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Optical absorption in commercial single mode optical fibers induced by gamma rays and complex radiation fields

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The optical absorption in 13 SM fibers from 6 manufacturers was studied as a function of dose, dose rate, light power, wavelength and temperature. Two pure Si-core fiber exhibits extreme low radiation induced absorption.

Summary

Introduction

In the 27 km long LHC tunnel, some 8000 kilometers of single mode optical fibers are being installed for accelerator controls and for beam instrumentation. Most of these fibers will be exposed to low or intermediate levels of radiation (approximately 1-10 Gy per year). Around 85% of the fibers are made of Germanium doped (Ge-doped) silica from Draka Fibre Technology BV hereafter referred to as the "Draka 445755"fibre. This is a standard communication fiber, manufactured using the Plasma Chemical Vapour Deposition (PCVD) process. Initial optical absorption measurements during irradiation with with ⊠ rays from a 60Co source [1] showed that the remnant attenuation for light at a wavelength of 1310 nm is linearly depended on the total absorbed dose and equal to 0.01 dB Gy-1 km-1 at least up to doses of some 100 Gy. In large majority of the accelerator tunnel, radiation induced attenuation is therefore not an issue.

Approximately 1300 fibers in the LHC tunnel (representing a total of 2500 km fiber length) will be exposed to much higher dose rates of 50 kGy per operational year (180 days) [2]. The total ionizing dose in these areas is deposited by various types of particles at different energies and such a radiation field is referred to as a complex high energy radiation field. The use of the standard Draka 445755 optical communication fiber in these areas is excluded because the attenuation of light at 1310 nm would reach approximately 25 dB per operational year and largely exceed the 7 dB/km power budget limitation imposed by accelerator controls applications and by beam instrumentation.

This paper reports on the joined efforts from CERN and Fraunhofer INT and to find a large quantity of commercially available single mode optical fiber with a constant quality and an optical absorption not exceeding 7 dB per km for light at 1310 nm after a total dose of 500 kGy in a complex radiation field.

Experimental

Sample screening test

Test procedure

All irradiation tests have been carried out with a calibrated 60Co source at Fraunhofer INT (TK1000 Gammamat) in accordance with the IEC 60793-1-54 specifications [3] and at room temperature (24–28℃). The light from the laser diode light source (LD Profile 1310) is divided by a coupler to a reference and measurement channel. The reference channel compensates drifts of the light source. The fiber samples are wound up on aluminum spools to assure homogenous irradiation by the point source on the centre of the spool. The light transmitted via the fibre samples and via the reference channel is measured with a high precision dual channel optical power meter (HP 8153).
Before each irradiation, the system stability in terms of noise and drift is verified. During irradiation, the noise and drift observed via the reference channel was always inferior to 1% of the total induced loss. By varying the length of the samples, the total induced loss after irradiation in each sample was kept between 2 and 5 dB. By limiting the total attenuation in the samples during irradiation, a good 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 the other. The total uncertainty in the optical absorption measurements presented here is estimated to be below 5%.

Attenuation measurements at constant dose rate

Seven commercial companies were contacted and invited to participate in the radiation screening test for the LHC project. Eventually 12 fiber samples from 6 different manufacturers were obtained, including the

standard Draka 445755 communication fiber already installed in other parts of the LHC tunnel. The other glass silica based fibers had a Ge-doped core (2 fibers), a pure silica core (4 fibers) or no information from the manufacturer was given on the composition of the fiber core (5 fibers).
All samples were exposed to gamma rays under near identical experimental conditions. Only for one specific sample, the light power was increased from 10 microW to 40 microW to improve the stability of the measurement chain. It was later verified experimentally that photo bleaching effects in this specific fiber sample are negligible and that the variation of light power had no influence on the measurements.
Figure 1 shows the induced loss in dB/km as a function of the dose for each of the fibers on a logarithmic scale (figure 1, left) and on a linear scale (figure 1, right). Amongst the Ge-doped fibers, the Draka 445755 standard communication fiber (black dotted curve) has the lowest induced loss. The pure silica core (PSC) fibers show a lower induced loss as compared doped silica fibers which is in agreement with previous experimental observations [4]. Sample #7 (PSC) and #12 show a remarkably low attenuation for light at 1310 nm above a total dose of 4 kGy.

Figure 1: Induced loss in dB/km as a function of the dose for each of the fibers in the screening test (double logarithmic scale on the left, linear scale on the right). Ge-doped fibers are plotted with dotted lines, pure silica core (PSC) fibers are plotted with solid lines and the samples with an unknown composition are plotted with dash-dot lines.

Dose rate dependence studies

To study the radiation induced loss under conditions closer to those expected for 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: Variation of the optical absorption as a function of the dose rate for sample #7 and #12 (double logarithmic scale on the left, linear scale on the right).

It was found that samples #7 and #12 again showed the lowest absorption of light at 1310 nm for all dose rates. In general, all fiber samples showed an increase in attenuation with increasing dose rates as expected. However, sample #7 is an exception to this general observation. For this fiber, variations in the dose rate have a very small or even negligible impact, in particular at higher total dose (figure 2). Compared to the second best performing fiber (sample #12) the induced loss at 100 kGy in fiber sample #7 is approximately 10 times lower.

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 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 fiber sample #7 annealed at the highest rate reaching a recovery of 80% with respect to the conditions before irradiation after 104 seconds.

Detailed tests in a pulsed, complex high energy field

Test procedure

Samples #6, #7, #11, #12 and the Draka 445755 fiber 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 60Co 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 0.15 Gy/hr and a peak dose rate of 0.3 Gy/hr. The dose rate to the fibers 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 fiber samples on line during the mixed field radiation test. 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 fiber 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.

Attenuation measurements

Samples #6, #7, #11, #12 and the Draka 445755 fiber sample were irradiated during the SPS proton campaign in 2006 during 120 days at a constant temperature of 26 degrees. Figure 3 shows the attenuation of light at 1310 nm as function of time (figure3, left) and as a function of the dose (figure 3, right). During this irradiation campaign, the total dose to the fibers is increasing at a constant rate except during the occasional technical stops of the accelerator. These stops are clearly visible in figure 3 (left) and are marked by the onset of an exponential decrease in the attenuation (annealing).

The total accumulated dose in this campaign is 512 Gy. These experiments will continue during the SPS proton campaign 2007 which is planned to begin on the 25th of May. We are confident to be able to discuss the attenuation at higher total dose and to provide a comprehensive and complete comparison with the 60Co data at the conference.

Figure 3 : Radiation Induced attenuation of 5 selected fiber samples a pulsed, complex, high energy radiation field as a function of time (left) and as a function of the total dose (right).

Conclusions

In this study a commercially available SM fiber has been found that fully fulfills the requirements for the LHC. The radiation induced absorption of light at 1310 nm does not exceed the 4 dB/km at dose rates below 10 kGy per hour. In addition, the fiber shows exceptional annealing behavior. The fiber manufacturer of sample #7 is Fujikura Ltd. Japan (reference RRSMFB0602). The fiber is produced under very specific and tightly controlled circumstances using the standard Vapor phase Axial Deposition technique with Outside Vapor Deposition. Based on the results presented in this paper, CERN has recently purchased 2500 km of fiber length which is presently being prepared for installation in the LHC tunnel.

Provided the required corporate approval is obtained, data on the radiation induced attenuation of the series production samples will be presented during the conference together with the optical properties of the series production.

References

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