exail

Fiber Optic Radiation Sensing

Unlocking advanced architectures for radiation monitoring

1 Introduction

Dosimetry relates to the measurement of the Total Ionizing Dose (TID) or dose rate in radiative environments. Knowing accurately the total dose and/or dose rate is essential in many applications like nuclear, high-energy physics, space and medical applications from a human safety perspective, for process control and for instrument safety.

Several types of dosimeters are widely available such as ionization chambers, semiconductor detectors (silicon diode detectors, RADFETs), or dosimeters based on thermoluminescence (TLD) and optically stimulated luminescence (OSL). Each technology of dosimeter offers its own set of characteristics in terms of sensitivity, type and energy or particles that can be detected, directivity, degradation over time, live or post-irradiation reading, form factor and price. An in-depth review of the most usual dosimetry technics and some key metrological considerations are presented in [1].

"At a macroscopic level, two main effects dominate when an optical fiber is exposed to radiation: Radiation-Induced Attenuation (RIA) and Radiation-Induced Emission (RIE)"

Optical fibers are sensitive to radiation, like most electronic and optical components. At a macroscopic level, two main effects dominate when an optical fiber is exposed to radiation: Radiation-Induced Attenuation (RIA) and Radiation-Induced Emission (RIE).

At a microscopic level, ionizing radiation generates point defects in the silica matrix of the optical fiber. The nature of these point-defects is related to the fiber's composition, and extensive work has been devoted to mapping all the point defects associated with undoped SiO_2 as well as those associated with dopants such as Germanium (Ge), Fluorine (F), and Phosphorous (P). Optically active point defects can for our purpose be classified into two categories:

- Light-**absorbing** point defects, which contribute to the Radiation Induced Attenuation
- Light-**emitting** point defects, which contribute to the Radiation Induced Emission

Figure 1: Left, representation of Radiation Induced Attenuation (RIA) with the gradual darkening of a fluorophosphate glass exposed to radiation [2]. Right, Radiation Induced Emission (RIE) resulting in light being emitted and guided by an optical fiber exposed to radiation (courtesy of B. Brichard, SCK-CEN).

"Fiber-based dosimetry on the other hand leverages either RIA or RIE to retrieve the total ionizing dose (RIA dosimetry) or dose rate (RIE dosimetry) from an optical measurement performed with a radio-sensitive fiber"

While most optical fibers exhibit some RIA and RIE, these effects are undesired for most applications and usually kept to a minimum.

Fiber-based dosimetry on the other hand leverages either RIA or RIE to retrieve the total ionizing dose (RIA dosimetry) or dose rate (RIE dosimetry) from an optical measurement performed with a radio-sensitive fiber. Radio-sensitive fibers are tailored optical fibers developped to show enhanced sensitivity to radiations and good dosimetry properties, such as a linear response. This technical note delves into the main properties of fiber-based dosimetry, an approach that also leverages the well-known advantages of optical fibers, such as its low-volume and weight, its immunity to EM interference, good overall radiation resistance and the possibility to use the fiber as a distributed sensor.

2 RIA dosimetry

RIA dosimetry relies on the evolution of the fiber's radiation-induced attenuation as a function of the Total Ionizing Dose (TID). At a microscopic level, the radiation induced attenuation originates from absorbing point defects, also known as color centers, created in the silica matrix by incoming ionizing radiation. The nature of the color centers and their associated optical absorption bands strongly depends on the chemical composition of the core and cladding of the optical fiber [3]. Figure 1 below shows the absorption bands, and the structure of the corresponding point defects associated with a Phosphorous-doped optical fiber.

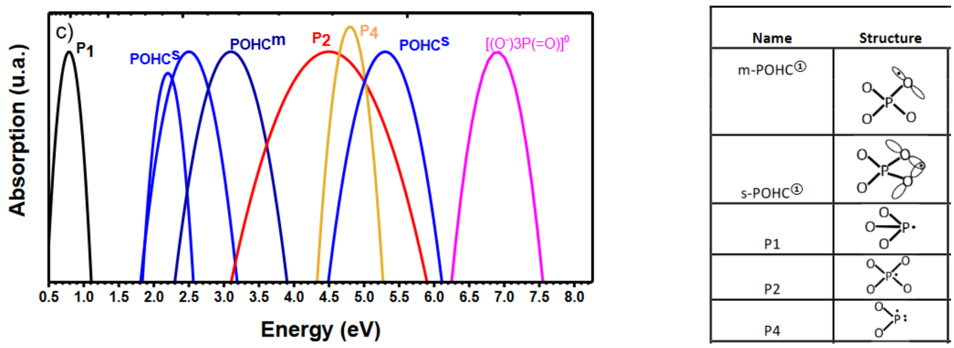

Figure 2 : Left : absorption bands of different types of color centers for a Phosphorous-doped optical fibers, from [3]. Right : structure of different types of point defects found in P-doped optical fibers, from [4].

RIA dosimetry requires the RIA to increase monotonously with the total dose to be able to retrieve the TID level unambiguously from the RIA. If the radio-sensitive fiber has a linear response, the RIA can be expressed as a function of the fiber's sensitivity, fiber length and total dose.

$$RIA_{(dB)} = Sensitivity_{(dB/km/Gy)} \, . \, Length_{(km)} \, . \, Dose_{(Gy_{(SiO2)})} \tag{1}$$

The same equation can be used to calculate the dose level (TID) from the measured RIA, knowing the sensitivity and length of radio-sensitive fiber used. RIA dosimetry does not strictly require a linear response, just a monotone response, but working in the linear region greatly simplifies the calibration and calculations. The actual fiber's response will usually deviate from the ideal linear response beyond a certain dose level, showing a saturation effect that can for example be seen in Figure 5 beyond 500 $Gy_{(SiO2)}$.

The influence of external parameters such as temperature and dose rate on the fiber's response should be carefully evaluated, the ideal radio-sensitive fiber should have a response independent of the temperature and dose rate, two physical parameters which are in general unknown and not necessarily constant over time. In addition, the RIA should remain constant when the irradiation stops (no recovery effect) and should not be affected by the probe signal used for the measurement (no photobleaching effect).

"The ideal RIA radio-sensitive fiber should have a response independent of the temperature and dose rate"

It is key to realize that the radiation induced attenuation is very much wavelength dependent, and that the RIA response at a given wavelength is intrinsically related to the properties of the microscopic point defect(s) that contribute to the optical absorption at this wavelength. As a result, a radio-sensitive fiber may exhibit excellent dosimetry properties at one wavelength but a very different behavior at other wavelengths, because the point defects at play are different. Each wavelength of interest should therefore be investigated independently to validate key characteristics such as the radiation sensitivity, linearity, temperature and dose rate dependance, recovery and photobleaching effects.

With RIA dosimetry, the gradual darkening of the radio-sensitive fiber under radiation ultimately results in a completely opaque fiber. When the optical attenuation exceeds the dynamic range of the interrogation system, the RIA and dose level can no longer be measured, and the photosensitive fiber must either be replaced, or the RIA recovered for example using photobleaching [5].

"With RIA dosimetry, the gradual darkening of the radio-sensitive fiber under radiation ultimately results in a completely opaque fiber"

The following paragraph details the use of the IXF-RAD-SENSE-SM-1550 fiber, a Phosphorous-doped optical fiber developed specifically for dosimetry applications around 1550 nm (0.8 eV) where the RIA originates from the P1 defect, as shown in Figure 2. Aluminum-doped fibers have also been developed for dosimetry in the visible wavelength range to offer an increased radiation sensitivity compared to P-doped fibers. The principles and guidelines discussed in this technical note also apply to Al-doped fibers such as the IXF-RAD-SENSE-HI fiber.

2.1 IXF-RAD-SENSE-SM-1550

Exail offers a family of radio-sensitive optical fibers for dosimetry applications, including the IXF-RAD-SENSE-SM-1550 fiber which is designed for RIA dosimetry around 1550 nm. This radio-sensitive fiber is a Phosphorous-doped single mode fiber available with acrylate and polyimide coating, with a pristine optical loss ≤ 2 dB/km at 1550 nm.

"The IXF-RAD-SENSE-SM-1550 is a Phosphorous-doped radio-sensitive fiber designed for RIA dosimetry around 1550 nm"

Figure 3 : Left: cleave of a IXF-RAD-SENSE-SM-1550 radio-sensitive fiber designed for RIA dosimetry around 1550 nm.

In the 1450 – 1650 nm wavelength range, the RIA originates from the so-called P1 defect related to the Phosphorous atoms under ionizing radiations. The spectral dependance of the P1 defect is shown in the insert of Figure 5 and Figure 7. This radio-sensitive fiber has been extensively studied by the LabH6 (Exail's joint laboratory with Jean Monnet University in France) and by CERN. The IXF-RAD-SENSE-SM-1550 has been progressively deployed to monitor the radiation level along several of CERN's accelerator rings: Proton Synchrotron Booster (157 m), Proton Synchrotron (628 m), Super Proton Synchrotron (6911 m), and more recently the Large Hadron Collider (7 km).

The IXF-RAD-SENSE-SM-1550 fiber exhibits a linear response with a sensitivity of 4 dB/km/Gy$_{(SiO2)}$ at 1550 nm and a linear response up to ~500 Gy$_{(SiO2)}$. The RIA response has also been evaluated at different temperatures and over 7 decades of doses rates between 21 µGy$_{(SiO2)}$/h [6] and 3600 Gy$_{(SiO2)}$/h [7], showing little dependance to these two parameters. The IXF-RAD-SENSE-SM-1550 fiber has also been exposed to atmospheric neutrons at Triumf [8], 480 MeV protons [9], and mixed fields within the CHARM facility at CERN [10] showing a repeatable sensitivity of 4 dB/km/Gy$_{(SiO2)}$ at 1550 nm, independent of the particle type.
In addition, the batch-to-batch repeatability of the fiber's sensitivity was evaluated in [11] and showed an excellent repeatability, as can be seen in Figure 7.

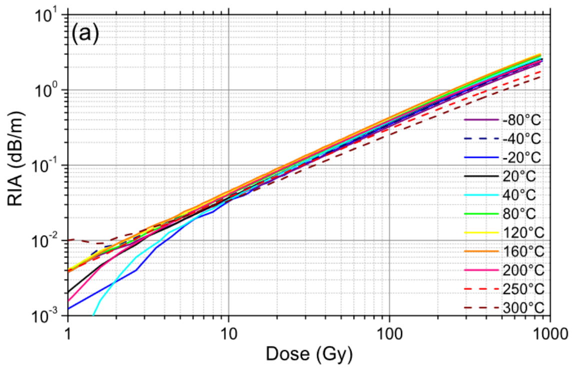

Figure 4 : RIA for different temperatures (@1 Gy/s), from [2]. ±15 % variations of RIA are observed across -80 °C / +120 °C.

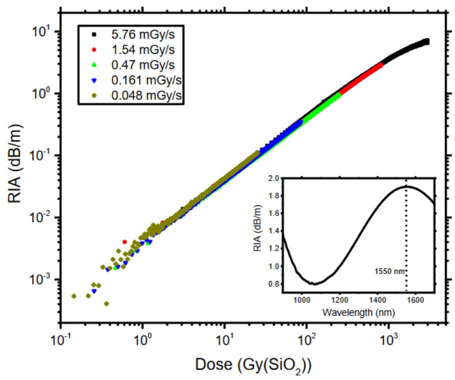

Figure 5 : RIA versus dose measured for different dose rates under ^{60}Co gamma rays, from [9].

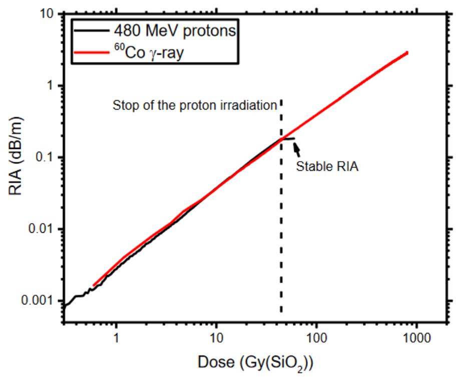

Figure 6 : RIA as a function of the Total Ionizing Dose for ^{60}Co gamma rays, and 480 MeV protons, from [4].

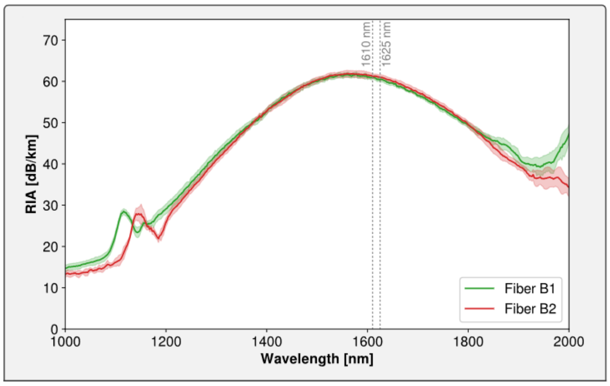

Figure 7 : Comparison of the spectral RIA of 2 fibers manufactured from 2 different preforms for a TID of 12.9 Gy$_{(SiO2)}$, showing an excellent batch to batch repeatability, from [11].

The IXF-RAD-SENSE-SM-1550 is primarily intended to be used around 1550 nm where its radiation response has been extensively evaluated. The availability of optical components such as optical sources and detectors designed for operation around 1550 nm also greatly facilitates the development of dosimetry systems in the 1450 – 1650 nm wavelength range. The RIA response tends to deviate from the ideal 4 dB/km/$Gy_{(SiO2)}$ linear response beyond 500 $Gy_{(SiO2)}$ where a saturation effect becomes visible. If one solely wants to work in the linear regime, this sets the maximum acceptable TID. It is also possible to use the radio-sensitive fiber beyond 500 $Gy_{(SiO2)}$ within the saturation region: the reduced sensitivity of the fiber at higher dose can greatly extend the system's lifetime with a decrease in measurement accuracy which tends to become more acceptable at higher doses.

Probing the IXF-RAD-SENSE-SM-1550 fiber using a wavelength on the edge of the P1 defect, such as 1310 nm, can help to reduce the fiber's radiation sensitivity if necessary while keeping the valuable characteristics of the P1 defect for dosimetry applications.
The IXF-RAD-SENSE-SM-1550 radio-sensitive fiber can also be used at shorter wavelengths to reach increased sensitivities, the wavelength dependance of the sensitivity is shown in [12]. A coil of P-doped radio-sensitive fiber was for example used as part of the Lumina project at 638 nm to reach an increased sensitivity of 137 dB/km/$Gy_{(SiO2)}$ [6], compared to 4 dB/km/$Gy_{(SiO2)}$ at 1550 nm, although the dosimetry properties in the visible are not as good as around 1550 nm.

"Photobleaching experiments performed on the IXF-RAD-SENSE-SM-1550 fiber have shown that the fiber's attenuation after irradiation can be recovered to its pristine value using high power visible light"

Finally, photobleaching experiments performed on the IXF-RAD-SENSE-SM-1550 fiber have shown that the fiber's attenuation after irradiation can be recovered to its pristine value using high power visible light [5], opening the way to reusable sensors.

2.2 Point & distributed sensing

The radio-sensitive fiber at the heart of an RIA-based dosimetry system can be simply coiled and packaged as a point sensor.

Alternatively, the radio-sensitive fiber can be deployed along a facility or an area of interest to have a distributed radiation measurement along the length of the fiber, with the use of an adequate interrogator. The radio-sensitive fiber will usually need to be cabled to be more robust and prevent any risk of mechanical failure.
The multi-point configuration is somewhat an intermediate approach between the point and distributed architectures, with several point sensors cascaded in series one after another.

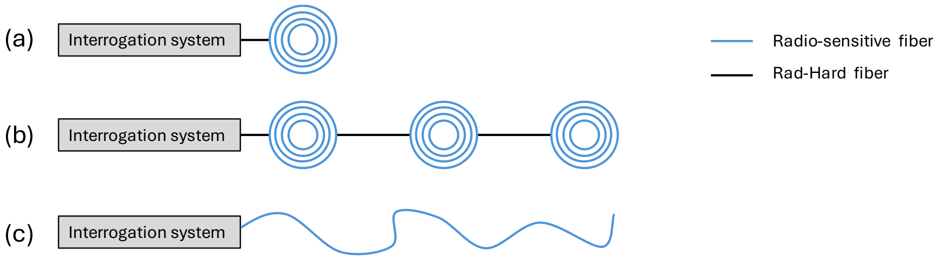

Figure 8 : Point (a), multi-point (b), and distributed (c) architectures.

The table below details the type of interrogation system possible for each architecture:

	Point	Multi-point	Distributed
CW source + detector	✓	✗	✗
Distributed interrogator (OTDR, OFDR)	✓	✓	✓

"The multi-point and distributed architectures must use a distributed interrogator to spatially resolve the optical loss along the fiber length"

The multi-point and distributed architectures must use a distributed interrogator to spatially resolve the optical loss along the fiber length. Optical reflectometers such as OTDR [8], [13] and OFDR [14] have already been used for fiber dosimetry experiments and can be used as distributed interrogators for point, multi-point and distributed configurations.

The distributed architecture can span several hundred meters and truly leverages the possibilities offered by optical fibers compared to other dosimetry technologies. A distributed Fiber Optic Radiation Sensing (DFORS) system can provide a 1 m spatial resolution with a measurement time of the order of 1 minute (temporal resolution) effectively replacing dozens or hundreds of point sensors with near real-time data acquisition and processing [9], [10], [15], [16], [17].

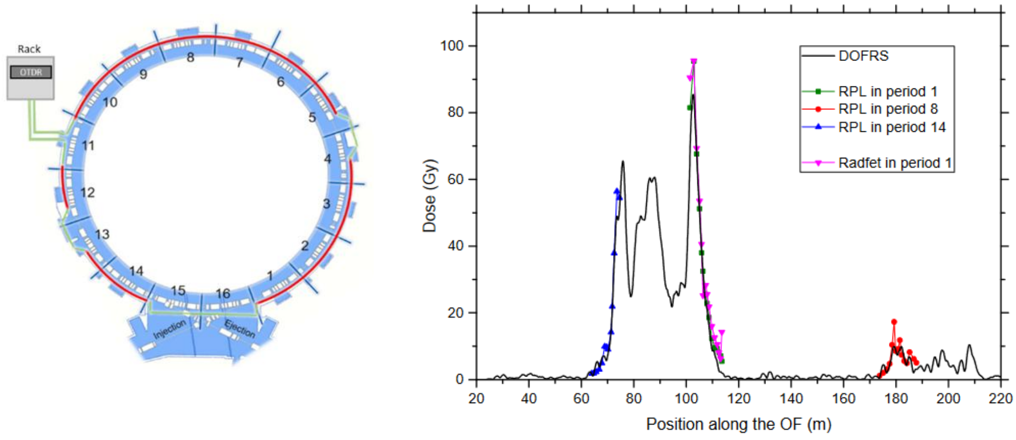

Figure 9 : Left: representation of the distributed radiation sensing architecture used at CERN with the IXF-RAD-SENSE-SM-1550 deployed around the Proton Synchrotron Booster (PSB), with an OTDR interrogator. Right: comparison of the dose obtained from RPL dosimeters positioned along the SBS, and from the distributed optical fiber radiation sensing (DOFRS) system in solid black line, from [15].

“Distributed Fiber Optic Radiation Sensing (DFORS) enables spatially resolved radiation measurements and truly leverages the advantages of optical fibers, in the same way as distributed temperature sensing (DTS), distributed strain sensing (DSS) or distributed acoustic sensing (DAS)**”**

Distributed Fiber Optic Radiation Sensing (DFORS) enables spatially resolved radiation measurements and truly leverages the advantages of optical fibers, in the same way as now widely deployed sensing methods such as distributed temperature sensing (DTS), distributed strain sensing (DSS) and distributed acoustic sensing (DAS).

2.3 Design guidelines

As often, it is useful to start with the expected requirements such as radiation sensitivity, sensor’s lifetime, spatial and temporal resolution. These estimates enable to quickly check the feasibility of measuring the expected dose level and provide some preliminary information regarding the most suitable configuration: point, multi-point or distributed.
It is worth noting again that RIA-based dosimetry is inherently a TID measurement, dose rate can only be accessed via a time derivative of the TID.

For a point configuration, the RIA can be estimated easily for different lengths of radio-sensitive fiber and dose levels using Equation 1. Increasing the length of sensing fiber increases the RIA proportionally and therefore increases the sensitivity of the sensor, but this comes at the expense of the sensor’s lifetime. Equation 1 uses the dose deposited in silica, expressed in $Gy_{(SiO2)}$. If this value is not available, it can be estimated for photons from the dose deposited in water (Figure 7 from [1]) or more generally from the particle type, energy and fluence using the simulations performed in [18].

"While the length of radio-sensitive fiber determines the expected RIA for a given dose, it is critically important to also ensure that this loss can be accurately measured by the interrogation system considered"

While the length of radio-sensitive fiber determines the expected RIA for a given dose, it is critically important to also ensure that this loss can be accurately measured by the interrogation system considered. Indeed, the overall performance of the dosimetry system strongly depends on the interrogator being used to measure the RIA, as the performances in the optical domain in terms of measurement noise or dynamic range directly affect the calculated radiation level, derived from the optical measurement.

For distributed interrogators, benchtop and OEM OTDRs are for example available from Viavi Solutions, with a dynamic range of typically 6 to 8 dB for the OEM versions. A detailed analysis of the metrology of several commercially available OTDR is available from [11], providing useful data for the dimensioning of dosimetry system using a distributed interrogator. OFDR interrogators can also be used but tend to be more of a laboratory instrument intended to measure shorter fiber lengths, while being pricier than OTDRs. The use of a micro-OTDR from Viavi solutions for multi-point dosimetry is for example detailed in [13].

For point dosimetry, interrogators using a continuous wave (CW) source and powermeter can achieve much higher dynamic ranges, typically beyond 60 dB, with noise levels of just a few mdB. These interrogation systems can also be very compact and cost-effective but are limited to point sensing configurations.

One should then consider more closely the optical budget, with on one side the characteristics of the interrogator, and on the other side the expected radiation level and progressive darkening of the radio-sensitive fiber due to the RIA. One key aspect of the point and multi-point configurations is the possibility to define the length of radio-sensitive fiber, to adjust the sensitivity of the sensor to the expected radiation level. For a given dose level, the RIA increases linearly with the length of radio-sensitive fiber and therefore can be more easily measured for longer lengths of fiber. However, this quicker increase of RIA also means a reduced lifetime, so there is a compromise to find between sensitivity and sensor's lifetime. Spools of a few tens or hundreds of meters of radio-sensitive fiber can be easily manufactured as small point sensors of diameter 6-8 cm.

With a fully distributed configuration, the radio-sensitive fiber is deployed and therefore there is no possibility of increasing the radiation sensitivity by locally increasing the length of radio-sensitive fiber, as with the point and multi-point configurations. Radio-sensitive fiber with an increased radiation sensitivity exists, for example using Aluminum doping, but the operating wavelength tend to be in the visible range, making the design of the interrogation system more challenging, especially for multi-point and distributed configurations that usually rely on commercial distributed interrogators designed for NIR operation.

3 RIE dosimetry

RIE dosimetry relates the dose rate from the flux of photons emitted by Radiation Induced Luminescence (RIL) from a radio-sensitive fiber. As such, it provides real-time dose rate information, as well as the TID information by integration.

An RIE-dosimetry system consists of 3 elements, shown schematically in Figure 10.

1. A scintillating material or radio-sensitive optical fiber
2. A delivery fiber that transports the emitted photons
3. A high sensitivity photodetector for photon-counting

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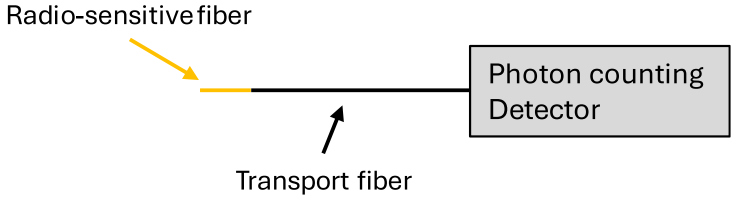

Figure 10 : representation of a RIE-based dosimetry system. The radio-sensitive fiber (typically a few cm long) is shown in orange, and the transport fiber (up to several tens of meters) in black.

The thickness of the scintillating material or length of radio-sensitive fiber determines the spatial resolution of the sensor. Radio-sensitive fibers doped with Nitrogen [19], Ce^{3+} Cerium ions [19] and Gd^{3+} Gadolinium ions have been investigated in the literature. Some of the key characteristics of a RIE radio-sensitive fiber are its emission wavelength (usually in the UV-Visible range), the photon generation yield, stability of the response for a constant dose rate, and linearity with the dose rate. Despite being relatively short, some level of RIA within the radio-sensitive fiber may affect the radio-sensitive's fiber response over time as the TID increases.

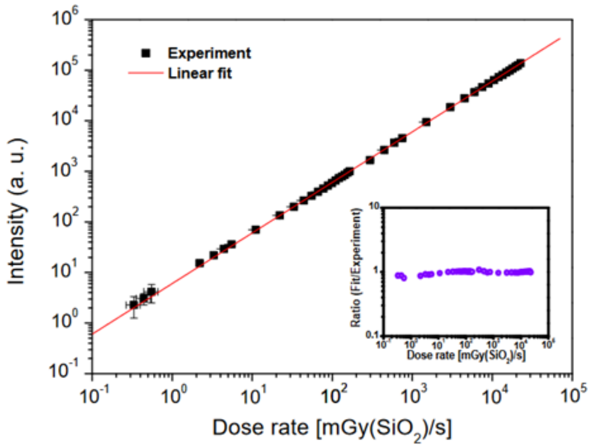

Figure 11 : RIE intensity as a function of dose rate for a Ce^{3+} doped fiber, from [19].

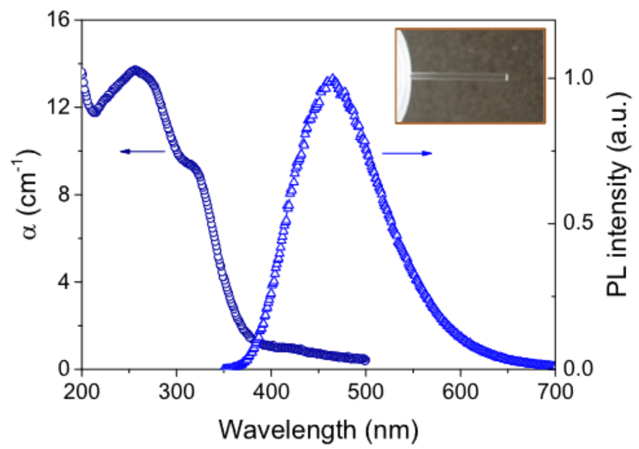

Figure 12 : Optical emission of Ce^{3+} ions (in light blue, right scale) under 351 nm laser excitation, showing the 460 nm emission wavelength of Ce^{3+} ions, from [20].

RIE-dosimetry relies on photon-counting and is an absolute measurement. The complete dosimetry system must therefore be calibrated to account for effects such as the photon coupling efficiency between the radio-sensitive and transport fiber, the optical loss of the transport fiber, and the detection efficiency of the detector. In addition, the generation of photons by Cherenkov effect (a phenomenon appearing when a charged particle moves in a dielectric medium with a speed greater than the speed of light in that medium) may affect the overall system's response and should be either calibrated or compensated.

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Step-index multimode fibers are widely used as transport fiber thanks to their large core (105 µm, up to several hundreds of µm) and high numerical aperture of 0.22, enhancing the photon collection efficiency. These multimode fibers are well-suited to transport signals in the lower part of the visible spectrum with minimal loss. The emission wavelength of the radio-sensitive fiber or scintillating material depends on its composition, for example 460 nm for Ce^{3+} Cerium ions, 550 nm for Nitrogen doping, and 314 nm for Gd^{3+} Gadolinium ions. Some RIA should also be expected within the transport fiber: the use of a fiber that has been tested under radiation by the fiber manufacturer can greatly help in estimating the RIA at the wavelength and TID of interest. Finally, the transport fiber should preferably be cabled with an opaque jacket to prevent the detection of ambient photons.

RIE dosimetry has been shown to cover a wide range of dose rates, from 0.1 $Gy_{(SiO2)}$/h up to extreme dose rates of 40 $Gy_{(H2O)}$/s found in proton therapy [19] and 10^9 Gy/s for ultrashort X-ray pulses [21].

4 Dosimetry system

A complete dosimetry system requires a radio-sensitive fiber assembly, an interrogation system, and calibration. Together with long-terms partners and the LabH6 joint laboratory, Exail has been involved in the design and manufacturing of dosimetry systems such as the Lumina [12], [22] and GlowRIA dosimeters to increase the maturity and technology readiness level of fiber-based dosimetry systems.

Lumina is a fiber-based dosimeter developed in partnership with the CNES, Hubert Curien laboratory (Jean-Monnet university) and CERN to monitor the radiation level inside the International Space Station [6]. Lumina was put into service inside the ISS in August 2021 and sends back radiation information to this day, providing a large data set from which crossings of the South Atlantic Anomaly (SAA) and solar particle events could be detected [12].

"Exail works closely with the LabH6 joint laboratory (Jean Monnet University) to be at the forefront of fiber-based dosimetry"

Exail works closely with the LabH6 joint laboratory (Jean Monnet University) to be at the forefront of fiber-based dosimetry. Recent advances also focus on simulation tools such as Geant4 to better quantify the dose deposited within the fiber's core as a function of the particle type and energy [18], while also taking into consideration the geometry of the fiber assembly (e.g fiber coil) and complete system with its packaging.

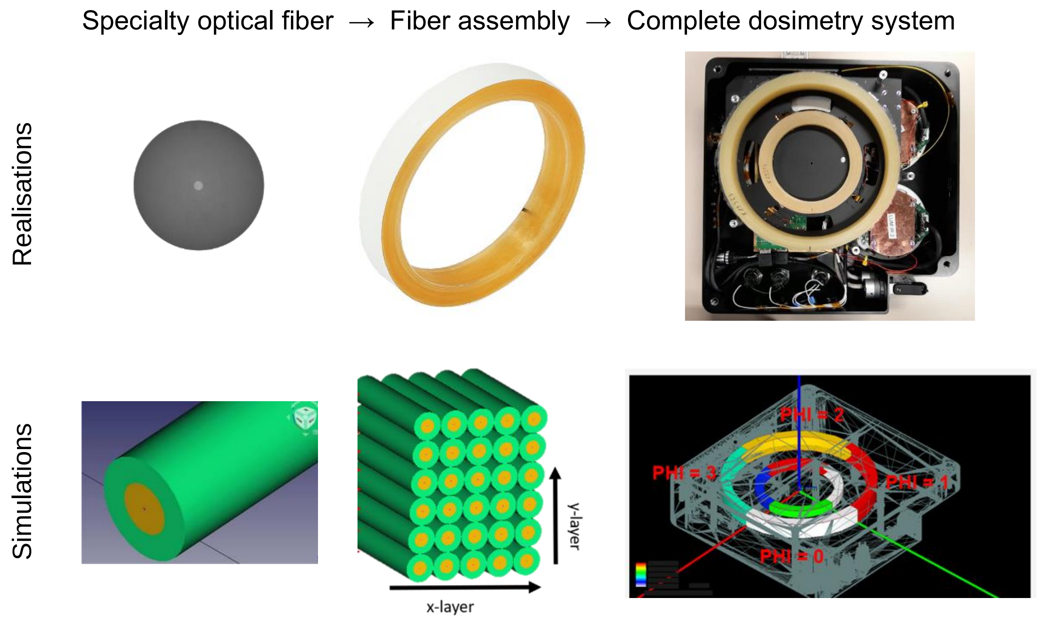

Figure 13 : From fiber to fiber-assembly and complete dosimetry system, Exail develops innovative solutions for fiber-based dosimetry. Exail's LabH6 joint laboratory can simulate the dose deposition at the fiber level, fiber assembly level and complete system's level using Geant4.

5 Conclusion

This technical note details the use of specialty optical fibers for dosimetry applications, also known as Fiber Optic Radiation Sensing (FORS). RIA-based dosimetry has been extensively studied in literature and is now a mature technology, for example deployed at CERN to monitor radiation leakage along the particle beams. It leverages the use of Phosphorous-doped fibers which have a linear dependance of the RIA with the Total Ionizing Dose (TID). RIE-based dosimetry on the other hand uses scintillating materials which emit photons under radiation, with a flux of emitted photons proportional to the dose rate. RIA and RIE dosimetry are two distinct fiber-based dosimetry technics which offer complementary solutions to address diverse radiative environments and requirements.

"Fiber-based dosimeters can provide valuable advantages for certain use cases such as the ability to easily deport the interrogation system away in a radiation-safe zone, and the possibility of having a distributed architecture with meter-scale spatial resolution"

Fiber optic radiation sensing is still a relatively novel approach compared to other technologies such as TLD or ionization chambers that have been used for decades. Fiber-based dosimeters nevertheless can provide valuable advantages for certain use cases such as the ability to easily deport the electronic interrogation system away in a radiation-safe zone, and the possibility of having a distributed architecture with meter-scale spatial resolution, effectively replacing dozens or hundreds of point sensors with a single sensor with a live reading.

Exail is committed to further develop these technologies through projects and collaborations to bring innovative solutions to demanding dosimetry applications and needs, please feel free to contact us for more information.

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