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Quality Control Studies of Wavelength Shifting Fibers for a Scintillator-based Tail-Catcher Muon-Tracker Linear Collider Prototype Detector

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Abstract

Detailed measurements of the wavelength shifting fiber response to a stable and reliable light source are presented. Details about materials, a double reference method, and measurement technique are included. The fibers studied were several hundred KURARAY, Y-11, multiclad, 1.2mm outer diameter wavelength shifting fibers each cut from a reel to about one meter length. The fibers were polished, mirrored, and the mirrors were UV epoxy protected. Each fiber passed quality control requirements before installation. About 94% of the fibers have a response within 1% of the overall mean.

Introduction

To take full advantage of the physics potential of the future electron-positron international linear collider, the detector [1] should have unprecedented performance. For example, hermeticity and resolution constraints require that the calorimeter be placed inside a superconducting coil. Consequently, the hadron calorimeter must be compact and limited in depth to about 1m. The relatively thin hadron calorimeter requires additional calorimetric sampling behind the superconducting coil to estimate and correct for hadronic leakage. A US-European group is pursuing the construction of a cubic meter sized scintillator-steel prototype Tail-Catcher and Muon Tracker (TCMT), which has fine and coarse sections. The construction of the TCMT involves DESY, Northern Illinois University (NIU), and Fermilab.

The Northern Illinois Center for Accelerator and Detector Development (NICADD) at NIU proposed and is leading construction of the TCMT prototype. The TCMT consists of 16 steel absorber layers and 16 active medium cassettes, with dimensions about 1m x 1m. Each cassette has ten extruded scintillating strips as the active medium. Each strip is 5mm thick, 10cm wide, and about 1m long [2]. A wavelength shifting (WLS) fiber is inserted into the scintillating strip through a co-extruded hole and is not glued. The WLS fiber is connected to a silicon photo detector, used as readout. NICADD will explore the TCMT prototype performance with test beams.

Relative light yield and attenuation length are measured to assess the quality of fibers. Because the TCMT prototype does not use clear fibers, and the WLS fiber length is about a meter, the attenuation length of the WLS fibers was not monitored. The main goal of the quality control (QC) studies for the TCMT WLS fibers was to identify and remove those fibers with lower response than average. WLS fibers may have lower response because of faulty polishing, faulty mirroring, or fiber problems (such as cracks). After the QC of the extruded scintillating strips [3], the WLS fiber QC was the second step in the TCMT assembly.

In this note, the results of controlled measurements of WLS fiber response to a stable and reliable light source are discussed. The details of WLS fiber preparation and the method of measurement are included. These results may be useful for any detector using WLS fibers.

Materials and Methods

The TCMT requires 320 WLS fibers. KURARAY Y-11, multiclad, 1.2 mm outer diameter fibers were used. The WLS fiber length is 1035mm, about one inch longer than the strip. The additional fiber length is used for a collar that captures the fiber, provides exact positioning, and holds the fiber end in front of the photo detector active area ($1mm^2$). The fiber was inserted into the strip via a co-extruded hole. The co-extruded hole position may deviate up to 2mm from the collar center. After the collar, the fiber end displacement from the center of the photo detector active area was within 0.1mm.

Fibers were cut from a reel. The fiber ends were polished using a fly diamond technique. One end of the fiber was mirrored using aluminum sputtering, and the mirror was UV epoxy protected. The UV epoxy protection was in a form of a clear thin film around the mirrored fiber end. The fibers were processed in two groups; the results for the larger group are described here.

A schematic of the QC WLS fiber measurement apparatus is shown in Fig.1. The fibers were tested by exciting them with light from a scintillator irradiated with a radioactive source Sr-90 (5mCi). The BC-408 scintillator had a 100mm square shape and 10mm thickness Fig.2. The edges of the scintillator were not polished or painted. The scintillator had two machined key-shaped grooves for WLS fibers. The groove dimensions were: 0.053" inner diameter, 0.040" width of neck, and 0.078" depth. No attempt was made to optimize the groove dimensions. The grooves were parallel and 25mm from the edges of the scintillator. The scintillator was wrapped in two layers of Tyvek. To open the grooves for fiber insertion, two holes of about 1.3 mm diameter were made in the Tyvek wrapping on the same side of the scintillator. The scintillator, fibers, and a photomultiplier tube were placed inside a light-tight box.

The radioactive source was placed on the center of the scintillator with an accuracy of approximately 0.2 mm. For this particular geometry, the displacement of the radioactive source from the scintillator center could be as much 10 mm, which may introduce a non-reproducibility of the response up to 1%. Because the Tyvek had a slippery surface, a template was used to improve reproducibility of the radioactive source positioning.

Measurements Procedure

The measurements were made in batches. In each batch no more than sixteen fibers were examined. Of the 16 fibers two were permanently connected to the PMT (fibers 2 and 3 in Fig.1). One of those two fibers was permanently connected to the scintillator (fiber 2 in Fig.1) and both of them were used for reference measurements.

The fibers tested were also connected to the PMT. Because the PMT photo cathode sensitivity was not uniform [4], the fibers were connected to the PMT via a light guide (crystal) [5]. The combination reduced the PMT non-uniformity to less than 1% (see more details in the next section). Test fibers were connected to the crystal through a thick template with holes (Fig.3). The template holes were about 1.3mm in diameter with 4mm distance between them. Each template hole perpendicularly aligned a fiber to the crystal surface. Kapton tape was used to keep them in the template holes.

Finally, the scintillator, PMT, fiber 2, and most parts of the others fibers were permanently fixed to the test bench to avoid movement. Each test fiber was inserted into the hole also used by fiber three. The distance between the far end of the scintillator groove and the nearest point where the fibers were fixed to the test bench was less than a foot. This created a light spring effect or tension, which helped keep the fiber inserted to the very end of the groove. The first and the last measurements in each batch were with fiber 3. To reduce any cross talk during the measurements, the scintillator and the fibers were covered with Tedlar.

Uniformity of the PMT R580 response

The PMT response varies with the precise location of illumination on the photo cathode (PC) [4]. To reduce the PMT non-uniformity response across the PC area, a light guide (crystal) was used [5]. A clear acrylic crystal in the form of a square shaped rectangular parallelepiped with dimensions 16mm x 50mm was used to distribute the light. The crystal was positioned at the PC center. In front of the crystal an additional square shaped rectangular parallelepiped with holes was used to hold the fibers. This holder was made of delrin and had sixteen holes each with an inner diameter of 1.3mm.

To fully calibrate the system, the response of the PMT to the 16 possible fiber positions was mapped. The PMT mapping measurements were started with both WLS fibers 2 and 3 connected to the PMT and to the scintillator. After the output current was measured, fiber 3 was disconnected from the PMT and the output current was measured again. The second measurement (fiber 2 connected, fiber 3 disconnected) was used as a main reference. Using fiber 3, this procedure was repeated for the next fourteen holes with the main reference measurements as well. The goal was to verify that the output current with fiber 3 disconnected (main reference) was within 0.5%. If that was the case, the responses from the different holes were accepted. This simple precaution assured the stability of the measurement system for every particular PC area under the test. The results are shown in Fig. 4. The standard deviation for the response normalized to the average value was 0.21%.

WLS fiber response

A number of steps were taken to ensure the reproducibility of the results to 1% or better. The first step was to develop a measuring system with a relatively low background. That means that the PMT output must have low “dark” current compared to the current resulting from the radioactive source. In this particular case, with the high voltage at 1300V, the “dark” current was less than 1nA in all cases. The “dark” current was due to the PMT and the scintillator. The average PMT output current with the radioactive source present was a few μA. This figure means the “dark” current was less than 0.1% of a typical measurement.

The second step was to demonstrate reproducibility of the main reference measurements using fiber 2, PMT high voltage, and the radioactive source. The main reference measurement had to be reproducible with its nearest neighbor within 1% or better. The time delay between main reference measurements was short to ensure uniform conditions. As shown in Fig.5, 1% reproducibility was demonstrated.

The third step validated the amount of light available to the WLS fiber under test. This was checked using fiber 3. The PMT current measurement with both fibers 2 and 3 inserted into the scintillator validated the full system calibration (calibration reference).

Finally, WLS fiber 2 and the scintillator with the radioactive source were used as a custom calibrated source of light. This light source was permanently connected to the photo cathode. WLS fiber 3 was used to confirm the amount of light available to test the WLS fibers. The calibration was repeated before and after the measurements. If the two calibration values were consistent, the measurements were accepted.

Results

The results for one set of fourteen fibers are shown in Table 1. This particular set of measurements included fibers with low response. The first and the last measurements with fibers 2 and 3 (calibration references) were 2251 and 2250 nA. The mean value of the fifteen reference measurements was 1321.6nA with a standard deviation of 2.82nA (0.2%). These values show that the measurement system was stable in both calibration and main reference. However, the normalized responses showed a low response for fiber numbers #312 and #320. If fiber #312 response was not included in the calculation of the average value, the excursion of fiber #320 was obvious.

Table 2 shows the calibration current at the start and at the finish of each set of sixteen measurements. The ratio of the final to initial numbers shows the possible change inside a particular measurement set (short term time) was within 0.4%. The ratio of any start value to the start value at the very beginning (that was set #1) characterizes the relative changes over a long time, which was 1.5%. Measurements inside a set could not be adjusted, but the calibration between sets could be readjusted by introducing a correction, which was found from the calibration ratios.

Fig.6 shows the normalized response of a few hundred WLS fibers. The response of fiber #312, which was about 72%, was not included in Fig.6. The distribution of WLS fibers looks peaked compared to a normal distribution.

The double reference method provides a basis for assessment of the impact of thermally straightening by measuring fiber response before and after straightening the

WLS fiber ends. Thirty-seven WLS fibers were cut from a reel at NIU, then fly diamond polished, aluminum mirrored, and UV protected at Fermilab. Two fibers were used for the double reference measurements at NIU. Fig.7 shows that the response of thermally straightened WLS fibers is 1.4% greater, on average, than the response of the non-straightened fibers with the standard deviation 1.5%.

Discussion

A double reference method was used in a low background system to test the response of a few hundred WLS fibers. The main reference verified the electronic repeatability at each step with a standard deviation of ~0.25%. The calibration measurements were reproducible in a short period of time with an accuracy of about 0.5% or better. However, over a longer time the calibrations differed and in some cases required adjustment. In the case of measurements within a batch, high accuracy measurements were obtained without any adjustments.

In the case of QC for WLS fibers polished and mirrored at Fermilab, the double reference method indicated 94% of the fibers had uniform response with standard deviation of about 1%. Only one of 223 WLS fibers had a low response of about 72%. The others had a response 92% or higher than the mean of the 222 measured fibers. The TCMT QC study demonstrates that WLS fiber preparation and handling techniques at Fermilab provide a high-quality product.

The WLS fiber ends can be thermally straightened without damage. Straightening WLS fibers before polishing and mirroring may reduce assembly labor.

Acknowledgments

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Figures and Tables

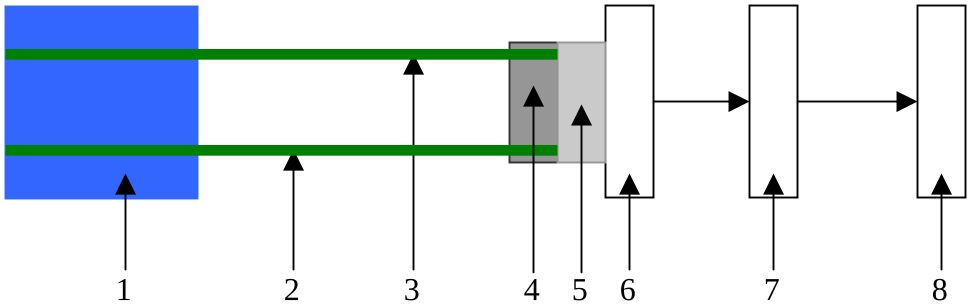

Fig.1. WLS fibers QC test schematic: 1- scintillator BC-408, 2 – WLS fiber permanently connected to the scintillator and to the PMT, 3 – WLS fiber permanently connected to the PMT, 4 – fiber holder, 5 – crystal, 6 - photo multiplier tube (PMT) Hamamatsu R580, 7 – picoammeter Keithley 6485, 8 – PC based data acquisition system

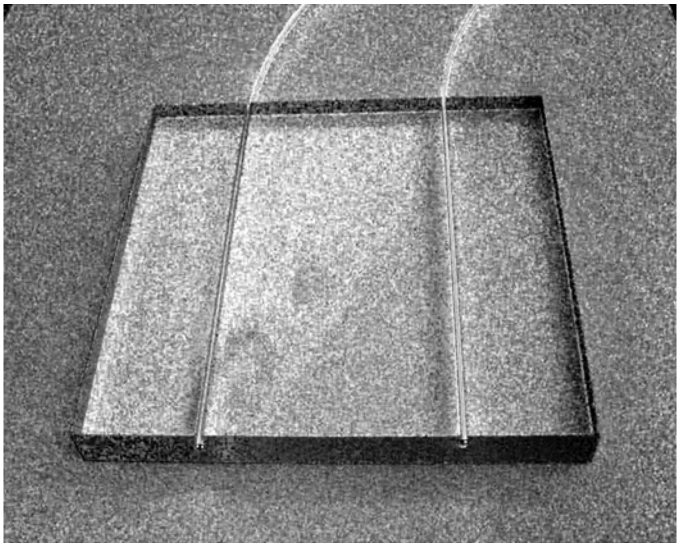

Fig.2. Cast scintillator BC-408 with WLS fibers inserted into key shaped grooves.

Fig.3. The template placed on top of the crystal (left) and a PMT housing head (right).

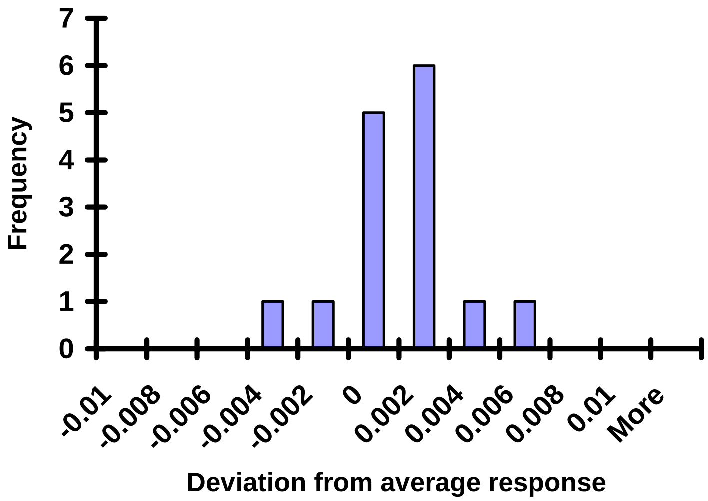

Fig.4. Frequency of the normalized deviations from the average response for the Hamamatsu PMT R580 photo cathode equipped with the crystal shown in Fig. 3.

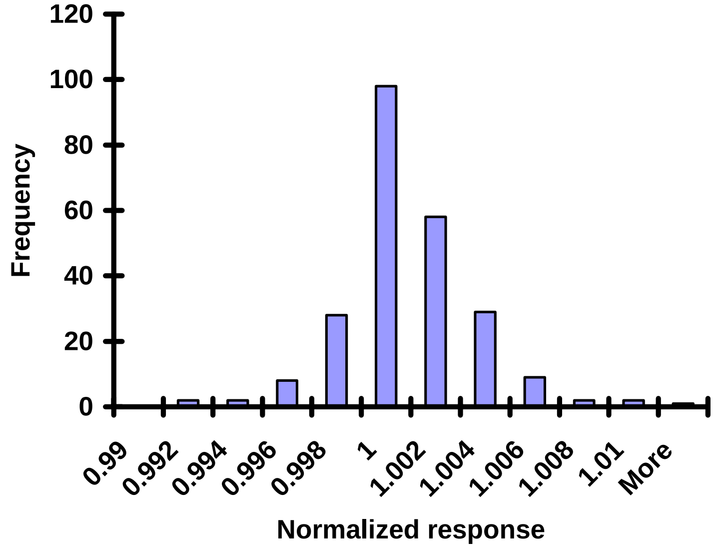

Fig. 5. Fiber response normalized to the average main reference response for a few hundred measurements.

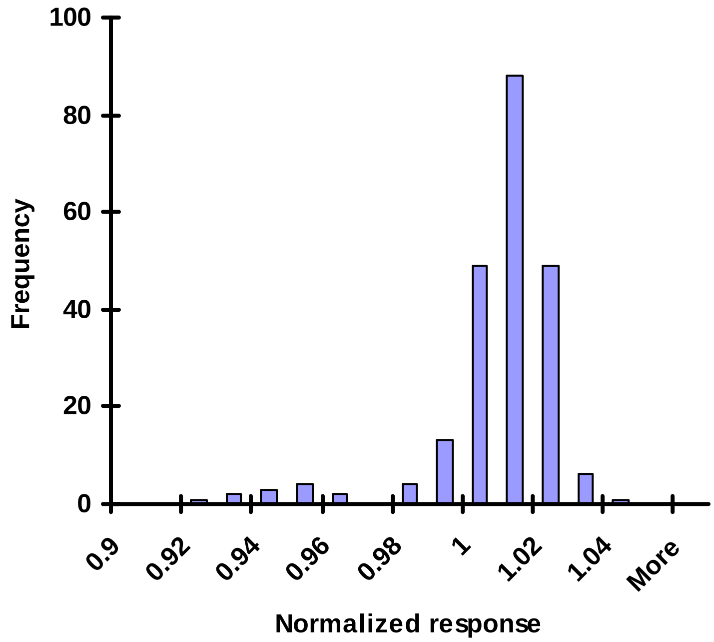

Fig.6. Normalized response of 222 WLS fibers. 210 fibers are in the peak (94%).

Table 1. Test response of fourteen fibers in absolute and normalized terms. Data were normalized to averages. In the "Fiber number" column the **2-3** represents the

response of fibers 2 and 3.

Fiber number	Fiber Response [nA]	Main Reference [nA]	Normalized Fiber Response	Normalized Main Reference
2-3	2251	1319		0.998
308	2278	1318	1.024	0.997
309	2276	1319	1.023	0.998
310	2296	1324	1.032	1.002
311	2298	1324	1.033	1.002
312	1652	1326	0.742	1.003
313	2277	1319	1.023	0.998
314	2285	1324	1.027	1.002
315	2289	1319	1.029	0.998
316	2261	1320	1.016	0.999
317	2289	1320	1.029	0.999
318	2250	1321	1.011	1.000
319	2271	1322	1.021	1.000
320	2152	1327	0.967	1.004
321	2281	1322	1.025	1.000
2-3	2250			

Table 2. Calibration currents (fibers **2-3**) that characterize the reproducibility of measurements in the short and long term. The measurements were taken over several weeks.

Measurement Set	Fibers 2-3 Start [nA]	Fibers 2-3 Finish [nA]	Ratio Start to Finish	Ratio to Start #1
1	2219	2220	1.000	1.000
2	2224	2217	0.997	1.002
3	2212	2212	1.000	0.997
4	2207	2216	1.004	0.995
5	2230	2231	1.000	1.005
6	2233	2242	1.004	1.006
7	2253	2245	0.996	1.015
8	2244	2250	1.003	1.011
9	2252	2253	1.000	1.015
10	2244	2235	0.996	1.011
11	2237	2240	1.001	1.008
12	2251	2255	1.002	1.014
13	2251	2250	1.000	1.014
14	2260	2250	0.996	1.018
15	2238	2238	1.000	1.009
16	2253	2243	0.996	1.015

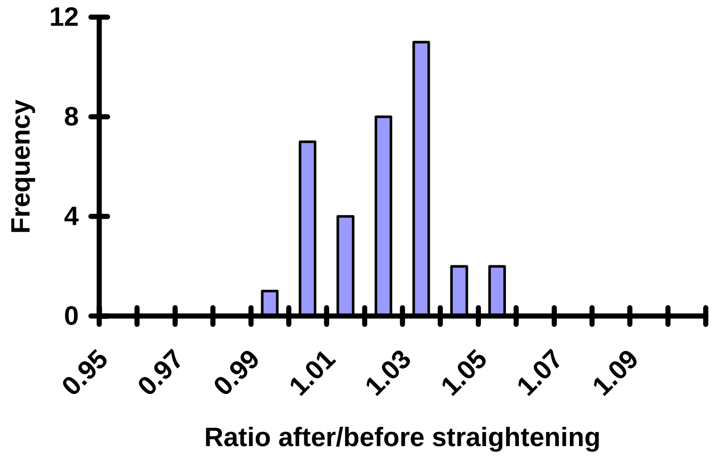

Fig.7. Thermally straightened WLS fibers.