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TRACK RECONSTRUCTION WITH A CENTRAL TWO-SHELL SCINTILLATING FIBRE TRACKER (SFT)

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Abstract

We present a track reconstruction algorithm designed for the scintillating fibre tracker (SFT), having in view the upgrade of the L3 detector for LEP II. This algorithm can also be applied for particle tracking at future hadron colliders. The tracking elements are polystyrene fibres of 60 μm diameter, which are arranged as fused coherent bundles into fibre layers. We study in particular a tracking set-up, which consists of two concentric cylindrical shells each of 8 mm thickness, placed at $r = 18.7$ cm and $r = 31.4$ cm radius from the collider axis. The tracking reconstruction algorithm was tested with Monte Carlo generated e^+e^- events at 185 GeV c.m. energy and by comparing them with the reconstructed events. It achieves for particle momenta above 0.2 GeV/c a track reconstruction efficiency of nearly 100% for primary charged tracks with less than 1% contribution of ghost tracks. The average error on the reconstructed momenta for single tracks is around 3% and the average error on the reconstructed total momentum per event is around 6%.

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1. INTRODUCTION

The actual layout of the L3 detector [1] at the Large Electron Positron (LEP) collider is well adapted for muon detection with its almost hermetic coverage of precisely positioned multiwire gas chambers. Also, the electromagnetic calorimeter composed of bismuth germanium oxide (BGO) crystals together with its BGO endcaps provides excellent electron and gamma detection at high momentum resolution. At present, the weak component of the detector is the tracking of charged particles inside the free barrel region bordered by the BGO crystal arrangement. Therefore, it has been proposed [2] to replace the present time expansion chamber (TEC) by fine grain scintillating fibres arranged in two or three concentric cylindrical shells with different radial distances from the collider beam. To increase further the polar angle ϑ coverage ($13^\circ < \vartheta < 167^\circ$), silicon strip disks (FSD) are foreseen to extend the scintillating fibre tracker (SFT) angular range ($26^\circ < \vartheta < 154^\circ$).

Particle detection with scintillating organic solids is a well-established method. It has been refined during the last decade by the fibre technique, where scintillating cylindrical cores of polystyrene with diameters ranging from several micrometres up to a few millimetres are surrounded by a cladding layer of lower refractive index [3]. These fibres trap by total reflections on their core-cladding interfaces a small fraction ($\sim 5\%$) of the scintillation light, induced by ionization losses, and guide it via many subsequent total reflections to the fibre ends. There, it is in most cases detected by the photocathode of a photomultiplier or of an image intensifier.

The cell dimensions of a fibre tracker are defined by the lengths and by the diameters of its individual fibres. Since these diameters reflect on the tracker's occupancy, its spatial and its 2-track resolution, we are interested in keeping them small. The lower limit is dictated mostly by reflection losses in the fibres. Realistic diameters of fibres range from $30\text{ }\mu\text{m}$ to $100\text{ }\mu\text{m}$. Such thin fibres must be produced as fused coherent bundles of rectangular cross-sections with edge dimensions between 1 mm and 3 mm [4].

Fig. 1 The L3 detector set-up used for Monte Carlo simulations.

Of course performance and precision in event reconstruction of such a tracking system of scintillating fibres must be verified with a simulation study as closely related to reality as possible before building the detector itself. For this purpose 185 GeV Monte Carlo events were generated and tracked into a simulated detector (Fig. 1), the hits of their charged particles were digitized, a pattern recognition algorithm was designed and applied for event reconstruction. The quality of the reconstructed tracks was evaluated, their momenta were determined, and the final results were compared with the original generated events.

2. LAYOUT OF THE SCINTILLATING FIBRE TRACKER (SFT)

The fibre tracker [2] covers the barrel region inside the BGO calorimeter with two cylindrical shells of 0.187 and 0.314 m radius (distance from LEP axis) and 8 mm thickness each (Figs. 2 and 3). Each shell is composed of four layers with different fibre orientation (Fig. 3). Fibres stretched parallel to the collider axis (ϕ -layers) indicate the (r, ϕ) -coordinates. The two other layers (u- and v- layers) with oblique fibres, running at angles α of 5 degrees with respect to the parallel ones, provide via their corresponding stereo view the z-coordinate of a particle track. In this way, the area to be covered with readout electronics comprises only the endsections of the fibre shells. This results in a tremendous reduction of readout channels as compared to semiconductor detectors, where, in contrast, the cylindrical surface of each detector layer must be covered by front-end electronics. To improve the magnetic flux density from 0.5 to 2 Tesla, a solenoid is mounted inside the barrel region (see Fig. 2).

Fig. 2 The r - z plane of the SFT and the superconducting solenoid. Together with the Silicon Microvertex Detector (SMD) and the Forward Silicon Disks (FSD) the inner tracking covers between 13 and 167 degrees polar angle (± 2 rapidity).

Fig. 3 Arrangement of the scintillating fibre shells. The magnified parts show the subdivision into the straight φ layers and the oblique u and v stereo layers. The z -coordinate is obtained through the measured symmetric angles β via the relation: $z = r\beta / \sin \alpha$, α = stereo angle between u (or v) and φ and r the radial distance.

A three-shell version without the barrel solenoid is also considered (the third shell is positioned at 0.45 m radius and the magnetic flux density provided by the large solenoid outside the muon chambers is 0.6 T). The track length inside the SFT would increase and therefore counterbalance the flux density difference of 1.4 T so that a similar momentum resolution would be achieved in the barrel region.

Fused fibre bundles of 1.35 m length with square cross-sections of 2 mm edges containing about 1000 individual fibres of 60 μm diameter are used. The individual fibres are of hexagonal shape and share their cladding accordingly with their adjacent neighbours resulting in a packing fraction (ratio between the scintillating and the total volume) of 0.85. The precision and the two-track resolution of this bundle arrangement are 18 μm and 42 μm , respectively [5].

The readout of fibre signals must preserve their spatial accuracy and their time resolution. At the same time it should cope with the large amount of 60 μm fibres (some 6 million), since it is hardly possible to read them individually. The adopted solution [2] is to read the fibres with proximity focused imaging tubes. The light coming from the fibres is, after transmission through the tube's optical fibre window, converted into electrons by a photocathode. These photoelectrons are accelerated by a potential difference to 15 keV towards the anode of the tube consisting of 10 silicon pixel chips. Each chip, 4 mm (φ) $\times$ 8 mm (r) in active surface, is organized as a pixel array of 16 lines (r) and 64 columns (φ) (Fig. 4). The pixel size is 500 μm (r) $\times$ 63 μm (φ). The pixel dimension in the radial direction covers 10 fibres. In this way, each readout tube views about 10^5 fibres with 10^4 pixels which cover 3.2 cm^2 of fibre-end cross-section. The fine segmentation in the φ -coordinate matches the bending direction of particle tracks in the solenoidal field, therefore preserving the precise position- and momentum-resolution achieved by the small fibre-diameters.

Fig. 4 Pixel readout organization.

Each pixel is coupled to its own, complete, electronic readout chain occupying the same silicon area. This readout chain contains a fast, charge-sensitive preamplifier (CSA), a comparator, a delay and a memory element [6]. The charge signal created by a photoelectron inside a pixel is amplified by the CSA, discriminated by the comparator and gated into the memory by a strobe signal. The binary data from the columns are sequentially clocked out as 16-bit words via parallel shift registers into an external 'first in first out' (FIFO) memory. The typical clock rate is 10 MHz, which enables one to read out the chip in 6.4 μs . For every tube, the 10 chips are read out in parallel. Finally, the data contained in the FIFO memories are sent via a fast transmission line towards the data acquisition system where on-line track information can be provided by digital signal processors within microseconds. Thus, the tracker would be able to provide a fast first-level trigger decision. To preserve the required spatial precision, the tubes would be oriented parallel to the solenoidal field of the detector. In this way, the electrons are spiralling along the magnetic flux lines. Field uniformities as expected for the L3 solenoid are more than sufficient to achieve the required spatial resolution of the readout tube.

Table 1

Comparison of the main parameters between the two-shell version of the scintillating fibre tracker (SFT) and the time expansion chamber (TEC).

Tracker	SFT	TEC
r_{inner} (mm)	187	110
r_{outer} (mm)	314	427
Length (mm)	1350	980
Coverage of polar angle ϑ [deg]	$26^\circ < \vartheta < 154^\circ$	$40^\circ < \vartheta < 140^\circ$
Fibres (SFT)/sense wires (TEC)	6.5×10^6	1392
Hits per particle track (average)	65	62
Lorentz angle (deg)	–	2.35
Cell busy time (μs)	< 0.1	9.5
Left/right ambiguity	no	yes
$\sigma_{r\varphi}$ (μm)	18	58
z-measurement	Stereo view	Z chambers
σ_z [μm]	300	700
$\sigma_{\text{double track}}$ [μm]	60	700

The main parameters of the two trackers (SFT and TEC) are compared in Table 1. Outstanding improvements would be achieved by the SFT for the two-track resolution, the z -measurement, the coverage of the polar angle and the detector-cell busy time, which determines the occupancy. The p_t momentum resolution versus the polar angle for a 60 GeV/c charged particle is shown in Fig. 5 for the two versions of the SFT and for TEC.

Fig. 5 Momentum resolution of 60 GeV/c electrons versus polar angle and rapidity for the TEC and the SFT.

3. EVENT GENERATION AND DETECTOR SIMULATION

Neglecting Bhabha events, the most frequent processes at LEP II will be $e^+e^- \rightarrow q\bar{q}$ and $e^+e^- \rightarrow W^+W^-$. For the event generation we have used the Monte Carlo package PYTHIA 5.6/JETSET 7.3 [7] with the parameter setting used in the L3 simulation program.

The SFT has been simulated, with GEANT 3.159 [8], as a component of the proposed L3 configuration for LEP II. Its readout tubes are positioned at both ends of each SFT shell. Geometry, materials and tracking media have been extracted from the current set of the L3 simulation programs. In detail, we selected only those L3 detector components that could have an influence on the SFT response (due to backscattering for instance): the beam pipe, the silicon microvertex detector (SMD), the superconducting coil and the barrel BGO.

In the detector simulation, whenever a track hits either a shell layer or a silicon disk, its space coordinates and its four-momentum components are stored into a file used as input for the digitization program [9]. A major advantage of the SFT is that it produces several hits per fibre layer: when a charged particle passes through a layer, the number of hits produced in the readout tube along the projected trajectory follows a Poisson distribution, i.e. the probability to have n hits within the path length t is:

$$P_n = \frac{(ht)^n}{n!} e^{-ht} \quad (1)$$

with h being the number of photoelectrons produced per mm thickness of scintillating fibres in r - ϕ projection:

$$h = 10 \times \left[e - \left(\frac{L}{2} + z \right) / \Lambda + 0.7 \times e - \left(\frac{3L}{2} - z \right) \right] / \sin \vartheta \text{ [mm}^{-1}\text{]}, \quad (2)$$

where z means the z -coordinate which is zero at the collider's interaction point, the factor 10 is the number of photoelectrons for $z = -675$ mm (next to the readout tubes), $L = 1350$ mm is the fibre length and $\Lambda = 780$ mm the attenuation length, obtained from an approximation of the measured hit density curve [10]; ϑ is the polar angle at which the particle intercepts the fibre. The first term in the square bracket is due to photons emitted from the particle interaction with a fibre layer, reaching directly the readout tube after a travel of z [mm]; the second term is due to photons travelling to the opposite end of the fibres, being reflected there by an end-face mirror back to the readout tube. Since the readout tubes occupy more space than the circumference of the cylindrical end-sections, they are alternatively arranged at the two end-sections ($z = \pm 0.68$ m) of each fibre shell. This is taken into account in the simulation.

The detected photoelectrons arise from Poisson-distributed particle hits along the trajectory. Moreover, the coordinates of each hit are smeared according to the fibres cross-section [$\Delta r_{\max} = 52 \mu\text{m}$, $\Delta(r-\varphi)_{\max} = 60 \mu\text{m}$]. Taking into account the hexagonal shape of the fibre cross-sections, the actual smearing is applied by flat distributions with $\sigma_r = 20 \mu\text{m}$ and $\sigma_{r-\varphi} = 22.5 \mu\text{m}$. The pixel readout for each tube consists of 10 silicon chips, each chip including 64×16 pixels in (φ, r) projection. Since the radial pixel dimension is much larger than the fibre cross-section, several fibre hits will produce a pixel signal. The intensity of the pixel signal is the sum of the intensity of the fibre hits. An example of the simulated pixel readout signals (with signal intensity by grey levels) in a small section of one shell for a LEP II event is shown in Fig. 6.

4. TRACK RECOGNITION ALGORITHM

The track recognition algorithm is based on the fact that each layer of the SFT provides not only position coordinates for the tracked particles, but also track directions (Fig. 6). Therefore, each layer yields microvectors which indicate precise roads to the following layer or shell with corresponding microvectors. These sequences of microvectors are the building blocks for the complete tracks. In this section, all steps, from the search for occupied pixels in the readout tubes until the completed tracks, will be detailed.

We expect that the pixels switched on (occupied) by a passing particle are aligned in a more or less contiguous way in each layer. Track reconstruction consists at first in recognizing the occupied pixels in each of the fibre layers which belong to a contiguous part of a track. We shall call this a microtrack (Fig. 6).

Fig. 6 Graphic display of the pixel readout for an inner shell section of the SFT. The shell thickness is 8 mm. Grey levels range from 0 photoelectrons in a pixel (white) to 8 or more photoelectrons in a pixel (black). In general, low- p_t tracks contain more occupied pixels but less photoelectrons per pixel. The layers boundaries are also shown.

To trace a particle track we choose the following strategy. First, we arbitrarily choose one occupied pixel in the ϕ_2 -layer of the outer shell to initiate the track search. Around this pixel we determine a window with a fixed width of two ($126\ \mu\text{m}$) or three ($189\ \mu\text{m}$) pixels in the ϕ -direction. Then, we move this window in steps on both sides of the initial pixel to look for another occupied pixel having lower or higher ϕ -values. This operation ends as soon as no new occupied pixels fall into the moved window. This window procedure is demonstrated in Fig. 7.

Fig. 7 By moving a window of width ϕ (in this example: 3 pixels or $189\ \mu\text{m}$) to the left or to the right of a randomly chosen initial occupied pixel, we find other occupied pixels forming a microtrack.

If a track has a gap in the ϕ -direction greater than the applied window width, our tracking algorithm will not identify it as one coherent microtrack. Instead, our procedure will lead to different microtracks aligned along the same track in the layer considered. This is most frequently the case for low- p_t tracks ($p_t < 0.2\ \text{GeV}/c$). These tracks produce big path lengths inside each layer (many pixels are occupied with only few or no photoelectrons) owing to their inclination versus the radial direction (see the marked microtracks in Fig. 6).

Once microtracks in all SFT layers have been found, we start pairing those of layer ϕ_2 with microtracks in layer ϕ_1 . To that end a straight line is fitted through each microtrack of layer ϕ_2 (see Fig. 8). This microtrack pairing procedure is done for all ϕ -layers of the inner and of the outer shell. Microtracks which could not be paired during this procedure are discarded from further analysis.

Fig. 8 By a straight line fit on the microtrack in layer ϕ_2 and considering the correct error propagation, we obtain a search corridor around the extrapolated central angle ϕ_c given by $[\phi_c + \Delta, \phi_c - \Delta]$. In this range we expect to find the microtrack in layer ϕ_1 corresponding to the original one in layer ϕ_2 .

The next step in track reconstruction consists in finding all symmetric microtracks in layers u and v which belong to the microtrack pairs ϕ_1 and ϕ_2 already found in the previous step. The microtracks (ϕ_1, ϕ_2, u, v) that belong to the same particle track form a *triplet*. There are two conditions which hold for a triplet:

- the microtracks in u and v must be symmetric in ϕ with respect to the microtrack pair (ϕ_1, ϕ_2) ;
- the angle β (Fig. 3) $= \Delta\phi$ between the microtracks u or v and ϕ must be smaller than $\beta_{\max} = 215$ mrad. This is a direct consequence of the stereo angle α between the u and v fibres and of the rapidity $\eta_{\max}$ covered by the outer shell: $\beta_{\max} = \sin \alpha \sinh \eta_{\max} \Delta\phi_{\max}$.

If these two conditions are satisfied, then the z -coordinate and its error can be calculated from the relations

$$z = r \Delta\phi / \sin \alpha \quad \text{and} \quad \sigma_z = \sigma_{r-\phi} / \sin \alpha . \quad (3)$$

Figure 9 shows an example of a triplet. After all triplets in the inner and outer shell have been found, the pixels in the u and v microtracks are shifted towards the expected track (i.e. shifted by $\pm\Delta\phi$, Fig. 10).

Fig. 9 A typical microtrack pattern from a particle passing through a tracker shell. The pixels in the layers u and v belonging to the track are shifted in positive and negative ϕ -direction by an angle $\Delta\phi$ which is proportional to the z -coordinate of the track. The ensemble of the four microtracks is called a *triplet*.

Fig. 10 The resulting track segment after shifting the u and v microtracks by $\Delta\phi$. The resulting ensemble of pixels is called *track segment*.

These newly formed objects are called *track segments*. Once such track segments are formed, we start pairing them from the outer shell with those in the inner shell, by first defining a search window in the inner shell. Under the assumption that particles move on a helix, we construct a probable circular trajectory (helix projected on the r - ϕ plane) defined by the following three conditions:

- the circle passes through the origin (interaction point of the collider);
- it passes through the centre of the outer shell track segment;
- its tangent at the centre of the outer shell track segment coincides with the direction indicated by this track segment.

Then we construct two other circles by changing only the third condition above, namely the tangent slope taken is now $\tan \omega \pm 4\sigma_{\tan \omega}$, with $\sigma_{\tan \omega}$ being the standard deviation of $\tan \omega$ given by the fitting procedure. As a result we obtain for the projection to the inner shell a $\Delta \approx 6\sigma_{\tan \omega}$ search window (from $\phi_{in} + \Delta$, $\phi_{in} - \Delta$) (Fig. 11) (this procedure is repeated for the u- and v-layers). In this window we will look for track segments. If the search is successful, both track segments in the inner and in the outer shell are assigned to one track. In case two track segments are found in the same window, the reconstructed z-coordinates of the track segments are used to remove this ambiguity. However, as the order of magnitude of Δ is ~ 10 mrad (which corresponds to ~ 1 mm on the inner shell), this ambiguity is rather improbable and the z-coordinates are used as a redundant check.

Fig. 11 Construction of a search window at the inner shell starting with a track segment from the outer shell. Three circles are constructed which define a search window of $\phi_{in} \pm \Delta\phi_{in}$.

5. RESULTS AND CONCLUSIONS

The event reconstruction consists in first recognizing particle tracks and then fitting them to extract the physical quantities for the analysis. In our algorithm this is done at the same time, since the microvector information already contains an approximation of the kinematical

quantities of the particle*. As a result of this procedure, track recognition efficiencies and ghost generation will be calculated and finally the reconstructed total momentum resolution per event and the reconstructed single-particle momenta resolutions will be derived.

Figure 12 displays a generated event in a front view of the detector. Some tracks seem to suddenly stop in the detector. The reason for this is that they simply leave the detector in the forward (or backward) direction. The same event, but this time reconstructed with our recognition algorithm, is shown in Fig. 13. We see that only the curling low- p_t tracks (less than 0.2 GeV/c) are not reconstructed: there is no need to find this type of track which, most of the time, is uninteresting from the physics point of view. The tracking reconstruction efficiency, found by comparing the generated with the reconstructed tracks on a statistical sample of 100 events, is roughly 98% for tracks with momenta higher than 0.2 GeV/c (note that primary tracks with momenta smaller than 0.1 GeV/c would not even reach the outer shell) and the percentage of ghost tracks (which carry only 1% on the average of the total momentum of the event) is less than 1%.

Fig. 12 Example of a generated LEP II event. Only tracks crossing the SFT are displayed.

Fig. 13 Example of the reconstructed event. Only the 24 tracks crossing both SFT shells are reconstructed.

* In particular, the fitting is done at present in the simplest possible way, by taking the centres of the reconstructed track segments in the outer and inner shells plus the beam position.

Let us now consider the quality of the event reconstruction. The most interesting criterium for this is to compare the total reconstructed (transverse) momentum P_t^{rec} per event to the generated one P_t^{gen} per event. The errors are defined as

$$\frac{\Delta P_t}{P_t^{\text{gen}}} = \frac{P_t^{\text{rec}} - P_t^{\text{gen}}}{P_t^{\text{gen}}} , \quad (4a)$$

$$\frac{\Delta P}{P^{\text{gen}}} = \frac{P^{\text{rec}} - P^{\text{gen}}}{P^{\text{gen}}} . \quad (4b)$$

The results for 100 events are reported in Fig. 14. The residual distributions for both P and P_t give a statistical error between 6% and 7% per event. The mean is practically zero, which proves that not reconstructing tracks below 0.2 GeV/c does not visibly affect the measured total momentum of the event.

Fig. 14 Distribution of the reconstructed total (transverse) momentum per event P (P_t) for 100 events analysed.

Another important test for the tracking algorithm is the quality of the reproduced single-particle momentum (p , p_t) and production angle (ϕ_0) at the origin. The relative momentum errors ($\delta p/p$, $\delta p_t/p_t$) are again defined according to relations (4), by replacing P with p and the angular error is given by

$$\delta \phi_0 = \phi_0^{\text{rec}} - \phi_0^{\text{gen}} . \quad (4c)$$

In Fig. 15, the absolute values of the errors (4a) and (4c) for single particles are shown versus p_t^{gen} . Since these errors vary with the momentum we calculated the average statistical error for p and p_t for three different ranges:

$$0.2 < p_t < 1 \text{ GeV/c}; \quad 1 < p_t < 10 \text{ GeV/c}; \quad 10 \text{ GeV/c} < p_t .$$

Fig. 15 Absolute value of $\delta p_t/p_t$ and $\delta\phi_0$ [Eqs. (4a),(4c)] for all reconstructed tracks versus p_t . A simple analytical estimation of the same quantities versus p_t [Eqs. (5a),(5b)] is also shown.

As we can see from the $\delta p_t/p_t$ distribution for $1 < p_t < 10$ GeV/c (Fig. 16), the error follows a Gaussian distribution the mean value of which is slightly shifted towards the negative side. The standard deviation of the distribution (sigma) varies between $\pm 2\%$ and $\pm 4\%$ for the three p_t ranges considered. A comparison between generated and reconstructed tracks is summarized in Table 2.

Table 2

Parameters of the $\delta p_t/p_t$ distributions, as obtained in three different p_t ranges.

p_t range [GeV/c]	Number of tracks	Mean value	Standard deviation
$0.2 < p_t < 1$	747	- 0.013	0.024
$1 < p_t < 10$	846	- 0.004	0.022
$10 < p_t$	129	- 0.0001	0.038

A shifted mean value means that on average the reconstructed p_t is slightly smaller than the generated one. This systematic error decreases with increasing p_t . Such a behaviour is understood in terms of energy loss by ionization within the tracker material: the values for the generated particle momenta correspond to the particles stemming from the e^+e^- collision, i.e. before any passage through the detector material. Therefore, these generated momenta are always slightly higher than the reconstructed ones. As ionization loss is almost independent of the particle momentum in the momentum range considered, the absolute systematic error stays nearly constant, resulting in a lower relative error for high- p_t tracks.

Fig. 16 Residual distribution for reconstructed p_t for $1 < p_t < 10$ GeV/c.

The size of sigma is mainly due to multiple scattering which induces deviations of particle directions. Only for momenta higher than 10 GeV/c does the measuring error become predominant. The curves superimposed in Fig. 15 are the following analytical estimates of $\delta p_t/p_t$ and $\delta\phi_0$ versus p_t :

$$\frac{\delta p_t}{p_t} = \sqrt{\left(\frac{4 \times 10^{-3}}{p_t}\right)^2 + (0.03)^2 + (1.7 \times 10^{-3} \times p_t)^2}, \quad (5a)$$

$$\delta\phi_0 = \sqrt{\left(\frac{2 \times 10^{-4}}{p_t^2}\right)^2 + \left(\frac{2 \times 10^{-1}}{p_t}\right)^2 + (2 \times 10^{-2})^2}. \quad (5b)$$

Both relations take the tracker material into account. The related energy loss and multiple scattering constitute the first and the second term in the square root, the third term represents the measuring error [4].

To conclude, the tracking and reconstruction algorithm applied to the SFT in a simulated LEP II environment shows that the detector performs well according to the requirements. Above 0.2 GeV/c, the reconstruction efficiency is close to 100% with less than 1% contribution of ghost tracks. The individual tracks are recognized in a rather fast tracking procedure through the two shells of the SFT. The granularity of the 60 μm fibres and of the pixel size in the readout tubes provides particle momenta with an average error of 3%. The average error on the reconstructed total momentum per event amounts to 6%, showing no visible effect for the loss of particles below 0.2 GeV/c.

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