Bragg curve imaging of 6.75 MeV protons with lithium fluoride crystals and fluorescence microscopy

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Use of hadrons in oncological radiotherapy has seen a remarkable growth in recent years due to the excellent ballistic properties of heavy particles, which release most of their energy at the end of their path [1]. A linear accelerator for proton therapy is under development at ENEA C.R. Frascati in the framework of the TOP-IMPLART Project carried out by ENEA in collaboration with ISS and IRE-IFO [2]. Even though still below clinically relevant energies, the proton beam has been already characterised thanks to collaborations with scientific and industrial partners. In this context, lithium fluoride (LiF) crystals have been proposed and used as luminescent radiation detectors for Bragg curve imaging [3].

LiF is an alkali halide material with peculiar physical and optical properties, useful for applications in optoelectronics, integrated optics as well as in X-ray imaging and dosimetry [4], thanks to its tissue equivalency. It can host laser-active electronic defects, known as colour centres (CCs), characterised by wide tunability and good stability even at room temperature [5].

Irradiation of LiF by ionising radiation of various kinds induces the formation of CCs, mainly the primary F centre (an anionic vacancy occupied by an electron) and the aggregate F_2 and F_3^+ CCs (two electrons bound to two and three anion vacancies, respectively). The F_2 and F_3^+ CCs possess almost overlapping broad absorption bands, centred at a wavelength of ~450 nm, known as M band [5]. By optically pumping in the M band, the F_2 and F_3^+ CCs simultaneously emit broad photoluminescence (PL) bands peaked at 678 nm and 541 nm, respectively [6].

In this work, it is shown how Bragg curves of the TOP-IMPLART proton beam are recorded and stored as latent fluorescent images in LiF. A preliminary study was recently published by using LiF thin films as radiation detectors [7]; here, results regarding irradiation of LiF crystals with 6.75 MeV protons are reported for the first time.

In the experiment, 10×10 mm^2, 1 mm thick polished LiF crystals are longitudinally placed along the path of the proton beam to create a depth distribution of CCs in the material. The PL radiated by F_2 and F_3^+ CCs belonging to this distribution is detected by a Nikon Eclipse 80-i C1 fluorescence microscope under blue lamp illumination, and stored in a computer as an image acquired by a s-CMOS camera. An example of such an image is shown in Fig. 1 for an irradiation with 6.75 MeV protons. In it, the segment AB indicates a one-dimensional PL profile that is later used for comparison with theory. To this purpose, Monte Carlo simulations of linear energy transfer (LET) profiles are performed with SRIM software [8]. The calculated LET profiles – Fig. 2 shows one of them corresponding to 6.75 MeV protons passing through a 50 µm thin Kapton window, 5 mm in air, and then entering LiF bulk – are not directly comparable with the experimental PL depth profiles, although the Bragg peak position is the same. Therefore, the SRIM output is elaborated within a Matlab code to take into account (a) the proton beam energy spread, and (b) the PL vs. dose relationship, including saturation effects due to high CC concentration. Indeed, the detected PL signal cannot be considered as linearly dependent on the absorbed dose above a certain threshold, see Fig. 3. Figure 4 shows the resulting theoretical PL profile (again, for 6.75 MeV protons) compared with the corresponding experimental profile of segment AB in Fig. 1.

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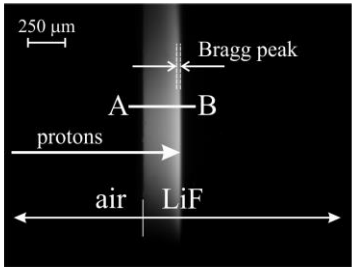

Figure 1. PL image, as detected by a fluorescence microscope with a s-CMOS camera, due to F_2 and F_3^+ CCs formed in a LiF crystal irradiated with 6.75 MeV protons.

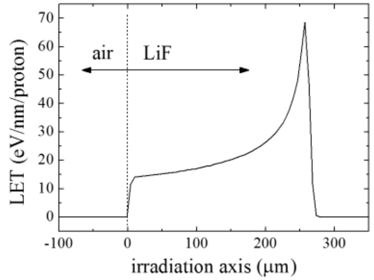

Figure 2. Monte Carlo simulated depth profile of the energy released by 6.75 MeV protons into the LiF bulk material.

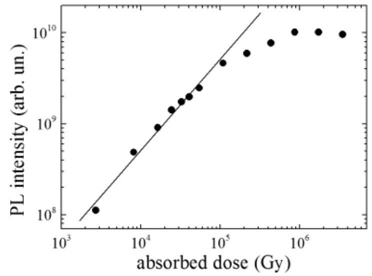

Figure 3. Experimental spectrally integrated PL intensity of CCs formed at various doses in a LiF crystal by irradiation with 6.75 MeV protons. Saturation at doses above ~10^5 Gy can be clearly seen. The superimposed straight line evidences the linear part of the curve.

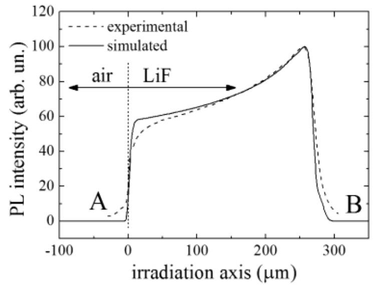

Figure 4. Comparison of the experimental PL profile corresponding to AB in Fig. 1 with its simulated counterpart, obtained by elaborating in Matlab a number of LET profiles resulting from SRIM calculations, and also by taking into account the saturation shown in Fig. 3.