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Performance of multiclad scintillating and waveguide optical fibers read out with visible light photon counters *

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ABSTRACT

We have measured the performance of scintillating fiber detectors read out with visible light photon counters (VLPCs). Both single clad and multiclad scintillating fibers have been tested. For a system comprised of 3m long multiclad scintillating fibers of 830μm diameter optically coupled to 8m long multiclad waveguide fibers of 965μm diameter and read out with HISTE-IV VLPCs, we detect an average of 6.2 photoelectrons from the far end of the scintillating fiber if the fiber end is unmirrored and 10 photoelectrons if the fiber end is mirrored. A minimum of 2.4 detected photoelectrons is required for efficient particle detection in high energy physics tracking applications. Hence our result indicates a factor of 2.5 and 4 safety margin in required light yield for the unmirrored and mirrored cases respectively. Given this substantial detected photoelectron yield, cosmic ray tracks are easily detected in fiber arrays, and excellent performance characteristics are expected for the fiber trackers designed for the D0 experiment at the Fermilab Tevatron Collider and SDC experiment at the SSC laboratory.

1. INTRODUCTION

We have been studying the performance of scintillating fiber tracking detectors for general applications in high energy physics experiments and specifically for the D0 experiment at Fermi National Accelerator Laboratory and for the SDC experiment at the Superconducting Super Collider Laboratory. Key performance characteristics of these detectors include: fast fluorescence decay time, high effective quantum efficiency, excellent spatial resolution, and good radiation resistance. In this document we report substantial and significant progress in the efficiency of these detectors - measured as high detected photoelectron yield. Keys to this success have been the use of multiclad scintillating and waveguide fibers developed by Kuraray Corporation and the development of the HISTE-IV visible light photon counters (VLPC) by Rockwell International Science Center. VLPC characteristics and VLPC use with scintillating fibers for tracking have been documented elsewhere in these proceedings[1-4], and in the literature.[5-11] The development of multiclad scintillating fiber is recent however and initial studies of these structures for tracking applications have indicated excellent results.[12]

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Figure 1 displays the crosssectional profiles for single clad and multiclad fibers. The conventional, single clad fiber consists of a polystyrene core of refractive index n=1.59, and an acrylic cladding of polymethylmethacrylate (PMMA) having a refractive index n=1.49. The thickness of the cladding wall is typically 3% of the diameter. Hence for an 830μm diameter fiber, the core diameter is 780μm and the cladding wall is 25μm thick. For multiclad fiber, the polystyrene core is surrounded by two claddings: an inner clad of PMMA and an outer cladding of fluorinated acrylic having a refractive index n=1.42. The multicladding has two important benefits. First, the lower refractive index of the outer clad improves the numerical aperture of the fiber substantially (a factor of 1.7). This means greater light trapping (by this factor) in total internal reflection. Second, the fiber is mechanically more flexible and robust than the single clad fiber.

To make a fiber into a scintillating fiber, the core polystyrene is doped with organic fluorescent dyes which are selected appropriate to a given experimental application. For the collider physics applications of interest to our group, excellent optical transmission, fluorescence speed, and radiation damage characteristics are required.[10] This has led us to select as our standard composition a polystyrene core into which are incorporated 1% by weight of p-terphenyl (PTP) and 1500ppm of 3-hydroxyflavone (3HF). This scintillator has a fluorescence decay time of 7.8nsec and fluorescence emission peaked near 530nm. This spectral emission is poorly detected by vacuum photomultipliers and the appropriately matched photosensors are solid state imaging devices (silicon or GaAs). VLPCs are currently the photodetectors of choice for this spectral region, having a quantum efficiency ~70% for visible wavelengths [6,8,10] as well as the additional, essential properties of fast response and high rate capability.[7]

Initial comparative studies of single clad and multiclad fiber[12] utilized UV light excitation of the scintillator and a silicon photodiode to measure the integral luminescence. The scintillating fibers were of 830μm diameter and 4.3m length and were optically connected to waveguide fibers of 850μm diameter and 6m length which "piped" the light to the silicon photodiode. The spectral sensitivity of the photodiode is similar to that of the VLPC. The optical interconnection between the scintillating and waveguide fibers was accomplished using lucite ferrules and silicone oil optical couplant. Surface preparation of the ends of scintillating and waveguide fibers which were mated together optically within the ferrules was accomplished using a diamond finishing machine developed at Fermilab.[13] The far ends of the scintillating fibers were also optically finished and left unconnected and unmirrored.

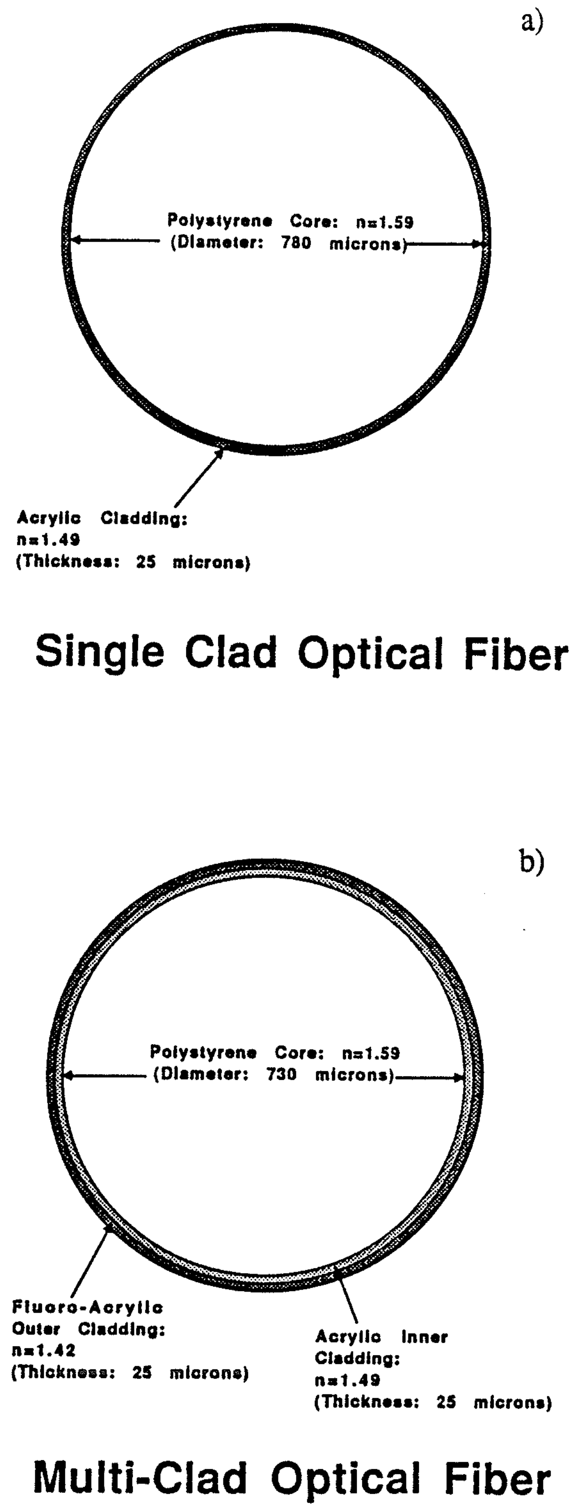

Figure 1. Crosssectional profiles of scintillating and waveguide optical fibers used in the measurements. (a) schematic of single clad fiber; (b) schematic of multiclad fiber.

Figure 2 displays the results obtained when a UV lamp is moved along a scintillating fiber from the near end (near the splice with the waveguide fiber) to the far end, for several different single clad and multiclad fibers. In all cases the multiclad fiber provides substantially greater light yield as well as better attenuation length characteristics. The improvement factor is 1.6 between the average of the multiclad fiber response (upper family of curves in the figure) and the best case single clad fiber response (most upper-lying of the lower family of curves in the figure). When this value is corrected for the smaller active core of the multiclad fiber, the result is comparable to the geometric factor of 1.7.

2. FLUORESCENCE EFFICIENCY STUDIES

A schematic of the test arrangement for measurements of fiber performance with VLPCs is shown in Figure 3. The apparatus consists of five scintillating fibers of 830μm diameter and 3 meter length optically spliced to clear waveguide fibers of 965μm diameter and 8 meter length. Optical splicing was accomplished utilizing lucite ferrules as described above but with mineral oil as the optical couplant. There are two such splices. The first splice mates the 830μm scintillating fiber to the 965μm waveguide fiber. The second splice mates the 965μm waveguide fiber to identical 965μm optical fiber within a cryogenic cassette which supports VLPC operation.

The photodetectors are HISTE-IV VLPCs which must be operated cryogenically at a temperature in the 6K-6.5K range. Hence the devices are situated in a compact cryogenic "cassette" [10] which resides in a 5 liter liquid helium dewar. Light from the scintillating fiber is transmitted via clear fiber waveguides to the VLPCs which operate cold. Typical quantum efficiency for the HISTE-IV VLPCs at wavelengths of interest (530nm) is ~70%, and typical gain for the devices is 10^4 electrons per detected visible wavelength photon. This electron signal is further amplified by a factor $\geq 10^3$ using QPA02 preamplifiers developed by Fermilab.[14] These analog signals are then driven differentially over 80ft of flat cable to transformer receivers which produce negative polarity pulses which are digitized using LRS 2249W CAMAC ADCs. Data acquisition is controlled using a MacIntosh IICi computer.

A typical running cycle covers ~24 hours, depending upon the fill of the 5 liter helium dewar within which the VLPC cryo-cassette is situated. Data samples include pedestal and LED calibration studies and light yield and timing studies using cosmic rays and a radioactive source (Bi207). A series of ~150 data runs have been logged over six week period, and over 40 cool downs (cycles) of the 5 liter dewar and cryocassette system have been undertaken successfully. Typically the temperature of the VLPCs is maintained colder than a typical maximum value of 6.5K, and under normal running conditions the temperature will slowly vary over the range 6.0K to 6.5K during a 24 hour cycle with no obvious degradation in VLPC performance. We now discuss the various measurements that have been undertaken.

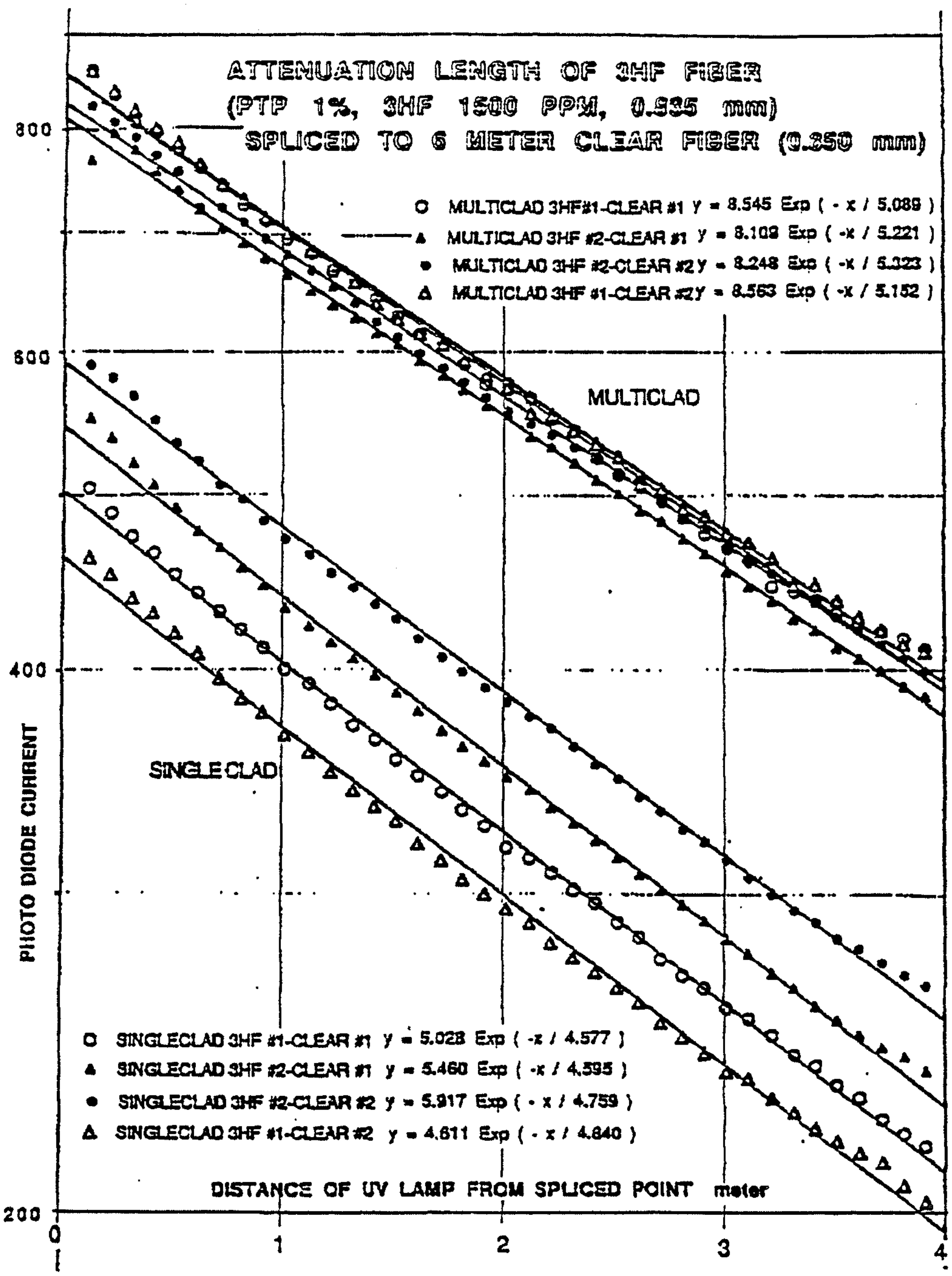

Figure 2. Comparative study of the integral light yield for single clad vs multiclad fibers using UV light excitation. In each case the scintillating fiber of 4.3m length is spliced to 6m long clear optical fiber of the same type as the scintillator. Light detection was implemented with a silicon photodiode whose spectral characteristics are similar to VLPCs. Performance is clearly superior for multiclad fiber.

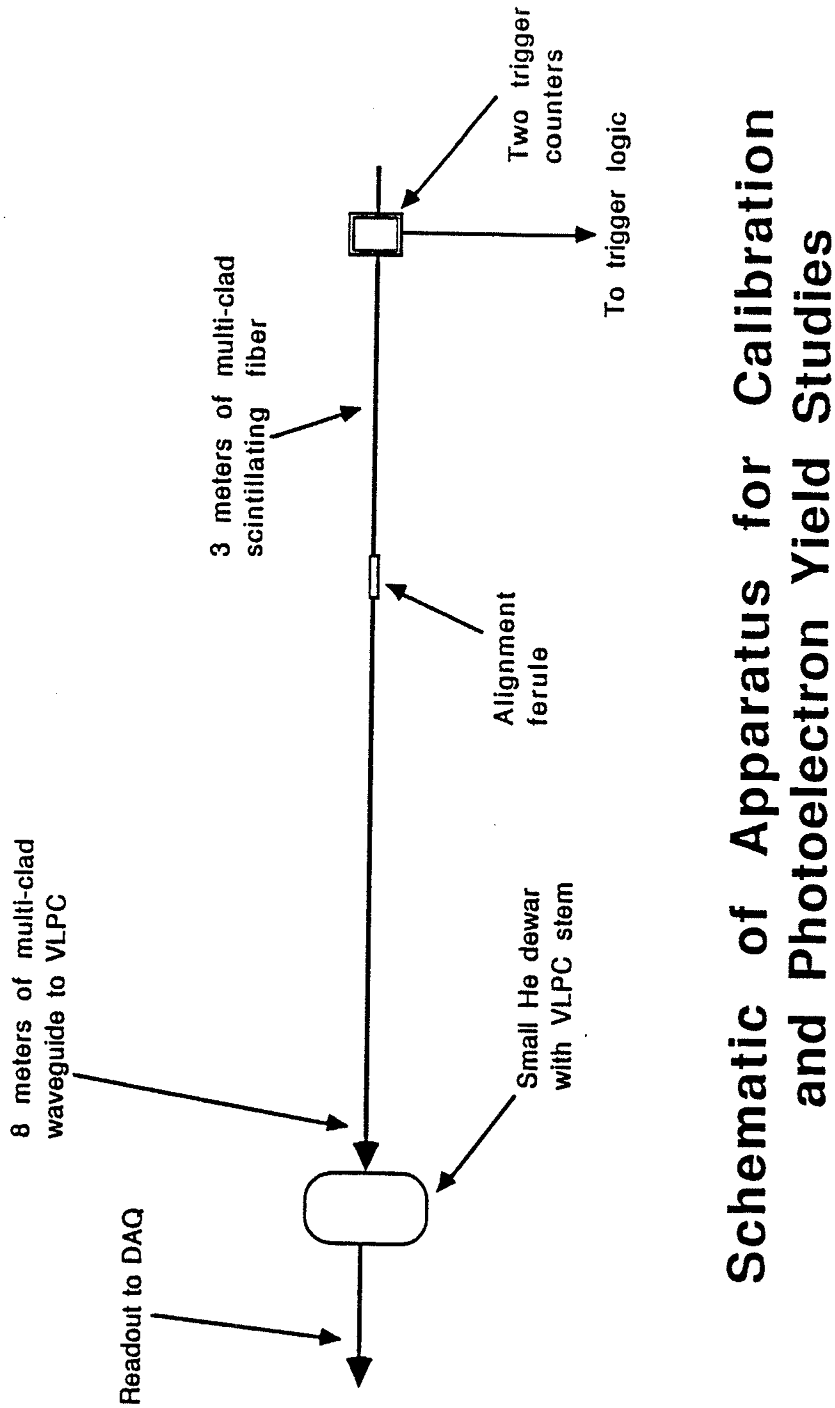

Figure 3. Schematic of the apparatus used for the fiber efficiency studies. Excitation of the fiber can be accomplished by cosmic rays, radioactive sources, of light emitting diodes (LEDs).

2.1 Calibration Studies

The photoelectron yield measurements were recorded under two sets of amplifier operating conditions, and hence calibration of the system was important for determining the photoelectron values for a given configuration. The VLPC bias voltage was set at V_{bias}=-7.5V and remained unchanged. The voltage for the QPA02 preamplifiers was set initially at V_{qpa}=3.8V and was later raised to V_{qpa}=4.5V.

The calibration was provided by pulsed light emitting diode (LED), with light injected into the far end of the scintillating fiber for unmirrored or mirrored ends. In the configuration planned for the D0 experiment at the Fermilab Tevatron, the far ends of the scintillating fibers are mirrored. The mirroring is accomplished by pressing a piece of aluminized mylar superinsulation against the finished end of a fiber. The fiber and the mirror are registered in a machined connector, and a thin film of mineral oil is used to assure a direct contact of fiber to mirror. Initial bench tests of this mirroring technique by our group using photodiodes have indicated excellent reflectivity, typically greater than 50%. Because the mirror film is not a perfect reflector, some light is transmitted through the material. This has led us to test the possibility of injecting light from a pulsed calibration LED through the mirror and into the fiber to check for continuity, operational characteristics, and registration and placement of each fiber/VLPC channel, leaving the mirror in place. Both red and green LEDs were used for the calibration, with driving pulse shape and amplitude controlled by a LRS 9210 pulse generator.

Figure 4 shows the response from a fiber/VLPC channel to light from a green LED without the mirror film and from a red LED under the mirroring conditions described above. The horizontal axes are in ADC channels (least counts) at a scale of 0.25pC per channel. Calibration at the higher QPA02 operating voltage was performed with the red LED. The left-hand peak in the spectrum generated with the red LED (Fig.4b) is centered at channel 12.7 and corresponds to pedestal (no signal other than amplifier noise). The single photoelectron peak is situated at channel 37, the two-photoelectron peak is situated at channel 60.5. Peaks corresponding to three and four simultaneously detected photoelectrons are in evidence but with reduced intensity. From the peak values for 0,1,2 photoelectrons, we obtain a spacing of 24 least counts (channels) per photoelectron. This corresponds to ~6 pC per photoelectron, consistent with our expectations for VLPC gain and QPA02 gain, and with the pulse shape of the analog waveform into the ADC: a roughly triangular pulse of 10mV height and 50nsec base into 50Ω. Calibration at the lower QPA02 operating voltage was performed with the green LED. As Figure 4a indicates, the scale under this condition is 20 counts per photoelectron.

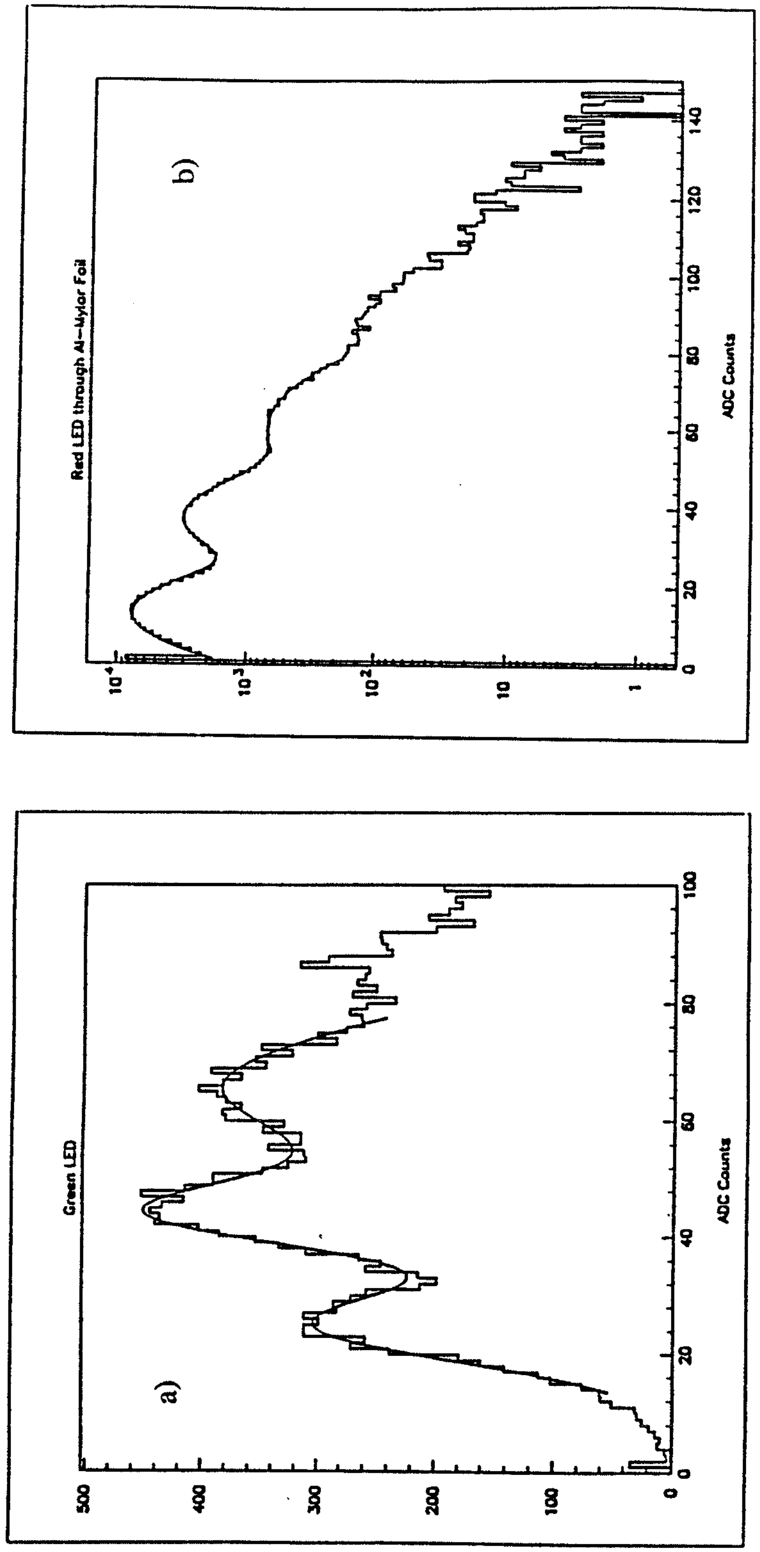

Figure 4. Excitation of the fibers with LEDs for system calibration: (a) excitation of the fiber through the end using direct illumination from a green LED; (b) excitation of the fiber through the end covered with an aluminized mylar mirror using a red LED. In each case individual peaks corresponding to simulateously detected photoelectrons (pe) are successively are 0pe (pedestal), 1pe, 2pe and so on. (Scale: 1ADC count=0.25pC.)

2.2. Studies of Photoelectron Yield

The scintillating fibers could be triggered on events initiated by a Bi207 beta source or by cosmic rays, using apparatus as shown in Figure 3 and Figure 5. Trigger scintillation counters were placed above and below the fibers, forming a trigger telescope. Additionally discriminated signals from the scintillating fibers themselves could be included in the trigger. This was essential for pulse timing studies in the fibers.[15]

2.2.1. Single Clad vs Multiclad Fiber

The fiber studies were intended, in part, to confirm the substantial improvement in overall light collection from multiclad fibers relative to single clad fibers. For these studies, a single clad and multiclad fiber were read out from both ends through 8m of waveguide. Figure 5 displays the arrangement. With the Bi207 source and trigger counters placed at 50cm from one end of the scintillating fibers, data could be simultaneously recorded by a second VLPC through the far end, corresponding to 2.5m of path length through the scintillator. Additionally, the fiber/VLPC signals were included in the trigger: a coincidence of the signals above single photoelectron level was required from each end of the fiber.

Figure 6 displays the comparison of the performance of the single clad and multiclad fibers. The most likely values of photoelectron yield for each of the cases are tabulated in Table 1. As the Table 1 indicates, the detected photoelectron yield from the far end of the multiclad fiber exceeds that of single clad fiber by a factor of 1.8, consistent with the photodiode studies descibed above.

TABLE 1

Study of Photoelectron Yield from Single Clad and Multiclad Fiber

Type	Trigger Location	Excitation	Pedestal (counts)	Mean Value (counts)	Yield (mean-ped)	Yield (rel to single clad)
Single Clad	Near End	Bi 207	22.3	125	102.7	1
Single Clad	Far End	Bi 207	25.3	87.8	62.5	1
Multiclad	Near End	Bi 207	22.0	169.5	147.5	1.4
Multiclad	Far End	Bi 207	21.8	134.7	113	1.8

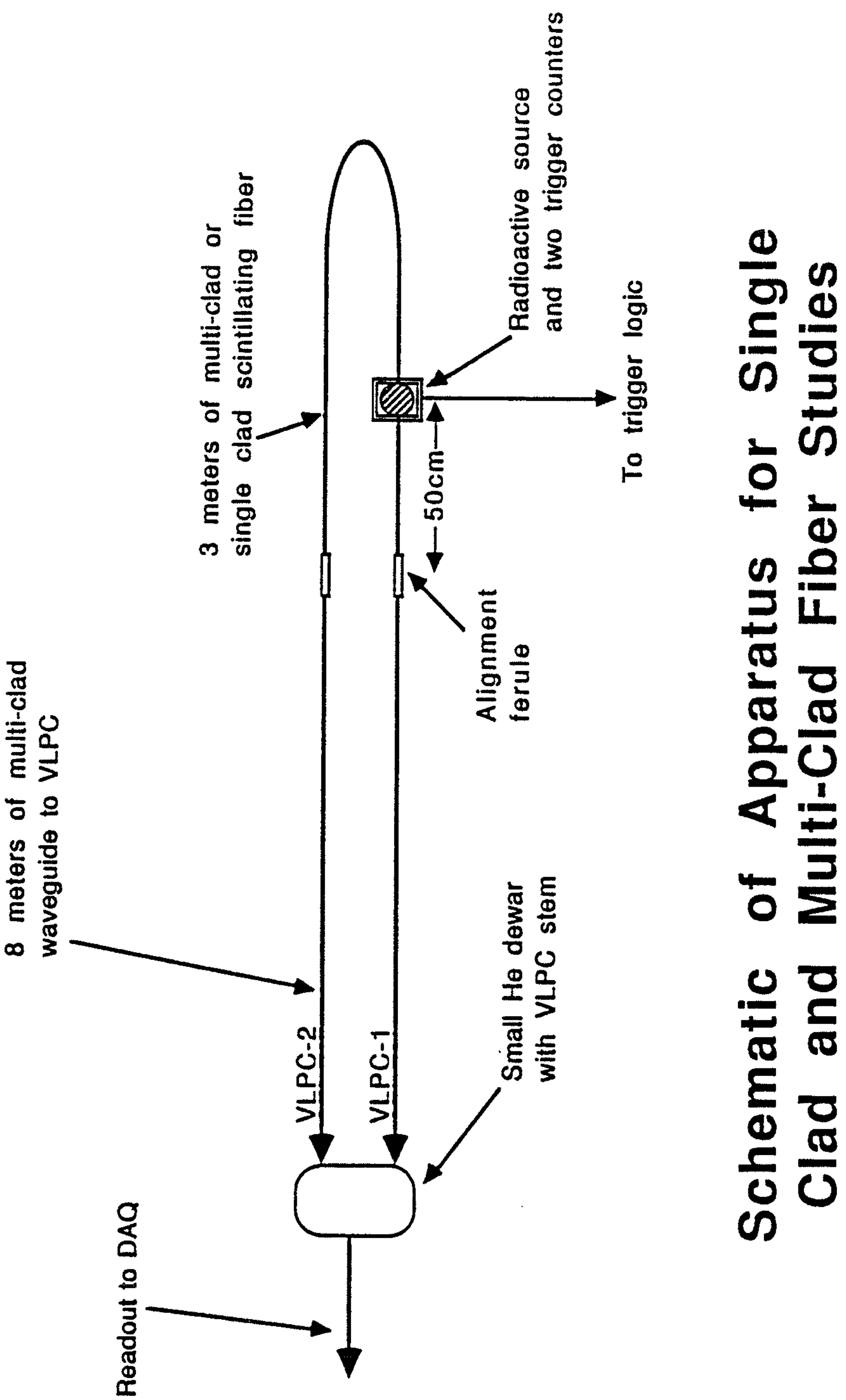

Figure 5. Schematic of the apparatus used during the studies of performance of single clad and multiclad fiber.

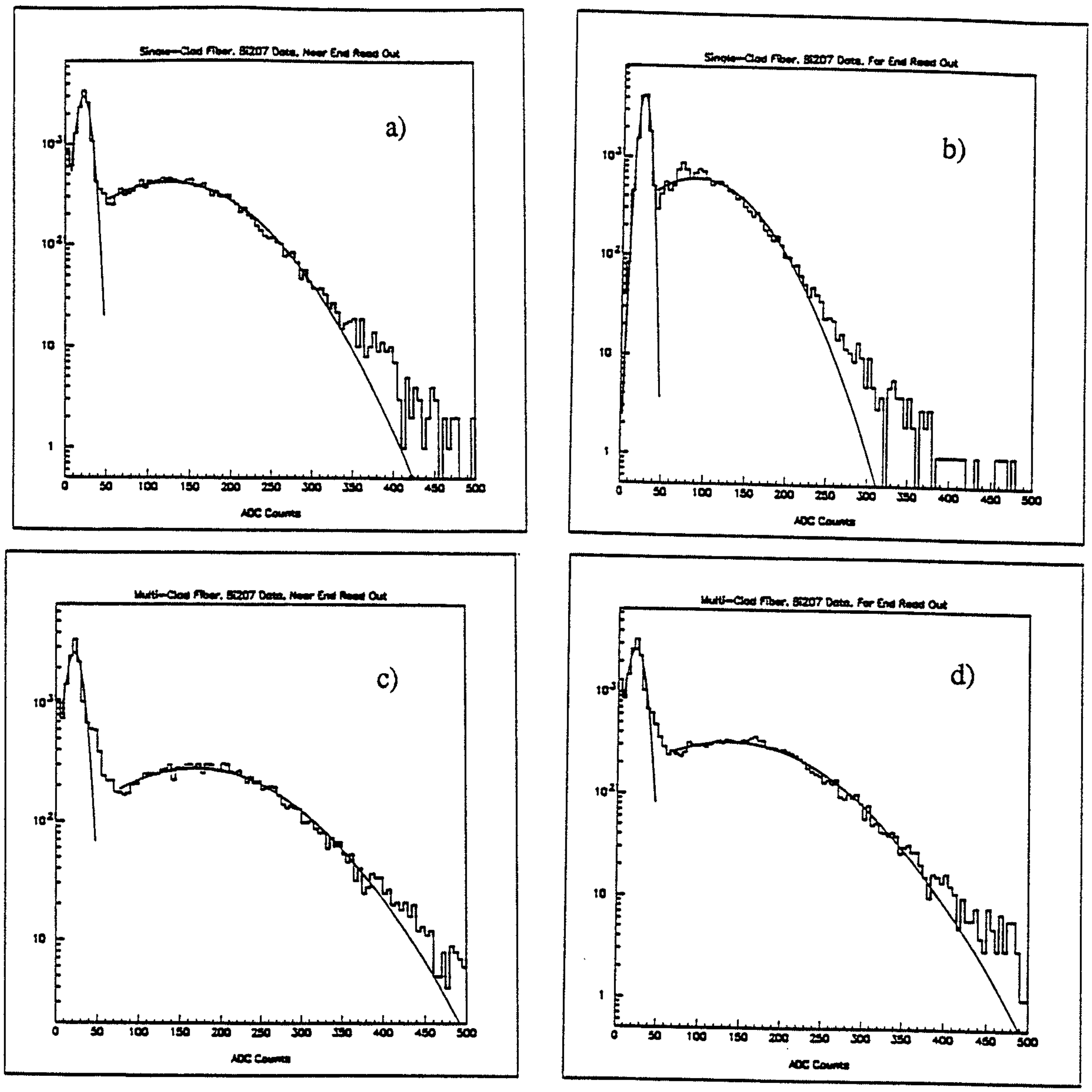

Figure 6. Detected photoelectron spectra obtained from single clad and multiclad fibers of 830μm diameter using a Bi207 radioactive (beta) source: (a) source placed at 50cm from the near end of a single clad fiber; (b) source placed at 250cm from the near end of the single clad fiber; (c) source placed at 50 cm from the near end of a multiclad fiber; (d) source placed at 250cm from the near end of the multiclad fiber. (Scale: 1ADC count=0.25pC.)

2.2.2. Fiber Mirroring Studies

We have studied the performance of multiclad fibers with mirrored and unmirrored ends. The mirroring procedure is described in Section 2.1 above. Excitation of the fibers was by Bi207 source at two different source locations: near the splice to the optical waveguide (40cm of scintillator); and near the far end of the fiber (280cm of scintillator). For these and other tests described below, the apparatus is arranged as indicated in Figure 3. The fibers were not included in the trigger for these studies. As shown in Figure 7, the mirroring affords substantial improvement in light collection for both far end and near end excitation. The values of the most likely photoelecron yield for each distribution are summarized in Table 2. Most importantly, the improvement in light collection from the far end with the mirror is a factor of 1.6.

TABLE 2

Study of Photoelectron Yield from Multiclad Fiber with end Mirroring

Type	Trigger Location	Excitation	Pedestal (counts)	Mean Value (counts)	Scale (counts/pe)	⟨PE⟩ Yield
Unmirrored	Far End	Bi 207	18.7	155	20	6.8
Unmirrored	Near End	Bi 207	19.4	176	20	7.8
Mirrored	Far End	Bi 207	18	238	20	11
Mirrored	Near End	Bi 207	19.4	264	20	12.2

2.2.3. Fiber Excitation Studies

Since data can be accumulated with a beta source much more rapidly than with cosmic rays, a comparative study was performed with fiber excitation by Bi207 and cosmic rays. The comparison was performed for excitation at the far end of the fiber, corresponding to 280cm of scintillator. Figures 7c and 7d display the Bi207 data and Figures 8a and 8b display the equivalent results for cosmic ray triggers. In each case, the source data gives slightly greater response, presumably due to the greater scattering through the material of the low energy electron which produces the trigger. Additionally there is a Compton scattering component due to gamma rays from the source.[16] However the results are very comparable to cosmic ray triggerd data - indicating that the use of Bi207 gives a reasonably equivalent response in the scintillator to that expected for a minimum ionizing particle. Table 3 summarizes the results of these studies.

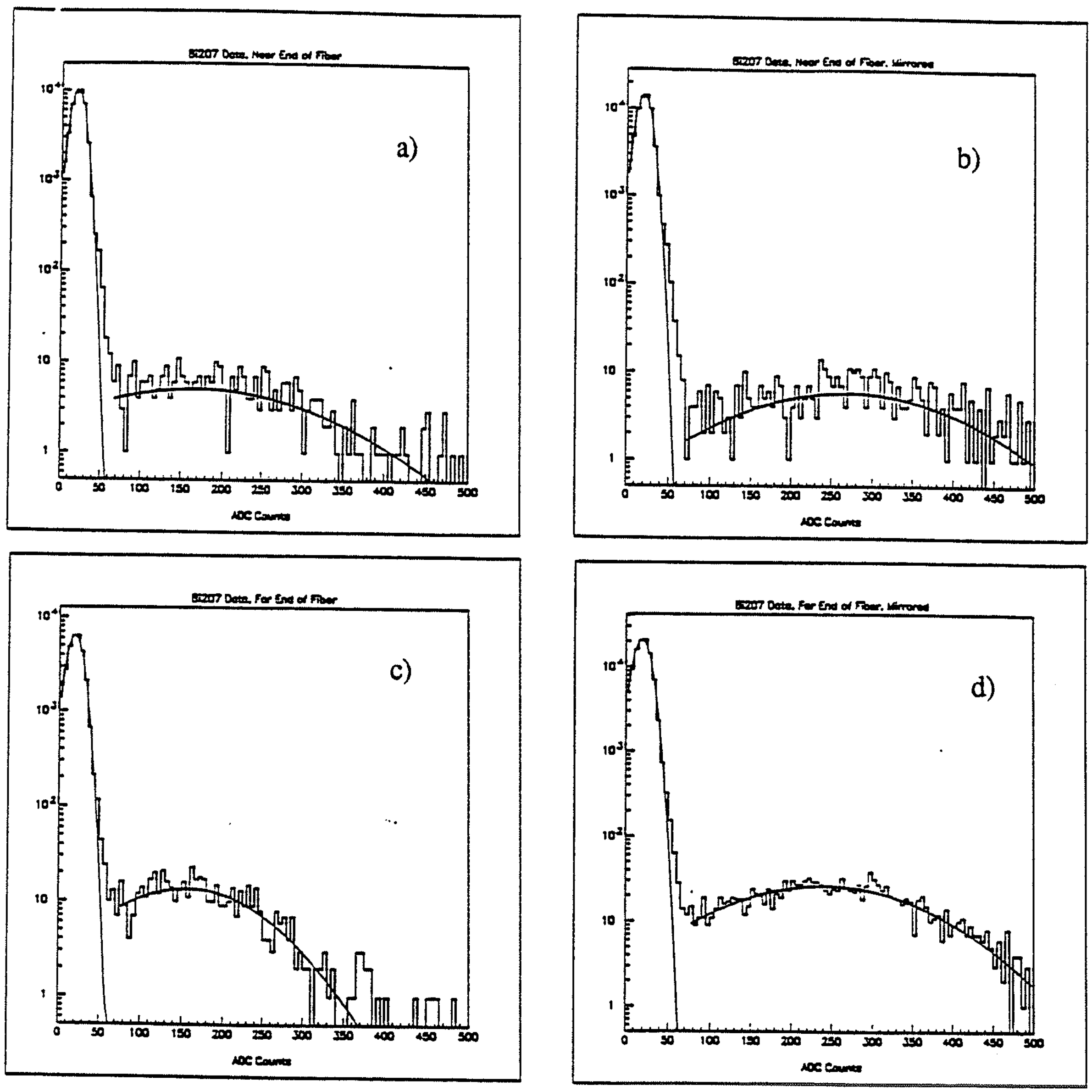

Figure 7. Comparative study of the photoelectron yield from multiclad fiber with mirrored and unmirrored ends using a Bi207 source. Trigger counters are positioned at the near end of the fibers. Case (a) is unmirrored, case (b) is mirrored. Trigger counters are placed at the far end of the fibers. Case (c) is unmirrored, case (d) is mirrored.

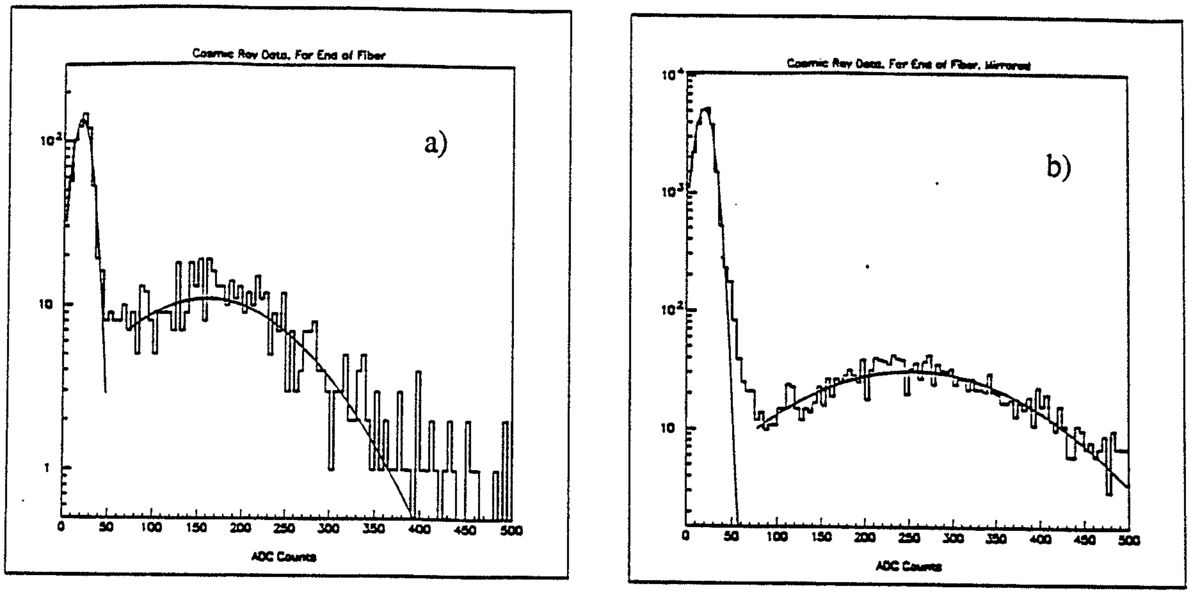

Figure 8. Comparative study of the photoelectron yield from multiclad fiber with mirrored and unmirrored ends using cosmic rays. Trigger counters are positioned at the far end of the fibers. Case (a) is unmirrored, case (b) is mirrored. (Scale: 1ADC count=0.25pC.)

TABLE 3

Study of Photoelectron Yield from Multiclad Fiber with Bi207 source and Cosmic Ray Excitiation

Type	Trigger Location	Excitation	Pedestal (counts)	Mean Value (counts)	Scale (counts/pe)	⟨PE⟩ Yield
Unmirrored	Far End	Bi 207	18.7	155	20	6.8
Unmirrored	Far End	Cosmic Rays	20	165	23.4	6.2
Mirrored	Far End	Bi 207	18	238	20	11
Mirrored	Far End	Cosmic Rays	19.1	223	20	10.2
Mirrored	Far End	Cosmic Rays	21	255	23.4	10

Figure 9 displays the results of the cosmic ray data with mirrored end and triggered at the 280cm location on a linear scale. Figure 9a shows the data; Figure 9b shows the data with a Landau Distribution superimposed. The Landau form represents the shape of the data well, as expected.

2.2.4. Rudimentary Tracking Study

With the substantial photoelectron yields obtained with the scintillating fibers, we have used five fiber/VLPC channels to look for tracks of cosmic rays. The fibers were stacked into a triangular array of six elements, five of which were read out into VLPCs. The structure was formed from plastic fiber-optic capillaries produced by Biogeneral Corporation. Trigger counters were placed above and below the stack. For this study, the fibers were not included in the trigger, but pulse height was recorded for each fiber element upon a trigger recorded in the trigger telescope. The lower right hand element in the array was inactive. Examples of tracks are shown in Figure 10. For example, in Figure 10a, the cosmic ray passed through the upper and lower central elements and also passed through the "crack" between the elements of the middle layer leaving no measureable signal in either of those fibers. The same condition applies for Figure 10d. Tracks of different incident azimuth are shown in Figures 10b and 10c.

3. SUMMARY AND CONCLUSIONS

The use of multiclad scintillating fiber offers significant advantages over single clad fiber for light collection. When used with VLPCs photosensors and over long lengths of fiber scintillator and waveguide, we observe a factor of 1.6 improvement in detected photoelectron yield over convention single clad fiber. Additionally, mirroring of the fiber end improves the detected light yield from all locations in the scintillating fiber, and under the test conditions described above affords a factor of 1.6 improvement over an umirrored scintillating fiber in detected photoelectron yield from the far end of the fiber.

These results confirm the predictions of earlier studies and beam tests with less optimum detection elements, and affirm the viability of scintillating fiber tracking for the SDC experiment at the SSC Laboratory and the D0 experiment at the Fermilab Tevatron. For experiments requiring less stringent demands on fiber length, such as fixed target experiments, the photoelectron yields will be even greater.

We are currently establishing a cosmic ray test facility of 3,000+ channels of fibers with VLPC readout at Laboratory 6 at Fermilab to study system performance of a large scale array of fiber detector

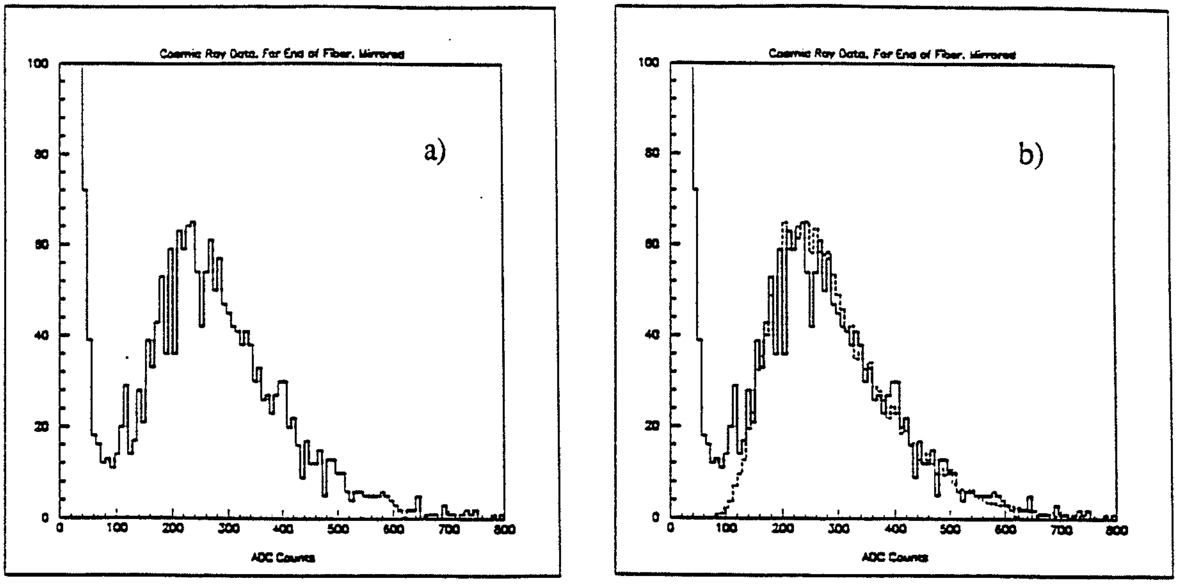

Figure 9. Spectrum of cosmic ray data recorded with mirrored, multiclad fiber. Trigger counters are positioned at the far end of the fiber. (a) Raw spectrum; (b) spectrum fit with a Landau distribution.

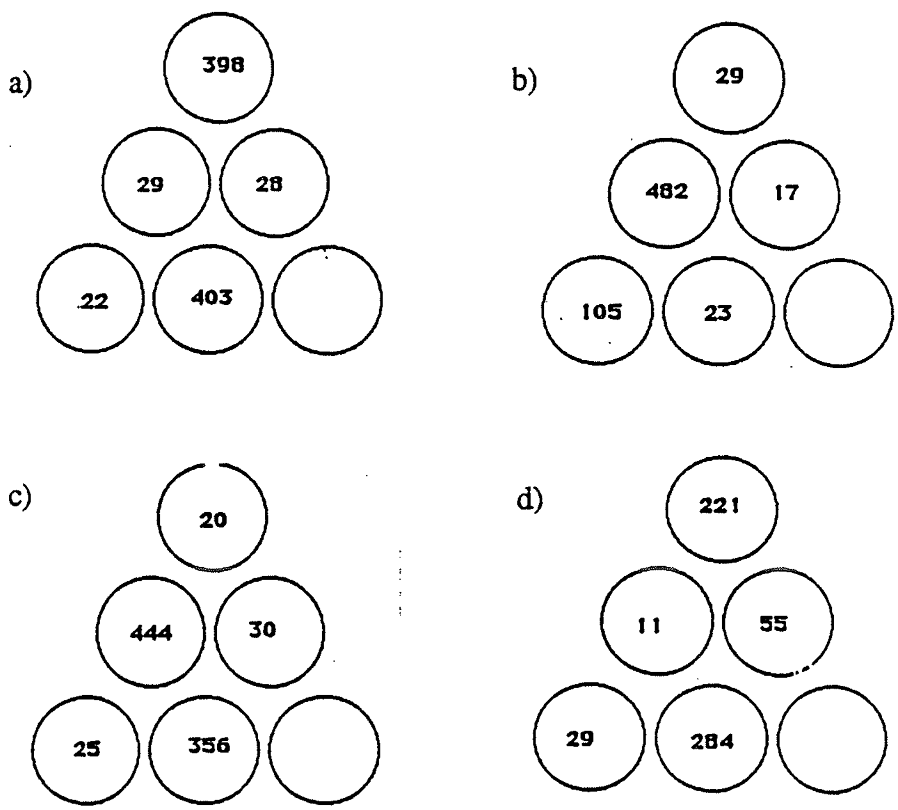

Figure 10. Sample cosmic ray tracks recorded in a small array of five active fiber/VLPC elements. Photoelectron yield for each fiber is indicated within theschematic circle representing each fiber. Fiber in the lower right hand corner is inactive.

elements. This system will be operational in Fall 1993. Additional studies of timing of signals from the fibers are in progress in our small scale array and a system of 32 fiber channels for tracking and stability studies is in preparation.

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