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The Radiation Tolerance of Specific Optical Fibers at -25ºC

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Abstract

This research project seeks to characterize a number of optical fibers in an irradiated, low temperature environment. The purpose of these tests is to qualify suitable fibers for use in the optical links with the high luminosity upgrade of the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN).

In the LHC experiments such as ATLAS and CMS, silicon pixel detectors are commonly used to precisely measure the trajectories of charged particles. These detectors operate in a high radiation environment and in an ambient temperature of -20 to -30ºC to reduce radiation damage to the silicon sensors, hence the requirement of radiation tolerance at low temperatures for the readout optical links in which the fibers are deployed.

A number of new fibers, both single-mode and multi-mode, have been selected for their decreased bend sensitivity and improved bandwidth. Given that the LHC luminosity upgrade requirement is much more stringent than these fibers' originally-intended applications, as well as prior knowledge that radiation induced absorption (RIA) is highly temperature-dependent, the vendor's specification data will be replaced with our own beam test results.

An optical test bench is needed to characterize optical fibers in ionizing radiation from a ^{60}Co gamma ray source at the Brookhaven National Laboratory in February of 2011. Such a multi-channel optical measurement setup is not commercially available and is therefore designed in-house. My task in this research work is to estimate, adjust, and calibrate the dynamic range of the optical power injected into and measured from the fibers. Multiple 850nm VCSEL laser are used as the sources and TI OPT101 chips are used as the detectors; one laser and one chip will be used per fiber in the multi-channel setup. The dynamic range for each can be shifted up or down by altering the voltage supplied to the detector and the current supplied to the laser.

The calibration process, LabVIEW routine, design and construction of the chamber, final irradiation tests on the fibers, and experimental results will be presented. My research contributes to the optical link R&D project with the Fermi National Laboratory, Oxford University, and CERN, and my work progress is integrated into the project flow of this international collaborative group.

Key Words: Fibers, Radiation, Temperature

1. Introduction

Optical fibers are materials of high refractive index, such as silica glass, used to transmit data over long distances in the form of light. Utilizing the principle of total internal reflection, optical fibers allow for such data transmission to occur with negligible loss of signal strength. The two main categories of optical fiber are multi-mode (MM) and single-mode (SM). MM fibers can transmit multiple rays (modes) of light, but over shorter distances and at low bit rates due to the pulse broadening effect that occurs. SM fibers transmit only one mode at a time, but at high bit rates over long distances due to the lack of pulse broadening[1].

The ATLAS[2] (A Toroidal LHC Apparatus, depicted in Figure 1**)** and CMS[3] (Compact Muon Solenoid, depicted in Figure 2) particle physics experiments at the European Organization for Nuclear Research (CERN) seek to learn about the forces that formed and still act on the universe. Using the Large Hadron Collider (LHC), scientists from all over the world monitor collisions of high-energy particles that replicate the state of the universe at its very beginnings. Detection systems identify the particles involved and record their energy and momentum. Amongst other objectives, ATLAS and CMS seek to discover the Higgs boson, extra dimensions, and dark matter.

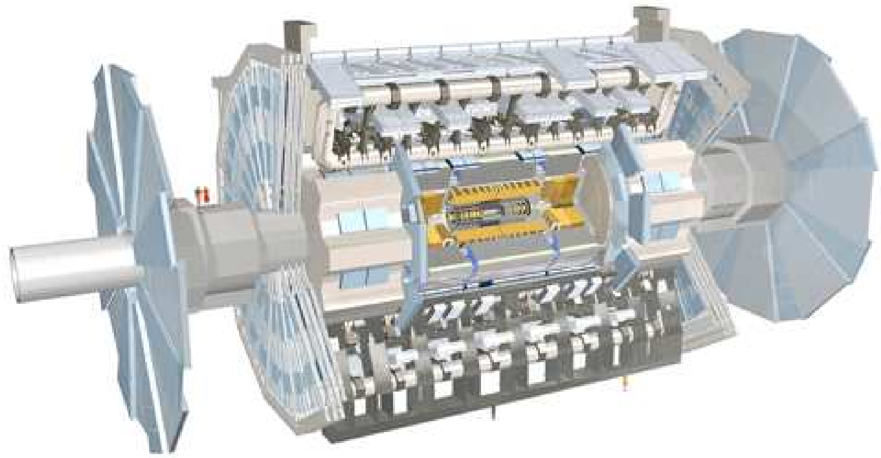

Figure 1. The ATLAS detector

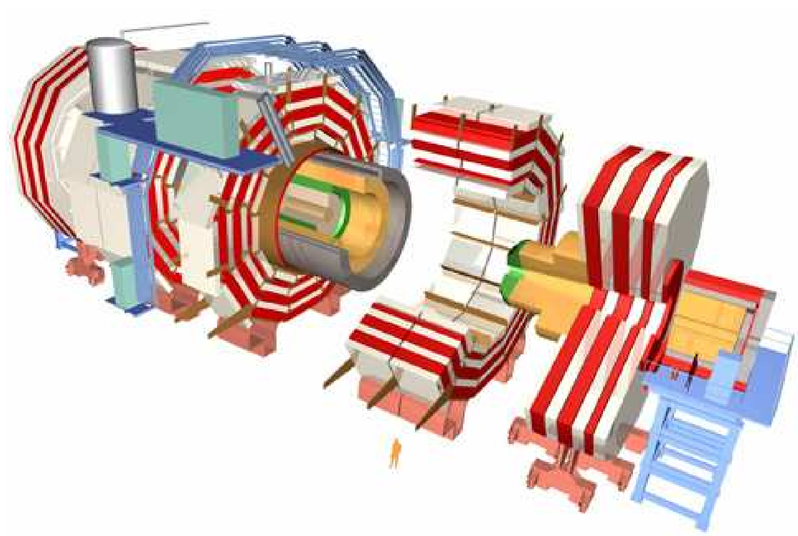

Figure 2. The CMS detector

Both ATLAS and CMS use optical fibers to transfer data from the front-end detectors to the back-end computers. The fibers within 12 meters of the front-end detectors are exposed up to a total ionizing dose of 250 kGy(Si) in a 10 year operational lifetime. In some applications, the 2 meters closest to the front-end are kept in a cold environment near -25 °C. Ionizing radiation damages the molecular structure of the fiber's glass core, causing its internal reflection properties to erode with time as new energy levels appear in the glass and absorption increases at operational wavelengths[4]. The fibers in the ATLAS and CMS detectors would need to withstand radiation the high radiation doses and low temperatures in order to remain functional.

The Versatile Link project was founded in April 2008 to develop a radiation-tolerant optical interface for the proposed LHC upgrades. This interface requires two-way data transmission capabilities of up to 5 Gb/s via optical fibers that are qualified to withstand radiation doses of up to 500 kGy(Si) at room temperature and at low temperatures of approximately -25ºC[5]. The upgrade is to utilize MM fibers with an operational wavelength of 850 nm and SM fibers with an operational wavelength of 1310 nm. Scientists from CERN, Oxford University, Fermi National Laboratory, and Southern Methodist University (SMU) work on the project.

The Versatile Link Project has conducted several experiments since its inception geared towards achieving its goals. In 2008, several optical fibers were tested at room temperature to 650 kGy at various dose rates. Two MM fibers and one SM fiber were qualified for use in the LHC upgrades for warm operations[7]. In 2009, two multi-meter fibers were tested at -25 °C to 30 kGy at 0.5 kGy/hr. It was observed that radiation-induced absorption (RIA) is temperature-dependent[6]. In 2010, fibers were tested at -25 °C to 500 kGy at 27 kGy/hr. Two SM fibers were qualified. One SM fiber and one MM fiber showed high levels of RIA during the experiment, but due to the high dose rate used these fibers cannot necessarily be excluded as LHC upgrade candidates[7].

The experiment described in this paper is the next step towards attaining the Versatile Link Project's goals. The purpose was to determine the RIA of certain fibers subjected to a relatively low radiation dose rate at low temperatures. Also, this experiment tested two new optical fibers, the ClearCurve OM3 and SMF28XB, that could potentially render obsolete some of the fibers previously tested.

2. Experiment Setup

Six fibers, four MM and two SM, were tested for radiation tolerance. A ^{60}Co gamma radiation source at Brookhaven National Laboratory (BNL) bombarded the fibers with ionizing radiation at a dose rate of approximately 70 Gy(SI)/hr. The fibers were placed in a chest freezer so that a temperature of about -25ºC could be maintained[8]. Figures 3 and 4 depict the experiment's setup. Over the course of the experiment, the fibers received a total dose of approximately 10 kGy(Si).

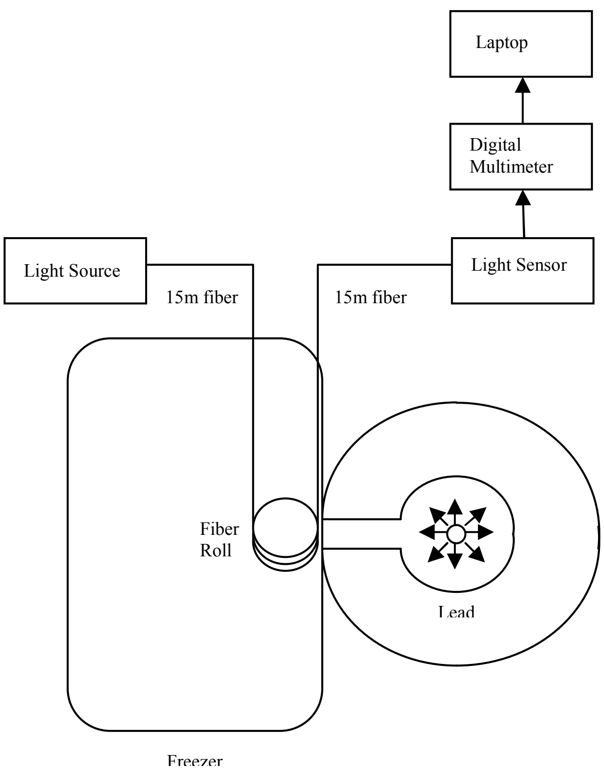

Figure 3. Diagram of experiment setup

Figure 4. Freezer-radiation source setup at BNL

To test the fibers' resilience against radiation damage, a laser diode was connected to one end of each fiber, and a sensor was connected to the other end to measure how much of the light had passed through the fiber. A Vertical-Cavity Surface-Emitting Laser (VCSEL) diode generated 850 nm light for each MM fiber, and a Fabry-Perot laser diode produced 1310 nm light for each SM fiber. For the MM fibers, a multi-channel light meter, pictured in Figure 5, was designed in-house so that up to 12 fibers could be tested at a time. Monolithic photodiodes with on-chip transimpedance amplifiers converted the light into voltage, and a Keithley Model 2700 digital multimeter acquired data regarding the voltage (in V) and optical power (in dBm). For the SM fibers, an HP 8163 Lightwave multimeter with two HP81536A power sensors, pictured in Figure 6, acquired the appropriate data. All multimeters linked to a laptop with a LabVIEW graphical user interface, as displayed in Figure 7, to display and store the acquired data.

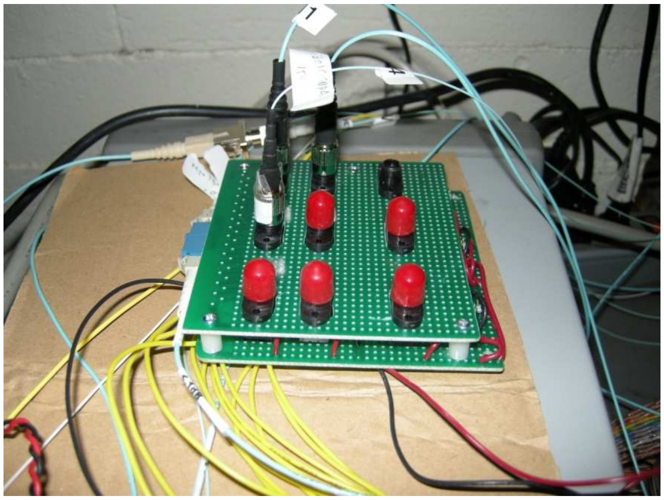

Figure 5. Multi-channel light sensor used to test MM fibers

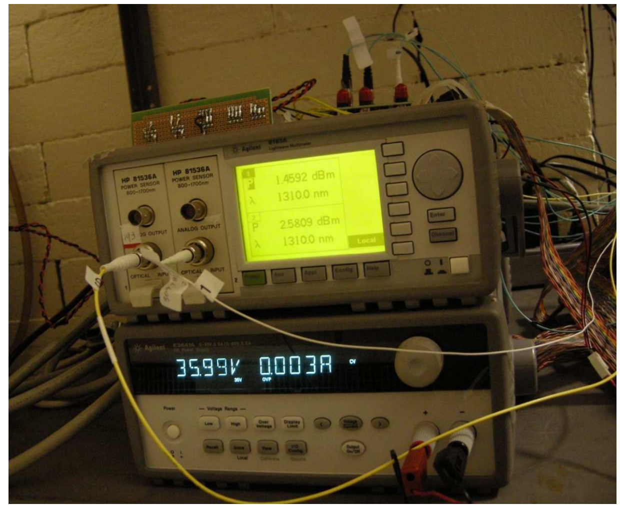

Figure 6. Multimeter and power sensor used to test SM fibers

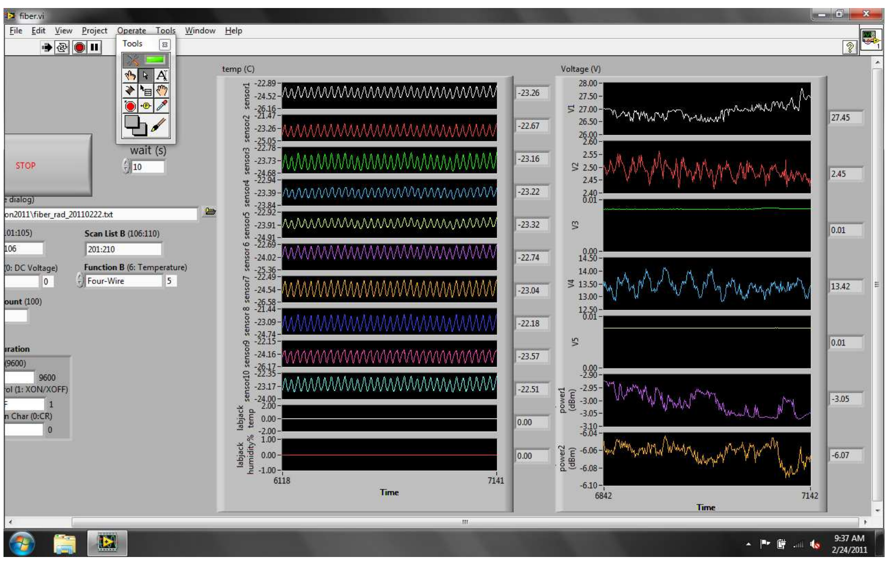

Figure 7. Screenshot of user interface

Before it could be used in the experiment, the multi-channel light meter needed to be calibrated. Using a LabVIEW program in conjunction with a commercial light meter, the optical powers and output voltages of the MM light meter were measured at certain currents of a VCSEL. Then, the optical power was plotted versus the voltage to determine the dynamic range of the light meter. Each power-voltage curve was fitted with a second-degree polynomial and the residuals between the measured values and the fitted values were calculated. Polynomials of higher degrees were fitted as well, but improvements were negligible. Under the assumption that the fits were suitable, calibration errors were calculated with Equation (1).

$$\sigma_{FIT} = \sqrt{\frac{\sum_{i=1}^{N}(P(i)-P_{FIT}(i))}{N-k}} \tag{1}$$

In this equation, σ_{FIT} is the calibration error; P(i) and $P_{FIT}(i)$ are the i-th measured and fitted values; N is the number of samples; and k is the degree of freedom (for the second degree polynomial, k is equal to 3).

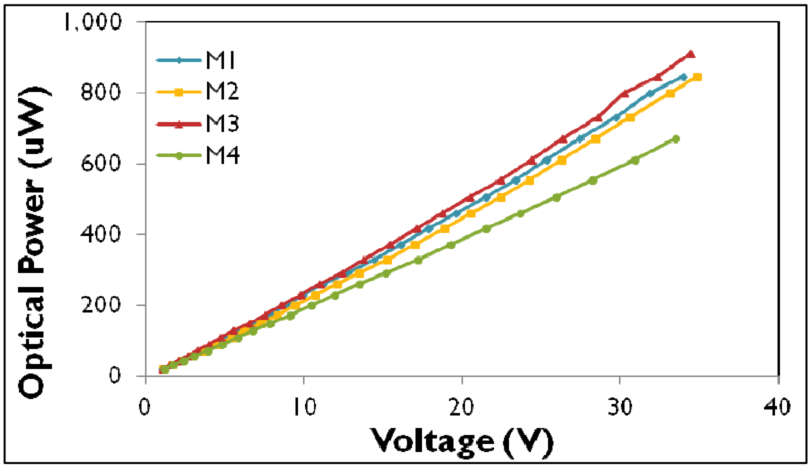

Figure 8. Power-voltage curves for each fiber

All channels were run without irradiation for one week. The standard deviation of the optical power was calculated to serve as the measurement error of each channel. The maximum measurement error was less than 0.001 dB/m. The major measurement errors came from optical power changes of the laser diodes due to temperature fluctuation. The calibration errors were not dominant error sources.

3. Results and Discussion

Six different fibers were tested, with the dose rate and total dose varying for each fiber due to varying distances from the radiation source; the fibers that were positioned closer received a higher dose and vice versa, as detailed in Table 2. The RIA of each fiber was calculated with Equation 2, where P(t) is optical power at time t and t_0 is the time the irradiation started.

$$\mathrm{RIA} = 10 * \log_{10}[\frac{P(t_0)}{P(t)}] \tag{2}$$

Figure 9 illustrates the time trends. For each fiber, the RIA increased sharply at first but then gradually flattened over time until the irradiation ceased. The RIA recovered sharply once the irradiation stopped. Several hours after transportation at room temperature, the fibers were again placed in a freezer in a non-radioactive environment to monitor any additional changes. All of the fibers annealed somewhat, sharply at first and then more gradually, but the RIA never returned to 0. When they were removed from the freezer, the RIA jumped slightly before annealing back to its approximate value before exposure to room temperature.

Figure 10 illustrates the dose trends. The ClearCurve OM3 experienced the lowest RIA of all the fibers, while the Infinicor SX+ experienced the highest.

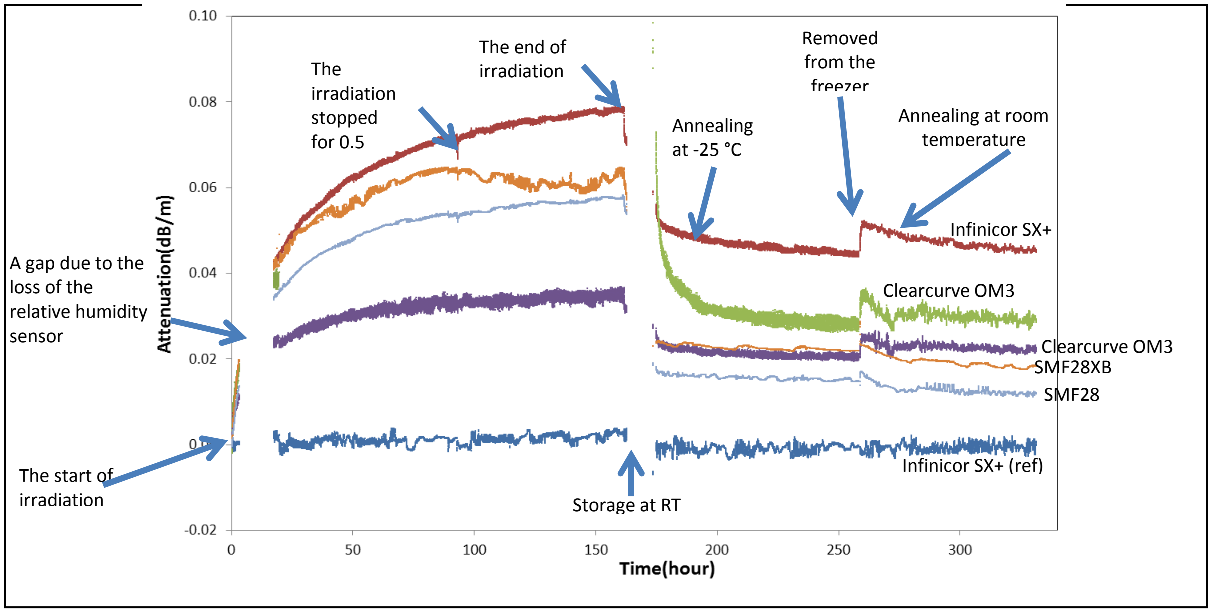

Figure 9. Graph of RIA vs. time

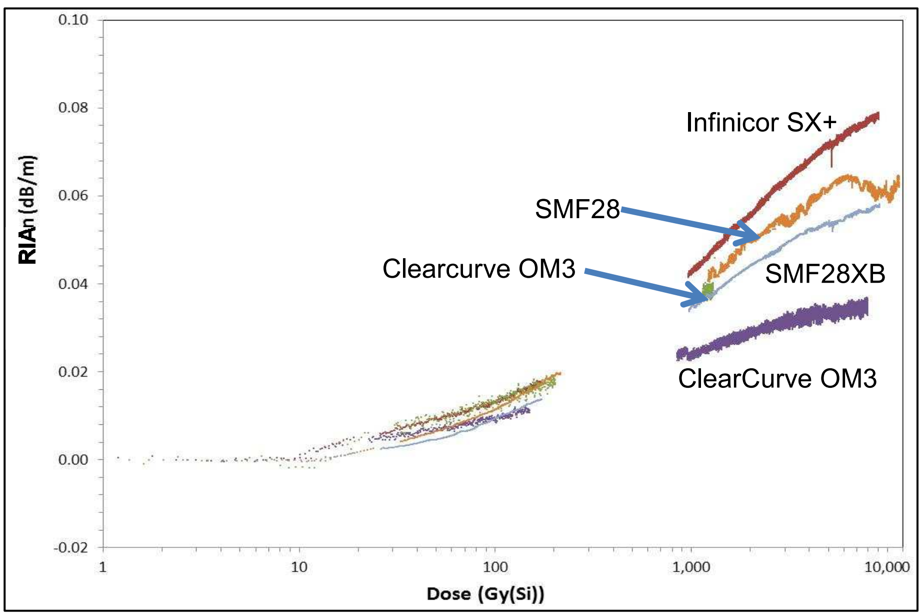

Figure 10. Graph of RIA vs. dose

Table 2: Experimental results; fiber M1 was used as a control and placed outside of the radiation chamber at room temperature, while fiber M3 was removed during the course of the experiment for other purposes.

Ch ID	Manufacturer	Part #	Mode	Length Exposed to Radiation (m)	Dose Rate (Gy/hr)	Total Dose (kGy)	RIA (dB/m)
S1	Corning	SMF28XB	SM	166.56	56.19	9.08	0.057
S2		SMF28		74.11	70.59	11.40	0.063
M1		Infinicor SX+	MM	0.00	0.00	0.00	0.000
M2				170.45	55.75	9.00	0.076
M3		ClearCurve OM3		69.55	66.13	10.68	N/A
M4				118.96	48.91	7.90	0.034

Comparing the results for the Infinicor SX+ tested to those of previous Versatile Link experiments further confirmed the correlations between temperature and RIA and between dose rate and RIA. As Figure 11 illustrates, radiation dose rate is the largest contributing factor to RIA. For either temperature, the higher the dose rate, the higher the RIA; the reverse is true as well.

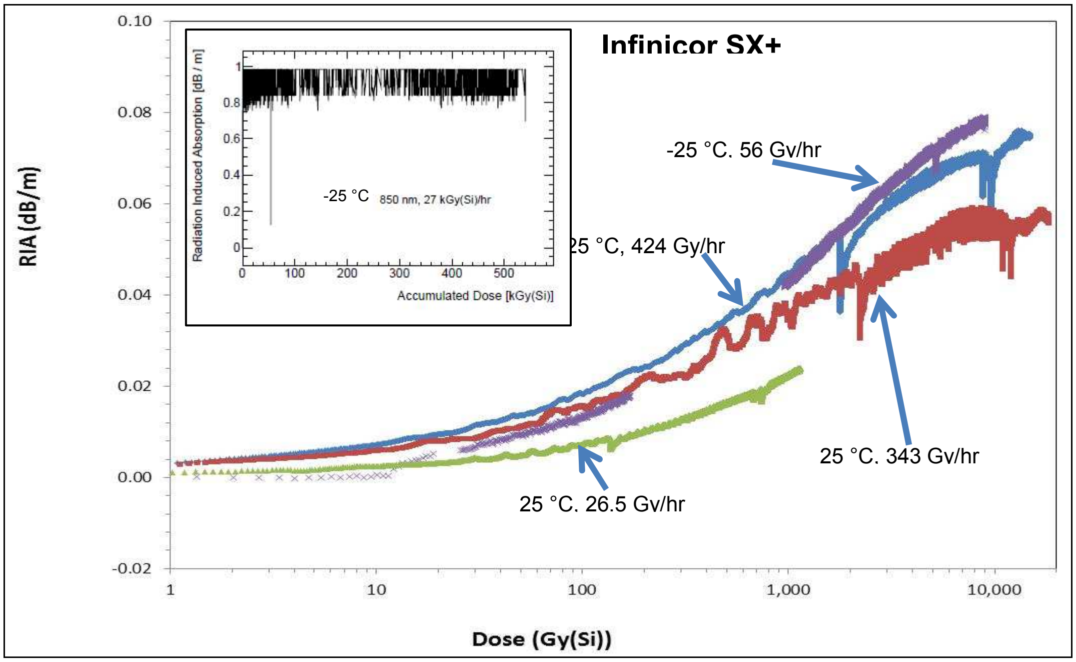

Figure 11. Comparison of the Infinicor SX+ with previous results

4. Conclusions and Future Work

Six optical fibers have been tested in ^{60}Co gamma rays to about 10 kGy at about 70 Gy/hr in an ambient temperature of -25ºC. The newer optical fibers, the ClearCurve OM3 and SMF28XB, experienced a lower RIA than their older counterparts, the Infinicor SX+ and the SMF28. All of the fibers tested are viable candidates for use in the proposed LHC upgrades, although still more tests are needed to qualify them. This experiment contributes to the knowledge pool of radiation-tolerant optical fibers, opening the door for applications in particle physics, space exploration, and many other scientific endeavors.

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6. References

1. McGraw-Hill Encyclopedia of Science and Technology, 5th ed., *Optical Fibers*, 2011, http://www.answers.com/topic/optical-fiber.

2. The ATLAS Collaboration, "The ATLAS Experiment at the CERN Large Hadron Collider," *Journal of Instrumentation* 3 S08003 (August 2008), http://iopscience.iop.org/1748-0221/3/08/S08003/.

3. The CMS Collaboration, “The CMS experiment at the CERN LHC,” *Journal of Instrumentation* 3 S08004 (August 2008). http://iopscience.iop.org/1748-0221/3/08/S08004/.

4. B. Arvidsson et al., “The Radiation Tolerance of Specific Optical Fibres Exposed to 650 kGy(Si) of Ionizing Radiation,” *Journal of Instrumentation* 4 P0701 (July 2009), http://iopscience.iop.org/1748-0221/4/07/P07010.

5. L. Amaral et al., “The Versatile Link, a Common Project for Super-LHC”, *Journal of Instrumentation* 4 P12003 (December 2009), http://iopscience.iop.org/1748-0221/4/12/P12003/.

6. C. Issever et al., “The Radiation Hardness of Certain Optical Fibres for the LHC Upgrades at -25 ºC”, presented at the topical workshop on electronics in particle physics (TWEPP), Paris, France, September 21-25, 2009, http://indico.cern.ch/getFile.py/access?contribId=7&sessionId=31&resId=0&materialId=paper&confId=49682.

7. B.T. Huffman et al., “The Radiation Hardness of Specific Multi-Mode and Single-Mode Optical Fibres at -25◦C beyond a Full SLHC Dose to a Dose of 500 kGy(Si),” *Journal of Instrumentation* 5 C11023 (November 2010), http://iopscience.iop.org/1748-0221/5/11/C11023/.

8. Nnadozie Tassie, “The Effects of Radiation and Low Temperatures on Optical Fibers,” presented in the National Conference on Undergraduate Research (NCUR), Ithaca College, Ithaca, NY 14850, March 31 - April 2, 2011.