Attenuation Length and Timing Resolution of Scintillating Fibers for Hall D

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Abstract

The Hall D Barrel Calorimeter design consists of layers of scintillating fibers sandwiched between thin sheets of lead. Among the R&D issues that will be investigated in the pursuit of the optimal design for this device is the selection of the scintillating fiber type which must be based on superior light-attenuation and timing-resolution characteristics. The first series of tests to compare single– and multi–clad fibers from different manufacturers, using cosmics and 100 MeV pions at TRIUMF, are reported herein.

1 Introduction

The barrel calorimeter (BCAL) is a crucial Hall D detector subsystem. This device will be responsible for the detection, identification and total energy measurement of all neutral (photons, neutrons) and charged (protons, pions) particles within its volume. These demands place stringent constraints on its performance characteristics.

Specifically, the BCAL must provide the best possible energy and timing resolutions, low threshold of detection, and the ability to completely contain the electromagnetic showers, resulting from the conversion of photons into electrons and positrons. The dynamic energy range for photons over the complete list of induced reactions in the liquid hydrogen target spreads from as low as 20 MeV to as high as 1 GeV, as a result photons tend to emerge at much larger angles than heavier particles. Since the total energy of all the final state particles must be determined, sufficient energy from electromagnetic showers produced must be contained within the barrel calorimeter to allow the correct reconstruction of the photon's energy. To achieve this, the barrel calorimeter must be designed in such a way so that it covers its entire allocated solid angle confined by $14^o \leq \theta \leq 138^o$ and $0^o \leq \phi \leq 360^o$. As well, a high Z material (e.g., lead sheets) and sufficient thickness in radiation length ($\geq 15X_o$) are demanded so as to provide the means for containing the electromagnetic showers from escaping from the rear of the BCAL. These requirements are coupled to the minimum inner radius of the BCAL, which will allow for the placement of the interior subsystems (chambers, start/vertex counter and target), in setting the radial dimensions of the BCAL (0.65 m - 0.90 m). It's longitudinal dimension is largely dictated by the length of the solenoid magnet, resulting in a length of 4.5 m.

The basic design of the calorimeter follows closely that of the KLOE calorimeter [4]. The design envisions a matrix consisting of lead sheets of 0.2 to 0.5 mm thick and 1 mm diameter scintillating fibers. The lead sheets will be "grooved" and the fibers will be glued in these grooves, parallel to the central axis of the Hall D detector. The scintillation photons will travel down the scintilating fiber, to Winston-cone light guides and eventually to photomultiplier tubes attached at the ends of them, thus producing an electrical signal. Consequently the inherent properties of scintillating fibers play a crucial role. The criteria which must be evaluated include:

- Light collection efficiency (cladding),
- Amount of scintillation light produced (doping), and
- Attenuation of the light as it travels down the fiber (attenuation length).

To this end, fibers from two different manufacturers and of two different types were procured by the SPARRO Group at the University of Regina, to be tested in connection to their light attenuation and timing resolution. Specifically, the tested fibers were Kuraray SCSF-81 single–clad [5], Pol.Hi.Tech.0046 single– and multi–clad [6]. All fibers were 1 mm in diameter and were procured in the summer of 2000. In addition, in the summer of 2001, a second bundle of single–clad Kuraray fibers was procured.

2 Notes on Timing Resolution and Attenuation Length

2.1 Timing Resolution

Both the cosmic ray and TRIUMF $\pi/\mu/e$ measurements were accomplished by sandwiching the fiber bundles between two scintillator counters in coincidence mode, definining the event trigger. The setups involved at least four PMT's arranged as shown in Figure 1.

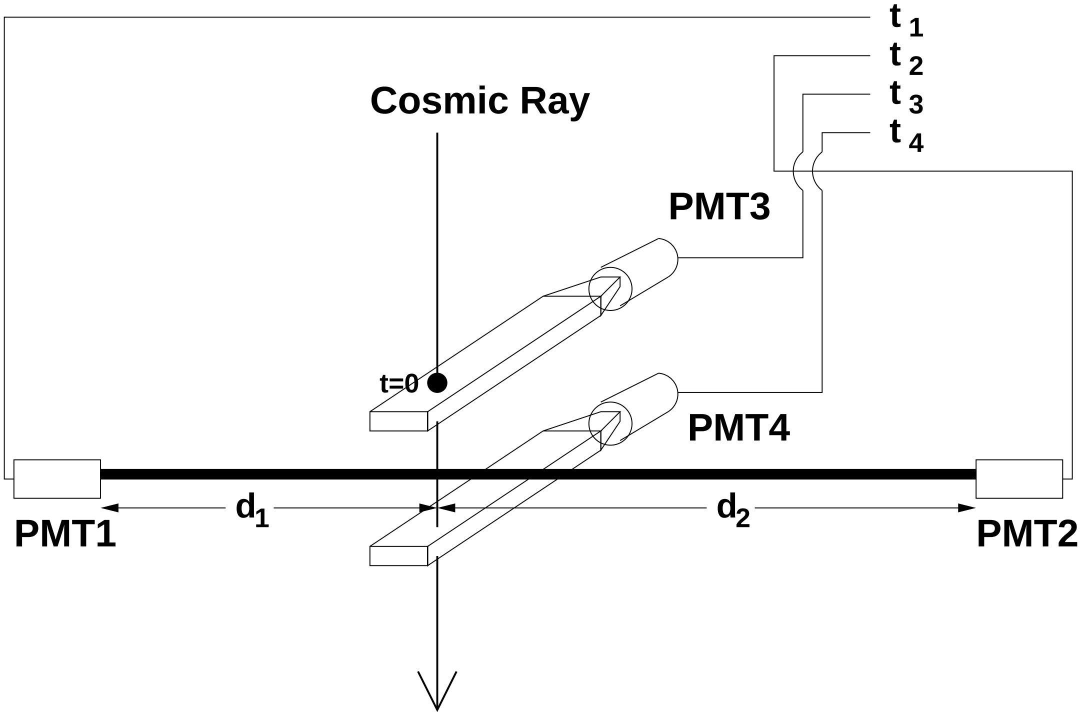

Figure 1: *Schematic diagram of experimental setup used for both cosmics and TRIUMF runs. Additional counters, used in some of the measurements, are not shown here.*

It can be easily shown that the time difference between the fiber left and right PMT's is given by the equation:

$$\Delta T = \eta \left[\frac{n}{c}(2d_1 - L_{fiber}) + T_{CONSTANT} \right], \quad (1)$$

where d_1 is the distance from one of the PMT's, L_{fiber} is the total length of the fiber, c is the speed of light, n is the index of refraction of the fibers, and η is the TDC conversion factor in channels/ns.

Therefore, a plot of ΔT vs. d_1 (measured in cm) will result in a straight line, with the slope of the line being given by

$$m_{\Delta T} = \frac{2\eta}{c} n. \tag{2}$$

For the Lecroy TDC that was used for the cosmic ray runs, the conversion factor was 200 ps/channel, therefore, $\eta = 5\ channels/ns$. Thus:

$$m_{\Delta T} = \frac{2 \cdot [5\ channels/ns] \cdot n}{30\ cm/ns} = \frac{n}{3}[channels/cm]. \tag{3}$$

Given that $n \sim 1.7$ [4], it is expected that $m_{\Delta T} \approx 0.57\ channels/cm$. Likewise, simply plotting the TDC peak location vs. position for each PMT should result in a slope:

$$m_{single} \approx \frac{1}{2} m_{\Delta T} \tag{4}$$

and therefore a predicted value of $m_{single} \approx 0.285\ channels/cm$.

2.2 Unfolding the Timing Resolution

To determine timing resolution of the fiber bundles, the software mean time and the left-right timing difference must be computed. These quantities should have constant values at any given point along the fiber. However, there are some uncertainties associated with these values, which arise from inherent timing resolution of PMT's involved and photon statistics. It is easy to show that the width of the softare mean timing peak is given by

$$\sigma^2_{MT} = \sigma^2_{L/R} + 2\sigma^2_{TR} \tag{5}$$

where $\sigma_{L/R}$ is the contribution from an individual fiber PMT, and σ_{TR} is the contribution from the trigger (finger) counter, while the width of the L/R timing difference distribution is related to the position resolution:

$$\sigma^2_{PR} = 2\sigma^2_{L/R} \tag{6}$$

In the above, it has been assumed that the left and right fiber timing resolutions are equal to one another, which is a reasonable approximation given that the phototubes were the same model, and the gains were approximately matched in hardware. In other words, it is possible to determine the value of $\sigma_{L/R}$ using the above equations in two independent ways:

$$\sigma_{L/R} = \sigma_{TD}/\sqrt{2} \quad and \quad \sigma_{L/R} = \sqrt{(\sigma^2_{MT}/2) - \sigma^2_{TR}} \tag{7}$$

2.3 Attenuation Length

To evaluate the attenuation length of the various fibers tested, it is necessary to evaluate first the ratio of the means of the left and right PMT ADC values at each position along the beam. To understand this, consider that the attenuation of light as it travels along the fiber is given by

$$I(z) = I_0(z)e^{-z/\lambda} \tag{8}$$

where z is the distance from the point of impact of the beam along the fiber to the appropriate PMT, λ is the attenuation length, and $I_0(z)$ is the amount of light produced at the interaction point. In practice, it is found that the amount of light produced at the interaction point is a function of z, as can be seen in Fig. 2, where the three ADC spectra are from the TRIUMF data taken at 90 cm, 150 cm, and 210 cm with respect to the left fiber end PMT. Consequently, the ADC values for the two PMT's in question may be expressed as

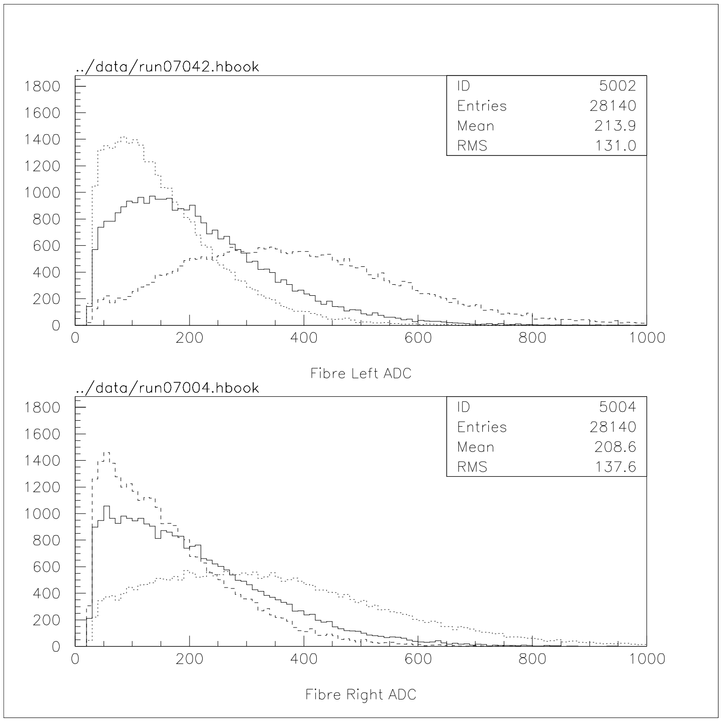

Figure 2: *ADC spectra for fiber PMT's*

$$ADC_{left} = f(z)e^{-z/\lambda} \; and \; ADC_{right} = f(z)e^{z/\lambda}, \tag{9}$$

where $f(z)$ is the geometric mean calculated from

$$f(z) = \sqrt{(ADC_{left} ADC_{right})}. \tag{10}$$

Thus, a reliable method to extract the attenuation length value is to take the ratio between the two ADC values above:

$$ln(ADC_{left}/ADC_{right}) = -2z/\lambda. \tag{11}$$

Plotting the ADC ratio values at different positions on a semi–log scale results in a straight line with a slope of $-2/\lambda$.

3 Fiber Bundle Preparations

The scintillating fibers were procured in spools. Fiber strands of approximately 3 m in length were cut and their ends were polished using 3 grades of sandpaper (1500 grit, 3 micron and 0.3 μm) from a fiber polishing kit. A microscope was used to inspect each fiber end and polishing was continued until the ends looked flat and with as few imperfections as possible.

The fibers were then bundled (nine fibers per bundle) and inserted in black electical-grade tubing. As this tubing was not entirely opaque, for the cosmic ray tests it was wrapped with black electrical tape to eliminate light leaks and to hold the fibers in place. Approximately 5 cm of bare fibers protruded from each end, and these were inserted in a 3 mm-diameter, 1 cm-deep hole drilled in a $1\frac{5}{8}$" plexiglass light rod that was subsequently coupled to a standard dynode-chain PMT (8575 2" Burle PMT [7]) using optical grease [8]. The same optical grease was also inserted in the hole and smeared on the ends of the fibers. The fibers and PMT's were placed in the "coffin", a black wooden box approximately 4 m in length designed to block out light completely [9]. Two scintillator paddle counters were used to provide the "trigger" or interaction point of the cosmic rays with the SciFi, as depicted in Figure 1.

This method of fiber coupling worked reasonably well for the cosmic ray tests since the fiber ends and the PMT's were not moved. Instead, the trigger counters were scanned across the length of the fiber bundles. However, for the TRIUMF tests the fiber bundles had to be moved to place different points in the beam. This motion caused problems in being able to reproduce the fiber coupling and, therefore, the black tubing method (termed “loose mode”) was abandoned in favour of a new arrangement.

The new arrangement began with a 3 m-long piece of 2”-wide black optical tape that was placed sticky side up on a long table and was held down at intervals by narrow 1”-wide black optical tape. Five fibers were placed parallel to one another on the sticky side of the wide tape, leaving about 5 cm free at each end. Short (1”-2” long) pieces of large cable ties were placed at intervals along the edge of the two outermost fibers and parallel to them to hold all five fibers in place. An additional four fibers were placed on top of the original five and staggered so that each of the upper-layer fibers fell between two lower-layer ones, and then another piece of the wide black optical tape was placed on top to seal them from light leaks and to hold them in place. The fiber ends were then inserted into the light rod as described above, and these new fiber ribbons (termed “5/4 stack”) were held firmly against the PMT housing by using wide optical tape. The description of this arrangement may be found as well in reference [10].

It should be mentioned that in 1992 the KLOE collaboration had determined that the Kuraray fibers exhibited a sensitivity to UV light, whereas the Pol.Hi.Tech. batches did not. By 1994, Pol.Hi.Tech. modified the doping in their scintillating fibers which resulted in an improvement of their light attenuation. However, this most likely rendered these fibers sensitive to UV light. In the preparations in Regina and TRIUMF precautions were taken to avoid exposure of the fibers to fluorescent lighting. (Prior to learning about this UV sensitivity, the Y2000 batch of Kuraray fibers had been exposed to UV lighting for a total of approximately two hours.)

4 Tests with Cosmic Rays

4.1 Setup

The preliminary tests to determine the attenuation length and timing resolution of the fibers were done using cosmic rays at the Regina Hall D test lab. Although statistics were limited, the tests were useful in providing general ideas for appropriate electronics, software, and physical setup, as well as for trends of the fiber performance, to the benefit of the subsequent TRIUMF measurements.

The event trigger was set to be a coincidence between the two paddle counters, and leading edge discriminators were used to produce the logic timing signal. These signals were then fed into CAMAC ADC (LeCroy 2249A) and TDC (LeCroy 2228) units. The TRIUMF Midas DAQ system [11] was used to analyze the data collected. The high voltage (HV) of each counter was selected to be in its plateau region. The final high voltage values and thresholds used for the cosmics ray measurements are displayed in Table 1.

PMT No.	HV (Volts)	Threshold (mV)
1	2500	15
2	2500	15
3	2100	50
4	2200	50
5	2400	20

Table 1: *High voltages and discriminator thresholds used during the cosmic ray tests.*

4.2 Measurements and Results

Each of the three fiber bundles tested was inserted in turn in the coffin and the trigger counter pair was positioned at five different locations along the fiber length, shown in Table 2. The same PMT's were used to test all three fiber bundles, thereby assuring that the PMT gain or transit time as a function of HV stability was not a factor in the measurements.

Fiber Bundle	A (cm)	B (cm)	C (cm)	D (cm)	E (cm)
Kuraray	20.0	152.0	267.5	221.5	78.0
Pol.Hi.Tech. single	22.0	157.0	273.0	228.5	70.0
Pol.Hi.Tech. double	30.0	158.5	276.0	214.0	80.0

Table 2: *Geometry of length scan measurements. All distances are with respect to counter FL (fiber left). All three bundles were in loose mode configuration, i.e. inside the black tubing.*

4.2.1 TDC Information

Figure 3 shows TDC comparisons. The peaks appear in positions that are in agreement between the two sets of measurements, dependant somewhat on the geometrical alignment. These spectra were fitted by Gaussian distributions to extract their means in order to calculate the TDC conversion factor and the index of refraction of the scintillating fibers.

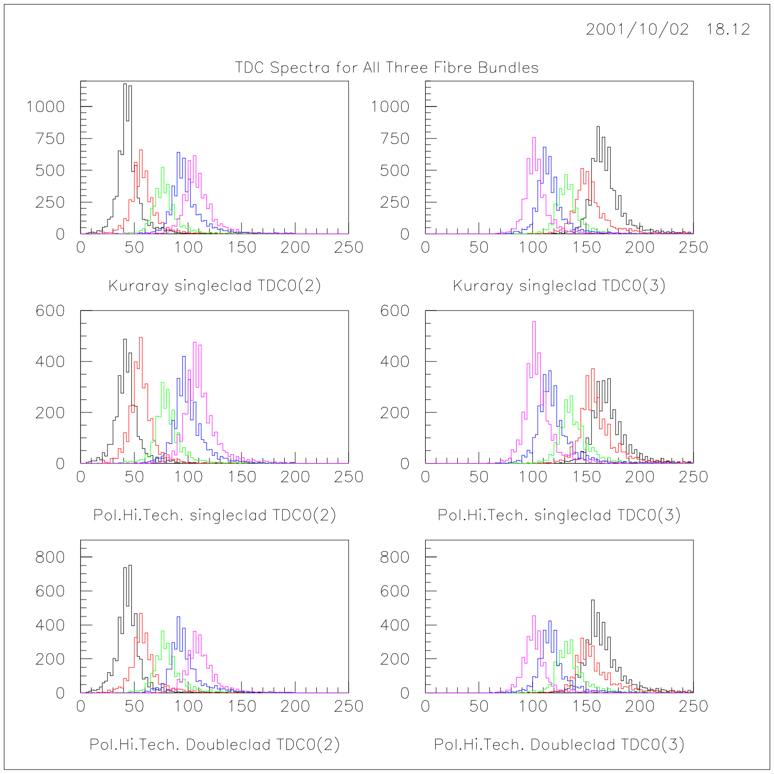

Figure 3: *Comparison of TDC spectra for the three fiber bundles for PMT1 (FL) on the left and PMT2 (FR) on the right. The curves from left to right for PMT1 and right to left for PMT2 correspond to the distances in Table 2.*

The differences in distance and in TDC peak centroid were calculated for all pairs of points in Table 2. These were then used to calculate the speed of light in the Kuraray and Pol.Hi.Tech. single–clad fiber bundles respectively. The resultant values were 18.78±0.63 and 18.53±1.27 cm/ns, which correspond to an index of refraction around 1.60. This result is near those found by KLOE [4] which ranged between 1.74 and 1.80.

Next, the fitted TDC peak location was plotted versus the distance from each PMT. The slopes and y-intercepts of these plots were (0.264, 37.6), (0.257, 98.4), (0.270, 36.9) and (0.259, 100.4) for PMT1 and PMT2 from the Kuraray and single–clad Pol.Hi.Tech. measurements, respectively. These slopes are in agreement with the expected number of $m_{single} \approx 0.285\ channels/cm$, as presented in equation (4). The slope of each graph, once multiplied by the TDC conversion factor, is equal to the inverse of the speed of light in the fibers, following equations (3) and (4). The extracted values were consistent with an index of refraction of 1.60 once again, using the conversion factor of 200 ps/channel.

The summation of the left and right PMT TDC values corresponds to the mean time of the two ends and should be a constant. Indeed, both Kurary and Pol.Hi.Tech. data exhibit an approximately flat behaviour as a function of position, averaging at 210 and 215 channels, respectively. If the functional dependence of the TDC peak on position for each PMT shown above is added, the total TDC offset is obtained. If these numbers are in turn substracted from the the mean-time values, and then multiplied by the TDC conversion factor of 200 ps/channel and the calculated speed of light, the total length of each fiber bundle is calculated: 284.4 cm and 299.8 cm, respectively. These numbers are in agreement with the measured lengths of approximately 284 cm and 291 cm. Note that the measured lengths were approximate only because they were taken when the fibers were already in the black tubing, and thus it was not possible to ensure that each fiber was stretched out completely.

4.2.2 ADC Information

Figure 2 shows that as one moves further from the PMT along the fiber bundle, less light is produced. The results are summarized in Section 6 and behave as expected: the attenuation is exponential as a function of distance from the PMT read out. Figure 4 shows the plots of the geometric means and left/right ratios for the three fiber bundles that were tested. The detailed procedure of extracting the attenuation length was explained above in Section 2.3.

5 TRIUMF Tests

5.1 Setup

The fiber and trigger PMT's were fastened on a dexion support stand, and each fiber ribbon was mounted on a 2x4 piece of lumber which was nailed onto a 4 m long 4x4 piece that was positioned at beam height. The 4x4 was moved progressively past the beam focus to put the appropriate spot of the fibers in the beam for our length scan, in order to extract the attenuation length. This process allowed for a robust coupling of the fibers to the PMT's.

With its axis oriented at an angle of 90° with respect to the beam, the fiber bundle was placed between a large paddle counter (PR) and a finger counter (TR) 1 cm wide and 4 cm in height, as depicted in Figure 5. Two additional counters (PF and PD) were placed immediately after the beam pipe vacuum window and at the back wall of the area, spaced

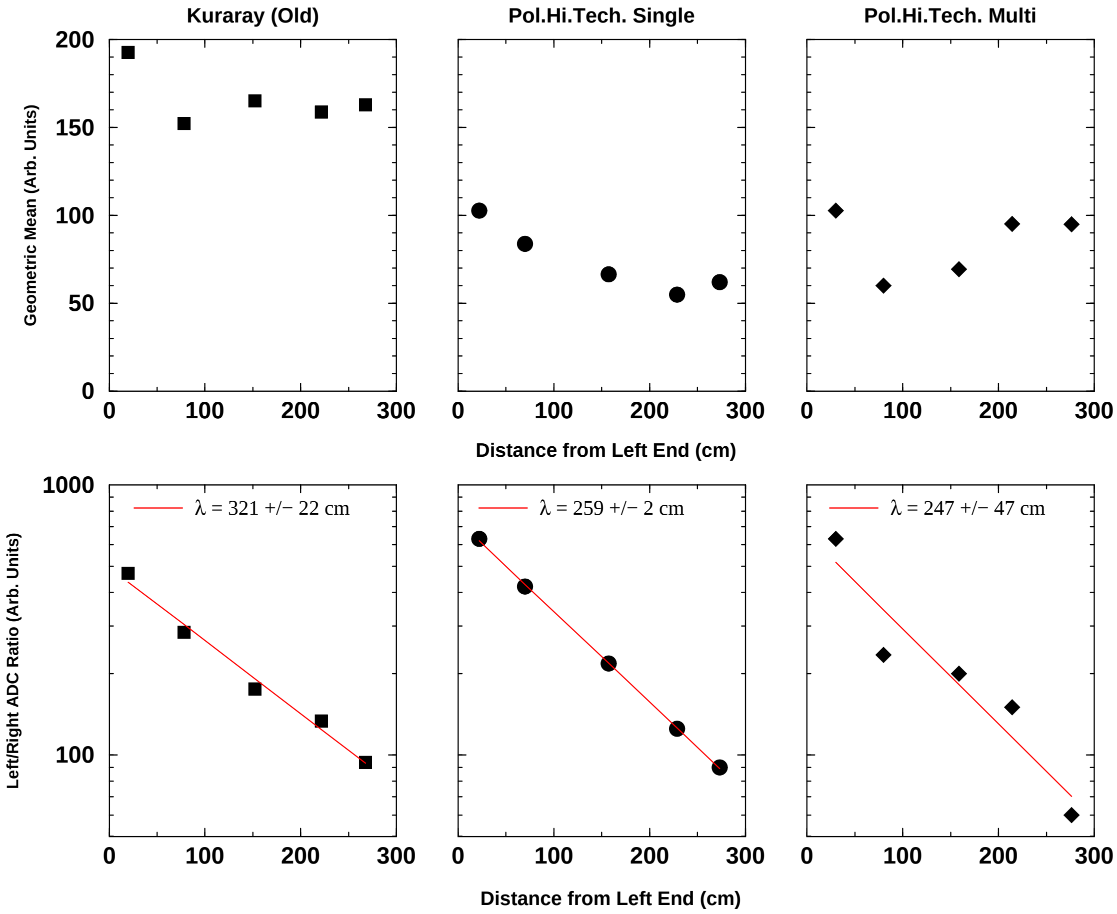

Figure 4: *ADC attenuation spectra.*

413 cm apart. Photographs of the experimental setup are shown in Figure 5.

5.2 Measurements and Results

The beam tests at TRIUMF were conducted in the M11 area in the meson hall, using pions with 100 MeV incident kinetic energy (195 MeV/c momentum). The M11 beam energy of $\sim$100 MeV corresponds to pions with a stopping power $\sim$20% above that of minimum ionizing particles. Scans of the magnetic field for the two dipole (bender) magnets of M11 and for two of the quadrupoles were carried out, in order to focus of the beam on the trigger/finger counter. The jaws and slits were set accordingly to yield a coincidence rate (see below) of $\approx$20 KHz. The cross–sectional area of the beam was $\sim 2\times2$ cm^2, and proton contamination in the beam was $\sim$2%. Pions, muons and electrons were present in the RF distribution (see

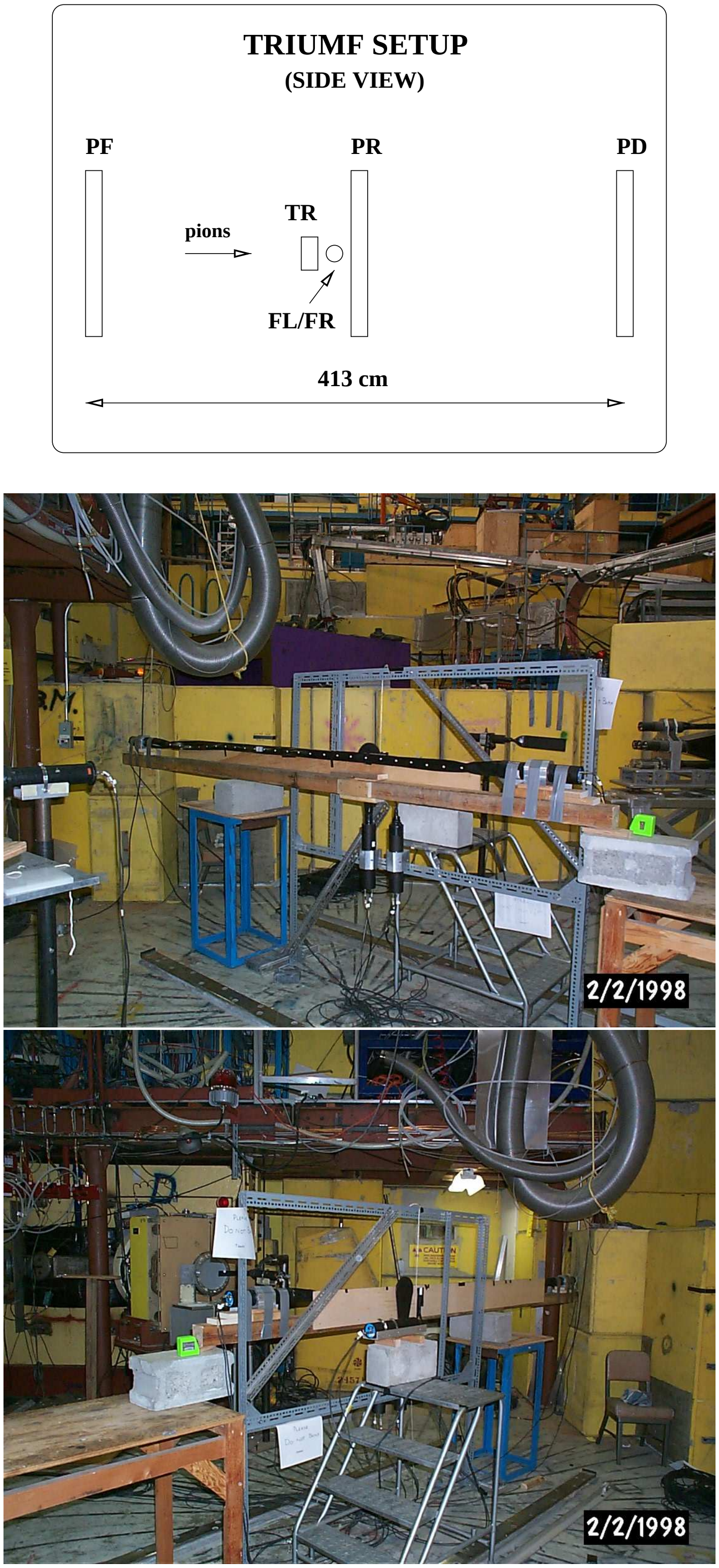

Figure 5: *Experimental setup at TRIUMF. Diagram: FL and FR represent the PMT's connected to the ends of the fiber bundles, TR is the small trigger counter and PR a larger paddle counter behind the fibers. The event coincidence was* $TR \cdot PR \cdot RF$*. Counters PF and PD were used to calculate the TOF in the experimental area. Photographs: the experimental setup on August 13, 2001.*

Figure 6). The extraction of the attenuation length for the fibers tested was not dependent on the particle species, and therefore the entire RF spectrum was used.

As in the cosmic ray case, the same PMT's were used to test all fiber bundles in all configurations. The event trigger was chosen to be a coicidence between the RF signal coming from the cyclotron, the paddle counter (PR), and the finger counter (TR), as shown in Figure 5. Constant fraction discriminators (TENELEC TC455) were used to produce the logic timing signals, thus minimizing time/amplitude correlation. ADC and TDC spectra were recorded for all counters in Figure 5 as was the RF timing spectrum.

Software cuts placed on the data to ensure good TDC values for all four PMT's, as well as ADC values above pedestal value for the fibers. Specifically, generous cuts were placed around the TDC peaks of FL, FR, PR and TR, and ADC cuts were placed on FL and FR to include the spectra above channel 25, thereby excluding only the pedestals. Representative TDC and ADC plots are shown in Figure 7. The TDC plots have cuts imposed which exclude the timeout peak at channel 4096. The ADCs have the TDC cuts, and are shown with and without pedestal cuts. The ADC lower limit was set at channel 25. Changing this to channel 50 did affected the geometric mean of the fiber PMT's but not the Left/Right ratio from which the attenuation length is extracted.

The total length of the fiber bundles was $\approx$300 cm. However, due to spatial limitations in the experimental area, measurements were taken with beam intercepting the fiber bundle at distances from $\approx$40 cm to $\approx$260 cm. Several measurements were carried out.

1. Group-1: Scans of all fiber bundles were performed, in 10 cm increments, measured from the beam left end of the bundle. These measurements were used to extract the attenuation length and timing resolution of the different fibers.

2. Group-2: Data were taken at two different configurations of the Pol.Hi.Tech. multi–clad fiber bundle with respect to the beam line, shown in Figure 8. This was done to ensure that the relative orientation of the fiber stack with respect to the beam did not affect the results of the group-1 measurements. The latter were taken in the vertical orientation.

3. Group-3: The Pol.Hi.Tech. multi–clad fiber bundle was scanned in front of the beam in the vertical direction from 135.5 cm to 137.5 cm from the floor, with the beam striking

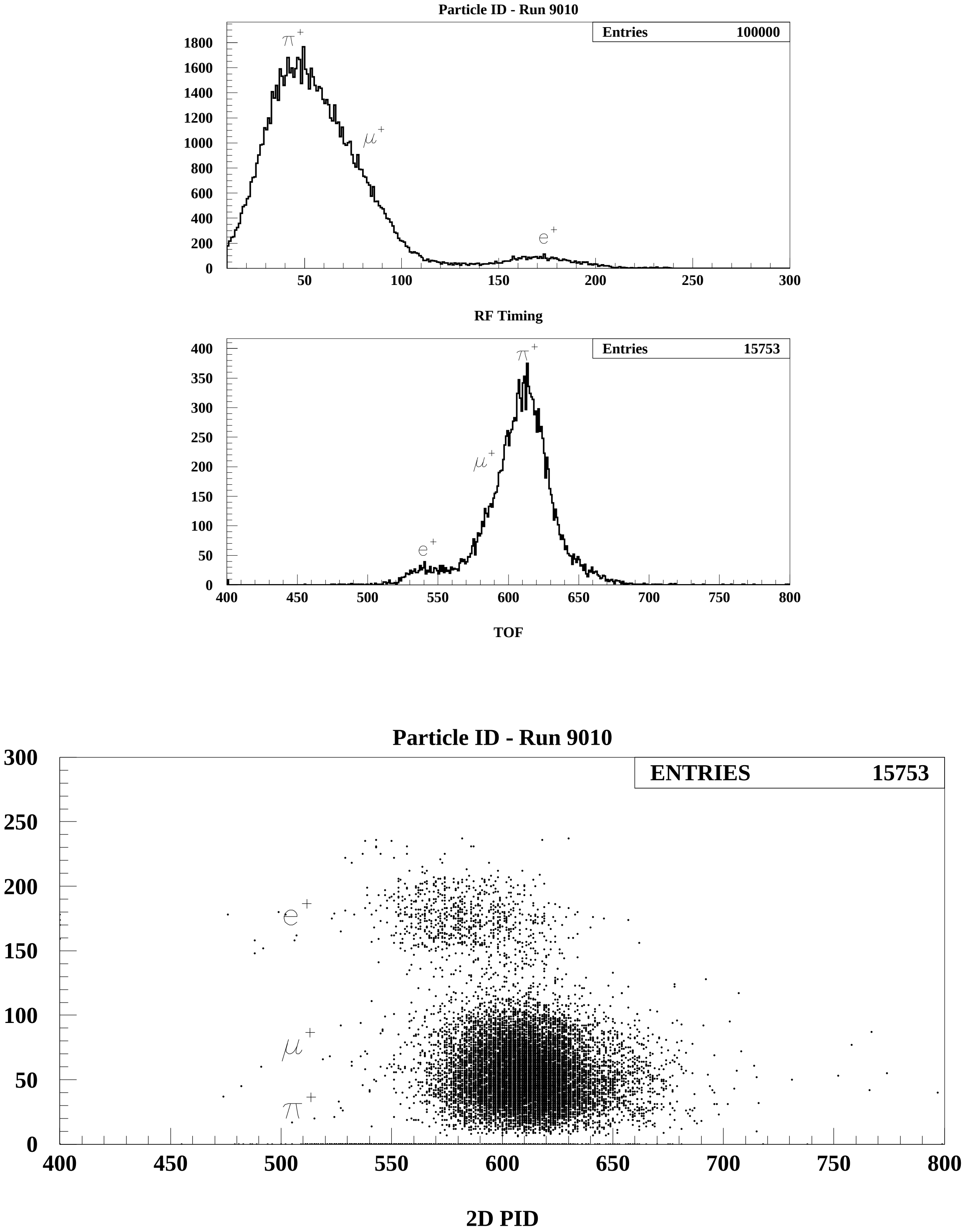

Figure 6: *Top panel: RF spectrum from one of the Pol.Hi.Tech. multi–clad runs, with the pion beam striking 100 cm from PMT1. Middle panel: the TOF spectrum between counters PF and PD. These are separated by 413 cm. Bottom panel: RF versus TOF.*

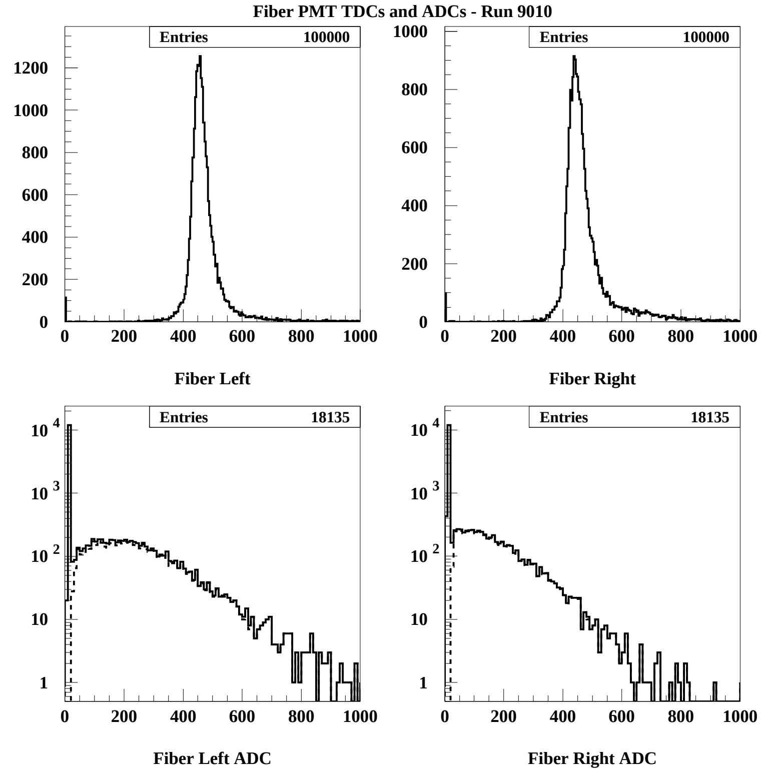

Figure 7: *Top panels: Fiber Left and Right TDC spectra, with TDC cuts applied to exclude the TDC timeouts. Bottom panels: Fiber Left and Right ADC spectra. The solid line shows the spectrum with only the TDC cuts applied, and the dashed line has ADC cuts as well, to eliminate the pedestals.*

the midpoint of the bundle. Again, this was aimed at cross-checking the dependence on the fiber bundle orientation. The nominal beam height was measured to be 136.5 cm.

4. Group-4: Again, the Pol.Hi.Tech. multi–clad fiber bundle was used to perform a forward/reverse measurement, where the same point along the fibers was measured with the fiber facing forward or backward. This was done to ensure that differences in the stray magnetic field from the Cyclotron did not affect one fiber PMT differently than the other.

5. Group-5: The two Kuraray fibers were placed on top of each other in the vertical position, to further investigate the dependence of the results on fiber thickness traversed.

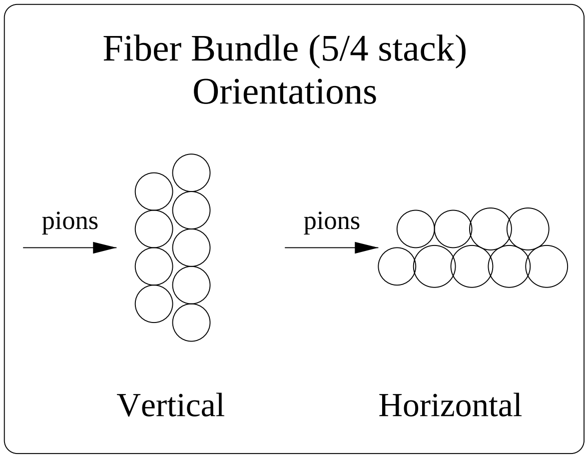

Figure 8: *Two different configurations of the Pol.Hi.Tech. fiber bundle 5/4 stack. Left, the one used for the attenuation length and timing resolution measurements presented below (group-1). Right, the configuration rotated by 90^0 to test the validity of our results (group-2).*

5.2.1 ADC Information

The extracted attenuation length values are plotted in Fig. 9, for all fiber bundles.

It is evident that the attenuation lengths of the Kuraray fibers are quite reproducible between different fiber samples, as well as different geometrical configurations. The loose bundle (black tubing) configuration resulted in $\lambda = (285 \pm 7)$ cm, whereas the more stable 5/4 stack produced $\lambda = (283 \pm 2)$ cm, in excellent agreement. The Kuraray Y2001 batch in a 5/4 stack configuration yielded a consistent $\lambda = (273 \pm 3)$ cm.

From the single–clad Pol.Hi.Tech. bundle results, it was concluded that there existed at least two points along the fiber bundle where the fibers may have been broken, thus resulting in the discontinuities seen in the attenuation data at distances of $\approx$125 cm and $\approx$180 cm from the Fiber Left PMT. Thus, the extraction of the attenuation length for this bundle was meaningless.

The Pol.Hi.Tech. multi–clad fibers had an attenuation length of $\lambda = (234 \pm 3)$ cm, considerably shorter that the Kuraray fibers.

The Group-3 and 5 measurements demonstrated that the attenuation length did not depend on the precise positioning of the fibers at beam height nor on the effective thickness of scintillating fiber material, as expected. The Left/Right ADC ratio of the fiber PMT's remained constant during these measurements.

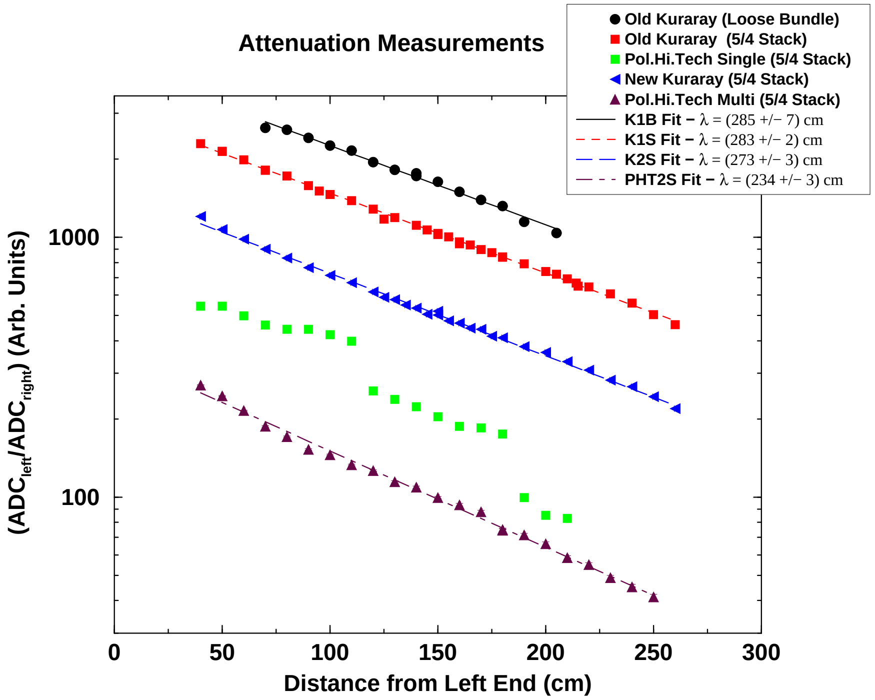

Figure 9: *Attenuation length measurements for various fibers. The Pol.Hi.Tech. single–clad fibers appear to have been broken or stressed at the locations where the discontinuities appear in their curve (unconnected squares).*

Finally, past experience with running in the M11 area has shown that the stray magnetic field of the TRIUMF Cyclotron can affect PMT gains. Therefore, measurements of $\vec{B}_{vertical}$ and $\vec{B}_{axial}$ (parallel to the fibers) were recorded, using a NMR probe. The field components were measured in $\approx$20 cm intervals along the entire range of locations of the PMT's, for the full length scans of the measurements. The PMT's are most susceptible to the axial field. Its value was below 0.5 G nearly everywhere, except around 1.5 m from the beam center toward the right fiber PMT, where it became around 2 G. In order to dispell concerns of the effect of the magnetic field, several of the measurements were repeated (Group-4) by reversing the direction of the fiber bundle, and thus the PMT's, from left to right. The reversed measurements yielded the same value for the attenuation length as that from the forward scans, within error bars.

5.2.2 TDC Information

Although the results obtained using equations (5) or (6) were found to be consistent with one another, equation (6) is more robust since it does not require information about the timing resolution of the trigger/finger counter PMT. Nevertheless, the timing resolution of the finger counter was determined using the data from a separate run where two finger counters of similar characteristics were used. The TDC spectrum for the second finger counter triggered by the TR counter is shown in Figure 10. The Gaussian fit gives a sigma of 14.44 channels, or 722 ps (the TDC conversion factor for the TRIUMF tests was 50 ps/channel). From this value and equation (6) the trigger jitter was extracted to be $\sigma_{TR} = 510$ ps.

The left panel in Figure 10 shows data for the extracted timing resolution, $\sigma_{L/R}$, for several positions along the fiber. Our suspicion of breakage in the Pol.Hi.Tech. single–clad fiber bundle is supported also by the timing resolution for this bundle which is poorer compared to the other fiber bundles. This can be explained in part by lower light collection due to the breaks in the fibers and also possibly by the increased number of reflections within each fiber. Statistically it appears that Kuraray fibers have superior timing resolution to the Pol.Hi.Tech. fibers. This implies that Kuraray fibers have better light production and light collection capabilities compare to the Pol.Hi.Tech. fibers.

The right panel in Figure 10 shows the timing resolution for the Pol.Hi.Tech. multi–clad bundle in the horizontal and vertical configurations, as shown in Figure 8, and for different high voltage values. It is immediately noticable that the timing resolution is much better when the fiber bundles are oriented horizontally with respect to the beam. This can be explained by the difference in the average thickness of fiber material that the pion traverses for these two orientations.

The amount of light produced is proportional to the thickness of material, and the timing resolution is inversely proportional to the square root of the number of photons produced. The average thickness for vertical orientation is given by

$$< t_v >= 9r\pi/10, \tag{12}$$

while the average thickness for the horizontal orientation is given by

$$< t_h >= 9r\pi/4, \tag{13}$$

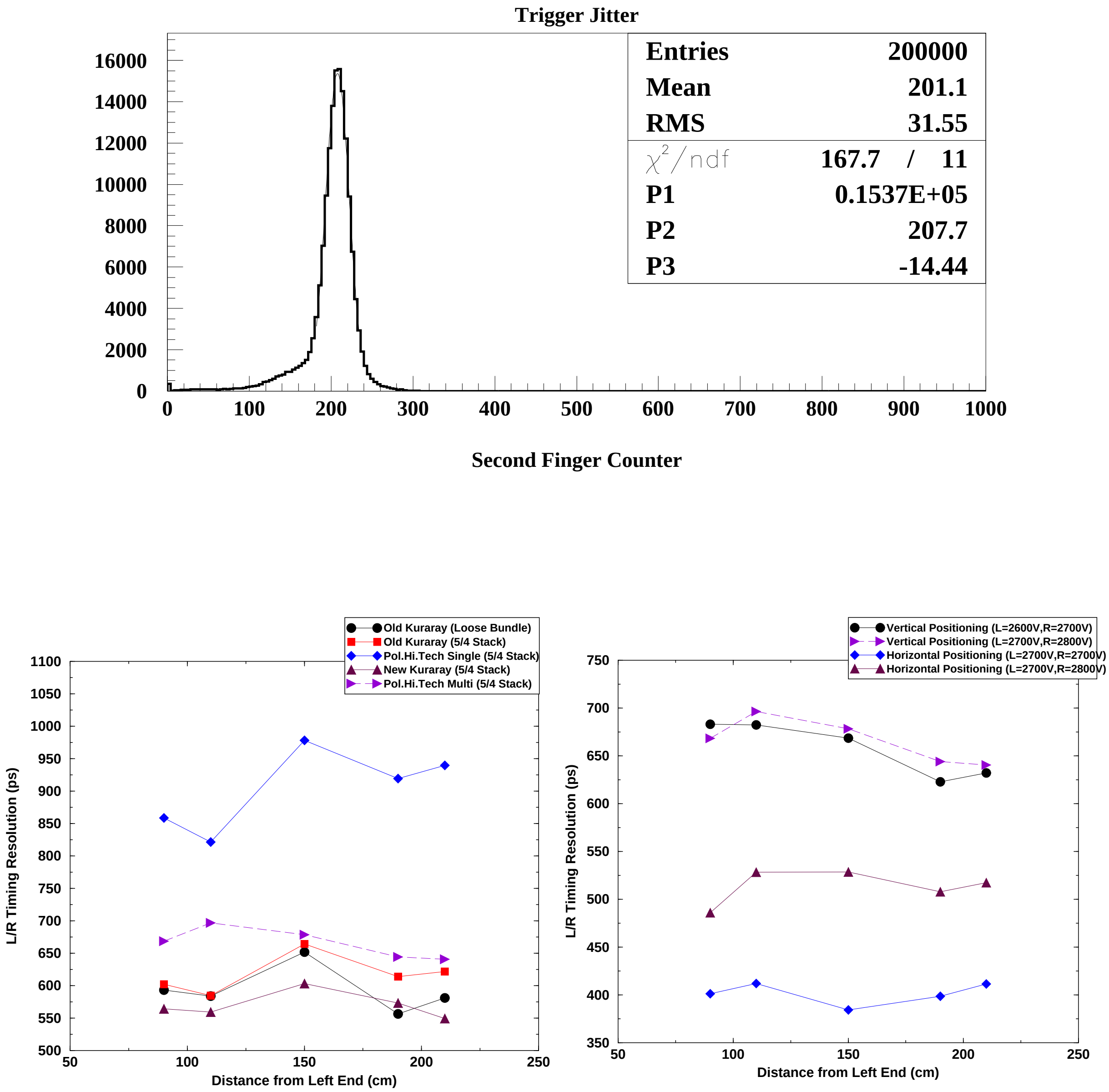

Figure 10: *Top panel: Timing jitter as defined by the coincidence of two small finger counters. Bottom panels: Left, timing resolution measurements for all fiber bundles; Right, timing resolution for the horizontal and vertical configurations as well as for different voltages of the Pol.Hi.Tech. multi–clad fibers. The Pol.Hi.Tech. multi–clad curve in the left panel is the one indicated as "Vertical Positioning (L=2700 V, R=2800 V)" in the right panel. These PMT high voltage settings were in fact the nominal settings for all the vertical configuration runs.*

where r is the radius of an individual fiber. Hence, we have that

$$\frac{\sigma_h}{\sigma_v} = \sqrt{\frac{< t_v >}{< t_h >}} = \sqrt{\frac{2}{5}} \sim 0.63 \tag{14}$$

It should be noted that this value strongly depends on the angle of the orientation of fibers with respect to the beam line and can be obtained only when fibers are oriented exactly vertical/horizontal to the beam line. In fact, we suspect that the "Horizontal Positioning (L=2700 V, R=2800 V)" curve at 550 ps in the right panel was not properly oriented, and as a result the full thickness in equation (13) was not being traversed. By using the average values of the horizontal curve at the (2700 V, 2700 V) high voltage setting and any of the two vertical configuration curves in the right panel of Figure 10, $\sigma_h/\sigma_v \sim 400$ ps/650 ps = 0.62, in excellent agreement with the prediction in equation (14).

Next, the curves in the right panel of Figure 10, for the different HV's applied, can be understood as follows. The different bias had essentially no effect for the vertical configuration, since in this mode the average thickness of fibers traversed depends very little on the precise vertical alignment. However, the sensitivity to the alignment is much more critical in the horizontal case, which may explain the large effect of the bias change.

Finally, the timing resolution was unaffected by the Group 3 and 4 configurations of the fiber bundles, as compared to the standard vertical configuration of a single bundle. The Group 5 results were consistent with expectations on the timing resolution from the effective doubling of the traversed fiber thickness.

6 Summary and Conclusions

During the summer of 2001, measurements were obtained of the performance of scintillating fibers, using cosmic rays at Regina and 100 MeV pions at the TRIUMF M11 beam line. Three types of fibers were tested in various configurations: Kuraray SCSF-81 single–clad, and Pol.Hi.Tech.0046 single– and multi–clad.

The results for the attenuation length and timing resolution measurements are summarized in Table 3, and compared with equivalent results published by the KLOE Collaboration [4]. It should be mentioned that the KLOE Collaboration also tested BICRON [13] scintillating fibers, but recent price quotes from BICRON revealed that these are too costly for the Hall D project and so were excluded from testing for this reason.

Batch	Fiber Type (mode)	Attenuation Length (cm)		
		Cosmics	TRIUMF	KLOE
1992	Bicron BCF-12			226 ± 3
1993	Bicron BCF-12			286 ± 8
N/A	Kuraray SCSF-81 single–clad			321 ± 5
1992	Pol.Hi.Tech.0046 single–clad			284 ± 5
1993	Pol.Hi.Tech.0046 single–clad			267 ± 6
2000	Kuraray SCSF-81 single–clad (loose)	321 ± 22	285 ± 7	
2000	Kuraray SCSF-81 single–clad (5/4 stack)		283 ± 2	
2001	Kuraray SCSF-81 single–clad (5/4 stack)		273 ± 3	
2000	Pol.Hi.Tech.0046 single–clad (loose)	259 ± 20		
2000	Pol.Hi.Tech.0046 multi–clad (loose)	247 ± 47		
2000	Pol.Hi.Tech.0046 single–clad (5/4 stack)		Broken	
2000	Pol.Hi.Tech.0046 multi–clad (5/4 stack)		234 ± 3	

Table 3: *Attenuation length determined using 2" PMT's following the cosmics runs and the TRIUMF beam tests. The results are compared to those from KLOE [4] and also separately reported [12].*

As was mentioned in Section 5, the Kuraray fibers showed a consistenly superior performance as per the light attenuation coefficient. They also exhibited a better timing resolution. However, the Pol.Hi.Tech. multi–clad fibers performed better in terms of light yield, based simply on the observation that for the same bias and gain the mean of the ADC spectra for these fibers was higher. In this respect the multi–clad fibers appear to be superior to the single–clad ones, and as far as the light attenuation is concerned, the Kuraray were overall better than the Pol.Hi.Tech. Thus, it was concluded, that multi–clad fibers should be ordered from Kuraray and tested as well.

Regarding the timing resolution, all fiber bundles gave $\sigma = 550 - 700$ ps. This is consistent with the KLOE results [4] which had $\sigma = 300$ ps for the Pol.Hi.Tech. and Kuraray fibers and 400 ps for the Bicron fibers, when the number of photo-electrons collected was $N(p.e.) = 30$. These numbers rise to 500-800 ps for $N(p.e.) \leq 10$. From the TRIUMF measurements, fitting of the ADC spectra yielded $N(p.e.) \leq 4$. Thus, the TRIUMF results are consistent, at least qualitatively, with those from KLOE.

A more detailed analysis of the TRIUMF results will be carried out in the near future, and an understanding of the systematically higher values for the light attenuation coefficient in the cosmics tests will be sought. In addition, the 5/4 stack fiber bundles will be tested with cosmic rays at Regina once again, to improve the statistics over those obtained last summer.

Future measurements with a prototype BCAL segment will cetainly yield $N(p.e.)$ in the tens of photo-electrons and thus allow a more direct comparison to the KLOE numbers.

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