COMMISSIONING RESULTS OF THE TOP-IMPLART 27 MeV PROTON LINEAR ACCELERATOR*

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Abstract

The results of a 27MeV proton LINAC commissioning are presented. The LINAC, operating at the ENEA Frascati Research Center, consists of a 425MHz injector followed by a 3GHz booster. The injector is a commercial LINAC, the PL7 model produced by ACCSYS-HITACHI, composed by a duoplasmatron proton source with einzel lens, a 3MeV RFQ (Radio-Frequency Quadrupole) and a 7MeV DTL (Dritf-Tube LINAC). Wide injection current range (0-1.5mA) is obtained varying extraction and lens potentials. The booster LINAC consists of sequence of 3 SCDTL (Side-Coupled DTL) modules whose output energies are 11.6MeV, 18MeV and 27MeV, respectively. Each of the 3 modules requires less than 2MW peak power. All modules are powered by a single 10MW peak-power klystron. The output beam has been characterized at 10Hz PRF (Pulse Repetition Frequency) using fast AC transformers, Faraday cup and ionization chamber for current (and, by integration, charge) monitoring, whereas energy has been measured using a novel detector based on LiF (Lithium-Fluoride) crystals. Systematic measurements have been performed to investigate the sensitivity of output beam to machine operating parameters (SCDTL temperatures, stability of injector and RF power) highlighting the existing correlations. The LINAC is part of a 150MeV protontherapy accelerator under development in the framework of the TOP-IMPLART Project.

INTRODUCTION

TOP-IMPLART (Terapia Oncologica con Protoni – Intensity Modulated Proton Linear Accelerator for Radio Therapy) is a Regione Lazio (local government) founded project [1] for the development of a compact-size proton LINAC for cancer treatment with the main characteristics shown in table 1.

Table 1: TOP-IMPLART Accelerator Characteristics

Parameter	Value
Depth in tissue (max)	15 g/cm^2
Proton energy (max)	150 MeV
Dynamic energy variability	90-150 MeV
Dose rate	1-10 Gy/min

The TOP-IMPLART LINAC, is a 150MeV pulsed accelerator, under development at the ENEA Frascati Research Center, where it is currently under assembling and testing, inside a dedicated 30 meter concrete bunker.

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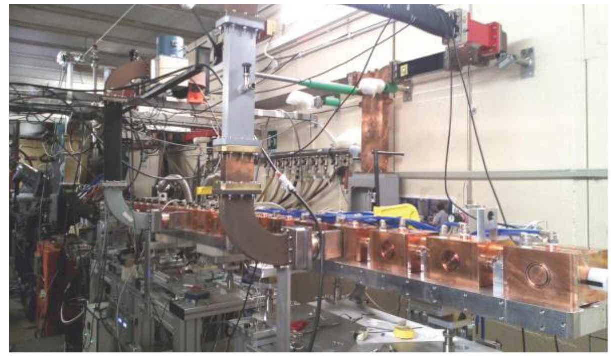

Figure 1: Actual layout of the TOP-IMPLART LINAC.

TOP-IMPLART is composed by two main sections: a commercial 7 MeV injector, produced by AccSys-Hitachi company, operating at 425 MHz, followed by a high-frequency booster operating at 2997.92 MHz designed by ENEA. The two frequencies have no harmonic relation and, thus, no RF synchronization between the sections has been adopted.

The injector is composed by a duoplasmatron ion source followed by an RFQ and a DTL. The booster is composed by SCDTLs [2,3] up to 65 MeV and CCLs up to 150 MeV. Actually only three, of the four SCDTLs (see Fig. 1) in the medium energy section are operational, reaching an output energy of 27MeV, with the fourth SCDTL expected to be installed by the end of the year, to reach 35MeV. The principal design parameters of the medium energy section are summarized in Table 2. The four SCDTLs are powered by a single TH2090 klystron tube (15MW peak-power, 15kW average) installed into a PFN (Pulse Forming Network) modulator developed in around 1990. Klystron and modulator have been adapted to the requirements of the TOP-IMPLART project and integrated into the accelerator.

The pulse length is 15μs-80μs for the injector and, 1μs-4μs for the booster. The PRF can be varied between 1 and 100Hz. In its present layout, closed loop feedback is fully operational in the duoplasmatron source (current control) and in the RFQ (frequency, phase and amplitude feedback), and only partially in the DTL (only frequency and phase feedback). The booster section operates in open-loop.

Table 2: Medium Energy Section Characteristics

SCDTL #	1	2	3	4
# tanks	9	7	7	5
Cells/tanks	4	5	6	6
Bore Hole diameter (mm)	4	4	5	5
Total Length (m)	1.12	1.1	1.4	1.1
Output Energy (MeV)	11.6	18	27	35

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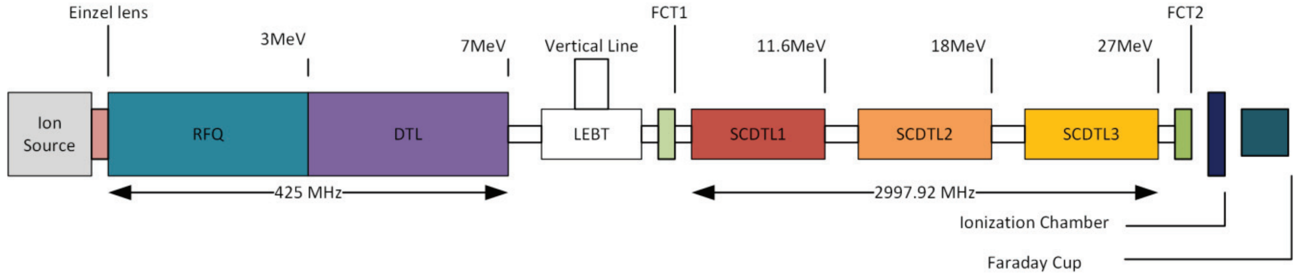

Figure 2: Schematic layout of the part of the TOP-IMPLART LINAC actually in operation.

Beam Diagnostics Instrumentation

TOP-IMPLART application requires precise control of output beam, current (and charge), energy, and position, those parameters are subject to measurement during all the construction of the accelerator.

The principal diagnostic implemented in the booster section consists of two AC current transformers ("FCT1" and "FCT2" in Fig.2) to measure the input and output current, respectively. The output transformer operates at atmospheric pressure (outside the vacuum pipe) and can be moved as long as the accelerator construction progresses. The current transformers have been produced by Bergoz Instrumentation according to the specification provided by ENEA. Table 3 summarizes their main characteristics (mechanical and electrical). The short axial length of the transformer has been one of the specification allowing for integration in the space between SCDTL sections, without significantly altering the spacing in the FODO lattice.

The transformers have been provided with calibrated amplifiers to obtain an overall gain of 1000V/A over a 1MΩ load, with a negligible droop for µs-duration pulses.

Output current and charge are also measured by a Faraday cup and a ionization chamber, the latter designed by ISS (Istituto Superiore di Sanità, Roma), operating at a bias voltage of 200V. Electrodes are realized with aluminated mylar (12µm mylar, 4µm aluminum). Electrodes spacing is 2mm. This redundancy is necessary as the low current level in the booster section (10-40µA) is almost at the bottom of the sensitivity of the current transformer.

A new multielectrode chamber is under development [4].

Table 3: ACCT Main Characteristics

Parameter	Value
Mechanical	
Outer Diameter	95 mm
Inner Diameter	10 mm
Bore Hole	6 mm
Axial Length	20 mm
Electrical	
Bandwidth (3dB)	>1 MHz
Gain (1MΩ load)	10V/10mA
Droop	<0.45%/ms
Output noise (mean)	<500µV
Output noise (stdev)	<2mV

Beam energy is measured by analyzing the Bragg peak position in a lithium fluoride (LiF) crystal. Commercially available 10x10 mm^2, 1 mm thick polished crystals have been positioned with the polished faces parallel to the beam propagation direction. The protons lose energy interacting with the crystal and creating color centers whose density is proportional to the dose [5]. As such centers emit visible photoluminescence after irradiation in the blue spectral range, by a fluorescence microscope equipped with a sCMOS camera the visible image of the irradiated LiF crystal is acquired: the photoluminescence intensity is proportional to the energy lost by protons in the crystal and the beam energy is obtained by measuring the distance between the crystal border and the intensity peak. The energy reference values are obtained by SRIM/TRIM simulations. Beam position and dimension are obtained from image analysis of the spot generated by the beam on a fluorescent target. The spot image is acquired by a monochromatic digital camera Basler model acA640-120gm equipped with an F2/35mm lens, each pulse, synchronously with the pulse trigger and digitized.

COMMISSIONING RESULTS

Commissioning of the 27MeV beam has been carried on observations spanning from 5 to 20 minutes after a warm-up time of 2 hours.

Injector Stability

The current provided by the injector is controlled varying the voltage on an einzel lens placed after the ion source. Figure 3 shows the current, measured on FCT1, at different lens voltages, keeping the extraction voltage constant at 28.4kV.

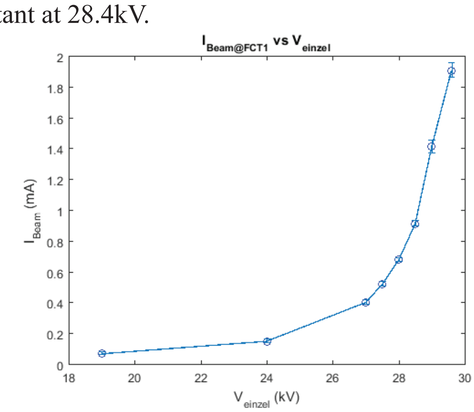

Figure 3: Injector beam current at different einzel potentials. Error bars represent 3 standard deviations.

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Data analysis reveals that the variation of the injector current is below 3% (3σ) for einzel voltages down to 27kV.

An increase of variability is observed at lower voltages (and beam current) that is, most probably, due to the noise level in the system. The stability of the injector current is determined by the stability of the current generated by the ion source and of the fields in the RFQ and DTL.

In order to identify the sources of variability, the above mentioned parameters have been analyzed.

The proton current, generated by the ion source, is measured by the injector electronics and presented as a voltage signal proportional to the current. This signal has a mean of μ=2.01V and a standard deviation of σ=0.01V (corresponding to 1.5% at 3σ), roughly half of that of beam current. The remaining part of the variability is due to the variability of the RFQ and DTL fields.

Figure 4 shows the results of the spectral analysis of the measurements for a lens voltage of 29.6kV: The injector current periodogram (top panel) shows peaks in two regions. The first region extends from 0Hz to 0.7Hz and the second from 2.1Hz to 2.2Hz. The center and bottom panels clearly show that the spectral components in the first region are due to the arc current (the ion source), whereas the one in the second region to the DTL field. No significative spectral components have been identified for the RFQ. The peaks present in DTL field can be attributed to the missing amplitude feedback loop.

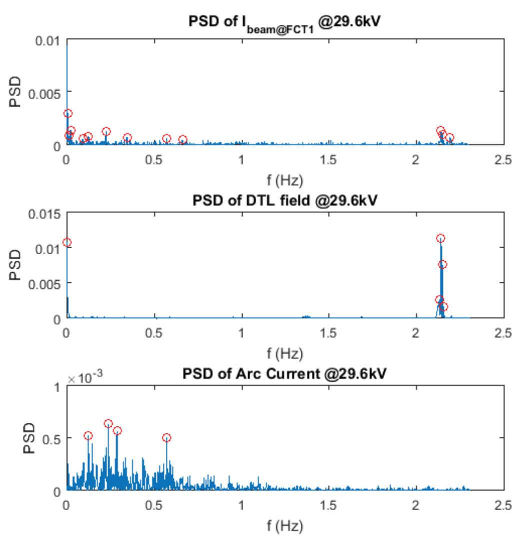

Figure 4: Power Spectral Density of the injector current (top panel), DTL field signal (center panel) and, arc current (bottom panel).

RF Power Stability

Figure 5 shows the RF distribution network of the medium energy section of the 3GHz booster. Full description of the RF generation and distribution network of the TOP-IMPLART LINAC is presented in [6]. The variable power dividers PD1 and PD2 sets the correct RF level for the SCDTL structures and the phase relations are established by the phase shifters PS1 and PS2.

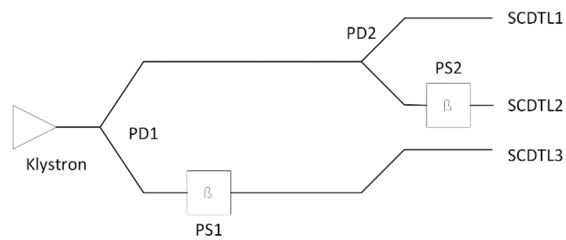

Figure 5: Schematic representation of the RF drive system for the medium energy section, in the present layout.

The peak power at the input of PD1 and electromagnetic field envelope for the three SCDTLs have been measured (Fig. 6): the power at PD1 input is 6.3MW (5% stability) with a temporal evolution shown in the top left panel.

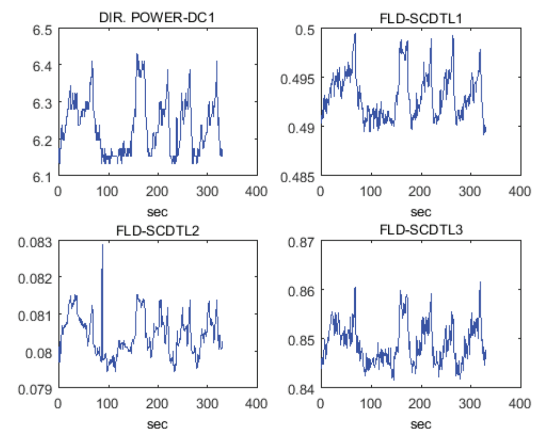

Figure 6: RF power (MW) at the input of PD1 (top left) and electromagnetic fields envelope (V) in the three SCDTLs.

SCDTL field are measured by a loop pickup placed in the accelerating tanks connected to a detector diode. The values in Fig. 6 are the voltage developed on the diodes at 50Ω load. The stability of the fields is better than 2.7%.

Beam Energy

Beam energy, as measured using the LiF crystal, is shown in Fig. 7.

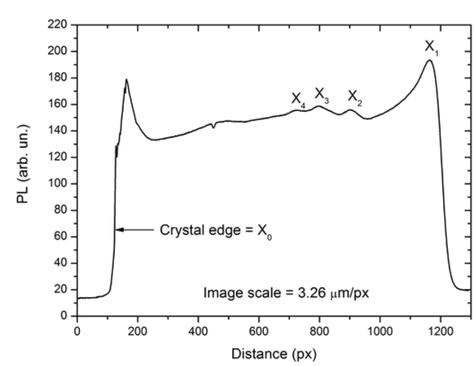

Figure 7: Photoluminescence intensity profile in LiF.

The intensity profile shows four peaks at different positions in the crystal. X1 is the Bragg's peak corresponding to an energy of 27MeV (energy has been computed with SRIM). Table 4 reports all peaks energies.

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Table 4: Beam Energy Peaks in LiF

Peak #	Distance (µm)	Energy (MeV)
X_1	3390±4	27
X_2	2356±4	23.1
X_3	2194±4	21.2
X_4	1956±4	20.0

Spot Size and Centroid Stability

The output beam is elliptical, with the horizontal axis larger than the vertical one. This is consistent with the quadrupole arrangement in SCDTL3, as the last quadrupole focuses on the vertical axis. Spot size and position of the centroid has been evaluated for three different einzel lens voltages: 29.6kV, 27.5kV and 20kV. Spot size does not change in all three measurements. The horizontal and vertical axes measure (average value ±1 standard deviation) σ_x=1.56±0.0092 mm and σ_y=1.17±0.0054 mm.

Spot centroid position shows a slight dependence with the einzel lens voltage that is lower than 150µm in the x direction and 60 µm in the y direction. The temporal analysis of beam position reveals a correlation between x and y centroid position oscillation as it is shown Fig. 8 for an einzel lens voltage of 27.5kV. This correlation is the consequence of the rotation of one or more quadrupoles in the accelerator.

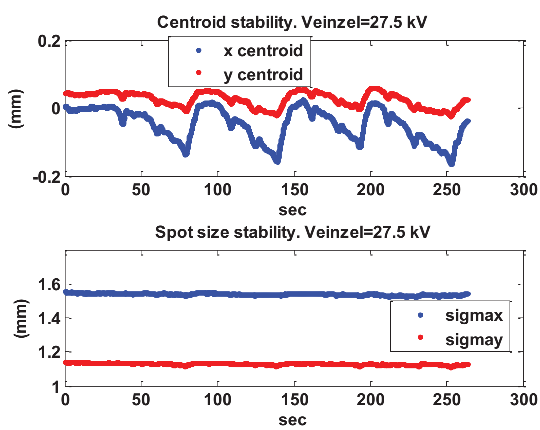

Figure 8: Centroid position and stability vs time for einzel lens voltage of 27.5kV.

Output Beam

The current and charge of the 27MeV beam has been measured. Current measurements have been performed using both the Faraday Cup and FCT2, placed after a 500µ thick aluminium spacer inserted to stop secondary electron emission from the beam pipe. Figure 9 shows that both measurements agree on the pulse current value of 40µA (the Faraday cup develop 2mV on a 50Ω load). The lower bandwidth of the FCT2 is evident from the comparison of signal rise times, nevertheless is sufficient to reach the final amplitude level for the 3.2µs TOP-IMPLART pulse width.

The ionization chamber has been used to measure the output pulse charge. Figure 10 shows the measured charge for different values of the einzel lens voltage.

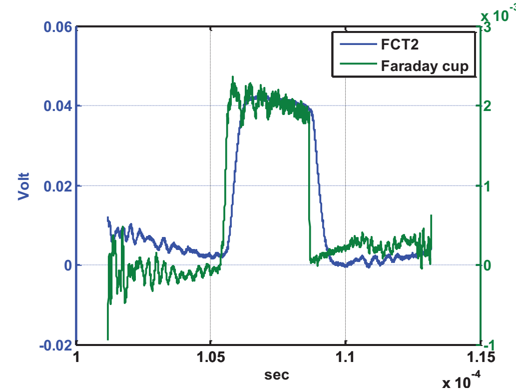

Figure 9: 27MeV current pulse measured by FCT2 and the Faraday Cup (terminated on 50Ω impedance).

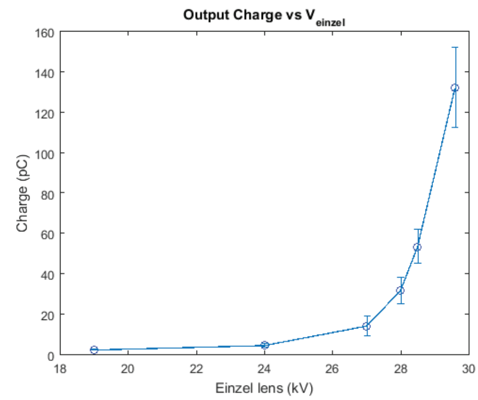

Figure 10: 27MeV beam pulse charge versus einzel lens voltage (Error bars represent 3 standard deviations).

CONCLUSION

The commissioning results for the 27MeV beam of the TOP-IMPLART accelerator have been presented. The accelerator is undergoing a major upgrade consisting in the completion of the medium-energy section, the replacement of the old klystron and modulator with a TH2157A 10 MW peak power klystron and the K1 solid state modulator produced by SCANDINOVA. Feedback loop for the new system will be installed and tested to improve the stability.

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