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STABILITY ANALYSIS OF THE TOP-IMPLART 35 MeV PROTON BEAM

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Abstract

The TOP-IMPLART (Intensity Modulated Proton Linear Accelerator for RadioTherapy) is the demonstrator of a 150 MeV proton linear accelerator devoted to cancer treatment application under development at ENEA-Frascati. It is a full linear machine composed by a 425 MHz 7 MeV injector and a high frequency linac operating at 2997.92 MHz. The first accelerating section, installed and in operation, consists of 4 SCDTL structures and delivers a 35 MeV beam in 3 microseconds pulses at a maximum repetition frequency of 50 Hz. The principal advantage of a linear accelerator, in a therapeutic application, is the quick setting possibility (up to pulse-to-pulse, in principle) of the physical properties of the proton beam, offering larger flexibility (compared to traditional circular designs) and improved precision on dose delivery to the patient. The short and long range stability of the machine have been analyzed measuring on a pulse by pulse basis both the output beam characteristics and other machine parameters in order to identify those that mainly affect the beam stability. This work describes the methodology used in this study, the main results achieved and the future developments.

INTRODUCTION

TOP-IMPLART linac is a machine aiming to demonstrate the feasibility of a fully linear solution for protontherapy, funded by Regione Lazio (local government) within the framework of the TOP-IMPLART project [1].

TOP-IMPLART accelerator is under construction at the ENEA Frascati Research Center with a planned final energy of 150 MeV and an actual energy of 35 MeV. The linac consists of a commercial injector (model PL7, produced by AccSys-Hitachi) operating at 425 MHz followed by a high-frequency linac operating at 2997.92 MHz, designed by ENEA (Accelerators and Medical Applications Laboratory) [2].

The injector employs a duoplasmatron ion source and accelerates protons with an RFQ (up to 3 MeV) and a DTL (up to 7 MeV). The 7 MeV beam is matched to the high frequency booster in a short LEBT (Low Energy Beam Transfer line) using an arrangement of 4 quadrupoles. The booster is composed by SCDTLs up to 71 MeV and CCLs to reach 150 MeV [3,4]. In 2017 the medium energy section of the booster has been completed and successfully commissioned, reaching the energy of 35 MeV.

Figure 1 shows the layout of the medium energy section. It is composed by 4 SCDTL modules powered by a single klystron tube and fitted with mechanically actuated power dividers (PD) and phase shifters (PS), providing phase and amplitude control for each module. There is no RF synchronization between the injector and the booster because the two chosen frequencies have no harmonic relation. Temperature stabilization and static vacuum of each module is independent and provided by a chiller (CH) and two ion pumps (IP), respectively.

Fixed beam diagnostics, consisting of Rogowski coils, is positioned at the input (ACCT1) and at the output (ACCT2) of the section. Each module is provided by a movable mechanical tuner for the fine adjustment of the resonance frequency.

SCDTL-3 has been fitted with an Automatic Frequency Control (AFC) system that operates the motorized tuner of the module [5].

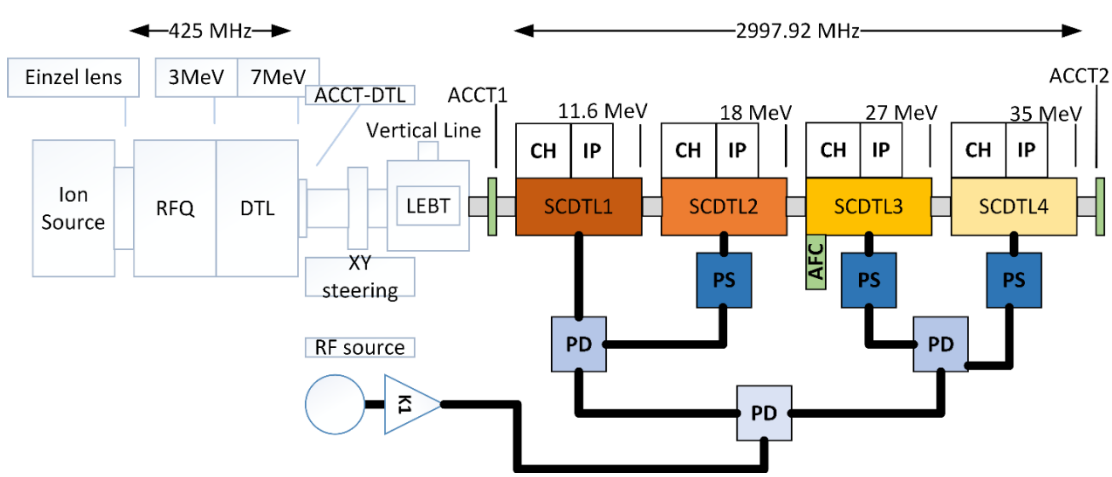

Figure 1: Actual layout of the TOP-IMPLART linac with the medium energy booster section in colors.

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STABILITY ANALYSIS

The most important parameter for the TOP-IMPLART accelerator (being a medical machine), is the dose delivered to the patient, that occurs in short pulses 1-4 µs long, with a charge per pulse variable up to 60 pC and, a maximum repetition frequency of 50 Hz (upgradable to 100 Hz). Variable pulse length and repetition frequency allows dose variation on each pulse, opening the possibility to reduce the treatment time, with respect to conventional machines. However, the Dose Delivery System operates between pulses and there is no possibility to interrupt the beam during the pulse. The risk of overdosing is mitigated, at system level, by reducing the fraction of the dose delivered per pulse and, at machine level, by improving the stability the charge delivered in each single pulse. The last strategy (machine level) requires a pulse-by-pulse analysis of the parameters that affects the pulse charge on a short time scale (a few seconds) and on a long time scale (hundred second) to identify the causes of variability and take appropriate corrective actions.

Table 1 reports the signals that have been used in the stability analysis, each one, with its expected range. Cavity fields, reflected power and klystron forward power are envelopes obtained using a zero-bias Schottky diodes. The klystron RF forward power is sampled at the input of the first power divider after the klystron in Fig. 1.

Table 1: Signals Considered in the Stability Analysis

Signal	Range (mV)
Cavity fields (SCDTL1-4)	80-300
Reflected power (SCDTL1-4)	30-4000
Input Current (ACCT1)	0-2000
Output Current (ACCT2)	0-40
Faraday Cup	0-1500
Klystron RF forward power	0-1500
Injector Arc Current	0-1000
Injector RFQ field	0-5000
Injector DTL field	0-6500
AFC error	0-700

Input, output current signals (ACCT1, ACCT2 respectively) are voltage signals produced by the Rogowsky coils read-out electronics (transimpedance value 1000 V/A). The Faraday cup signal is the voltage obtained from a custom designed cup connected to a FEMTO DHPCA-100 variable current amplifier (set to 10.000 V/A transimpedance value). The injector signals (Arc current, RFQ and DTL fields) are voltage signals made available from the injector electronics and simply recorded without applying any conversion factor. The AFC error signal is connected to the AFC system on SCDTL3 and is used for the resonant frequency control of the module (see [5]). We performed a similar analysis in [6] on 27 MeV beam at SCDTL-3 exit, without the possibility to acquire the signals on each pulse, because the firmware of the oscilloscopes used (Tektronix DPO3014) could not transfer traces data over the Ethernet connection at a frequency higher than 4Hz (driven by a MATLAB scripts). Moreover, traces acquisition was not synchronous. That systems provided an insight on long term stability of the machine only. To overcome the limitation of the oscilloscope-based system we developed the setup shown in Fig. 2 [6].

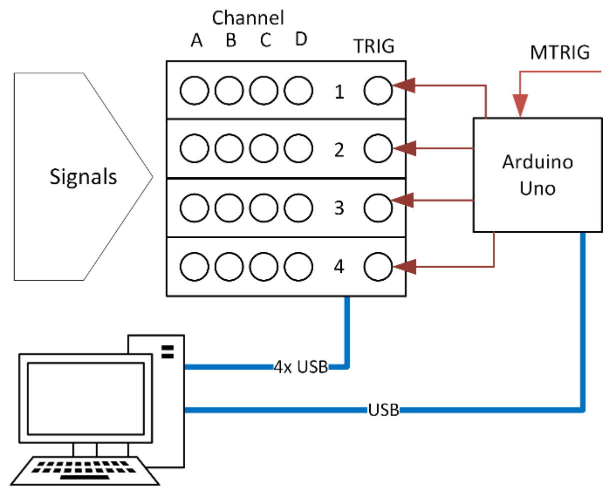

Figure 2: Pulse-by-pulse acquisition system.

The units numbered 1,2,3 and 4 in Fig.2 are PicoScope 3405D, PC based oscilloscopes that can record multiple captures (each capture corresponds to one pulse) in their memory and transfer them on the PC at the end of the acquisition. The different ranges of the signals we have to acquire (Table 1) require the use of a digitizer with an oscilloscope-type analog front end. Each capture consists of 1.000 samples (with sample time of 16 ns) and up to 10.000 captures are stored. Synchronization among PicoScopes is obtained by trigger gating with an Arduino board.

STABILITY ANALYSIS RESULTS

The stability analysis has been conducted with the accelerator running at 20 Hz PRF, acquiring 5.000 pulses, corresponding to 250 s of observation time. The chosen observation time is sufficient to analyze the dynamics of the temperature oscillations. Data from the oscilloscopes have been analyzed using MATLAB. Each signal in each capture has been reduced from 1.000 samples to one representative value by taking the average of 60 samples (960 ns) in the terminal region of the pulse. The obtained values are packed into a vector to perform statistical analysis.

By the preliminary analysis done at the output of SCDTL-3 in [7] the main causes of variability were found to be related to the injector stability, RF power stability and, temperature oscillations. RF power related instability has been removed by the replacement of the old radiofrequency (RF) power source. The new RF power source reduced the variation in the output power from ±2% to ±0.2%. Actually we have identified two distinct source of beam current instability, a long term one, attributed to the

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temperature variation and, a short term one, related to injector output current instabilities (caused by arc current and DTL field fluctuations (addressed in [7]).

Long-term Stability Analysis

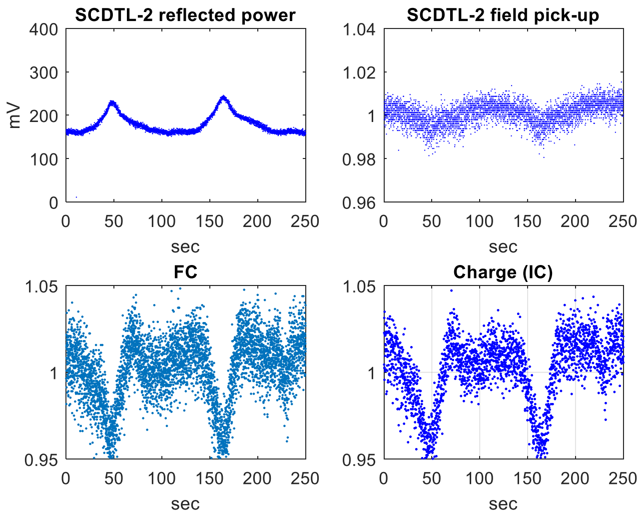

Figure 3: Long-term stability analysis plots.

Long term stability, in the context of this work, evaluates the variability in the output current arising from thermal transient (i.e. temperature oscillations, linac thermalization). Analysis showed that most of the variability in the output is produced by SCDTL-2 and SCDTL-3 alone, where the measured total frequency excursion during the thermal cycle is around 50 KHz. However, when the AFC system is active on SCDTL-3, its influence is cancelled, as described in [5].

Table 2: Long-term Stability Summary

Parameter	Value
Output charge (±1σ)	0.02 (rms)
Output charge period	117 (s)
Faraday's Cup (±1σ)	0.02 (rms)
Faraday's Cup period	117 (s)
Field SCDTL2 (±1σ)	0.005 (rms)
Field SCDTL2 period	118 (s)
Temperature SCDTL2 (±1σ)	0.09 (rms)
Temperature SCDTL2 period	118 (s)

Figure 3 shows the envelope of the reflected power at SCDTL-2 (top left), the envelope of field inside the linac (top right), the output charge measured with the integral ionization chamber (bottom left) and, the output current measured with a Faraday cup (bottom right). All the values, except reflected power, have been normalized to the average value of each plot to enhance data readability. The output current and charge are the result of the acceleration in the four SCDTL modules. Figure 3 clearly shows that output current and charge variability match the variability of the accelerating field in SCDTL-2 that, in turns, depends on its temperature oscillations. The negative peaks in both the current and the charge are temporally aligned with the peaks in the reflected power (where the accelerating filed has minima). Table 2 reports a summary of the long term stability analysis results in the described operative conditions.

Short-term Stability Analysis

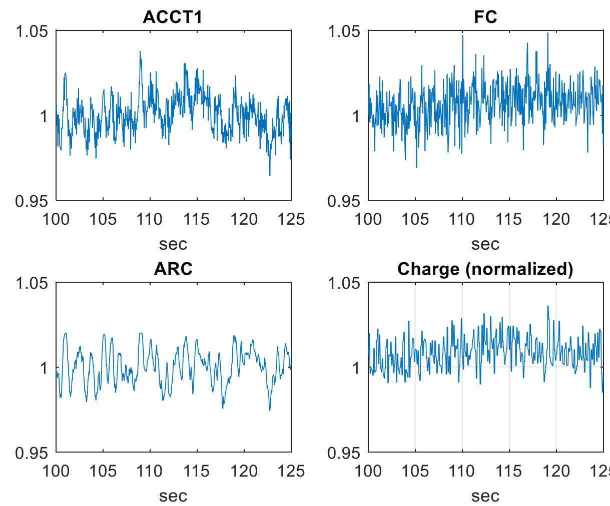

Figure 4: Short-term stability analysis plots.

The short-term stability analysis of the output beam has been performed on a time windows of 25 s where the linac operates at resonance). Figure 4 shows the injected current (ACCT1, top left), and the arc voltage (ARC, bottom left) that show the same pattern. The dependence of the injected current from the arc current variability affects the output current (top right) and charge (bottom right). Table 3 reports the RMS values of the signals in the short-term window.

Table 3: Short-term Stability Summary

Parameter	Value
Output charge (±1σ)	0.0095 (rms)
Faraday's Cup (±1σ)	0.0119 (rms)
Arc current (±1σ)	0.0102 (rms)
Injected current (±1σ)	0.0114 (rms)

The stability of the output charge between pulses is 1% RMS and this with the stability of the current measured using the Faraday's cup and with the stability of the injected current that, is related to the arc current fluctuations.

CONCLUSIONS

The next tasks are to fit an AFC unit on every module to cancel the long-term instability caused by the temperature changes and reduce the magnitude of any residual oscillation by improving the temperature control algorithm.

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