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STATUS OF THE TOP-IMPLART PROTON LINAC

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Abstract

The TOP-IMPLART (Intensity Modulated Proton Linear Accelerator for Radio Therapy) proton linac, is a RF pulsed linac, designed for proton therapy, consisting of a low frequency (425 MHz) 7 MeV injector followed by a sequence of accelerating modules operating at 3 GHz under construction, assembly and test at the ENEA Frascati Research Center. The accelerator features also a vertical low energy (3-7 MeV) line for irradiation of samples in horizontal position. The segment currently completed includes 8 SCDTL modules up to 71 MeV grouped in two sections each one powered by a 10 MW klystron driven by a SCANDINOVA K100 modulator with a variable pulse length (1-5 us) at a repetition frequency of 25 Hz. The output current can be varied up to 30 μA. The beam is mainly used for radiobiology experiments and dosimetry systems tests, but the flexibility in beam characteristics makes it suitable also for applications different from proton therapy, as the irradiation of electronics components to verify their behavior in the space environment. In this work, the current status of the accelerator and beam characteristics measurements are presented with an overview of the experiments carried on it.

INTRODUCTION

The TOP-IMPLART linac is a pulsed proton linear accelerator under construction and commissioning at the ENEA Frascati Research Center in a partnership with the Italian Institute of Health (ISS) and the oncological hospital Regina Elena-IFO in Rome. Accelerator development is funded by Regione Lazio with the aim of developing a technological demonstrator for a linear accelerator for proton therapy. The final particle energy expected for the TOP-IMPLART linac is 120 MeV, the maximum achievable energy compatible with the available space in the 27 meters long ENEA bunker.

Linac development and construction has been intermixed with experiments directed to optimize beam delivery strategies and design beam diagnostic systems adapted to the peculiar beam pulsed structure.

THE TOP-IMPLART LINAC

The TOP-IMPLART linac (see Fig. 1) is composed by a commercial injector, PL-7 model, developed by AccSys Technology Inc. (Pleasanton (CA), USA) and an high frequency booster composed of two SCDTL (Side Coupled DTL) sections designed by ENEA. PL7 is a 7 MeV linac consisting of a compact duoplasmatron H^+ ion source working at a voltage of 30 kV.

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The beam extracted from the source is focused by an einzel lens into a 3 MeV RFQ followed by a 7 MeV DTL, each powered by a 350 kW triode based amplifier. The nominal operation frequency of the injector is 425 MHz (with a tuning range of ±100 kHz).

The high frequency booster consists of two sections of 4 SCDTL accelerating module each. The first section accelerates the beam to an energy of 35 MeV and the second one to an energy of 71 MeV. Each section is powered by a 10 MW peak power klystron amplifier operating at a frequency of 2997.92 MHz (S-band). The main beam parameters are listed in Table 1.

The output beam current can be varied by changing the voltage on the einzel lens in the injector or acting on the length or the temporal superposition of the two klystrons pulses. A magnetic scanning system is under realization and will be installed to test and demonstrate the implementation of 4D irradiations based on active control of energy and intensity and x-y spot scanning.

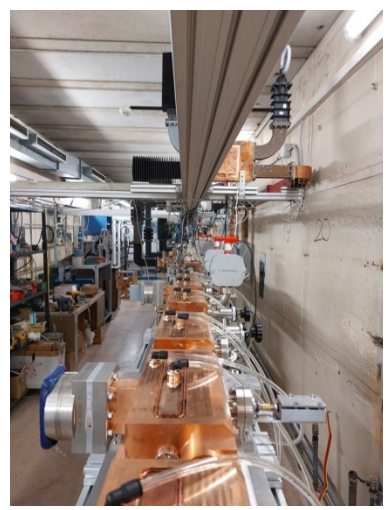

Figure 1: TOP-IMPLART linac.

Table 1: Main Beam Parameters

Parameter	Value
Max. Output Current (pulsed)	30 μA
Beam pulse width	1 -5 μs
Beam pulse repetition rate	10 – 100 Hz
Beam size at the linac output	<3 mm

The MEBT line features also a vertical extraction line for the injector 3-7 MeV beam consisting of a 90° bending magnet directing the beam toward the ceiling for irradiation of samples that must stay in horizontal position, like cell cultures in Petri dishes.

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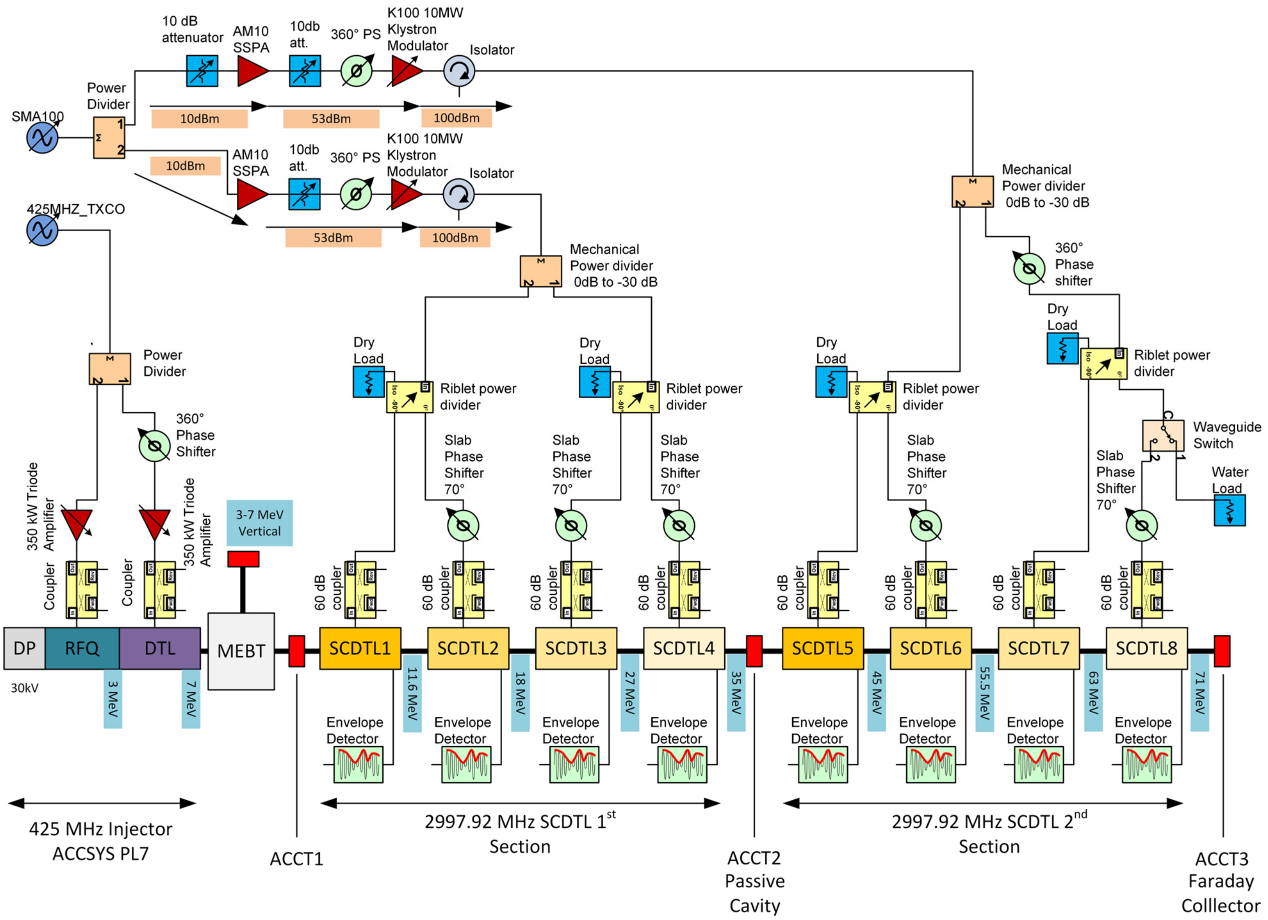

Figure 2: TOP-IMPLART linac schematic representation showing RF distribution network and beam diagnostics.

TOP-IMPLART RF Distribution

Radiofrequency generation and distribution is shown in Fig. 2. Injector and booster RF systems coexists independently. The high frequency booster is powered by two Canon E37325, 10 MW, S-band klystrons, installed into Scandinova K100 modulators. The modulators have been fitted with an amplitude and phase control system to provide correct RF phasing to the accelerating modules. The RF power is delivered to the accelerating modules using a two levels corporate-type distribution network consisting of WR284 waveguides and components filled with SF6 (Sulfur Exafluoride) at a pressure of 1.5 bar. All components are motorized to perform small adjustments during operation. The top level of the network splits the power between couples of modules using high power three-hybrids power dividers. This solution has been chosen to operate the linac with an incomplete section where not all four modules are present, a situation that occurs during commissioning. The second level delivers the correct power to each module. The power dividers in this levels are variable 3dB hybrids made by ENEA following the design in [2]. Correct phasing between the modules of each section is guaranteed by a dielectric slab phase shifter (with a an achievable phase shift of nearly 70 deg.) in the last three modules of each section. The RF distribution network of the 2nd section differs from the first one because a 360° phase shifter is used after the top level power divider and because a waveguide switch is used to turn off SCDTL8. Both components are used to test energy modulation of the beam, by deviating RF power or by altering the phase in an accelerating module.

RF power delivery to structures is controlled sampling the forward power, reflected power and cavity field envelopes of each module.

TOP IMPLART Beam Diagnostics

Pulse current is monitored along the linac in three different positions, using AC current transformers and a passive cavity [3]. The injected current is measured at the output of the MEBT using an AC current transformer (ACCT1 in Fig.1). The second measurement position is at the output of the first section where the 35 MeV beam current is monitored by the combination of ACCT2 and the passive cavity. The cavity detector is necessary to obtain reliable measurements for pulse currents below 10 uA. The third measurement position the output of the linac. It consists of a combination of a ACCT3 followed by a Faraday collector measuring the beam current in air after the titanium window sealing the pipe. The ACCT measures all the output current whereas the Faraday collector can be screened with aluminum foils of controlled thickness to measure the fraction of the current passing the screen only.

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This is particularly important when commissioning new modules and the correct amplitude and relative phase of the radiofrequency must be discovered. The total current at the output, measured by the ACCT is compared by the fraction measured by the screened collector and when they match, the module acceleration is correct.

TOP-IMPLART Output Beam

TOP-IMPLART linac is now fully operational at 63 MeV and commissioning of the 71 MeV beam (acceleration through SCDTL8) is underway. The main operational parameters are summarized in Table 2.

Table 2: TOP-IMPLART Actual Operation Parameters

Parameter	**Value**
Injected current (pulsed)	0.5 – 1.5 mA
Injector current pulse width	8 µs
Booster RF pulse width	4 µs
Beam current pulse width (FWHM)	2.4 µs
Beam pulse repetition rate	25 Hz
Beam output energy	63 MeV
Beam output current (max.)	30 µA

Figure 3 shows the beam current measured in the three positions of Fig. 2 when the linac operates at 63 MeV.

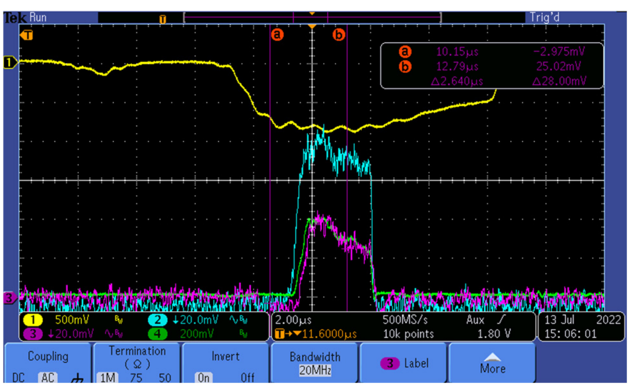

Figure 3: Screen image of the 63 MeV acceleration.

An injected current of 0.7 mA, measured by ACCT1 (yellow trace in Fig. 3, 500 µA/div scale), produces a current of 36 µA at the output of the first section (light blue trace in Fig. 3, 9 µA/div scale), as measured by ACCT2.

The output current is measured by ACCT3 (pink curve, 10 µA/div scale). ACCT3 is screened by a 1 mm aluminum foil to stop secondary electrons, and by the Faraday collector screened with 14.3 mm thick aluminum screen (for a total 15.3 mm thick screening). Both detectors measure the same current of 20 µA with a perfect overlap of the two curves. This overlap of the curves means that all the particles pass through an aluminum thickness of 15.3 mm and, thus, no residual particles at lower energies are present in the beam, as would be the case of incorrect acceleration due to errors in filed amplitude and phase settings.

Energy measurement has been performed by the analysis of the Bragg peak position of the 63 MeV beam on a EBT3 film (see Fig. 4) sandwiched inside a custom made phantom placed at 50 cm from the linac exit. The Bragg peak occurs 32 mm (in water), the correct value for an energy of 63 MeV at the linac exit taking into account the energy degradation due to the Titanium window, the 1 mm Aluminum foil on ACCT3 and the beam expansion in air.

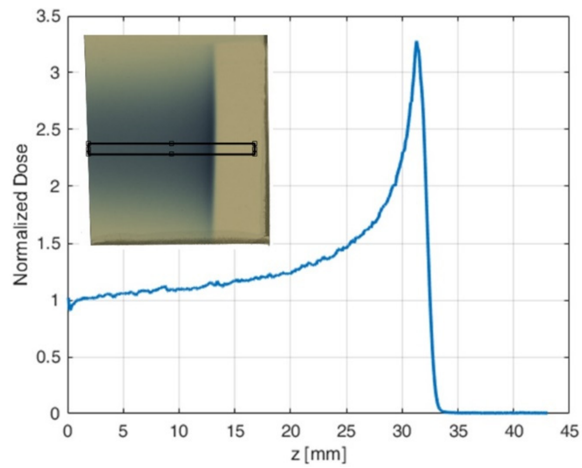

Figure 4: Bragg peak measured at beam output using EBT3 radiochromic film. The z-coordinate corresponds to the penetration depth in water.

Experimental Activity

Large part of experimental activities occurred at energies of 35 MeV and 55.5 MeV. TOP-IMPLART pulsed beam has been used for *in-vitro* and *in-vivo* radiobiology experiments and the for the characterization of radiation-induced damage of materials and electronics components [4-6]. For these experiments in addition to the diagnostics described above, mainly devoted to the commissioning and routine control of accelerator, dosimetric monitors such as integral and 2D ionization chambers, diamond and LiF based sensors are used [1, 4] for dose and fluence measurements.

Since 2021 TOP-IMPLART linac is included in the ASIF (ASI Supported Irradiation Facilities) project coordinated by the Italian Space Agency (ASI) and in other research and development programs focused to the validation of space-related technologies and in the prevention and preparedness to radiological and nuclear emergencies.

CONCLUSION

The status of the TOP- IMPLART linac has been presented. The accelerator reached a beam energy of 63 MeV with a maximum current of 30 µA. Commissioning of the last module of the fourth section (71 MeV) in underway. The third section that will bring the energy to 120 MeV has been designed and procurement procedures are expected to start in September. The RF plant for the third section has been already installed and commissioned.

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REFERENCES

[1] L. Picardi *et al.*, "Beam commissioning of the 35 MeV section in an intensity modulated proton linear accelerator for proton therapy", *Phys. Rev. Accel. Beams*, vol. 23, p. 020102, Feb. 2020. doi:10.1103/PhysRevAccelBeams.23.020102

[2] V. Veshcherevich, "An Adjustable Short Slot Hybrid for Precise RF Power Divider System for Cornell ERL Injector Cavities", Cornell, Ithaca, NY. USA, Rep. ERL04-3, 2004.

[3] F. Cardelli *et al.*, "Design and test of a compact beam current monitor based on a passive RF cavity for a proton therapy linear accelerator", *Rev. Sci. Instrum.*, vol. 92, no. 11, p. 113304, Nov. 2021. doi:10.1063/5.0062509

4] C. De Angelis *et al.*, "The TOP-IMPLART proton linear accelerator: interim characteristics of the 35 MeV beam", Radiation Protection Dosimetry, pp.1-6, 2019. doi:10.1093/rpd/ncz142

[5] G. Bazzano *et al.*, "Radiation testing of a commercial 6-axis MEMS inertial navigation unit at ENEA Frascati proton linear accelerator", *Adv. Space Res.*, vol. 67, no. 4, 2021. doi:10.1016/j.asr.2020.11.031

[6] G. Bazzano *et al.*, "Beam characterization methods at the TOP-IMPLART proton linear accelerator: An application to space components qualification", in *Proc. 2021 IEEE 8th Int. Workshop on Metrology for AeroSpace (MetroAeroSpace'21)*, Naples,, Italy, Jun. 2021, pp. 37-41. doi:10.1109/MetroAeroSpace51421.2021.9511719