Experimental Study of a Cylindrical Scintillating Fiber Detector

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Abstract

A tracking detector made of scintillating fibers is being developed at FNAL, for the experiment E835. The tracker will be used for the measurement of the polar angle θ, i.e. of the coordinate along the beam.

The small amount of light from the fibers will be detected by solid state devices (Visible Light Photon Counters) with very high quantum efficiency.

This paper reports the performance of a fiber tracker prototype, as measured at FNAL. We present results on light yield/mip, efficiency and homogeneity of response.

We measured an average number of about 14 photoelectrons per mip and an efficiency higher than 99 %.

I. Introduction

The experiment E760 at FNAL has studied the spectroscopy of $c\bar{c}$ bound states, formed in $p\bar{p}$ annihilations. An upgrade of the detector is in progress, in preparation for the next data taking period (experiment E835 [1]), scheduled to start in early 1996. In order to be able to withstand the proposed factor 5 increase in luminosity, the existing inner tracking detectors have to be replaced or modified. The requirements for such detectors are: angular resolution of the order of a few milliradians, high efficiency and high-rate capability.

We investigated the possibility to use a scintillating fiber tracker for the measurement of the polar angle θ, i.e. of the coordinate along the beam axis. Due to the recent improvements in both fiber technology and photon detection techniques[2], a double layered tracker with the above requirements is feasible. In order to provide the required angular coverage (full azimuthal coverage, and θ acceptance from 15 to 65 degrees) each layer will be a cylinder with $\sim$ 15 cm radius and $\sim$ 50 cm length. Analog signals from the fibers will be discriminated and OR-ed together in order to have a first level trigger based on θ.

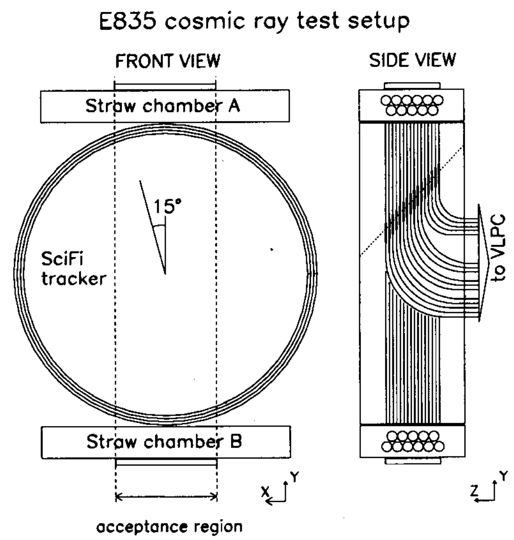

Figure 1: Layout of the apparatus for the cosmic ray test: dashed lines show the acceptance constraints imposed by the trigger counters; a dotted line indicate the junction between scintillating and clear fibers

II. Prototype construction

In order to understand the mechanical problems arising from the design, and to verify light output and reliability of such a detector, we built a prototype with about one tenth the number of channels.

The prototype (fig.1) is composed of two layers of $\sim$ 50 scintillating fibers each, wrapped on two concentric cylinders, made of acrylic material. The fibers have been properly positioned into V-shaped grooves dug on the cylinder surface. The groove depth is linearly increasing with ϕ, so that, after one turn, each fiber overlaps itself radially: in this way each scintillating fiber will describe a spiral on the plane normal to the cylinder axis (z axis). The inner cylinder has 56 fibers, 93.5 cm long, with a pitch of 1.016 mm; the outer cylinder has 48 fibers, 98.5 cm long, 1.196

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mm pitch. The thickness of the cylinders on the prototype is 3.175 mm and the maximum groove depth is 1.524 mm. The fiber diameter is 0.835 mm, with a core diameter of 0.744 mm.

The scintillating fibers used (Kuraray SCSF-3HF Multiclad) consist of a polystyrene core, doped with 1.25% p-terphenyl, and 1500 ppm 3-hydroxyflavone (3HF). The latter acts also as a wavelength shifter ($\lambda_{em} \approx 530$ nm), minimizing self-absorption of the light in the fiber core: the attenuation length has been measured [3] by the D0 collaboration on both scintillating ($L_{att} = 5.5$m) and clear ($L_{att} = 10.4$m) fibers.

In order to increase the light yield, the far end of 46 fibers (22 in the inner cylinder, 24 in the outer one) has been polished and a thin aluminum layer has been deposited on the surface.

Each fiber is coupled to a 4 meter long Kuraray Clear Multiclad lightguide, 0.835 mm in diameter. The optical connection between scintillating and clear fiber is a critical point: in order to achieve the highest possible transmission efficiency across the junction, the two fiber ends were polished with a diamond fly cutter [4] and thermally spliced together by a flash lamp. To protect the junction from transversal stresses, the splicing point has been covered with a 2 cm long heat-shrinking sleeve.

Due to the physical constraints imposed by the detector geometry, the clear fibers have to be bent a few centimeters downstream of the junction, with a bending angle of 90 degrees, and curvature radii from 2 cm to 6 cm. Fibers were assembled in a clean room, where the ambient light was screened using Kodak 0302 filters, to avoid UV damage of the SCSF-3HF fibers [5]. After the assembly, fibers were checked with a movable UV source: 2 fibers were reported to be broken (one due to mishandling, one due to a bad splicing quality), and the precision of fiber positioning was measured to be better than 100 μm.

III. Cosmic Ray Tests

GaAs or silicon based photosensitive devices are needed to ensure high quantum efficiency in the green region of the visible spectrum, and very interesting results have been achieved in recent years [6, 7]. The Visible Light Photon Counters (VLPC), manufactured by the Rockwell International Science Center, are solid state devices with very high quantum efficiency ($\simeq 60\%$) and a gain in the range $10^4 \div 10^5$. Their operational principles have been extensively described elsewhere [8, 9]

The VLPCs used in this test, labeled HISTE-IV, are produced in chips with 8 round pixels each (1mm diameter) and are mounted in modules (*cassettes*), with 128 channels each; the cassettes are then put in a liquid helium cryostat to maintain the devices at an operating temperature between 6 K and 7 K. The characterization, test and development of these devices have been carried out by the D0 Fiber Tracking Group with our collaboration.

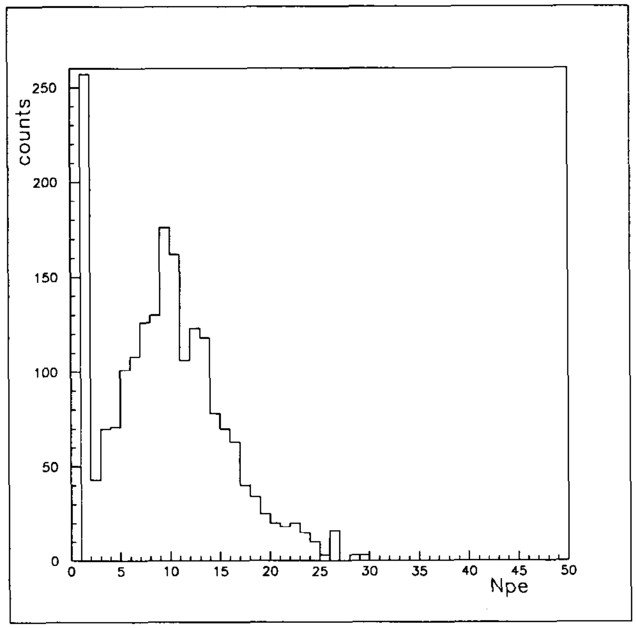

Figure 2: Signal distribution from a single fiber. The horizontal scale is in photoelectrons.

Two independent setups (prototype, trigger scintillators and additional tracking detectors), sharing a common data acquisition system, have been installed by the D0 [10] and E835 collaborations, maximizing the acceptance overlap between the detectors. The E835 test setup is shown in fig. 1. The geometric acceptance is defined by two $5.5 \times 10\ cm^2$ trigger scintillators, which select cosmic ray tracks with a maximum inclination of 17.6^o with respect to the vertical direction. Each recorded cosmic track is expected to intersect twice both fiber cylinders, in two regions corresponding to $\sim 20\%$ of the entire active area of the prototype. The cosmic ray trigger was provided by the triple coincidence between the two above mentioned counters and one scintillator of the D0 setup (not shown in the figure). The trigger rate was about 0.1 Hz. An additional tracking system consists of two straw tube detectors, one above and one below the scintillating fiber prototype. Each detector consists of 11 straw tubes, 1 cm in diameter, arranged in two staggered layers.

The light produced in the scintillating fibers was transmitted through the clear fibers to the VLPC system. Signals from the VLPCs were amplified using QPA02 preamplifiers [11] and then digitized by Fastbus 1885N LeCroy ADCs, with an integration time of 100 ns. The VLPC system was calibrated sending light pulses to each fiber, from a LED source.

IV. Results and Discussion

We report here the results of the analysis of approximately 50000 cosmic rays tracks taken at constant VLPC temper-

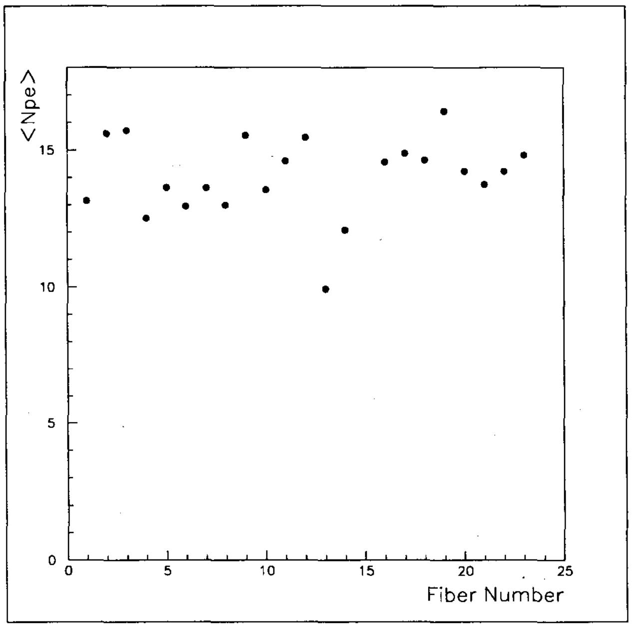

Figure 3: Average number of photoelectrons for fibers with mirrored end

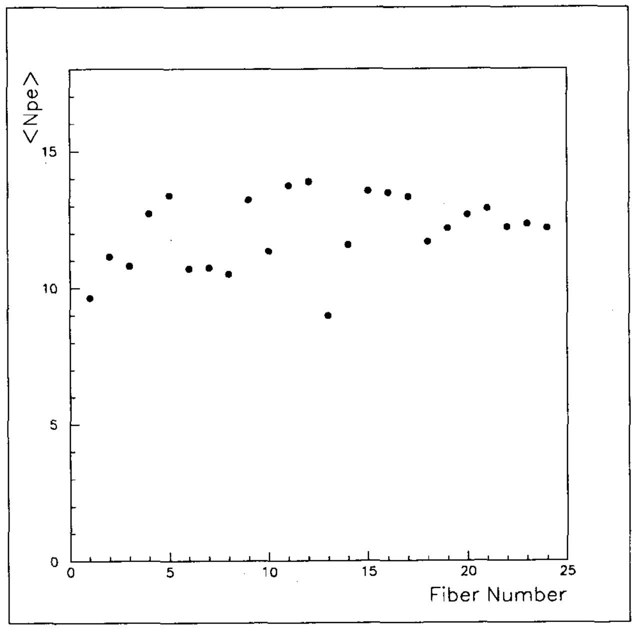

Figure 4: Average number of photoelectrons for fibers with non mirrored end

ature (T=6.5 K) and 2 different bias voltages (V_{bias}=6.5 V and 6.8 V). The data were collected over a period of several months, when our prototype was connected to one VLPC cassette.

Fig. 2 shows a typical signal distribution from a single fiber, with a cut at 1 photoelectron. From such a distribution we can extract the average number of photoelectrons and its dispersion.

The average number of photoelectrons from all fibers of the outer cylinder as a function of fiber number is shown as an example in fig. 3 for the fibers with aluminized end and in fig. 4 for those with non aluminized end. Table 1 summarizes the number of photoelectrons, averaged over the entire detector, for the two bias voltage settings and for the two types of fiber. These values are obtained by linear fits to distributions such as the ones shown in figures 3 and 4. We observe that the average signal increases by about 10 % when going from 6.5 V to 6.8 V and that the fibers with aluminized end show an increase of more than 20 % in light yield. The data in figs. 3 and 4 show a spread of less than 20 % in the average number of photoelectrons, which is an indication of good homogeneity in the detector response.

Table 1
Average number of photoelectrons for various settings

	6.5 V	6.8 V
mirror	13.6 ± 0.3	14.6 ± 0.3
no mirror	11.0 ± 0.3	12.2 ± 0.3

Table 2
Efficiency values for the two bias voltages and for various cuts on the fiber signal.

cut	6.5 V	6.8 V
1.5 pe	99.3 %	99.9 %
2.5 pe	98.2 %	99.4 %
3.5 pe	96.8 %	98.4 %

To check if there is a macroscopic deterioration in light output due to the bending of the clear fibers we looked for a possible correlation between the average number of photoelectrons from each fiber and the bending radius. No such correlation was found, as can be seen from figures 3 and 4, where the bending radius increases with the fiber number.

In order to evaluate the efficiency of the fiber tracker prototype we first reconstructed the cosmic ray tracks using the straw tube detectors. These tracks were extrapolated on the fiber detector and the residuals were then computed between the reconstructed track and the nearest hit fiber. A fiber was defined as hit if it gave a signal above a certain threshold. The efficiency was then computed as the percentage of events in which a hit fiber was spatially correlated to the external track. The raw efficiency obtained in this way is essentially the geometric acceptance, i.e. about 93 % for the inner and 86 % for the outer layer. Table 2 shows the final efficiency values for the two operating voltages and for various cuts on the fiber signals,

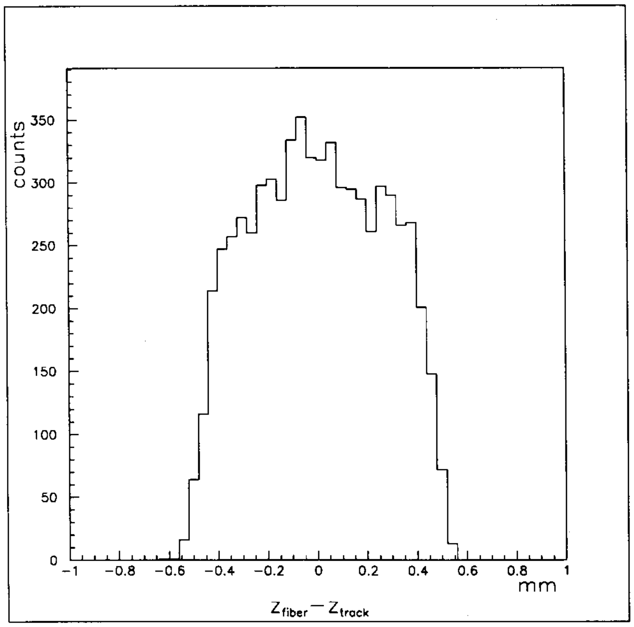

Figure 5: Track residuals (Monte Carlo)

after correcting for acceptance (by Monte Carlo) and dead channels. All numbers in table 2 have an error of $\pm$ 1%. We note that, for each given bias voltage, there is a decrease of a few percent in efficiency as the cut on the fiber signal is increased. This is consistent with the fraction of tracks whose path inside the fiber is so small that the number of photoelectrons produced is smaller than the cut, as we checked by Monte Carlo. We finally observe that the efficiency is slighly higher for the higher bias voltage.

Monte Carlo simulations have been made to evaluate efficiency and resolution of the detector in the final design. This consists of two layers with radii of 144 mm and 152 mm, with pitches between fibers of 1.1 mm and 1.16 mm respectively. Tracks originating from a non point-like interaction region ($\sigma_{x,y} = 2.5mm, \sigma_z = 3.0mm$) were generated, and the interactions with the 2 layers of the detector were simulated.

The single track efficiencies of the inner and outer layers were found to be 92.2 % and 90.7 % respectively, yielding a combined efficiency of 99.8 %, with the requirement of at least one hit and a cut on the fiber signal at 3.5 photoelectrons.

The resolution has been evaluated from the distribution of the residual $z_{fiber} - z_{track}$. Such a distribution, for the case of one hit fiber, is shown in fig. 5. A fit to this plot gives a value $\sigma = 250\mu m$, which is consistent with the expected value ($744\mu m/\sqrt{12}$).

V. Conclusions

We studied the performances of a scintillating fiber detector with cylindrical geometry, whose development has been possible thanks to the availability of high light-yield fibers and high quantum efficiency photon detectors (VLPC). The average number of photoelectrons has been measured to be 13.6 at 6.5 V bias voltage. No decrease in light yield has been found due to bending of the clear fibers. We measured an efficiency in excess of 99 %. These performances meet well the requirements for the scintillating fiber detector for the E835 experiment.

VI. Acknowledgments

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