module number, before (a) and after (b) having applied the alignment algorithm.

Figure 6

Distribution of $(x_{meas} - x_{ext})/\sigma_{ext}$

Figure 7

Misalignment parameters vs. number of tracks used for the χ^2 minimization for half-shell B.

Figure 8

Residue distribution of inner modules vs. outer modules.

Figure 9

Residue distribution in the overlapping regions

Figure 10

(b)

(a)

Figure 1
Microvertex view (a) $R\Phi$ view (b) half view

Figure 2
The residue due to a Δy misalignment, seen in the module local reference frame

Figure 3
The typical shape of a module as measured at the POLI machine.

Figure 4
Angles in yz plane between the detectors and the modules.

Figure 5
Residue distribution vs. module number, before (a) e after (b) having applied the alignment algorithm.

Figure 6
Distribution of $(x_{meas} - x_{ext})/\sigma_{ext}$

Figure 7
Misalignment parameters vs. number of tracks used for the χ^2 minimization for half-shell B.

Figure 8
Residue distribution of inner modules vs. outer modules.

Figure 9
Residue distribution in the overlapping regions

Figure 10
Missing distance distribution obtained using the DELPHI microvertex

Figure 11
Missing distance distribution obtained joining the microvertex to the DELPHI central tracking system.

Figure 12
 Missing distance distribution obtained using the nominal description of the microvertex.