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The radiation tolerance of specific optical fibers for the LHC upgrades

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Abstract

Optical fibers in the readout system for the LHC upgrades will operate in a harsh radiation environment. The fibers within 12 meters from the front-end detectors are exposed up to 250 kGy(Si) total ionizing dose in their 10 year operational life time. In some applications, the fibers within the tracking volume are kept in a cold environment near -25 °C. The paper presents the identification of suitable optical fibers for the LHC detector upgrades.
Several optical fibers have been tested to 650 kGy(Si) at room temperature with various dose rates of ^{60}Co gamma rays. Two MM fibers and one SM fiber have been qualified for use in the LHC upgrades for warm operations. Four optical fibers have been tested to 500 kGy(Si) at -25 °C with 27 kGy(Si)/hr 60Co gamma rays. Two SM fibers have been qualified for the LHC upgrades for cold operations. Several optical fibers, including two MM fibers, have been tested up to 11 kGy(Si) at -25°C with 70 Gy(Si)/hr 60Co gamma rays and exhibited moderate RIA, indicating that all fibers under test are potential candidates for the LHC upgrades for warm and cold operations.

Radiation damage to electronic components; Radiation damage evaluation methods; Optical detector readout concepts

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 dielectric wave guide techniques, 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 accommodate multiple rays (modes)

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of light, but can only transmit over short distances (up to a few hundred meters) due to the pulse broadening effect that occurs. SM fibers can accommodate only one mode at a time, but can transmit over long distances (over tens of kilometers) due to reduced pulse broadening [1].

The ATLAS [2] (A Toroidal LHC Apparatus, depicted in Figure 1**)** and CMS [3] (Compact Muon Solenoid, also depicted in Figure 1) 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.

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 to a total ionizing dose of up to 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, creating charged scattering sites. These sites cause the light transmitted down the fiber to scatter in to non-propagating modes, resulting in radiation-induced absorption (RIA) along the length of the fiber [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 either MM fibers with an operational wavelength of 850 nm or 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.

2. Experiment Setup

As an important step towards achieving its goals, the Versatile Link project is testing off-the-shelf optical fibers for radiation tolerance. As of TIPP 2011, four experiments have been conducted, subjecting the fibers to various radiation doses at either room temperature or at approximately -25ºC. Table 1 lists the fibers that have been tested thus far. The Corning fibers were commercially-available as of the tests described in this paper, although the Infinicor SX+ is no longer so. None of the Draka fibers tested reached the open market, but instead served as prototpes for the DrakaElite™ line of MM and SM fibers; some of these fibers will be tested in the future. Fibres X and Y are patent-pending designs produced by CERN and undisclosed companies.

Table 1. Fibers tested

Manufacturer	Part number	MM/SM	Operational wavelength (nm)
Corning	ClearCurve OM3	MM	850
	Infinicor SX+	MM	850
	SMF-28	SM	1310
	SMF-28e+	SM	1310
	SMF-28XB	SM	1310
Draka	Draka-1	MM	850
	RHP-1	MM	850
	RHP-1 SRH	MM	850
	RHP-2	MM	850
Manufacturer X	Fibre X	SM	1310

Manufacturer Y	Fibre Y	SM	1310

The Belgian Nuclear Research Center (SCK-CEN) near Mol, Belgium is one of two facilities at which the Versatile Link Project has carried out its fiber radiation tests. Two gamma radiation sources at SCK-CEN bombarded the fibers to simulate the LHC's radioactive environment. The "Brigitte" source utilized rods of ^{60}Co to deliver high dose rates of up to 27 kGy(Si)/hr. The "Rita" source, also ^{60}Co, provided a dose rate of up to 1.01 kGy(Si)/hr. Figure 1 illustrates these two radiation sources. As a side note, gamma radiation sources were chosen for safety reasons; once the source was covered, the radiation dissipated within seconds.

No temperature control system was necessary for experiments conducted at room temperature. For the tests conducted at -25ºC, however, a dual-phase temperature control system was developed at Oxford for use at SCK-CEN. Carbon dioxide (CO_2) entered the system at a pressure of 50 bar and condensed into a liquid via the Joule-Kelvin Effect. The fibers were then cooled as CO_2 evaporated in liquid-gas dual phase.

The other fiber testing site was at Brookhaven National Laboratory (BNL). There, a ^{60}Co gamma source provided a dose rate of up to 0.4 kGy(Si)/hr. The dose rate was adjusted by placing the fibers at different distances from the source. For the low temperature experiments, the fibers were placed in a chest freezer in order to keep them at an ambient temperature of -25ºC [6]. The freezer's control electronics were shielded with lead bricks so that they would not be damaged by the radiation. Figure 1 provides a graphic representation of both cooling systems.

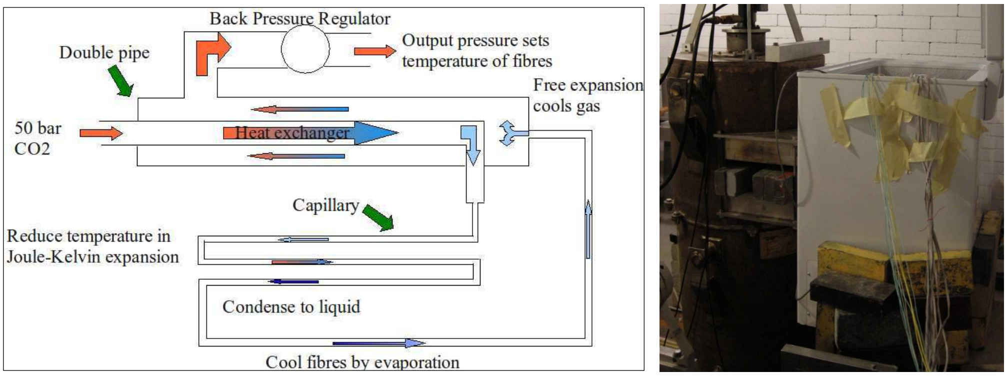

Fig. 1. (a) SCK-CEN CO_2 cooling system; (b) BNL cooling system

3. Experimental Results

To evaluate the effectiveness of each fiber under radiation, a signal was propagated at one end and then measured at the other. Vertical Cavity Surface-Emitting Lasers (VCSEL's) channelled light of a 850 nm wavelength through the MM fibers, while edge-Emitting Lasers (EEL's) directed light of a 1,310 nm wavelength through the SM fibers. At the end of each fiber opposite the light source, the remaining signal was converted to a voltage and measured. Each voltage was then translated into optical power, and each power result was used in Equation 1, where P(t) is optical power at time t and t_0 is the time the irradiation started, to determine the fiber's radiation-induced attenuation (RIA) at its particular time.

$$\mathrm{RIA} = 10*\log_{10}[\frac{P(t_0)}{P(t)}] \quad (1)$$

Figure 2 depicts the results of an experiment conducted in 2008 at the SCK-CEN "Brigitte" and BNL facilities. When tested to a total dose of 650 kGy(Si) at a dose rate of 22.5 kGy(Si)/hr, all of the MM fibers tested (the Infinicor SX+, Draka-1, Draka-RHP-1, and Draka RHP-2) performed reasonably well. The RIA that they experienced was between 0.1 and 0.5 dB/m [4]. This fiber was also qualified for warm operations. The Infinicor SX+ was also tested at BNL to a total dose of 10 kGy(Si), at dose rates of 0.424, 0.343, and 0.0265 kGy(Si)/hr; peak RIA was 0.06 dB/m in these conditions [4]. Of the fibers tested, only the Infinicor SX+ and Draka-RHP-1 were judged sufficiently robust to be qualified for warm operations at the LHC. The only SM fiber tested, the SMF-28, was a standout performer; its peak RIA was less than 0.07 dB/m when tested to 650 kGy(Si) at 22.5 kGy(Si)/hr [4].

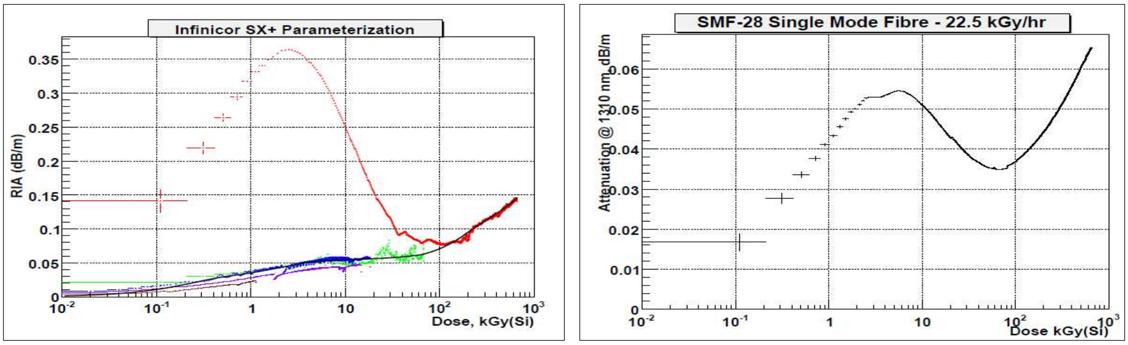

Fig. 2. (a) Infinicor SX+ results at room-temperature under dose rates of 22.5 (red), 1.01 (green), 0.48 (dark blue), 0.38 (light blue), and 0.026 (light green) kGy(Si)/hr with a fit (black), SCK-CEN and BNL; (b) SM results at room-temperature, SCK-CEN

Figure 3 depicts the results of an experiment conducted in 2009 at the SCK-CEN "Rita" facility. The Infinicor SX+ and Draka-RHP-1 fibers were tested to a total dose of 30 kGy(Si) at a dose rate of 0.5 kGy(Si)/hr. Both fibers were tested at temperatures of -4 and -25ºC. The Infinicor experienced a maximum RIA of ~0.8 dB/m, while the Draka experienced a maximum RIA of ~0.5 dB/m [7]. It was first observed in this experiment that RIA is temperature-dependent; with the exception of the Infinicor at doses up to ~5 kGy(Si), the fibers experienced a higher RIA at the lower temperature of -25ºC; the Draka best exemplifies this trend.

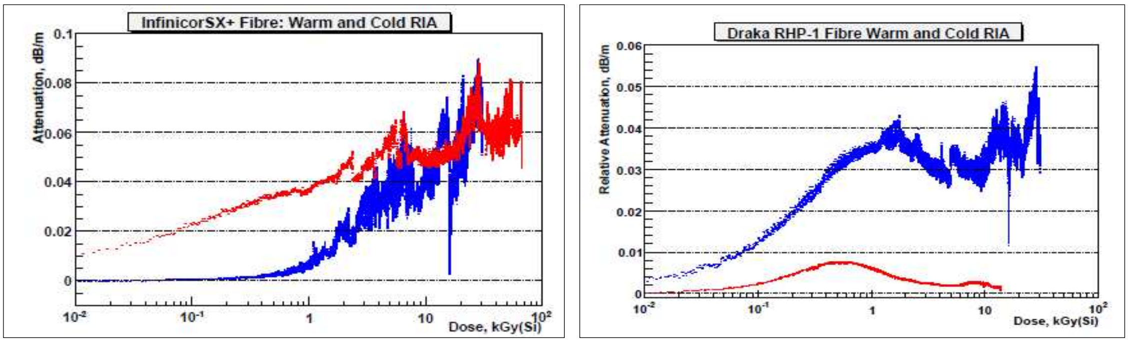

Fig. 3. (a) RIA of Infinicor SX+ at -4 (red) and -25 (blue) ºC; (b) RIA of Draka-RHP-1 at -4 (red) and -25 (blue) ºC

Figure 4 depicts the results of an experiment conducted in 2010 at the SCK-CEN "Brigitte" facility, in which several fibers were tested at -25ºC at 27 kGy(Si)/hr to 500 kGy(Si), approximately twice the total lifetime dose the fibers would experience in operation at the LHC[8]. Two of the SM fibers tested, Fibres X and Y, experienced very low RIA and, as such, were qualified for use at the LHC. The other SM fiber, the SMF-28e+, and the one MM fiber tested, the Infinicor SX+, saturated almost immediately; the RIA for both of these fibers fluctuated at ~1 dB/m, the maximum possible value [8]. If such an RIA were to occur during operation, the fibers would be rendered inoperative. However, because of the very high dose rate used, the Infinicor and SMF-28e+ cannot necessarily be excluded as candidates for the LHC upgrades.

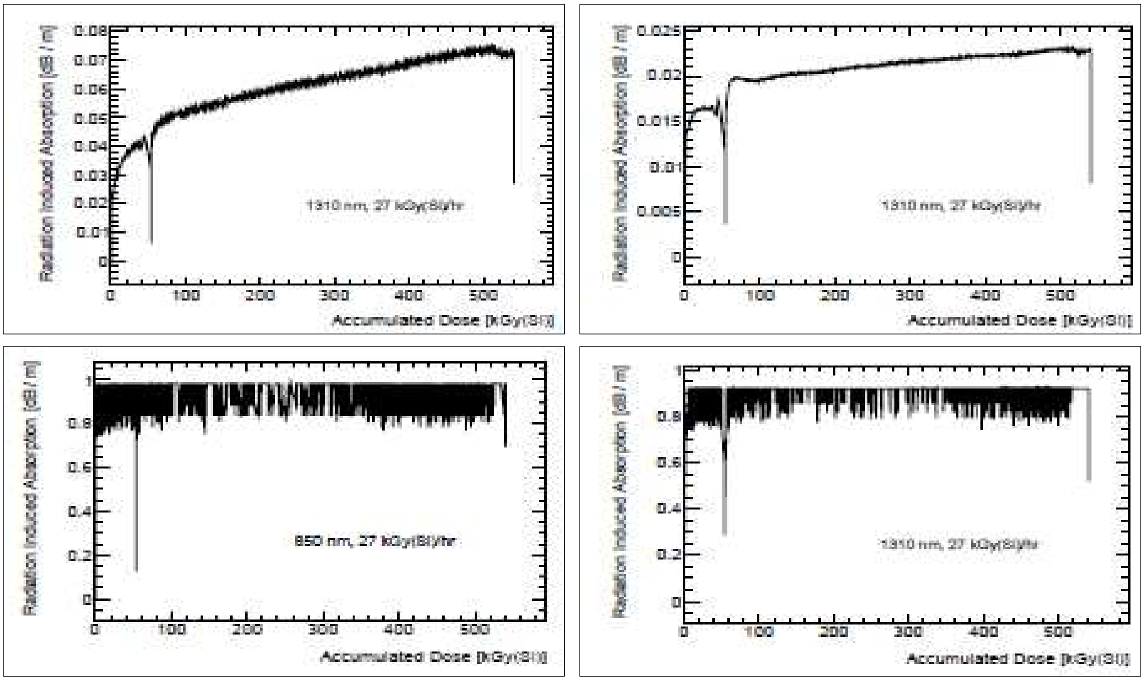

Fig. 4. (a) RIA of Fibre Y; (b) RIA of Fibre X; (c) RIA of Infinicor SX+; (d) SMF-28e+

Figure 5 depicts the results of an experiment conducted in 2011 at BNL, in which fibers were tested at -25ºC to a dose of 10 kGy(Si) at a dose rate of ~60 Gy(SI)/hr. In this experiment, two new fibers, the SMF-28XB (SM) and ClearCurve OM3 (MM), were tested, as they could potentially render some of the previously-tested fibers obsolete. These same two fibers performed better than their older counterparts, the SMF-28 and Infinicor SX+; the ClearCurve experienced an RIA of 0.03 dB/m, while the SMF-28XB experienced an RIA of 0.057 dB/m [9]. However, all of the fibers were qualified for low-radiation operations at the LHC.

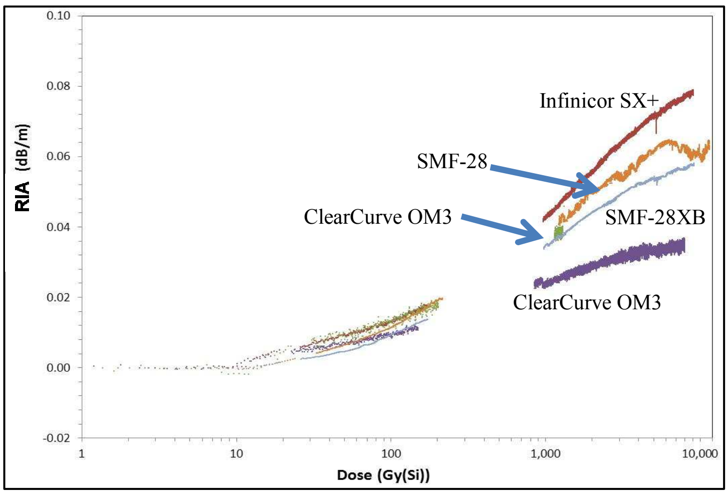

Fig. 5. RIA of fibers for 2011 BNL experiment (on previous page)

4. Conclusions

Since 2008, the Versatile Link Project team has tested multiple optical fibers for use in the fiber optic data links, as part of the proposed LHC upgrades. Two MM fibers (the Infinicor SX+ and Draka-RHP-1) and one SM fiber (SMF-28) have been qualified for warm operations at the LHC. Two SM fibers (Fibres X and Y) were qualified for low-temperature operations at the LHC in a high-dose test. During this test, the MM fibers experienced very high RIA. The Infinicor SX+, despite experiencing high RIA at a high dose rate, is still a viable MM candidate because it exhibits low RIA at a low dose rate, and because the dose rate used was far higher than what a fiber would experience in the LHC. The newer ClearCurve OM3 and SMF-28XB perform even better at a low dose rates than their older counterparts, but still must be tested at high doses. Most of the fibers tested are viable candidates for use in the proposed LHC upgrades, although further tests are needed to fully qualify them. Another fiber radiation test was conducted during the summer of 2011, subjecting fibers to a relatively high radiation dose of 220 kGy(Si), but at a lower dose rate. However, the results are not available for publication in these proceedings. All of these experiments contribute to the knowledge pool of radiation-tolerant optical fibers, opening the door for applications in particle physics, space exploration, and many other scientific endeavors.

Acknowledgements

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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] 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.

[7] 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.

[8] 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).

[9] Joshua Abramovitch, "The Radiation Tolerance of Specific Optical Fibers at -25ºC," presented in the National Conference on Undergraduate Research (NCUR), Ithaca College, Ithaca, NY 14850, March 31 – April 2, 2011.