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THE DESIGN AND THE CONSTRUCTION OF THE SCINTILLATING FIBER DETECTOR FOR THE UA2 EXPERIMENT

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Abstract

The scintillating fiber detector S.F.D. is a key part of the upgraded UA2 experiment. It includes 60 000 scintillating fibers 1 mm in diameter and 2 m long, arranged in 24 coaxial layers fitting in a cylindrical space from 760 to 880 mm in diameter around the $p\bar{p}$ intersection. The fiber layers are arranged in 8 stereo triplets. Each one contains one fiber set parallel to the axis, and 2 others inclined at angle $\pm 20^0$ on the average.

The S.F.D. has 2 separate functions : The inside layers give a precise localization of the particles, the outside layers also initiate the electromagnetic showers by conversion in a lead sheet 1.5 radiation length thick.

The main noteworthy characteristics are :

– Each fiber is optically tested. When not rejected, its scintillating efficiency and attenuation length are recorded.

– The position of every fiber in space is measured and recorded.

– Each fiber is individually read out.

Introduction

The possible use of scintillating fibers in detectors for elementary particle physics has been considered since the mid fifties. During the past several years remarkable advances in that technology have been achieved by means of an extensive research and development program in the Department of Elementary Particle Physics at Saclay [1]. A wide variety of applications to experimental elementary particle physics instrumentation is under consideration [2]. In this article we describe the specific application of this technology to the improvement program for the UA2 apparatus at the CERN Proton – Antiproton Collider [3]. The measurement of particle trajectories in the new central detector is complicated by severe spatial constraints. Figure 1 shows a section of the cylindrically symmetric geometry of the central detector. The Jet chamber Vertex Detector serves to reconstruct the interaction point along the beam axis. Photon conversions are identified by the Silicon Strip Detector and the Transition Radiation Detector gives improved electron identification efficiency. The purpose of the Scintillating Fiber Detector (SFD) is to provide good tracking efficiency and spatial resolution (< 1 mm) and good localisation of the electromagnetic shower origin, in order to reduce the overlap between electron and hadronic sources. The technical challenge is to achieve these goals in a region limited to a cylindrical shell 60 mm thick at an average radius of 413 mm.

General Description

A schematic view of the SFD is shown in figure 2. The mechanical stability tolerances of the detector are rigorous, since it is constrained on the outside by the central calorimeter and on the inside by the transition radiation detector. It is required to support the 250 kg layer of lead distributed non uniformly along the length of the cylinder, most of its weight at the center. Tolerances on the deformation of the detector are about a millimeter. The inner mechanical support for the detector is a cylindrical carbon fiber shell 3 mm thick, with an inner diameter of 766 mm

Eighteen layers of scintillating fibers of 1 mm diameter arranged in six triplets constitute the tracking part of the SFD. Each triplet consists of a layer of fibers parallel to the axis of the cylinder, and two layers of fibers placed at angles of $\pm 15^0 45$ with respect to the axis in order to allow a measurement of the position of the particle trajectory along the length of the cylinder. Outside this tracking region of the detector is another carbon fiber cylinder of 4 mm thick, upon which the layer of lead is mounted.

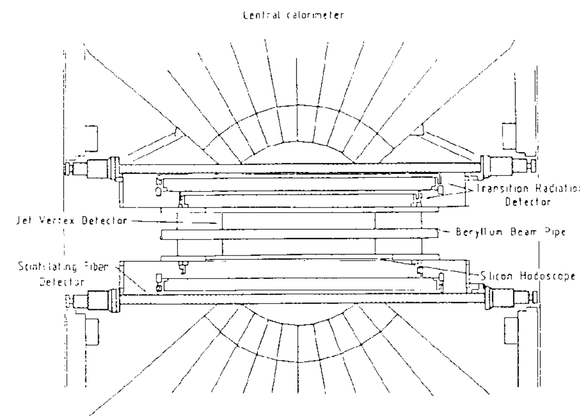

Figure 1. Vertical section of the cylindrically symmetric central detector of the UA2 upgrade.

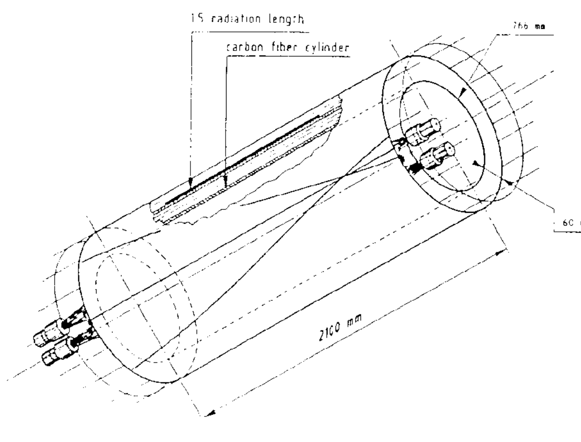

Figure 2. Schematic view of the scintillating fiber tracking and preshower detector

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The origin of an electromagnetic shower induced in the lead by the passage of an electron or photon can be detected in the six layers of scintillating fibers outside the lead. These layers are arranged in two triplets, the stereo layers angled at $\pm 21°$ with respect to the cylinder axis.

At each end of the cylinder, half of the sixty thousand fibers are glued into sixteen light collector plates which determine their positions as viewed by the readout chain. These plates arrange the fibers into 48 rows adapting the image to the 80 mm diameter circular face of the first image intensifier in the readout chain, and insuring a minimum distance between fiber centers of 1.3 mm. The fiber ends which are not viewed by the readout chains are polished and aluminized. A system of pulsed light injection allows the illumination of a pattern of fibers uniformly distributed throughout the light collector plate image, thus permitting the measurement of optical distortions in the readout chain.

The readout system, which is described in detail elsewhere [4], views the light collector plate with a chain of image intensifiers. The first demagnifies the image by a factor of four, focussing it onto a multichannel plate which has a gain of about 10^3. A final image intensifier focusses the image onto the 5.8 mm x 4.3 mm photosensitive surface of a charge – coupled device (CCD), which stores the image. The CCD can be cleared during the 4 μs between beam crossings in the case that no readout trigger is generated by the UA2 first level trigger. When the readout is triggered the multiplexed output of each CCD is digitized by a flash ADC and the result is stored in the UA2 data acquisition. The performance of the readout chain and the associated electronics has been measured in a test of a prototype scintillating – fiber tracking and preshower detector in beams of pions, electrons, and muons. Results on detection efficiency, position resolution, shower detection, and track/shower association are available in reference 4.

Physical Properties of Scintillating Fibers

The core material of the scintillating fibers consists of purified polystyrene. The delocalized electrons of the phenyl radicals in this material enhance its scintillation properties. Wavelength shifters in the core material serve to shift the spectrum of the light emitted by the polystyrene from an average of 300 nm to an average of 430 nm. The high degree of transparency of polystyrene for wavelengths between 400 nm and 500 nm then permits propagation of light over long distances, resulting in the attenuation lengths of 1.5 – 2.0 meters characteristic of these fibers. It is worth mentionning that after 1 m propagation the light spectrum is at an average of 450 nm. Furthermore, these shifted wave lengths are well adapted to the spectral response of many photocathodes.

The high index of refraction of polystyrene (~ 1.6) allows a large numerical aperture without recourse to optical cladding of very low index (fluorine or silicon based), which poses a variety of problems : crystallinity (and hence diffusion), adherence, and application. For the optical cladding of the UA2 fibers, a polyvinyl acetate was used to provide adequate protection to the fiber core. Its index of refraction of 1.46 allows the capture of the scintillation light emitted in a cone of angle 23°, which constitutes an excellent performance for optical fibers (figure 3). Table I lists the principal characteristics of the fibers used in the fabrication of the UA2 detector.

For applications in elementary particle physics instrumentation, the radiation hardness of scintillating plastic fibers is an issue of primary importance. The deterioration of their performance is due principally to the increasing opacity of polystyrene to the scintillation light, effectively reducing the attenuation length. Figure 4 shows the results of a study [5] of the induced absorption of polystyrene optical fibers when subjected to doses of ^{60}Co γ – rays up to 10^7 rads. For a dose of 10^6 rads, an

Table I: Optical and mechanical properties of the UA2 scintillating fibers

Index of refraction of the core at 450 nm	1.61
Index of refraction of the cladding	1.463
Numerical aperture	0.62 ($\pm$ 38°)
Internal angle of numerical aperture (θ)	23°
Capture efficiency (1 – cos (θ)/2)	0.04
Wavelength of scintillation light	450 nm
Scintillation decay time	3 nsec
Attenuation length	1.5 – 2.0 m
Tolerance on diameter	3 %
Thickness of cladding	10 $\pm$ 2.5 μ
Maximum temperature	70° C
Minimum radius of curvature	150 mm

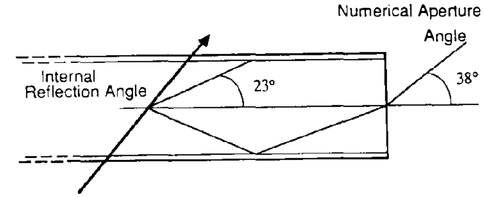

Figure 3. The numerical aperture of polystyrene fibers cladded with polyvinyl acetate.

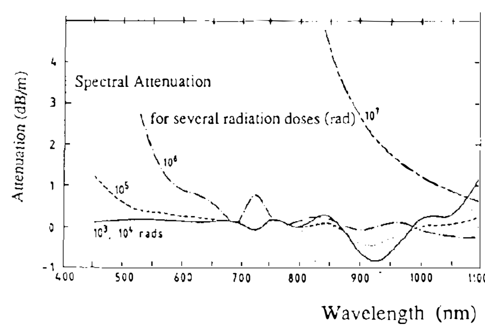

Figure 4. Attenuation induced in polystyrene fibers by various radiation doses (see ref.5)

induced absorption of under 1 dB/m was observed for wavelengths of 500 nm. A more recent study [6] of the attenuation induced in polystyrene fibers by ^{60}Co radiation yielded values of 2.0 dB/m and 3.4 dB/m for doses of 0.9×10^6 rads and 2.5×10^6 rads respectively. This may be compared to the intrinsic spectral attenuation of polystyrene fibers shown in figure 5.

Figure 6 shows the light yield as a function of the distance between a phototube (RTC XP 2262 B) and a ^{90}Sr source, for 2.3 m long fibers polished at both ends. The curve in figure 6a is the result of a fit to the yield using the sum of two exponential functions. In figure 6b the measurements are shown for fibers where a reflector was placed at the end opposite the phototube. The curve is obtained from the fit in figure 6a assuming a reflection coefficient of 55 %.

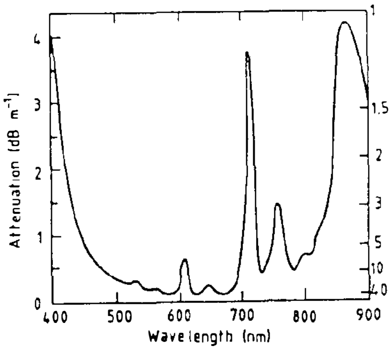

Figure 5. Spectral attenuation of 0.5 mm diameter polystyrene fibers.

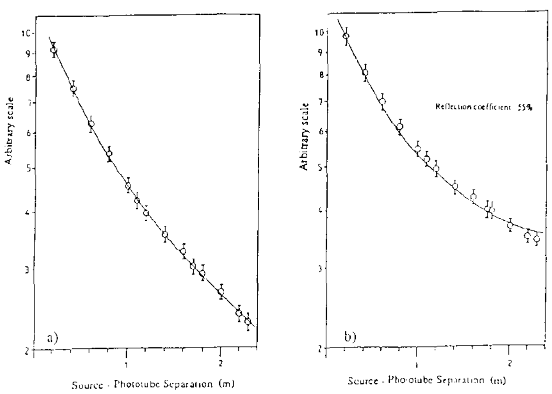

Figure 6. Light yield for UA2 fibers as a function of source – phototube separation.
a) Without reflector. The curve is the result of a fit to the sum of two exponential functions, yielding attenuation lengths of 0.46 and 2.35 m.
b) With reflector. The curve uses the result of a) and assumes a reflection coefficient of 55 %.

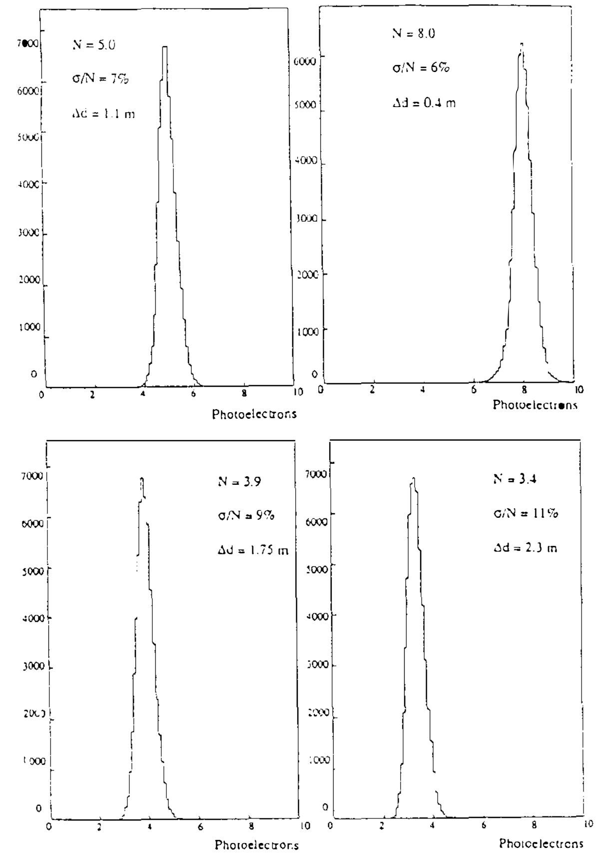

Figure 7. The light yield in units of photoelectrons/minimum – ionising particle for the 60 000 fibers used in the UA2 detector for four source – phototube distances.

During the construction phase of the SFD, the light yield and attenuation of all the fibers was monitored and recorded. Figure 7 shows the light yield measured for all 60 000 fibers used in the construction of the detector, measured at four source – phototube distances. Figure 8 shows the degree of uniformity as a function of layer number. Finally, figure 9 shows the average yields measured for all the fibers as a function of the source – phototube distance. Also shown is the parametrisation weighted by the sine of the production angle of a particle emanating from the center of the UA2 detector, i. e., the correction for the path length of a straight trajectory through a fiber. The worst case is a particle close to perpendicular to the fibers at the center of the detector. To estimate the performance of the detector a further normalization is needed to account for the efficiency of the image – intensifier chain ands its coupling to the fibers. The beam tests with the full readout chain described in reference 4 showed that a minimum ionizing particle passing through the fiber at a distance of 1.3 m from the light collector plate produces 2.8 photoelectrons at the first photocathode, corresponding to an efficiency ~ 90 %.

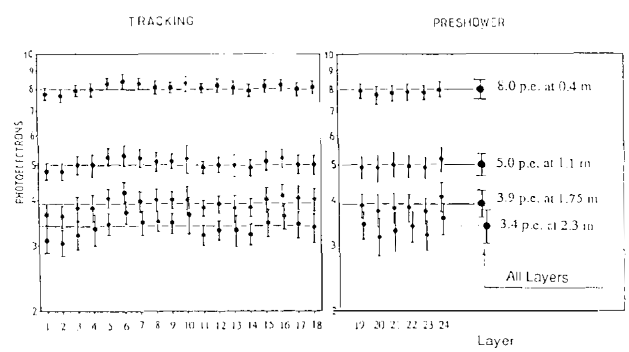

Figure 8. The uniformity in light yield of the UA2 fibers as a function of layer number. The error bars represent the σ of the corresponding distributions.

Fabrication of the Scintillating Fibers

The scintillating optical fibers are obtained from the heating and drawing of preformed cylindrical bars 30 – 40 mm in diameter and 400 – 700 mm long. These bars were fabricated and doped with wavelength shifters at Optectron [7] . Each provided roughly 500 meters of 1 mm diameter fiber. The entire operation of producing the fibers consists of six principal steps, each requiring a specific detailed technology :

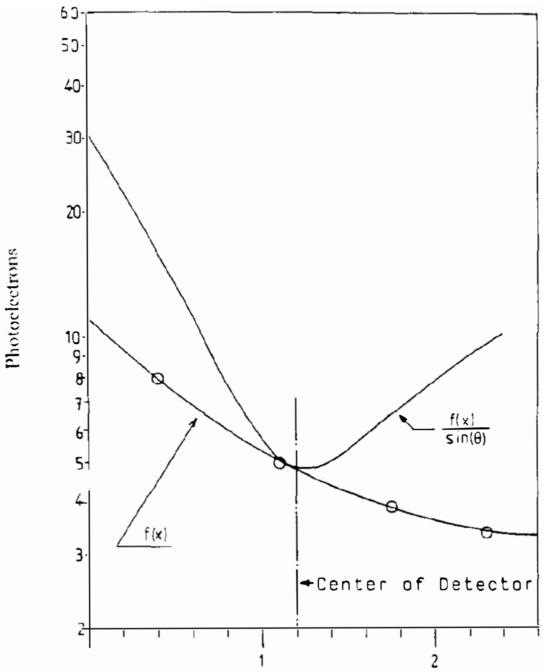

Figure 9. The average light yield of the UA2 fibers for the four Source positions. Also shown is the correction for the increased path length in the fiber for a particle produced at the center of the detector.

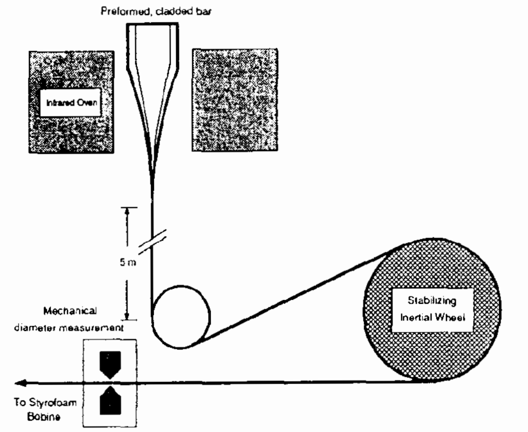

Figure 10. Schematic diagram of the fiber – drawing apparatus.

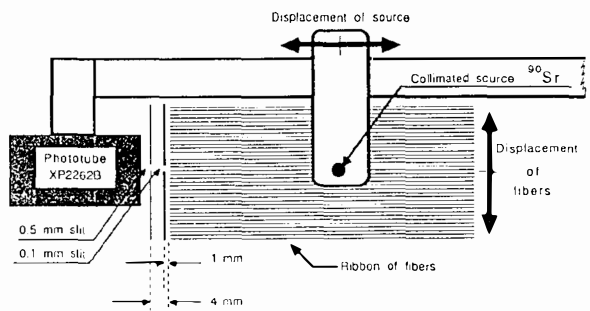

Figure 11. Test bench used to monitor the light yield of the fibers used in the construction of the detector.

– Purification of the monomer (styrene), eliminating stabilisers and other impuruties. At the end of this step the fluorescent materials butyl – PBD and dimethyl – POPOP are added to the monomer.

Polymerization performed in vacuum.

– The milling and polishing of the preformed bars.

– The deposition of the optical cladding material and the subsequent evaporation of the solvent.

– The drawing of the bar heated to a temperature of 200 – 210° C in an infra red oven (figure 10). The diameter of the resulting fiber is controlled by adjusting the speed with which the fiber is pulled.

– The aluminization of the fibers is performed by sputtering at Vacotec [8] , in order to avoid cross – talk and increase the mechanical protection. The 500 meters of fiber stored on styrofoam spools were passed through a sputtering apparatus, resulting in a layer of about 0.1 micron of aluminum. The light yield for samples of the aluminized fiber was monitored during the operation. The sputtering process was shown to reduce the yield of the fibers by less than 5 %.

The Assembly of the Detector

The Preparation of the Ribbons

As described in the General description, each layer of fibers was subdivided into 32 azimuthal regions. Hence the first step in assembling the detector was to arrange the fibers in ribbons corresponding to an azimuthal angle of $2\pi/32$ to an accuracy of half a fiber width. This step was performed at Gantois [9] , where 74 – 84 fibers (depending on the radius and stereo angle of the layer) were placed adjacent on adhesive strips, and were cut to 2.6 m lengths.

The light yield of each of the fibers was then monitored on a calibrated test bench at Saclay (figure 11). The test bench consisted of a light – tight box, inside of which were mounted a photomultiplier tube, a ^{90}Sr source, an aluminum beam to support a ribbon of fibers, and stepping motors to allow the displacement of the source along the length of the fibers, and of the ribbon across the face of the phototube. The light from the fibers was collimated by two slots 0.5 mm and 0.1 mm wide separated by 3 mm. The stepping motor advanced the ribbon in steps of 0.1 mm and allowed the determination of the light yield of an individual fiber in about ten bins, peaking at the center of the fiber. The yield of the fibers was normalized to the yield for minimum ionizing particles of fibers used in the beam tests described in reference 4. All fibers to be used in the construction of the detectors were required to yield at least 4 photoelectrons, from the XP2262B photocathode, per minimum ionizing particle at a distance of 1.1 m. This standard necessitated the replacement of about 20 % of the fibers, resulting in the uniformity shown in figure 8.

After the light yield verification, stacks of about forty ribbons were polished and aluminized on one end. The sputtered aluminum coating performed by C.D.V. [10] achieved a reflection coefficient of about 50 %. The light yield of all the fibers was again measured on the test bench in order to monitor the quality of the aluminization. A black varnish was then applied to the aluminized ends of all fibers not intended to serve as fiducial fibers for the light injection system. The transmission coefficient of a few percent sufficed in providing the pattern of fiducial fibers illuminated by the calibration – flasher system. The light from the flasher system was distributed over the ends of the ribbons containing fiducial fibers by 1 mm thick diffusing acrylic plaquettes illuminated with optical fibers

The Rolling of Cylindrical Layers

Two cylindrical carbon–fiber shells 3 mm and 4 mm thick were used as mechanical support for the fiber layers, corresponding to the tracking and preshower sections. The cylinders were constructed by the Société Courtaulds [11]. The preshower cylinder was wrapped in lead sheets which were then milled in such a manner that any linear trajectory from the center of the cylinder traverses 1.5 radiation lengths (8.4 mm) of lead. Hence the radial thickness of the lead varied from 8.4 mm at the middle of the cylinder to 5.8 mm at the ends of the preshower region, which was 1100 mm long (figure 12). A layer of Rohacell was then added and milled to achieve a cylinder of 433 mm radius.

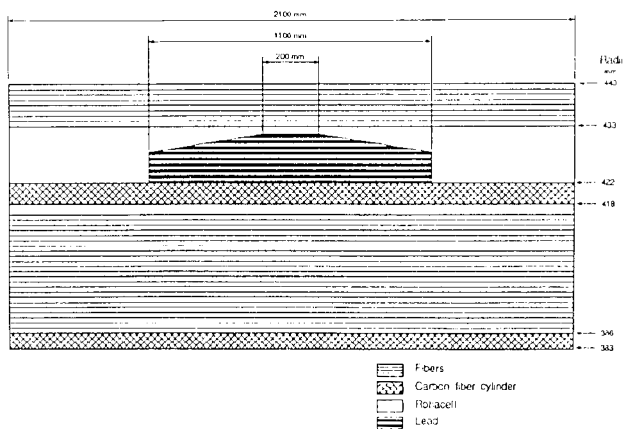

Figure 12. Section of the scintillating–fiber detector showing the tracking, lead, and preshower regions to scale.

In preparation for the application of a layer of fibers to the cylinder, the 32 ribbons were placed adjacent on a steel table 3 m × 4 m, levelled to an accuracy of a few tenths of a millimeter. Their adhesive backing was then exposed and the cylinder, suspended on a motor–driven axle, was rolled one revolution, moving the length of the table. The mechanical tolerances of the system were such that the gap between the first and last fiber was typically a few tenths of a millimeter and uniform along the length of the cylinder. Between each triplet of layers a 4 mm thick layer of Rohacell was applied and milled to thickness of ~ 1 mm, to re-establish the uniformity of the radius. After each layer was rolled onto the cylinder, a position–sensitive transducer was used to sample the radius of the cylinder 20 000 times in one revolution (about 8 times per fiber) with an accuracy of a few microns and the result stored on floppy disk for five different longitudinal locations. These data allowed the reconstruction of the relative fiber positions for survey information. Figures 13 and 14 indicate the degree of uniformity achieved in fiber position. Occasional gaps of a few tenths of a millimeter occurred between ribbons.

Preparation of the light collector plates

The 32 light–collector plates were mounted on the tracking cylinder and the fibers threaded into the holes as each layer was added. Once the preshower and tracking cylinders had been fitted together in their concentric positions, the remaining preshower fibers were threaded into the corresponding holes in the light collector plates. In final preparation for the optical contact with the image–intensifier chains, the fibers were then potted with a resin glue, milled flat, and polished (figure 15).

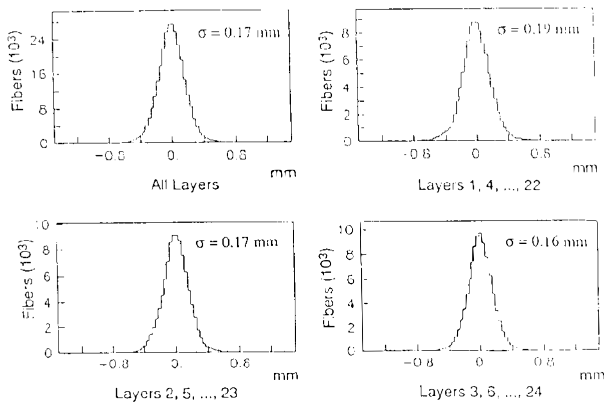

Figure 13. The deviation of the measurement fiber positions from a survey parametrisation which uses an azimuthal origin, an azimuthal width, and a stereo angle for each of the 24 × 32 ribbons of fibers.

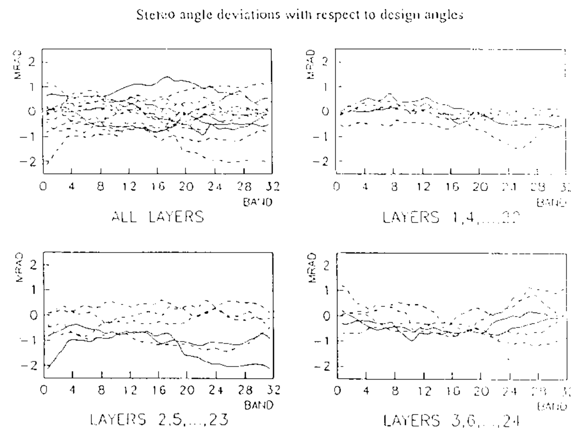

Figure 14. The deviations of the measured stereo angles from the design values.

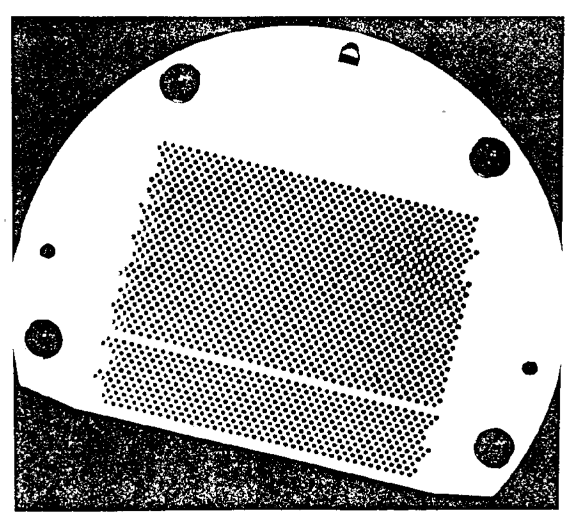

Figure 15. A light collector plate with the fibers inserted, glued, and polished.

Conclusion

The development by SACLAY of efficient clad scintillating fibers allow the realization of new detectors. Capitalizing on a longterm reseach and development program in that technology, the STIPE division of the Department of Elementary Particle Physics has constructed a tracking and preshower detector for the UA2 improvement program. Stringent efficiency, resolution, and measurement redundancy requirements have been satisfied, despite severe spatial constraints. The pipelined nature of the fabrication and assembly procedures allowed the timely completion of the project. The construction phase of the project began with the initiation of fiber fabrication in July of 1986, and culminated with the installation of the scintillating–fiber tracking and preshower detector in the UA2 apparatus during the first week in May. 1987. From a general point of view, fiber detectors display several important advantages, such as compactness, fastness, hermeticity, resistance to radiation damage and fine grain resolution. For these reasons, they seem to be particularly well suited to the requirements of the next generation of high energy accelerators.

Acknowledgements

The construction of the SFD required a number of widely varying technical tasks. We would like to recognize the competence and dedication of the STIPE technical staff in its rapid and ingenious execution of these tasks. In particular the contribution of the teams involved in the fiber fabrication and testing, detector design and assembly is greatly acknowledged. Further thanks are in order to the EF division at CERN, which supervised the aluminization of the fibers at Vacotec. The novelty of the industrial expertise rendered necessary detailed collaboration with the staffs of Optectron, Vacotec, Gantois, C.D.V, and Courtaulds. Without the pleasant and fruitful interactions which occured, the successful completion of the project would have been jeopardized. Finally, we would like to cite the valuable counsel of Jean - Marc Gaillard and Otto Gildemeister as indispensable to the task of integrating the detector into the UA2 apparatus.

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