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HIGH-RESOLUTION DIAGNOSTICS OF THE TOP-IMPLART 71 MeV PROTON BEAM USING PHOTOLUMINESCENT COLOR CENTERS IN LiF CRYSTALS *

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Abstract

A LiF crystal plate is irradiated edge-on by the nominal 71 MeV proton beam of the TOP-IMPLART linac, after it has traversed several materials plates and air gaps. The irradiation induces the formation of point defects in the LiF crystal, known as color centers, some of which emit visible radiophotoluminescence when optically excited with blue light. This property is exploited to map the energy deposited by the protons within the LiF crystal, by visualizing the luminescent pattern of the color centers using a fluorescence microscope. Analysis of this pattern, which replicates a superposition of monochromatic proton Bragg curves, enables the estimation of the beam energy spectrum at the LiF crystal position. The corresponding energy spectrum at the linac exit is then inferred by applying a theoretical backpropagation method.

INTRODUCTION

TOP-IMPLART (Terapia Oncologica con Protoni—Intensity Modulated Proton Linear Accelerator for Radio-Therapy) is a radio frequency (RF) pulsed linear proton accelerator developed at the ENEA Frascati Center laboratories as a prototype for proton therapy, and is now evolving into an irradiation facility for various fields of application [1, 2]. The accelerator consists of a 7 MeV, 425 MHz injector, followed by a 3 GHz booster composed of a series of eight side-coupled drift tube linac (SCDTL) accelerating modules. A scheme of the accelerator is reported in Fig. 1.

The proton beam can be accelerated to 71 MeV or 63 MeV (by switching off the last module) in 2.5 µs pulses, with a typical repetition rate of 25 Hz and a maximum pulse current of 25 µA [3]. Intermediate and lower energies can be obtained by using suitable degraders.

This work employs a recently developed technique for beam energy measurement, which is based on analyzing the spatial distribution of dose deposited in lithium fluoride (LiF) crystals through the detection of radiation-induced luminescent defects. Indeed, upon exposure to various types of ionizing radiation, including accelerated ions, LiF forms stable lattice point defects known as color centers (CCs) [4]. Among them, the F_2 and F_3^+ centers—consisting of two electrons bound to two and three anion vacancies, respectively—emit visible radiophotoluminescence (RPL) in the red and green regions of the spectrum, respectively, when optically excited within their nearly overlapping absorption bands in the blue region [5]. For the proton energies tested so far, the emitted RPL intensity has been found to vary linearly with the absorbed dose up to approximately 10^5–10^6 Gy [6, 7]. Beyond this threshold, saturation effects begin to appear [8–10].

Under appropriate irradiation geometry, these characteristics can be exploited to map the dose distribution deposited by a proton beam within a LiF crystal plate. As described below, an experimental method combining this mapping with subsequent data analysis is applied to characterize the energy spectrum of the 71 MeV TOP-IMPLART beam.

ENERGY DIAGNOSTICS METHOD

The method employed to characterize the energy spectrum of a proton beam consists essentially of two experimental phases, illustrated in Fig. 2, followed by the analysis of the resulting data.

In the first experimental step, referred to as the irradiation phase, a thin LiF crystal plate is irradiated in air, with its edge facing the incoming proton beam. This irradiation induces the stable formation of a spatial distribution of CCs, whose local density is directly proportional to the energy deposited by the protons at each point, provided that the dose remains below the previously mentioned threshold of 10^5–10^6 Gy. Consequently, along the beam penetration direction (z-axis), the CC density reflects a superposition of Bragg curves corresponding to the monochromatic components that constitute the proton beam energy spectrum. In the subsequent step, the readout phase, the visible RPL emitted by F_2 and F_3^+ centers is detected from the top face of the crystal using a fluorescence microscope. A two-dimensional map of the RPL emission is then recorded as a high-resolution image for further analysis.

A rectangular region of interest (ROI) is selected within the RPL image (see Fig. 3). By integrating the pixel intensity along the x-axis within this ROI, a one-dimensional profile of RPL intensity as a function of proton penetration depth (z-axis) is obtained. The RPL intensity profile is then fitted using a weighted superposition of monochromatic Bragg curves, calculated through an analytical model [11] that accounts for fluence reduction due to multiple Coulomb scattering through the faces of the LiF crystal [12]. The weight of each monochromatic Bragg curve is iteratively determined using a localized random search (LRS) algorithm [13]. The resulting distribution of these weights, as a function of the corresponding monochromatic energies, is assumed to rep-

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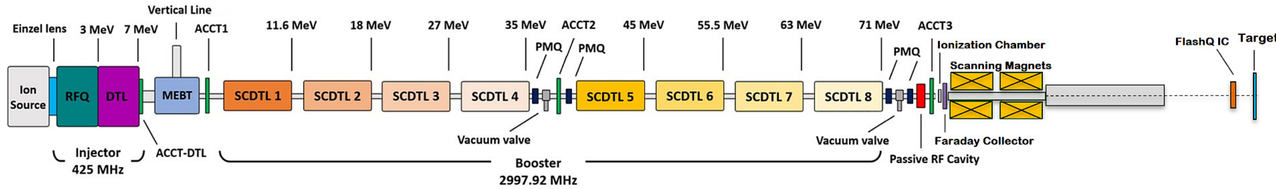

Figure 1: Scheme of the TOP-IMPLART proton accelerator.

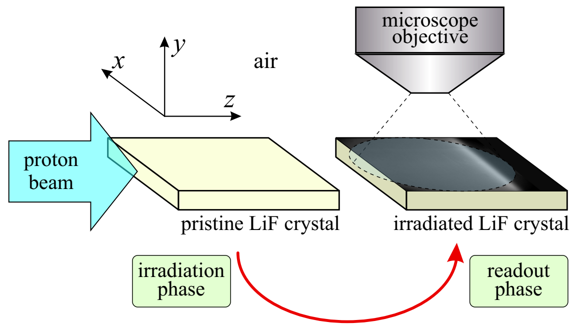

Figure 2: Schematic illustration of the two experimental phases used for proton beam energy diagnostics.

Figure 3: Two-dimensional image of the RPL intensity. The yellow rectangle indicates the ROI used to extract the one-dimensional RPL intensity profile for analysis.

resent the reconstructed energy spectrum of the proton beam at the LiF crystal position. Finally, the energy spectrum of the proton beam at the linac exit is retrieved using a spectral backpropagation method, which relies on transfer functions derived from the theoretical direct propagation of individual monochromatic beams along the accelerator delivery line [14].

EXPERIMENTAL APPLICATION

In the following, we present an experimental application of the energy diagnostics method described above, carried out during the commissioning of the 71 MeV accelerator delivery line for a pencil beam.

Materials and Methods

The sample used to characterize the nominal 71 MeV beam of the TOP-IMPLART proton accelerator was a polished, commercially available LiF crystal (MaTeck GmbH, Germany) with dimensions of $10 \times 20 \times 1$ mm^3. The irradiation geometry was configured such that the proton beam impinged on one of the 1 mm-thick sides of the crystal at zero-angle grazing incidence, as schematically illustrated in Fig. 2 (on-edge irradiation).

Before reaching the crystal, the proton beam exiting the linac passed through a 25 µm thick titanium window and an air gap of 247.8 cm. The beam current per pulse was 25 µA, and the total irradiation time was 160 s. Assuming a Gaussian profile, the beam's full width at half maximum at the crystal position, as determined from measurements using Gafchromic EBT3 films, was FWHM $\approx$ 32 mm. Based on these parameters, the average dose absorbed by the crystal was estimated to be ~600 Gy, which is well below the threshold above which saturation phenomena occur.

The fluorescence microscope used in the readout phase was a Nikon Eclipse 80-i, equipped with a 440 nm pE-100 coolLED source and an Andor Neo sCMOS camera. The RPL map was acquired at 4× magnification.

The one-dimensional RPL profile extracted from the RPL map was fitted using a custom LRS algorithm implemented in Matlab R2010a [15]. For each monochromatic energy component, the corresponding Bragg curve in LiF was computed using the previously mentioned analytical model [11], which also incorporates the in-crystal fluence reduction resulting from multiple Coulomb scattering [12]. The obtained energy spectrum was virtually backpropagated to the linac exit using transfer functions analytically derived as described in [14], with a program developed in Wolfram Mathematica v. 14.1 [16].

Proton Beam Energy Spectrum Estimation

Figure 3 shows the RPL intensity map acquired with the fluorescence microscope after irradiation of the LiF crystal. By integrating the pixel intensities along the x-axis, the experimental RPL intensity profile along the z-axis, reported in Fig. 4, was obtained. The spike observed at $z = 0$

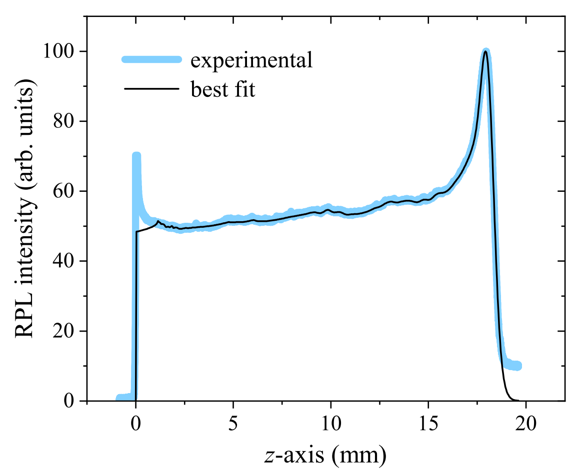

Figure 4: Experimental and best fitting RPL intensity profiles.

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is attributed to light scattering at the crystal edge. In the same figure, the theoretical fitting curve derived using the previously mentioned LRS algorithm is also shown.

The energy spectrum at the crystal position, also obtained through the LRS algorithm, is presented in Fig. 5. To apply the algorithm, the proton energy range from 14.5 MeV to 75 MeV was discretized into 400 equally spaced bins.

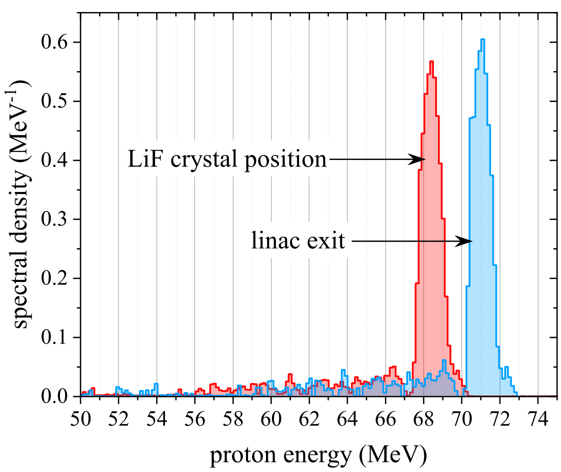

Figure 5: Proton beam energy spectra at the LiF crystal position and at the linac exit.

Figure 5 further shows the energy spectrum at the linac exit, reconstructed using the backpropagation method introduced in [14]. This spectrum features a main peak centered on the most probable energy, which corresponds to the design value of 71 MeV, and a low-energy tail resulting from out-of-phase particles transported through the final accelerating modules. The parameters of the main peak for both the spectrum at the LiF crystal position and at the linac exit are summarized in Table 1.

Table 1: Parameters of the main peaks of the spectra shown in Fig. 5.

Position	**Mean energy (MeV)**	**FWHM (MeV)**
LiF crystal	68.41	1.31
linac exit	71.05	1.28

CONCLUSIONS

In recent years, the diagnostics method based on the analysis of RPL emitted by CCs formed in LiF crystals upon irradiation has proven to be a reliable approach for characterizing the energy spectrum of the TOP-IMPLART proton beam. The method has been progressively refined to achieve better fits of the experimental RPL intensity profiles and to account for in-crystal fluence reduction effects due to multiple Coulomb scattering. These effects become particularly significant at the considered energy of 71 MeV for the typical 1 mm thickness of the LiF crystals used in the diagnostics.

Regarding the experimental application presented for the commissioning of the TOP-IMPLART delivery line, the energy parameters obtained for the proton beam at the linac exit are in good agreement with the design values, confirming the excellent performance of the accelerator.

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