Optical absorption in commercial single mode optical fibres for the LHC machine

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Abstract

The optical absorption of light at 1310 nm and 1550 nm in various commercially available Single Mode (SM) fibres samples has been studied. The absorption was measured as a function of dose, dose rate, temperature and light power. The samples were irradiated with gamma rays from a ^{60}Co source and exposed to a complex radiation field from high energy physics. One fibre sample with an F-doped core exhibits extreme low absorption of light at 1310 nm during irradiation up to doses of at least 100 kGy.

I. Introduction

Optical fibres are widely used in the LHC to communicate with the accelerator equipment in the tunnel and underground areas. The typical length of such an optical connection is 3-4 km. In total nearly 8000 kilometres of single mode optical fibres have now been installed in the machine mainly for LHC controls and communication and for beam instrumentation. The large majority of these fibres are standard SM communication fibres made of Germanium doped (Ge-doped) silica from Draka Fibre Technology BV, manufactured using the Plasma Chemical Vapour Deposition (PCVD) process. Initial optical absorption measurements during irradiation with γ rays from a ^{60}Co source [1] showed that the attenuation for light at a wavelength of 1310 nm in these fibres is linearly depended on the total absorbed dose and equal to 0.01 dB per Gy per km. For most of the installed fibres, radiation induced attenuation is therefore not an issue because they will be exposed to low or intermediate levels of radiation not exceeding 10 Gy per year.

The situation in the LHC collimation areas around point 3 and point 7 is very different however. The radiation levels in these areas will be significantly higher than anywhere else in the accelerator tunnel which is imposing a certain number of constraints on the radiation tolerance of accelerator equipment, including the optical fibres. Monte Carlo simulations [1,2] predict dose rates of the order of 10 kGy per year at nominal beam intensities. At these doses, the use of the standard Draka 445755 optical communication fibre is excluded because the attenuation of light at 1310 nm would reach approximately 25 dB per operational year while the available power budget for accelerator controls and beam instrumentation applications is only 7 dB/km.

A joined effort between Fraunhofer INT institute and CERN was initiated to find more suitable optical fibres for these particular areas in the LHC. Eventually 12 samples from various manufacturers were collected and used in an initial screening test. The best performing samples from the screening test were then using in second test in which parameters such as wavelength, light power, dose rate and temperature were varied. Before making the final selection, the best performing samples from the screening test were equally exposed to a radiation field from high energy physics in the SPS North Experimental Area.

In the remainder of the paper, a description of the test results is given. It will be showed that the Fluorine doped (F-doped) SM fibre manufactured by Fujikura Ltd Japan has a remarkable low absorption of light which, at high doses, becomes independent of the total accumulated dose. It will also be shown that the evolution of the Radiation Induced Attenuation in a high energy physics radiation field such as those found in the LHC, is very similar to that observed during γ ray irradiation with a ^{60}Co source.

II. Experimental

A. Sample collection

A total of 13 fibre manufacturers were contacted and invited to provide samples for the initial screening test. The requirement for the radiation tolerance of the optical SM fibres was defined in terms of attenuation of light in the long wavelength region (1310-1550nm) which should be less then 10 dB per km after a total dose of 100 kGy. Commercially available products were preferred although prototypes were admitted for the screening test. Furthermore, it was specified that a series production lot of 2500 km would be needed on a rather short time scale, approximately 1.5 years after the start of the sample test. Eventually 6 different manufacturers provided a total of 12 fibre samples, including the standard Draka 445755 communication fibre already installed in other parts of the LHC tunnel. The other silica glass based fibres had a Ge-doped core (3 fibres), a pure silica core (3 fibres), a F-doped core (1 fibre) or no information from the manufacturer was given on the composition of the fibre core (5 fibres).

B. Test Procedure

Most of the irradiation testing described here has been carried out with a calibrated ^{60}Co source at Fraunhofer INT (TK1000 Gammamat) in accordance with the IEC 60793-1-54 specifications [3] and at room temperature (24–28°C). Light from a laser diode light source (LD Profile 1310) is divided by a coupler to a reference and measurement channel. The reference channel is used to compensate for the drift of the laser diode light source. Fibre samples are wound on aluminium spools to assure homogenous irradiation by the point source located at the centre of the spool. The light transmitted via the fibre samples and via the reference channel is then measured as a function of time with a high precision dual channel optical power meter (HP 8153).

The system stability in terms of noise and drift is verified before each experiment. During irradiation, the noise and drift observed via the reference channel was always below to 1% of the total induced loss. The length of the samples was adapted to keep the total induced loss after irradiation in each sample between 2 and 5 dB. By limiting the total attenuation in the samples during irradiation, a compromise is found between the signal to noise ratio in the measurements on the one hand and the light power of the measurement channel on so as to minimise the impact of photobleaching effects. The total uncertainty in the optical absorption measurements presented here is estimated to be below 10% (not taking possible temperature effects into account).

C. Screening test

All samples in the screening test were exposed to γ rays under near identical experimental conditions : wavelength 1310 nm, total dose 10 kGy, dose rate 0.2 Gy/s, temperature 24-28 degrees, sample length 50-200 m, light power 10 µW. Only for one specific sample, the light power was increased from 10 µW to 40 µW to improve the stability of the measurement chain. It was later verified experimentally that photo bleaching effects in this fibre sample are negligible and that this variation had no impact on the measurements.

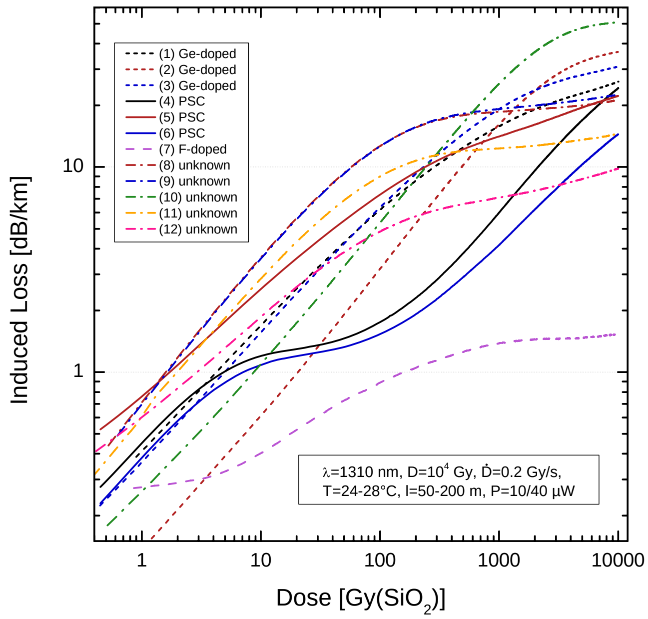

Figure 1: Induced loss as a function of dose for the fibre samples in the screening test.

Figure 1 shows the induced loss in dB per km as a function of the dose for each of the fibres on a logarithmic scale. Amongst the Ge-doped fibres, the Draka 445755 standard communication fibre has the lowest induced loss. The pure silica core (PSC) fibres have lower absorption for light at 1310 nm as compared to the Ge-doped silica fibres which is in agreement with previous experimental observations [4]. Sample #7 (F-doped) and #12 (unknown composition) have the lowest attenuation after a total dose of 10 kGy. The evolution of the loss as a function of dose in the sample #7 with a F-doped core is very different from that in the other samples and there is a remarkably low attenuation for light at 1310 nm above a total dose of 4 Gy.

D. Parameter dependence studies

To study the radiation induced loss under conditions more similar to those expected in the LHC, the optical absorption of 1310 nm light was also measured at different dose rates. Samples #6, #7, #11, #12 and the Draka 445755 sample were irradiated up to a total dose of 100 kGy at dose rates varying between 0.02 Gy/s to 3.1 Gy/s.

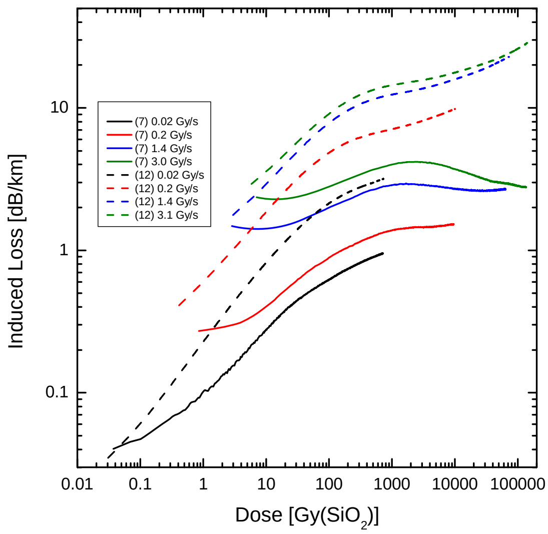

Figure 2: Dose rate dependence for the two best performing fibres (sample#7 and sample#12) in the screening test.

It was found that samples #7 and #12 showed again the lowest absorption of light at 1310 nm at a total dose of 10 kGy or at all dose rates. In general, all fibre samples showed and increase in attenuation with increasing dose rates as expected. Sample #7 (F-doped core) is an exception to this general observation. Variations in the dose rate seem to have a very small or even negligible impact in the attenuation for this fibre, in particular at higher total dose (figure 2). At high dose rates, the induced loss may even decrease with increasing dose and the attenuation curves for sample #2 shown in figure 2 seem to converge to the same final value for the induced loss which is 2 dB/km.

The exceptional performance of the F-doped fibre (sample #7) under irradiation is even more striking when compared to the second best performing sample from the screening test using a linear scale (figure 3).

Similar results were obtained in other experimental conditions. In particular, it was found that varying the wavelength, the light power or the temperature had a very small impact on the radiation induced optical absorption in samples #7 and #12. In fact, in none of these experiments did the attenuation of light in sample #7 exceed the 4 dB/km.

Another remarkable result was obtained during isothermal annealing experiments. The radiation induced damage in the F-doped fibre annealed at the highest rate reaching a recovery of 80% with respect to the conditions before irradiation after only 104 seconds.

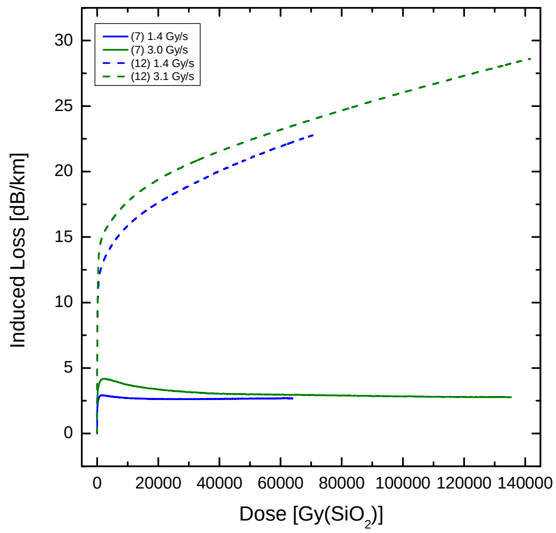

Figure 3: Induced loss for the two best performing fibres (sample#7 and sample#12) in the screening test at 1.4 Gy/s and 3.0 Gy/s.

III. High Energy Physics radiation field

A. *Experimental*

Samples #6, #7, #11, #12 and the Draka 445755 fibre sample were equally irradiated in a complex radiation field in the primary target hall of the Super Proton Synchrotron (SPS) at CERN. The aim of this experiment was to compare the optical absorption induced by gamma rays from a ^{60}Co source to that induced by secondary particles in a hadronic shower at very high energies (up to 450 GeV) and to quantify the possible beneficiary effects of short term annealing at room temperature in a pulsed radiation field of a high energy accelerator.

The radiation spectrum in the radiation test facility of the SPS [5,6] is very similar to that expected in the LHC tunnel but the dose rate is considerably higher which makes this area ideally suited for LHC baseline equipment testing [7]. In the SPS, fixed target beams are accelerated from 14 GeV/c to 450 GeV/c in 3 seconds and then dumped on various primary targets during a 5 second long extraction procedure. This process is repeated every 14.4 seconds 24 hours per day and 7 days per week which creates a pulsed radiation field in the test facility with an averaged dose rate of 5 Gy per day and a peak dose rate of 23 Gy per day. The dose rate to the fibres is measured on line with various types of ionization chambers [8] and a remote radiation monitoring system using Radiation Sensing Mosfets (RADFETs) [9].

Two independent systems were used to measure the radiation induced attenuation in the fibre samples on line during the mixed field radiation test which ensures a reliable long term monitoring. The first system is based on a planar wave guide system to distribute light of a very stable LED light source with cable leads to the fibre samples in the irradiation zone. The light is guided back and multiplexed with a high precision micro-electro-mechanical switch to an optical power meter. The second system is using a direct measurement with an optical time domain reflectometer (OTDR) connected to the same micro-electro-mechanical switch. During the test, all components of the test setup are shielded from EM radiation and operated at a constant temperature.

B. *Attenuation measurements*

The fibre samples were irradiated during the SPS proton campaign in 2006 during 120 days at a constant temperature of 26°C. Figure 4 shows the attenuation of light at 1310 nm as a function of dose. During this irradiation campaign, the total dose to the fibres is increasing at approximately constant rate although there are occasional interruptions due to maintenance and repairs of the SPS.

During these occasional stops, the damage in the fibres anneals. When beam is re-established, the losses rapidly regain their initial global growth curve (memory effect). This indicates that annealing effects will probably not provide an increase in the operational margins.

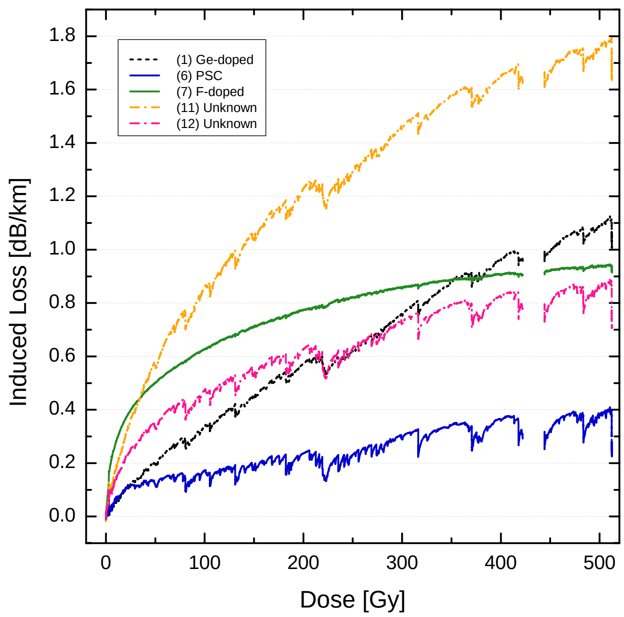

Figure 4: Induced losses in various fibre samples as a function of total dose in a high energy physics radiation field.

In contrast with the other samples, the annealing in the F-doped fibre (sample #7) is barely visible. In addition, the evolution of the absorption as a function of accumulated dose is very different and the earlier observed saturation is practically attained after 500 Gy.

More detailed studies have revealed that there is no significant difference between the radiation induced losses during gamma ray irradiation and irradiation in a high energy physics field. This indicates that the radiolysis process rather than the knock-on process as main radiation damage effect causing the absorption at 1310 nm. Although the radiation tests in the primary target hall of the SPS will continue during the 2007 proton campaign to achieve higher total doses, it is not expected that different radiation effects will occur.

IV. CONCLUSIONS

A commercially available radiation tolerant SM fibre has been found that fulfils the particular radiation tolerance requirements for use in the cleaning sections of the LHC machine. The select fibre has an F-doped core and cladding and is manufactured by Fujikura Ltd. Japan (reference RRSMFB0602). The evolution of the radiation induced loss as a function of the total dose is very different from all other fibres that have been studied here. For light at 1310 nm, the induced losses do not exceed the 4 dB/km at dose rates up to 10 kGy per hour. At high doses, the loss saturates and becomes independent of the accumulated total dose. In addition, the F-doped fibre shows exceptional annealing behaviour.

Based on the results presented in this paper, CERN has recently purchased 2500 km of fibre length which is presently being prepared for installation in the LHC tunnel. Further research is ongoing and aimed at providing a better understanding of the radiation effects in the F-doped fibres.

V. REFERENCES

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