PROCEEDINGS OF SCIENCE

Scintillating array for real–time high–resolution ion therapy dosimetry – Initial Design and Simulations

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Radiobiology is a multidisciplinary area where the effects of radiation in cells, tissues and organs are studied. To understand the biological effects of radiation it's important to have a measurement of the energy deposition at the micro or even nano-scale. This project is focused in the development of a detector that offers radiobiology researchers the possibility to achieve real-time dose measurement at the submillimiter scale. The technique chosen resorts to scintillation dosimetry with plastic optical fibres. The optical fibres offer a very good spatial resolution down to 0.25 mm and good tissue equivalence. In this work we present the inital design of the detector, ready for construction. The detector will be built as an irradiation box with a sensitive area composed of an array of plastic optical fibres with the possibility of mapping the dose in one plane or in two orthogonal planes with a spatial resolution of 1×1 mm^2, 0.5×0.5 mm^2 and 0.25×0.25 mm^2 depending on the optical fibres used. The detector will be prepared to receive a cell culture plate and for moving it in front of the detector's sensitive area.

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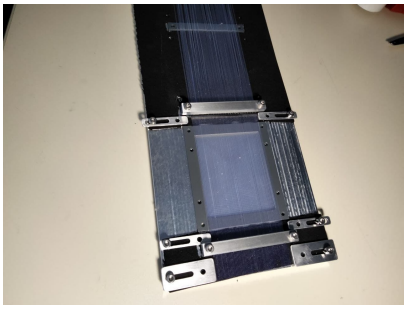
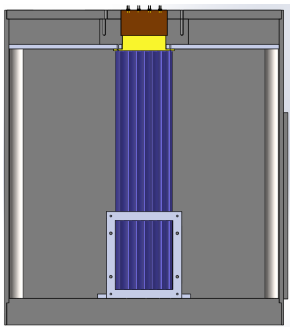
1. Introduction

In radiotherapy it is important to know how cells in organs react to radiation. This is the field of study of radiobiology. A standard output from radiobiology studies are the cell survival curves. The cell survival curves show the fraction of cells in a given population that is able to survive a given value of absorbed dose of radiation. From the cell survival curves the Relative Biological Effectiveness (RBE) can be extracted. This quantity compares the dose of a test radiation to the dose of standard radiation needed to produce the same biological effect. The RBE is a complex variable to study because it depends on the dose, dose rate, linear energy transfer (LET), cell type, among other factors. The LET is the average energy deposited per unit path length along the track of an ionizing particle. Even with all other parameters fixed, it is possible to have a different RBE for radiation with the same LET, depending on the track structure of the particles. A detector able to deliver information on the dose and LET distribution at the micrometer scale is then of high importance.

In these proceedings, we report on a detector that is being developed to offer real time dose measurement, good spatial resolution, and tissue-equivalence. During the development of this detector, the possibility of attaching a cell culture directly on top of the detector's sensitive area will be explored. This technique avoids the errors produced by the cells culture plates in the dose measurements.As proof-of-concept, skin cell cultures will be used. Skin is interesting to study since the dose absorbed by the skin is non negligible when microbeams are used and the literature shows that it is not easy to measure the dose transferred to skin [1]. This detector uses scintillating optical fibres that will be placed side by side forming a planar array. The possibility of having two orthogonal planes will also be studied. Using the two planes it is possible to have 2D position information. The detector's spatial resolution will be a direct function of the optical fibre's dimensions. In the prototypes, fibres of 1, 0.5 and 0.25 mm will be tested.



(a)

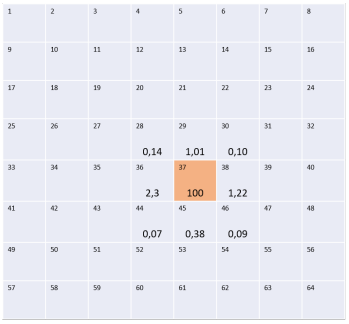


(b)

Figure 1: Instrumentation for the detector assemble: a) Tool used to assemble the optical fibre planar array. The optical fibres placed, forming the mentioned array, are shown; b) CAD image of the inside of the detector.

2. Detector design

The detector's box is made of Polyoxymethylene (POM) plastic. The fibres used in this detector have a core made of polystyrene and a cladding made of Poly(methyl methacrylate) (PMMA). The box has 34 cm height, 31.5 cm width, and 16 cm depth. The height and width were chosen in such a way that the bending of the fibres is not a problem in a future design with a 2D array (two planes).



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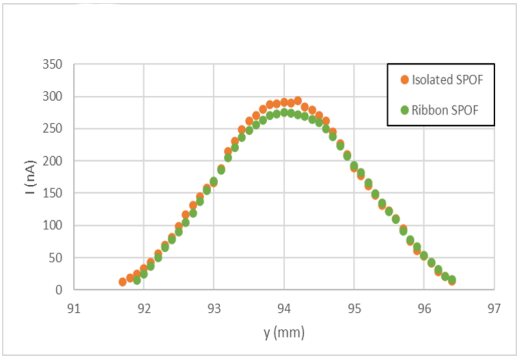

(b)

Figure 2: Measurements used to characterize the MAPMT and the scintillating plastic optical fibre (SPOF) ribbon. (a) Crosstalk in the photocathode. The rectangle in orange represents the cell being stimulated by the light emited by the optical fibre; (b) Distribution of the signal measured in the LOMAC detector for one isolated fibre and a ribbon of fibres. The horizontal axis corresponds to the position of the stimulated fibre. The measurements were performed with a blue LED stimulating one optical fibre, using a stepper motor to ensure the correct positioning of each fibre in front of the collimator used in the PMT. Note that his measurement was done with a different PMT from the MAPMT used in the detector.

The detector has an aperture at the front and another at the back for beam entering and exiting. The apertures are covered with a thin aluminum foil, preventing room-light to enter. The inside of the detector will have a volume where the optical fibres will be placed as well as the cell culture and the linear stage that will allow the multiwell cell culture plates (these are cell culture plates composed of 96 culture wells) moving in front of the optical fibres.

The protoptype uses a multianode photomultiplier (MAPMT) with 64 different anodes [2]. placed at the top of the detector's box. Figure 1b shows the current design of the detector with 64 fibres.

3. Photodetector and DAQ board tests and optical crosstalk evaluation

The signal-to-noise ratio, stabilization along time and the optical crosstalk in the interface between the anodes and the optical fibres were tested (see Figure 2a), reaching the conclusion that this crosstalk is negligible. The MARTA Data Acquisition (DAQ) board [3] developed at LIP is used and the DAQ's response in time and frequency were tested.

The crosstalk between optical fibres was measured at the LIP's LOMAC laboratory using the following procedure: i) five fibres are placed side by side; ii) one of the fibres (always the same) is stimulated with a LED; iii) the light exiting the fibres is detected by a PMT (different from the MAPMT used in the detector) which detects the light from one fibre at a time. The light output from the non-stimulated fibres is very small when compared to the light output of the stimulated fibre. Figure 2b shows that after the stimulated optical fibre is removed from the front of the PMT's collimator, positioned at $y = 94$ mm, the signal has the same behaviour as the isolated fibre. By moving the non-stimulated fibres in front of the collimator, we find that the behaviour of the read signal is analogous to that of the isolated fibre, indicating that the optical crosstalk between the fibres is not a crucial factor in the development of this detector and these can be put together without optically isolating each of them.

4. Optical fibre array assemble and quality control

A mechanical support was built to ensure the flatness of the fibre array. The tool is designed in such a way that the optical fibres are made to be juxtaposed by the pieces placed at the array extremity and mid-section (see Figure 1a). To assess the influence of array flatness in the signal readout, a Monte Carlo simulation of an off-plane fibre was done, where an array of 64 optical fibres was placed in air and then irradiated with a proton beam of 13.8 MeV with a diameter at its origin of 2.3 cm. The central fibre was displaced along the beam axis forward and backwards relative to the array plane. The energy absorbed by the displaced fibre was compared with the other fibres. The simulation shows that a forward displacement (increasing of air thickness) of 0.7 mm will induce a 5% decrease in the signal measured by a 1 mm fibre. For 0.5 mm fibres the displacement to achieve a 5% signal reduction is about 0.4 mm. According to these results it is important to find a way to control the array flatness down to 0.1 mm fibre displacement if signal variations between fibres are expected to be kept below 1%. After testing different methods, it was concluded that confocal microscopy with fluorescence showed the most adequate results for this purpose.

5. Assessment of shielding requirements and optical photons transport simulations

Monte Carlo simulations of the system's shielding to neutrons, energy deposition in the sensitive part of the detector, and optical photons transport, were made using the FLUKA program [4]. In the simulations proton beams of 13.8 MeV and 100 MeV were considered. The proton beam had to cross 50 cm of air before hitting the entrance window of the detector. On exiting the acelerator the beam is monodirectional with a cross-section of 2.3 cm in diameter. Except for the energy of 100 MeV all other beam parameters are consistent with the existing cyclotron existing in ICNAS [5] facility (Coimbra, Portugal).

There are two main things to consider when it comes to shielding how is the measured signal different when the dose deposited by neutrons and photons is considered, and how radiation can damage the electronics placed on the detector (PMT, DAQ, interface PCB). The simulations show that for the 13.8 MeV beam the contribution of neutrons and photons are below the 1% reference for the energy absorbed by the optical fibres. The contribution is also below the 1% reference for the 100 MeV proton beam.We expect these fluences are low enough to discard the need of special shielding of the electronics. However, at the time of writing, we are waiting for information from Hamamatsu on the MAPMT radiation hardness to reach a definite conclusion.

The simulations were also used to understand the shape of a signal produced when the optical fibres are stimulated and they create optical photons. For this simulation the optical photon production and propagation was turned on. The photons were produced in the optical fibre's core and a volume that corresponds to the PMT was placed on top of each optical fibre to score the number of optical photons. The results can be seen in Figure 3. From this simulation it is possible to conclude that the optical fibres that absorb the largest amount of dose (the beam has aimed at the central fibres) are capable of showing a very distinct signal from the other fibres, which reinforces the idea that optical crosstalk will not play an important role in this detector.

6. Futures prospects

Future work will be focused on the conclusion of the detector's assembly, this part of the work will include an important input from the mechanical workshop at LIP-Coimbra. The readout of the

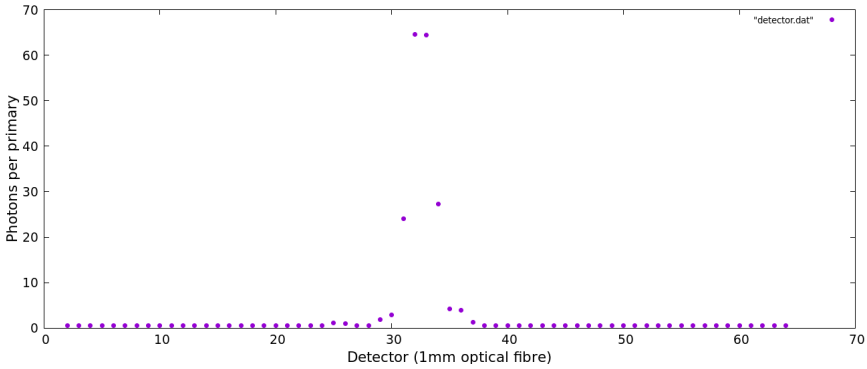

Figure 3: Scintillation photons that reach the detector placed at the top of ecah optical fibre. The number on the horizontal axis corresponds to each optical fibre. Simulation performed with a 13.8 MeV proton beam with 2.3 cm diameter in its origin.

signal produced in the optical fibres will be aided by an interface that will help connecting the PM to the DAQ board. This interface is ready for production and will be tested in the near future. Once the system is built it is important to test it with the types of radiation used in therapy: electrons, X-rays and protons. The first set of tests will be performed without cell cultures, to check the detector's readout without the perturbation introduced by the cells. After that it will be important to perform the tests with cell cultures. Development of a software to automatize the data processing and of a Graphical User Interface (GUI) to aid in the data visualisation will occur in parallel to the assembly and testing of the detector.

Acknowledgements

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