

## STATUS OF THE COMMISSIONING OF THE LIGHT PROTOTYPE

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### Abstract

The company ADAM (Application of Detectors and Accelerators to Medicine), a CERN spin-off, is working on the construction and testing of its first linear accelerator for medical application: LIGHT (Linac for Image-Guided Hadron Therapy). LIGHT is an innovative high frequency proton linac designed to accelerate proton beams up to 230 MeV for proton therapy applications. The LIGHT accelerator consists of three different linac sections: a 750 MHz Radio Frequency Quadrupole (RFQ) accelerating the beam up to 5 MeV; a 3 GHz Side Coupled Drift Tube Linac (SCDTL) up to 37.5 MeV; and a 3 GHz Cell Coupled Linac (CCL) section up to 230 MeV. The compact and modular design is based on cutting edge technologies developed for particle colliders and adapted to the needs of hadron therapy beams. A prototype of LIGHT is presently under commissioning at CERN. This paper describes the design aspects and the different stages of installation and commissioning of the LIGHT prototype with emphasis on beam tests results obtained during the past year at different energies.

### INTRODUCTION

Proton therapy is a very dynamic and growing market for particle accelerators, with 10% increase per year in the number of patients [1]. At present only cyclotrons or synchrotrons are used to accelerate protons to energies relevant for deep seated tumours treatment. The LIGHT accelerator is the first high frequency linear accelerator working at 3 GHz [2] designed as an industrial product for proton therapy. It consists of three different linac sections [3]: a Radio Frequency Quadrupole (RFQ), a Side Coupled Drift Tube Linac (SCDTL) and a Cell Coupled Linac (CCL) section.

### THE LIGHT PROTOTYPE AT CERN

The first prototype of the LIGHT accelerator is being commissioned at CERN. It is intended as a demonstrator of the LIGHT system, where all sub-systems will be integrated. The commissioning is performed in stages of increasing energy up to 70 MeV. The energy is limited by the available space in the accelerator hall, but this is sufficient to validate and demonstrate the acceleration process with all three types of accelerating structures of LIGHT. Figure

1 shows a 3D model of the LIGHT prototype inside the bunker test area located on CERN LHC-point2 site. The prototype configuration includes a proton source and Low Energy Beam Transfer (LEBT) line, the 750 MHz RFQ designed and built by CERN [4], four modules of SCDTL and four modules of CCL.

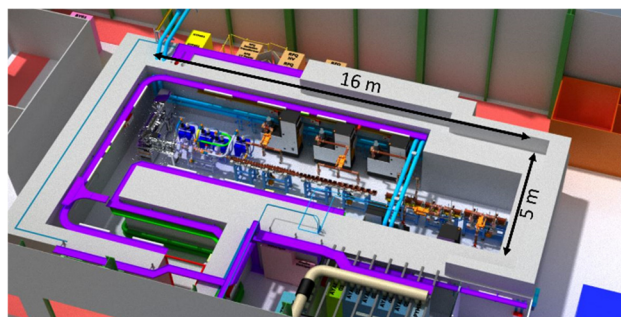


Figure 1: Model of the LIGHT prototype at CERN, as it will look like at 70 MeV.

### Source and Low Energy Beam Transfer Line

The source and LEBT (also called LIGHT proton injector assembly) have been produced by Pantechnik. The source is an ECR type source (Monogan M-1000), followed by a sequence of elements intended to:

- Focus and steer the beam (Einzel lenses and steerer)
- Regulate the beam current (Electrostatic plates)
- Separate unwanted particle species (90° dipole)
- Generate beam pulses (Electrostatic chopper)

### The Radio Frequency Quadrupole

The Radio Frequency Quadrupole is the first 750 MHz RFQ ever built [5]. It is made of four modules and it accelerates the proton beam up to 5 MeV in only 2 meters. It is powered by four Inductive Output Tubes (IOTs) from Thales, delivering 100 kW peak power each. Due to space constraints the choice was made to install the IOTs close to the RFQ structure, inside the shielded vault.

### The Side Coupled Drift Tube Linac

After the RFQ, the beam is injected into the SCDTL. The design of the SCDTL is based on the experience of the IMPLART project of ENEA (Frascati, Italy) [6], and has been adapted to cover the energy range from 5 to 37.5 MeV. Differently from the IMPLART design, in LIGHT, the RFQ works on the fourth sub-harmonic of the SCDTL cavities,

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enabling a good longitudinal matching. The SCDTL section consists of four modules with different number of drift tube linac tanks each, as summarized in Table 1.

Between each accelerating tank, compact Permanent Magnet Quadrupoles (PMQs) are installed to focus the beam in a FODO-like lattice. The cavities are fed by RF power generated by two 3 GHz klystrons from Toshiba (model E3779,A) mounted on modulators from Scandinova (model K100) and capable of delivering RF pulses of 5  $\mu$ s at 200 Hz with a peak power of up to 7.5 MW.

Table 1: Parameters of SCDTL of the LIGHT Prototype

SCDTL Module	Mod1	Mod2	Mod3	Mod4
Number of Tanks	11	13	9	7
Bore hole [mm]	4	4	4	5
Length [m]	1.12	1.70	1.52	1.60
Power [MW]	0.83	2.59	2.46	2.48
Energy [MeV]	7.5	16	26.5	37.5

Each accelerating module is equipped with RF pickups, used to monitor the RF fields inside the cavity. Figure 2 shows the RF pulse envelopes measured on a fast acquisition oscilloscope of the signal from the pickups installed on the RFQ and on the first SCDTL module.

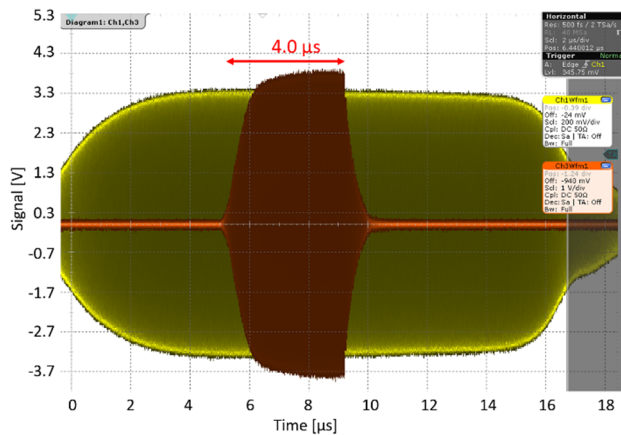


Figure 2: Example of RF pulse envelopes measured from RF pickups installed on RFQ (yellow) and SCDTL (red).

### The Cell Coupled Linac

The CCL structures, designed by ADAM based on the experience of the LIBO prototype [7], are used to accelerate the beam up to the final energy of 230 MeV. For the prototype installation, a maximum energy of 70 MeV will be used (Table 2). The CCL modules work at 3 GHz and uses the same klystron-modulator systems used for the SCDTL cavities.

Table 2: Parameters of CCL of the LIGHT Prototype

CCL Module	Mod1	Mod2	Mod3	Mod4
Number of Tanks	2	2	2	2
Bore hole [mm]	5	5	5	5
Length [m]	0.80	0.83	0.76	0.81
Power [MW]	2.21	2.21	2.31	2.33
Energy [MeV]	44.9	52.9	61.3	70.2

## COMMISSIONING STATUS

The commissioning of the LIGHT prototype is performed in steps of increasing energy. At each step a new module is added in the beam line and the beam is fully characterized by means of a movable diagnostic test bench.

### Staged Commissioning Plan

Seven commissioning phases have been identified, according to the installation and testing of the modules on the beam line:

- 1) Source and LEBT, beam up to 40 keV;
- 2) RFQ installed and beam up to 5 MeV;
- 3) SM01 on line, beam up to 7.5 MeV;
- 4) SM02 on line, beam up to 16 MeV;
- 5) SM03 on line, beam up to 26.5 MeV;
- 6) SM04 on line, beam up to 37.5 MeV;
- 7) CM01 to CM04 on line, beam up to 70 MeV.

The commissioning of the LIGHT prototype has started at the end of the summer 2016 with the installation and tests of the proton injector assembly [3]. The beam commissioning of the RFQ was successfully performed in 2017 and the measurements are reported in [8].

The commissioning has reached now Phase 4 and the present configuration of the LIGHT prototype is shown in a top view in Fig. 3. The RF modules not on the beam line are under RF conditioning [9].

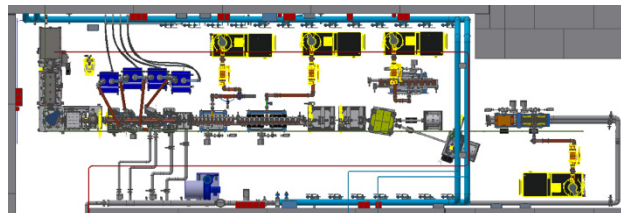


Figure 3: Top view of the present configuration of the LIGHT prototype with two SCDTL modules on the beam line followed by the diagnostic test-bench.

### The Diagnostic Test Bench

The measurements on the LIGHT prototype are performed using a moveable diagnostics test bench, described in [10]. The diagnostic test bench allows the measurements of:

- Beam current
- Average beam energy and energy spread
- Transverse beam profiles and position
- Transverse beam emittances

In addition to the moveable test bench, some permanent diagnostic devices installed in Medium Energy Beam Transfer (MEBT) lines between the linac sections were also used during the commissioning.

## BEAM MEASUREMENTS RESULTS

The commissioning of the structures up to 7.5 MeV has been finalized. During the commissioning, the RF amplitude and phase set points for the first SCDTL module were found by longitudinal phase scans. The PMQ position was

optimized to achieve the maximum transmission. The main properties of the beam have been measured and are reported in the following.

### Beam Current

A proton beam pulse current of 50  $\mu\text{A}$  has been consistently measured at the exit of the RFQ. A beam current of 39  $\mu\text{A}$  during the pulse has been measured at the output of SCDTL module1. The overall transmission through the RFQ is about 20% and through SCDTL it is 78%.

### Beam Energy

To measure the beam energy, the beam was directed to an optical screen placed in a dispersive region after the spectrometer dipole. A picture of the beam taken on this screen is shown in Fig. 4. The dipole magnet was set to a current of 47.5 A, equivalent to a central energy of 7.5 MeV. The energy was also measured independently by a Time of Flight (ToF) system, currently under development as presented in [11].

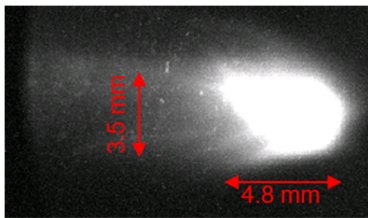


Figure 4: Picture of the beam spot taken on the optical screen in the dispersive region.

### Beam Profile and Beam Emittance

The horizontal and vertical beam profiles could be measured at two different locations (Pos1 and Pos2 in Fig. 5) along the beam diagnostics test bench by means of a moveable slit and Faraday Cup system (D-box) [10]. These measurements are used to determine beam size, as well as beam divergence, in conjunction with two Beam Position Monitors (BPMs) providing the beam centre of mass position.

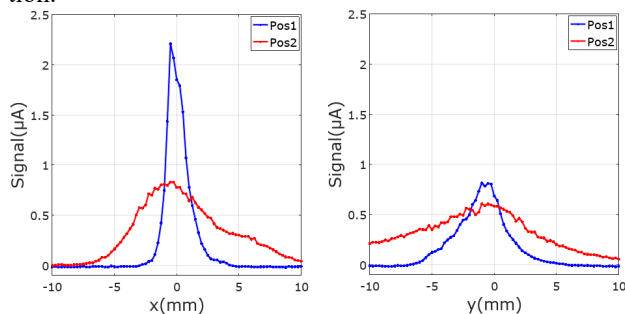


Figure 5: Horizontal (left) and vertical (right) beam profiles taken at two different positions after SCDTL module1.

At low energy, two D-box are used to measure the beam emittance as well, by two slits and a Faraday Cup. An example of phase space plots of a multi-particle beam generated from the measurement data is shown in Fig. 6.

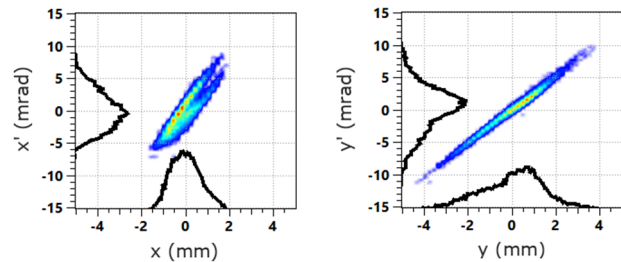


Figure 6: Measured emittance at 7.5 MeV in horizontal and vertical plane after SCDTL module1.

## CONCLUSION

LIGHT will be the first commercial 3 GHz linac for proton-therapy. The first prototype is under commissioning at CERN. The commissioning is done in stages of increasing beam energy.

Proton injector, RFQ and the first SCDTL module have been integrated and can be controlled with a dedicated control system. A data-logging system has also been implemented, allowing to perform data analysis and monitor trends on vacuum, cooling temperature and RF signals.

The main results of the beam measurements performed up to this stage are summarized in Table 3.

Table 3: Summary of the Beam Measurements

	RFQ input	MEBT 1	SCDTL Mod1
Beam energy [MeV]	0.04	5.03	7.5
Beam current [ $\mu\text{A}$ ]	250	50	39
Hor Emittance (norm, rms) [ $\pi$ mm mrad]	0.032	0.032	0.11
Ver Emittance (norm, rms) [ $\pi$ mm mrad]	0.025	0.025	0.08

The commissioning of the LIGHT prototype will continue with the next commissioning stages with the goal of validating the integration of all sub-systems with beam.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge all CERN colleagues for their kind support with the work described here. Special thanks go to CERN BE and KT divisions.

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