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Use Of Plastic Optical Fibers For Charged Particle Tracking In High Energy Physics

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USE OF PLASTIC OPTICAL FIBERS FOR CHARGED PARTICLE TRACKING IN HIGH ENERGY PHYSICS

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ABSTRACT

A large tracking detector consisting of scintillating plastic optical fibers has been chosen by the D0 collaboration as a part of a planned upgrade at the Fermilab Tevatron. The tracker will utilize a state of the art photodetector known as the Visible Light Photon Counter. The benefits of fiber tracking in high energy physics will be presented along with recent progress in several key areas, including: optimization of scintillating dyes and light yields, fiber construction, fiber ribbon manufacture and placement, optical transmission and photodetection. The current status of the D0 development effort will be outlined, including results from the characterization of 5000 channels of VLPC. Finally, results from simulations of expected detector performance will be shown and discussed.

INTRODUCTION

The field of experimental high energy physics involves the study of the fundamental constituents of matter and the forces which govern their interactions. The rich spectrum of elementary particles is understood to be made up from combinations of six "flavors" of constituents known as quarks, much in the same way that the periodic table of the elements can be built up with protons, neutrons and electrons. These six quarks, along with six leptons, are believed to make up all the matter of the universe. While most of the periodic table is accessible in nature for study, the vast majority of the elementary particles must be created in the laboratory, where physicists exploit Einstein's famous relation of $E = mc^2$: the energy (E) of a beam, or beams, is converted through collisions into the masses (m) of the elementary particles.

The physics understanding comes through detailed study of these collisions, namely the measurement of which particles are produced, how often and with what momentum and energy. Experimentally these studies are made with large, sophisticated particle detectors which are designed to detect and measure as many of the final collision products as accurately as possible. An integral part of nearly all particle detectors are the tracking detectors. Generally speaking, tracking detectors measure the traces of ionization (the "tracks") left behind by charged particles in some detector medium, and use these traces to deduce important properties of the particle, such as direction, velocity and momentum.

Over the years the experimental methods used for charged particle tracking have changed as dramatically as our understanding of the physics. Rutherford detected alpha particles scattering off a nucleus by visually detecting the flash of light emitted by the alpha passing through a zinc sulfide screen. In the succeeding decades particle detection techniques have included the bubble chamber, optical spark chambers, multi-wire proportional chambers and silicon strip detectors. As the field has progressed, so have the demands on detectors. In particular, throughout the history of the field, both the rate at which detectors must operate and the complexity of the collisions they study continues to increase. It is the desire to study complex events at very high rates that has motivated the development of the scintillating fiber tracking detector.

SCINTILLATING FIBER DETECTORS

A scintillating fiber (SciFi) detector combines the old technology of scintillating plastics with the new technology of fiber optics. Fig. 1 shows a schematic view of a generic SciFi detector for a colliding beam experiment. Plastic optical fibers doped with scintillating dyes are precisely placed on support cylinders which surround the point where two beams collide. Charged particles which

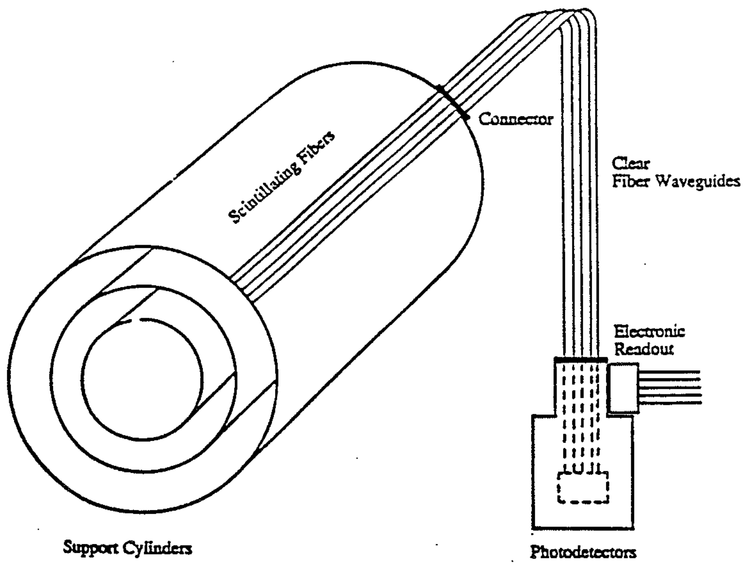

Figure 1. Schematic view of a generic scintillating fiber tracking detector.

are produced in the collision pass through the fibers and deposit energy, which is converted into scintillation light. A fraction of that light is optically trapped in the fiber and travels to the end of the cylinder, where the doped fiber is mated to a clear optical fiber, which in turn pipes the light over some distance to a photodetector. The photodetector responds to the light input with an electronic output which can be discriminated, or digitized, and read out by a computer. From the patterns of hit fibers the paths of the charged particles which passed through the detector can be reconstructed.

A variety of technically demanding challenges must be met in order for this technique to work well as a particle detector. The location of the active fibers must be precisely known. The scintillating dyes should produce enough light to be detected while maintaining a low level of self-absorption. Fiber-to-fiber connections need to have optical transmissions of near 100%, the clear fiber must transmit light over large distances and the photodetector is required to have good efficiency.

Several scintillating fiber detectors have been proposed and are under development around the world, each with its own unique way of attacking the challenges listed above.[1] Perhaps the most ambitious of these detectors is the tracker being built as part of the upgrade of the D0 experiment at Fermilab.[2] D0 is studying proton-antiproton collisions at the world's highest energies, nearly 2 TeV in the center-of-mass, and the detector upgrade will allow D0 to fully explore the physics of these collisions over the next 10 years or more. The remainder of this paper will concentrate on the D0 scintillating fiber tracking detector.

THE D0 SCIFI TRACKER

A quarter-section view of the upgraded D0 central detector is shown in Fig. 2. The D0 detector is designed to measure the production of both charged and neutral particles over nearly the entire 4π solid angle. The SciFi detector surrounds a compact silicon strip vertex detector, and both are situated within a superconducting solenoid. The solenoid provides a 2 Tesla magnetic field to deflect the charged particles and enable momentum measurement. In the region outside the magnet (not shown) is a large system of calorimeters which detect and measure the energy of neutral particles, and surrounding everything are planes of muon detectors, muons being the only particles likely to penetrate to that distance. According to the current Fermilab schedule, the first colliding beam run with the upgraded D0 detector will begin in early 1997. In this scenario, detector construction must be completed by mid-1996 to allow for installation and commissioning.

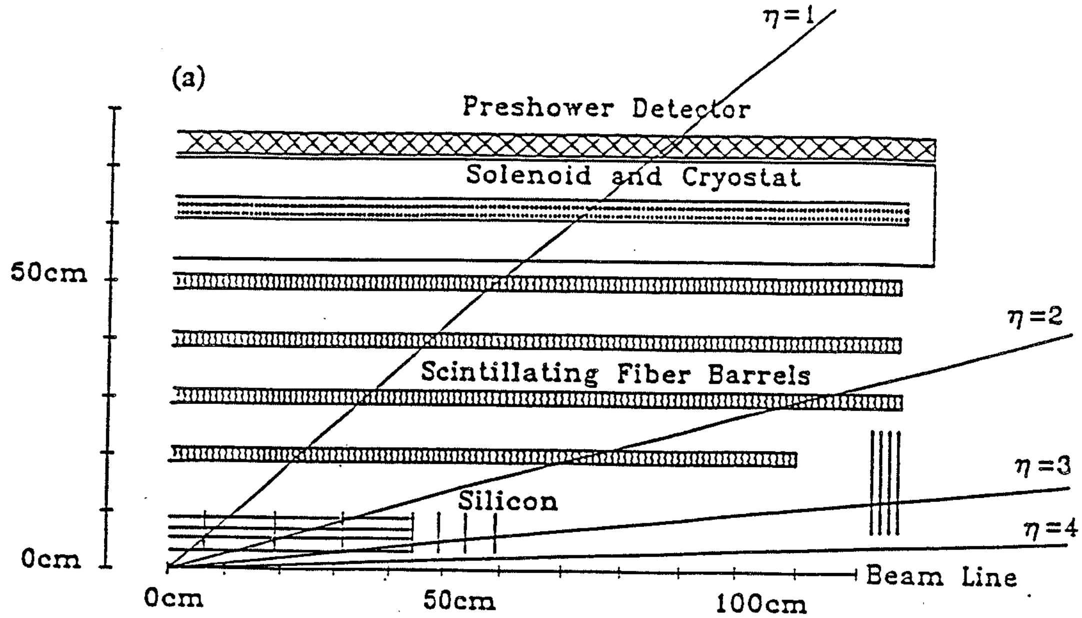

Figure 2. Quarter-section view of the D0 upgrade central detector.

Table I lists some of the parameters of the D0 SciFi tracker. Each of the four support cylinders contain 8 layers of scintillating fibers, four in the axial direction and two each at small stereo angles(±θ). This fiber "superlayer" gives a 3-dimensional space point at each cylinder. The clear waveguide fibers are about 8 meters in length in order to pipe the scintillation light from the D0 active volume to the photodetectors, which are located outside the central calorimetry.

Table I. Parameters of the D0 fiber tracker

Barrel	Radius(cm)	Length(cm)	# of Fibers	Stereo Angle
Superlayer1	20	220	11,566	± 1.3 deg
Superlayer2	30	254	17,333	± 2.0 deg
Superlayer3	40	254	23,111	± 2.7 deg
Superlayer4	50	254	28,888	± 3.3 deg
TOTAL			80,888	

A great deal of progress has been made recently towards optimizing the individual components which make up this detector. The details of several of these developments are reviewed in the following subsections, after which the latest results from tests of scintillating fiber tracking systems are presented.

Scintillator

Over the past several years, extensive research has been carried out to find the optimal scintillating dyes applicable to fiber tracking. Desired characteristics include high light output and a fast decay constant. In D0, the active fibers are doped with a combination of 1% p-terphenyl (PTP) aand 1500 PPM of 3-hydroxyflavone (3HF).[3] Energy deposited in the polystyrene fiber core is rapidly transferred non-radiatively to the primary dye of PTP, followed by a waveshift from the primary to the secondary dye, 3HF. The fluorescence of 3HF has a decay constant of under 8 nsec. The light emission of 3HF peaks at a wavelength of 530 nm, in the yellow-green part of the visible spectrum, and the polystyrene fiber core has good optical transmission at this wavelength.

Optical Fiber

Optical fibers work on the principle of total internal reflection. The core of the fiber is surrounded by a cladding of lower index of refraction, so that light striking the core-cladding interface below the critical angle is trapped inside the core and propagates along the fiber. The fibers used in D0 make use of an important new development in plastic fibers, multi-clad construction. As shown in Fig. 3a, the polystyrene core is surrounded by two claddings - first an acrylic of index n=1.49, then a fluorinated material of index n = 1.42. The benefit of adding this second cladding is illustrated in Fig. 3b. For light rays in the plane of the fiber axis, the fraction of light trapped is 5.3% as compared to 3.1% for single clad fiber. An additional benefit is that the multi-clad fiber is mechanically more flexible and robust than single-clad fiber.

Several tests have been performed to verify that the expected increase in light trapping is realized with the multi-clad fiber. The first tests, performed at Fermilab, compared the light output of single and multi-clad fibers doped with 1500 PPM of 3HF and spliced to 6 meter lengths of clear fiber. The active fibers were excited with a UV lamp and read out with a photodiode. Averaging over several fibers, an increase of 1.7 was obtained for the multi-clad fibers. Results from another series of tests, carried out at Notre Dame,[4] are shown in Fig. 4. In this test, 3 meter lengths of 3HF fiber were spliced to 8 meter lengths of clear fiber. The active fiber was excited with a ^{207}Bi source and read out with VLPC's (a photodetector discussed in detail below). The narrow peak at about 25 ADC counts in both plots corresponds to the pedestal value of the ADC. The peak of the broad distribution at larger counts corresponds to the most likely value of VLPC response. A gain of approximately 20 ADC counts per photoelectron was obtained by injecting LED light into the non-readout end of the fiber and measuring the number of counts between the observed photoelectron peaks. By comparing the most likely values of the photoyield spectra for single and multi-clad fiber, an increase in light yield of 1.8 is seen for the multi-clad fiber when the source is far (~ 2.5 meters) from the joint connecting the clear and active fiber. Another study showed that the light yields from the ^{207}Bi source agree with light yields due to cosmic rays to within 10%, indicating that the large improvement in light yield should be realized in the actual tracking detector by using multi-clad fiber.

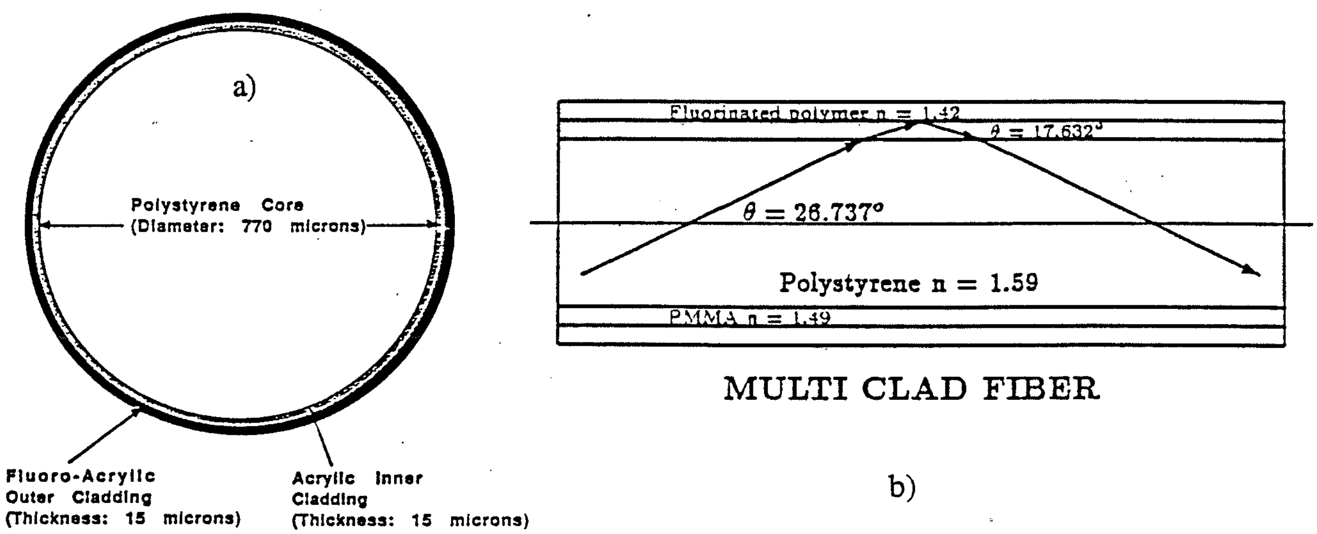

Figure 3.a) Construction of multi-clad fiber. b) Critical angles of multi-clad fiber, illustrating the additional light trapping.

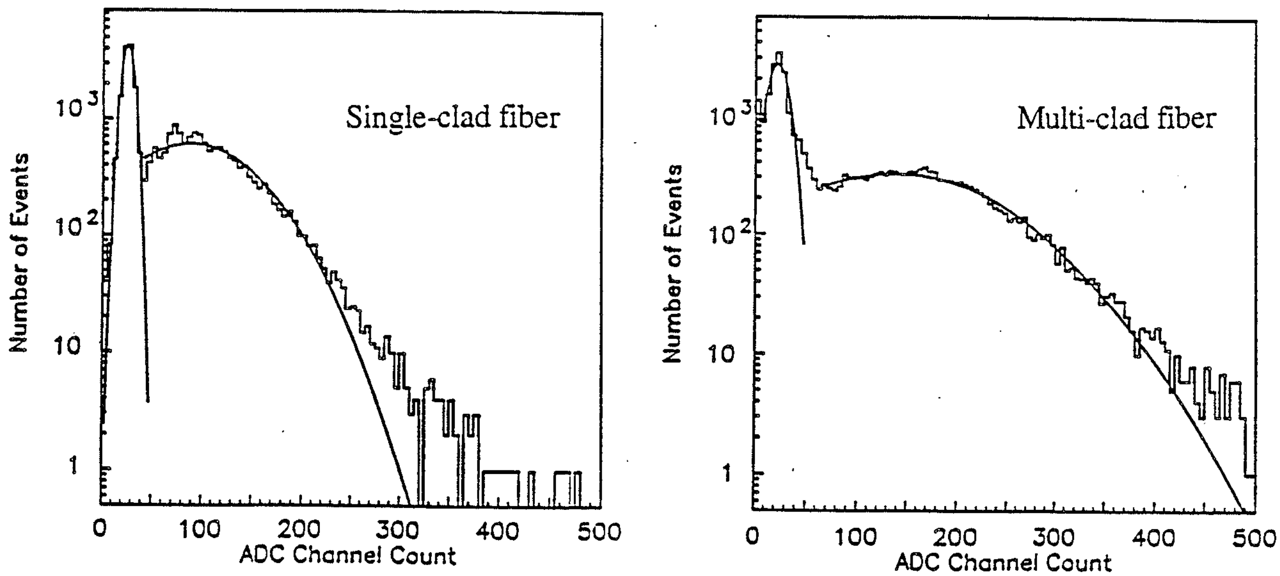

Figure 4. Pulse height distributions of single-clad and multi-clad scintillating fibers excited by a ^{207}Bi source and read out with VLPC's.

Ribbons, Cylinders and Connectors

Before scintillating fibers are placed onto support cylinders, they are first made into ribbons. The "standard" ribbon is a doublet structure, 128 fibers wide (Fig. 5). The 830 μm diameter active fibers are spaced by 870 μm center-to-center. The two layers in the doublet are offset by 1/2 fiber diameter relative to each other, to provide an overall high detection efficiency per doublet. The inherent position resolution of a ribbon doublet is 120 μm. Two methods to make accurate ribbons have been developed. In the first, a layer of fibers are placed in a machine-grooved plate. The second layer of fibers are laid in the spaces between the fibers making up the first layer, and whole doublet is glued to make a ribbon.[5] In the second method, two separate singlet layers are made with grooved plates, then glued together to make the doublet ribbon. In both methods, the center-to-center spacing can be maintained to within an RMS of less than 10 μm along the entire length of a 3 meter ribbon. The average thickness of a doublet ribbon is about 0.4% of a radiation length.

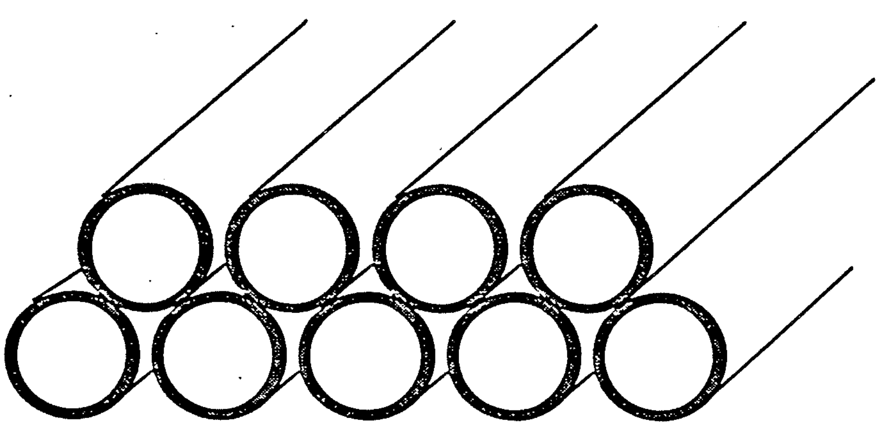

Figure 5. Schematic of a fiber doublet ribbon.

The support cylinders to be used in D0 will be made of Hexcel covered by a carbon-fiber skin. This creates a cylinder which is relatively light, strong and adds a minimal amount of inactive material to the tracking detector. Test cylinders have been constructed and measured values of roundness and sag are well within the required specifications.[6] The technique developed to accurately mount the ribbons onto their support cylinders utilizes a large coordinate measuring machine (CMM) which can measure the ribbon's location relative to the cylinder throughout the mounting process.[6]

Although the design details are still under development, the D0 fiber tracker will have at least two fiber-to-fiber connections per channel, one at the end of the cylinder and another at the photodetector. These connections are required to be mechanically robust, reliable over time and they must have a good optical throughput. The two techniques under discussion involve: a) splicing clear fiber "pigtails" onto the ribbons and mating these to the 8-meter-long clear fibers with connectors, or b) mate the scintillating fibers to the 8-meter-long clear fibers directly with connectors. With either technique the long clear fibers will have a 965 μm diameter (compared to 830 μm diameter scintillating fiber) to lessen the demands on fiber-to-fiber alignment within the connectors.

In either scheme, connectors mating large numbers of fibers (32-128) are required. Light transmission measurements have been performed with connectors made from Delrin plastic. These connectors are made up of two mating pieces, each with a matched, rectangular array of 128 machined holes. The fibers are glued into the holes and connector faces are finished with a diamond fly-cutter. The two pieces are screwed together, with alignment pins for precise registration. Repeated tests of such a connector show that the average optical throughput across the connector is better than 95%.[7]

Visible Light Photon Counter

There are stringent requirements on any photodetector to be used in a fiber tracking detector. The photodetector must be capable of detecting single photons with a high efficiency, at high rates and with large gain. D0 has chosen to use the Visible Light Photon Counter (VLPC), developed by Rockwell International Science Center.[8,9] Several of the key parameters of these devices are listed in Table II. The 1mm diameter pixel active area, fast rise time, high gain and good quantum efficiency (QE) make them an excellent match to the needs of the fiber tracker.

Table II. Geometric and operating characteristics of the VLPC.

VLPC Parameter	Value
Active Area	1 mm diameter
Pulse rise time	< 5 ns
Average gain	20,000
Gain dispersion	< 30 %
Effective QE at 560 nm	≈ 60 %
Dead time	none (continuous)
Dark pulse rate	≈ 50 kHz
Saturation pulse rate	25 MHz
Average power	1.6 μW/channel
Operating bias voltage	6-8 V
Operating temperature	6-8 K

The VLPC's are produced in the form of a bare die containing an array of 8 pixels. The array is then mounted onto an aluminum-nitride substrate. Once mounted, wire bonds connect the active area of the pixel to readout pads located on the substrate. The layout of an 8-channel VLPC array, mounted on its substrate, is shown in Fig. 6. This VLPC-substrate "hybrid" is then mounted into a molded Torlon carrier.The carrier has 8 holes which are precisely aligned with the VLPC pixels, and into which the clear optical fibers carrying the scintillation light to the VLPC's are permanently glued.

One complication in using VLPC's is the operating temperature of 6-8 K, requiring that the detectors are maintained in a cryogenic environment. In the current design, 16 VLPC arrays are housed in a container known as a "cassette", shown schematically in Fig. 7a. The VLPC arrays are mounted on a copper isotherm at the bottom of the cassette. Short lengths of clear fiber bring the light signals down from an optical connector at the top of the cassette, and special low-capacitance ribbon cables take the VLPC output signals back up to the preamplifier cards mounted outside the cassette volume. The cassettes are operated in a liquid helium cryostat, also shown schematically in Fig. 7b. The cassettes are mounted into cylindrical tubes which sit in the helium volume. The cold helium vapor rising up the walls of these tubes intercepts heat flow and keeps the VLPC's at their operating temperature. Currently a cryostat containing 24 cassettes, supporting a total of 3072 channels of VLPC, is being operated as part of a large-scale cosmic ray test.

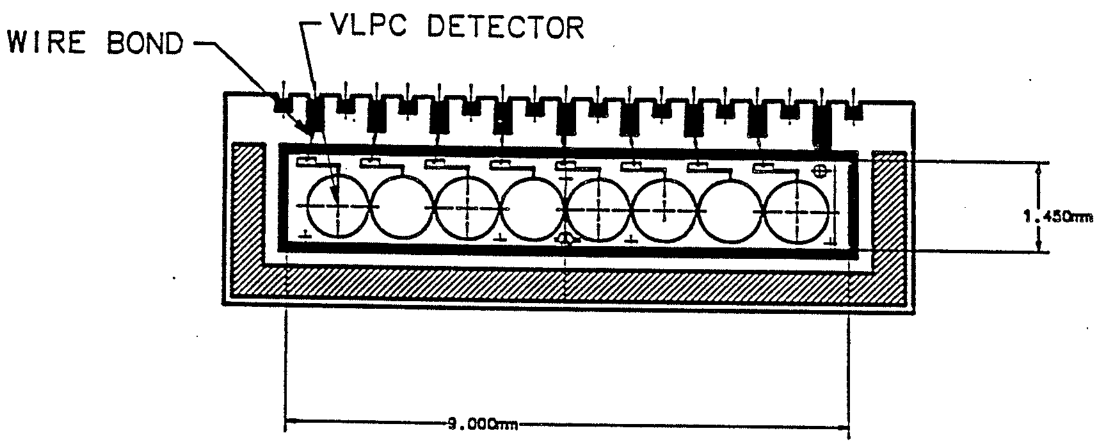

Figure 6. Layout of an 8 channel VLPC array, mounted on a support substrate.

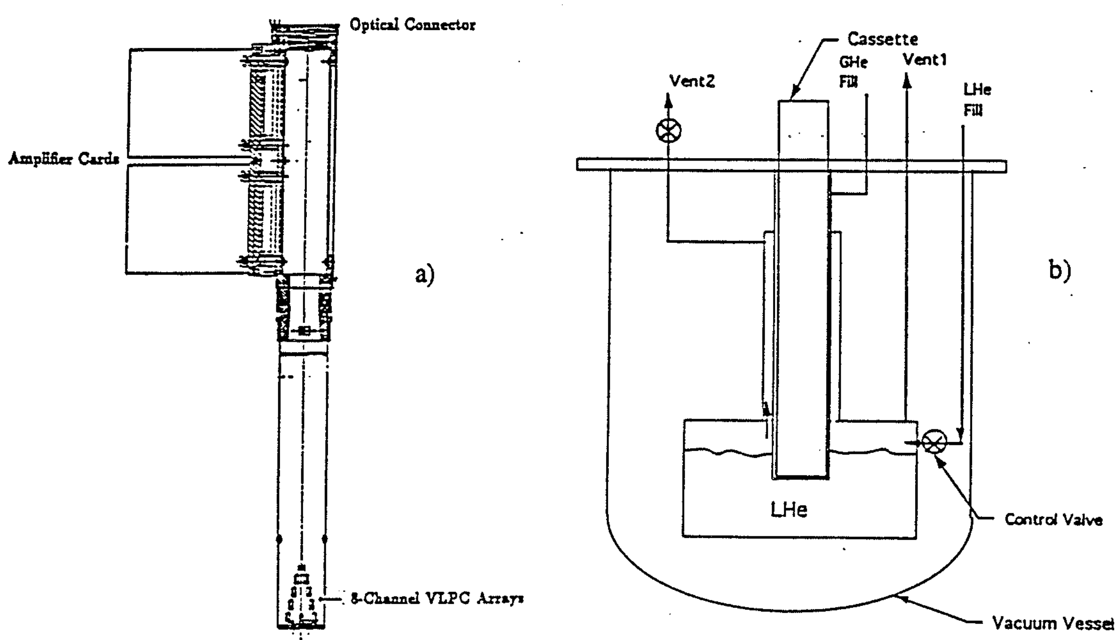

Figure 7. Schematic views of a VLPC cassette and cryostat.

The first study of large numbers of VLPC arrays has recently been completed at Fermilab.[10] A special test cassette was constructed in which 8 VLPC arrays could be inserted, tested and then removed. Light from an LED was optically mixed and then distributed by clear fibers to each of the 64 pixels. Figure 8 shows typical ADC spectra obtained from an 8-pixel VLPC array. Clearly visible are the first few individual photopeaks in response to the LED light. The distance between the peaks measures the relative gain of the pixel, while the ratio of 2nd to 3rd photopeak areas measures relative quantum efficiency. In this way the relative performance of 5000 channels of VLPC were studied as a function of operating temperature and bias voltage. As an example, Fig. 9 shows the variation of relative quantum efficiency as a function of bias voltage for several operating temperatures. The points plotted are averages over all the measured VLPC channels. The results were consistent with expectations for these devices. By comparing the VLPC response to that of photodetectors of known QE, the mean quantum efficiency of the 5000 channels was measured to be approximately 60% at a bias voltage of 6.5 V and temperature of 6.5 K. The total number of bad pixels was less than 250, corresponding to a good channel yield of over 95%.

This 5000 channel characterization study proved that the current design of VLPC performs adequately for fiber tracking. Even so, a new run of devices is underway at Rockwell in which the chips will be further optimized to obtain higher QE and a reduced single-photon noise rate. The new devices will be characterized in the same way and results should be available by late 1994. Also under development is a new cassette design which packs the VLPC arrays with a higher density. This will be necessary because of the limited space available for cryostats in the D0 upgrade.

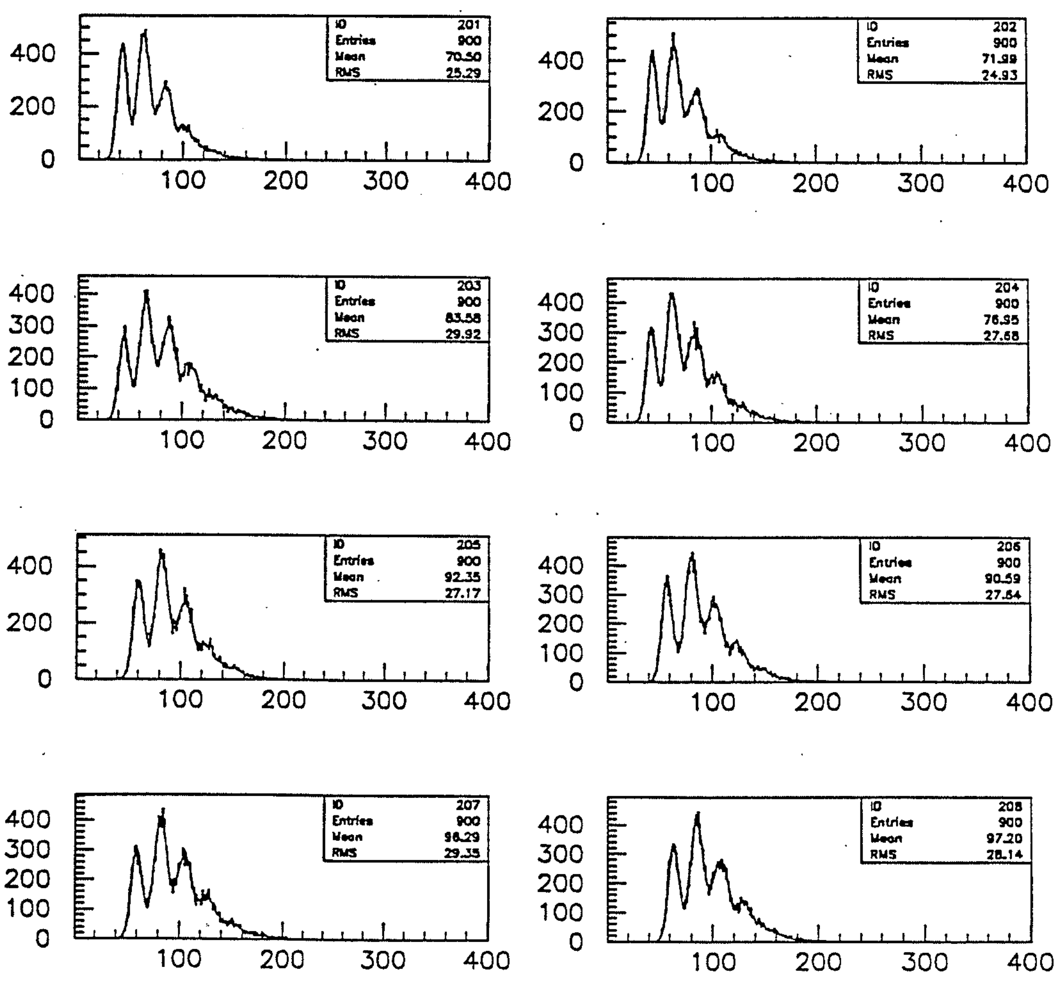

Figure 8. Typical ADC spectra of 8 VLPC pixels illuminated by LED light.

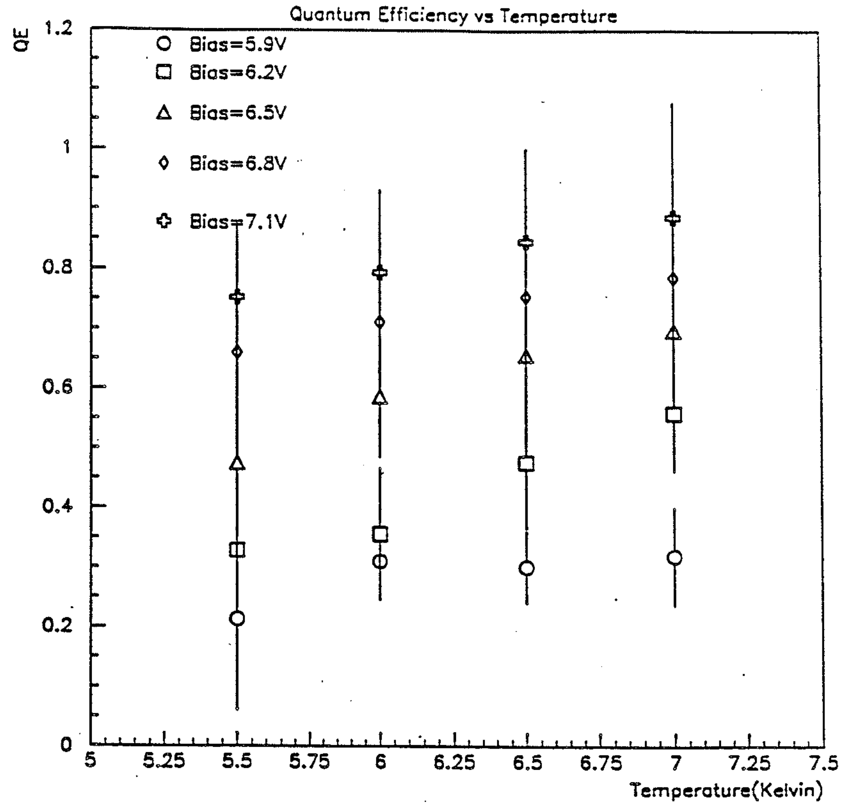

Figure 9. VLPC QE as function of temperature for several bias voltages.

Readout

In the current fiber tracking tests, the VLPC outputs are sent to a charge sensitive preamplifier based on the QPA02 chip. The amplified signal is in turn digitized by a separate ADC. For the final tracking detector, a single chip is desired which will amplify, shape and discriminate each VLPC output, giving a digital response for each hit fiber. The VLPC gain of roughly 20,000 means that the charge input to the preamp is about the same as for silicon strip detectors, so D0 is planning to build electronic readout systems for both the silicon and fiber tracking detectors based on the SVX-II chip at Fermilab. One added feature of the fiber electronics will be a fast digital pick-off for the axial fiber channels. This will allow the fiber tracker to participate in the fast triggering of the D0 detector.

TESTS OF SCIFI TRACKING SYSTEMS

The preceding section described the status of research and development of the key components that make up a scintillating fiber tracking detector. The results clearly show that the performance and understanding of these components is at an advanced stage. Even so, it is essential to prove that the individual parts can be assembled together and operated as a system. Several tests aimed at demonstrating the viability of fiber tracking have been performed recently. Key goals of these tests have been to measure the position resolution and light yield of a fiber system. Since the number of photons produced in a fiber by a charged particle obeys statistical laws, the mean number of photons must be large enough to insure that all tracks are detected efficiently. For the D0 fiber tracker, a minimum of 2.5 detected photoelectrons per fiber is required.

Beam tests involving small numbers of scintillating fibers were carried out at Fermilab[11] and BNL.[12] The measured tracking resolutions were as expected, but observed light yields were too low for efficient tracking. However, both of these tests used single-clad fibers and an early version of VLPC. In summer 1993, a series of tests carried out at Notre Dame examined the light yield of 3 meter lengths of multi-clad fiber doped with 1500 PPM of 3HF, read out through 8 meters of clear multi-clad fiber into VLPC's.[3] The active fibers were excited with a ^{207}Bi source. The diamond-finished ends of the scintillating and clear fibers were mated by pressing them together in lucite ferrules. Measurements of the light yield were taken for source locations at the near and far ends of the scintillating fiber. The effect of mirroring the non-readout end of the scintillating fibers was also studied - the mirroring was accomplished with an aluminized mylar foil. The results of these measurements is summarized in Table III. In the worst case, a mean number of 6-7 photoelectrons was observed from the far end of the fiber, with no mirroring. However, in the D0 fiber tracker, the lowest photon yields are expected for particles passing through the fibers in the middle of the tracker, at a distance of only 1.4 meters from the clear fiber splice. These particles traverse the fibers at a 90° angle with respect to the fiber axis - the shortest possible path length in the fiber. Tracks passing through the far end of the scintillating fibers will give more light because those particles traverse the fiber at an oblique angle and thus deposit more energy in the fiber. In addition, the non-readout ends of the fibers will be mirrored in D0. Detailed simulations of the D0 fiber detector show that fully efficient tracking is achieved when the mean number of photoelectrons is greater than 2.5.[13] Table III shows that the tracker designed for D0 should have adequate light yield to track efficiently, with a safety factor of at least 4.

Table III. Photo yield results for 3HF scintillating fibers spliced to clear waveguide fibers and read out by VLPC's.

Mirroring	Source Location	Excitation	Most Probable PE Yield
Unmirrored	Near End	Beta	7.8
Unmirrored	Far End	Beta	6.8
Unmirrored	Far End	Cosmic Rays	6.2
Mirrored	Near End	Beta	12.2
Mirrored	Far End	Beta	11.0
Mirrored	Far End	Cosmic Rays	10.2

The aforementioned tests have proven that the fiber tracking concept works well, at least for small numbers of channels. The next step is to demonstrate that a large scintillating fiber system can be operated stably over an extended period of time. For this purpose a cosmic ray test is currently being commissioned at Fermilab.[14] The test detector contains 3 fiber superlayers (24 layers and 3072 channels total) - one mounted at the top of a 2-meter-long support cylinder, one at the bottom of the cylinder and the third (or middle superlayer) on a flat board at the cylinder symmetry axis. As shown in the inset to Fig. 10, the fiber detector sits upon a 2-meter stack of steel with trigger counters above and below. The steel filters out low momentum particles and gives a minimum trigger threshold of about 2.5 GeV/c. The scintillating fibers are mated to 8-meter-long clear waveguide fibers with diamond-finished connectors made of Delrin plastic. The clear fibers pipe the light to VLPC's mounted in the cassettes and cryostat discussed above.

The cosmic ray experiment tests essentially all the key components of the fiber tracker as an integrated system, under realistic operating conditions. The three-superlayer configuration will enable detailed measurements of tracking efficiency, position resolution and light yields. At the time of this meeting, 14 of the 24 total cassettes are installed and running. The cryostat is operating stably and is capable of controlling the temperatures of individual cassettes to ± 15 mK. Preliminary results on the light yield and tracking efficiency are consistent with expectations. The inherent tracking ability of the fiber system is evident in Fig. 10, an event display which shows a "zoom" view of part of the middle superlayer. This superlayer is made up of two axial doublets which are separated by 1.5 cm, with the two stereo doublets directly on top of the upper axial doublet. Only fibers with ADC counts greater than 800 (~ 2-3 photoelectrons) are drawn, and the cosmic ray track is clearly seen with no background. The number of photoelectrons detected in the hit fibers range from 8 to 15, and seven of the 8 possible fiber layers show hits.

All of the 24 cassettes required for the full cosmic ray test are assembled and the complete detector will be instrumented shortly. By the end of summer 1994, detailed results of the operation and performance of this 3,000 channel scintillating fiber tracker should be available.

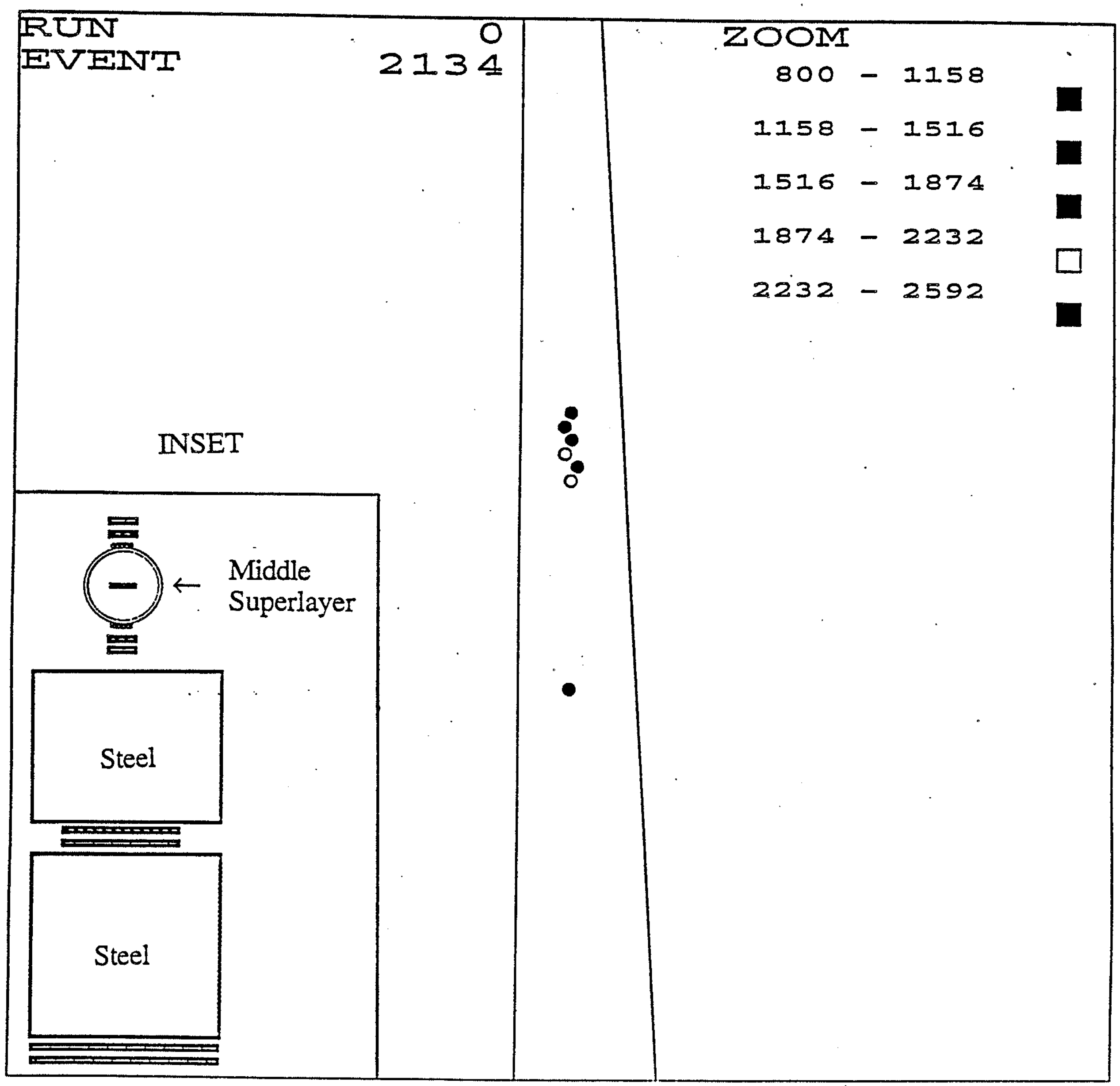

Figure 10. Event display of cosmic ray track seen in the D0 SciFi test detector.

SUMMARY

Particle physics tracking detectors based on scintillating optical fibers are being proposed for a variety of experiments around the world. Several features of SciFi detectors, including good position resolution, excellent time response, uniformity of material and relative ease of operation, make them attractive choices for experiments studying high-rate, complex events at present and future accelerators. The D0 collaboration has chosen to build a scintillating fiber tracker as part of a major detector upgrade. The key components of this detector are well understood, and recent system tests indicate that the D0 fiber tracker will be able to track particles at the Fermilab Tevatron with very high efficiency and excellent position resolution.

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