Phosphosilicate Multimode Optical Fiber for Sensing and Diagnostics at Inertial Confinement Fusion Facilities

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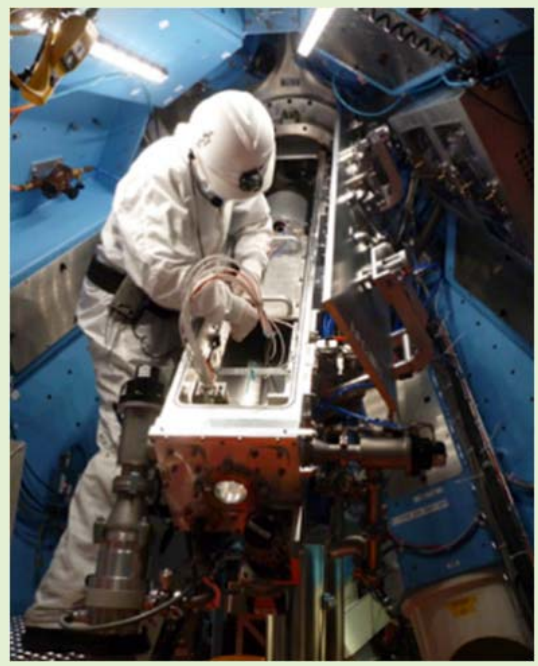
***Abstract*—We characterized the radiation response in the visible domain of a new multimode graded-index (GI) phosphosilicate optical fiber (GIMMF), exposed to the harsh environment (pulses of 14-MeV neutrons, X-rays, and γ-rays) associated with laser experiments at the OMEGA facility. The growth of permanent radiation-induced attenuation (RIA) was measured in situ after a series of laser shots involving a large production of 14-MeV neutrons (yields > 10^{14} n per shot). RIA linearly increases with accumulated neutron fluence without recovery between shots. The obtained results allow a precise evaluation of this GIMMF vulnerability when implemented as part of laser or plasma diagnostics. Our work also reveals the potential of this class of optical fiber to serve as a radiation monitor in the radiation-rich mixed environments of megajoule class laser facilities and to provide a very fast and online estimation of the accumulated deposited dose at various locations of their experimental halls. In our experimental test configuration at OMEGA, 14-MeV neutrons are estimated to contribute to about 55% of the total deposited dose on the fibers, and the other optical losses are related to X-ray and γ-ray contributions. Those measurements could be, for example, benchmarked to the radiation maps obtained by Monte Carlo simulation tools, potentially facilitating the evaluation of the aging of diagnostics, components, and systems as well as their maintenance operations.**



***Index Terms*— Dosimetry, fusion, neutrons, optical fibers, radiation effects, radiation-induced attenuation (RIA).**

I. Introduction

MEGAJOULE lasers are major components of the programs devoted to the study of nuclear fusion by inertial confinement (FIC). Using 351-nm lasers, these facilities, located either in France (Laser Mégajoule, LMJ [1]) or in the USA (National Ignition Facility, NIF [2]), are able to focus up to a few MJ of ultraviolet (UV) laser light on a volume of a few mm^3 reaching such a high energy density that Deuterium–Tritium (D–T)-filled glass microballoon implosion experiments can be performed. These experiments induce electromagnetic perturbations and radiation constraints consisting of a pulse mixing X-rays, 14-MeV neutrons, and γ-rays [3]. Within the experimental hall of the facilities, all the equipment (laser and plasma diagnostics [4] and control

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command links [5]) will be exposed to these radiations. Being generally more robust than microelectronics, the optical fiber technology presents several advantages for integration in these facilities, such as their immunity to most of the electromagnetic perturbations associated with these experiments [6], [7], [8]. Numerous studies have been conducted to evaluate the vulnerability of commercial telecom-grade optical fibers for control-command applications at telecommunication wavelengths [6], [9], but also on more advanced fiber designs for the diagnostics which need to operate in the UV and visible domains. Some of these challenges concern the plasma and laser diagnostics designed to characterize the time shape of the transient signals related to fusion experiments [1]. Due to the very short times to be considered (typically less than 1 ns), specific waveguides with low dispersion properties are required to enable high-precision measurements for some of the laser diagnostics. It is not possible to operate the laser diagnostic with single-mode (SM) optical fibers that could overcome the dispersion issue. Indeed, to be SM in the UV, the fiber core diameter needs to be very small (typically below 3.5 μm). Such a small core size strongly limits the injected laser power and prevents its temporal characterization. Then, the laser diagnostics requirements imply the use of multimode optical fibers having large-size cores [10], [11]. The first consequence of this specification is that the "radiation-hardened" pure-silica-core fibers with their step-index profiles, leading to large dispersion, are inadequate candidates for such specific applications, while they can still be used for energy diagnostics [14]. For the laser diagnostics, we then have to use multimode optical fibers with graded-index (GI) refractive-index profiles allowing us to reduce the dispersion impact on the measurement quality.

In the past, a phosphosilicate multimode optical fiber was developed in Russia for such applications and is today implemented in some of these facilities [8], [9]. More recently, an alternative fiber of the same category has been developed by iXblue (France), with a core size of 250 μm, meeting the very specific requirements associated with the laser diagnostics in terms of dispersion at 351 nm and has been implemented at LMJ in France. Up to now, the aging of candidate optical fibers was evaluated using several radiation test facilities in order to partially reproduce the environment: pulsed X-ray machines for dose rate effects, 14-MeV neutron accelerators, and γ-ray sources for steady-state characterization of ionization and displacement damage effects [4], [12]. In this work, we characterized for the first time the response of the GI phosphosilicate optical fiber (GIMMF) from iXblue in a radiation environment directly representative of FIC facilities. The obtained results enable a better estimation of fiber aging with respect to the profile of use at these facilities. Furthermore, our results show that this fiber could also provide an in situ monitoring of the deposited ionizing dose in the experimental hall of these facilities and facilitate the survey of the aging of diagnostics, components, and systems as well as their maintenance operations.

II. Experimental Procedure

A. Tested Graded-Index Multimode Optical Fiber

The fiber under test (FUT) is a graded index multimode fiber (GIMMF) with a core diameter of 250 μm, a cladding diameter of 300 μm, and an acrylate coating. It has been

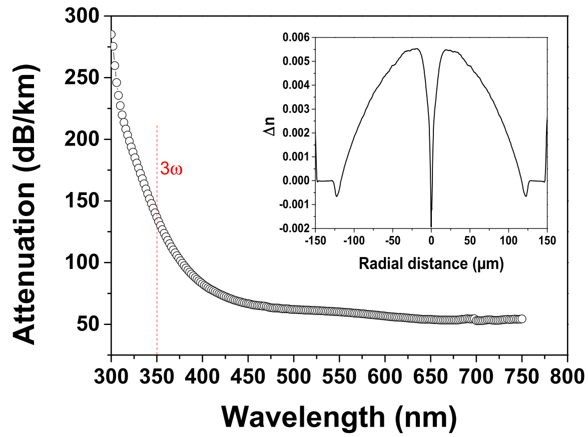

Fig. 1. Illustration of the spectral dependence of the GIMMF attenuation before irradiation. Inset illustrates the GIMMF refractive-index profile (measured at 631 nm).

manufactured by iXblue [13] through the modified chemical vapor deposition (MCVD) process. Its refractive-index profile has been chosen to achieve minimal dispersion at 351 nm (or 3ω), the operating wavelength of the laser diagnostics of megajoule class lasers, such as NIF or LMJ. Furthermore, this fiber should also provide low attenuation levels ($<$0.2 dB/m) at this wavelength and over the whole visible domain, a requirement fulfilled by selecting the phosphorus dopant to tailor the glass refractive index. Both the fiber refractive-index profile, measured at 631 nm with an interferometric fiber analyzer, and the attenuation curve of the GIMMF before irradiation, obtained by a cut-back analysis, are illustrated in Fig. 1.

B. OMEGA Facility Tests

The experiment was conducted at the OMEGA facility of the Laboratory for Laser Energetic (LLE), University of Rochester, New York, USA [14]. The maximum laser energy on OMEGA is 30 kJ, but it produces enough 14-MeV neutrons and other radiations as in MJ laser facilities at much higher shot rates. Therefore, it is a more convenient and less expensive facility for diagnostic development and equipment tests. The experimental setup selected for the characterization of the GIMMF is schematically illustrated in Fig. 2. The FUT has been placed inside the CEA Vulnerability Diagnostic Target Insertion Module (CEA-VD TIM) together with experiments devoted to the radiation characterization of CMOS image sensors [15]. The TIM is inserted within the OMEGA Target Chamber (see the figure in the abstract), aligned with respect to the DT target, and then placed under a vacuum. A 10-m-long sample of the GIMMF has been coiled and placed at a distance of 37 cm from the DT target. Small fiber pigtails, made of radiation-hardened optical fibers (polymicro solarization resistant multimode optical fiber, see [16]), have been spliced to the FUT and used to transport the signal from and up to the vacuum feedthroughs (cutting the transmission below 400 nm) connecting the TIM to the rest of the acquisition chain.

All the measuring equipment were located at La Cave, the instrumentation zone below the experimental hall. Ge-doped MMF 30-m-long pigtails were used to connect the light source and the detector to the TIM. These fibers are known to present a lower radiation sensitivity than phosphosilicate optical fibers (at least by a factor of 10 around 400 nm, higher at longer wavelengths [17]) and are exposed to low neutron flux. It can then be considered that the

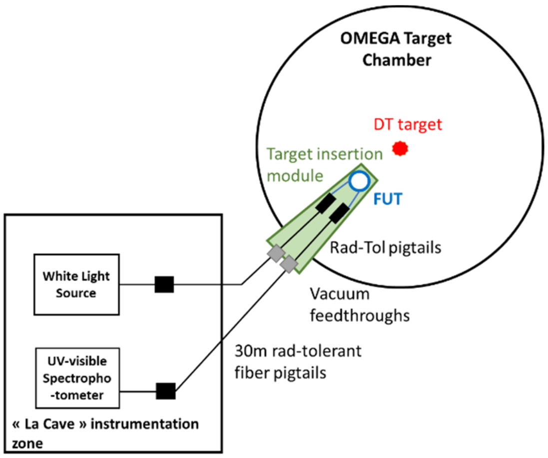

Fig. 2. Illustration of the experimental setup built to characterize the radiation response of the phosphosilicate GIMMF during the neutron experiments at the OMEGA laser facility.

radiation-induced attenuation (RIA) from these transport fibers is negligible with respect to one of the 10-m-long P-doped FUTs. We used the DH2000 white light source from Ocean Optics and the HR4000 spectrophotometer (integration time set at 1 or 2 s) from the same manufacturer to record the spectral (400–900 nm) and time evolutions of the transmitted signal before ($P(\lambda, t_0)$), during and after the shot: $P(\lambda, t)$. It should be noted here that due to the fact that we have our FUT inside the TIM under vacuum, we had to use vacuum feedthrough devices that limit the transmission to wavelengths above 400 nm. At OMEGA, we cannot then access the UV RIA values as it is usually done at other facilities (such as the X-ray machine at LabHC) where we operate in the air and then are not concerned by this limiting component.

The RIA can then be calculated using (1), considering the noise of our acquisition chain $N(\lambda)$ (measured before each shot with the light source is OFF)

$$\mathrm{RIA}\,(\lambda, t) = -\frac{10}{l}\log\left(\frac{P\,(\lambda, t) - N\,(\lambda)}{P\,(\lambda, t_0) - N\,(\lambda)}\right). \tag{1}$$

During the test campaign, a series of 14 shots have been conducted at room temperature using targets making it possible to reach neutron yields (Y) as high as 10^{14} neutrons per shot. It is possible to calculate the neutron fluence deposited on the fiber, knowing its distance d from the source via the following equation:

$$F = \frac{Y}{4\pi d^2}. \tag{2}$$

The equivalent dose D in Gy(SiO_2) deposited by 14-MeV neutrons in the P-doped silica core can be estimated using the conversion factor given in (3), which was calculated using Geant4 [18], [19], for our particular fiber geometry and composition

$$D = \frac{F}{10^{11}}. \tag{3}$$

The main characteristics of the performed experiments are listed in Table I. No RIA data were obtained for shots n°6 and n°8 during which we tried to acquire more information on the observed radiation-induced emission (RIE). All the 14 shots have been done in one day, with typical delays between the shots of 30 to 60 min.

TABLE I

Review of Shot Characteristics and Equivalent Dose Deposited in the GIMMF

Shot number	Ref. Shot LLE	Yield (n)	Fluence (n/cm²) on FUT	Dose (Gy) on FUT from 14 MeV n
1	93837	1.45×10^{14}	8.43×10^{9}	0.084
2	93838	1.73×10^{14}	1.01×10^{10}	0.101
3	93841	8.75×10^{13}	5.09×10^{9}	0.051
4	93842	1.73×10^{14}	1.01×10^{10}	0.101
5	93844	1.85×10^{14}	1.08×10^{10}	0.108
6	93845	1.75×10^{14}	1.02×10^{10}	0.102
7	93846	1.82×10^{14}	1.06×10^{10}	0.106
8	93847	1.86×10^{14}	1.08×10^{10}	0.108
9	93848	1.82×10^{14}	1.06×10^{10}	0.106
10	93849	1.75×10^{14}	1.02×10^{10}	0.102
11	93850	1.80×10^{14}	1.05×10^{10}	0.105
12	93851	1.77×10^{14}	1.03×10^{10}	0.103
13	93852	1.72×10^{14}	1.00×10^{10}	0.100
14	93853	9.74×10^{13}	5.66×10^{9}	0.057

The neutron fluences received by the FUT are very large, comparable with those achievable with a $Y = 4 \times 10^{16}$ neutrons at a distance of 6 m from the source, typical for plasma or laser diagnostics at NIF or LMJ. At the end of the experiments, the accumulated dose on the FUT associated with the 14-MeV neutrons was $\sim$1.33 Gy(SiO_2) (or 133 rad). It is important to remind that this calculated dose level does not contain the contributions from the X-rays and γ-rays that are also present in the successive pulses. It is known that 90% of the dose is generated during the first 370 ns of the experiment, and the dose rate, initially at a high level, drops rapidly to a negligible level [20]. Typical equivalent dose rates above 10^6 Gy/s are then associated with such OMEGA laser experiments.

III. Experimental Results

In this section, we summarize the data acquired during the neutron experiments, showing the impact of each laser shot on the signal transmission in the GIMMF and quantifying its degradation versus the neutron fluence (or equivalent dose).

A. Radiation Effects on the GIMMF

Fig. 3 illustrates a typical result observed during one of the shots. Before exposure to the mixed pulse, the transmission of the fiber is stable. The laser shot is associated with the detection of two different phenomena.

The first one is the RIE that is in this case certainly related to Cerenkov emission [21] in our multimode fiber induced by the 14-MeV neutrons, since no radioluminescence is usually observed in phosphosilicate glass [22]. This RIE is detected only when the shot occurs during a spectrum acquisition. It is, therefore, not present in all our results as sometimes, the shots occur between two successive spectrophotometer acquisitions. Unfortunately, this was the case during shots 6 and 8, for which we switched OFF the white light source but were not successful in recording the RL. In any case, the Cerenkov emission could be an issue for laser and plasma diagnostics if no mitigation techniques, such as filtering or adjustment of the time profile measurements, are used.

The second effect is the RIA, which is clearly observed for all laser shots. After irradiation, the fiber is darkened due to the generation of point defects and in the case of the P-doped

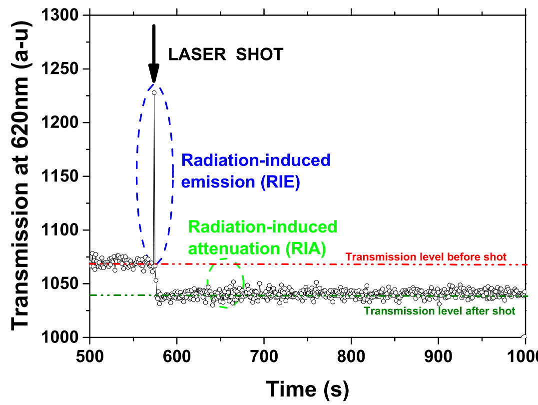

Fig. 3. Illustration of a typical response of the GIMMF to a laser shot. Both radiation-induced emission (RIE) and radiation induced attenuation (RIA) phenomena can be observed.

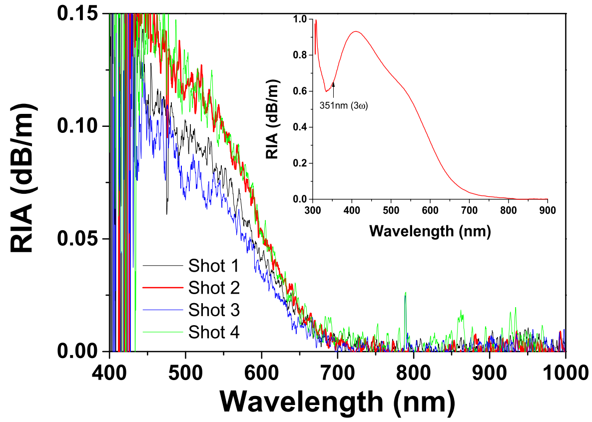

Fig. 4. Illustration of the RIA measured just after the first four laser shots of the neutron experiments. Reported RIA values are those corresponding to each shot, not accumulated RIA versus shot. Inset illustrates a typical RIA spectrum measured under steady-state X-rays at dose of 1 Gy.

optical fibers, it is known that the RIA is large, quite stable at room temperature, and caused by P-related point defects [23]. In this spectral domain, losses are mainly explained by the contribution of the phosphorus-oxygen hole centers (POHCs) whose properties have been studied in a number of previous studies [17], [24].

B. Spectral Dependence of the RIA

Fig. 4 illustrates the RIA spectra measured during the first four shots on the 10-m-long sample. The observed RIA spectral dependence is typical of the ones measured for a variety of P-doped optical fibers under transient or steady-state exposures, with loss levels as high as 0.15 dB/m at shorter wavelengths. The inset of Fig. 4 reports the RIA spectrum measured at a dose of 1 Gy during a steady-state X-ray irradiation of the same fiber. From this measurement, we can see that RIA usually increases up to 400 nm and then decreases a little before increasing again around 300 nm. This is today well explained by P-related defects, the POHC (stable and metastable forms) absorption bands explain the visible RIA above 400 nm, while below the losses are resulting from a contribution of both the POHC absorption tails and the optical absorption band of the P2 defect [18], [25]. It is interesting to note that operation at 351 nm (3ω laser wavelength), of major interest for laser diagnostics, does not represent the worst case scenario compared with plasma diagnostics that could have to

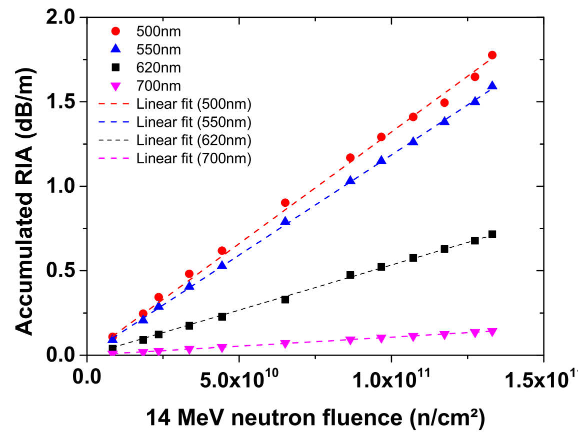

Fig. 5. Illustration of the RIA dependence on the accumulated 14-MeV neutron fluence at four different wavelengths (500, 550, 620, and 700 nm) during the successive laser shots. Dashed lines are the best linear fits of these experimental data with the law RIA(λ, D) = $a_\lambda \times F$, F being the neutron fluence as provided by the LLE diagnostics. $a_{500\text{ nm}} = 1.32 \times 10^{-11}$; $a_{550\text{ nm}} = 1.18 \times 10^{-11}$; $a_{620\text{ nm}} = 5.34 \times 10^{-12}$; and $a_{700\text{ nm}} = 1.06 \times 10^{-12}$ dB m^{-1} n^{-1} cm^2.

operate in a larger spectral domain covering both the UV and visible ranges.

C. 14-MeV Neutron Fluence Dependence of the RIA

As a consequence of the RIA, the fiber transmission decreases shot after shot, potentially reducing the lifetime of plasma or laser diagnostics based on such fiber. To estimate these cumulative effects, we plotted in Fig. 5 the evolution of the RIA at four different wavelengths [500, 550, 620, and 700 nm] as a function of the neutron fluence accumulated shot after shot. The fluence was calculated knowing the neutron yields of the successive laser shots (given in Table I) and through (1) and (2). It is clear from these results that the RIA (in dB/m) linearly increases with the 14-MeV neutron fluence at the following rates: $a_{500\,\text{nm}} = 1.32 \times 10^{-11}$; $a_{550\,\text{nm}} = 1.18 \times 10^{-11}$; $a_{620\,\text{nm}} = 5.34 \times 10^{-12}$; and $a_{700\,\text{nm}} = 1.06 \times 10^{-12}$ dB m^{-1} n^{-1} cm^2.

These acquired data are very useful as they allow for estimating the lifetime of the fibers implemented at ICF facilities and predicting the aging of the fibers in the visible domain for a given profile of use and implementation design. Typically, the optical losses expected around 351 nm should range between the ones measured at 500 and 550 nm. It also shows that the degradation of the fibers may be used to monitor the facility radiation environment and this will be more deeply investigated in Section IV.

IV. Discussion

The OMEGA experiments allow a direct characterization of the vulnerability of the GIMMF to the complex mixed environments of fusion-devoted facilities. It is also interesting to compare these results to those obtained through more usual radiation tests with X-rays or γ-rays. To achieve this, we compare the transient radiation response of this GIMMF to its response to steady-state X-ray irradiation. In Fig. 6, we compare the RIA growth kinetics at four wavelengths as a function of the equivalent dose related to the sole contribution of the 14-MeV neutrons [obtained through (3)] and to the 40-keV X-ray deposited dose. The X-ray tests were performed using the 100-kV X-ray machine at the University

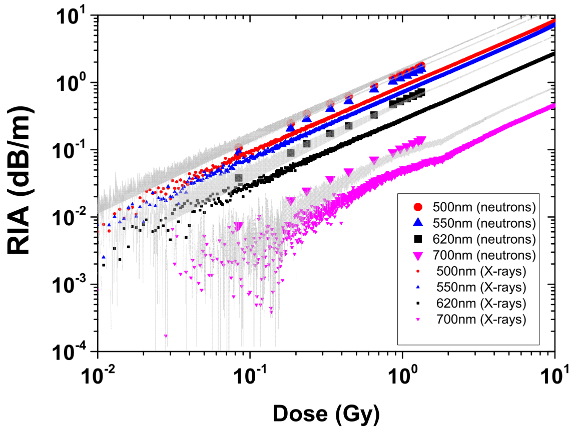

Fig. 6. Comparison between the RIA equivalent dose (provided by the 14-MeV neutrons) dependences of RIA measured at Rochester (data of Fig. 5) at four different wavelengths with the RIA X-ray dose dependence measured during steady state X-ray irradiation (500 μGy/s, RT) at the same wavelengths. In gray, the steady-state results are multiplied by an arbitrary factor of 1.8 to fit the transient data.

of Saint-Étienne, at room temperature and with a dose rate of 500 μGy(SiO_2)/s. RIA spectra were measured using the same experimental setup as for OMEGA tests. As shown in Fig. 6, despite different particle types and about 12 orders of magnitude in terms of dose rate, the RIA levels are quite comparable. In fact, the RIA measured at OMEGA is 1.8 times larger than the ones measured under X-rays (the gray curves of Fig. 6 are the raw data multiplied by this factor).

We do not expect this 1.8-factor difference to be explained by the relative contributions of ionization and displacement damages between X-rays and neutrons [26]. Indeed, it is today well established that the RIA response of the fibers is mainly driven by ionization processes and this was clearly shown for this class of fibers in the visible domain previously [27], [28], and more recently in the infrared domain with atmospheric neutrons [29], [30]. This difference can arise from two main causes, between which our experiments cannot easily distinguish. The first one could be a slight dose rate dependence of the RIA at 620 nm. It is known that in this spectral domain, the phosphosilicate fiber presents good dosimetry properties, so small dose rate dependence [31] but here the difference between dose rates is especially high (typically 12 orders of magnitude). The second reason, that is contributing for sure, is that in addition to the equivalent dose deposited by the 14-MeV neutrons, we should also consider the dose deposited on our fiber samples by the X-rays and γ-rays associated with the OMEGA shots. Due to the complex architecture of the TIM, it was not possible to calculate exactly this contribution.

V. Conclusion

In this article, we investigate at the OMEGA laser facility the response of a multimode graded-index phosphosilicate fiber (GIMMF), manufactured by iXblue, with low dispersion properties in the UV-visible domain, exposed to the pulsed mixed environment associated with fusion ignition shots, mainly associated with 14-MeV neutron, X-ray, and γ-ray constraints. Our results show that in the UV-visible range of wavelengths (500–800 nm), the RIA levels measured 1 s after the shots linearly depend on the neutron fluence, with a maximum growth rate of 1.32×10^{-11} dB m^{-1} n^{-1} cm^2 at 500 nm. The obtained results offer a clear view of the vulnerability of this new optical fiber that is used in the design of laser or plasma diagnostics at megajoule class laser facilities. Interestingly enough, despite about 12 orders of magnitude in terms of dose rate, the RIA levels measured under steady-state X-rays are close (a factor of 1.8) to the ones measured under transient exposures. This factor can be at least partially explained by the contribution of X-rays and γ-rays to the induced losses. This demonstrates that the more usual steady-state X-ray or γ-ray irradiations are an efficient tool to assess the transient vulnerability of this class of optical fibers to the mixed pulsed environment of these laser facilities. Moreover, the obtained results showed that it should be possible to use the response of this class of phosphosilicate optical fibers in the visible domain to monitor the radiation dose inside the facilities, to better estimate the aging of the implemented systems. This response could also, as done recently at CERN [23], be used to benchmark the results of Monte-Carlo simulation codes and their associated radiation maps. Depending on the fiber profile of use, the induced losses can be too high to ensure the operation of the diagnostics during the whole facility's lifetime. Work is thus in progress to develop a radiation-hardened version of this GIMMF with a fluorine-doped core in order to improve its radiation hardness.

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