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HIGH POWER RF TRANSMISSION LINES OF THE LIGHT PROTON THERAPY LINAC

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Abstract

The Linac for Image-Guided Hadron Therapy (LIGHT) machine [1] is designed to accelerate a proton beam up to 230 MeV to treat deep seated tumours. The machine consists of three different kinds of accelerators: Radio-Frequency Quadrupole (RFQ), Side Coupled Drift Tube Linac (SCDTL) and Coupled Cavity Linac (CCL). These accelerating structures are fed with Radio Frequency (RF) power at 750 MHz (RFQ) and 3 GHz (SCDTLs and CCLs). This power is delivered to the accelerating structures via the high power RF transmission network (RFN). In addition, the RFN needs to offer other functionalities, like protection of the high RF power feeding stations, power splitting, phase and amplitude control and monitoring. The maximum power handling of the RFN corresponds to a peak RF power of 8 MW and an average RF power of 9 kW. It functions either in Ultra-High Vacuum (UHV) conditions at an ultimate operating pressure of 10^{-7} mbar, or under pressurized gas. The above listed requirements involve different challenges. In this contribution we exhibit the main aspects to be considered based on Advanced Oncotherapy's (AVO) experience during the commissioning of the RFN units.

OVERVIEW OF LIGHT SYSTEM

The Linac for Image-Guided Hadron Therapy (LIGHT) machine [1] consists of several subsystems to produce, accelerate, transport and deliver protons to treat deep seated tumours. It has the capability to deliver the required dose sending pulses with a duration of 5 µs, 200 times per second and being able to change the proton energy electronically pulse by pulse. The main subsystems are:

- LIGHT Proton Injector (L-PIA) that produces continuous proton pulses of 5 µs at 200 Hz and modulates their intensity.
- LIGHT Radiofrequency Quadrupole subsystem (L-RFQ) that comprises the necessary devices to produce, amplify, transport, monitor and control RF at 750 MHz to feed an RF quadrupole cavity that is capable of capturing the proton pulses produced by the source, bunching and accelerating them up to 5 MeV.
- LIGHT Side Coupled Drift Tube Linac subsystem (L-SCDTL) composed of two units with the necessary equipment to produce, amplify, transport, monitor and control the 3 GHz RF power to feed accelerating cavities boosting protons up to a fixed energy of 37.5 MeV.
- LIGHT Coupled Cavity Linac subsystem (L-CCL) composed of 10 units able to produce, amplify, transport, monitor and control the 3 GHz RF power to feed 15 CCL cavities able to dynamically modulate the energy of the protons from 70 to 230 MeV.
- After the main Linac other subsystems transport and deliver the beam to one or several treatment rooms, which are out of the scope of this contribution.

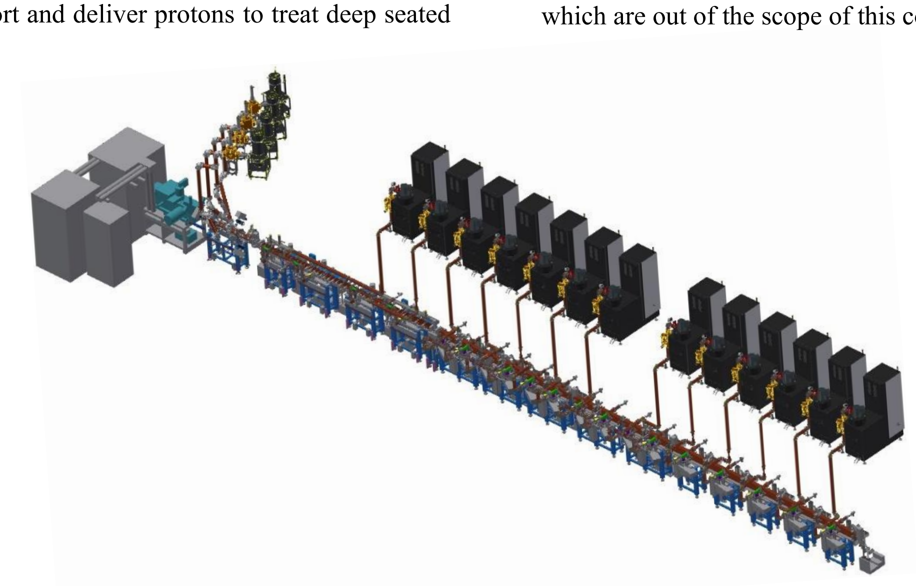

Figure 1: 3D model of the full LIGHT. The 3 GHz RF Network is visible connecting the high power stations to the accelerator.

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RF Network is a subcomponent of L-RFQ, L-SCDTL and L-CCL in charge of transporting, monitoring and manipulating the high power RF from the high power amplifier to the RF cavities.

LIGHT RF NETWORK

The LIGHT RF Network is a distributed apparatus over several subsystems of the LIGHT machine. The L-RFQ is required to transport RF pulses of up to a length of 10 µs, a maximum RF peak power of 120 kW, RF at 750 MHz at a pulse repetition rate of 200 Hz. In addition, it needs to offer protection against reflected power to the high power amplifier and monitoring of the transported signals. For L-SCDTL and L-CCL, the RFN needs to transport RF pulses of 5 µs length, at a maximum RF peak power of 7.5 MW, 3 GHz RF and 200 Hz pulse repetition rate. It also needs to offer protection to the high power amplifiers against reflected power as well as signal monitoring. In some cases, it needs to split the power to feed several cavities using the same amplifier with the possibility to change RF amplitude and phase independently for each cavity. In the following sections we describe our design to meet the above requirements. Figure 1 shows the full LIGHT.

Design and integration

Due to the differences in requirements, two different designs have been used for the RFN. One for a 750MHz RFN and another for a 3GHz RF network.

750 MHz RFN: it is built using 3 1/8 and 4 1/2 inches, 50Ω hard coaxial lines to offer the best compromise between compactness, power handling and insertion losses. The RFQ accelerator needs feeding from 4 high power amplifiers, therefore, the system has 4 independent but similar RFN coaxial lines, each one containing the following functional devices: one bi-directional coupler (BDC) at the output of the amplifier to monitor the production of RF and the reflection in order to interlock the system in case of failure, one circulator to remove reflections from cavity during RF transients and a second BDC at the input of the cavity to monitor the pulses delivered for acceleration. The coaxial lines work at atmospheric pressure. A PEEK window separates the vacuum cavity side. Besides the functional components, the 750 MHz RFN is tailored to the installation site by using elbows and straight parts. The support of the network is a key point to be considered in the integration to relieve any stress to the RF cavity and power amplifier. Figure 2 shows an integration of the network.

3 GHz RFN: it is built using heavy wall rectangular waveguides (WR284). They offer the right compromise between power handling, compactness, and insertion losses. The waveguides are pressurized at 3.6 bars with SF_6 to mitigate potential arcs due to the high peak RF power handled. The pressure is monitored and the system interlocks if it drifts away of the working region. An RF window is used just before the RF cavity to separate the pressurized section from the cavity which works in vacuum at a pressure lower than 10^{-7} mbars. For some CCLs, two modules are fed by a single power amplifier. In those cases, the RFN splits the power using a magic tee and it integrates a 360 degrees phase shifter able to adjust not only the phase but also the amplitude. After splitting the power, it is important to keep the RFN temperature stable to not induce phase drifts between the two fed modules. In all cases, the 3GHz RFN integrates an isolator to protect the amplifier from reflections coming from cavities during RF transients. The RFN foresees the use of a sliding short to match the accelerating cavity impedance.

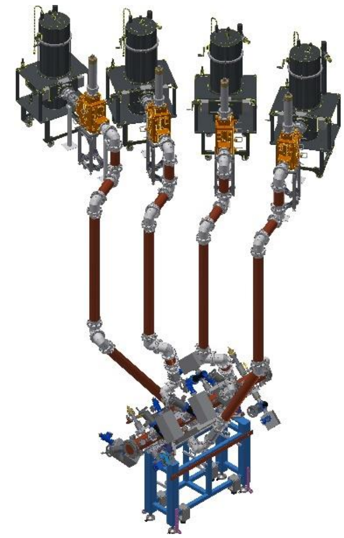

Figure 2: 3D model of 750MHz coaxial lines

Figure 3: 3D Model of 3GHz RF Network.

Manufacturing and Site Acceptance Tests

The RF pulses are monitored at the output of every amplifier and the input of every cavity using BDCs. Besides the above functional components, the RF network is composed of straight parts, E-bends and H-bends to tailor it to the installation site. Being this RF network typically heavier than the coaxial lines, the integration and design of supports is critical for a successful commissioning. Figure 3 shows an integration of one 3GHz RF network.

The manufacturing of the LIGHT RFN is externalized to several specialized suppliers that need to meet strict quality control processes to ensure that the components are

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produced meeting mechanical tolerances, RF requirements and cleanliness for those under high vacuum.

After reception of components from manufacturing, they undergo the following site acceptance test (SAT) to ensure they meet the requirements before installation:

- Mechanical Inspection to ensure their dimensions are produced as per design. In some cases dimensional control is performed to check the geometrical tolerance of flanges as they are critical to ensure good electrical connection;
- Cooling SAT: for components with integrated cooling circuits, pressure and cooling connector tests are performed;
- Pressure and vacuum SAT: each individual component to be installed under pressure or vacuum is tested and validated against a range of acceptance parameters such as leak rate and outgassing rates (RGA) to meet our requirements;
- Low Power RF SAT: functional or critical components, such as isolators, RF windows, magic tees, loads and BDCs are characterized using a vector network analyser (VNA) to meet our requirements. Other components like straight sections and elbows are either randomly tested or tagged after visual inspection if suspected of potential non-conformity.
- Motion SAT: the sliding shorts and phase shifters in the LIGHT RF system are linear actuator devices driven by stepper motors. Functionality tests on the devices must be carried out to ensure they behave as intended. This includes: motion and range testing ensuring that the motor can travel its intended range with appropriate velocity, acceleration, and deceleration; connectivity tests to be accessible via a unique IP on the Network to send movement commands; limit switch testing to prevent damage if the actuator reaches its maximum range and encoder readback tests that provides feedback to the control system and enables the motor's position, speed, and acceleration parameters to be monitored.
- High Power SAT: some critical components (i.e. isolators, circulators and RF windows) are validated stand alone at high power before installation as a functional failure during commissioning could damage high power amplifiers or accelerating cavities.

Installation

The installation of the RFN is a delicate process that needs to be carefully performed. It relies in detailed working instructions to ensure that the process meets the quality required to not compromise the components once exposed at high power. The installation of the RFN is done sequentially connecting component by component starting from accelerating cavities and finishing on the amplifier side. The process ensures that no stress is induced in the accelerating cavities, where the alignment to the beam line is crucial. In the process, RFN supports are pre-installed and ready to hold the components to not introduce stress on the assembly. Some components are pre-assembled in the lab before being installed in the final position to ease or boost the process depending on the needs of the installation site. It is important to ensure the cleanliness of the main flanges before the connection, their alignment and to apply the proper torque to not compromise the electrical continuity. The torque of the fasteners is performed by following gradual star sequence to remove stress on the connection. All the installation is performed using clinical gloves to not contaminate the waveguides and the installation of every component is tracked in a report for future reference.

High Power Validation and Nominal Use

After the RF network is installed and before it is approved for final use, it must be validated to ensure it complies with the requirements. The tests include the following:

- Pressure, vacuum, and cooling tests of the integrated assembly when applicable;
- High power ramp up to nominal power, with careful monitoring of the signals to detect potential failures or arcs. For SF6 pressurized networks, a quality analysis of the SF6 is performed periodically. The detection of SO2 by-product in the SF6 analysis is a clear indication of arcing inside the RFN, usually due to a bad electrical contact between two components;
- Phase shifter and sliding short calibration, performed to find the matching points for each accelerating cavity and the working ranges for the phase shifter and attenuator when applicable.

CONCLUSION

The LIGHT accelerator relies on the RFN to transport, manipulate and monitor the high-power RF used by the accelerating cavities. The RFN has been designed to meet all the AVO requirements and is tailored to each installation site. In this paper we have dissected the main points we have found important to consider after our experience with the design, installation, and commissioning of the first LIGHT system.

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