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Alignment of the NOMAD-STAR detector

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Abstract

This note describes the alignment of the NOMAD-STAR detector. This is the B_4C-silicon target installed in the NOMAD spectrometer in 1997. NOMAD-STAR is composed of modules of 12 silicon detectors each giving a total length of 72 cm. Ten of these modules (called ladders) are assembled to form a layer. There are five layers interleaved with passive boron carbide plates. The total surface of silicon is 1.14 m^2. Energetic muons from the flat-top of the CERN SPS cycle provide the necessary information to perform a very precise software alignment. This alignment is needed to ensure that the impact parameter measurement needed for the identification of taus in a detector like NOMAD-STAR will not be limited by the error in the alignment.

1. Introduction

One of the most interesting current problems in particle physics and cosmology is the possibility that neutrinos have non-vanishing masses and that there are oscillations among the different families. Until 1998, two experiments, CHORUS and NOMAD [1–4] were searching for the exclusive $\nu_\mu(\nu_e)\leftrightarrow\nu_\tau$ oscillation mode in the CERN-SPS beam. To understand the design of a large surface silicon tracker for a future $\nu_\mu(\nu_e)\leftrightarrow\nu_\tau$ oscillation experiment [5–9] we built an instrumented silicon target (NOMAD-STAR) which was installed in the NOMAD spectrometer in the beginning of 1997 (Fig. 1).

The NOMAD-STAR detector shown in Fig. 2 was installed upstream of the first NOMAD drift chamber. It follows the concept of a passive target followed by sensitive layers proposed in Ref. [5]. It consists of four layers of boron carbide (B_4C) which constitute most of the mass of the target (45 kg), interleaved with layers of single-sided silicon microstrip detectors. An additional layer of silicon detectors is added downstream for better track reconstruction. Boron carbide provides the best compromise between high density and long radiation length for low Z materials. The five layers of silicon microstrip detectors[1] have an active surface of 1.14 m^2.

As shown in Fig. 3 each active layer consists of 10 overlapping modules (ladders) assembled with 12 silicon microstrip detectors and read out from only one side by low-noise electronics (VA1 chip). The silicon microstrip detectors are those used in the

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[1] Manufactured by Hamamatsu Photonics, Japan.

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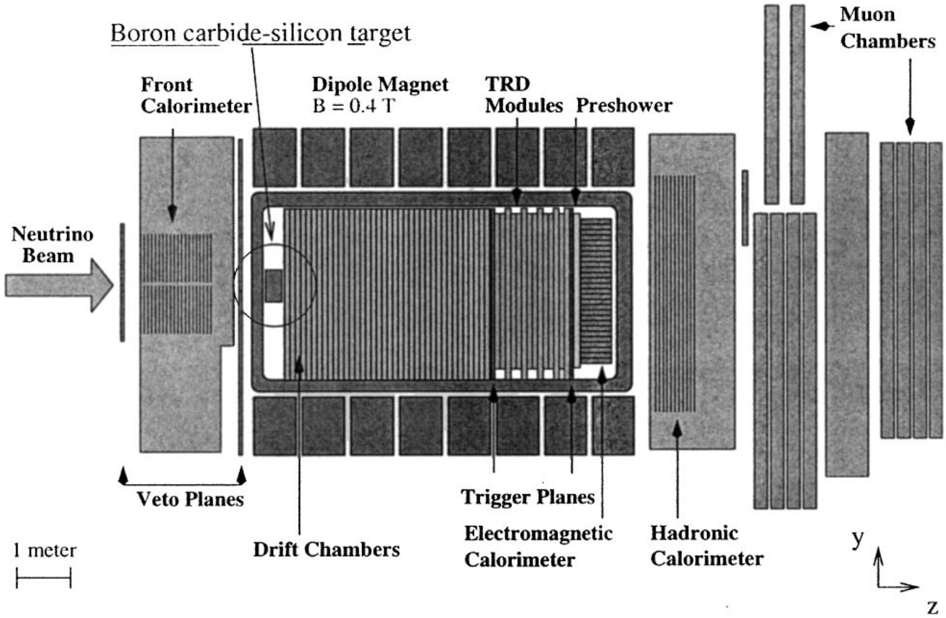

Fig. 1. The NOMAD detector with the silicon target (NOMAD-STAR).

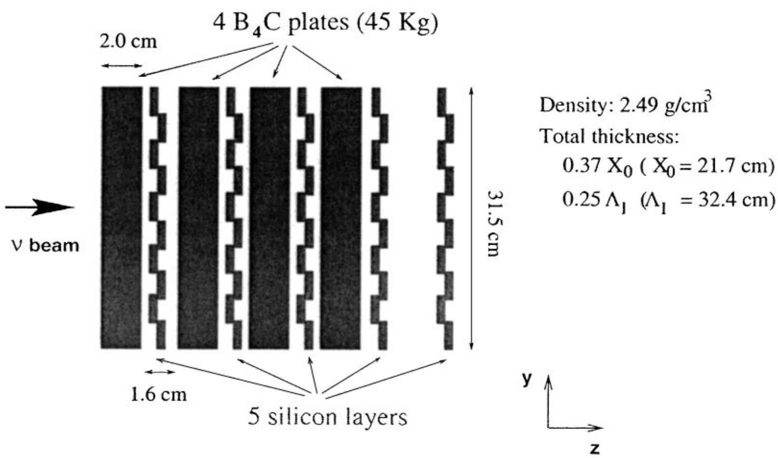

Fig. 2. Schematic of the side view of the silicon target.

DELPHI experiment [13]. These are single sided, 33.5 mm $\times$ 59.9 mm wide, with strip and readout pitches of 25 and 50 μm, respectively. The detectors are AC coupled, FOXFET biased [10] passivated with silicon oxide. Each detector has 641 readout strips, but to match the channel pitch of the readout chips, 640 strips are read out. The strips are oriented in the direction parallel to the NOMAD magnetic field (X). The NOMAD-STAR design allows the measurement of the YZ projection of a track.

The performance of these silicon ladders in terms of signal-to-noise ratio, hit finding efficiency and spatial resolution has been described elsewhere [11].

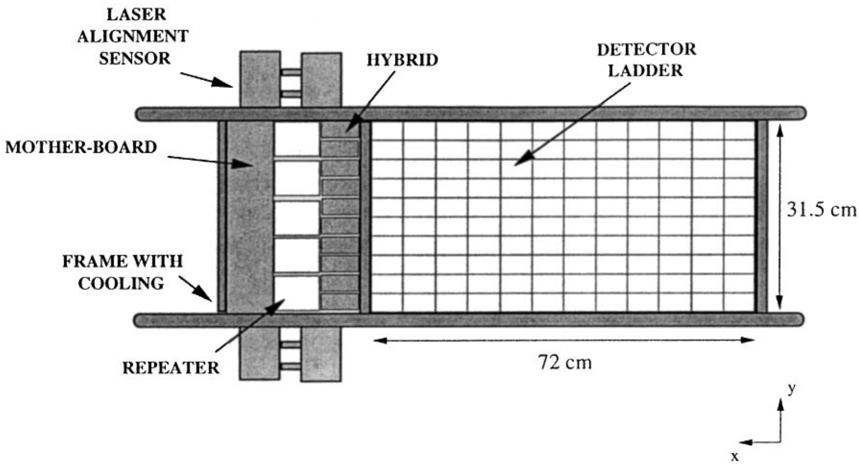

Fig. 3. Individual silicon layer with 10 ladders and 12 detectors per ladder.

Tau identification in NOMAD is based exclusively on the use of kinematical techniques. The NOMAD-STAR detector will allow a precise determination of the event vertex, and therefore of the impact parameter of tau decay candidates. The NOMAD apparatus has been described elsewhere [3,4] and a detailed description of the NOMAD-STAR detector can be found in Ref. [12].

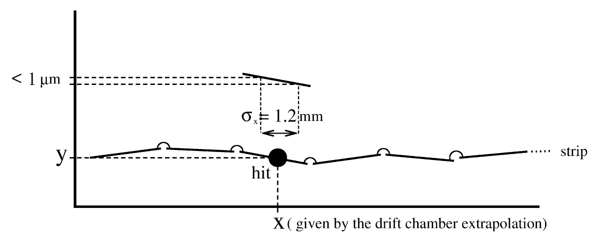

Fig. 4. Strip along a ladder.

2. Test-beam: intrinsic resolution

A ladder of nine detectors was tested in the West Area of CERN with the X5 beam (test-beam on July 96, see Ref. [11]). The CERN SPS beam consisted of negative pions with momenta higher than 100 GeV/c, thus the multiple scattering was considered negligible, and these were reconstructed with a particle telescope consisting of four layers of silicon detectors in each of the X and Y orientations. We use a model of capacitive couplings (both to the back-plane and to the neighbouring strips) to calculate the hit position (see Ref. [11]). Using this algorithm, the measured residuals from this test-beam have a Gaussian width $\sigma_{\text{residuals}} = 5.1$ μm.

Substracting the extrapolation error from the telescope ($\sigma_{\text{extrap}} \sim 3$ μm) we obtain the intrinsic resolution of the ladder which is ~ 4 μm. For a ladder of 12 detectors we expect this resolution to be about 5 μm.

3. The NOMAD-STAR alignment

In order to have a good point resolution, the positions of all individual silicon detectors inside STAR have to be well known. The electrical response of a ladder by itself gives us the relative position of the hit with respect to the ladder but not its position in the global reference system. Although the detectors were glued nearly parallel to each other, a strip inside a ladder defines a series of segments, corresponding to each bonded detector, instead of a straight line (Fig. 4).

Thus, to know the location of the hit in the global system, the X position of the hit is needed as well as the exact position of each detector in the global reference frame. The X position of the hit is given by extrapolating back from the Drift Chambers (DC) and the position of all detectors will be calculated with the alignment.

As the strips inside a ladder are nearly parallel to the X-axis, the error in the Y position of a hit coming from the error in X is negligible, so the DC resolution in X (1.2 mm) is sufficient (see Fig. 4).

The alignment is divided in two parts:

- *Optical survey*: Optical measurement of all the detector positions before the installation of STAR inside NOMAD.
- *Alignment by software*: Correction of all the detector positions using muons crossing the detector.

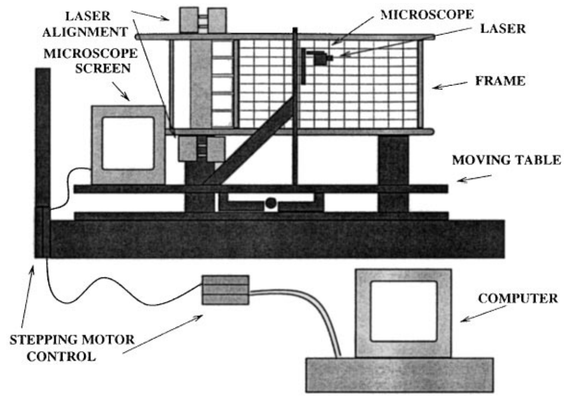

Fig. 5. System used for surveying the layers of NOMAD-STAR.

4. Optical survey

The optical survey was done in the laboratory before the installation of STAR inside NOMAD. A full description of the survey can be found elsewhere [14].

The surveying was performed using a CCD camera with magnifying optics, mounted on a rudimentary measuring table. As shown in Fig. 5, the silicon layer under survey was mounted vertically, facing the camera. The axes for the measurements were defined as for NOMAD. The camera could be moved independently along the three axial directions, with a cross-hair on the monitor screen indicating the centre of the field of view of the camera.

The camera could be moved by stepping-motors in increments of 1 μm, although the precision of the measurements was limited by the quality of the image and the precision of the movement.

Four points (close to the corners) were measured per detector, giving a total of 48 points per ladder. Each ladder was measured by at least two different surveyors to check for any discrepancies. In the rare cases in which discrepancies were found, the estimated theoretical position of the detectors was used to determine which of the two measurements was at fault.

The coordinates of the detectors were taken as the average of the measured coordinates by each of the surveyors. The measured differences between the surveyors were used to estimate the systematic error of the survey in the X-position (6.4 μm), the Y-position (6.6 μm) and the Z-position (14.1 μm).

5. Alignment by software

The position of an individual detector in space is defined by one translation $\boldsymbol{r}_0$ and one rotation R, which can be described by three angles or three orthogonal unitary vectors ($\boldsymbol{u}$, $\boldsymbol{v}$, $\boldsymbol{w}$). Via a χ^2 minimization with a planar model, the four points per detector from the survey are transformed into the quantities $\boldsymbol{r}_0$, $\boldsymbol{u}$, $\boldsymbol{v}$, $\boldsymbol{w}$. Using this constraint, the information is optimized and the survey errors are reduced (from $\sigma_{y_0} = 6.6$ to 4.0 μm).

The optical survey gives the initial $\boldsymbol{r}_0$, $\boldsymbol{u}$, $\boldsymbol{v}$, $\boldsymbol{w}$ which serves as the starting point for the software alignment.

The optical survey by itself is not sufficient since each individual detector has an intrinsic resolution of around 4 μm and the precision of the survey has to be preserved during and after the installation of the detector. Internal movements in STAR are then possible so we have to consider three possibilities:

- A ladder is a very stiff system, thus the movements of the detectors inside a ladder are very small. Hence, a ladder-by-ladder alignment is sufficient. The optical survey has an important role here since it is the only way to determine the relative positions of individual detectors inside a ladder (because there are no overlaps within a ladder).
- Each silicon plane is nearly parallel to the XY plane. Allowances are made for rotations and shifts of the ladders within each of the planes.

- A silicon frame has quite a large mechanical freedom inside the support basket (also called the mini-basket), so rotations and shifts involving the Z coordinate are also important.

The software alignment has been done ladder by ladder. The position of a ladder is defined by the position of the first detector.

Sections 5.1–5.6 explain the kind of techniques used for the alignment. In Section 6, we will present the step-by-step application of these techniques to the alignment.

5.1. Muons

The alignment by software has been done using the information of energetic muons passing through the detector. These muons are those from the flat-top of the SPS beam.

The resolution in Z diminishes as the angle of the muon increases. The muons we have available for the alignment are mostly perpendicular to the silicon planes so the information about the Z position of the detectors is minimal. In Fig. 6, it is possible to see a clear correlation between the angular distribution of the muons with their momentum, the angle being larger on average for low-energy muons.

Multiple Coulomb scattering is one of the main source of uncertainties in the alignment procedure. The multiple scattering at 30 GeV between two silicon planes is of the same order as the intrinsic resolution of a ladder (5 μm). We have to find the best possible compromise between angle (more information in Z) and momentum (less multiple scattering).

Clearly, the best solution is an independent alignment for the XY projection and the projections involving Z.

- *Alignment in XY*: High momentum muons with a very small angle ($p > 50$ GeV, $\theta_{\text{muon}} \in [-0.5, 0.5]^{\circ}$). If the angle is small the alignment in XY does not depend on the Z position of the ladders.
- *Alignment in Z*: High angle muons ($\theta_{\text{muon}} \in [-10, -2.5]^{\circ}$), which imply low momentum (10 GeV on average).

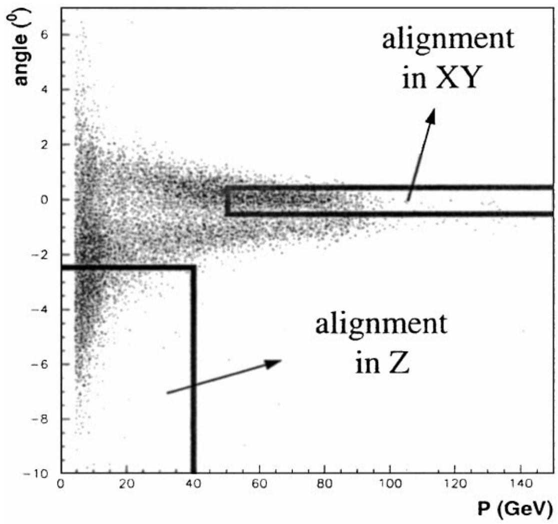

Fig. 6. Angle-momentum regions used for the alignment in XY and the alignment in Z.

5.2. Trajectories of particles in a magnetic field

It is well known that the trajectory of a particle inside a constant magnetic field is a helix. We can always choose our reference system in such a way that the magnetic field goes along the X-axis, $\boldsymbol{B} = (B,0,0)$. In this reference frame, and using the z coordinate as a parameter:

$$\chi \equiv \frac{y''[z]}{[1 + (y'[z])^2]^{3/2}} = \frac{qB\,0.3}{p_{\perp}} \tag{1}$$

$$x''[z] = 0 \tag{2}$$

where $\chi = 1/R$ is the curvature, R being the radius of curvature and $p_{\perp} = \sqrt{p_y^2 + p_z^2}$ the tranverse momentum to the magnetic field, 0.3 is the speed of light in vacuum (if R is in meters, $p_{\perp}$ is in GeV/c and B is in Tesla) and q is the charge of the particle. The solutions to these equations are

$$y = Y_{\text{c}} + \sqrt{R^2 - (z - Z_{\text{c}})^2} \tag{3}$$

$$x = a_x + b_x z \tag{4}$$

which represent the parametric equations of a helix using the z coordinate as a parameter. The XZ projection (Eq. (4)) is a straight line and the YZ

projection a circle (Eq. (3)). (Y_c, Z_c) is the centre of the circle and R its radius.

The Kalman filter technique has been used in the past for track fitting [15]. A matrix formalism can be used to implement a Kalman filter when the equation of motion is linear. Since the equation of a circle is non-linear, we performed a Taylor expansion around $z = 0$ to make the problem linear in the parameters (R, Y_c, and Z_c).

$$y = \sum_{n=0}^{\infty} \beta_n z^n \tag{5}$$

$$\beta_n = \frac{1}{n!}\frac{d^n}{dz^n}(Y_c + \sqrt{R^2 - (z - Z_c)^2})_{z=0}. \tag{6}$$

Depending on the features of the detector and on the energy of the particles to be measured the number of terms in the expansion may vary. There are three variables we have to consider:

- the magnetic field B
- the momentum component transverse to $\boldsymbol{B}$ at the point (Y_0, Z_0), $(\boldsymbol{p}_0)_\perp = (p_{0_y}, p_{0_z})$
- the maximum longitude of the extrapolation, l_{max}.

All the coefficients of the Taylor expansion depend on those variables through the parameters R, Y_c and Z_c. The maximum extrapolation error made when we neglect the nth term is $\beta_n(B, p_y, p_z) l^n_{max}$. Comparison of the extrapolation error in quadrature with the other errors, like multiple scattering and intrinsic resolution, determines the order of the expansion.

We have to remark here that the Hall effect does not affect the precision of the alignment because it only introduces global shifts in a constant magnetic field. For a magnetic field of 0.4 T the Hall angle for holes is 0.7°, which implies global shifts of the order of 2 μm.

5.3. The cubic model

NOMAD-STAR can reconstruct the YZ projection of a track, which will be a circle because of the magnetic field along X. As we saw in Section 5.2 the circle can be expanded by a power series. Let us calculate the number of terms needed to describe the particle trajectories in the NOMAD-STAR detector. The values of the relevant parameters are:

- $B = 0.4$ T,
- $l_{max} = 3.6$ cm, the distance between two silicon planes, and
- $(p_y)_{max} = 3$ GeV and $(p_z)_{min} = 1$ GeV.

The first five terms of the Taylor expansion of the circle will be:

$$\beta_0 + \underbrace{\beta_1 l_{max}}_{11\ \text{cm}} + \underbrace{\beta_2 l^2_{max}}_{1500\ \mu\text{m}} + \underbrace{\beta_3 l^3_{max}}_{20\ \mu\text{m}} + \underbrace{\beta_4 l^4_{max}}_{0.4\ \mu\text{m}}. \tag{7}$$

If we compare these terms with the intrinsic resolution of a ladder (5 μm) it is clear that a cubic is sufficient.

5.4. Minimization of residuals

The way to align our detector is by minimizing the residuals in it. A residual is the difference between the predicted position of the hit and the measured position given by the electrical response of a ladder. The predicted position of a hit is the extrapolation of the reference track to the plane where the ladder which has to be aligned is supposed to be located. Of course the hit in that ladder is not included in the reference track. A Kalman filter technique is used to build the reference track with one or more hits in silicon including the DC information as well. The Kalman filter is also used to calculate the prediction in the ladder to be aligned. The detector parameters are found via a χ^2 minimization of the residuals.

5.5. Alignment in the XY plane

The silicon ladders are almost contained in the XY plane so the initial alignment has to be performed in that plane. Three parameters describe the position of a detector inside a plane: two shifts (x_0 and y_0) and one angle θ. But a silicon ladder provides only one coordinate (almost equivalent to the Y coordinate in the NOMAD reference frame, because the strips are nearly parallel to the X-axis, see Fig. 7). Therefore, we do not have any information about the shift x_0.

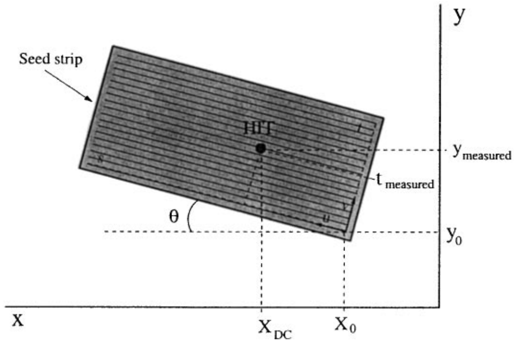

Fig. 7. Alignment in the XY plane.

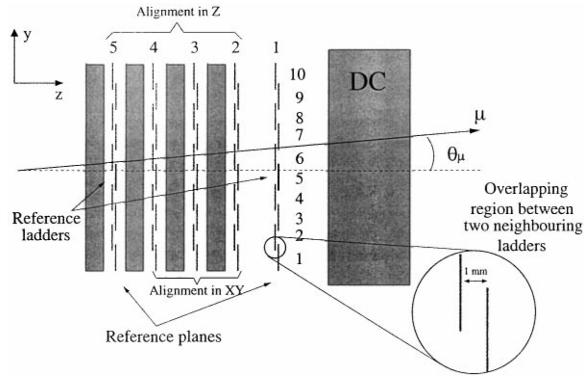

Fig. 9. The alignment procedure.

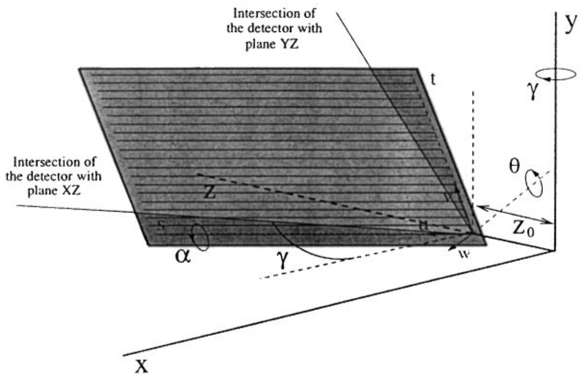

Fig. 8. Definition of parameters for the alignment in Z.

To be independent of the Z position of the ladders we have to choose particles nearly perpendicular to the silicon planes. Of course, we make an error when we assume that ladders are in the XY plane and the muons are perpendicular to that plane, but this error is negligible compared to the intrinsic resolution.

5.6. Alignment in Z

As we have demonstrated in Section 5.1 the alignment in Z requires high angle tracks in the YZ plane with respect to the Z-axis. We have to choose the parameters to be corrected in such a way that the alignment in Z does not affect the previous alignment in XY (Fig. 8):

- the angle γ describes the rotation around the Y-axis,
- the angle α describes the rotation around the axis defined by $\boldsymbol{u}$, and
- the shift z_0.

6. Alignment procedure

The muons available are quite straight so most of them pass through the corresponding ladder (at the same height) for each plane (see Fig. 9). We define a set of ladders as the five ladders (one per plane) located at the same height. Sections 6.1–6.4 describe the sequence of steps in which the alignment takes place.

6.1. Alignment with DC

The optical survey gives us the position of all the silicon detectors with respect to the mini-basket. Its position in the NOMAD reference frame after the installation of NOMAD-STAR was measured with a precision of 0.4 mm. Since the NOMAD DC provide the link between STAR and the external coordinate system, we need to know the location of STAR with respect to the DC. The first step of the alignment consists in correcting the position of all the ladders by minimizing the residuals defined by the DC extrapolation and the hit in the corresponding ladder (Fig. 9). This procedure locates STAR in the NOMAD reference frame with a precision of around 120 μm.

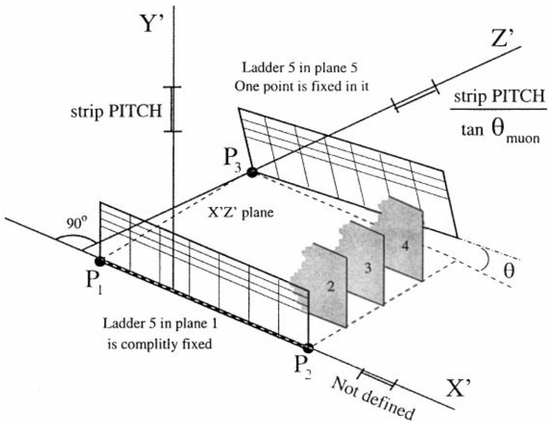

Fig. 10. Definition of the internal reference system.

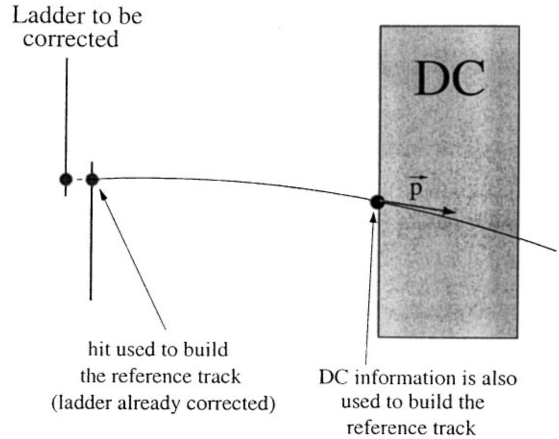

Fig. 11. Alignment by overlaps.

6.2. The internal reference frame

To achieve an intrinsic resolution of around 5 μm for an individual ladder from a relative alignment of 120 μm with respect to the DC, the final alignment has to be completely internal, so we need to define an internal reference system for NOMAD-STAR.

The axes are defined in Fig. 10. The X'-axis is given by P_1 and P_2, two points of ladder 5 in plane 1 (the closest to the DC). This ladder remains untouched after the alignment with the DC. The Z'-axis will be perpendicular to X' containing P_3 ($\boldsymbol{r}_0$ of ladder 5 in plane 5). Once Z' is defined we can move P_3 along the Z'-axis when performing the alignment. Finally, Y' will be perpendicular to the other two axes. The strip pitch defines the scale of the Y'-axis, while the scale of the Z'-axis is given by the projection of the strip pitch to this axis given by muons (the Z' scale has no meaning before the alignment). The scale of the X'-axis is not defined but is not important because we cannot measure the X coordinate with the silicon.

As we can see in Fig. 10, there exists a relative angle (θ) between the reference ladders that can be corrected keeping the internal reference frame invariant. The way to correct this angle is by using the iterative procedure explained in Section 6.4 for the set of ladders 5, allowing changes in θ and y_0 for planes 2–4 and changes only in θ for plane 5 (y_0 fixed, see Section 5.5). This step has to be done before the alignment by overlaps.

6.3. Alignment by overlaps

The way in which the internal reference frame has been defined in Section 6.2 only works for muons crossing ladder 5 in planes 1 and 5. To extend the internal reference system to the whole detector we must relate the positions of all the ladders in these reference planes (1 and 5). This is done by aligning the ladders in these planes taking ladder 5 as reference. The way to do it is by using the hits passing across the region where two contiguous ladders overlap (Fig. 11), which extends along 60 strips (3 mm). The distance between these ladders in Z is only 1 mm. In addition, multiple scattering can be neglected because there is no passive material between them. Therefore, tracks with only two hits (in both overlapped ladders) are sufficient to get a good alignment between them. The reference track is built with the hit in one of the ladders that overlap and the information coming from the DC. Residuals in the other overlapped ladder are minimized in order to achieve the relative alignment. If ladder 5 in planes 1 and 5 are the reference ladders, we start aligning ladder 6 and 4 using the overlaps 5–6 and 5–4, respectively. Afterwards overlaps 6–7 and 4–3 allow us to align ladders 7 and 3, and so on.

6.4. Iterative alignment

This is the most complicated part of the alignment. It allows us to define the scale in Y' for the

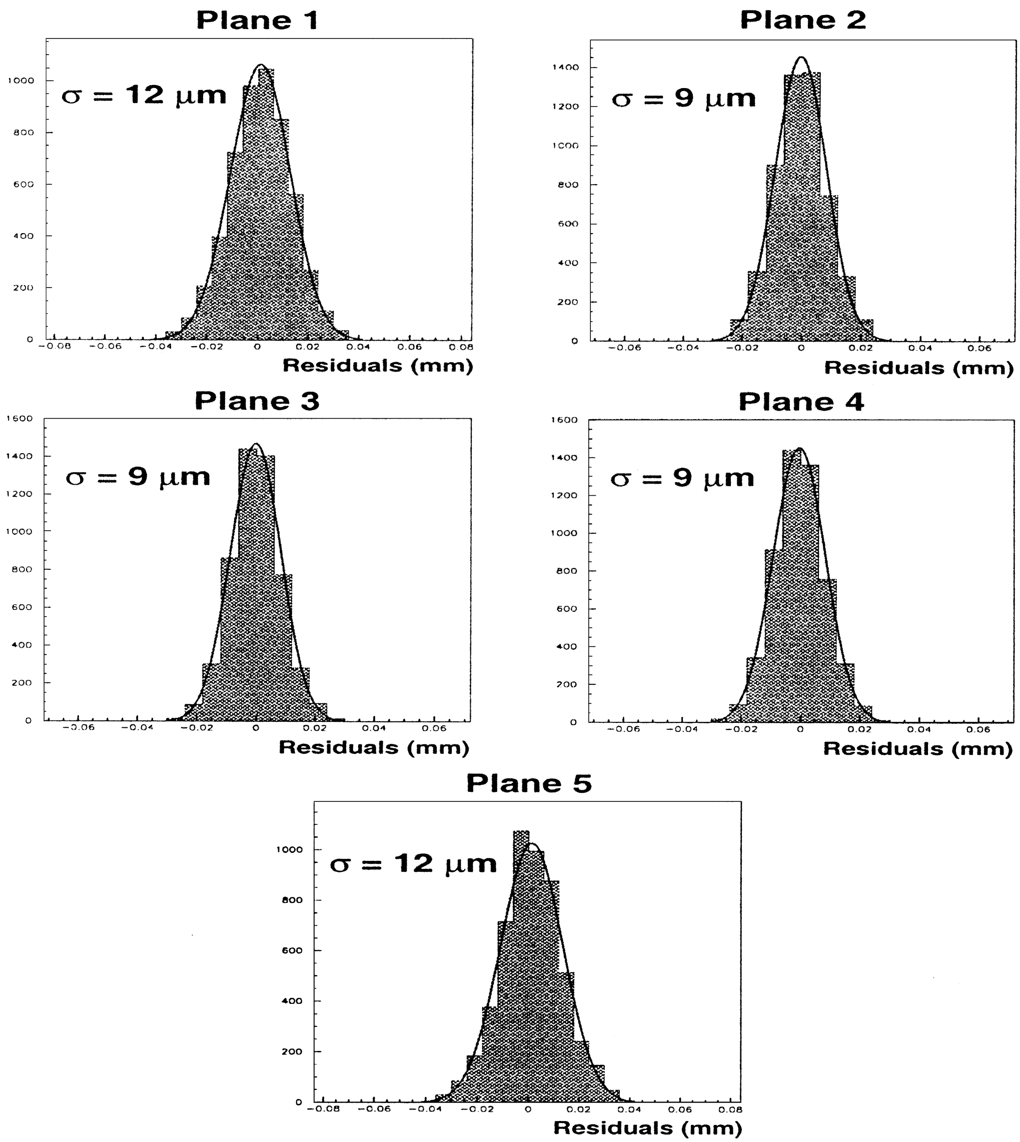

Fig. 12. Distribution of residuals after the alignment.

inner planes and in Z' for the whole detector. Once the outermost planes have been aligned, the alignment in XY of the inner layers and the alignment in Z are performed in an iterative way. Let us consider a set of ladders (5 ladders, one per plane, each one in the same position within a plane. See Fig. 9).

We only use tracks with hits in all planes. For the average of many tracks we have to correct the position of the ladder that makes the χ^2 of the track worst, or equivalently, the one which gives the best χ^2 when the hit is removed from the fit. We repeat this process until the χ^2 is stable (when the change is less than 1%). This operation has to be repeated for the 10 sets of ladders, performing both the alignment in XY and the alignment in Z.

- The alignment in XY (see Section 5.5) is done first, using very straight muons. Only ladders in the inner planes (2–4) are allowed to be corrected in order to keep the internal reference frame invariant (see Section 6.2).

- The alignment in Z (see Section 5.6) requires high angle tracks. It involves planes 2–5. Plane 1 defines the origin.

One can also perform a cross-check to make sure that everything is consistent. Having aligned two contiguous sets of ladders independently to each other, we can check that the residuals are centred at zero using the overlaps between them for the inner planes.

7. Results

Fig. 12 shows the residuals after the alignment for muons with high momentum ($p > 50$ GeV), and low angle ($\theta_{\text{muon}} \in [-0.5, 0.5]^\circ$).

We have found the error in the residuals to be 9 μm for the three inner planes (planes 2–4) and a higher value of 12 μm for the two outer planes (planes 1 and 5) as expected. This is an effect of the Kalman filter since in an inner plane we have information from both sides of the plane to predict the position of the hit. However, for an outermost plane, the information is only on one side. The error due to multiple scattering and the one related with the extrapolation is then larger in the case of the outermost planes.

8. Conclusions

The silicon-target NOMAD-STAR is made of ladders 72 cm long. Despite the large length of the modules, a very precise software alignment can be performed with muons passing through the detector. The precision of the alignment (error in the mean of the residuals) is better than 3 μm for all the ladders (depending on the statistics in each ladder). That is good enough to ensure that the impact parameter measurement needed for the identification of taus in a detector like NOMAD-STAR will not be limited by the error in the alignment.

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