Wavelength Shifting Fiber Quality Assurance for the NOvA Experiment

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Abstract
Wavelength shifting fibers are a critical component in the detectors for the NOvA long-baseline neutrino oscillation experiment at Fermilab. Michigan State University designed and constructed Quality Assurance Scanners to measure the properties of the wavelength shifting fiber, and set a performance standard. In a quality assurance procedure, a sample of fiber from each spool of produced fiber is compared to this performance standard. Here we describe the construction of the scanners, the stability of their operation, and quality assurance measurements from the first 1000 km of delivered fiber.

Introduction

NOvA is a long-baseline neutrino oscillation designed to observe the appearance of electron neutrinos in a beam of nearly pure muon neutrinos after the particles travel 810 km from Fermilab, Batavia IL, to a detector in Ash River, Mn. Identification of electron neutrino interactions requires a low-density detector to allow the produced electrons to be tracked prior to the generation of an electromagnetic shower, and to minimize backgrounds from interactions producing photons, e.g., from pi-zero decays, that convert to electron-positron pairs. In the NOvA detectors, liquid scintillator acts as the neutrino target and as a detector for energy deposited by the products of the neutrino interactions.

In the NOvA detectors, blue light generated in liquid scintillator-filled tubes, up to 15 m in length, is converted to green light by a loop of wavelength shifting optical fiber. By total internal reflection a fraction of the converted light is transmitted within the fiber to the end of the loop where it is detected by an avalanche photodiode (APD). Over a 3-year period, the Kuraray Co., Japan, will supply NOvA with 13,000 km of 0.7 mm diameter double-clad fiber. The fiber is delivered to Michigan State University (MSU) on large diameter (0.9 m) spools, each containing about 3.4 km of fiber. A sample of fiber from each delivered spool is tested with a Quality Assurance Scanner (QAS), designed and constructed at MSU. Spools that pass the Quality Assurance (QA) criteria will be returned to the original crates, stored, and then shipped when needed to the NOvA module factories in Minnesota. An identical QAS was provided to the Kuraray Factory in Japan, and is used in the factory as part of their Quality Control procedures. This minimizes the possibility that below specification fiber will be shipped to the US.

The Quality Assurance Scanner

The average length of fiber in each tube of the NOvA far-detector is ~32 m, folded into a loop so that the far-end is ~16 m from the APD. Both ends of the loop are viewed by a single APD element, thus the light generated in the fiber travels a short distance to the APD in one direction and a long distance in the other direction. Due to attenuation in the fiber, the minimum yield is obtained for light generated near the end of the fiber loop, though the minimum is rather flat near the end of the tube, so that the QAS is designed to measure a 26 m length of fiber.

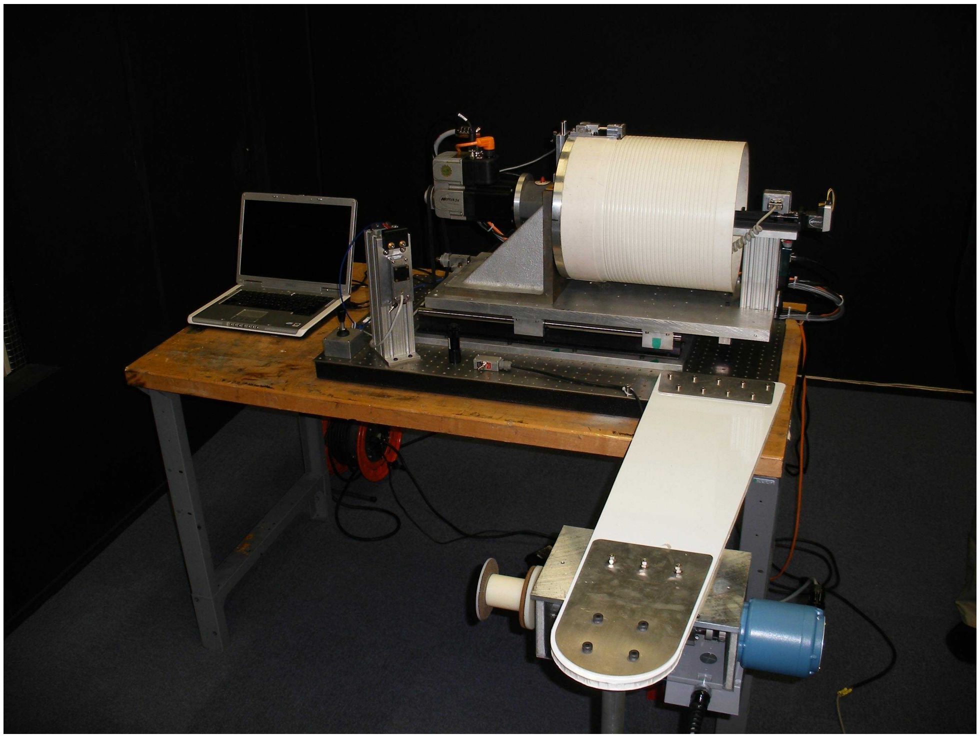

Figure 1. Quality Assurance Scanner for NOvA wavelength shifting fiber

The QAS is mounted to a small lab bench, as shown in Fig. 1. The entire operation and data acquisition of the QAS is controlled from the laptop computer seen on the left side of the bench. A spool of fiber is mounted on the fixed hub in the foreground that is driven by a synchronous motor through a constant torque coupling. The coupling is set to generate a 50 g tension on fiber that is being removed from the spool and wound into a spiral groove in the 31.83 cm diameter drum (white). Holes, 3 mm in diameter, are drilled in the spiral groove and through the drum wall placing the holes at 1 m intervals along the groove.

The drum is mounted on a longitudinally moving plate. A stepping motor controls the rotation of the drum and drives the mounting plate along the drum axis to keep the spiral groove aligned with the spool as fiber is wound onto the drum. Within the drum is a cantilevered track on which a collimated LED light source is driven by a stepping motor to known locations that illuminate the fiber through the holes. The holes insure that no reflected light can enter the fiber at that point. To maintain a constant light intensity, the LED current is controlled via feedback from the signal generated by a photodiode in the same housing. The fiber being scanned is not cut from the spool, allowing the fiber remaining on the spool to serve as a non-reflecting termination. After the scan data is collected, the scanned section of fiber is rewound onto the spool.

Once 27 m of fiber is wound onto the drum the polished end of the fiber is released from the drum and inserted into one of two ferrules located on the tower on the left of the base plate near the laptop. Behind one ferrule is a quartz optical fiber leading to a CCD spectrometer from which a precision spectrum can be readout. Behind the other ferrule is an amplified photodiode to measure the total light output from the fiber. The photodiode has the same quantum efficiency wavelength dependence as the APD used in the NOvA detectors. The QA data consists of spectra and total light output at 26 illumination distances from 1 to 26 m.

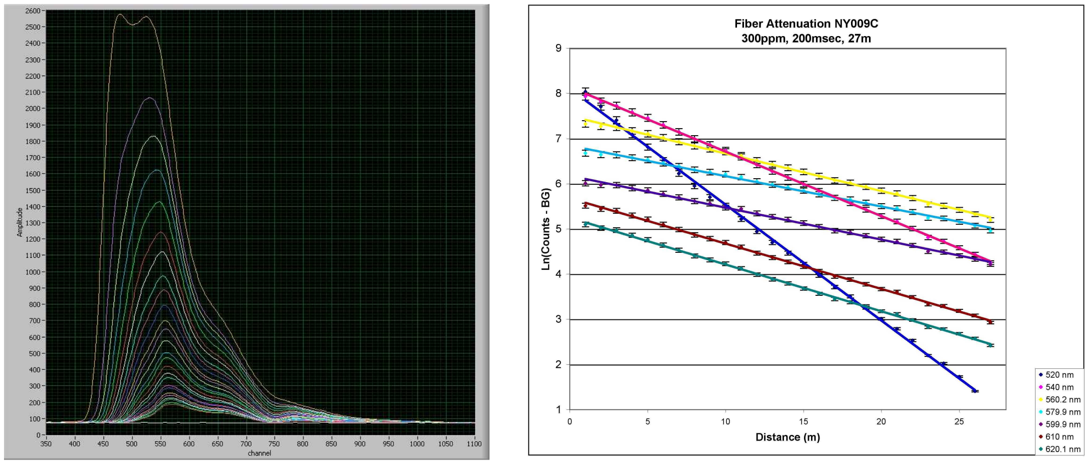

Figure 2. The 26 spectra exiting a fiber illuminated at 1 m intervals (left). Log of the light intensity at 7 representative wavelengths vs. distance of the illumination point from the end of the fiber (right).

At each of the 26 illumination distances from 1 to 26 m, the spectrometer produces light intensities at wavelengths between 350 and 850 nm, as shown in Fig. 2. Also, the light intensity at representative wavelengths exhibits a truly exponential attenuation. Therefore, the attenuation length at representative wavelengths forms a convenient summary of the spectral data. The attenuation data provides detailed information on the fiber performance that been shown to be sensitive to small variations in early production fiber samples.

Quality Assurance acceptance criteria

In February 2009 during the R&D phase, we received 100 km (30 spools) of fiber intended for the IPND. We developed the QAS and the scanning procedures using this sample. By November 2009 we had run this sample through a number of scanning cycles to gain confidence in the QAS design. During this period we developed an understanding of the average fiber properties and the variations one could expect. When illuminated at 26 m from the end of the fiber, we found a 10% variation in the light yield from each spool. We were therefore prepared to evaluate the first production fiber to be delivered in January 2010.

Prior to the start of production, a second QAS was built, calibrated against the MSU scanner, and disassembled for shipping to the Kuraray factory near Niigata Japan. MSU personnel travelled to Japan to perform a reassembly of the QAS and instruct Kuraray personnel in its operation. We performed a number of scans on spools of fiber that were being prepared for the first shipment. Our analysis of this QA data indicated that the light output and attenuation lengths of this fiber was equal to or better than any sample of fiber that we had received previously. We made the proposal, which was accepted, that the average light output at each distance from this first shipment of 350 km of fiber would be the reference fiber light output. In subsequent shipments, photodiode measurements of the total light output from each spool at each distance must greater than 70% (3 sigma) of the reference fiber light output.

The first shipment of fiber arrived at MSU in early January 2010. The average of the light output

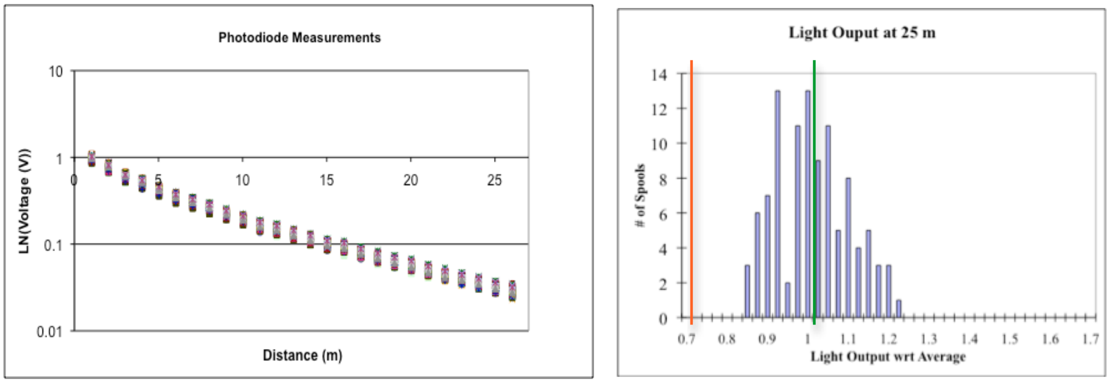

Figure 3. Light output measurements in the QA of 104 spools in the first shipment of 350 km of fiber. On the left, the log of the light intensity at distances of 1 – 26 m from the fiber end, and on the right, the light intensity of each spool at the 25 m compared to the reference.

measurements in the QA of the first shipment of fiber from Kuraray, as shown in Fig. 3, forms the NOvA QA reference for all future shipments. In previous samples the RMS of the light output from the fiber was about 5% when illuminating the fiber at 1 m from the photodiode, increasing to about 8% at 15 m, and to 10% at 25 m. The RMS values in this first production sample were consistent with these values.

The second shipment arrived in February 2010 and the third in March. The QA measurements were completed within a month of delivery to MSU. The photodiode measurements were similar

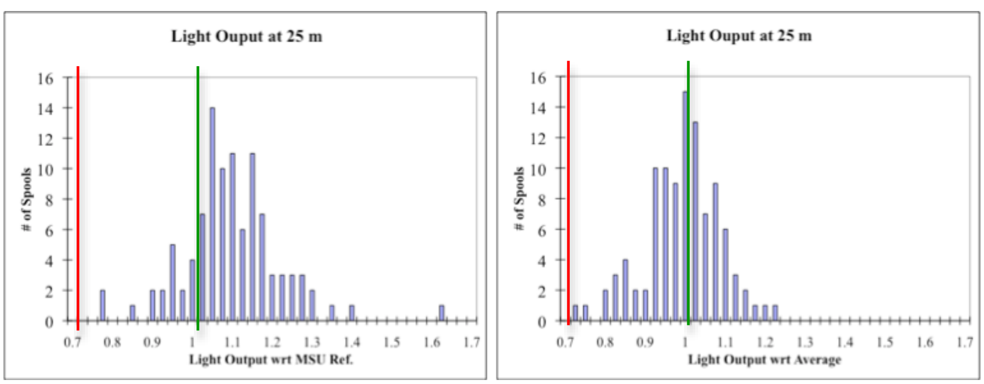

Figure 4. QA measurements of the light output of the fiber illuminating it 25 m from the photodiode for all spools in the second (left) and third (right) shipments of 350 km fiber.

to the reference fiber, with the mean output of the second shipment about 5% higher than the reference, with the third having a mean light output equal to the reference. The RMS values in both shipments are similar to the reference fiber and all but one spool had a light output above the 70% acceptance level. The QA of a single spool in the third shipment gave results that were only 30-40% of the expected light output. We cut 100 m of fiber from this spool and made a new measurement, but the light yield did not improve. The light output of this spool appeared normal when measured in Japan leading to the suspicion that the fiber was damaged in shipment. We sent the spool back to Japan and an analysis of the damage is being investigated.

QAS calibration and stability

For the QAS to yield reliable measurements, the light source intensity must remain constant in the US and Japan. The current for the light source LED is controlled by feedback from a monitoring photodiode. In each scan the output of the monitor photodiode and the LED current are recorded. If the feedback system is working properly, the photodiode current will remain constant, while

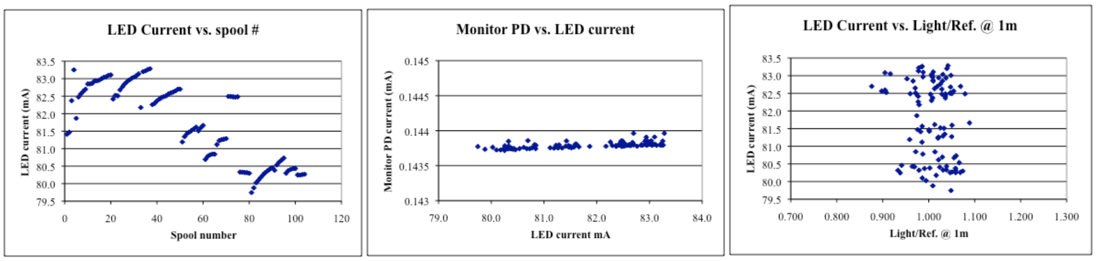

Figure 5. Data confirming the light source calibration and stability. There are systematic changes of about 5% in the LED current (left) during QAS measurements in Japan. These changes are driven by feedback from the monitoring photodiode, which shows the expected constant response (center). Also, the light produced by fiber from each spool (right) is uncorrelated with the LED current.

the LED current varies to achieve the constant monitor current, as is seen in Fig. 5. The light source will have a constant intensity if the monitoring photodiode is unaffected by variations in the environment. The light produced by the fiber illuminated at 1 m from the output photodiode, shows no correlation with the LED current, implying that the LED light source intensity has remained constant.

A test of the QAS reliability is a comparison of the measurement of the light output of fiber from the same spools at Kuraray and at MSU, as shown in Fig. 6. The two measurements usually differ by less than 3% percent, so that the measurement uncertainties are smaller than the variations in the fiber properties. Any large variations in the fiber properties are usually seen in the data from both sites. The points are systematically below the line of equal calibration, which indicates that the intensities measured at MSU are about 2% larger than those at Kuraray. Only the rare spool of fiber close to the acceptance level of 70% of the reference fiber will be affected by this small difference.

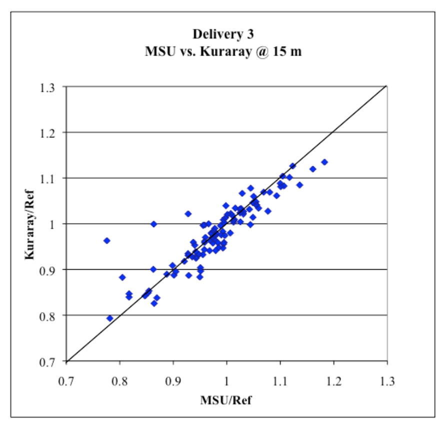

Figure 6. QAS measurements at Kuraray and at MSU on the same spools of fiber are compared.