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COMMISSIONING OF THE 71 MeV BEAM DELIVERY LINE OF THE TOP-IMPLART ACCELERATOR*

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Abstract

TOP-IMPLART is a pulsed RF proton linear accelerator in operation at the ENEA Frascati Research Center originally built as a technological demonstrator for a full linear solution to proton therapy, it is currently evolving towards a facility available to research and industrial users in different fields, ranging from biomedical to aerospace applications. It consists of a commercial AccSys PL7 model 425 MHz injector followed by eight SCDTL accelerating modules operating at 3 GHz. Proton beams in the range 1-6 MeV are available from a vertical delivery line placed at the exit of the injector, and at 63 MeV or 71 MeV (intermediate and lower energies are achieved by degraders) from a horizontal delivery line at the exit of the accelerator, where a pulse current variable up to 25 µA is provided in pulses 2.5 µs long at a typical repetition rate of 25 Hz. Our contribution presents the first experimental results from the commissioning of the high-energy line. It is a multi-purpose in-house designed line featuring a magnetic scanning system and a set of instrumentation, diagnostics, and target positioning frames placed on motorized platforms allowing for customizable irradiation setups.

INTRODUCTION

TOP-IMPLART linac is a pulsed proton linear accelerator in operation at the ENEA Frascati Research Center. It was developed as part of the TOP-IMPLART Project [1], funded by Regione Lazio, in collaboration with the Italian Institute of Health (ISS) and the Regina Elena-IFO oncological hospital in Rome to become a technological demonstrator for the full linear approach to proton therapy.

The accelerator is composed of a 425 MHz injector linac, followed by eight SCDTL modules operating at 2998 MHz. The maximum energy available at the output window is 71 MeV. However, it is possible to achieve a secondary energy level of 63 MeV by turning off the radiofrequency in the last accelerating module. Intermediate and lower energies can be obtained using passives degraders. The beam is delivered in pulses with 2.4 µs FWHM (Full width Half Maximum), at a typical repetition rate of 25 Hz.

The proton beam is used in radiobiology experiments—with output energies corresponding to a water-equivalent range of 30 to 40 mm—as well as in radiation hardness testing of electronic devices and assemblies. The beam at the accelerator exit window has a diameter of approximately 3 mm FWHM. Irradiation of larger samples can be accomplished either by using a passive scatterer (lead foil), which enlarges the irradiated area at the expense of fluence and dose rate, or through a magnetic scanning system integrated into the delivery line.

The line, designed at ENEA [2] specifically for the TOP-IMPLART beam, has been fully installed, and has undergone preliminary commissioning tests.

71 MEV BEAM DELIVERY LINE

The delivery line, illustrated in Fig. 1, begins with an extraction section located at the accelerator's output, which includes two permanent magnet quadrupoles (PMQs) and non-interceptive diagnostic devices.

The primary function of the extraction section is to shape the beam into a circular profile with a 3 mm FWHM diameter at the accelerator's exit and to measure its intensity. Beam intensity is monitored using a low-noise, dual-core current transformer (model ACCT-CF1"1/3-7-20-UHV-2CORE by BERGOZ) and a passive cavity detector [3].

The beam exits the extraction section through a 25 µm-thick titanium window and travels approximately 13 cm through air. In this region, a custom-built integral ionization chamber (IC) monitors the pulse charge, enabling dose-controlled irradiation.

After the IC, the beam reaches a remotely operated platform equipped with different diagnostics and control components: a Faraday collector [4], a scattering foil holder, an optical spot measurement system (telescope), and an open slot that allows the beam to continue to the end of the delivery line. The Faraday collector functions as a beam shutter, blocking the beam from reaching the target and enabling verification of the machine setup. Positioned in front of the collector, a 19 mm-thick aluminum block stops protons with energies below 70 MeV, allowing only higher-energy protons to be collected. By comparing the total beam current measured by the energy-insensitive current transformer with the current detected by the Faraday collector, the fraction of protons with energies above 70 MeV can be estimated [5]. Agreement between both measurements confirms that all protons in the pulse have the correct energy and that the accelerator is properly set (the aluminum block is replaceable with a 16 mm one for the 63 MeV beam). Once the beam exits the platform, it enters an X-Y

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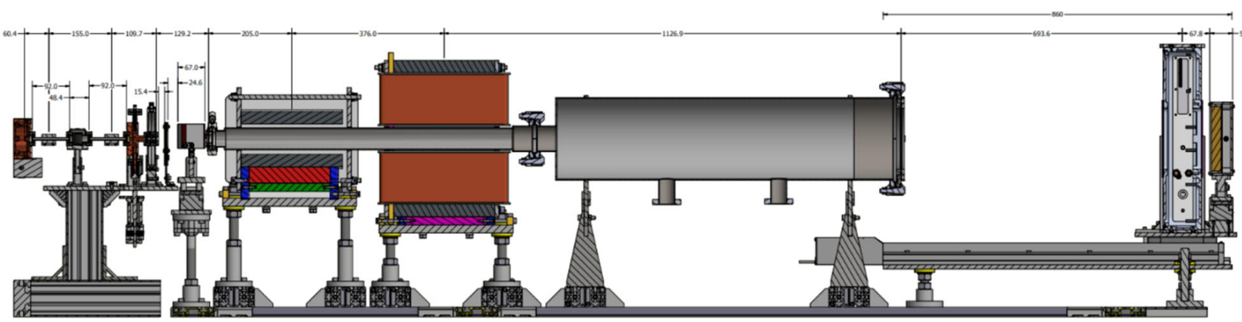

Figure 1: CAD drawing of the TOP-IMPLART delivery line. All dimensions are in mm.

magnetic scanning system that deflects the 71 MeV proton beam over a maximum area of 10 cm × 10 cm, at 2.5 meters from the accelerator window—conventionally referred to as the target plane. To preserve beam quality, a 1.7-meter-long helium-filled pipe is placed within the magnet gap and is supplied by a semi-automatic system that monitors the internal pressure.

The pipe is sealed from the external environment with aluminum-coated Mylar windows (20 µm Mylar, 2 µm aluminum coating). The 200 mm diameter of the exit window precludes the use of vacuum inside the pipe, as the pressure differential could cause the window to rupture.

After exiting the scanning pipe (see Fig. 2), the beam travels through air for 63 cm to reach the target plane. At this location, a commercial 2D ionization chamber (De.Tec.Tor model FlashQ [6]) with a 13 cm ×13 cm sensitive area is used to measure the beam spot centroid position and width. The FlashQ device includes four channels: two integral channels with different gain settings to extend the dynamic range, and two 128-strip channels with 1 mm pitch—one oriented along the X direction and the other along the Y direction.

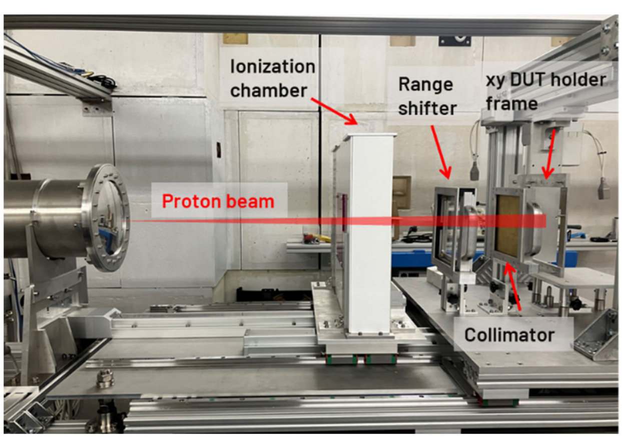

Figure 2: Delivery line past the scanning pipe exit during commissioning. The FlashQ chamber is positioned at the reference plane, followed by the target positioning platform.

The FlashQ is mounted on a linear actuator that allows it to travel along the beam axis, from the pipe exit up to 70 cm further downstream—passing through the target plane. This configuration enables beam alignment checks and, during irradiation, allows it to be retracted toward the pipe exit to clear the path and position the target at the intended location.

To protect the target during setup and testing—particularly in the absence of a dedicated delivery room—a remotely operated shutter measuring 13 cm × 13 cm is installed behind the FlashQ. This shutter also functions as a Faraday collector. The target positioning platform is equipped with a collimator, a range shifter, and a motorized cartesian frame used to expand the irradiated area.

PENCIL BEAM CHARACTERIZATION

During the initial phase of commissioning, the pencil beam was characterized in terms of spot size and energy.

Taking advantage of the ability to move the FlashQ IC along a rail aligned with the beam propagation direction, the beam broadening in the air path after the scanning pipe was tracked from the pipe exit up to a distance of 73 cm. Figure 3 presents the results for the 71 MeV beam, showing that the beam spot reaches a size of approximately 25 mm FWHM at the target position.

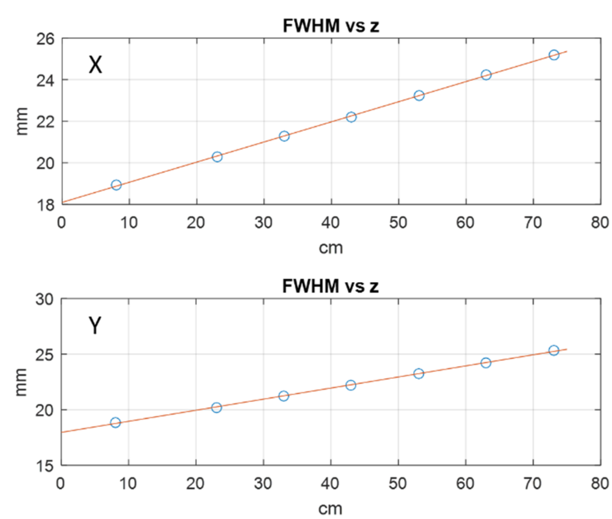

Figure 3: Pencil beam transverse dimensions in cm in X and Y direction measured with the FlashQ strip ionization chamber. Measurements are identified by circles.

At the target plane, the proton energy was also measured under two accelerator configurations: with the last accelerating module turned off and on. The measurements were performed using Bragg-curve analysis in lithium fluoride

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(LiF) crystals [7], yielding energies of 61.8 MeV (with an FWHM energy spread of 851 keV) and 69.3 MeV (with an FWHM spread of 986 keV), respectively. These values account for the energy loss caused by interactions with materials encountered along the beam path through the delivery line.

SPOT SCANNING FIRST TEST

Magnetic scanning was tested with the 71 MeV beam. The FlashQ detector was positioned at the target plane, with a radiochromic film mounted on its front surface. A vertical scan was carried out, delivering eight evenly spaced spots (50 % FWHM overlap) across the field of uniform intensity, controlled using the integral ionization chamber.

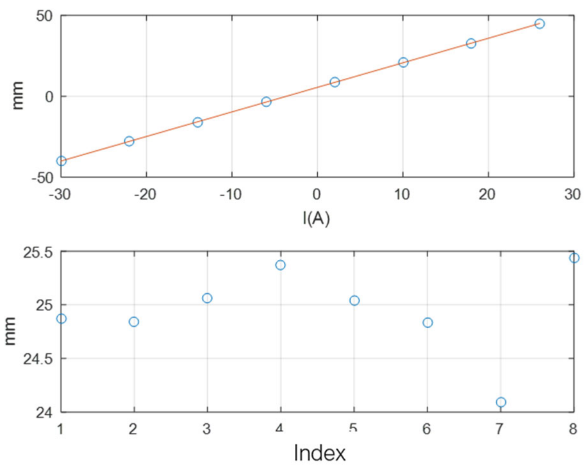

Figure 4: Pencil beam centroid positions (top) as a function of magnet driving current, along with corresponding FWHM spot sizes (spot index in abscissa). Measurements were acquired using the FlashQ detector.

Figure 4 presents the centroid positions and corresponding spot sizes (expressed as FWHM) for the eight scanned spots. Scanning across the full 10 cm × 10 cm area requires a maximum magnet current of 27 A. The assessment of spot size uniformity is limited by the 1 mm pitch of the IC strips and is, in fact, more accurate than the values reported in the figure.

Each spot in the scan was configured to deliver an equal dose in order to generate a constant intensity plateau. Figure 5 presents the positions and intensities of the scanned spots, expressed in ionization chamber counts, proportional to the delivered charge and regulated by the delivery control system.

To this end, the integral ionization chamber at the entrance of the delivery line monitors the charge of each pulse and stop irradiation (with single pulse resolution) once a predefined charge threshold is reached. Figure 5 shows the charge delivered to each spot, as recorded by the FlashQ ionization chamber, highlighting the accelerator's dose control precision.

The total dose delivered during the scan was recorded on a radiochromic film (left panel of Fig. 6) and compared to

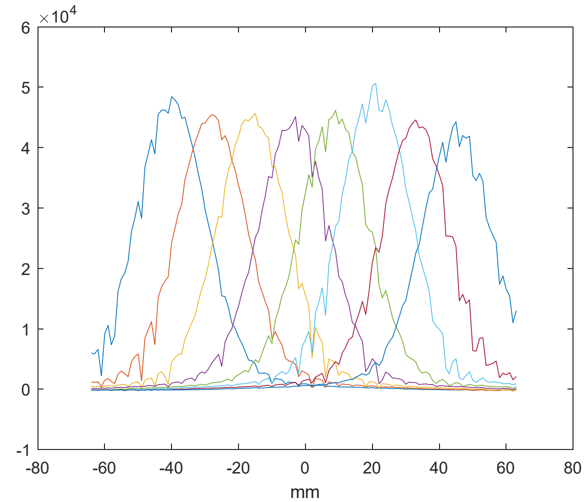

Figure 5: Intensities of the spot forming the scan as measured by the FlashQ in count units.

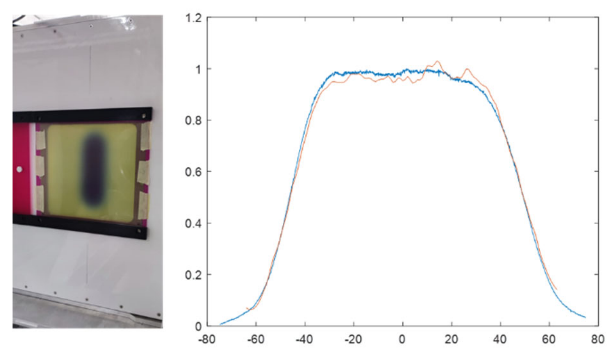

Figure 6: The left panel shows the scan pattern recorded on the radiochromic film. The right panel compares the normalized intensity profiles obtained from the film (blue curve) and from the sum of the FlashQ measurements (red curve).

the summed intensities of the individual spots measured by the FlashQ detector (left of Fig. 6), after a normalization.

CONCLUSION

Preliminary measurements of commissioning of the high-energy delivery line of the TOP-IMPLART accelerator has been presented, demonstrating its dose control and magnetic scanning capabilities. Horizontal scanning was also tested, yielding comparable results. Future work will focus on further characterization of the beam and automation of the irradiation process.

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