

Radiation damage to doped Si Fibres in the LHC tunnel

Author(s) / Department-Group: A. Presland (AB/ABT), T. Wijnands (TS/LEA), L. De Jonge (TS/EL), T. Sugito (Draka Comteq NKF Kabel B.V. The Netherlands)

Keywords: Optical Fibres, radiation induced attenuation, LHC tunnel

Summary

Radiation induced attenuation in Germanium (Ge) doped and Ge majority Germanium-Phosphor (Ge-P) bi-doped optical fibres for the LHC tunnel is investigated. After a short description of the basic damage mechanisms, experimental data from a gamma irradiation test with a ^{60}Co source is presented. It is shown that the formulations derived from standard kinetic models for defect generation can be used to describe the observed radiation induced attenuation. A prediction of the radiation induced attenuation in Ge-P and Ge doped fibres in the cleaning sections around IP7 during a nominal operational year of the LHC is given.

1. Introduction

Many LHC electronics will be installed in the tunnel close to beam in order to optimise performance, increase the S/N ration and to reduce cabling costs. Data from low-level electronics in the tunnel is mainly transmitted via a fieldbus protocol (WorldFIP) to the SR surface buildings using either copper or an optical fibre as a medium. The 3 major distributed control systems in the tunnel that use WorldFIP protocol over fibre optical links are the Quench Protection System, Power Converters and the Cryogenics system. Another big consumer of fibres in the tunnel is the BLM/BPM system that transmits raw data from the low level BPMs/BLMs crates directly over a fibre optical links to the surface at a rate of 40 MHz.

Data transmission over optical fibres in the tunnel can be advantageous as compared to transmission over copper signal cables. Optical fibres are blown in pre-installed polyethylene tubes and additional fibres can be easily added on demand without access to the tunnel [1]. In addition, the signal attenuation in a (un-irradiated) fibre is lower as compared to copper and this may eliminate the need for the use of radiation hard repeaters in the system architecture.

However, fibres in the LHC tunnel will suffer from radiation-induced attenuation, which may eventually halt the communication of data after a few years of nominal operation of the LHC. In the next few sections, it will be shown that radiation-induced attenuation depends mainly on the type and the concentration of dopants (such as Phosphor (P), Fluorine (F) and Germanium (Ge)) in the amorphous silicon dioxide (a-SiO₂) fibre core. At present Ge-P-doped and Ge-doped fibres are being installed in the LHC tunnel.

In the remainder of this note, the basic radiation effect mechanisms for radiation-induced attenuation in doped amorphous Silicon core fibres are reviewed. It will be shown that the

formulations for the generation of defects in doped a-Si fibres can be used to describe the experimental data on the radiation induced attenuation observed during gamma irradiation of LHC type fibres. Finally, a prediction of the attenuation of light at 1310 nm for the LHC communication fibres around Pt7 is made.

2. Fibre optic technology

2.1. Single mode and multimode fibres

The basic optical fibre technology consists of two concentric layers of transparent media differing in refractive index and a protective outer buffer. Light injected into the core and striking the core-to-cladding interface at an angle greater than the critical angle will be reflected back into the core. Since angles of incidence and reflection are equal, the light will be reflected again at the opposite surface and the ray continues to propagate down the length of the fibre. Light striking the interface at less than the critical angle passes into the cladding and is absorbed.

Rays of light are channelled into modes determined by the possible paths of a ray travelling down the fibre. A fibre can support as few as one or as many as tens of thousands of modes (hence the name single mode (SM) and multimode fibres). The number of available modes that a fibre supports is very important because it determines the fibre bandwidth. More modes mean more dispersion and therefore less bandwidth.

High-bandwidth and low attenuation is obtained with single mode fibres. These fibres have a core so small that only one mode is supported. Because of the distances that need to be covered, only mono mode fibres are used in the LHC tunnel.

2.2. Doped amorphous Silicon (a-SiO₂)

All fibres installed in the LHC tunnel are made of doped amorphous Silicon. Amorphous silicon (a-SiO₂), like common glasses, is a semiconductor material with silicon atoms not arranged in an ordered structure. The loss of structure order results in defects such as dangling bonds and distorted Si-Si bonds (in both lengths and angles). These defects yield intermediate energy levels in the energy gap. When incident light excites electrons from the valence band to these intermediate energy levels, recombination with holes may occur. The trapped electron is then in a potential well and can act as an oscillator and therefore as an absorber of light. This phenomenon limits the light intensity in pure a-SiO₂.

Better optical performance can be obtained when the a-SiO₂ fibre is doped with impurities such as germanium, phosphor or fluorine. Adding impurities to the a-SiO₂ structure changes the energy structure. When a-Si is deposited under hydrogenation conditions (using a technique called Plasma Chemical Vapour Deposition or PCVD), the hydrogen atoms saturate dangling and weak bonds that results in the removal of defects and the creation of a defect-free energy gap of approximately 8 eV. In this case, electrons excited by light do not have enough energy to bridge the energy gap, the absorption of light in the fibre is strongly reduced.

Detailed knowledge on the doping concentration, the type of dopant and the manufacturing process are often kept secret by the manufacturer. Draka Comteq NKF Kabel B.V. in the Netherlands, the contractor for the procurement and installation of fibres in the LHC tunnel, is using germanium-phosphor doped a-SiO₂ fibres from Draka NK Cables Ltd manufactured using the MCVD (Modified Chemical Vapour Deposition) process and Germanium doped a-SiO₂ fibres from Draka Fibre Technology BV manufactured using the PCVD process.

2.3. Attenuation of light in a fibre

The attenuation for a fibre is specified in decibels per kilometer (dB/km). When they are delivered at CERN, the single mode fibres used in the LHC tunnel have an attenuation of approximately 0.35 dB/km for light at 1310 nm. For a complete fibre connection between 2 points, the attenuation will be superior to this number because of the optical joints and connectors. For the LHC, all optical connectors are inspected with an interferometer before installation and therefore a maximum loss of 1 dB per optical connection can be guaranteed.

The attenuation of an optical link also depends on the wavelength of light that is used. There are three low-loss windows of interest: 850 nm, 1310 nm, and 1550 nm. The 850 nm window is the most widely used in combination with multimode (MM) fibres because 850 nm LED light sources are inexpensive. The 1310 window offers lower loss but at modest increase in the cost of the LEDs. For SM fibres the 1550 nm window is mainly of interest in long distance telecommunications applications. SM fibres in the LHC tunnel and LHC experiments will mainly use laser light sources at 1310 nm.

In addition to the decreasing attenuation with increasing wavelength, several spikes in the attenuation curve may be present if the SiO₂ contains impurities or structural or point defects as described above. Even if the sample is initially free of absorption spikes, some may appear if the sample is exposed to radiation. This is because the radiation can activate pre-existing point defects that then begin to absorb photons of a specific energy. It can also create totally new point defects. The wavelength at which the defects absorb will depend on the structure of the point defect and, if it involves a dopant atom, the type of dopant involved.

3. Radiation effects in a fibre

3.1. Mechanisms for the creation of point defects by radiation

Point defects can be visualized as a localized distortion of the ordered atomic structure and they can be created by irradiating the fibre with particles (electrons, neutrons, ions, etc.) or by exposing the fibre to ionizing radiation (UV, X, γ , etc). The processes involved in the creation of such point defects by radiation are called the knock-on process and the radiolysis process.

In the knock-on the direct transfer of the projectile kinetic energy causes process atomic displacements. This may create a interstitial-vacancy (Frenkel) pair or a site distortion. In order to create a displacement defect it is necessary that the projectile gives sufficient energy to the atom to break its bonds and also to prevent recapture by the neighbouring atoms. The energy required for this is the displacement energy (in SiO₂ this is 10 eV and 20 eV for O and Si respectively). Several types of radiation in the LHC tunnel may produce displacements by knock on collisions: fast neutrons, thermal neutrons, energetic ions, energetic electrons and γ rays (indirectly).

In the radiolysis process the radiation changes the state of an electron but no stable or ionic atomic defects are initially formed. The energy absorbed appears in the form of 'hot' electrons (in a normally empty conduction band) and holes (in a normally occupied valance band) or in the form of excitons (electron-hole pairs bound to each other). These processes are followed by the separate localization of each at suitable lattice sites (traps) leading to stable electronic states and the creation of colour-centres. Finally if the electron-hole pair recombines non-radiatively and its energy is focused on an atom it may be converted into kinetic energy of the latter resulting in bond ruptures or in the creation of vacancy-interstitial pairs. The trapping of free charge carriers created by the radiolysis can also activate existing defects.

3.2. Absorption of light in a doped a-SiO₂ fibre under irradiation

A detailed study into the effects of Germanium (Ge) dopants [2] has shown that Ge-doped silica core fibres have an intense transient absorption following pulsed irradiation but good long-term recovery (annealing). Ge-doped fibres yield absorptions at 0.270 μ m and 0.213 μ m respectively when irradiated.

Another study [3] has shown that the addition of small amounts of P in an a-SiO₂ fibre result in an enhanced sensitivity during steady state radiation. P doping increases the induced loss at short wavelengths and results in a clearly resolved band near 1570 nm. The intensity of this band increases with the quantity of P in the fibre core and causes the radiation induced loss at 1570 nm be similar to that at 850 nm. Since the intrinsic loss of an undoped fibre has a minimum near 1500 nm this is particularly harmful.

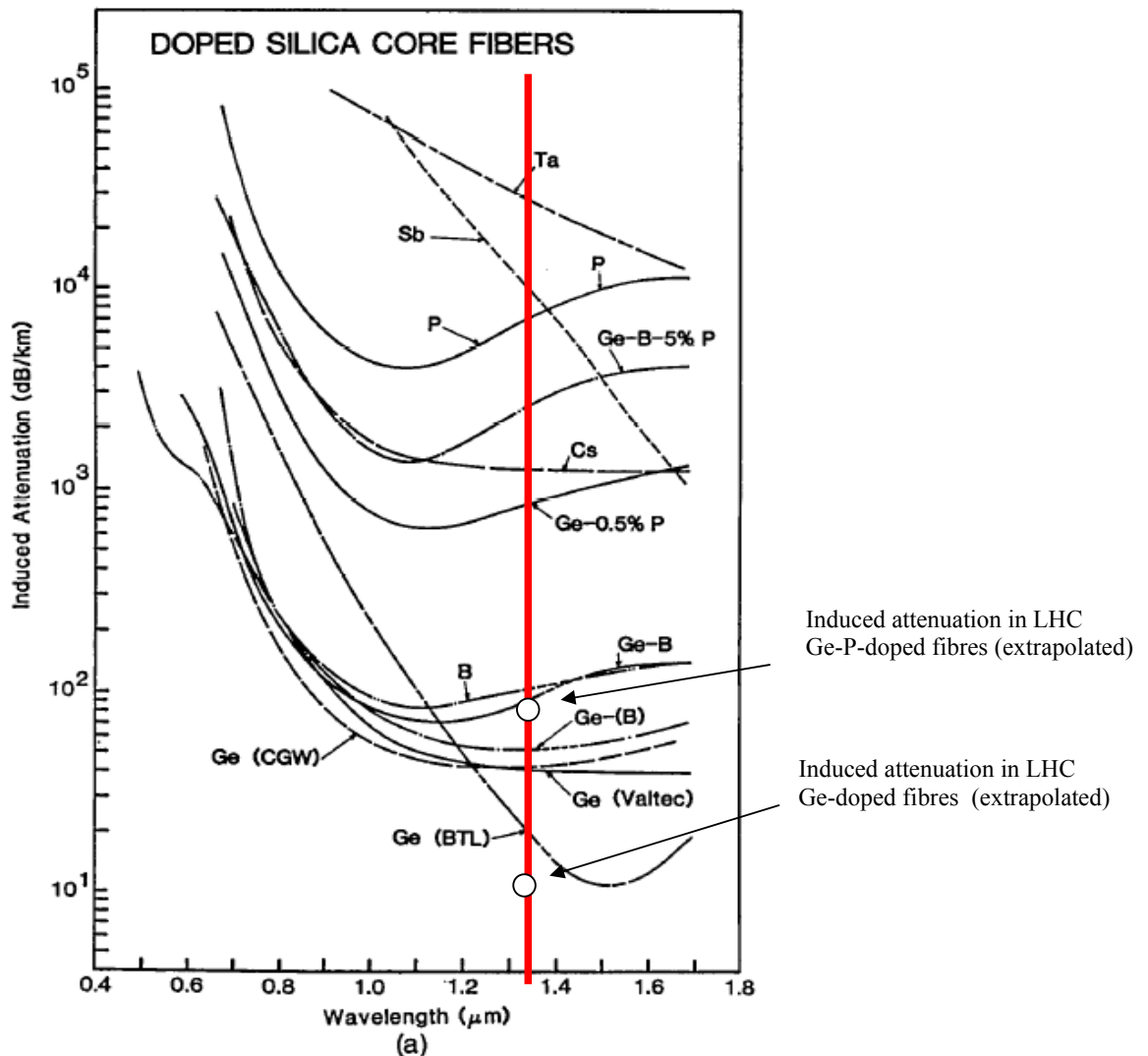


Figure 1. Radiation induced optical absorption spectra of doped silica core optical fibres after irradiation to 10³ Gy and 1 hr anneal [3]. The solid line indicates the wavelength of the light that will be used for the majority of the optical communications in the tunnel (1310nm).

The data shown in figure 1 [3] illustrate that P or Ge-P doped fibres have an order of magnitude higher induced attenuation under irradiation as compared to Ge doped fibres which is in agreement with our experimental observations presented in section 4.

Concurrent with the damage process, thermal and optical bleaching processes occur. These cause deactivation of absorption centres, for example by the liberation of a trapped charge. Activation and deactivation of absorption centres reaches equilibrium at a value of attenuation that depends on the dose rate. Attenuation will then be observed to saturate. Once irradiation has terminated activation will cease but the recovery processes will continue. This leads to the observation of short term recovery of fibre transmission. The radiation induced absorption centres continue to exist and once irradiation is resumed the attenuation levels quickly return to the saturating value as new charge carriers are created by radiolysis and start to populate the traps.

3.3. Kinetic Modelling of radiation induced attenuation

The dependence of the saturation value on dose rate (and temperature) is easily seen in a simple, first order kinetic formulations for defect generation. Considering the equation [4] :

$$\frac{\partial n}{\partial t} = a\dot{D} - \frac{n}{\tau} \quad (3.2.1)$$

where n is the defect concentration, \dot{D} the dose-rate, a the probability of defect generation and τ the characteristic lifetime of the defect. For an isothermal, constant dose-rate regime, the solution of (3.2.1) is a saturating exponential of the form :

$$n = a\dot{D}\tau(1 - \exp(-t/\tau)) \quad (3.2.2)$$

Since the characteristic lifetime of the defect, τ , is temperature dependent, it may be clear that the overall attenuation of light in a doped fibre is dose rate and temperature dependent. Transformation to a dose-equivalent formulation can be obtained by assuming that the saturating dose, D_s , is equal to the dose rate times the characteristic lifetime :

$$D_s = \dot{D}\tau \quad (3.2.3)$$

The kinetic response of irradiated fibres for a given wavelength is in general the sum of different contributions from the underlying absorption band kinetics. Several models exist for predicting or fitting the radiation response. To describe the experimental data presented in the next section we have used the kinetic model of Kyoto et al [5], already successfully used by the CMS collaboration [6]. This model considers the sum of saturating exponentials to describe the overall attenuation of light $A(t)$:

$$A(t) = \sum_{i=1}^{n-1} [K_i(1 - \exp(-t/\tau_i))] \quad (3.2.4)$$

This model (3.2.4) has our preference because it is using a more physics based approach and each of the terms is attributed to a colour centre of type i . The constants $K_1, 2, \dots, n-1$ correspond to the saturation values of the different contributions to the induced attenuation and are dependent on the dose rate :

$$K_i = K_i(\dot{D}) \quad (3.2.5)$$

However, most of the radiolysis attenuation as described by (3.2.4), will anneal when irradiation is stopped. For the period after irradiation, the recovery of the induced radiation is parameterised as :

$$A(t) = \sum_{j=1}^{m-1} [A_j \exp(-t / \tau_j)] \quad (3.2.6)$$

This formula can be derived from the basic kinetic formula (3.2.1) substituting $\dot{D} = 0$. The characteristic lifetime τ can vary in magnitude from minutes to infinity. The annealing behaviour of each defect is driven by temperature dependant relaxation kinetics and is different for each defect. For instance, in P-doped silica, the P1 defect [3] that dominates the attenuation in 1500 nm region is essentially annealing free at 51° C [7]. In pure silica fibres heated to 300° C all types of radiation-induced attenuation at all wavelengths is removed after 100 hours.

After the annealing period the attenuation in the fibres do not, however, regain the initial values before irradiation. In the absence of transient effects related to the dose rate, it is reasonable to assume that the number of colour defect centres (and thus the optical absorption of the fibre) is proportional to the total absorbed dose.

$$A(t) = K_n \quad (3.2.7)$$

$$K_n = K_n(D) \quad (3.2.8)$$

The range over which expression (3.2.7) is valid is limited because of the known saturation at very high doses and the transients observed during intense, pulsed irradiation. However, after a sufficiently long shutdown period, the attenuation in a LHC fibre in the tunnel will be almost entirely determined by the value of the total accumulated dose.

4. Experimental results

4.1. Experimental setup

The attenuation of the LHC type fibres under irradiation was studied in detail by irradiating the 2 types of LHC fibre with gamma rays from ^{60}Co in the POSEIDON irradiator at the nuclear centre of CEA-Saclay in Paris. The aim of the experiment was two-folded : (1) confirm the radiation induced attenuation as predicted by literature and earlier experiments in the TCC2 test area and (2) verify the resistance of the mini-tubes after irradiation to ensure that fibres can still be replaced even after several years of LHC operation. It was therefore necessary to irradiate 2 fibre drums with 1 km of SM fibre each.

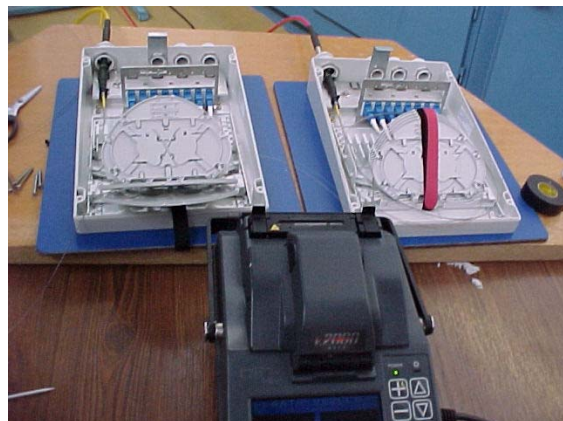


Figure 2 : (left) Cable drums in POSEIDON irradiation facility before exposure, (right) fibre connections and fibre splicing equipment outside the radiation bunker.

At the time of the experiment, the intensity of the ^{60}Co source was 631 kCi (22.5 kW). The dose rate at which the samples are exposed can be varied by increasing or decreasing the distance to the source. We choose to expose the cable drums at dose rates of 500 and 1000 Gy per hour.

Each cable drum contained 1 km of SM fibre in a polyethylene minitube. The first cable drum was wound with the Ge-P doped MCVD produced SM fibre from Draka NK Cables Ltd and exposed at a dose rate of 500 Gy/hr. The second drum contained 1 km of Ge-doped PCVD SM fibre from Draka Fibre Technology BV and was exposed at 1000 Gy/hr.

Attenuation during irradiation was measured with an Optical Time Domain Reflectometer (OTDR). The OTDR injects a series of optical pulses into the fibre and measured the intensity of light that is scattered and reflected back. By the integrated intensity of the return pulses as a function of time, one can estimate the fibre's length and overall attenuation.

4.2. Attenuation under irradiation

4.2.1. Ge-Doped SM fibres

Figures 2a,b and c show the radiation-induced attenuation in the Ge-doped LHC SM fibre sample when irradiated at 1 kGy/hr. The irradiation was interrupted after approximately 33 minutes for approximately 2.5 hrs to study the annealing behaviour. Figure 2a shows a saturating exponential attenuation as function of the total dose, as expected. When irradiation is stopped, the damage anneals partially. During a second exposure the attenuation bounces back to its previous saturated level.

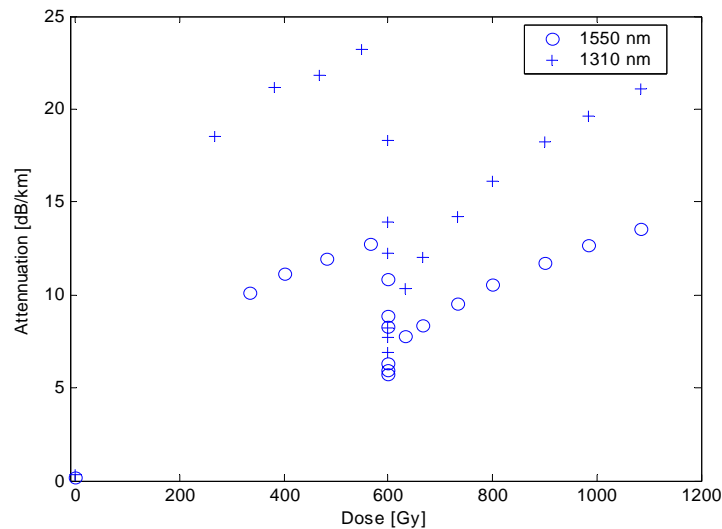


Figure 2a : (left) Radiation induced attenuation in an LHC fibre (Ge-doped SM fibre) as a function of dose (dose rate of 1000 Gy/hr). Irradiation was interrupted for 2.5 hrs after a total dose of 600 Gy to study the annealing behaviour.

Figure 2b shows the same attenuation data as function of time. This figure clearly shows the strong annealing effect when irradiation is interrupted. The attenuation in the fibres does not, however, regain the initial values before irradiation. When the samples are irradiated again, the attenuation follows the same saturating exponential development as before. After the

second annealing period the remnant attenuation is higher (indicated with arrows) than after the first annealing period suggesting the existence of a dose dependent, linear contribution as in (3.2.7).

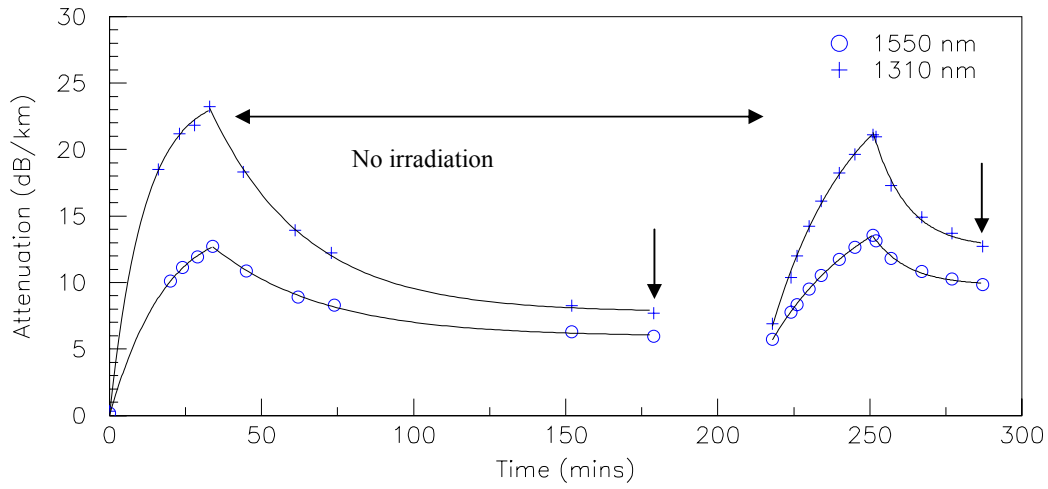


Figure 2b. Radiation induced attenuation of an LHC fibre (Ge-doped SM fibre) as a function of time (dose rate 1000 Gy/hour). The kinetic model fits to the growth and anneal data have been superimposed.

The existence of a linear term has been investigated further in figure 2c, which shows the attenuation of the Ge doped SM fibre as a function of total dose after each annealing period (i.e. the points indicated with arrows in figure 2b). Indeed, the dependence on dose is quasi linear and approximately equal to 0.01 dB/km per Gy for light at either wavelength. When extrapolated to a total dose of 10 kGy, these values are lower than those for Ge-doped fibres shown in figure 1. It may be that this has been caused by the partial “self-shielding” of the cable on the drum.

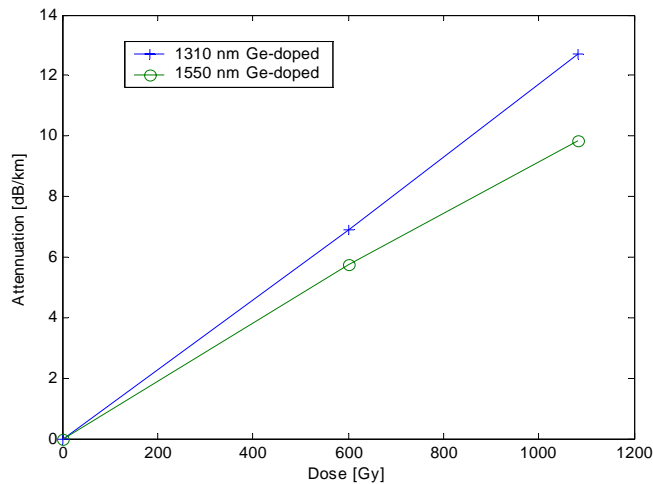


Figure 2c: Radiation Induced attenuation in Ge-doped SM fibres as function of the total accumulated dose after a complete annealing at room temperature.

As such permanent radiation induced attenuation to fibres in the tunnel will probably be most harmful, it would be worthwhile to investigate the dose dependence of the linear term in more detail in forthcoming radiation experiments.

4.2.2. Ge-P-Doped SM fibres

Figure 3a shows the radiation-induced attenuation of the Ge-P-doped SM fibres as a function of the dose for the same two wavelengths. The Ge-P-doped SM fibre in this experiment was irradiated at 500 Gy/hr. In contrast with the Ge-doped SM fibres, the Ge-P-doped SM fibre does not show any short term annealing and the attenuation is approximately equal to 0.08 dB/km per Gy for 1310 nm and 0.12 dB/km per Gy for light at 1550 nm.

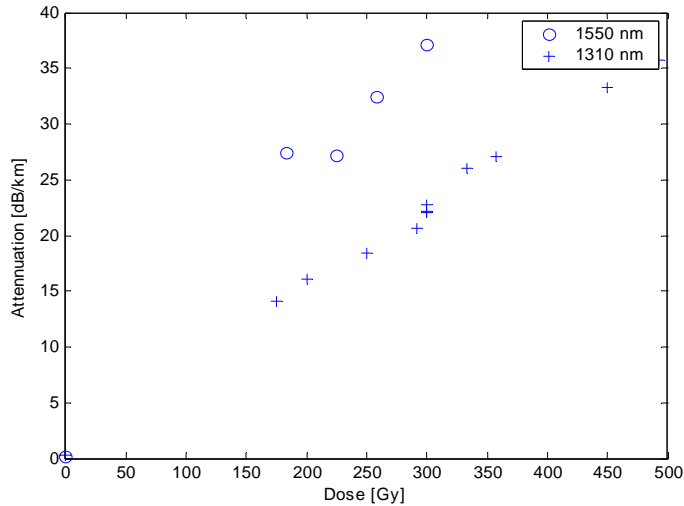


Figure 3a. Observed radiation induced attenuation in an LHC fibre (the Ge-P-doped SM fibre) as a function of total dose (dose rate 500 Gy/hr).

The absence of annealing is more apparent in figure 3b which show the same radiation induced attenuation data for the Ge-P-doped SM fibre as a function of time.

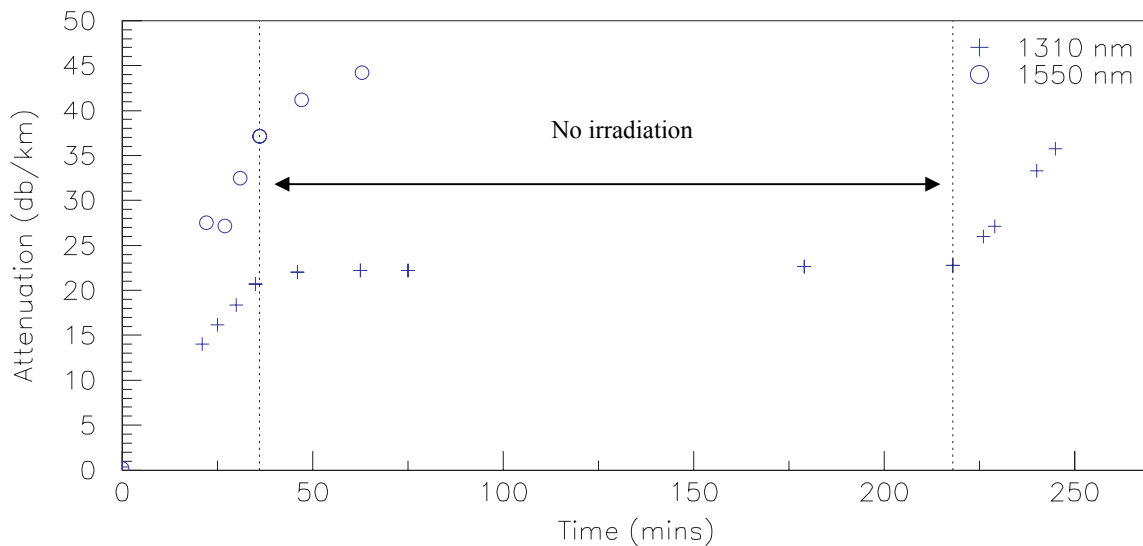


Figure 3b. Radiation induced attenuation of an LHC fibre (the Ge-P-doped SM fibre) as a function of time (dose rate 500 Gy/hour).

The attenuation in the Ge-P-doped SM fibres is more pronounced for light at 1310 nm as compared to light at 1550 nm, while the inverse is true for Ge-doped SM fibres. This can be understood by reference to figure 1. The Ge-doped fibres exhibit a ‘UV tail’ due to chlorine impurities that reaches minima close to 1200 nm before increasing again after 1400 nm. This increase is probably due to a combination of OH overtones at 1395 nm and P impurities in the core leading to a P-OH overtone at 1.600 nm [8]. For the Ge-P-doped fibres the attenuation is due to the broad P1 defect [3] centred on 1570 nm with a short wavelength Gaussian tail extending to 1100 nm.

4.2.3. Fit to kinetic models

The formulations derived in section 3 have been used to fit the attenuation data for the Ge-doped fibre during irradiation and annealing. The resulting plots are shown in figure 2b with the fit parameters tabulated below.

Damage fit coefficients	1310 nm Ge-doped fibre	1550 nm Ge-doped fibre
K_1 [dB/km]	24.20	14.50
τ_1 [mins]	11.16	17.40

Table I. Fitting parameters for the radiation-induced attenuation in Ge doped SM fibres for light at 1310 nm and 1550 nm.

Recovery fit coefficients	1310 nm Ge-doped fibre	1550 nm Ge-doped fibre
A_1 [dB/Gy.km]	15.34	6.75
τ_1 [mins]	31.14	35.92

Table II. Fitting parameters for the annealing at room temperature of the radiation-induced attenuation in Ge doped SM fibres for light at 1310 nm and 1550 nm.

The dynamic response of Ge-doped SM fibres under irradiation at 1 kGy/hr can be described well with a single, dose-rate dependant, saturating exponential as proposed by the kinetic model from Kyoto [5]. The permanent damage that remains after a sufficiently long annealing period at room temperature is linear dependent on the total accumulated dose. This confirms early observations in [9] where the optical-loss versus dose curves for several types of fibres are linear over several decades before the fraction of occupied colour centres starts to saturate and the curves becomes flat.

At the radiation levels investigated in this report the attenuation in the Ge-P-doped SM fibre shows neither evidence of saturation during irradiation nor of annealing after irradiation. The attenuation can be described by a single dose dependent term. This behaviour is consistent with that reported in [7] where it has been attributed to the broad P1 defect at 1570 nm. Our study finds that after a total dose of 500 Gy and a complete annealing period at room temperature, the attenuation in the Ge-P-doped SM fibre is a factor 8 worse than that in the Ge-doped SM fibre for light at 1310 nm. For light at 1550nm, the attenuation is a factor 12 worse than in Ge-doped SM fibres.

5. Estimate of radiation induced attenuation in the LHC tunnel

To estimate the radiation induced attenuation in the tunnel we have used the fibre layout as presented in [1]. In point 7, communication fibres from the SR7 surface building reach low level electronic crates located under the cryostats in the tunnel by passing through the Long Straight Section, the Dispersion suppressors and the regular ARC.

We consider here an optical fibre that connects a low-level electronics crate located under a cryostat at the mid ARC to an acquisition crate in the local control room in SR7. This fibre will be damaged by radiation from beam-gas interaction in the ARC and from radiation due point losses in the Dispersion Suppressor and the Long Straight Section where the collimators are located. The dose rate in these areas during nominal operation have been simulated with cascade codes and the results can be found in [10] [11] [12] and [13] assuming the usual 200 days of LHC operation per year (4800 hours) at nominal intensity with fill durations of approximately 15 hours with 5-hour turnarounds.

Tunnel Area	Distance [m]	Dose rate [Gy/h]	Total Annual Dose [Gy]	Attenuation [dB/y]	
				1310 nm Ge-P doped fibre	1310 nm Ge doped fibre
LSS R7	270	0.625	3000	64.8	8.1
DS R7	170	0.002	10	0.14	0.02
Half ARC	1214	0.001	5	0.49	0.06
Total	1654	-	3015	65.4	8.1

Table III. Estimates of the annual radiation induced attenuation in an optical fibre around IR7 based on the fitting parameters in section 4.

Table III gives estimates of the radiation-induced damage in the 2 SM fibre types assuming that the attenuation depends only on the total accumulated dose. The overall attenuation for an optical connection between the tunnel and the SR surface building may be superior due to losses in the optical connectors (around 4 dB in total, i.e. 0.5 dB per connector) and radiation-induced degradation of the lasers or light emitting diodes [14].

6. Conclusions & future work

The SM fibres in the LHC tunnel will show an increase in the attenuation of light at 1310 nm due to radiation damage from ionising radiation. The attenuation will depend on the wavelength of the light, the type and concentration of dopants in the Si-core, the total accumulated dose and the dose rate. This phenomenon has been investigated by conducting radiation experiments with SM fibres identical to those installed in the LHC tunnel that are either Ge-P-doped or Ge-doped.

The observed attenuation in **Ge-P-doped SM fibres** irradiated at a dose rate of 500 Gy/hr is 0.08 dB/km per Gy for light at 1310 nm which is approximately 8 times higher than that in Ge-doped SM fibres. The attenuation increases linear with the total dose and no saturation of the attenuation has been observed up to a total dose of 0.5 kGy. When the irradiation is stopped, Ge-P-doped SM fibres do not show any measurable short term annealing effect though the possibility exists that anneal occurs but is not observable on the timescales considered.

Ge-doped SM fibres show a saturating exponentially increasing attenuation at a high dose rate (1 kGy/hr) and the level of saturation is approximately 20 dB/km. There is a strong short term annealing when the irradiation source is turn off. At room temperature, the attenuation does not return to the level of the un-irradiated fibre. The remnant attenuation is approximately linearly dependent on the total dose and equal to 0.01 dB/km per Gy.

We suspect that the influence of the dose rate on the attenuation is a transient effect and that this effect will reduce or disappear at the lower dose rates that are expected in the tunnel. In the absence of a dose rate dependency, the expected dose dependent attenuation induced by radiation in the fibres right of Pt 7 (i.e. between the UJ and the mid-ARC) would be **65 dB per year** for Ge-P-doped SM fibres and **8 dB per year** for Ge-doped SM fibres.

In conclusion, the Ge-doped SM fibres from Draka Fibre Technology BV show better radiation resistance compared to Ge-P-doped SM fibres from Draka NK Cables Ltd and we recommend the use of Ge-doped SM fibres only for the installations in the cleaning sections around IR3 and IR7. During LHC operation, it would be advisable to perform attenuation measurements at regular intervals to monitor the radiation-induced damage of the fibres. It may be that fibres in the LSS around IR3 and IR7 need to be replaced every 1-2 years.

In a future radiation experiment, we would like to investigate, for both fibre types, the dose rate dependence of the attenuation increase, evaluate the dose dependant linear contribution and assess the impact of annealing at the time-scales of the LHC duty cycle. Furthermore, we would like to search for the existence of a saturation limit for Ge-P-doped fibres up to a total dose of 3000 Gy.

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