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LIGHT: A LINEAR ACCELERATOR FOR PROTON THERAPY*

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Abstract

ADAM, Application of Detectors and Accelerators to Medicine is a Swiss Company based in Geneva Switzerland established on 20th December 2007. ADAM was founded to promote scientific know-how and innovations in medical technology for cancer treatment. In 2007 a first partnership agreement was signed with CERN and in 2011 ADAM has been officially recognized as CERN spin-off. After the first research results other partnership agreements were signed between ADAM and CERN with the main goal of establishing a framework within which the two parties can collaborate to develop novel technologies for detectors and accelerators. Currently ADAM research activity is mainly focused on the construction and testing of its first linear accelerator for medical application: LIGHT (Linac for Image-Guided Hadron Therapy). LIGHT is an innovative linear accelerator designed to revolutionise hadron therapy facilities by simplifying the infrastructure and make them profitable from an industrial point of view while providing a better quality beam. The current design allows LIGHT to accelerate proton beam up to 230 MeV with several advantages comparing to the current solutions present in the market.

INTRODUCTION

Many of the accelerator and detector technologies developed in the field of particle physics have found an application in industry and medicine. Proton therapy is a very dynamic and growing market for particle accelerators, with 10% increase per year in the number of patients [1].

After ADAM was founded in 2007 a first partnership agreement was signed with CERN and in 2011 ADAM has been officially recognized as CERN spin-off. Examples of projects developed by ADAM in the past years include: i) Intra Operative Radio-Therapy (IORT) linac at high frequency; ii) dosimeter for micro-dosimetry measurements (based on Si detectors used in CMS tracker [2]); iii) X-eye, a compact 6 MeV C-band accelerator for conventional radiotherapy; iv) the First Unit prototype of LIGHT. Currently ADAM research activity is mainly focused on the construction and testing of its first linear accelerator for medical application: LIGHT (Linac for Image-Guided Hadron Therapy). In this work the LIGHT system is described in detail, with a particular emphasis on the technical solutions inspired by technologies either developed or in use at CERN.

THE LIGHT SYSTEM

Electrons linacs are widely spread in hospitals for producing X-rays used in conventional radiation therapy. On the contrary only cyclotrons or synchrotron are used to accelerate protons to energies relevant for the treatment of deep seated tumours. The LIGHT accelerator is the first high frequency linear accelerator working at 3 GHz [3] designed as an industrial product for proton therapy.

The LIGHT accelerator consists of three different linac sections (as shown in Fig. 1): a Radio Frequency Quadrupole (RFQ), a Side Coupled Drift Tube Linac (SCDTL) and a Cell Coupled Linac (CCL) section.

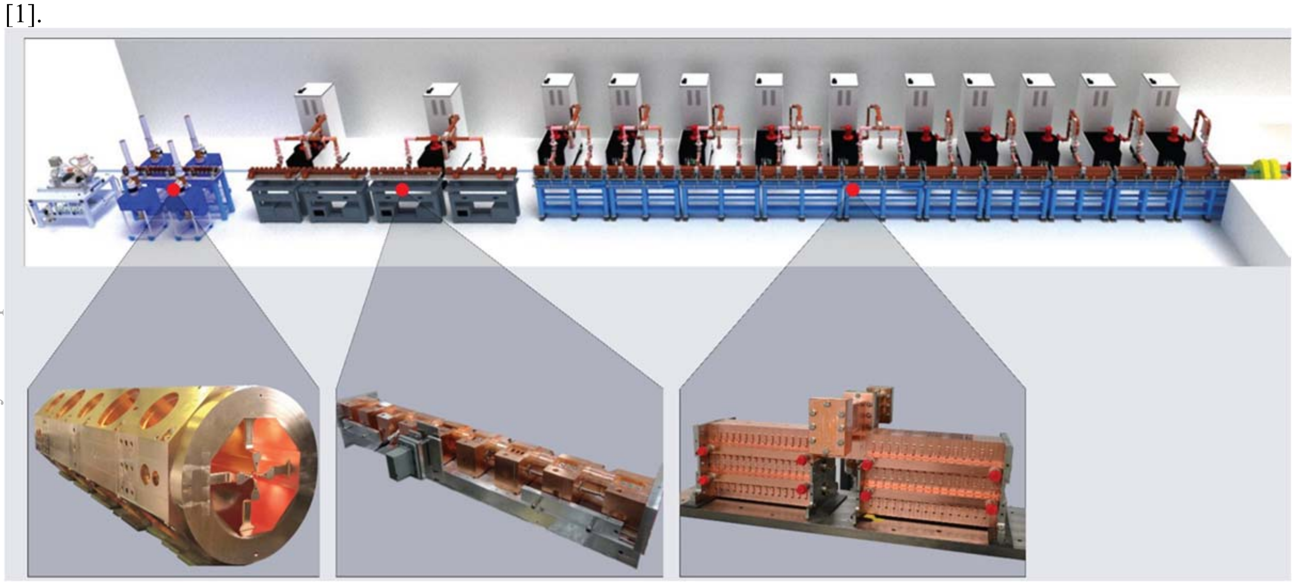

Figure 1: Artistic view of full size LIGHT accelerator. The three different types of cavities used are highlighted with a picture for each type.

Each section is adapted to the increasing speed of the protons [4] which are accelerated up to 230 MeV in about 25 meters as indicated in Table 1.

Table 1: Overall Layout of LIGHT

Section	Number of modules	Length [m]	Energy range [MeV]
RFQ	4	2.0	0.04-5.0
SCDTL	4	6.2	5.0-37.5
CCL	15	15.5	37.5-230

The present design uses a proton source from Pantechnik [5] able to accelerate the beam to 40 keV and to chop it in pulses of 5 us at 200 Hz. After the source, the high frequency RFQ - developed by CERN [6] – is used as injector, reaching an energy of 5 MeV. The beam is then injected into 4 modules of SCDTL with an exit energy of 37.5 MeV. The SCDTL design follows the experience of ENEA (Frascati, Italy) [7]. The CCL structures - based on the experience developed by ADAM for the 'First Unit' project and on the design of the LIBO prototype [8] - accelerate the beam up to the final energy of 230 MeV.

RF Unit Layout

A modular approach has been used for the design of the linac. An RF unit is composed by several sub-systems:

1. Accelerating system.
2. Cooling system.
3. Vacuum system.
4. RF power system.
5. RF network system.
6. Control and interlock system.
7. Focusing system.
8. Support and alignment system.

An RF unit, with the different sub-systems by which it is composed, is depicted in Fig. 2.

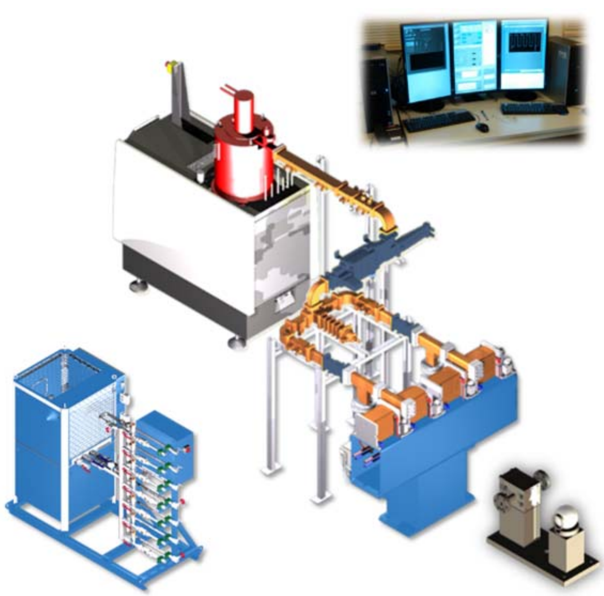

Figure 2: RF unit with all the sub-systems.

The accelerating system consists of RF resonant copper structures (two CCL modules in Fig. 2) which allow to accelerate the proton beam with typical gradient of the order of 18-20 MV/m. Each module is divided into tanks, and each tank contains a certain number of accelerating gaps (or cells).

The cooling system is required to stabilize the temperature of the structure and to remove the heat generated by the dissipated power on the surface wall under high-power operation.

The vacuum system is used to keep the RF structure under Ultra-High Vacuum (UHV) condition with typical operating pressure below 5 10^{-8} mbar.

The RF power system is based on modulator-klystrons units that are able to deliver 7.5 MW of peak power during 5 μs pulses at 200 Hz. Both modulator and klystron are commercially available products.

The RF network based on standard WR284 waveguides allows to transmit the power to the accelerating system. A circulator is added to protect the klystron from reflected power.

A first version of control and interlock system is being developed in-house and allow to validate, operate and condition each RF sub-unit.

The focusing system consists of a sequence of focusing and defocusing Permanent Magnet Quadrupoles (PMQ) placed between each tank to form a quasi-periodic focusing channel based on a FODO (Focus/Defocus) lattice. Extreme care in the positioning and alignment of PMQ is required.

The support and alignment system is a critical piece of equipment, allowing to reach and maintain the required position tolerance of the accelerating structures and focusing system. The alignment procedure is based on laser tracker measurements and on a common reference network installed in the accelerator hall.

Features of LIGHT

The LIGHT accelerator has a number of features, important for a proton therapy machine, that are specific to linacs [9]. In particular:

- A pulsed beam structure - with a repetition rate of 200 Hz – with variable intensity and energy pulses.
- An extremely small beam emittance (of the order of 0.25 mm mrad normalized) which makes it possible to use small aperture magnets for the transfer lines and gantry.
- Almost no beam losses, implying a reduced size and cost for shielding and easier maintenance.
- The possibility to vary the energy electronically from pulse to pulse, without the need of degraders and absorbers.

All the above mentioned features make the LIGHT accelerator very well suited for active dose delivery with spot scanning technique, and adapted to the treatment of moving organs by volumetric rescanning with tumour tracking.

TECHNOLOGY TRANSFER

A number of technologies developed and in use at CERN has inspired the present design of LIGHT. ADAM worked actively in the last years to push forward and to make use of ideas and R&D projects towards a commercially available system.

The LIBO and the First Unit Prototypes

The use of 3 GHz linacs for protons was first investigated by TERA, CERN and INFN with the design, construction and test of the Linac Booster (LIBO) prototype [8]. LIBO has been designed and built under the leadership of Mario Weiss (CERN) by TERA Foundation in collaboration with CERN and the INFN Sections of Milano and Naples. The LIBO unit is made of 4 tanks coupled together by three “bridge couplers”. Based on this development ADAM has designed, built and tested the first prototype of a LIGHT accelerating unit, by applying an industrial approach [10]. The first unit prototype introduced several improvements to the LIBO prototype, for instance by reducing the size of the bridge couplers and allowing for an open space between each tank, where the PMQ (used to focus the beam) can easily be placed. This came together with a significant reduction of the costs. The First Unit prototype built by ADAM in 2008-2010 is shown in Fig. 3.

Figure 3: First unit prototype of LIGHT, built by ADAM in 2008-2010.

Ultra-High Precision Machining

The high frequency (X-band) structures realization thoroughly studied by the CLIC (Compact Linear Collider) project find an application in the LIGHT machine.

The CLIC project pushed the industries to develop new technologies - such as tailor made Computer Numerical Controlled (CNC) machines - to satisfy the stringent requirements of the cavity machining [11]. Indeed, variation around the nominal values coming from the machining of the copper accelerating cells cause resonant frequency shifts. Micrometre tolerances are needed to achieve the required operating frequency. After machining, high temperature brazing is needed to come to the final product.

Despite the difference in the frequency used (3 GHz for LIGHT, 12 GHz for CLIC), the technology and know-how related to the design, high precision machining, brazing and RF tuning of accelerating structures, was then available for LIGHT .

This represented for ADAM a crucial step for starting the industrial design and development of the first prototype of the LIGHT accelerator.

The production of hundreds of cells has been put in place using cutting edge technologies developed for the CLIC requirements, combined with state of the art industrial approach and quality control processes. Figure 4 is an example of the pieces machined and brazed by VDL [12] for the LIGHT accelerator.

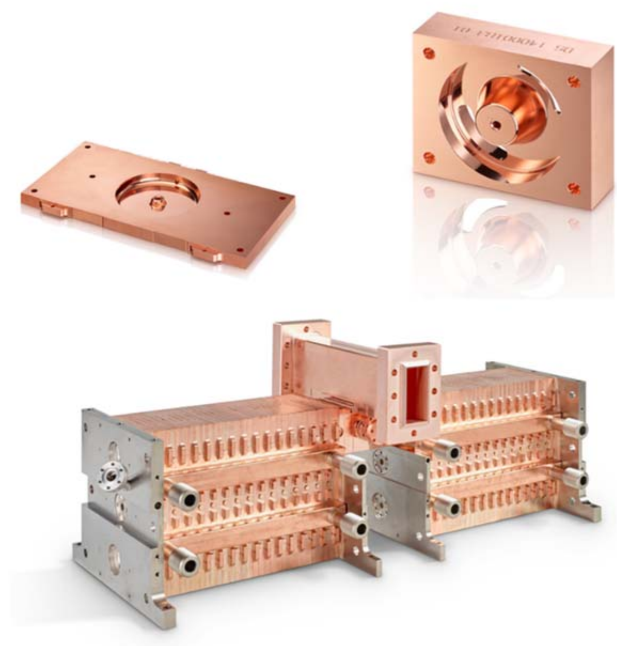

Figure 4: Example of the quality of accelerating cells, bridge coupler cell and full module machined and brazed by VDL [12].

The Modulator-Klystron Systems

The RF power system for the SCDTL and CCL of the LIGHT machine is based on Scandinova modulators (K1 Type) [13] equipped with Toshiba klystrons (mod. E3779) [14]. The same scheme is used in the X-band high-gradient test stands (the so-called “X-boxes”) operated at CERN for the high-power testing of CLIC accelerating structures [15]. The experience developed at CERN could be transferred in the setup and operation of the klystron-modulators systems of LIGHT, one of which is shown in Fig. 5.

ADAM and Scandinova continuously collaborate to address specific requirements for the use of such system out of research laboratories and in industrial environment.

Figure 5: Modulator-klystron system installed at the ADAM test facility.

The High Frequency RFQ

CERN experience in the design of RFQ for the LINAC4 project led to the optimized design of the most compact RFQ ever built, using a frequency that is more than the double of the frequency used for LINAC4 (352 MHz).

The 750 MHz RFQ designed by CERN [6] is used in LIGHT as injector to bunch, focus and accelerate the beam up to 5 MeV in 2 meters. The frequency was chosen to be in the 4th sub-harmonic of the main RF frequency used for the rest of the linac (3 GHz). The design was optimized to match the acceptance of the subsequent sections of LIGHT. In particular the decision was taken to lose the protons that are not accepted by the SCDTL section at an energy well below 1 MeV, so to avoid activation of components. The machining and brazing of the four modules was performed at CERN. The RF power is generated by four Inductive Output Tubes (IOT) able to provide a total peak power of 400 kW. Figure 6 shows the RFQ installed at the ADAM test facility.

Furthermore the experience in the beam dynamics studies and commissioning of linac [16] represent a valuable input for the commissioning of the LIGHT system.

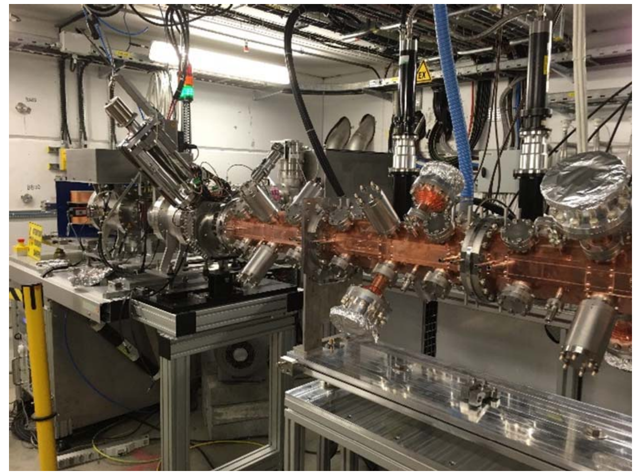

Figure 6: Picture taken after the installation of the 750 MHz RFQ at the ADAM test facility.

SYSTEM COMMISIONING

The first prototype of the LIGHT system is now under commissioning at the ADAM testing area. All the ancillary systems (vacuum, cooling, electrical power network, etc.) have been installed to guarantee the correct operation of the units. Controls, interlocks and personnel access system are already implemented to assure the safety during operation. Installation and commissioning of the components will be performed in stages, starting with the source commissioning and the conditioning of the RFQ.

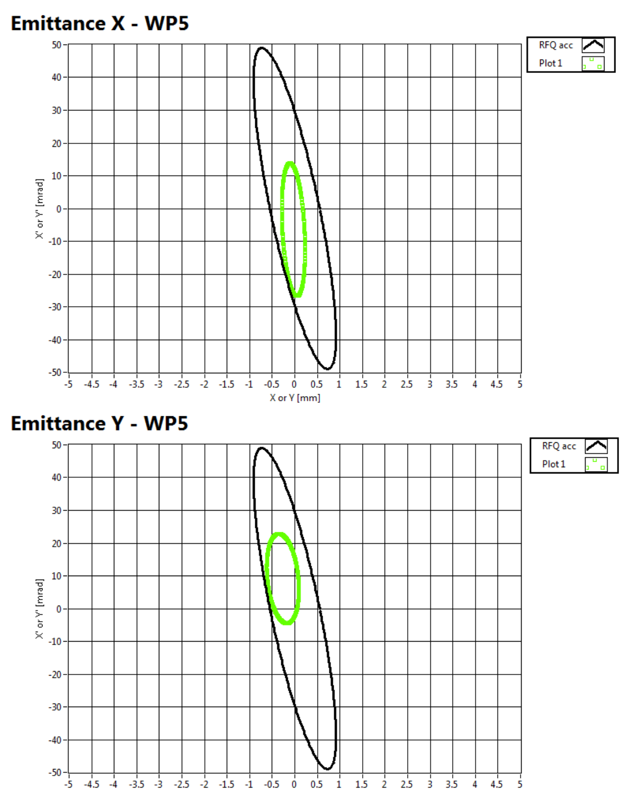

Figure 7: Example of reconstructed emittance, measured at the entrance of the RFQ during source commissioning.

A dedicated test bench allowing for the characterization of the beam has been designed, together with beam instrumentation that is used to monitor the beam performance along the linac during the different commissioning phases. An example of the measured beam from the proton source is given in Fig. 7. The plots show the RMS transverse beam emittance, which is well within the expected acceptance of the RFQ in both horizontal and vertical planes.

CONCLUSION

LIGHT is the first commercial 3 GHz linac for protontherapy in construction. A modular approach has been used in the design of the linac, which is divided in 12 RF units.

The beam produced by LIGHT will have unique properties which make it well suited for active spot scanning technique.

A number of technologies developed and in use at CERN have inspired the present design. In particular the highest frequency RFQ in the world is used as injector – giving extremely small emittances. LIGHT, which is at the heart of the proton therapy system of ADAM/AVO, represents a good example of technology transfer and collaboration between physics laboratory and industry for medical applications.

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