THE TOP-IMPLART LINAC: MACHINE STATUS AND EXPERIMENTAL ACTIVITY

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Abstract

The TOP-IMPLART (Intensity Modulated Proton Therapy Linear Accelerator for Radiotherapy) linac is a 150 MeV pulsed proton linear accelerator for protontherapy applications under realization, installation and progressive commissioning at ENEA. It is the first linac running with 3GHz SCDTL (Side Coupled DTL) accelerating modules. These constitute the first two sections of the whole linac up to 71 MeV proton energy, while the accelerating structure of the following part of the accelerator is under definition.

Each SCDTL section is powered by a 10 MW peak power klystron. The first section, consisting of 4 modules (7 to 35 MeV) has been completed and it is operational at low repetition rate (25 Hz). The second section, consisting of other 4 modules (up to 71 MeV), is currently under executive design. The output beam at each stage of the progressive commissioning is fully characterized. The beam is routinely employed in radiobiology experiments and detector evaluation. The paper presents the actual status of the machine, installation, beam characterization and an overview of the experimental activity results.

INTRODUCTION

The TOP-IMPLART (Intensity Modulated Proton Linear Accelerator for RadioTherapy) accelerator [1] is a proton linac designed for cancer treatment applications in the framework of a project led by ENEA in collaboration with ISS (Italian National Institute of Health) and IRE-IFO (Regina Elena National Cancer Institute in Rome). The construction of the accelerator up to 150 MeV (Fig.1) has been funded by the local government (Regione Lazio). It consists of a 7 MeV injector operating at 425 MHz followed by a 3 GHz booster and currently is under assembly and test in a 30 m bunker at the ENEA-Frascati Research Center.

The injector is a commercial linac (Hitachi-AccSys PL-7 model) composed of a RFQ and a DTL operating with pulses of 20 to 100 µs width and maximum repetition frequency of 100 Hz. The high frequency segment up to 150 MeV consists of 4 sections each one driven by a 10MW-4µs klystron tube.

The first two sections from 7 to 71 MeV are a sequence of SCDTL (Side Coupled Drift Tube Linac) modules, four in each section. The TOP-IMPLART linac is the first accelerator employing this type of structure [2] consisting of a chain of side-coupled DTL tanks with small PMQs (Permanent Magnet Quadrupoles) placed in the inter-tank space.

Table 1 lists the main parameters of the eight SCDTL modules. The first three from SCDTL-1 to SCDTL-3 (up to 27 MeV) are in operation and used in different types of experiments. The fourth structure (SCDTL-4) has been recently installed and used only passively for preliminary tests of beam transport aimed at checking and optimizing the alignment.

The following four modules up to 71 MeV have been completely defined and are under executive design.

The details of the higher energy (> 71 MeV) part of the accelerator, based on CCL (Coupled Cavity Linac) structures, are under definition.

Figure 1: 150 MeV TOP-IMPLART accelerator layout.

Table 1: SCDTL Modules Main Parameters

SCDTL	# 1	#2	# 3	#4	# 5	#6	# 7	#8
Tanks	9	7	7	5	5	5	3	3
Gaps/tank	4	5	6	6	7	7	8	8
Bore hole dia., mm	4	4	5	5	6	6	6	6
Energy out, MeV	11.6	18	27	35	45	55.5	63	71
Length, m	1.11	1.08	1.35	1.11	1.27	1.49	1.07	1.13

ACCELERATOR STATUS

Figure 2 shows the four SCDTL modules composing the first section of the TOP-IMPLART accelerator installed in the ENEA-Frascati bunker.

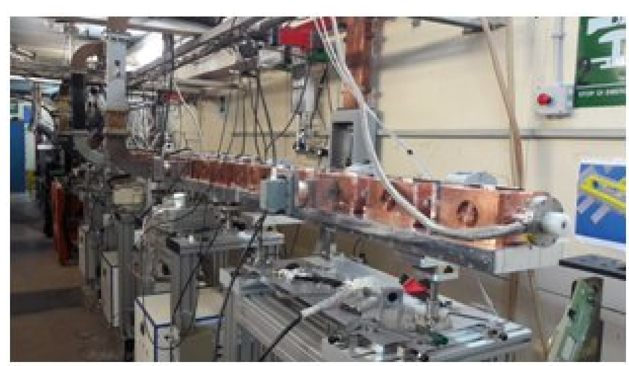

Figure 2: Current setup of TOP-IMPLART accelerator.

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Figure 3 shows schematically the RF distribution line aimed at setting the correct RF level for the SCDTL structures and the phase relations: a variable power divider splits the power in two branches each one provided with a power splitter with adjustable split-ratio; the three phase shifters (PS) set the phase on the last three structures. The power divider and one of the three PS are commercial device from MEGA Industries LLC (Gorham, Me, USA), whereas the other components are custom designed. No phase shifter is installed on SCDTL-1 because the injector and booster frequencies are not in harmonic relation. Provisionally a load is installed on the fourth structure branch for RF power damping while the fourth structure is used in transport mode only to extract the 27 MeV beam.

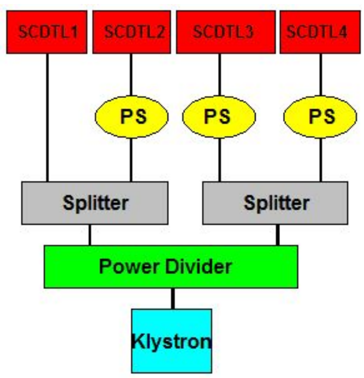

Figure 3: Schematic drawing of RF power distribution in the first section of TOP-IMPLART accelerator.

Preliminary tests through SCDTL-4 have been done in order to optimize the alignment of the PMQs mounted in the inter-tank spaces and accessible from outside.

The 27 MeV output beam is characterized using fast AC transformers, Faraday cup and ionization chamber for current and charge monitoring [3]. The energy has been inferred with two independent methods: measure of the range in aluminium, i.e. the thickness of an absorber that halves the beam current (usually indicated as R_{50}), and analysis of the Bragg peak in novel detectors based on LiF (Lithium-Fluoride) crystals [4].

At the output of SCDTL4 the beam spot has been seen on a fluorescent screen (Fig.4 left): the elliptical shape is determined by the final PMQ in the FODO lattice which is horizontally focusing. A proton current of 20 µA per pulse has been measured (Fig.4 right) in the same position by a fast current transformer (1000V/A over a 1MΩ load).

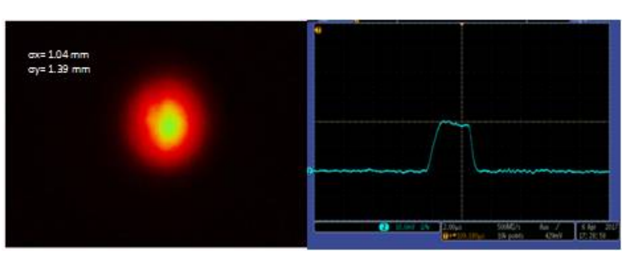

Figure 4: Output SCDTL4: (Left) Beam spot (Right) Pulse current on fast current transform.

RF System Upgrade

The commissioning tests of the accelerator [3] have been done using as RF generator an old klystron tube, the 15MW peak power TH2090, driven by a pulse forming network type modulator, present in the Laboratory since early 90's.

This system limits the maximum repetition frequency to 25 Hz; therefore in order to increase the repetition frequency up to 100 Hz and improve the overall stability of the system, the high level RF generator has been replaced with a TH2157A klystron driven by a solid-state modulator (SCANDINOVA K1 model).

The new system has been made operational in April 2017 and tested successfully on a water load at the maximum klystron peak power of 10.2 MW and up to a maximum repetition frequency of 100 Hz.

Figure 5 reports the oscilloscope records of the klystron voltage and current and the measurement of the jitter of the rising part of the klystron current pulse.

The pulse top flatness is ±0.0084 and the pulse temporal jitter is 2.7 ns (rms value).

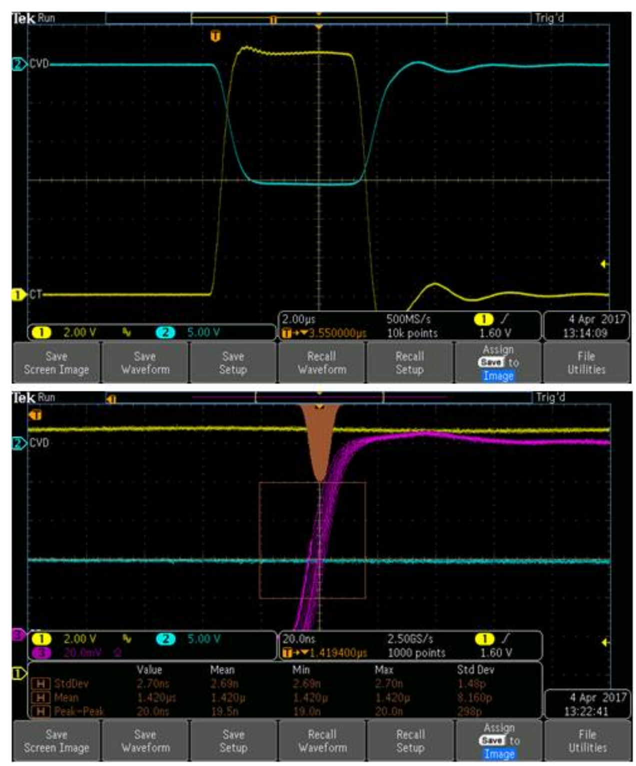

Figure 5: Scandinova K1 Modulator + TH2157A klystron test on water load. (Top): klystron voltage and current. (Bottom): klystron current jitter measurement.

After the tests on the water load the new system has been integrated with the existing plant (Fig. 6) and tested up to 9.4 MW (measured at the input of power divider) at a repetition frequency of 50 Hz.

Preliminary stability measurements of RF power versus time in these conditions have given a ratio standard deviation over average value <0.2%.

Figure 6: (Left) Scandinova K1 Modulator + TH2157A klystron installed on TOP-IMPLART accelerator.

EXPERIMENTAL ACTIVITY WITH THE 27 MEV PROTON BEAM

Even if the beam energy is still too low for clinical applications, during the phase of assembling and test the linac has been implemented and calibrated [5] for irradiating different type of samples and testing different types of detectors [6]. This experimental activity has been done not only in the framework of TOP-IMPLART Project but also for other research programs carried out by ENEA that benefit from the availability of protons in an energy range 18-27 MeV [7]: elemental analysis of cultural heritage objects by PIXE techniques in the framework of COBRA Project [8], irradiations of biological samples in the framework of BioXtreme Project funded by ASI [9].

As the beam pulse current provided by the accelerator is largely in excess with respect to the need of tests on biological samples the output charge is decreased by adjusting the voltage on an einzel lens placed after the proton source. The delivered dose is controlled by a thin ionization chamber (developed by ISS) placed at the accelerator exit and interfaced with the control system of the accelerator: when the total output charge reaches a predefined value corresponding to the desired dose, the RF power in the 3GHz accelerator is switched off. In such a way it is possible to control the total output charge during the irradiation with a precision of 0.5% compensating charge fluctuations from pulse to pulse.

Figure 7 shows the setup used for 2Gy dose-20 seconds treatments on spleen of anesthetized mice [10]: in order to provide the most homogeneous dose on target the samples are placed at 1 meter from the exit window and irradiated by the proton beam extracted in air. In this position the transverse dose distribution (measured by a GaFchromic EBT3 film) is gaussian with a rms size of about 15 mm in both directions giving a uniformity better than 95% on a circle with 1 cm of diameter. The beam energy drops from 27 to 24.5 MeV, corresponding to a depth in water of 6 mm. These in-vivo irradiations of specific anatomical districts of small animals are included in an experimental campaign aimed at studying the radiobiological effects of exposition to radiations during very long periods in space.

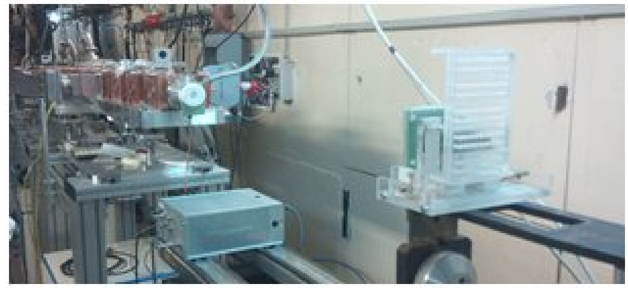

Figure 7: Irradiation setup of biological samples at 1 meter from the exit window.

For larger target size (10x10cm), in absence, at the moment, of a beam scanning system, a target handling system has been developed consisting in placing the sample in a box which is rotated during irradiation to cover the whole target area. The irradiation is done in two steps: in the first one the target is displaced 4.5 cm off the beam axis and in the second one is placed on the beam axis. In both steps the target is put in rotation with a speed of 1 turn in 4 seconds. In the second step the charge is set equal to 10% of the charge delivered on target in the first step. The dose uniformity achievable with this technique has been measured putting a EBT3 film in the place of the target (Fig.8): on a circle with 50.2 mm of radius we obtain a non-uniformity of ±7%.

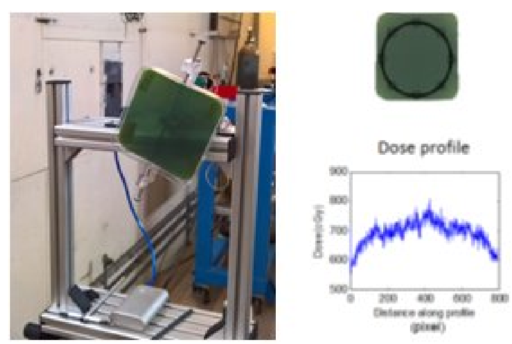

Figure 8: (Left): EBT3 film mounted on the target rotation system placed at 1.44 m from the accelerator exit (Right): Film analysis in a circle with 50.2 mm of radius.

This technique has been used to irradiate with doses of 0.5,5,10 Gy micro-tomato hairy roots contained in PETRI dishes for application in *in-vitro* experimental research on hairy root cultures, supposed to grow in extreme environments as those of space aircrafts [11].

REFERENCES

[1] C. Ronsivalle *et al.* "The TOP IMPLART Project", *Eur. Phys. J Plus,* vol. 126, no. 7, p. 68, 2011.

[2] C. Ronsivalle *et al*., "First acceleration of a proton beam in a Side Coupled Drift tube Linac", *European Physics Letters*, EPL, vol. 111, p. 14002, 2015.

[3] P. Nenzi *et al.*, "Commissioning results of the TOP-IMPLART 27 MeV proton linear accelerator", Proceedings of IBIC2016, Barcelona, Spain, p.686
[4] M. Piccinini *et al.*, "Photoluminescence of radiation-induced color centers in lithium fluoride thin films for advanced diagnostics of proton beams", *Appl. Phys. Lett.* Vol. 106, pp. 261108-1-4, 2015.
[5] C. De Angelis *et al.*, "Characterization of a 27 MeV proton beam linear accelerator", NEUDOS 2017 Conference Proceedings, Kraków, Poland, 2017.
[6] M. Vadrucci *et al.*, "Diagnostics methods for the medium energy proton beam extracted by the TOP IMPLART linear accelerator", presented at IPAC'17, Copenhagen, Denmark, May, 2017, paper THPVA091, this conference.
[7] M. Vadrucci *et al.*, "Irradiation activity with the TOP-IMPLART proton linear accelerator",RAD2017 Conference Proceedings.
[8] M. Vadrucci *et al.*, "A new small-footprint external-beam PIXE facility for cultural heritage applications using pulsed proton beams", in press on NIMB.
[9] BioXtreme Project. `http://bioxtreme.casaccia.enea.it`
[10] F. Novelli *et al.*, Effects of in vivo proton irradiation on mouse spleen cells, RAD2017 Conference Proceedings.
[11] M. Vadrucci, *et al*, "Proton irradiations of micro-tom red hairy roots to mimic space conditions",IPAC2015 Conference Proceedings, p. 2249.