The Radiation Hardness of Certain Optical fibres for the LHC upgrades at -25^0 C

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Abstract

A luminosity upgrade is planned in the future for the Large Hadron Collider at CERN (called SLHC). Two optical fibres have been tested in a bespoke cold container achieving a constant temperature of $\simeq -25^{o}$C during the entire exposure. The motivations and results of these tests are presented and two multimode and one single mode optical fibre have been identified as candidates for optical links within the joint ATLAS and CMS Versatile Link project.

I. Introduction

The SLHC programme aims to increase the integrated luminosity by a factor of 10 compared to that expected for the LHC. [1] The LHC studies were based on the assumption that the integrated luminosity available for physics would be 300 fb^{-1}, therefore the SLHC studes are based on the assumption that the integrated luminosity delivered will be 3000 fb^{-1}. Based on this scaling an equivalent whole lifetime dose of ionizing radiation is estimated to be in the region of 550kGy (dose on Si at a radius of 30cm from the beam line) using a simple scaling of levels already calculated for ATLAS [2] based on the ratio of integrated luminosities expected.

Two of the detectors in the LHC, ATLAS and CMS, intend to use optical communication systems to read out their inner detectors during the upgraded machine's operation. In order to design and build an optical data link able to withstand this environment a joint project was formed called the "Versatile Link" project between ATLAS, CMS, and CERN.[3] Our group has the responsibility, among other things, to find suitable optical fibres for use in the Versatile Link.

Optical fibres generally take damage from ionizing radiation through the breaking of chemical bonds within the amorphous structure of Silica. The doping elements used in optical fibres to alter their refractive index can sometimes be highly sensitive to ionizing radiation. It is well-known, for example, that the element Phosphorous, which is often used to aid the manufacturing process, produces severe attenuation in optical fibres even at relatively low levels of exposure to ionizing radiation. Because the damage process is one involving the molecular bonds, heat applied to a damaged optical fibre can help re-establish broken bonds and the fibre will anneal with added heat.

The inner detectors of ATLAS and CMS plan to use silicon detectors as the primary tracking elements within both detectors and silicon detectors maintain higher performance in radiation environments when they are kept cold. Unfortunately, cold operation has the opposite effect on optical fibres, "freezing in" defects that form during radiation exposure.[4]

A. Outline of this proceeding

A brief history of past radiation exposures is presented in Section 2 explaining some of our motivation for the current set of tests. In Section 3 we describe the sources, experimental setup, and procedures. Section 4 contains a description and analysis of the sensitivity of our tests. Section 5 is a description of the data and the experimental results we obtained. We explain our programme of future work in Section 6 and summarize our conclusions in Section 7.

II. Past Results

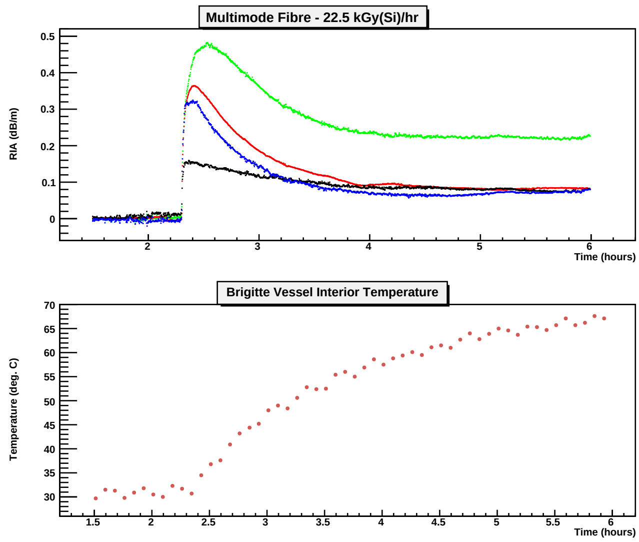

Figure 1: Shown is a plot of Radiation Induced Absorption during a previous radiation exposure. Four fibres are exposed here. The blue curve is Infinicor SX+ fibre and the black curve is Draka RHP-1 fibre. Below this is the fibre temperature showing a significant rise from room temperature during the radiation exposure.

Part of the motivation for these tests comes from fibre studies that our group conducted in August of 2008.[6] In the 2008 test we exposed 4 graded-index fibres to 630kGy(Si) in a gamma radiation source. It was from this test that we identified the two mutlimode (MM) fibres and one single-mode fibre (SMF-28) which we have qualified for use in the SLHC environment for warm operations. The focus of this paper is upon the two MM fibres identified from these previous studies, Infinicor SX+ by Corning and Draka RHP-1.

During this test we observed effects that we believed were partially related to the fact that our container could not maintain a stable temperature. The relevant portion of this test is shown in Figure 1. These results indicated that the sensitivity of RIA to temperature could be very significant. Furthermore, the literature indicates that RIA increases, potentially substantially, when the fibre is cold [4]. Both the CMS and ATLAS experiments intend to run optical fibres through detector volumes that are held at temperatures near -25°C. This motivated us to study RIA at a temperature close to this so that we might determine whether our two best candidate fibres from the August 2008 test would remain acceptable for use in the LHC upgrade.

III. The Radiation Sources and the Test procedure

All tests are performed at the Belgian Nuclear reactor facility SCK-CEN [5] located near Mol. Two sources have been used for the results presented here. All use gamma rays from the decay of ^{60}Co as the source of ionizing radiation. To achieve SLHC level exposure a facility, called “Brigitte”, is available which achieves a dose level of $\simeq$ 22kGy(Si)/hr. A much lower level source known as “Rita” achieves a dose rate of $\simeq 0.5$kGy(Si)/hr and was used for our recent cold fibre tests. The sources are located 8 meters underwater, which acts as a shield. This also means that, with a properly designed container, it is possible to measure the damage taken by the optical fibre as a function of exposure in both time and dose. For optical fibre tests, this capability is superior to methods that permit damage testing only before and after exposure.

The group at SCK-CEN can control the temperature of their radiation containers as long as this temperature is above the ambient level of the water (typically between 25°C and 30°C). Maintaining a constant temperature in Brigitte is a challenge because the number of Compton scattering electrons is so high that any material used to contain the fibres as well as the metal wall of the outer container will heat up. This process caused the temperature rise displayed in Figure 1. Previous tests by our group showed an additional 30°C rise in temperature after the fibre was lowered into the radiation zone. The lower dose rates in the Rita facility generally do not pose such a problem as long as ambient room temperature is one’s desired operational point.

As a result of these limitations our group constructed a container with an active cooling system. The container is approximately 450mm long and has a 200mm inner diameter. This cold container was designed for, and used, in the Rita facility. The active cooling elements were Peltier coolers. Exposures of the coolers separately indicated that they ought to be able to withstand up to 10kGy(Si) of dose and still operate effectively. Heat exchangers dumped the heat from the interior of the container into the surrounding shielding water. The volume of water is very large, many hundreds of cubic meters, and circulated so that it has a uniform temperature and forms an ideal heat sink for our purposes.

Optical fibres of 50m length are wound one layer deep around aluminium cylinders which fit inside the container. The fibres are wound in only one layer so that every part of the fibre is in physical contact with the cylinder. In one run up to two cylinders can be irradiated. The cylinders are thermally connected to each other and the upper cylinder is thermally connected to the 4 peltier cooling devices arrayed symmetrically about the central axis of the cylinder. Each of the cylinders has its own temperature measurement so that we can measure the temperature of each fibre during radiation. Pt100 devices were used for the temperature measurements. They are calibrated to within 0.5^{0}C of absolute temperature but relative temperature measurements are sensitive to within $\pm 0.01^{0}$C.

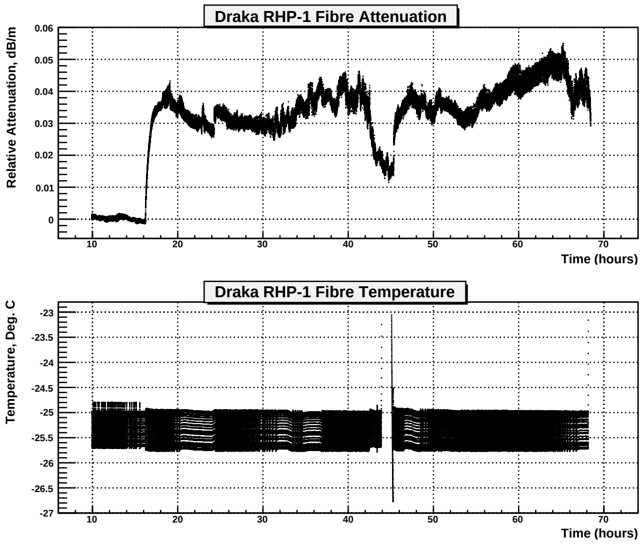

Figure 2: The top figure shows the RIA for our Draka fibre in the cold container as a function of time. The lower plot is of the fibre temperature during this same period of exposure. The cold container was lowered into the radiation environment near hour 16. It was temporarily removed from the radiation environment from hours 42-46. The lower plot is the temperature of that same fibre. The band at -25°C is present because the cooling system turns on and off to maintain a constant average temperature but this causes a $\pm 1^{\circ}$C variation throughout the exposure.

Each channel uses a separate laser light source at 850nm wavelength. This light is launched down a 25m length of patch fibre which runs into the container, through an ST connection to 50m of optical fibre under test, back through another ST connection and then returns through 25m of patch cable to a photodiode receiver. The laser and photodiode are in a shielded area and take no radiation damage. The lasers are all part of one VCSEL array[8] and each is driven by a current source with a stability of better than one part in 10^{4} with a nominal current of 10mA. In addition to the fibres under test, the light from one laser channel simply goes down to the chamber and straight back to a photodiode through an ST barrel connector. The reason for this is to be able to remove residual losses from the patch cables. As a result all of our measurements are quoted as attenuation figures relative to the received light level from this reference fibre.

IV. Current results

This summer two different radiation runs were performed in the Rita source at SCK-CEN. The first was 50m of prototype

Draka RHP-1 SRH fibre held near -4°C. During this test the cold container was operating at its maximum capacity and the cooling was essentially "best effort". Because of this variations of up to 2^{0}C were encountered during the exposure. (The Radiation Induced Absorption (RIA) in his test is shown later in Figure 6)

The cold container was redesigned for the second test using a set of stacked peltier coolers and better thermal contact from the warm side of the coolers to the heat exchangers. The second test held two fibres (Infinicor SX+ and the Draka fibre) to temperatures near -25°C. The Infinicor SX+ fibre had been previously exposed at room temperature ($+30^{\circ}$C) in this same source during 2008.

Figure 2 shows the extent of the test. The fibres were first lowered into the water tank but out of the radiation environment so that the system could cool down. During this time no serious change to the received light was observed that was not consistent with the inherent stability of our measurement apparatus. Once cold the container was left over night with the Draka fibre spool at -25°C while the lower spool holding infinicorSX+ fibre stabilized at -23.7°C. The temperature sensor on the Draka spool was used to control the coolers.

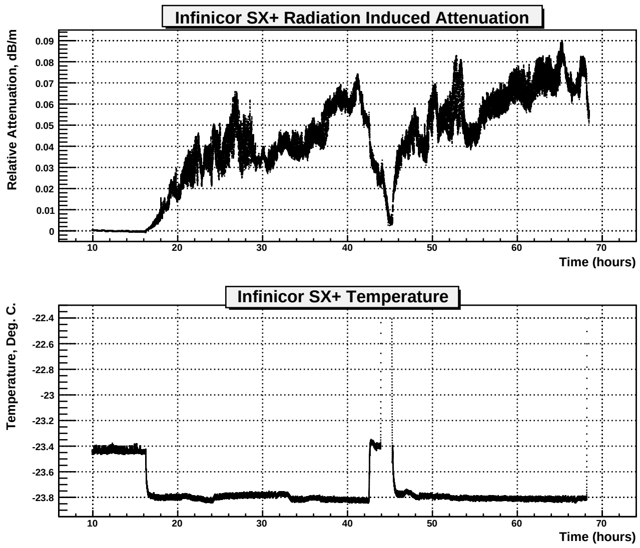

Figure 3: The top figure shows the RIA for Infinicor SX+ fibre from Infinicor SX+ in the cold container as a function of time. The lower plot is of the fibre temperature during this same period of exposure. The lower plot is the temperature of that same fibre. The cooling system turns on and off to maintain a constant average temperature but this causes a $\pm 0.05^{\circ}$C variation during the exposure.

Radiation exposure started just after hour 16 on the figure and continued until hour 42. At this point the container was removed from the radiation environment but maintained at the nominal temperature to allow for any photobleaching effects to become evident. After 1.5 hours the cooling system was turned off and the fibres were allowed to reach the water temperature ($+30^{\circ}$C) while still outside the radiation environment. The coolers were then re-engaged and once the nominal -25°C was again achieved the container was inserted back into the radiation area for further exposure where it remained until approximately hour 66.

Figure 3 shows the equivalent plot as Figure 2 but for the Infinicor SX+ fibre spool.

A. Annealing and Photo-bleaching Effects

Removing and replacing the fibres was done in order to determine the relative amount of photobleaching effects compared to effects due to temperature annealing. The Draka fibre in Figure 2 shows no indication of a change in attenuation when the temperature is increased outside of the radiation volume. Furthermore, when this fibre is re-exposed to radiation the level of RIA returns directly to the value prior to removal from the gamma source.

This is in contrast to the Infinicor SX+ fibre. An expanded view of it's behaviour during the time out of the radiation zone is shown in Figure 4. Here there is also a quick drop in attenuation once the container is removed from the radiation zone (the location of the blue line). Prior to turning off the coolers this reduction is beginning to stabilize. However, once the coolers are shut down (red dotted line) the attenuation again begins to drop. The level of attenuation almost returns to the baseline that existed prior to the start of any exposure in the first place. Unlike the Draka fibre, however, when the container is cooled and returned to the radiation zone (solid red line) the attenuation returns to a level between 0.02 and 0.03dB/m while the attenuation prior to removal was above 0.05dB/m.

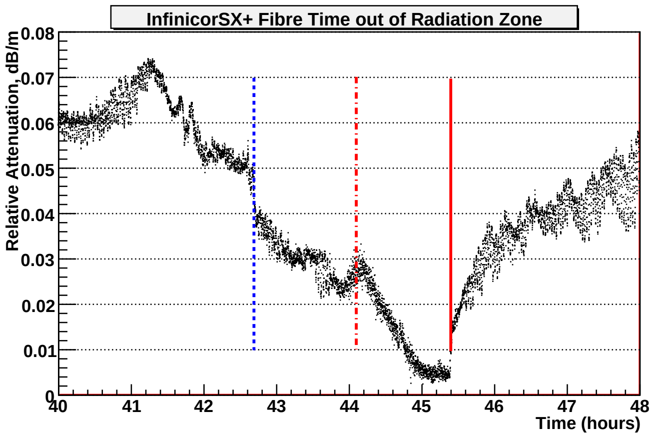

Figure 4: An expanded view of the previous figure during the time that the container was removed from the radiation zone and allowed to warm up. The vertical lines show where the container was removed, when the coolers were turned off, and when the container was returned to the radiation zone respectively.

From these results we conclude that the level of RIA reduction seen in the Draka fibre is due mainly to photobleaching effects. However, there is a measurable amount of temperature annealing present in the Infinicor SX+ fibre.

B. Comparison of RIA at different temperatures; same dose rates

Infinicor SX+ fibre from the same pre-form has been exposed in the Rita zone both at room temperature and at -23.7°C. The Draka fibre from the same pre-form has been exposed in the zone at -4°C and -25.5°C. Figures 5 and 6 show the results of these exposures. In both figures the red curve is the "warm" exposure while the blue curve is the "cold" exposure. In the case of the Infinicor fibre the effect of temperature annealing as described previously has the effect of underestimating the total damage that would have been taken if the container had not been extracted from the radiation zone and warmed to room temperature. Accounting for this it is clear that even in this case the Infinicor fibre would have shown greater RIA at cold temperatures than at room temperature. The Draka fibre clearly shows that, for every part of the radiation exposure, the cold fibre (at -25.5°C) is taking more damage than the "warm" fibre (at -4°C).

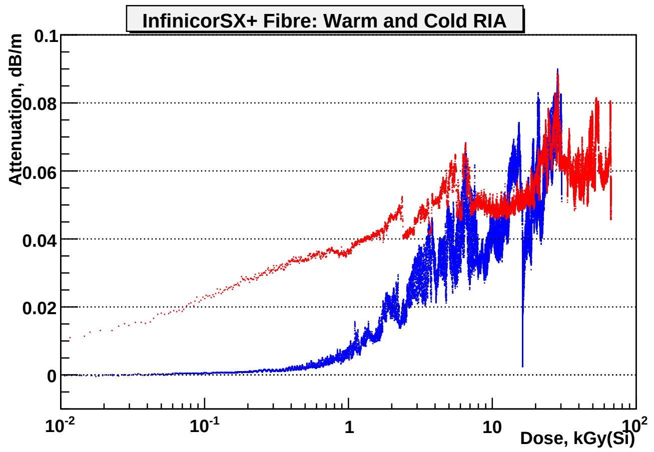

Figure 5: Plotted is the RIA for Infinicor SX+ fibre from the same spool, exposed at the same dose rate (within a factor of two), but with the fibre held at two different temperatures. The blue curve was held at -23.7°C while the red curve was exposed at $+30.0^{\circ}$C.

However, the reader might note that in Figure 5, at doses less than 1kGy(Si) the cold fibre is taking *less* damage than the same fibre held at room temperature. We do not understand this result as the dose rate difference between the two experiments was not significant enough to cause a substantial difference in damage.

These tests clearly demonstrate that the RIA for SLHC doses for these two MM fibres is larger at cold temperatures, compared to warm temperatures. However the behaviour of the RIA versus dose is too complicated to allow a reliable extrapolation to the full SLHC dose. Therefore further tests using cold operation and the full SLHC dose will be required.

C. High Temperature sensitivity of Optical Fibres during Radiation

Looking at Figures 2 and 3 it appears that there is a great deal of noise on short time scales relative to the time axis on those plots. There are instabilities in laser systems and some of those are manifest in our measurements here. However, most of the fast variation after the radiation begins is due primarily to very small changes in the temperature inside the container. One can see from the temperature plots in Figures 2 and 3 that overall temperature stability is very good. However, because the system's temperature is controlled by turning peltier coolers on and off in response to the Draka temperature sensor, there is still some variation on a few minute time scale and this is what causes the variation in RIA during the radiation exposure.

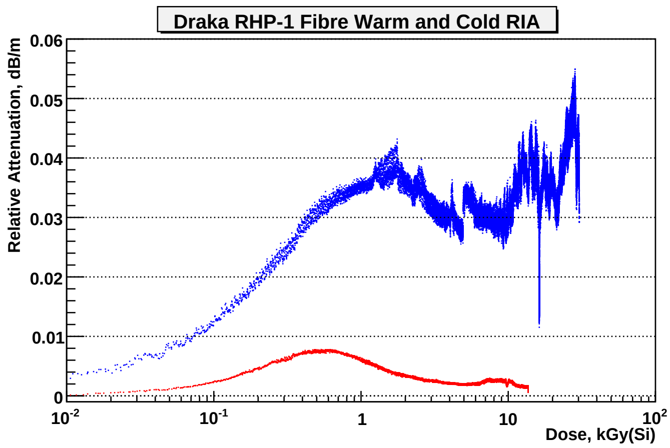

Figure 6: Plotted is the RIA for Draka RHP-1 SRH fibre from the same spool, exposed at the same dose rate (within a factor of two), but with the fibre held at two different temperatures. The blue curve was held at -25.5°C while the red curve was exposed at -4.0°C.

One can see this effect much more clearly if we zoom in on a particular region around the 55 hour mark in time which corresponds to 22.7kGy(Si) of integrated dose. A set of plots in this region is shown in Figure 7. The upper figure shows the individual attenuation measurements with sufficient resolution that one can easily see how the RIA is changing as a function of dose. Both fibre types are shown here. Below this are the temperatures of the two fibres for the same dose range. Note that the Infinicor fibre is very much more sensitive to temperature during radiation than the Draka fibre as the rms variation for the infinicor fibre is 0.0035dB/m while for the Draka fibre the rms variation is 0.0013dB/m while the temperature swing for the Draka fibre is much greater. This rather dramatic effect was unexpected but does demonstrate how sensitive Radiation Induced Absorption of fibres can be to temperature, when they are irradiated in a cold environment.

V. Future Plans

In order to understand the RIA for these fibres using cold operation up to the full SLHC dose, we will perform tests within the Brigitte radiation zone. The fibres will be cooled to around -30°C by an evaporative CO_2 cooling system. This will be a simple "blow-off" system where the coolant is vented to the atmosphere after use. The pressure from a standard CO_2 bottle will provide the work needed for cooling. The design is modelled on that of systems in use in the ATLAS experiment.[9]

VI. Conclusions

The ultimate reason for exposing these fibres cold to radiation is to determine whether or not, at full SLHC doses, they would be acceptable candidates for use in the Versatile Link project.

We have confirmed the results in the literature showing that the RIA of MM fibres is significantly larger at low temperatures compared to warm temperature. We have observed a new effect which we have not seen discussed in the literature, that the RIA of these MM fires is extremely sensitive to very small temperature changes, when irradiated cold. Since a reliable extrapolation of our results to the full SLHC dose is not possible, tests will be performed at low temperature to the full SLHC dose.

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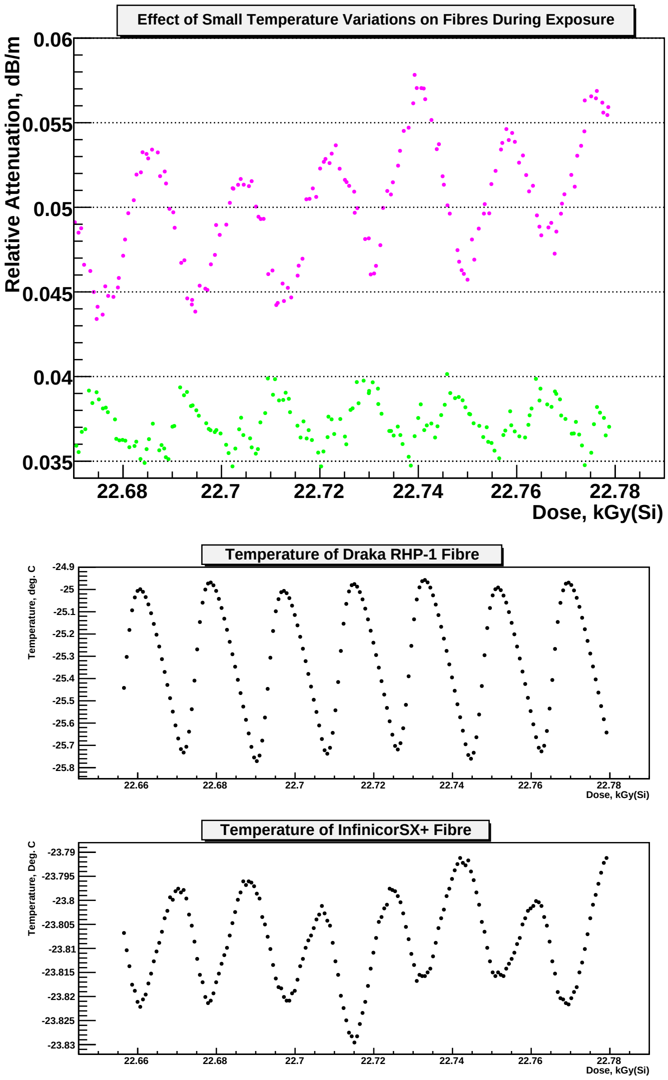

Figure 7: The upper plot shows the RIA for both the Infinicor SX+ fibre (pink) and the Draka RHP-1 fibre (green) where we have zommed in on the horizontal axis scale. The lower plot shows the temperature of those two fibres for the same dose. The Infinicor fibre's rms variation is 0.0035dB/m caused by a full-scale temperature variation of 0.03°C. The Draka fibre's RIA varies by 0.0013dB/m rms, and this is caused by full-scale temperature changes of 0.8°C.