LIGHT PROTON THERAPY LINAC LLRF SYSTEM DEVELOPMENT

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Abstract

Proton cancer therapy is a state-of-the-art medical treatment technique based on an accelerator beam production facility. The LIGHT linear accelerator design by AVO-ADAM offers a modular compact solution for precise control of the treatment dose delivery, both position and energy wise. Proton energy can be modulated at up to 200 Hz in a range from 70 to 230 MeV by varying the gradient of the accelerating structures. The normal conducting LINAC RF system is based on a 750 MHz RFQ and 12 S-band stations individually controlled. A customized LLRF system is being developed on the Libera LLRF platform for the LIGHT project. The paper is describing the required cavity field control functionality and the other subsystems such as master oscillator reference, cavity tuning, real-time control, data acquisition, control system and synchronization interfaces.

INTRODUCTION

The LIGHT (Linac for Image Guided Hadron Therapy) proton cancer therapy LINAC, designed by AVO-ADAM, is based on 13 normal conducting RF station modular design, conceived to modulate independently the RF power at 200 Hz, at the level of each high-power station. Together with low emittance it allows accurate dose delivery within the tumour volume and longitudinal layer switching on pulse-to-pulse basis. Moreover this feature opens up the highly desirable possibility to implement image-guided adaptive radiation therapy with protons, which is a unique property of the LIGHT system [1].

The compact LIGHT LINAC design consists of:

- a proton source at 40 keV providing currents up to 300 uA with pulses up to 20 us at 200 Hz repetition rate.
- an RFQ (Radio Frequency Quadrupole) at 749.48 MHz accelerating the protons up to 5 MeV, operated at the forth sub-harmonic of the 2997.92 MHz LINAC frequency. The RFQ RF system provides to the LLRF system, 4 cavity probe signals and 4 pairs of directional coupler forward and reflected signals.
- Two SCDTL (Side Coupled Drift Tube LINAC) high power RF units at 2997.92 MHz, delivering the beam at 37.5 MeV. Each SCDTL RF station provides 4 cavity probe signals and 3 pairs of directional coupler forward and reflected signals, as the klystron amplifier output is split between two accelerating structures.
- Ten CCL (Coupled Cavity LINAC) high power RF units at 2997.92 MHz accelerating beam up to 230 MeV. Five CCL units provide 2 RF probe signals and 2 pairs of directional coupler forward and reflected signals. In the other five CCL RF stations, 4 probes and 3 pairs of directional coupler signals are provided as the high-power drive is split among two accelerating structures.

In Figure 1 a scheme of the LIGHT proton accelerator compact design is presented. The total peak RF power required by the structures would therefore be 400 kW, 8 MW and 45 MW, respectively for the RFQ, SCDTL and CCL structures [2,3].

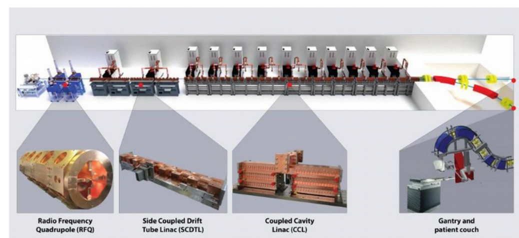

Figure 1: A scheme of the LIGHT proton accelerator.

THE LLRF SYSTEM REQUIREMENTS

To control the proton acceleration, it's required that all the 13 RF stations are tightly synchronized to the Master Oscillator (MO) and the LLRF system provides field control at the level of individual RF stations. Moreover, the LLRF system must apply the RF pulses of specific shape at nominal RF pulse length 20 µs and 7µs for the RFQ and the S-band structures respectively. Parameters defining RF pulse shape, it's amplitude and phase, must be provided to the LLRF system in real-time at 200 Hz rate in order modulate the proton energy according to the programmed treatment plan.

For cavity conditioning purpose, it's further required that the LLRF system has the ability to drive the cavity in a frequency range of 749.38 ± 1 MHz and 2997.92 ± 4 MHz. The LLRF system is also designed to automatically track the cavity resonant frequency within the range.

For the purpose of proton energy modulation, it is required that the LLRF system is operated in a 20 dB dynamic range, where also amplitude and phase stability requirements are specified (Table 1) [4].

To avoid the transmission of the reference MO signal over distance, it's required that the LLRF units controlling the RF stations are tightly synchronized to a common MO source to be installed at the same location of the LLRF units. The required stability for the MO signal distribution shall be within ±0.1°.

Table 1: Required Amplitude and Phase Stability

Parameter	**Requirement**	**Signal level**
RMS amplitude stability	< 0.05 %	0 dB_{FS}
RMS phase stability	< 0.05 °	0 dB_{FS}
RMS amplitude stability	< 0.1 %	> -20 dB_{FS}
RMS phase stability	< 0.1 °	> -20 dB_{FS}

Additional Requirements

For the purpose of cavity tuning, the LLRF system must continuously measure the cavity resonant frequency and report the results through a dedicated Modbus interface to an external cavity temperature controller, acting on the water cooling system.

The LLRF system must tolerate certain kind of RF system failure before triggering an interlock event. An archiving system shall be in place to record the evolution of all RF signals during the applied treatment, which implies the LLRF system shall have a dedicated data streaming interface.

The triggering scheme involves two separate trigger events per LLRF unit generated by the LIGHT control system. An RF pulse shape will be set depending on the trigger event: either a pulse pre-configured over the real-time interface or a pre-loaded on the LLRF unit start-up. This implementation grants flexibility to differentiate treatment run with beam from stand-by states without beam to keep the accelerator thermalized for the operation. The trigger events have to be synchronized with the MO reference to achieve the required phase and amplitude stability.

STATUS OF THE LLRF DEVELOPMENT

The LIGHT LLRF system is being developed on the Libera LLRF platform. The Libera LLRF system for LIGHT will be provided in two 19” 2U chassis. At the bottom of Figure 2, a 14-channel temperature stabilized RF front end is presented, to be used together with an AMC based Libera LLRF processing system (on the top of Figure 2). In the case of the RFQ LLRF system, the RF front end will integrated within the processing 19” 2U unit [5-7].

For the LIGHT LLRF application, the Libera LLRF system will be controlling the amplitude and phase of a probe signal through pulse-by-pulse feedback. Two separate amplitude and phase controllers will be in place in order to simplify the process of closing the loop. The pulse shape of the drive signal will be modulated by acting on the amplitude and phase envelopes by means of 2nd order spline polynomial sections, to be configured in real-time. For this purpose, an additional SER-RJ1 AMC module has been developed to enable the Control System (CS) to talk directly to FPGA. The CS, with enough time margin with respect to the applied trigger, will be sending a command over an RS-485 interface implemented on the SER-RJ1 module in order to define the pulse amplitude and phase shapes. For this purpose a specific protocol has been developed together by ADAM and Instrumentation Technologies teams, according to the requirements, to fulfil different LIGHT operation scenarios including the cases of real-time interface failure or RF system failure. In these specific cases, the LLRF system applies predefined RF pulse settings depending from the specific failure. The real-time LLRF control is entirely implemented in FPGA, while the slower settings are handled by the computing module in processing unit also connected to the Control System through an interface based on SCPI-like TCP/IP protocol.

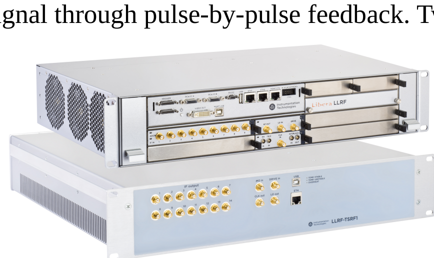

Figure 2: The LIGHT LLRF system implemented in the Libera LLRF platform.

The same SER-RJ1 AMC module features also a Modbus interface used by the LLRF system to talk to the external cavity tuning controller: cavity decay analysis is performed at the tail of the pulses and the cavity detune information is calculated, averaged among pulses and delivered at 1 Hz rate.

An RMO (Reference Master Oscillator) temperature stabilized RF source and distribution amplifier units are used to provide stable, low jitter MO signals to all 12 LLRF units at 2997.92 MHz and a sub-harmonic RFQ MO frequency at 749.38 MHz (Figure 3).

Figure 3: Instrumentation Technologies RMO and distribution amplifier temperature stabilized units.

According to LIGHT requirements the Libera LLRF systems has been upgraded to process two different trigger signals named as *idle* and *beam* triggers. The type of the trigger signal defines from which pulse parameters the RF is fired each trigger. A Trigger Synchronization Unit (TSU) has been developed for the purpose of aligning the provided Control System trigger signals to the MO reference with the ability to program arbitrary delays on individual trigger lines. The TSU is a 19” 1U unit and has the capability of processing 26 input trigger lines, provides 26 outputs and additional 13 outputs that can be further delayed for the purposed of triggering the

RF system modulators. All the TSU settings can be updated through the Control System.

The second Libera LLRF Ethernet interface is used for the archiving purposes. Demodulated 512 sample RF signal traces, from 7 to 13 channels (depending on the station configuration), are streamed at 200 Hz pulse rate within UDP packets over a dedicated network and collected by archiving servers during duration of the treatment.

The classical Libera LLRF threshold-based interlock triggering is upgraded to report failures detected on individual sources. The failures are detected on directional coupler reflected signals when the reflection exceeds a specified fraction of the forward signal. The failures locally detected by the new relative detection concept are locally counted for diagnostic purposes. When the number of counted failures in a preconfigured time window exceeds a certain threshold the interlock is triggered and the RF output is disabled, while individual failures would still enable to operate the RF system at lower power.

CONCLUSION

The LIGHT LLRF has been designed in most of its subsystems and the units are being produced, assembled and tested in order to be delivered to AVO-ADAM within the first half of 2019. It became possible as a result of a strong collaboration between AVO-ADAM and Instrumentation Technologies teams, as both companies are building up their positions in industrial accelerator applications. The innovative LLRF solution for LIGHT, based on the versatile Libera platform, ensures the performance for a successful accomplishment of this challenging medical accelerator project.

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