Radiation Tolerant Optical Fibers: From Sample Testing to Large Series Production

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***Abstract*— The process of selecting, manufacturing and installing a large quantity (2500 km) of commercially available radiation hard specialty fibres is described. Radiation tests of various types of fibres from different manufacturers provided sufficient understanding of the radiation effects to select the best performing fibre type. Systematic verification of a sample of each preform assured a constant quality of the series production and allowed assessing the impact of small variations in the manufacturing process on the radiation hardness and the optical transmission characteristics. The fibre cable installation technique based on micro jetting and plastic cable ducts has been validated for areas with high levels of radiation.**

***Index Terms*—Fluorine doping, large hadron collider (LHC), microduct cabling, optical fiber, radiation induced attenuation (RIA), The European Organization for Nuclear Research (CERN).**

I. Introduction

Silica (SiO_2) glass is well suited for guided optical transmissions because of the low attenuation of light. Indeed, many present day optical fibres are made of silica and are essentially long strands of SiO_2 composed of a central core surrounded by a cladding.

It is now widely accepted that exposure of silica fibres to ionizing radiation can lead to the increase of the attenuation of light because of the color center formation [1]-[3]. The radiation response is strongly correlated to the manufacturing procedure of the fibre [4]-[6] and to the irradiation conditions [7], [8].

Both the manufacturing process as the irradiation conditions involve many factors which all contribute to a certain extent to the observed radiation induced attenuation (RIA) in a given radiation environment. The difficulty in selecting a commercially available fibre is that so many degrees of freedom exist. One solution would be to vary each parameter individually between three or more levels and observing the RIA on line, but this would a very time consuming and costly exercise. Furthermore, it is always uncertain whether this approach will eventually converge to a solution that is acceptable (technically, time and cost wise) for the application at hand. Finally, the radiation response of fibers from a large series production has to be at least identical to that of the samples that were produced for, and used in, the radiation testing.

In this paper we present an alternative approach that consists in preselecting fiber manufacturers and specialty fiber samples on the basis of the application at hand. A well-defined irradiation protocol is then used to select the best performing candidates, thereby minimizing the amount of radiation tests on samples, reducing the systematic measurement errors and enhancing the reproducibility. The best performing samples in terms of RIA are exposed in a radiation environment that is almost identical to that in the final application and the RIA in the fibers is observed on line over a period of consecutive two years.

During the testing phase, the data analysis is conducted in close collaboration with the fiber manufacturers which allows assessing the impact of the manufacturing process on the radiation performance. It also provides additional insight in the underlying radiation effects. This knowledge allows us selecting the most appropriate radiation tolerant fiber for the application at hand (in this case a Fluorine doped (F-doped) single-mode fiber) for series production.

To ensure a constant quality of each production batch, systematic cross checking of the RIA for samples from each preform is conducted during the series production. Finally, the micro duct cable blowing technique over long distances was validated using irradiated (micro) ducts.

In the remainder of this paper, the technical requirements are briefly summarized in section II. In section III, the results of the radiation tests will be discussed followed by an interpretation of the observed radiation effects in section IV. Section V deals with the manufacturing of the series production while the quality assurance (QA) data is discussed in section VI followed by some concluding remarks.

II. Application field

The radiation tolerant optical fibers described here are used for the Beam Position Monitoring (BPM) system of the Large Hadron Collider (LHC) [9], [10]. The LHC is a high energy, high intensity proton-proton collider in which two counter rotating particle beams are accelerated and then collided at a centre of mass energy of 14 TeV (nominal value). The accelerator is installed in a 27 km long tunnel located 100 m

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underground.

One of the functions of the BPM system is to measure the horizontal and vertical position of the proton beams. The digital readout systems are located on the surface and connected to analogue front ends in the accelerator tunnel via single-mode fibres. Single-mode fibres are chosen because the distance between the front ends and the analogue readout can be several kilometers.

In some areas of the accelerator, radiation levels to these fibres and the fibre ducts may be as much as 10 kGy per operational year (200 days) when the LHC is operating at its nominal performance which is why radiation tolerance has been taken into account as an engineering constraint for this system. The constraints for the single-mode fibres are as follows.

In terms of radiation tolerance, the RIA of light at 1310 nm should not exceed 7dB/km for ten years of operation (corresponding to a total ionizing dose of 100 kGy).

Furthermore, the pristine (unirradiated) fiber should be compliant with the international standard ITU-T G.652.B [11] which recommends a loss inferior to 0.4 dB/km for light at 1310 nm and a loss inferior to 0.35 dB/km for light at 1550 nm.

For installation purposes, the fibre cable must be compatible with the microduct cable blowing technique [12-15] which has been used for the installation of almost all optical fibres for the LHC accelerator. Compatibility also means that the fibre cable can installed or replaced at any given point in time and in particular after the duct and the cable have received a total ionizing dose of 100 kGy.

Finally, the production capacity of the manufacturer must be sufficiently high in order to produce 2500 km of fiber within a year and at constant quality.

TABLE I
STANDARD IRRADIATION CONDITIONS FOR FIBRE SAMPLES

Parameter	Standard Conditions	Range	Unit
Dose	$1x10^4$	$1x10^3$-$5x10^6$	Gy
Dose rate	$2.25x10^{-2}$	$6x10^{-5}$-3.0	Gy s^{-1}
Temperature	28	20-60	°C
Wavelength	1310	1310-1550	10^{-9} m
LightPower	40	10-250	10^{-6} W

III. FIBRE SELECTION PROCEDURE

A. *Sample collection and screening tests*

Twelve fibre manufacturers worldwide were contacted with the request to provide radiation tolerant single-mode fiber samples for the application. Ten manufacturers replied and six manufacturers eventually supplied CERN with a total of ten different samples for radiation testing. In some cases, the manufacturers provided technical details on the samples.

The screening tests (see Fig. 1) were conducted under well defined experimental conditions summarized in table I and followed a custom-made radiation protocol described in detail in [16].

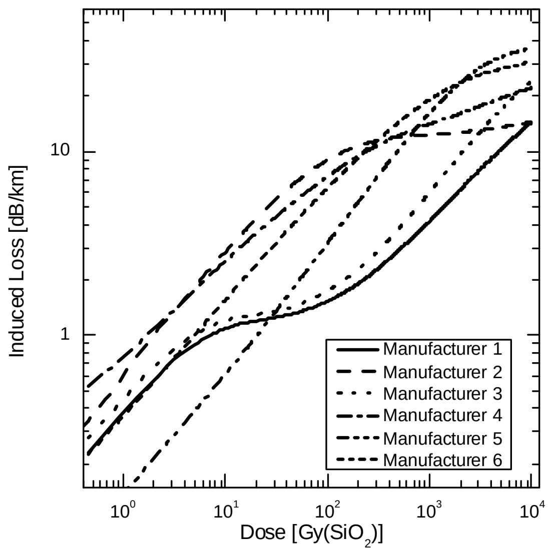

Fig. 1. Initial screening test results on the ten fiber samples from six different manufacturers under standard radiation conditions as defined in table I. The data show the RIA of light at 1310 nm up to a total dose 10 kGy (^{60}Co source).

B. *Detailed sample testing*

Fig. 2 shows the RIA of the best performing samples from two different manufacturers exposed up to 120 kGy at dose rates of 0.2, 1.4 and 3.0 Gy/s. Both fiber types are F-doped in the core and cladding but manufactured with different methods.

The attenuation in the sample from manufacturer 2 is slowly increasing as a function of dose and reaches rapidly the maximum of 7 dB/km at all three dose rates. However, for a given dose, the RIA is strongly reduced if the dose rate is lowered and the reduction in RIA is proportional to the square root of the dose rate.

The sample from manufacturer 1 is a single-mode fiber manufactured by Fujikura Ltd., Sakura, Japan with the product name RRSMFB Premium. The basic characteristics of this fiber can be found in [17]. This fiber shows a rather spectacular performance with a decrease of the attenuation at increasing dose. The RIA at 10 kGy remains well below the maximum of 7 dB/km specified in section 2 at all dose rates. Based on these results, it was decided to study the influence of the radiation field and the irradiation conditions on the RIA for this type of fiber.

In the screening test, the samples are exposed to gamma rays from a ^{60}Co source at a high but constant dose rate. In reality however, the fibres are exposed in a pulsed radiation field from high-energy physics (HEP) with different particle types and a different energy spectrum and at a very low dose rate.

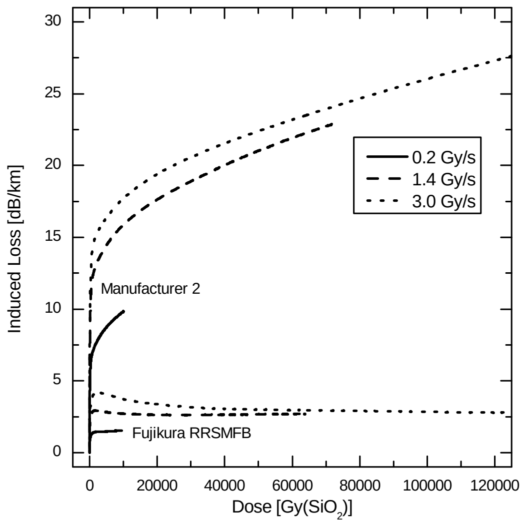

Fig. 2. RIA as a function in two different F-doped fiber samples from two manufactures irradiated at different dose rates of 0.2, 1.4 and 3.0 Gy/s using a ^{60}Co radiation source.

To address the first issue, the impact of atomic displacement was compared to that of ionization processes on the RIA in this fiber. For this purpose, the RRSMFB Premium fiber was exposed in a HEP radiation field for a period of almost 2 consecutive years [18] at very low dose rates (6x10^{-5} Gy/s and 2x10^{-4} Gy/s). The fluence to dose ratio in this radiation environment is typically 10^{9} neutrons.cm^{-2}.Gy^{-1} (energy threshold 20 MeV) and the 1 MeV equivalent neutron fluence is 10^{10} hadrons.cm^{-2}.Gy^{-1}.

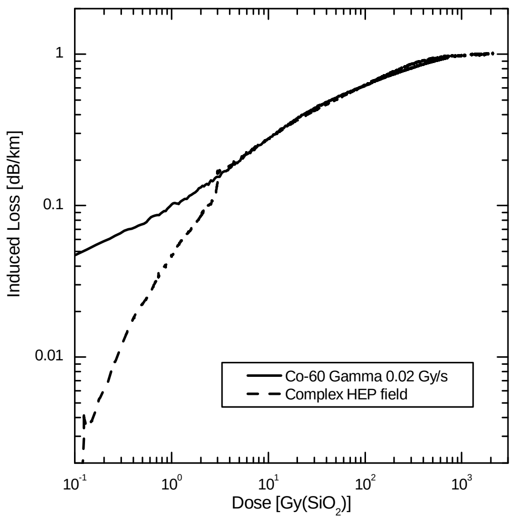

Fig.3. Comparison between RIA in the RRSMFB Premium fiber using gamma rays from a ^{60}Co source and exposure in a HEP radiation field similar to that of the operational environment in the LHC tunnel.

The RIA in the RRSMFB Premium fiber was measured on line and found to be almost identical to that from gamma ray irradiation with a ^{60}Co source at higher dose rate (see Fig. 3). This confirms other experimental observations [19], where the RIA was found to be dominated by radiolysis and proportional to the total ionizing dose. Although hadrons (predominantly neutrons) induce atomic displacement damage in the fibre, the effect on the RIA is very small because most of the interstitial-vacancies will effectively combine (approximately 97%).

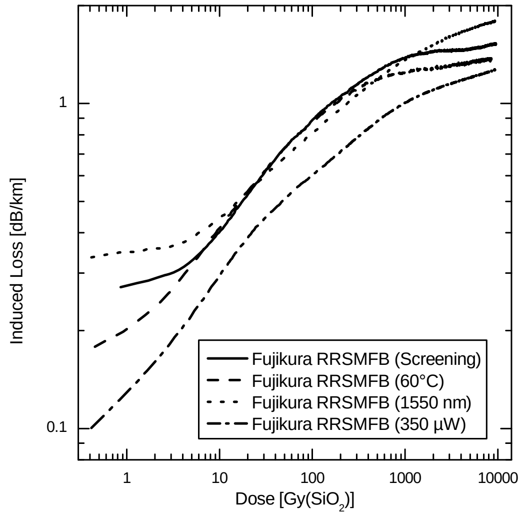

Fig.4. Impact on the RIA in the RRSMFB Premium fiber due to an variation of the temperature, wavelength or light power. The reference is a sample irradiated under the standard irradiation conditions during the screening test.

The second issue concerns the impact of the irradiation conditions. In [18], it was already shown that a small increase of the temperature (from 20°C to 60°C) or the light power (from 10 to 250 µW) does not have a significant impact on the RIA in this fiber type (see Fig. 4).

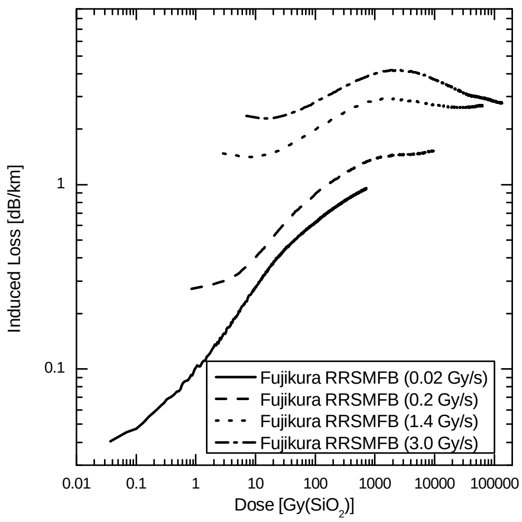

Fig.5. RIA as a function of dose rate in the RRSMFB Premium fiber (temperature 28°C, wavelength 1310 nm, lightpower 40 µW).

At dose rates above 10^{-4} Gy/s, dose rate effects can be observed which manifest themselves as an increase of the RIA for the same total dose when exposure is conducted at a higher dose rate. Consequently, the annealing rate after exposure is also influenced by the dose rate at which the irradiation was conducted.

Figure 5 shows the RIA in the RRSMFB Premium fiber as a function of the dose rate. For a total dose of 1 kGy, irradiation at 3 Gy/s leads to a threefold increase in the RIA as compared to an irradiation at 0.02 Gy/s. However, after an 8 hour annealing period at constant temperature, the RIA in both fiber samples is again almost equal (see Fig. 6) demonstrating that the concentration of permanent color defects both fibre samples after annealing is equal.

To finalize the study on the irradiation conditions in the RRSMFB Premium fiber, the effect of cyclic versus steady state irradiation was investigated (see Fig. 7). In this experiment, constant irradiation at a dose rate of 16 mGy/s is compared to cyclic irradiation at a maximum dose rate of 24 mGy/s, corresponding to an average dose rate of 16 mGy/s. Since the annealing of the RIA in the RRSMFB Premium fiber is almost nonexistent when irradiation is conduct at a low dose rate, the RIA quickly regains the same slope when irradiation is restarted. Indeed, after eight cycles and a total ionizing dose of 1 kGy, there is no significant difference in a global parameter such as the RIA between cyclic and steady state irradiation.

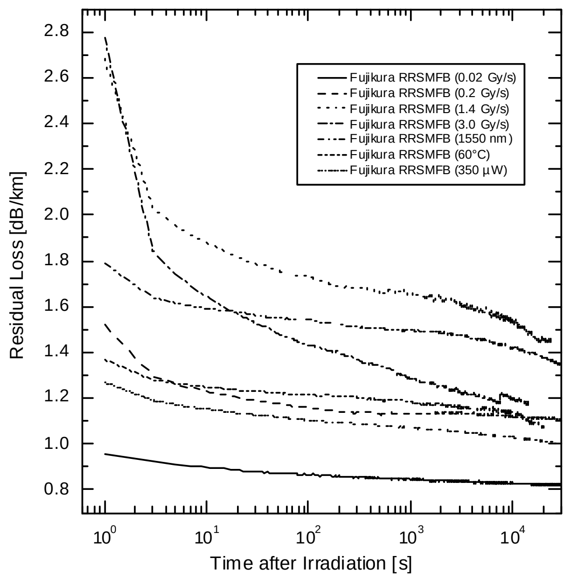

Fig.6. Annealing behavior of the RRSMFB Premium fiber samples shown in Fi.gs 4 and 5 as a function of time after irradiation.

From these experiments it was concluded that the beneficial effects of annealing for the application at hand can only be marginal and that, at sufficiently low dose rates, there is no fundamental difference between cyclic and continuous irradiation for this particular fibre.

These experiments confirm the findings in [18] (and references therein) that, in a HEP radiation environment, the attenuation of light at long wavelengths in the RRSMFB Premium™ fibre is only depended on the total ionizing dose to which the fibre was exposed and independent of the dose rate during the exposure. Furthermore, small variations of the temperature or the light power do not impact significantly on the RIA, at least up to a total dose of 1 kGy.

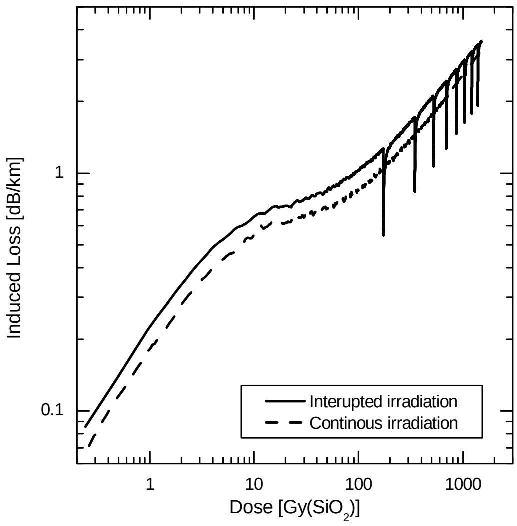

Fig.7. Comparison between cyclic and steady state irradiation of the RRSMFB Premium fiber using gamma rays from a ^{60}Co source (temperature 28°C, wavelength 1310 nm, lightpower 40 µW). The duty cycle for cyclic irradiation is 2 h exposure followed by 1 hour annealing.

Finally, the question arose at which total dose the RRSMFB fibre could be exposed before the attenuation of light at 1310 nm would exceed the requirements of the application at hand. This question is of relevance for future upgrades of the LHC collider when operated at higher intensities or when the mission duration is extended beyond 10 years. Hereto a single fibre sample was irradiated at a dose rate of 2.2 Gy/s to a total dose 4.6 x10^6 Gy.

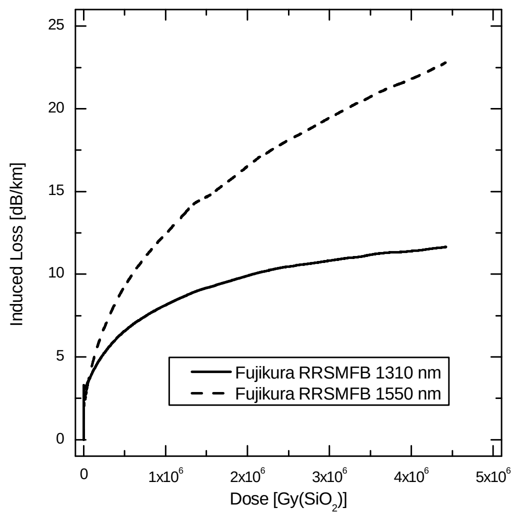

Fig.8. RIA at 1310 and 1550 nm as a function of the dose during irradiation of the RRSMFB Premium fiber at a dose rate of 2.2 Gy/s (^{60}Co source).

Although the RIA attenuation continues to increase with increasing dose, the limit of 7 dB/km attenuation is reached after a dose of 1x10^6 Gy which translates in safety factor of at least 10 for the application at hand.

IV. RADIATION EFFECTS

A. *Fluorine doping*

The RRSMFB Premium is an F-doped fiber with doping in the cladding and the fibre core. Fluorine doping is well known to improve the radiation hardness of optical fibres because of the large bonding energy between Si and F. The bonding energy of the silicon-fluorine bond is 582 kJ mol^{-1} and much higher than that of the silicon-oxygen bond (368 kJ mol^{-1}). The hard nucleophilic fluoride group can therefore be used to remove silicon groups with the driving force for the transformation being the formation of strong Si–F bonds.

Fluorine doping in the correct concentration of the core and cladding makes the silica fibre more radiation resistant because it reduces the concentration of defect precursors such as strained Si-O-Si bonds and impurity-related structures such as SiOH, SiCl and SiH. Other manufacturing techniques such as the fibre drawing tension and speed and minimizing the Chlorine concentration can also be used to reduce the precursor concentration.

Under radiation, the cleavage of an Si–O bond leads either to the production of a an *E'* center (≡Si·) and a non-bridging oxygen hole center (NBOHC, ≡SiO·) as in (1) or to the formation of an oxygen vacancy (≡Si-Si≡) and an interstitial oxygen atom (O^0) as in (2) [20]. (Here the three parallel lines represent the separate bonds and the dot the unpaired electron).

$$\equiv\text{Si-O-Si}\equiv \;\rightarrow\; \equiv\text{Si}\cdot + \cdot\text{OSi}\equiv \qquad (1)$$

$$\equiv\text{Si-O-Si}\equiv \;\rightarrow\; \equiv\text{Si-Si}\equiv + \text{O}^0 \qquad (2)$$

Formation of defect centers in silica containing Chlorine have been discussed in [21] and follow a reaction similar to (1):

$$\equiv\text{Si-Cl} \;\rightarrow\; \equiv\text{Si}\cdot + \text{Cl}^0 \qquad (3)$$

If the NBOHC interact with hydrogen, silanol (Si-OH) groups may be created via one of the following hydrogen cracking processes:

$$\equiv\text{SiO}\cdot + \text{H}^0 \rightarrow \;\equiv\text{Si-OH} \qquad (4)$$

$$\equiv\text{SiO}\cdot + \text{H}_2 \rightarrow \;\equiv\text{Si-OH} + \text{H}^0 \qquad (5)$$

Furthermore, there is the possibility that water molecules diffuse into the silica [22] and then break up at an O atom site of the lattice, resulting in the formation of two silanol groups:

$$\text{Si-O-Si} + \text{H}_2\text{O} \;\rightarrow\; 2\equiv\text{Si-OH} \qquad (6)$$

The formation of stable silanol groups is particularly important for this study because silanol has an optical absorption band at 1380 nm. Therefore, already in the production process (see below), it is important to use silica with a very low OH content that does not contain H_2.

The use of fluorine doping in the core and the cladding of the fibre in the correct concentration makes it possible to further reduce the silanol formation. Fluorine reduces the variations in the local bonding of the amorphous network by breaking up six member (and larger rings) with a small energy barrier, replacing them with particular strong SiF groups that have bonds which are very resistant to radiolysis.

In [23], it has been shown that is extremely important to precisely control the concentration of Fluorine in the core and cladding. When the concentration of Fluorine is too low, the relaxation of the lattice will be insufficient and silanol will still be produced following reactions mentioned here above. Too high Fluorine doping is equally counterproductive, probably because of the formation of silicon difluorides (=SiF_2) and structures with two adjacent SiF groups (=SiF-O-FSi=). Another explanation may be that the excessive Fluorine doping enhances the self trapping of holes and excitons [24] although no experimental evidence for this assumption exists.

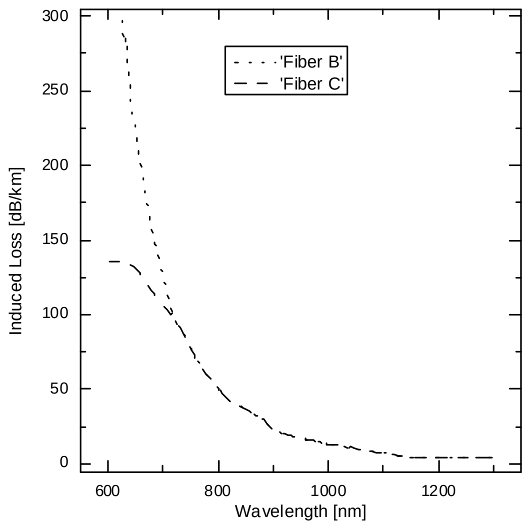

Fig.9. Comparing the RIA spectra for a fiber sample with low Fluorine doping in the core and cladding ('Fiber B') and high Fluorine doping in the core and cladding ('Fiber C'). The reduced attenuation of light at 630 nm in sample B is believed to be due to a lower concentration of NBOHCs (figure from [25], dose rate $1x10^5$ R/h, exposure time 30 minutes, ^{60}Co source).

The optimization process of Fluorine doping concentration in the RRSMFB Premium single-mode fiber has been described in detail in [23]. In this work, the RIA in two irradiated F-doped single-mode fibers with different doping concentrations in the core and cladding is compared (exposure at a dose rate of $1x10^5$ R/h for 30 min. with a ^{60}Co source). Figure 9 shows that the optical absorption at 630 nm is reduced in sample C which has a Fluorine content of 0.8wt% and 2.2 wt% in the core and cladding respectively against 0.2wt% and 1.6 wt% respectively in the core and cladding for sample B.

The reduction of the absorption at 630 nm in sample C is due to the more efficient suppression of NBOHCs which generate an optical absorption band at 630 nm and eventually lead to the formation of silanol [via (4) and (5)] with an optical absorption band at 1380 nm.

The dynamics of the formation and elimination process of silanol in the RRSMFB Premium single-mode fiber is rather complex and a detailed discussion on this subject is beyond the scope of this paper. However, it has been found that, under certain irradiation conditions, the formation and elimination rate of silanol is unbalanced resulting in rather unusual variations of RIA as a function of the dose. For example, the induced loss in the RRSMFB Premium single-mode fiber can actually *decrease* with *increasing* dose and the maximum RIA is not necessarily obtained at the maximum dose.

B. *Manufacturing process*

Among the key points of the manufacturing process of the RRSMFB Premium single-mode fiber are the dehydration process with Chlorine, the fluorine-doping concentration in the core and the cladding and the fiber-drawing speed and tension [23].

The core of the optical fiber preform is dehydrated with chlorine at a concentration of at least 0.01 ppm to reduce the OH content (the OH content of the core of this fiber is inferior to 1 ppm).

The Fluorine concentration in the fibre core is between 0.4 wt% and 1.2 wt% and the concentration in the cladding is between 1.6 wt% and 2.2 wt% giving rise to a relative refractive index difference of the core of the optical fiber preform based on the refractive index for the cladding of the optical fiber preform between 0.3 % and 0.5 %.

Furthermore, the drawing conditions of the fibre are optimized. The formation of defects and defect precursors is reduced when the drawing speed and the drawing tension are kept low. For the RRSMFB Premium single-mode fiber, the drawing speed is between 10 m per minute and 100 m per minute and the fibre drawing tension between 0.10 N and 0.4 N.

However, even at very low drawing speeds and drawing tensions, the thermal quenching process will still induce pre-cursors [5] and when the fiber is exposed to radiation, these pre-cursors will convert into color defects. If this conversion occurs on a timescale that is much shorter than that of the lattice relaxation process involving fluorine, large variations in the RIA may occur. This dose rate effect could explain the variations and spread in the induced loss observed at low doses (1 Gy or less) but high dose rates.

Apart from the RIA, other factors may have to be considered when selecting a specific value for the drawing tension or the drawing speed. A low drawing speed will result in a reduced production rate while a low drawing tension will reduce the ability to control the quality of the fibre. The latter may result in frequent interruptions of the drawing process when the fiber is not meeting the manufacturing specifications and the series production would consist of many short lengths of optical fiber.

C. *Quality assurance*

A rather tight Quality Assurance (QA) procedure was put into place to ensure that all fibres from the series production would have a similar performance under radiation as the samples that were tested in selection procedure. The QA procedure consists of exposing samples of each fibre perform under the following conditions : dose rate 1.6 Gy/s, temperature 28°C, wavelength 1310 nm, lightpower 40 μW, total dose 100 kGy. These tests are conducted using the standard fibre test protocol as defined in [16].

The manufacturer was therefore asked to deliver a 100 m long sample of each optical fiber preform that was used. The initial intention was test all 100 m samples that were received under radiation but when the production rate increased and the number of 100 m samples to be tested became too large, it was necessary to reduce the amount of fibres samples for radiation testing. Eventually, approximately one out of 3 (randomly picked) samples were exposed to a radiation dose of 100 kGy.

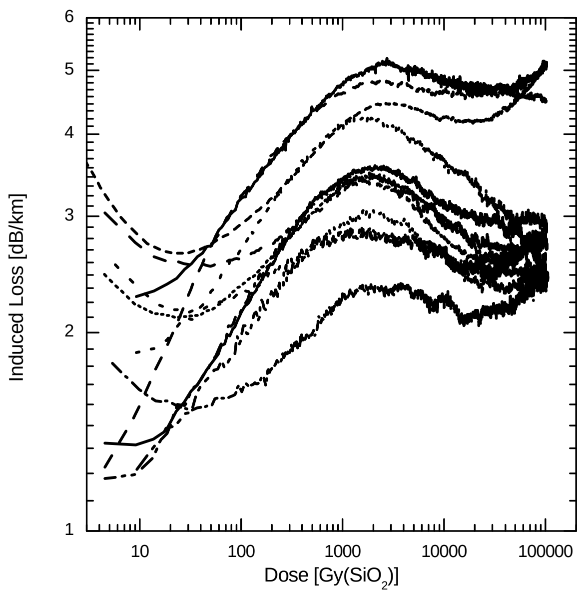

Fig.10. Comparing the RIA as a function of the total dose of randomly selected samples from the series production (dose rate 1.6 Gy/s, temperature 28°C, wavelength 1310 nm, lightpower 40 μW, total dose 100 kGy).

Fig. 10 shows the RIA as a function of dose in the samples that were taken from the series production. The irradiations are conducted at 1.6 Gy/s and dose rate effects as described in the previous section, are visible at the beginning of the irradiation.

Up to 100 kGy, the RIA in all fiber samples remains between 1 and 5 dB/km at 1310 nm which is well below the 7 dB/km at 100 kGy that was specified in section 2.

Above 10 kGy, three samples in Fig. 10 exhibit a significant higher induced loss as compared to the average. The production history of these samples was verified in detail in the factory checking the fabrication history of the core glass, the refractive index profile of the core and cladding, the variance of the relative refractive index difference, the fluorine doping of the core (refractive index profile, spectral differences), the drawing conditions and the spectrum of non irradiated parts of the same fiber. Unfortunately, none of these investigations provided a clear indication why the RIA in these fibers is significantly different as compared to the other samples that were produced under identical conditions.

D. *Series Production*

The series production of the RRSMFB Premium single-mode fibers started in October 2006. Until December 2006, some 500 km of optical fiber were delivered at an average production rate of approximately 200 km per month. For the first 500 km of fibre, the standard length on the spools was initially only 6 km making the cable manufacturing from the bare fibres more complicated. The fibers of the series production were coated with the standard UV cured acrylate resin coating.

In order to increase the quantity of fibre kilometers per month, the ITU-T G.652.B [11] constraint for the attenuation of light at 1310 nm in the pristine (unirradiated) fibre was relaxed from 0.4 dB/km to 0.6 dB/km. The increase in the acceptance margin allowed increasing both the fiber production per month and the standard length on the spools. In August 2007, the total of 2500 km of optical fiber had been delivered to CERN.

V. Fibre Installation

A. *Microduct Cabling Technique*

For the installation of the RRSMFB Premium single-mode fiber cables, the flexible and cost effective microduct cabling technique was chosen which also facilitates modifying the optical network at a later point in time. The microduct cabling technique consists in using a pressurized viscous flow of air in high density polyethylene (HDPE) ducts to push the cable into the ducts [26]. Rather than a large cable with hundreds of fibres, three to ten small ducts at a time are pulled into a protective conduit. A thin fiber-optic cable with a maximum of 24 individual fibers is then blown into each of these ducts.

The general contractor for the LHC project, Draka Comteq Telecom B.V. from Gouda in the Netherlands conducted the coloring and the cabling of the RRSMFB Premium single-mode fibers. Draka Comteq then operated in close collaboration with Mauerhofer & Zuber SA to install the 2500 km of radiation hard fibre cable in the underground tunnel. Throughout the installation of the entire optical network for the LHC project, Draka Comteq improved the blowing capacity of fibre optic cables gradually to reach 3100 meters of cable per hour.

B. *Radiation Hardness of cables and ducts*

Two final issues needed to be addressed to validate the installation of the radiation tolerant fibers with the microduct cabling technique. After accumulating a dose of 100 kGy of ionizing radiation:

- The fiber cables should still resist the pulling force and it should be possible to replace the fiber cable in the duct with the same microjetting technique and the lubrificated microducts.
- HDPE ducts should resist to the maximum pressure of 14 bar that may be required to blow fiber cables in or out of the ducts over long distances.

To address the first point, two complete drums with 1 km each of pristine cable ducts were each filled with a 24 fiber untitube cable using an air pressure of 8 bar. Under these conditions, the jetting speed as a function of distance was constant at 90 m/min. After irradiation to 3.6 kGy, the irradiated fiber cable was jetted out at 7 bar air pressure. A pristine unitube cable was jetted in at an air pressure of 8 bar reaching an almost constant velocity of 90 m/min from which it could be concluded that, up to 3.6 kGy, radiation damage does not increase the pushing force as defined in [13] and [26].

To address the second point, HDPE cable ducts samples were irradiated according to the IEC60544 and ISO 37 standards. The exposure was conducted in air to account for decomposition reactions with the radiation-induced reactive state of the polymers. The experiments were carried out a high dose rate (1 kGy/hr) and at room temperature. This accelerates potential diffusion limited oxidation effects and chemical dose rate effects (CDRE). Although not very common, CDRE caused by the slow breakdown of hydro peroxide intermediate species in the oxidation reaction has been found in low-density polyethylene materials [27].

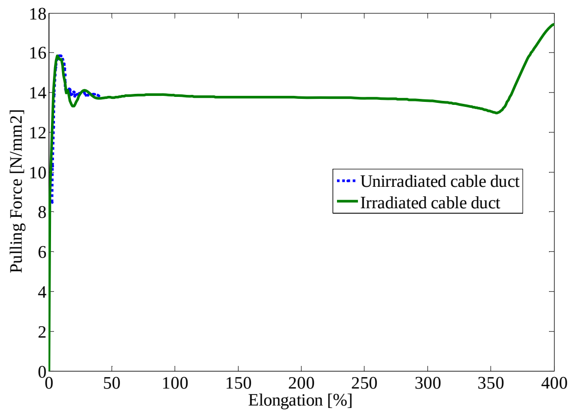

Fig.14. Elongation stress test of a pristine HDPE cable duct and a HDPE cable duct irradiated at 1 kGy/hr to a total dose of 330 kGy (gamma rays from a ^{60}Co source).

A total of eight duct samples were irradiated to a total dose of 330 kGy at a dose rate of 1 kGy/hr with gamma rays from a ^{60}Co source and then submitted to an elongation test (DIN 20257 standard) using the elongation at break as an end point criterion (see Fig. 11). The acceptance criteria used at CERN are specified as 50% of the initial value or 100% absolute value at the specified absorbed dose both of which were fulfilled by the HDPE ducts. The tests showed furthermore that the tensile stress at yield for an irradiated cable duct is almost identical to that of the pristine one.

VI. Summary and Conclusions

An extended survey of the radiation hardness of single-mode optical fibers was conducted. For the long wavelengths of interest to the telecommunication industry, the RRSMFB Premium single-mode fiber from Fujikura Ltd. was found to have an exceptional low RIA up to dose of 4.6 MGy of ionizing radiation. The RIA in these specialty fibers is dominated by radiolytic processes, the impact of atomic displacement is of minor importance and this was confirmed in a two year long exposure in a radiation area, almost identical to that of the application.

The manufacturing of the fibers is a delicate process where drawing tension and speed are feedback controlled and where the fluorine doping concentration of the core and cladding must be kept within well-defined limits. Small deviations of the optimized production parameters can results in large variations of the RIA at doses of 100 kGy or higher, although it is not always possible to trace back this deviation to a manufacturing parameter. Quality assurance of the series production is, therefore, strongly recommended.

The RRSMFB Premium single-mode fiber from Fujikura Ltd. can be installed over long distances (3 km or more) with the microduct cabling technique developed by Draka Comteq Telecom B.V. This technique can be used when the microducts and cables have been exposed to low levels of radiation (3.6 kGy), higher levels may also be possible although this has not yet been confirmed with experimental data.

Finally, the constructive collaboration between industry and research institutes has been a key element to the success.

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