Proton beam spatial distribution and Bragg peak imaging by photoluminescence of color centers in lithium fluoride crystals at the TOP-IMPLART linear accelerator

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A R T I C L E   I N F O

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- Photoluminescence
- Bragg peak
- Proton beam imaging
- Linac

A B S T R A C T

Solid-state radiation detectors based on the photoluminescence of stable point defects in lithium fluoride crystals have been used for advanced diagnostics during the commissioning of the segment up to 27 MeV of the TOP-IMPLART proton linear accelerator for proton therapy applications, under development at ENEA C.R. Frascati, Italy. The LiF detectors high intrinsic spatial resolution and wide dynamic range allow obtaining two-dimensional images of the beam transverse intensity distribution and also identifying the Bragg peak position with micrometric precision by using a conventional optical fluorescence microscope. Results of the proton beam characterization, among which, the estimation of beam energy components and dynamics, are reported and discussed for different operating conditions of the accelerator.

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1. Introduction

Lithium fluoride (LiF) is an alkali halide crystal with peculiar physical and optical properties. In particular, it is almost not hygroscopic and it is sensitive to ionizing radiation (X-rays, gamma-rays, electrons, neutrons, protons, alpha-particles and heavier charged ions) that induces the formation of laser-active electronic defects, known as color centers (CCs), characterized by a high stability at room temperature (RT). Such properties make LiF suitable for several applications, not only in optoelectronics [1] and integrated optics [2], but also in dosimetry [3,4].

Among the CCs formed by ionizing radiation in LiF, the aggregate F2 and F+ 3 ones (two electrons bound to two and three anion vacancies, respectively) can be exploited with great advantage. As they possess superimposed absorption bands both centered at about 450 nm, by optical pumping in this band, they simultaneously emit with high efficiency broad photoluminescence (PL) bands peaked at 678 nm and 541 nm, respectively [5], covering almost all the visible spectral range. These spectroscopic properties allowed using conventional and confocal fluorescence microscopy as reading technique of luminescent radiation detectors based on LiF crystals and thin films containing CCs. They were tested for extreme-ultraviolet and soft X-ray imaging applications [6,7], as well as for gamma-dosimetry [8], for the characterization of intense X-ray sources [9] and for X-ray micro-radiography of in vivo specimens [10].

In most recent years, oncological radiotherapy is exploiting hadrons for treating tumors that are located close to critical organs that would be unacceptably damaged by X-rays. This technique is experiencing remarkable growth, because protons and heavier particles (i.e. Carbon ions) possess advantageous ballistic properties: they lose most of their energy at the Bragg peak with a modest lateral diffusion, preserving the surrounding healthy organs during tumor irradiation [11]. In the framework of the TOP-IMPLART (Oncological Therapy with Protons—Intensity Modulated Proton Linear Accelerator for RadioTherapy) [12], a 150 MeV proton accelerator, designed as a sequence of linear accelerating modules, is currently being constructed and tested at ENEA C.R. Frascati. Against this backdrop, previous studies by our group have been dedicated to the investigation of the optical properties of CCs formed in LiF crystals and thin films by low energy protons [13,14] for proton beam diagnostics. In this paper, we present experimental results about the use, for the first time, of LiF crystal radiation detectors based on the PL of radiation-induced CCs for high spatial resolution proton beam characterization, in terms of both transversal intensity distribution and...
2. The TOP-IMPLART accelerator

The TOP-IMPLART accelerator is a 150 MeV proton linear accelerator devoted to cancer therapy applications under construction at ENEA C.R. Frascati in the framework of a project developed by ENEA, in collaboration with Italian National Institute of Health (ISS) and Regina Elena National Cancer Institute (IFO) of Rome. ENEA has the task of realizing the plant and providing support for preclinical testing. ISS will realize beam monitors and dosimetric and control systems, while IFO will study treatment plans and implement preclinical testing. At the end of the validation tests the accelerator will be moved to a hospital site where it will be made clinically available.

The accelerator is designed to produce a proton beam, emitted at high frequency repetition pulses (100 Hz), whose characteristics (position, energy and intensity) can be varied pulse by pulse in order to achieve a highly conformational therapy [12]. It consists of a 425 MHz injector followed by a sequence of 3 GHz linear accelerating modules. The injector is a commercial LINAC (ACCSYS-HITACHI PL7 model) composed by a 3 MeV RFQ (RadioFrequency Quadrupole) and a 7 MeV DTL (Drift Tube Linac). The transverse phase space of the injector output beam is matched to the acceptance of the high frequency booster (with a pipe of only 4 mm of diameter) by a LEBT (Low Energy Beam Transport) including four electromagnetic quadrupoles.

The modularity of the machine, typical of a linear accelerator (unlike circular machines usually employed in hadrontherapy facilities), allows to proceed by steps in the construction and test of each added module of the accelerator.

The measurements reported in this paper refer to the commissioning phase of the segment up to 27 MeV (see Figs. 1, 2), which is composed in its high frequency part by three SCDTL (Side Coupled Drift Tube Linac) modules [15] accelerating the beam to 11.6 MeV (SCDTL-1), 18 MeV (SCDTL-2) and 27 MeV (SCDTL-3), respectively. A single 10 MW peak power klystron is used to supply the three modules (plus a fourth module up to 35 MeV not yet mounted at the time of the measurements presented here) by a RF driving line, including a variable power divider system and two phase shifters, in order to set the electric field amplitude and phase in the accelerating structures for a proper acceleration.

Fig. 1 shows the main diagnostic system, consisting of two AC current transformers (FCT1 and FCT2) to measure the input and output currents, respectively. Output current and charge are also measured by a Faraday Cup (FC) and an ionization chamber. The main parameters for the injector and the 27 MeV booster during the commissioning tests are listed in Tables 1 and 2, respectively.

3. LiF-based proton imaging detectors

LiF-based detectors used in this work were commercially available (10×10 mm², 1 mm thick LiF crystals polished on both faces. When the proton beam penetrates the LiF crystal, it releases energy and creates stable \( F_3 \) and \( F'_2 \) CCs, whose local concentrations are proportional to the energy deposited in the material. As the emitted visible PL intensity is proportional to the CC concentration (below saturation) [14], by exposing one of the polished crystal faces perpendicularly to the beam propagation direction, the two-dimensional PL image of the transversal proton beam intensity distribution could be stored in the LiF detector (see Fig. 3). After irradiation, the stored image was read by the fluorescence microscope Nikon Eclipse 90-i C1, equipped with a Hg lamp. The Hg lamp blue emission, peaking at 434 nm, was selected to simultaneously excite the PL of the \( F_3 \) and \( F'_2 \) CCs [5] and an Andor Neo s-CMOS camera acquired the PL images with an 11-bit dynamic range. The Nikon software NIS Elements 4.20 was used to control the image acquisition system.

An advantageous application of these solid-state LiF-based radiation imaging detectors, exploiting the PL of aggregate CCs, is the possibility of imaging also the Bragg curve. In this case, the LiF crystals were mounted with the \((10 \times 10) \) mm² surfaces parallel to the beam propagation direction, in order to expose the 1 mm thick crystal side perpendicularly to the impinging protons. In this irradiation geometry, the beam hits the LiF crystal edge, penetrates the crystal and, by releasing its energy according to the plots in Fig. 4, it creates \( F_3 \) and \( F'_2 \) CCs, whose local concentrations are proportional to the linear energy transfer (LET), provided saturation has been not reached [13]. The curves in Fig. 4 were obtained by simulations with SRIM (Stopping and Range of Ions in Matter) software [16]. After exposure, by using the fluorescence microscope, the two-dimensional spatial distribution of the CC PL emitted by the proton irradiated LiF crystals was acquired. As discussed, below saturation the PL signal is proportional to the local defect concentration. With reference to Fig. 5, the PL intensity exhibits a strong increase at a fixed distance from the crystal edge. The increased signal intensity is representative of the Bragg peak position and corresponds to the maximum energy deposition by the proton beam (see Fig. 4). The PL intensity profile along the direction perpendicular to the LiF crystal edge was obtained by image analysis in ImageJ software (see Fig. 6). In the PL intensity profile, the position of the crystal edge was set where the initial steeply increasing PL signal reached its half-height value; the signal slope is steeper if the optical resolution of the microscope is higher. The distance from the crystal edge of the peak intensity of the luminescence profile corresponded to the distance of the Bragg peak. This value, in microns, obtained after knowing the image scale (μm/pixel) on the basis of the optical microscope objective magnification, was compared with the Bragg peak position provided by simulations with SRIM in our experimental conditions.

Summarizing, the CCs-based LiF imaging radiation detectors possess many advantageous features, among them large field of view (>1 cm²), wide dynamic range and they are directly read by a fluorescence optical microscope without any development procedure; moreover, they are insensitive to ambient light, as the luminescent point defects are stable at room temperature.

4. Proton beam characterization by LiF detectors

The use of luminescent CCs-based LiF crystal detectors, for high resolution proton beam characterization in terms of both spatial distribution and energy spectrum, was tested by performing exposures during the assembly of the accelerator in different layout configurations and operating conditions. The first measurements concerned the 7 MeV beam and were performed before mounting the high frequency part of the linac. Next measurements were done on the accelerated beam at the output of SCDTL-1 structure (before mounting the following modules) and at the output of SCDTL-3 with SCDTL-3 on and off (in this latter case, SCDTL-3 was just used as a transport line), as detailed below.

<table>
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<th>Table 1</th>
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<td><strong>Injector linac main parameters.</strong></td>
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<td>Pulse current</td>
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<td>Pulse duration</td>
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<td>Pulse repetition frequency</td>
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<td>Output beam nominal energy</td>
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<td><strong>Table 2</strong></td>
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<tr>
<td><strong>Booster linac main parameters.</strong></td>
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<tr>
<td>Pulse current</td>
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<tr>
<td>Pulse duration</td>
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<tr>
<td>Pulse repetition frequency (typical)</td>
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<tr>
<td>Output beam nominal energy</td>
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*Energy spectrum, during the assembly and commissioning of the segment up to 27 MeV of the accelerator, in different layout configurations and operating conditions.*
4.1. SCDTL-1 input

The first measurement was performed during the first phase of the injector commissioning at the exit of PL7 injector. A 50 μm thick Kapton window was mounted at the beamline output to keep the injector in vacuum while the LiF detector was placed in air at a distance of 5 mm from the window. The pulsed beam current impinging on the LiF crystal was about 2 μA in a 25 μs-long pulse at a repetition frequency of 50 Hz.

The left frame of Fig. 3 shows the PL proton beam image obtained by exposing the (10 x 10) mm$^2$ LiF crystal surface perpendicularly to the beam propagation direction. The right frame of Fig. 3 is a false-color representation of the left frame to highlight that the LiF-based detector is able to store information about the proton beam transversal intensity distribution with high spatial resolution and revealing even slight intensity differences. The elliptical shape of the spot depends on the vertical focusing of the last quadrupole in the LEBT.

After exposing the LiF crystal with the (10x10) mm$^2$ surfaces parallel to the proton beam propagation direction, the image shown in Fig. 5 was acquired. The intensity profile along the direction perpendicular to the crystal edge, reported in Fig. 6, was obtained by selecting a region of interest (r.o.i.) in ImageJ software and the Bragg peak distance from the crystal edge was found to be at (258 ± 7) μm. SRIM calculations give an energy of 6.3 MeV at the entrance of the crystal, corresponding to a beam energy in vacuum of 6.75 MeV, as reported in the plot of Fig. 7, due to the energy degradation in the Kapton window and in the air. At this energy, the Bragg peak position is very sensitive to the proton beam energy and the precision of ±7 μm corresponds to an error in the energy measurement of ±0.13 MeV. The uncertainty in the peak position (±7 μm) was determined by summing the error given by the image pixel size (±1 pixel) to the estimated uncertainty in the crystal edge position (±3 pixel), with a pixel size of 1.63 μm.
During these preliminary tests the injector did not work with the maximum field in the DTL section, which explains a slightly lower value of the measured energy respect to the design value of 7 MeV.

4.2. SCDTL-1 output

After mounting the first accelerating module (SCDTL-1) at the output of the injector to accelerate the proton beam to a nominal energy of 11.6 MeV, a test with LiF radiation detectors was performed. The injector pulse length was 25 μs, while the klystron pulse length was 4 μs, so only the protons included in this part of the pulse were accelerated in the SCDTL-1. However, the PMQs FODO (a sequence of Focusing and Defocusing lenses) lattice inside SCDTL-1 is able to transport also a large portion of non-accelerated protons, according to the beam dynamics simulation results, confirmed by the current measurements performed at the exit of SCDTL-1 [15]. The effect on the beam energy distribution at the SCDTL-1 exit is clearly evidenced by the LiF crystal detector. Fig. 8 shows the Bragg peak imaging and a selected r.o.i., whose corresponding PL intensity profile is reported in Fig. 9: a distinct peak, found at (290 ± 7) μm from the crystal edge, corresponds to particles not accelerated by the SCDTL-1 structure, but the intensity profile shows several weaker and broader peaks at greater distances from the crystal edge. In order to highlight the visibility of these peaks, another fluorescence image of the same irradiated LiF crystal was acquired with a six-time longer exposure time. The PL intensity profile of the same r.o.i. is reported in Fig. 10 and shows more clearly the presence of the other peaks at greater distances, while the PL signal of the 7 MeV beam component is saturated.

SRIM simulations allowed us to deduce the beam energies corresponding to the peaks shown in Figs. 9 and 11, as reported in Table 3.

Another proton beam characterization was performed by allowing it to propagate in vacuum, after exiting the SCDTL-1 structure, up to a distance of 40 cm through a tube of 5 mm diameter with 3 PMQs, at whose end the Kapton window was mounted. In this way it was possible to remove about 75% of the 7 MeV component to obtain a more balanced ratio with respect to the 11.6 MeV component. This result is confirmed in the PL image of the exposed LiF crystal, shown in Fig. 13. Two peaks with similar intensities are clearly visible, although they are not perfectly aligned along the same beam propagation direction (corresponding to the beam focusing line) perpendicular to the LiF crystal edge and the 40 cm-long tube allowed separating them. Two
Fig. 8. Bragg peak PL image of the proton beam at the SCDTL-1 output stored by CCs in a LiF crystal detector.

Fig. 9. PL intensity profile vs. proton penetration depth of the selected r.o.i. in Fig. 8. The 7 MeV beam Bragg peak is paramount, but also weaker PL peaks of the beam portion accelerated to energies higher than 7 MeV by SCDTL-1 are visible at distances greater than 300 μm (see text for details).

Fig. 10. PL image of the same exposed LiF sample shown in Fig. 8 acquired with a six-time longer exposure time.

Fig. 11. PL intensity profile of the selected r.o.i. in Fig. 10, where Bragg peaks of the proton beam portion accelerated to energies higher than 7 MeV by SCDTL-1 are clearly visible.

Fig. 12. Output beam energy distribution obtained by beam dynamics simulation. The arrows indicate the peaks corresponding to the measured energy values of Fig. 11.

regions of interest, r.o.i. #1 and r.o.i. #2, were selected on the PL image of Fig. 13 and their intensity profiles are reported in Fig. 14, where the energy values provided by SRIM are also reported for the Bragg peaks, in good agreement with the expected values.

4.3. SCDTL-3 output

Modules SCDTL-2 and SCDTL-3 accelerate the proton beam up to 18 and 27 MeV, respectively. LiF detectors have been used to characterize the beam at the exit of SCDTL-3 both in terms of transverse intensity and energy distribution. Fig. 15 shows the 27 MeV beam image, that is the transversal beam intensity distribution, obtained by exposing the LiF crystal surface perpendicularly to the beam propagation direction. The LiF crystal has been positioned 5 cm after the linac Titanium exit window (50 μm thick). Fig. 16 reports the beam measured profiles, x-distribution and y-distribution, obtained by integrating the beam intensity along y and x, respectively. The analysis of the measured profiles, which result normalized to the integrated beam intensity (that is the profiles area, see Fig. 16), gave a horizontal r.m.s. value \( \sigma_x = 1.18 \) mm and a vertical r.m.s. \( \sigma_y = 0.67 \) mm. The comparison with the computed spot image (see Fig. 17) shows a good agreement, in terms of
spot size and shape, with the only difference given by a displacement of the horizontal position of the centroid in the measured horizontal distribution (see Fig. 18), due to a slight misalignment in the focusing line.

Concerning the Bragg peak imaging, the proton beam was analyzed both at a distance of 5 cm from the exit window of SCDTL-3 and at a distance of 1 m. The former position is used for irradiating samples by a narrow beam, while the latter is used for irradiating up to 1 cm$^2$-wide samples by a homogeneous beam [17], as a homogeneity around 5% is achieved by exploiting the natural broadening of the beam in air. The above mentioned sample positions are called “Horizontal Line 1” (HL1, see Fig. 19) and “Horizontal Line 2” (HL2, see Fig. 20), respectively.

4.3.1. Bragg peak imaging at 5 cm distance from the exit window (HL1)

At the output of SCDTL-3 two nominal beam energies are available: 18 MeV and 27 MeV. The energy of the 27 MeV beam can be reduced to 18 MeV by switching off the RF power in SCDTL-3, as the PMQ lattice in SCDTL-3 is able to transport also the 18 MeV beam accelerated from 11.6 to 18 MeV by SCDTL-2. The duration of the output beam pulse is 4 μs, because the particles in the injected 25 μs-long pulse, not overlapping in time the 4 μs RF pulse, are filtered by the first two SCDTL modules. SRIM calculations performed for 18 and 27 MeV beams, in our experimental conditions, gave the Bragg peak depth in a LiF crystal target at 1620 and 3360 μm, respectively. Figs. 21 and 22 show the Bragg peak image with SCDTL-3 RF on and off, respectively and some regions of interest, selected for the analysis of the PL intensity profiles, are reported in Figs. 23 and 24. The r.o.i. #1 in Fig. 21 selects the central part of the beam with the highest current value and its corresponding PL intensity profile is reported in Fig. 23, where it is compared with the PL intensity profile of the r.o.i. selected in Fig. 22, showing the Bragg peak imaging of the 18 MeV beam coming out of the SCDTL-3 with the RF switched off, so just propagating through it. The Bragg peak distances from the crystal edge for the beams accelerated to 18 and 27 MeV were found to be at (1581 ± 7) μm and (3387 ± 7) μm, respectively, in rather good agreement with the values obtained by SRIM (1620 and 3360 μm, respectively).
Table 4

<table>
<thead>
<tr>
<th>Bragg peak distance (LiF imaging) (μm)</th>
<th>Beam energy (by SRIM) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1940 ± 7 (BP)</td>
<td>20.00 ± 0.04</td>
</tr>
<tr>
<td>2174 ± 7 (BP)</td>
<td>21.20 ± 0.04</td>
</tr>
<tr>
<td>2527 ± 7 (BP)</td>
<td>23.10 ± 0.04</td>
</tr>
<tr>
<td>3390 ± 7 (BP)</td>
<td>27.00 ± 0.04</td>
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In Fig. 21 not only the Bragg peak at 27 MeV energy is present, but also other peaks, corresponding to lower-energy beam components, which are more clearly visible in the r.o.i. #2, whose intensity profile is reported in Fig. 24. SRIM simulations, providing the beam energies corresponding to such peaks, are reported in Table 4. At these energies, an indetermination of the peak position of ±7 μm (determined as explained in Section 4.1) corresponds to an indetermination of the beam energy ±0.04 MeV.

Another measurement was performed after shifting the RF phase in the SCDTL-3 structure by 20°. The resulting Bragg peak imaging of the output beam is shown in Fig. 25, while the PL intensity distribution corresponding to the selected r.o.i. is reported in Fig. 26, compared with the one reported in Fig. 24 (no phase shift). Although the intensity distribution of the different energy beam components, reported in Table 4, is very sensitive to the used RF phase, only the relative peak intensities are changed in the PL profile, not their positions, and then their energies.

The presence of the lower-energy Bragg peaks can be explained by taking into account that, in each pulse, protons do not experience the electric field at their regime values while going through the three accelerating modules, because the accelerating field rise-time, being proportional to the quality factor Q of the resonator structure, increases from SCDTL-1 to SCDTL-3. This can be observed in the oscilloscope traces corresponding to the field pick-up signals of the three SCDTL structures (see Fig. 27). Consequently, when the SCDTL-1 and SCDTL-2 fields reach their regime values, the field in the SCDTL-3 has not yet completely raised. As the proton energy is strongly dependent on the field levels in the accelerator and the PMQ transport channel inside the SCDTL-3 is able to propagate also protons with an energy lower than the design value, a portion of the beam pulse consists of protons with energy lower than 27 MeV. This portion is expected to be partially filtered by the next structure (SCDTL-4). Fig. 28 shows the output beam current measured by a FC at the output of SCDTL-3 in two different conditions. In the first case a 0.5 mm thick aluminum slab was placed before the FC, to stop only secondary electrons of few hundred keV extracted by the high electric fields in the end parts of the structures; in the second case the slab thickness was 3.3 mm, which is slightly less than the penetration range in aluminum for 27 MeV protons. In the first case FC measurements (blue curve) gave the total charge exiting from the accelerator, but in the second case (green curve) only 70% of the pulse (corresponding to the charge effectively accelerated to the design energy of 27 MeV) is able to cross the aluminum slab, the remaining 30% being completely stopped, because consisting of lower energy protons. The secondary Bragg peaks revealed by the PL measurements in the LiF crystal detector (see Figs. 21 and 25) can be ascribed to protons exiting the accelerator in the first part of the pulse. A more quantitative analysis is reported in the next paragraph.

4.3.2. Bragg peak imaging at 1 m distance from the exit window (HL2)

At 105 cm from the exit window of SCDTL-3 the proton beam, naturally expanding in air, becomes an approximately round beam with a r.m.s. size of about 15 mm on both directions. Fig. 29 shows the...
Bragg peak image obtained with a LiF crystal detector. In HL1 the 10 mm long crystal side exposed to the proton beam plane intercepted the whole beam, but in this case it intercepts only the uniform part of the beam. The measurement results in HL2, reported in Fig. 30 (PL intensity profile) and Table 5, show that beam propagation through 105 cm of air reduced the energy of the different beam components (see Table 4 for comparison). However, unlike in HL1, where the shape of the Bragg curve is strongly affected by the transverse beam intensity distribution, in HL2 the curve does not depend on the position of the r.o.i. due to the beam uniformity. This means it is dominated by chromatic effects, that is the variation of stopping power with energy,
range straggling and beam energy spread. As the last one is due to accelerator characteristics, the measurement of the PL intensity profile provided by the Bragg imaging was used to reconstruct the energy spectrum of the beam in vacuum at the accelerator output immediately before the vacuum window, to investigate in detail the intensity of the low-energy components giving rise to the secondary peaks in the LiF detectors images. This analysis was performed by modeling the proton beam with two different codes. At first, the multi-particle beam dynamics code “LINAC” [18], typically used to design the accelerator, calculated the longitudinal and transverse motion of the beam from the injector to the SCDTL-3 output; then, the SRIM code, typically used to calculate proton interactions with matter, took the output coordinates in the 6-dimension phase space of the particles computed by LINAC and transported them through a sequence of layers consisting, as in our experimental conditions, in a 50 μm-thick Titanium window, a 105 cm-long path in air and the LiF crystal target. A number of different simulations was performed, in order to reproduce the pattern in Fig. 30, taking into account the fact that the pulsed proton beam depends on the beam energy distribution that changes during the pulse, according to the electric field amplitude in the accelerating structures. As reported in paragraph 4.3.1, the SCDTL-3 field reaches its regime value with a delay of about 0.5 μs respect to the fields in the previous two structures, so different beam dynamics simulations were performed by varying the SCDTL-3 field (Efield3) from 80% to 100% of the design value, after extracting the corresponding values inserted in the simulation for the fields in SCDTL-1 and SCDTL-2 from the electric field peak-up measurements shown in Fig. 27. The results in terms of particle energy distribution were grouped into two main sets, as shown in Fig. 31: a first set with 0.85 < Efield3 < 0.94 and a second set with Efield3 > 0.94, where Efield3 is defined as the electric field in SCDTL-3 normalized to its design value. The value Efield3 < 0.85 was not considered, because the corresponding field amplitude in both SCDTL-1 and SCDTL-2 is still too low to allow particle transport up to the SCDTL-3 exit, while Efield3 = 0.94 is the threshold value to achieve acceleration to 27 MeV. Fig. 32 shows the ionization curves in LiF, corresponding to the different Efield3 value ranges (magenta and black curves), as computed by SRIM code. After proper weighting, they were summed to give the blue curve, which is in good agreement with the pattern measured by the LiF detector, as shown in Fig. 33, confirming the origin of the measured secondary peaks that was qualitatively explained in Section 4.3.1.

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<td>1666 ± 7 (BP2)</td>
<td>18.10 ± 0.04</td>
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<tr>
<td>2008 ± 7 (BP3)</td>
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<td>2895 ± 7 (BP4)</td>
<td>24.65 ± 0.04</td>
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Fig. 25. Bragg peak PL image of the 27 MeV proton beam at the SCDTL-3 output, after a 20° RF phase shift, stored by CCs in a LiF crystal detector.

Fig. 26. PL intensity profiles vs. proton penetration depth of the selected r.o.i. in Fig. 25 (27 MeV beam, SCDTL-3 with 20° RF phase shift) and of the r.o.i. #2 in Fig. 21 (27 MeV beam, no phase shift).

Fig. 27. Oscilloscope traces of the electric field pick-up signal in the three SCDTL structures.

Fig. 28. Oscilloscope traces of the Faraday Cup signal proportional to the output proton current. The FC signal is a voltage read on $R = 50 \, \Omega$, corresponding to a scale of 20 μA/mV.

Table 5

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5. Conclusions

Solid-state radiation detectors based on the photoluminescence of radiation-induced point defects in LiF crystals have been used for proton beam characterization during the commissioning of the segment up to 27 MeV of the TOP-IMPLART linear accelerator. The high intrinsic spatial resolution and wide dynamic range of the LiF crystal detectors, together with the good efficiency of visible emission of the \( F_2 \) and \( F_3^+ \) CCs, allowed obtaining two-dimensional images of the beam transverse intensity distribution by a conventional optical fluorescence microscope as reading instrument. Moreover, using LiF crystals irradiated in a particular geometry, the CC fluorescence microscope images provided a direct imaging of the Bragg peak position with micrometric precision, which gives an estimation of the energy components of the impinging proton beam on the basis of comparison with SRIM simulations. By adjusting the acquisition parameters of the reading fluorescence microscope and exploiting the stability of the optically active CCs at RT, the PL peak intensity features of interest can be highlighted and identified, measuring their positions. In this way, both transversal intensity distribution and energy spectrum, during the assembly and commissioning of the segment up to 27 MeV of the linear accelerator, in different layout configurations and operating conditions, were obtained.

In conclusion, these measurements performed by LiF crystals, used as passive radiation detectors, allowed quantitatively describing the proton beam characteristics (number and energy values of the components) and verifying its propagation dynamics in the linac after comparison with simulations.

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