Fiber Quality Control Testing with the Ocean Optics, Inc. Spectrometer System

L. Snook

University of Regina, Aug. 20, 2002

1 Abstract

The centerpiece of the HallD project is a hermetic detector based on a central solenoidal cryomagnet. A crucial component of this detector is the Barrel Calorimeter. In its conceptual design, it consists of layers of scintillating fibers sandwiched between thin sheets of lead. In an effort to create a systematic method of testing the quality and calculating the attenuation length of these fibers, the Ocean Optics, Inc. (OOI) SD2000 computer-controlled spectrometer system was employed. This system allows for the comparison of different types of fibers (Kuraray vs. Pol. Hi. Tech) and different types of cladding (single vs. double). It also allows for the testing of the consistency of a batch of fibers, by testing random samples from within a batch to a “Gold” reference fiber.

2 Introduction

The design for the Barrel Calorimeter (BCAL) is similar to that of the KLOE [1] calorimeter. It is composed of 0.5mm sheets of lead which are grooved (swaged) and 1mm scintillating fibers that are glued into these grooves, running parallel to the detector axis. This creates a matrix of lead and scintillating fibers. The scintillation photons will travel down the length of the fibers to photo detectors (HPD's). Consequently, the optical properties of the fibers are of great importance.

The characteristics that can be tested using the OOI system include the attenuation of light as it travels the length of the fibers (attenuation length) and the amount of light collected (intensity of the spectrum through a specified length of fiber). Also, differences in the spectra can show which wavelengths are affected by the specific doping of the fibers.

To test these characteristics, fibers from two manufacturers were used. These are Kuraray[1] SCSF-81 single-clad procured in 2000 (“Old” Kuraray) and in 2001 (“New” Kuraray), Pol.Hi.Tech. 0046 single- and multi-clad procured in 2000, and Pol.Hi.Tech.[2] used in Pisa for Pb/SciFi matrix prototyping, and Kuraray multi-clad procured in 2002. As well, Bicron[3] clear fibers procured in 2000 and neutral density filters were used as a reference for the

---

[1] Kuraray Co., Ltd., Office of Corporate Communications, 3-1-6, Nihonnbashi, Chou-ku Tokyo 103-8254, Japan

[2] Pol.Hi.Tech., s.r.1.0, Carsoli, Italy

[3] Bicron Corporation, Newbury, Ohio, USA

spectrum of the source alone, as they contain no doping.

3 Spectrometer System

The Ocean Optics, Inc.[4] system consists of the following elements. An LS-1-LL Tungsten Halogen Lamp (2800K) connected via a 400 micron patch fiber (2m) to an FHS-UV Filter Holder Assembly (see figure 2). The FHS is a holder in which filters can be inserted and which also contains a light blocker. A 600 micron bifurcated fiber (each leg 1m in length) is attached to the Filter Holder Assembly. The #1 leg connects to a collimating lens which is held in the collimating lens holder. Sandwiched in the lens holder is a 20% neutral density filter (ndf) (see figure 3). A second collimating lens (on the opposite side of the ndf) is then connected to a 1000 micron patch fiber (#2), which goes to the "Master" channel of the SD2000 spectrometer unit. The other leg (#2) of the bifurcated fiber is attached via a custom connector to the test fiber. The same type of custom connector is used to connect the test fiber to a second 1000 micron patch fiber (#1) which goes to the "Slave1" channel of the SD2000 spectrometer. The SD20000 is connected to an ADC1000 - USB (see figure 3), which is finally connected to a laptop running Microsoft Windows XP Home via USB port. The system is controlled by the "OOIBase32" software package provided by OOI.

In summary, the light travels from the Tungsten source through a filter/blocker and into the fibers to be tested. The light is then transmitted through the fibers and into the spectrometer. The spectrometer is interfaced with a computer, and the amount of light collected is analyzed and graphed in the OOIBase32 software. The system in use has two channels. The Master channel is being used as a reference channel, with the light source travelling through a 20% ndf simply to attenuate the amount of light entering the spectrometer. The Slave1 channel is being used to test the fibers. No lenses or filters are being used in the test fiber paths.

---

[4] Ocean Optics, Inc. c/o Gamble Technologies Limited, Vancouver Office, 829 Dollarton Hwy., North, North Vancouver, BC V7G 1N5

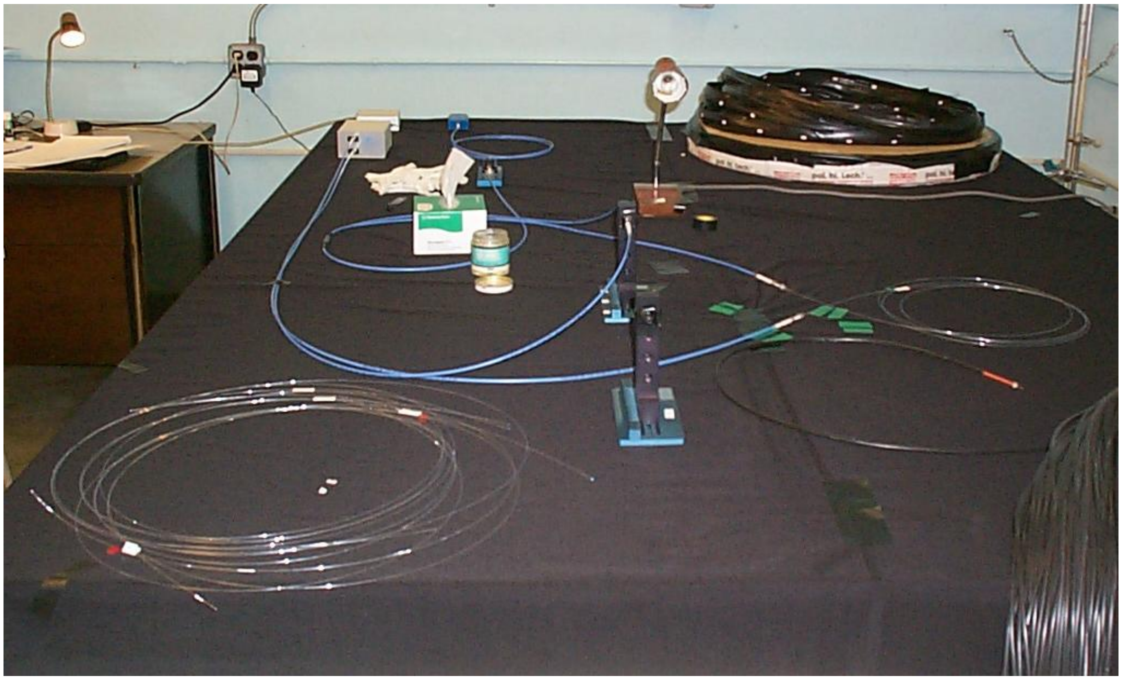


Figure 1: OOI Spectrometer System Experimental Setup

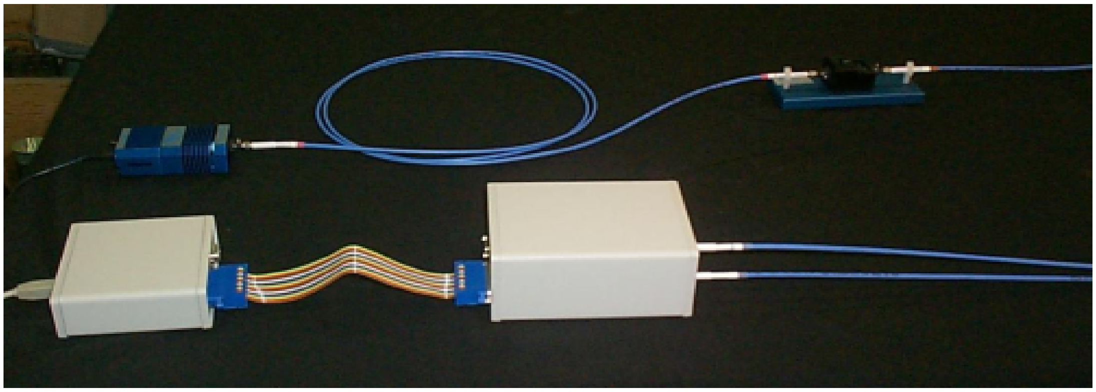


Figure 2: Close up of LS-1-LL light source, FHS-UV Filter Holder Assembly, SD2000 spectrometer and ADC1000 - USB

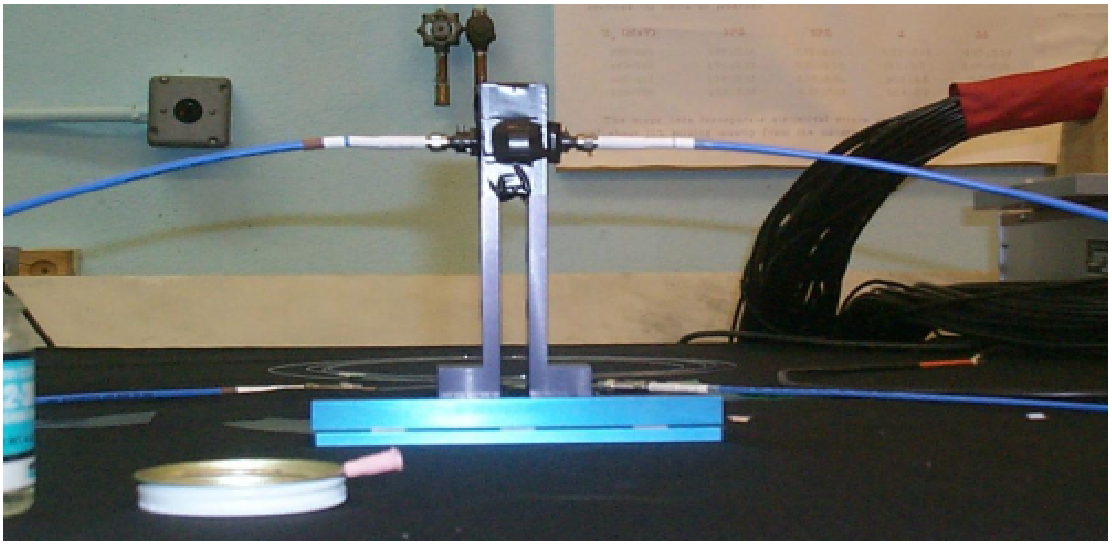


Figure 3: Lens holder with neutral density filter sandwiched and taped between collimating lenses

4 OOIBase32 Software

The light that is collected by the spectrometer is analyzed with the OOIBase32 Software. The first time the program is opened, it is necessary to enter the calibration data for the spectrometer, which is supplied by OOI. This is a set of four numbers for each channel that can be entered into the Wavelength Calibration window found under the Spectrometer menu in the Configure option. The “enable” check box must be checked for all channels. As well, to activate any slave channel, enable Master-Slave1 from the pull-down ADC1000 channel rotation menu in the Configure Data Acquisition menu under Basic. The software is now ready to use.

Each time the program is run, it is automatically in “Scope Mode” which simply shows a graph of Intensity (counts) vs. Wavelength. The wavelength ranges approximately betwen 340nm and 1020nm. The intensity has a maximum capacity of 4096 counts. In this mode the software is continually aquiring data from the spectrometer. There is an icon at the top of the window that shows a camera. This button activates “snap shot” mode, which stops the active accumulation of data and gives a still image of the spectrum at that particular moment. The other modes are “Absorption”, “Transmission” and “Irradiance”. These modes were of no interest for our particular set of experiments.

Formatting (colours, line sizes and graph scale) can all be adjusted using the Display Properties option under the View menu. The lighter colours (yellows) did not print well. The optimum line width is 2. Also, the scale can be adjusted by selecting the button with a box and four arrows.

An integration time needs to be set. This affects the collected intensity of the plot. Thus, if the plot is so large that it exceeds the 4096 count capacity, the integration time needs to be lowered. Conversely, if the amplitude of the spectrum is too small, then the integration time can be increased. However, to be able to easily compare spectra, they should be taken at the same integration time. With the final coupling method, the integration time used was 15msec.

To take a measurement, with the light source switched on and the blocker open, a reference spectrum is taken using the yellow light bulb button at the top of the window. Then, with the blocker closed, a dark spectrum is taken using the black light bulb button. With the blocker back open, the spectrum can be saved using the button with a floppy disk image. The reference and dark spectra must be taken before a spectrum can be saved.

To look at more than one spectrum at the same time simply involves overlaying 2 or more files. To do this, open the Overlay menu and select "select to add overlay". This browses the saved files and allows the user to choose which spectrum to overlay. Any currently open files will change to "snapshot" mode and a still image will be produced with as many overlays as selected (up to 8). To remove the overlay, simply select the file to be removed from the list under the Overlay menu.

There are several interesting features with the saving options. First of all, a "File Basename" and "Starting Index" can be set by going to the File menu then to the Autoincrement Filenames option. When a file is saved, it is named *File Basename.Channel.#####.** where you supply the File Basename and the starting index (#####) fields. The starting index field will increment by 1 each time a file is saved, creating a series of related files. When the spectrum is saved, four files are created for each active channel. The extensions of the four files are *.sample, .reference, .scope* and *.dark*. The *.dark* file contains the data taken in the dark spectrum. Similarly, the reference spectrum data is stored in the *.reference* file. The *.scope, .sample* and *.reference* files contain identical data.

The data from the *.dark* file for the 2 different channels – which indicates the dark current – is slightly different as shown in figure 4. This is an effect of the spectrometer. This can easily be accounted for by subtracting the dark spectrum from the *.scope* data for both channels.

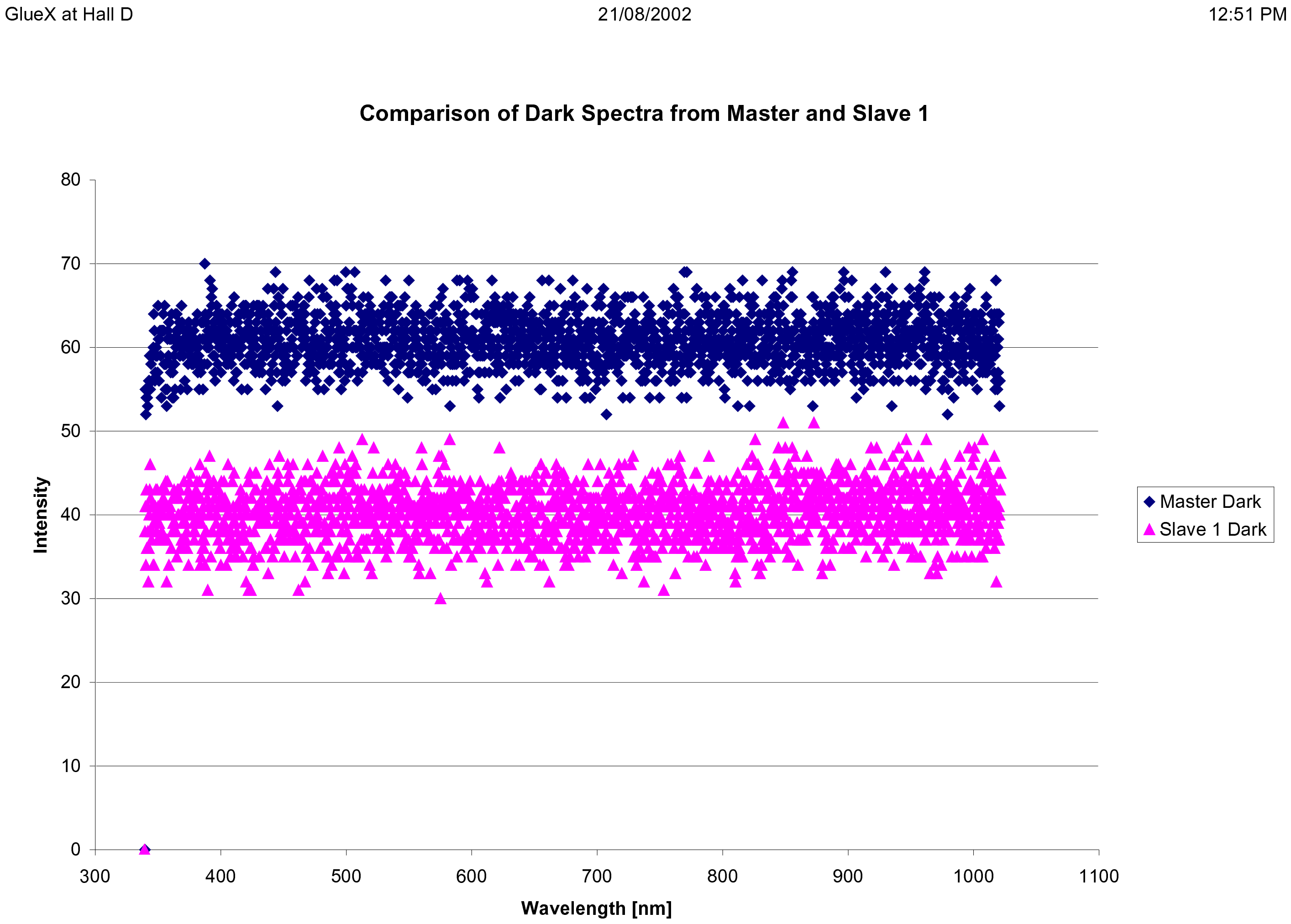


Figure 4: Dark spectra from the Master and Slave1 channels of the spectrometer

Note that for each data series (File Basename series) a *.reference, .scope, .sample* and *.dark* file are created. When a new spectrum is saved in the series, both the numbered file and the basename file are created. The program prompts the user to choose whether or not to overwrite the basename files. In all instances, "yes" was selected.

There appears to be a programming glitch in saving. If any overlays have been selected from the time the program was opened, or if "no" is selected in the overwriting prompt, the program will no longer save when asked to, but will continue to increment the starting index. If this happens, reset the starting index, then shut down the program and restart it. The program must be restarted from it's original location on the computer, not a shortcut, as the shortcut does not reset whatever is causing the program to stop saving.

The files are saved in a tab deliminated format. These data were imported into Microsoft Excel for the purposes of comparitive graphing and other data manipulations including attenuation adjustments. The files were opened in Notepad and then copied and pasted into an Excel window. It is possible to open the file directly into Excel, however this does not allow for multiple files to be opened into a single worksheet.

5 Coupling

In order to couple the test fibers to the OOI setup, it was necessary to develop a custom connection method. This became an interesting challenge. The issues in coupling were mainly in alignment of fiber to fiber, in the reproducibility of this alignment and in holding the fiber in place. If the results are not reproducible, then the comparison of 2 different fibers is meaningless. The fibers provided (mainly the bifurcated and the patch cables) had SMA connectors on their ends, and four bushing assemblies were purchased along with the OOI system in order to help with the coupling.

The coupling of the filter involved sandwiching the NDF between the collimating lenses in the lens holder as pictured in figure 3. The only issue with this is that a small change in the position of the lens is enough to change the intensity of the spectrum. This is probably caused by defocusing of the light by changing the distance between the lens and the filter. This was mainly eliminated by taping the lenses in place and further ensured by not touching or changing the NDF setup throughout the measurements.

Several different techniques of coupling the test fibers were employed before a final method was developed.

The original solution was to use the collimating lenses and the lens holder. Metal cylinders were drilled out to 1mm in the center and threads were cut into the outside. This threaded into the lens holder and butted up against the lens. The fiber was placed in the 1mm hole and butted up against the lens. This created problems in several ways. It caused stress on the fibers, as they were suspended above the level of the table. The setup also caused stress on the fibers as they had to be coiled to a small radius. Also, there was no way to guarantee that the fiber remained in all the way against the lens and that it would not recede due to the various stresses.

The second method involved removing the collimating lens holder and collimating lenses completely, and attempting a fiber-to-fiber coupling. SMA connectors from a light-calibration system using 0.1mm diameter fibers were drilled out to fit the 1mm diameter fibers. These were connected to the SMA connector of the manufacturer's fiber using a bushing assembly. The fiber was placed in the SMA connector and butted up against the manufacturer's fiber. This method was better in that less stress was placed on the fibers, however, there was nothing to guarantee that the angle of the fiber inside the connector would remain the same once recoupled. The main cause of this change in angle was again stress on the fibers. The main stress in this case was coiling the fibers in a tight circle due to a small workspace.

The next method was the same as the second, however, the workspace was moved from a side bench to the optical table in the lab. This allowed the fibers to be placed in a single loop, instead of coiled, thus removing stress. This method did help in not stressing the fibers nearly as much, however, there was still enough uncertainty due to the angle of the fiber inside the connector.

By taping down the manufacturer's fibers and the connectors, as well as using coloured tape to mark the path of the fiber, the results were greatly improved. However, there was still enough of a discrepancy between couplings to warrant a new method.

Using the same SMA connectors and bushing assemblies, a small sleeve of brass was made by the Machine Shop of the Faculty of Science at the University of Regina to fit inside the SMA connector, with a 1mm core drilled out (see figure 6). The tube was held into the connector by friction alone (see figure 5). The fiber then slid into the 1mm drilled out core and was again butted up against the manufacturer's fiber. The tube was approximately 4cm long, and because of the tight fit, held the angle of the fiber with respect to the connector and the manufacturer's fiber constant. The only problem with this method, was that the fibers could slip out of the connectors over time, causing a slow decrease in the intensity of the spectrum.

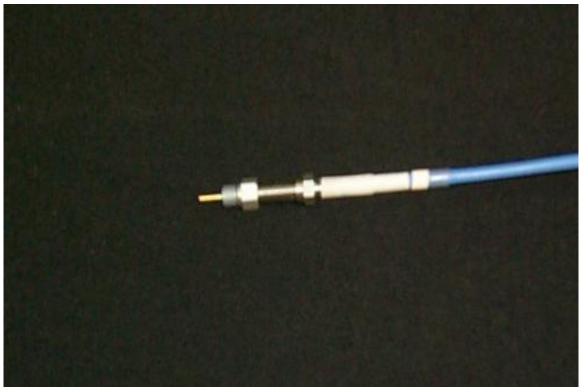


Figure 5: New connector assembled and connected to the P1000 patch fiber

Figure 6: New connector disassembled, showing optical couplant and syringe tip used for the coupling

The final method of coupling was simply to put a dab of Dow Corning[5] optical couplant on the end of the test fiber before sliding it into the brass sleeve (see figure 6). This improved the quality of the coupling in a few ways. Firstly, the optical couplant was viscous enough to hold the fiber in place. Secondly, the intensity of the spectrum was improved by a factor of 2, as the optical couplant removed the air gap and so there was less reflection and refraction of the light as it left one fiber and entered the other fiber. This also decreases the effect of uneven polishing of the fibers.

A few dangers do exist with this method of coupling. If too much optical couplant is used, then there is no room for the fiber inside the connector. Pushing the fiber in causes

---

[5] Dow Corning Corporation, Part No. Qw-3067, Midland, Michigan, 48640, USA

pressure to build and the fiber is pushed back out. Thus, after a measurement is taken, it is a good precaution to make sure the fiber is still tightly inside the connector. If it has slipped out, then some of the optical grease should be wiped off the fiber when it is extracted. This should be enough for the fiber to be able to fit properly. Also, it is possible (although unlikely) that an air bubble could form in the optical couplant. This would affect the intensity of the spectrum as it would cause reflections and refractions within the bubble.

6 Filters

To take a spectrum of the light source by itself was possible at a very low integration time (approximately 4msec in #2 leg of the bifurcated fiber and #1 patch fiber). However, to be able to compare this spectrum to the fiber measurements, at an integration time of 15msec, it was necessary to attenuate the light. This was accomplished using neutral density filters. The coupling of the filter was discussed in the coupling section. This method of coupling was used instead of using the FHS blocker assembly because the filters were too large to fit in the FHS.

Four different filters were tried (80%, 40%, 20% and 10%). The 80% attenuation was too large to accomodate the spectrum within the maximum of 4096 counts. The other 3 were tried and graphed (see figure 7). The factor between the 20% and 40% was not quite a factor of 2, but 2.25. The shape of these two curves is very similar and therefore the filter is not drastically affecting the shape of the curve. However, the 10% filter is strongly affecting the shape of the spectrum, and so was not used, and should be avoided.

7 Fibers

Fibers were taken from several different batches and different experiments. Thus, they were all prepared in slightly different manners. The "Old" Kuraray and the "New" Kuraray as well as the single- and multi-clad Pol.Hi.Tech. fibers were still in bundles from the experiments at TRIUMF [2]. These fibers were left in the bundles and not polished additionally. However, it was found that some of the bundles had not been handled properly and had been coiled too tightly. Thus, the two Pol.Hi.Tech. bundles both contained broken fibers. Because the fibers are in a bundle, it is impossible to tell whether the few fibers which still transmit light

GlueX at Hall D 21/08/2002 12:52 PM

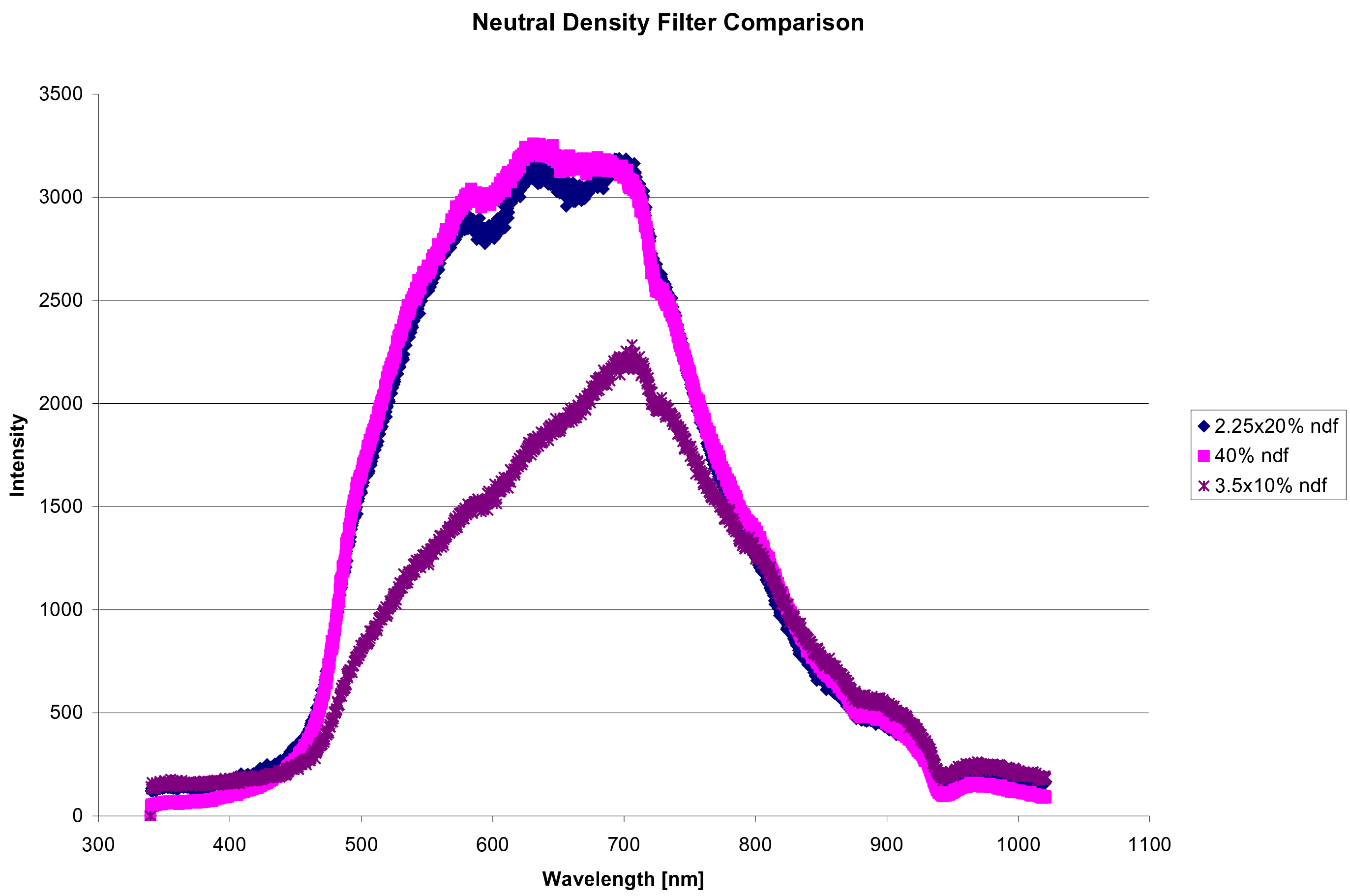


Figure 7: Normalized comparison of the three strengths of neutral density filters

have stress fractures. The singleclad bundle fibers showed a decrease in the intensity of light being transmitted. This suggests that moving the fiber bundle is enough to aggravate the fractures and possibly completely break the fiber at the stress points.

The rest of the fibers were cut into sections (with the exception of the Pol.Hi.Tech. fibers from Pisa which were pre-cut to 1m lenghts) and then the ends were polished using 3 grades of sandpaper (30μm, 3μm and 0.3μm) followed by a polishing cloth. A microscope was used to inspect the ends of the fibers.

It was found that polishing the fibers was enough to boost the intensity of the spectrum by a factor of 4. The implication of this is that inconsistent polishing could have a large effect on the intensity of the spectrum of a fiber.

In the process of developing a coupling technique, it was discovered that the fiber diameters vary from 0.98mm to 1.06mm between different manufacturers and also from one end of a fiber to the other. Table 1 shows the range of fiber diameters. All the fibers listed in table 1 are single fibers. None of them were inside bundles. The Pisa fibers were not specified as to single- or multi-clad, however under microscope, they appear to be multi-clad fibers.

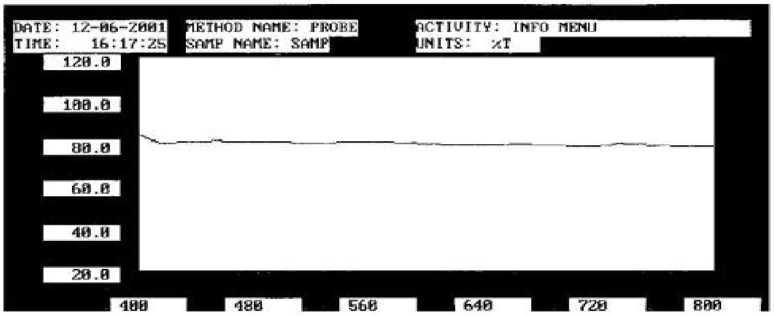
Fiber Type	Length (cm)	pt 1 (mm)	pt 2 (mm)	pt 3 (mm)	pt 4 (mm)
Bicron	155.5	0.99	0.995	0.98	1.00
Pol.Hi.Tech. Pisa	100.3	1.04	1.02	1.03	1.01
Pol.Hi.Tech. Multi 2001	192.0	1.05	1.03	1.01	1.03
Pol.Hi.Tech. Single 2001	79.7	1.02	1.02	1.04	1.06
Kuraray Multi 2002 #1	399.4	0.98	0.98	0.99	0.98
Kuraray Multi 2002 #2	399.4	0.99	0.99	0.99	0.99
Kuraray Multi 2002 #3	399.4	0.99	0.99	0.98	0.99
Kuraray Multi 2002 #4	399.4	1.00	0.99	1.00	0.99

Table 1: Variation in diameter between fiber types and along the length

This variation in diameter complicated the fiber-to-fiber coupling method, described previously, since the feed-through brass sleeve had to accomodate all diameters. Thus the fit through was not very “snug” for the smaller diameters, and a larger amount of optical grease was required for the larger diameters as the fit was too “snug”.

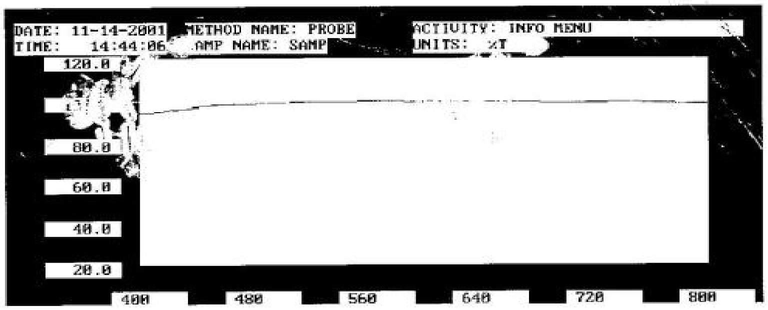
8 Normalization of Hardware

Through the course of the measurements, it was found that the two ends of the bifurcated fiber and the two patch fibers were not delivering the same amount of light. This was expected, as OOI provided light response curves for these fibers (figure 8). However, in an attempt to recreate these curves with the OOI spectrometer system, the results were quite different than expected. The difference between the bifurcated "legs" was larger than expected, while the difference between the patch fibers was less than expected.


DATE: 12-06-2001 METHOD NAME: PROBE ACTIVITY: INFO MENU
TIME: 16:17:25 SAMP NAME: SAMP UNITS: %T

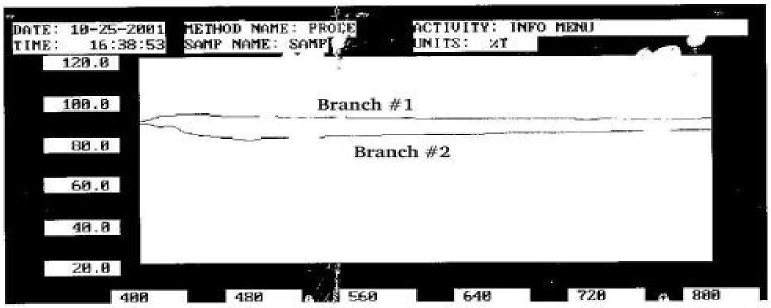
Fiber #1

P1000-2-UV/VIS_


DATE: 11-14-2001 METHOD NAME: PROBE ACTIVITY: INFO MENU
TIME: 14:44:06 AMP NAME: SAMP UNITS: %T

Fiber #2

P1000-2-UV/VIS JC_


DATE: 10-25-2001 METHOD NAME: PROBE ACTIVITY: INFO MENU
TIME: 16:38:53 SAMP NAME: SAMP UNITS: %T

Bifurcated Fiber

BIF600-UV/VIS

Figure 8: Top to bottom: Patch fiber #1, patch fiber #2 and bifurcated fiber light response curve provided by OOI.

To find the conversion factor between the #1 (80%) leg and the #2 (20%) leg of the bifurcated fiber, the FHS and the patch fibers were ignored. The light was passed through the blocker which had a 0.40 wratten[6] filter in place, and through the bifurcated fiber. In turn, each leg was placed in the Slave1 channel for reasons of consistency. The ratio of these two curves gives the conversion factor between the #1 and #2 legs of the bifurcated fiber (see figure 9).

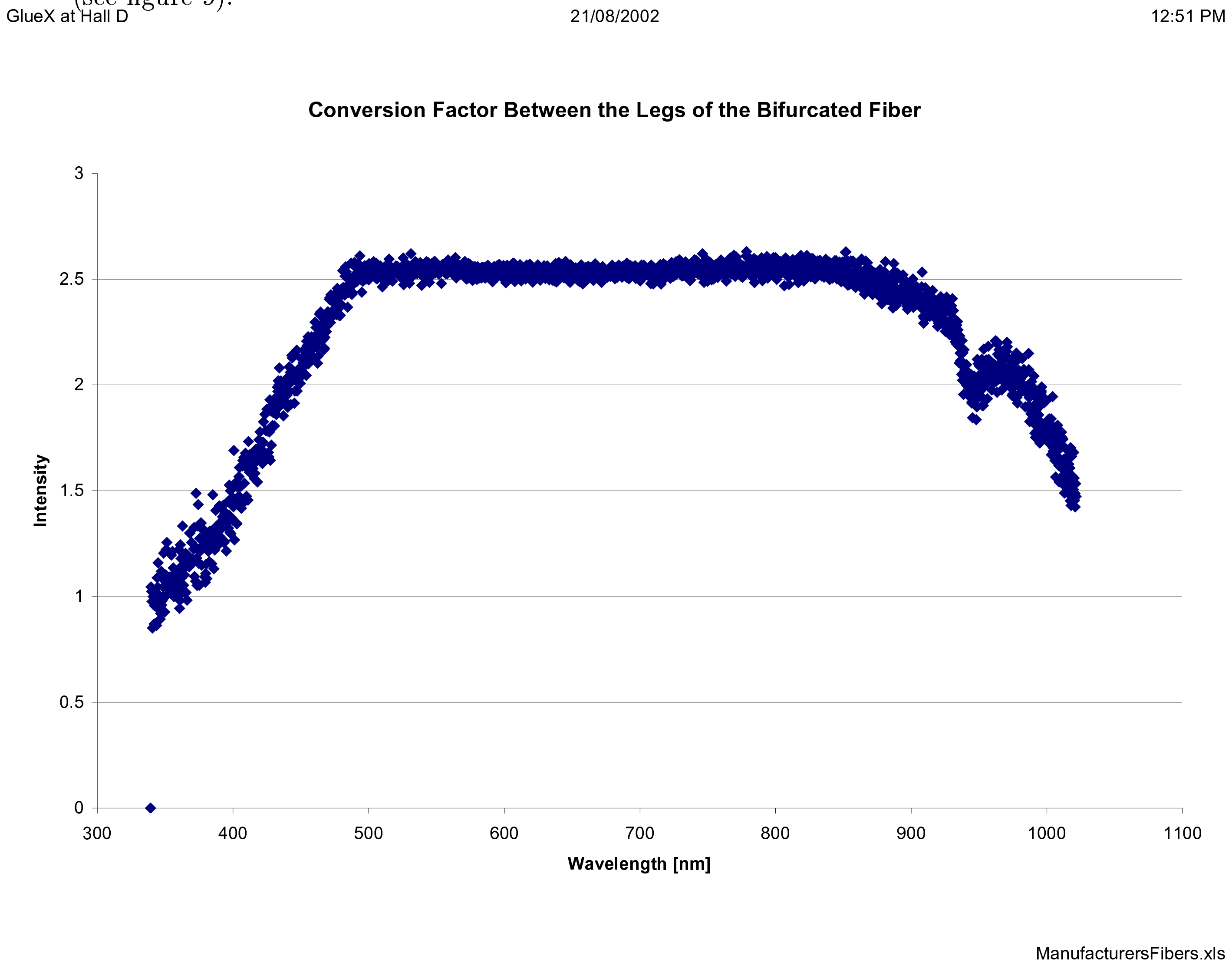


Figure 9: Conversion factor between the #1 and #2 legs of the bifurcated fiber

---

[6] Wratten Filter, Eastman KODAK Company, Rochester, NY, USA

To find the conversion factor between the two patch fibers, they were each connected in turn from the blocker directly to the spectrometer, with a 0.40 wratten filter in the blocker. The ratio of these two curves gives the conversion factor between the #1 and #2 patch fibers (see figure 10).

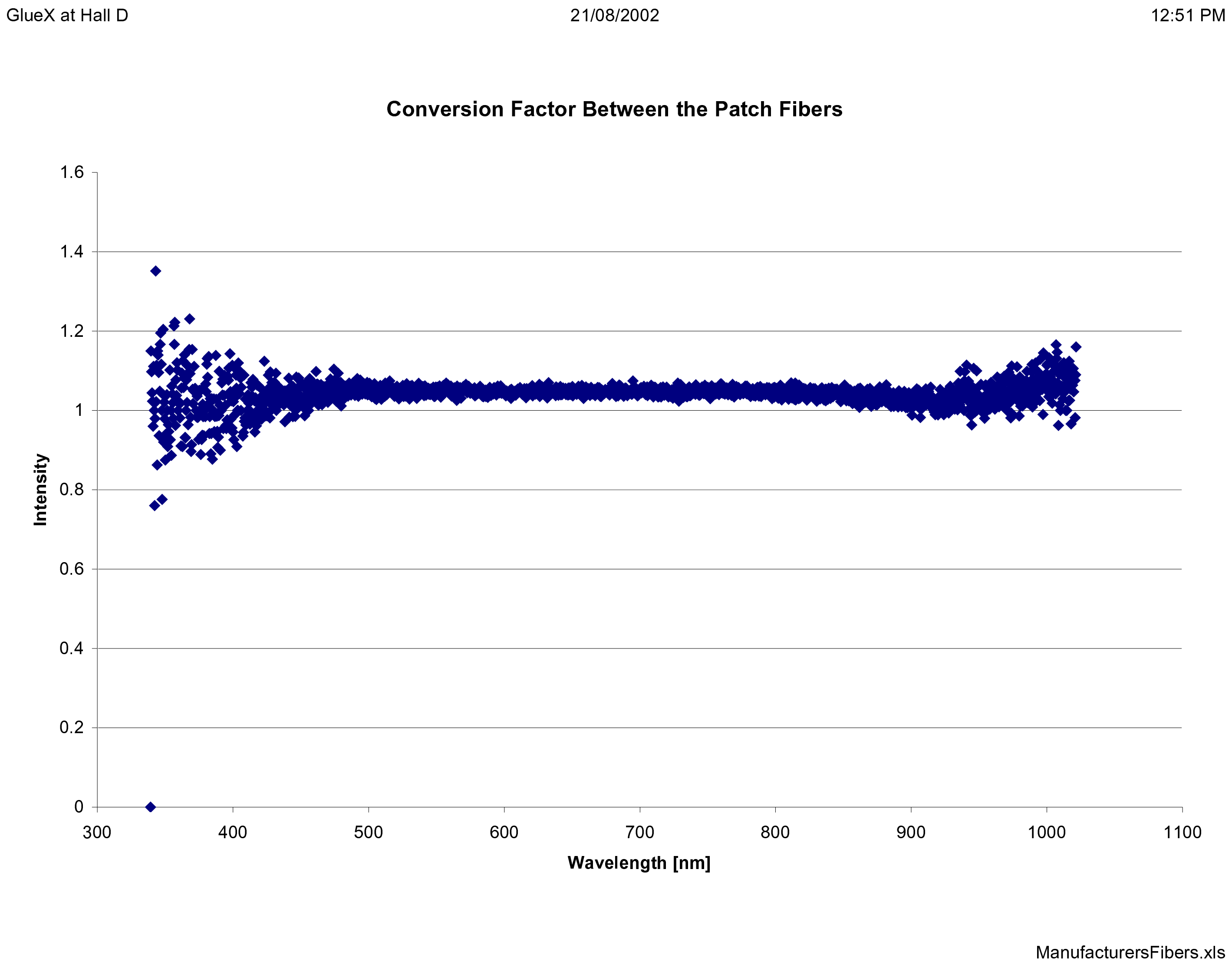


Figure 10: Conversion factor between the #1 and #2 patch fibers

9 Gold Fiber Measurements

One fiber was selected at random from each group of fibers, and was labelled as the "Gold" reference fiber. The spectrum of all the Gold fibers was measured at an integration time of 15msec using the final method of coupling. These spectra are shown in figure 11.

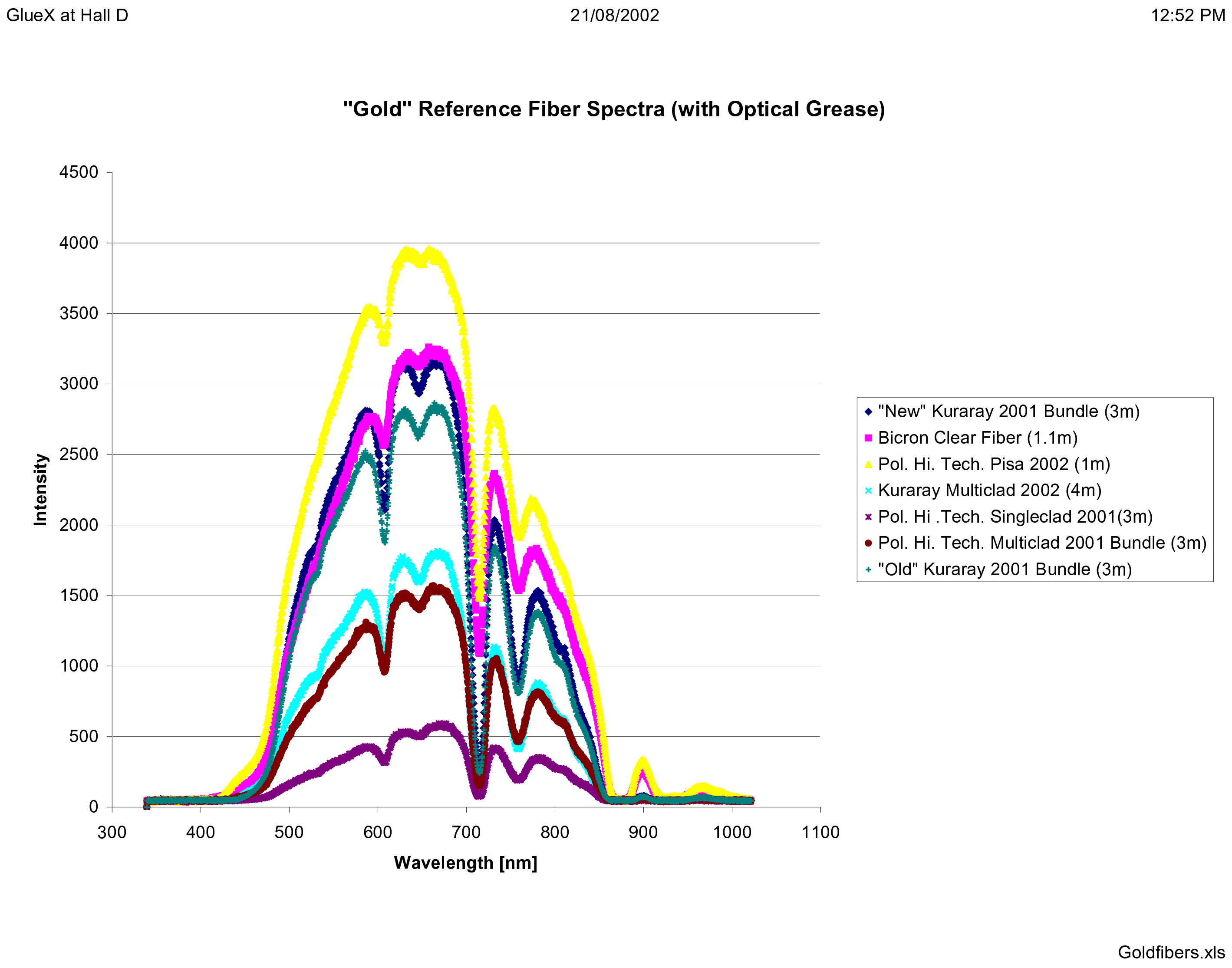
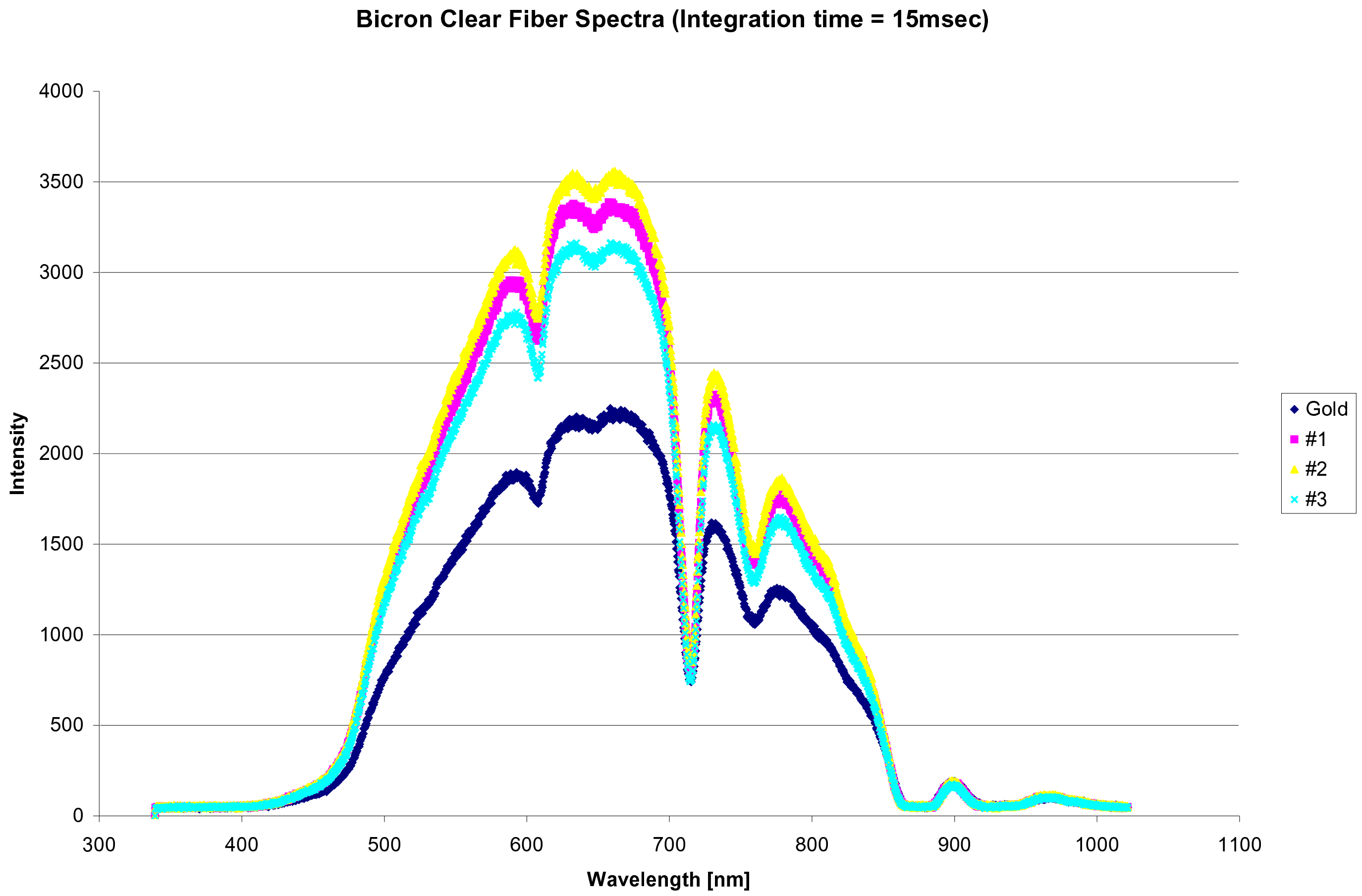


Figure 11: Graph of "Gold" reference fiber spectra

Following these measurements, a selection of fibers from the same groups were the measured and compared to the “gold” reference fiber. Figures 12 and 13 show representative data from these measurements.

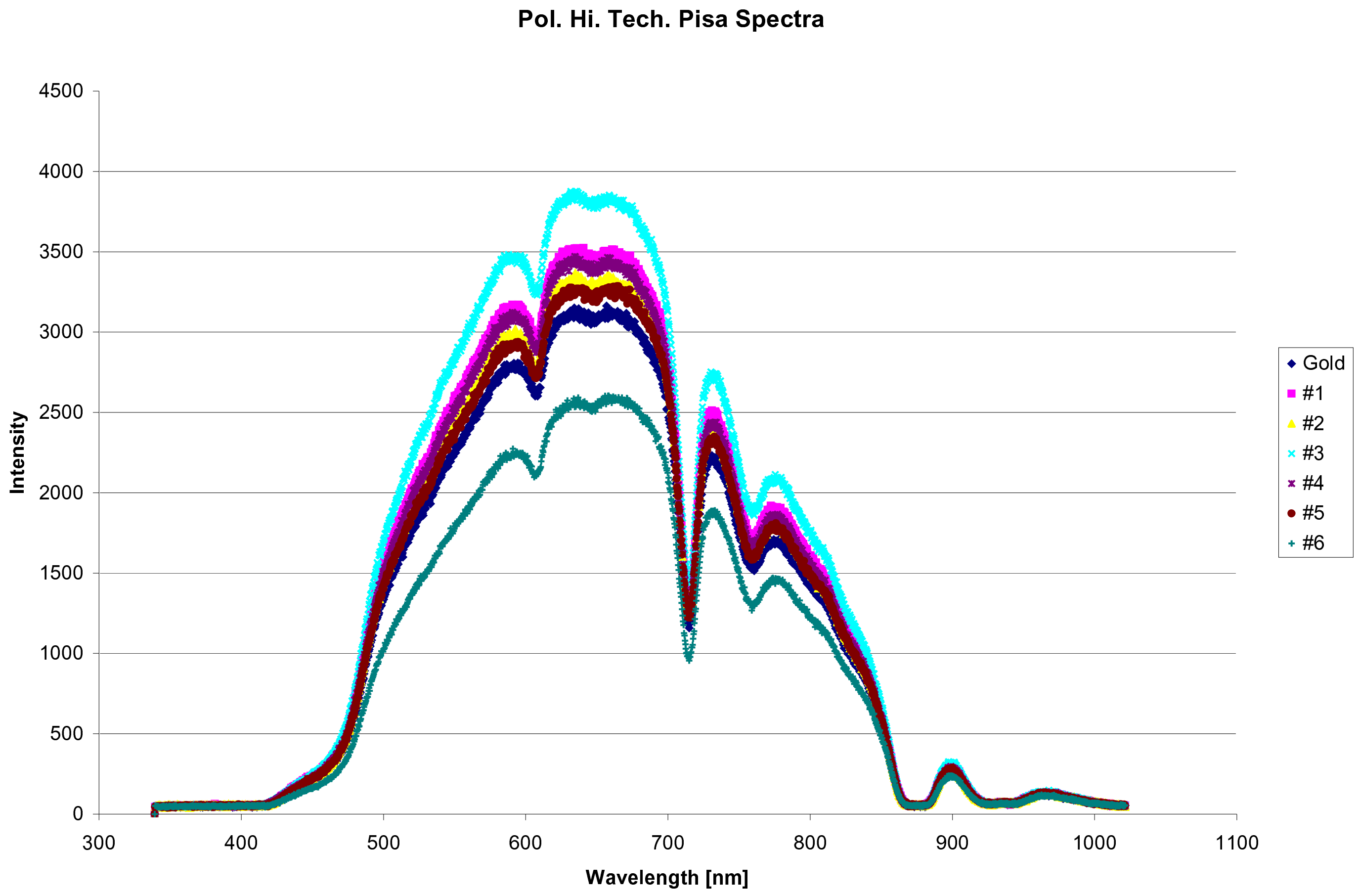
GlueX at Hall D 21/08/2002 12:47 PM



Bicron.xls

Figure 12: Spectra of a random group of Bicron clear fibers compared to the “Gold” reference Bicron fiber.

GlueX at Hall D 21/08/2002 12:47 PM



PHTPisa.xls

Figure 13: Spectra of a random group of Pol.Hi.Tech. Pisa fibers compared to the "gold" reference Pisa fiber

As the legend lists, not all the fibers were of the same length, so a comparative discussion is not possible due to the different attenuation factors. A few general comments, however, can be made. At first sight it is odd that the Pol.Hi.Tech. Pisa fiber has a larger intensity than the Bicron fiber, which has no doping. The Bicron fiber came from a fiber with a break, which was cut down and re-polished. And as can be seen in figure 12, the intensity of this fiber does not match other Bicron fibers. Thus, there are probably stress fractures along the length of the Bicron "Gold" fiber.

Discounting the Bicron fiber, the rest seem to behave monotonically as a function of length (Pol.Hi.Tech. Pisa has the highest intensity and Kuraray multiclad 2002 has the lowest). The data from the Pol.Hi.Tech single-clad fibers from 2001 TRIUMF tests [2] is not very meaningful, as the fibers were broken during transport between the University of Regina and TRIUMF.

The "New" and "Old" Kuraray and the Pol.Hi.Tech. Multiclad bundles are of the same length and so it is possible to qualitatively compare them to the results optained in TRIUMF as shown in table 2. The "Gold" fiber tests show that the "Old" and "New" Kuraray bundles have similar attenuation lengths. Hoewever, the "Gold" fiber tests seem to imply that the attenuation length of the "New" is longer than that of the "Old" whereas the TRIUMF results show the opposite. The results from TRIUMF involved averaging the light obtained from all of the fibers, and these tests only involved single fibers. This could explain the discrepancy between the results. It is clear that both of the Kuraray bundles have a longer attenuation length than the Pol.Hi.Tech. multiclad bundle, also shown in the TRIUMF results.

Fiber Bundle	Attenuation Length (cm)	Discrepancy (cm)
"Old" Kuraray	283	7
"New" Kuraray	273	2
Pol.Hi.Tech. Multiclad	234	3

Table 2: Attenuation lengths extracted from pion beam tests in TRIUMF.

The comparative graphs (figures 12 and 13) show fairly consistent results, with a small variation in the spectral intensity between fibers. This spread is very large in the bundled fibers, however this data is suspect, as it is possible that any number of fibers is either fractured or broken within the bundles.

10 Reproducibility of Results

Once the method of coupling was finalized, the fiber with the highest intensity was chosen from each bundle and used for "Deviation Tests". At six different dates and times, each of the seven fibers was coupled, a measurement was taken and then the fiber was de-coupled. The results of this process were very promising as shown in figure 14.

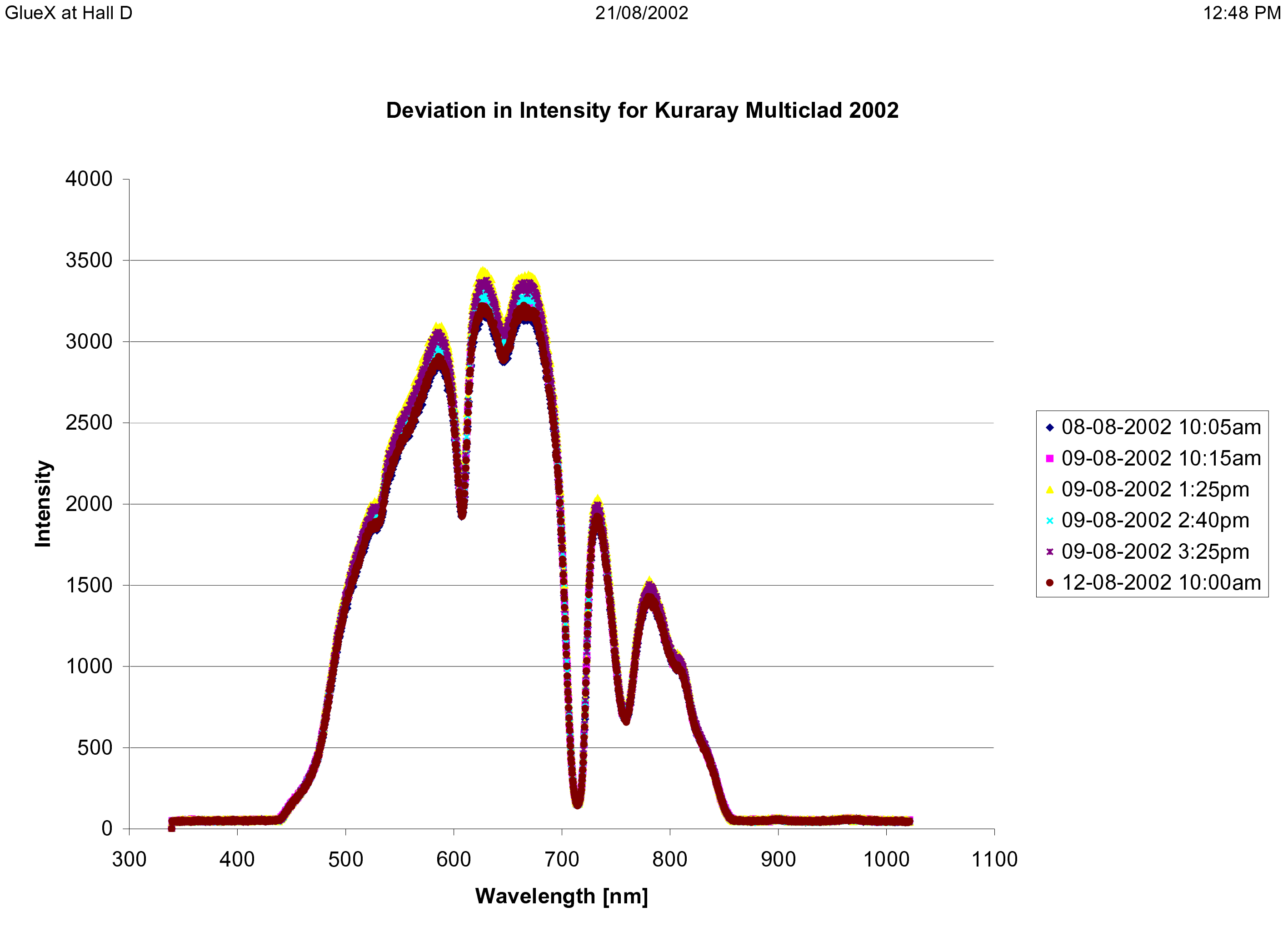


Figure 14: Results of the deviation tests for Kuraray Multiclad 2002 fiber

11 Attenuation Length

In order to determine the attenuation length of the Kuraray Multiclad 2002 fibers, seven fibers of lengths ranging from 1m to 10m were cut and polished. Measurements were taken for each fiber at an integration time of 15msec, and are shown in figure 15.

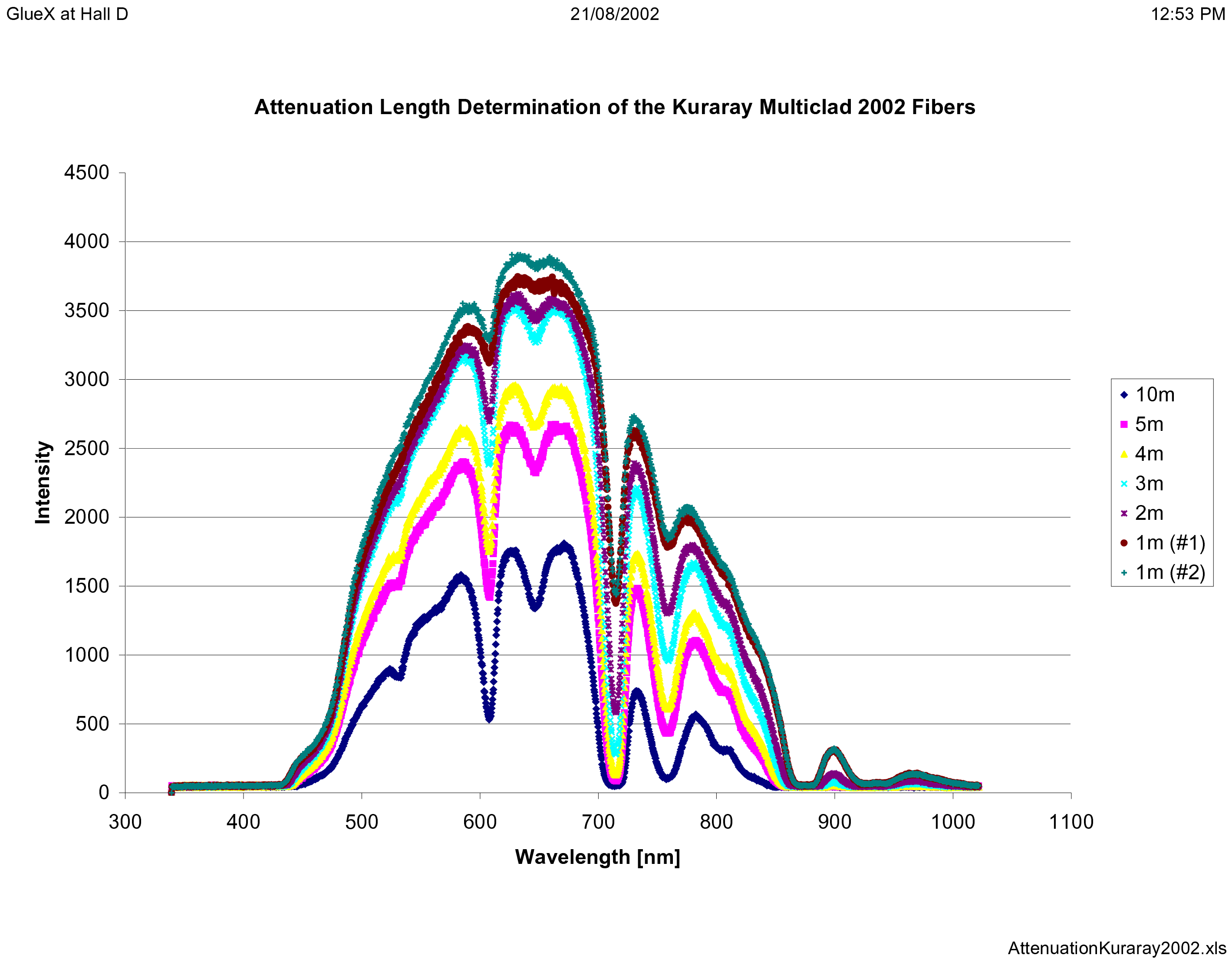


Figure 15: Spectra of different lengths of Kuraray Multiclad 2002 fiber for extracting attenuation information

As expected, the amplitude of the spectra increased with a smaller length. An attenuation length can be extracted using the ratio of any 2 of the curves on figure 15 using the equation:

$I_1 = I_0 e^{-\mu x_1}$

By taking the ratio, I_0 divides out, and the attenuation length μ can be calculated by taking the natural logarithm. Table 3 shows the values for the attenuation length calculated from various ratios and at two different wavelengths. Additional analysis is required to extract the corrected attenuation length from these ratios. Moreover, the determination of the incident intensity I_0 by other means is in progress and can be used to explicitly extract the attenuation length constant.

Wavelength (nm)	10m/5m (m^{-1})	5m/1m(#2)(m^{-1})	4m/2m(m^{-1})
450.32	0.122	0.224	0.197
500.02	0.110	0.123	0.134

Table 3: Table of attenuation length values calculated from figure 15

12 Conclusions

The OOI spectrometer system will be a useful tool in testing the relative quality of fibers, both testing between manufacturers' fibers and within a single batch. More analysis is required to extract quantitative attenuation information from the data obtained. The qualitative results seem to confirm the results obtained from the TRIUMF tests, with only slight variations in the attenuation length of the "Old" and "New" Kuraray bundles.

References

[1] A. Antonelli et al., Nuclear Instruments and Methods in Physics Research A **354** (1995) 352; M. Adinolfi et al., Nuclear Instruments and Methods in Physics Research A, submitted.

[2] S. Vidakovic, "Tests of Scintillating Fibres for the Hall D Barrel Calorimeter", SPARRO Group Internal Report, August 2001