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Optical properties of scintillating materials for high resolution dosimetry using FLUKA and data

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Abstract. Experimental work and Monte Carlo simulations using FLUKA were conducted to try to quantify cross-talk effect between adjacent scintillating optical fibers mounted as a ribbon. Ultraviolet LEDs peaking at 385 nm were used to illuminate the isolated fibers and ribbons of fibers with diameters of 1 and 0.5 mm. The response was compared between 0.5 mm and 1 mm fibers with and without different collimators at the exit end, and between isolated and ribbons of fibers for the same diameter. Preliminary simulations were done with a 2 MeV electron beam (emulating a Sr-90 source) irradiating a 1 mm fiber. A good agreement with the experimental data. However, it was not yet possible to produce an evaluation of the cross-talk effect for the fiber arrangement as a ribbon.

Keywords: optical fibers, scintillation, dosimetry

1 Introduction

1.1 Motivation

The LIP's Dosimetry research group is involved in projects with the purpose of developing a dosimeter capable of measuring energy depositions in sub-millimetric volumes using scintillating plastic optical fibers (SPF). The cells would be placed in a plate over the surface of a ribbon of fibers, as in figure 1, in order to measure with high resolution and in real time the dose given to colonies of cells.

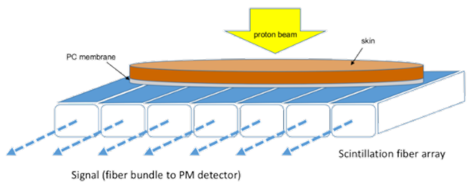

Figure 1. Schematic representation of the dosimeter.

During this internship the goal was to quantify the cross-talk effect between adjacent fibers. If the fibers are to be placed side by side there could be unwanted light transferred from one fiber to its neighbors. Monte Carlo simulations using FLUKA were developed and experimental measurements using the fibrometer at LOMaC/LIP were made in order to measure in separate the amount of light transferred between optical fibers and the impact on a measured signal.

Last year, a master student from the Universidade NOVA de Lisboa, developed her thesis [1] with this group, designing using FreeCAD [2], with the collaboration of the LIP Mechanical workshop, a new setup to hold and illuminate the fibers at the fibrometer (XT-Table). The XT-Table requires a set of LEDs to illuminate different fibers at a fixed distance from a photodetector and the more adequate LEDs were chosen from different sets of UV LEDs existing at the LOMaC/LIP. The XT-Table was assembled in the fibrometer and a few set of measurements were made in order to adjust the correct parameters for the XT-Table in the control software (LabVIEW^{TM}) and in the hardware settings. The work done during the internship started by reviewing these first data sets and in making the first direct comparisons of the different fibers mounted on the XT-Table.

1.2 The Fibers

The fibers used were Kuraray SCSF-78 (figure 2). These fibers are characterized by having three distinguishable transparent regions, a core and two claddings. The plastic scintillator core is made of doped polystyrene (PS), the internal cladding is made of polymethyl methacrylate (PMMA) and the external one of a fluorinated polymer (FP).

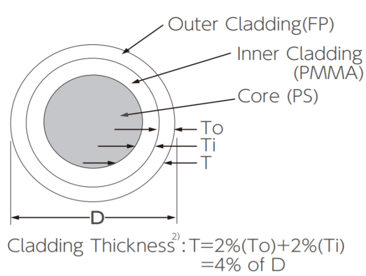

Figure 2. Cross section of a double cladding optical fiber as the Kuraray SCSF-78 [3].

The fibers properties needed to be taken into account for the simulations' input are presented in Table 1.

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Table 1. Kuraray SCSF-78 properties.

PS refractive index	1.59
PMMA refractive index	1.49
FP refractive index	1.42
Wavelength of scintillating light (Peak)	450 nm
Decay time	28 ns
Attenuation length	4 m

The blue light emission of the fibers corresponds to the maximum sensitivity of the used PMT (EMI9813KB). In order to maximize the scintillation efficiency process a selection of LEDs emitting ultraviolet light and peaking at 385 nm had been chosen.

1.3 The Fibrometer

The fibrometer [4] is a x-y table using two motors to cover all possible positions in an area of 3000x300 mmxmm (see figure 3). Along the x direction a light source is transported and test samples or setups are mounted over the table and moved along the y direction. At one end side a photodetector (PMT EMI9813KB) is mounted at a distance of 1 mm that can be adjusted if necessary. The photodetector is mounted inside a metallic shielding having a light guide made of lucite to distribute the light before it reaches the photocathode. The optical fiber light is further collimated using rectangular slits with a nominal width of 2.8 mm but other apertures can be used. The XT-Table was developed with the purpose of studying crosstalk in scintillating optical fibers with diameters of 1 , 0.5 and 0.25 mm. It was decided that for the current work the 0.25 mm fibers would not be used because they are hard to manipulate due to their fragility and also hard to characterize due to their dimensions.

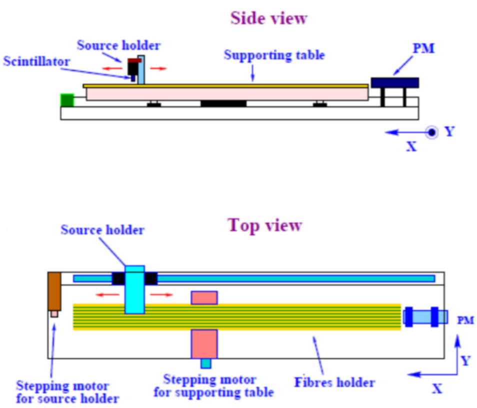

Figure 3. Schematic representation of the fibrometer [4]

Three LED boxes, each one designed to hold two LEDs, are used as light sources. These boxes are placed over the board supporting the fibers as represented in red in figure 4 and each box is used for each different fiber sizes. The distinction between these boxes are the pin-hole size apertures through where the light reaches a fiber with dimensions that are half of the cross-section of the fiber they are pointing. When mounted each pinhole is pointing at the center of a single fiber. One of the LEDs in each box illuminates the isolated fiber and the other one illuminates the first fiber in the ribbon. The board, also represented in the same figure, has fridges to place isolated fibers and ribbons of fibers with a width of 5 mm. In one ribbon would be then 5 fibers of 1 mm, 10 fibers of 0.5 mm and 20 fibers of 0.25 mm.

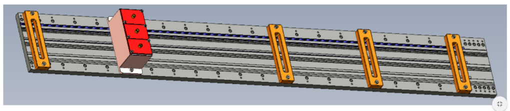

Figure 4. The CAD representation of the XT-Table [1]. In gray the fiber holder, orange the fixation bars and in red the LEDs boxes.

2 LEDs' Intensities

It was observed in previous measurements that differences on the measured signal were too high to be understood as any other effect besides the LEDs different I-V characteristics. Even though the LEDs came from the same batch, it is likely that there are differences and since this affects the results, it was necessary to have a clear understanding of the relations between LED's intensity and the fiber's (+ PMT) response. The LEDs' intensity was obtained from the measurement of the emission spectra using a Hamamatsu C10082MD mini-spectrometer. It was observed that all 6 LEDs had the same shape and peaked at the same wavelength value, but showing considerably different current-voltage (I-V) characteristics: for the same voltage a different intensity. As a measurement of the intensity the choice was to use the maximum from each spectrum. After these measurements, the LEDs were assembled in the XT-Table and a set of measurements irradiating the ribbon and isolated 1 mm fibers with all 6 LEDs were made with the fibrometer. The results from both procedures were compared using ratios between the LEDs pairs that are associated with each fiber size or mounted inside each LED box. These comparisons are summarized in Table 2.

Table 2. Each line corresponds to the ratios of the LEDs from each box. 1^{st} column: LEDs reference Box.LED. 2^{nd} column: isolated fiber current ratio measured with the fibrometer. 3^{rd} column: ribbon fiber current ratio measured with the fibrometer. 4^{th} column: LEDs intensities ratio measured with the spectrometer.

	Fibrometer		Spectrometer
LEDs	**Isolated Fiber**	**Ribbon**	**Intensity**
1.1/1.2	1.28	1.52	1.24
2.1/2.2	1.17	1.16	1.06
3.1/3.2	0.36	0.39	1.60

The results for Box 2 and Box 3 at the fibrometer have a reasonable agreement of about 0.8% and 8.3%, but that does not occur to Box 1 with a disagreement of the order of 18.7%. Comparing the fibrometer results with the spectrometer results a new ratio is produced that precisely shows this relative comparisons and they are summarized in Table 3.

Table 3. Each line corresponds to the ratios of the LEDs from each box. 1st column: LEDs reference Box.LED. 2nd column: comparison of the ratios of the second and forth column of table 2. 3rd column: comparison of the ratios of the third and forth column of table 2.

LEDs	Isolated Fiber/Intensity	Ribbon/Intensity
1.1/1.2	+3.2%	+22.6%
2.1/2.2	+10.4%	+9.4%
3.1/3.2	-77.5%	-75.6%

For Box 1 the difference relative to the isolated fiber is 3.2% which is within the uncertainty expected from measurements with the fibrometer. However, for the other boxes, the ratios' discrepancy is too high and with opposite signal for Box 3, reaching more than 70%. The observed differences has led to focus on the analysis of shape of the response curve. A deformation of the response curve can be by itself a demonstration that light is being transported along the neighboring fibers up to the PMT. The above measurements and comparisons must be revisited in a future analysis.

3 Experimental Measurements

The measurements with the fibrometer were made using fibers with diameters of 1 and 0.5 mm. The LEDs were placed at two different positions: 25 cm and 15 cm away from the tip of the fibers and with different slits to collimate the light output, one with 2.8 cm and the other with 0.8 cm length (see figure 5). From the previous analysis it was concluded that the measured intensities were not fully understood to be used. So to compare the shape of the curves the measurement resulting from each LED pointing to isolated fibers or the ribbons, the spectra were normalized to the maximum from a Gaussian fit.

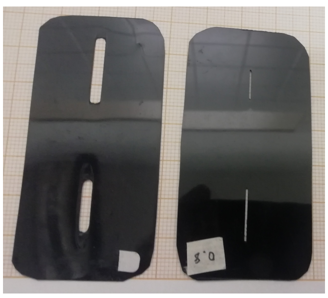

Figure 5. Photograph of the two slits.

The curves obtained with the 1 mm fibers are wider than the ones obtained with the 0.5 mm ones, like in the case when a larger slit to collimate the light is used. However, it was detected a bias produced by differences on the collimators, since for the same fiber in the same position and for the two used slits the curves are not centered the

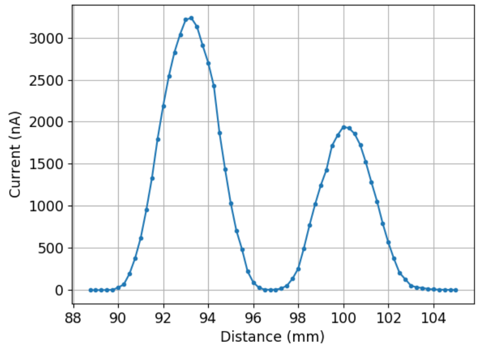

Figure 7. PMT's output. One of the curves corresponds to the 1 mm isolated fiber and the other to the ribbon of fibers of also 1 mm. The LEDs are 25 mm from the tip of the fibers, and the slit used of the one with 2.8 mm.

same position (see figure 6). This happens because the slits are not centered with each other and that must be corrected in order to compare the two responses. The choice of the collimator aperture did not have any impact on the conclusions and so for simplicity in what follows only data from 2.8 mm slits is used.

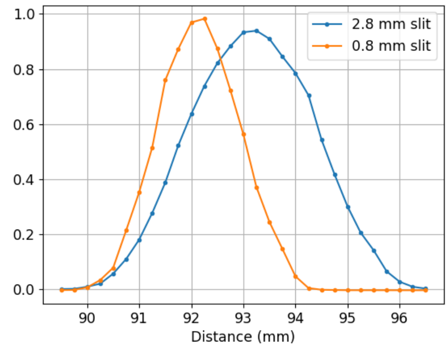

Figure 6. Plot of the 1 mm isolated fiber, with the LEDs 25 mm from the tip of the fibers, with the 2.8 and 0.8 mm slits.

In order to evaluate the cross-talk, the response from an isolated fiber was compared with the response from a ribbon for both fibers of 1 and 0.5 mm. One of the outputs for the 1 mm fibers is represented in figure 7. After normalizing the curves, it was necessary to align them in order to compare the widths. For the alignment, it was used millimetric paper in order to take a reference point in the board of fibers and make a correspondence of it into the recorded value in the output. Then, using the CAD model of the board, it was possible to map any point over the board width. Using this data, the center of the isolated fiber and the center of the fiber illuminated from the ribbon are set to zero and the two figures could be compared. One of the plots is represented in figure 8. The curves look to be identical in width, which leads to the conclusion that the existing cross-talk is below the sensitivity of the present setup and measurement procedure. There is, however, an obvious limitation on the method to achieve the alignment, since with a millimetric, one can

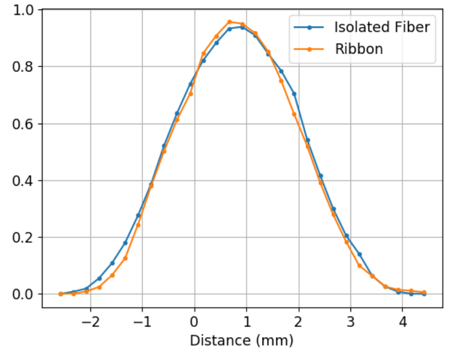

Figure 8. Curves of figure 7 normalized and aligned.

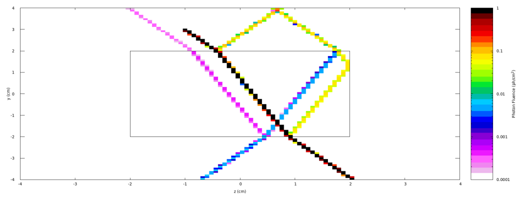

Figure 9. 3D plot of the fluence of optical photons, with the axes in cm. The square represents a box of polystyrene that is surrounded with air and the beam's initial position is (-1,3). One can identify reflected and refracted optical photons.

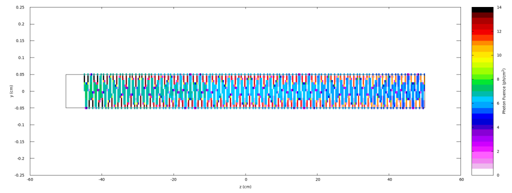

Figure 10. 3D plot of the fluence of optical photons, with the axes in cm. This represents the propagation of light through out a fiber of polystyrene.

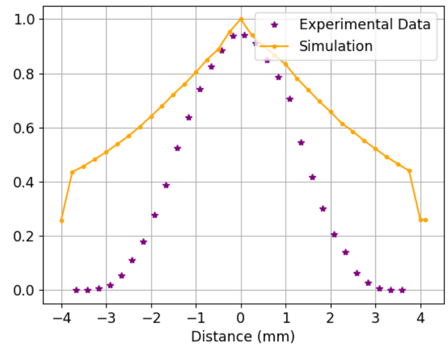

Figure 11. Plot with the simulated curve and experimental data curve for the 1 mm isolated fiber.

only achieve a precision of the order of 0.5 mm, which is too large for samples with a diameter below this value. Results for 0.5 mm fibers were also inconclusive. These smaller fibers in particular required a better precision mapping of the board transverse positions for an accurate comparison of the response curves. Three aspects of the measurement procedure were identified that must be corrected or better controlled in a next set of measurements using the XT-Table: the shift of the fibers along the length both for individual and ribbon fibers, the width to hold the ribbon was not uniform along the full length of the fiber and differences between fibers response due to differences on the polishing.

4 Simulations of basic optical properties

One of the goals of this work was to evaluate and learn the potential of the FLUKA [5] Monte-Carlo software package used in the propagation of light as well as the production of scintillation light. The simulations were implemented with the Graphical User Interface FLAIR [6]. In order to achieve a good control of this package, it was first verified the reflection and refraction of light in a box of polystyrene as shown in figure 9 and then the propagation of light throughout a fiber of the same material as shown in figure 10. For these simulations optical photons were used and it is important to mention that in FLUKA, by definition, the optical photons do not deposit energy, but they can be absorbed and diffused. Thus, it was not possible to implement a simulation that produced scintillating light from a LED source. With these simulations we were able to verify that FLUKA reproduces the basic optical properties of light propagation like reflection and refraction (Snell's law) and attenuation along the fiber.

5 Simulation of scintillation production and propagation

In order to produce scintillation in the simulation, we irradiate the fiber with an 2 MeV electron beam that emulates the Sr-90 source available in the laboratory. The source was placed 25 cm from the tip of the fiber, to excite it and produce optical photons that would be guided along the fiber length. It was necessary to introduce the scintillating properties of the fiber such as the decay time, the wavelength of the scintillating light and the fraction of deposited energy going into the scintillating photons. This value was estimated [7] for polystyrene emission at 450 nm (2.8 eV) to be 2.8×10^{-6} MeV $\times\, 12000\ \frac{\text{photons}}{\text{MeV}} = 0.033$ photons. Cherenkov production was not considered in the simulation.

The fiber was fully simulated including the two claddings with the proper materials and refractive indexes. Finally a pseudo-detector giving the optical photon fluence per primary particle was defined 1 mm away from the fiber. The output curve was normalized and compared to the normalized output curve of the experimental measurements (figure 11). From the comparison it can be seen that the simulation curve is considerably wider than the experimentally measured. That can be explained by the absence of key features in the cylinder box that has the PMT like the slit and aperture, the light guide and the efficiency and

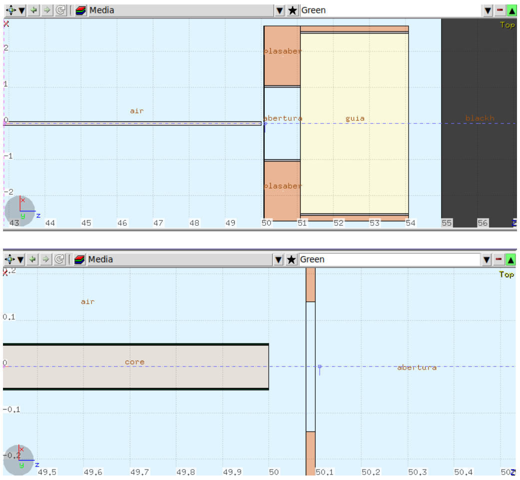

Figure 12. A simulation's geometry that is closer to the experimental setup. The picture below is a zoom of the above.

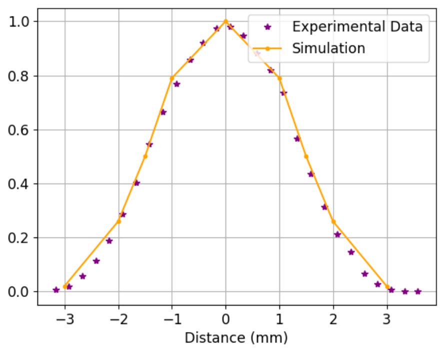

Figure 13. Plot with the simulated curve and experimental data curve for the 1 mm isolated fiber, after the simulation's geometry was brought closer to the experimental setup.

resolution of the PMT itself. This resulted in a mismatch in the geometric coverage of the simulated and the experimental setups. Thus, a geometry closer to the experimental setup was implemented in FLUKA, as we see in figure 12. A set of simulations were made positioning the fiber first centered relatively to the collimation slit ($x = 0$) and another four simulations considering shifts of the fiber by 1 , 1.5 , 2 and 3 mm. For each simulation the integral of the light reaching the end of the light guide was taken and all were normalized to the maximum ($x = 0$). The comparison of this simulations are shown in figure 13 shows a considerable good match between the two curves.

6 Conclusions

The goal of this internship was to quantify the crosstalk effect between adjacent plastic scintillating fibers. Therefore, Monte Carlo simulations were made as well as some experimental work with a fibrometer. A good agreement was found between the final simulation and the experimental measurements. However, some aspects of the simulation must be improved, such the inclusion of more that one wavelength for the scintillating emission. The emission spectrum must be characterized as closely as possible in the simulation. In addition, the features of the detection system must be further characterized and implemented in the simulations.

Some problems in the experimental setup were also found. Although the fiber board has fridges to place the fibers and parts to secure them, the fixation of the fibers must be improved, because they can move easily, which affects the results. Moreover, the alignment of the slits must be mend. The use of millimetric paper for centering the isolated fiber curve and the ribbon curve leads to errors and must be improved. Most importantly, the lack of proportionality between the fiber's response and the LED's intensity must be understood, so the maximums of the curves can be compared and not just the widths. Even though it wasn't yet possible to quantify the crosstalk effect, this internship was an added value in terms of simulations and trying to understand what needs to be improved for more accurate results and analysis.

Acknowledgments

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References

[1] F. Carvalho, Master's thesis, Universidade Nova de Lisboa (2019)

[2] *FreeCAD: Your own 3D parametric modeler*, https://www.freecadweb.org/ (2020)

[3] *Kuraray Catalogue*, https://www.kuraray.com/uploads/5a717515df6f5/PR0150_psf01.pdf (2020)

[4] J.G. Saraiva et al., Trans. Nucl. Sci. **51**, 1235 (2004)

[5] T. Böhlen, F. Cerutti, M. Chin, A. Fassò, A. Ferrari, P. Ortega, A. Mairani, P. Sala, G. Smirnov, V. Vlachoudis, Nuclear Data Sheets **120**, 211 (2014)

[6] V. Vlachoudis, *FLAIR: A Powerful But User Friendly Graphical Interface For FLUKA*, in *Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics*, edited by N. Svartholm (2009)

[7] S. Derenzo, M. Boswell, M. Weber, K. Brennan, *Scintillation properties*, http://scintillator.lbl.gov/ (2020)