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RF SYSTEM DESIGN FOR THE TOP-IMPLART ACCELERATOR

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Abstract

In the ENEA-Frascati research center a linear accelerator for proton therapy is under development in the framework of TOP-IMPLART Project carried out by ENEA in collaboration with ISS and IRE-IFO. The machine is based on a 7 MeV injector operating at a frequency of 425 MHz followed by a sequence of 2997.92 MHz accelerating modules. Five 10 MW klystrons will be used to power all high frequency structures up to a beam energy of 150 MeV. The maximum repetition frequency is 100 Hz and the pulse duration is 4 µs. The RF amplitude and phase stability requirements of the accelerating field are within ±2% and ±2 degrees respectively. For therapeutic use the beam energy will be varied between 85 and 150 MeV by switching off the last modules and varying the electric field amplitude in the last module switched on. Fast control of the RF power supplied to the individual structures allows an energy variation on a pulse by pulse basis; furthermore the system must be able to control the RF phase between accelerating structures. This work describes the RF power distribution scheme and the RF phase and amplitude monitoring system implemented into an embedded control system.

THE TOP-IMPLART ACCELERATOR

A RF proton linear accelerator is under realization in the framework of the TOP-IMPLART (Intensity Modulated Proton Linear Accelerator for RadioTherapy) Project leaded by ENEA in collaboration with the Italian Institute of Health (ISS) and Regina Elena National Cancer Institute IFO-Rome [1].The project is devoted to the realization of a protontherapy centre to be sited at IFO based on a 230 MeV accelerator. The first segment up to 150 MeV has been funded by Regione Lazio and is under realization and test at ENEA-Frascati [2]. It is composed (fig.1) by a low frequency (425 MHz) injector (ACCSYS-HITACHI PL7 model, RFQ+DTL) and a high frequency (2997.92 MHz) booster (SCDTL up to 35 MeV and CCL up to the final energy).

A LINAC-based proton therapy facility can provide, like synchrotron-based facility, both energy and intensity active modulation. However synchrotron accelerators typically vary the beam energy in no less than 1-2 seconds (the time it takes to complete a whole acceleration cycle), while LINAC can in principle vary the energy on a pulse by pulse basis, i.e. within a few milliseconds, without the need to dump the accelerated beam.

To guarantee patient safety through the correct actuation of the desired machine settings, some subsystems are identified as "critical", namely those systems actively responsible for the energy, intensity and spot size of the beam. To this end, the critical subsystems will provide the dose delivery system with an acknowledgment of their status on successful completion of the new settings, thus allowing beam acceleration in the next pulse.

THE RF SYSTEM

The block scheme of the TOP IMPLART RF system up to 150 MeV is shown in figure 1. The high power part foresees the use of a number of identical RF plants each based on a 10 MW klystron (TH2157) and its power supply (modulator). The power is split in 4 or 2 parts depending on the needs of the fed structures. Tight controls are used to stabilize the phase among the several klystron outputs. The energy is varied by changing the power of the klystrons supplying the accelerator structure. The TOP-IMPLART aims at changing the beam energy as quickly as possible, although, as in other protontherapy plants the limiting factor is the velocity of changing the beam transport line magnetic elements, that limits the repetition frequency to 100 Hz.

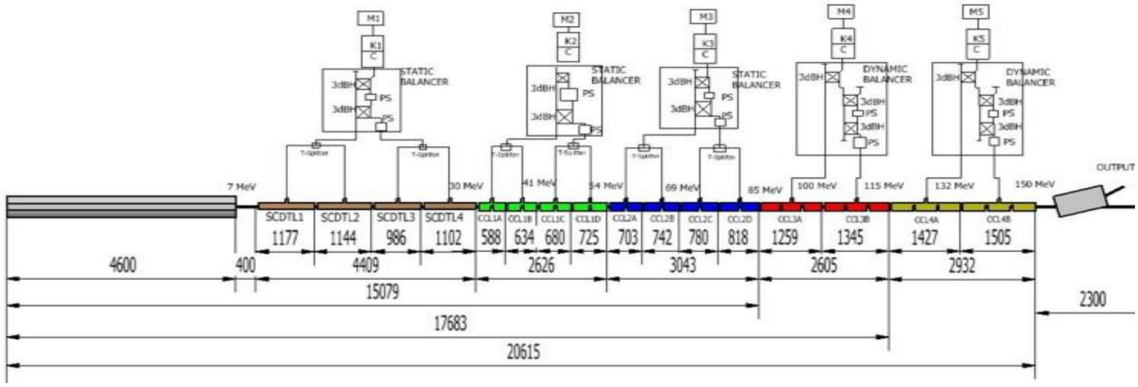

Figure 1: Block scheme of TOP-IMPLART RF system.

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The energy can be varied continuously in a range between 85 and 150 MeV using the last four modules by switching off the last modules and varying the electric field amplitude in the last active module.

In the spring of 2015 we are running only the SCDTL part of the system needing only a single klystron, being the total power requirement around 7 MW. The RF split in 4 branches is achieved as follows: a first split in two by means of a commercial [3] variable power divider with a power range between -0.1 dB and -30 dB composed by a sequence of a 3 dB hybrid, a phase shifter and another 3 dB hybrid; a second level of splitting is obtained by two home-made, very efficient riblet-based splits the first delivering power to SCDTL-1 and 2 and the second to SCDTL-3 and 4. Several -55/-60 dB calibrated directional couplers are placed in the RF line to retrieve information on the phase and amplitude of the signals driving the structures, and thus allowing the implementation of a stabilization loop. Each structure is also provided with a cavity field sensor and a motor actuated tuner for frequency control.

LOW LEVEL RF

One of the main characteristics of a full linear accelerating scheme is its modularity. To ensure the scalability in energy not only the RF power system, but the low level RF system as well is modular in structure. Each module is designed in principle equal to the adjacent one and it is equipped with the following elements:

- Low level RF source,
- Intermediate Amplifier RF (AM 10 Microwave Amps),
- Final Amplifier RF (TH2157 Thales, K1-P ScandiNova solid state pulse modulator),
- Measurement system of the RF variables to be monitored (analog downconversion and digital I/Q demodulation)
- Two separate control loops for the RF cavity tuning and for phase and amplitude control of the RF power signal that feeds the accelerating structures
- Fast Interlock control system (Arc detectors, VSWR detectors)

RF Reference Source Distribution

To allow an easy integration the low level RF sources of each module have been synchronized to a single reference source at 10 MHz. As shown in Fig. 2 an optical fiber link of PSOF type (Phase Stabilized Optical Fiber) guarantees a propagation delay temperature coefficient contained in 5 ps/m/°C. In such a way it is possible to compensate the phase drift of the reference signal source due to changes of both the refractive index and physical length by means of both a temperature control and an active drift compensation by a piezo stretcher [4], [5], [6]. Even the trigger signal of the RF macro pulse is reconstructed locally, from the master oscillator and the gating signal, to reduce the jitter.

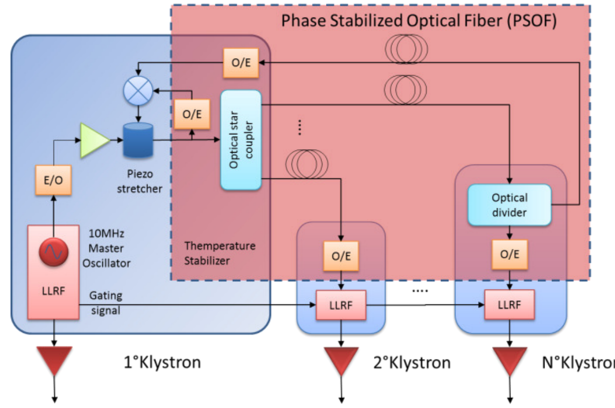

Figure 2: RF Reference Distribution.

RF Variables Measurement System

In order to ensure compliance with the specification on phase and amplitude control (better than ±2% and ±2 degrees respectively) it is necessary to reduce the phase jitter. For this reason the measuring system, the controller and the RF sources have been integrated on a single PXI-express Chassis (NI PXIe-1082: 8 Slot 3U, 7 GB/s system bandwidth) from National Instruments.

The measuring system of the RF variables is based on an intermediate analog demodulation at a frequency f_{IF} of 12.5 MHz, an analog to digital conversion and a digital I/Q baseband demodulation, thus allowing simultaneous acquisition of phase and amplitude values.

In fig. 3 the layout of the first RF power module feeding the 4 SCDTL structures is shown with the 16 points of measurement used to control and monitor the first RF unit.

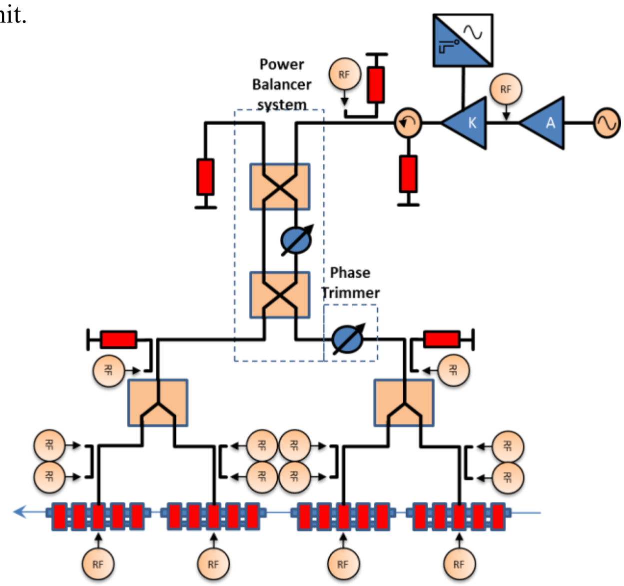

Figure 3: RF distribution to SCDTL structures.

Each point has different levels of power and dynamic; therefore the different signals are appropriately conditioned before being demodulated to operate on the double balanced mixer (X2M-10-41 Pulsar Microwave) in full dynamic and ensure noise levels tolerated by the analog to digital converter (14 bit ADC: AD9252 Analog Devices) and digital I/Q demodulator (Fig. 4).

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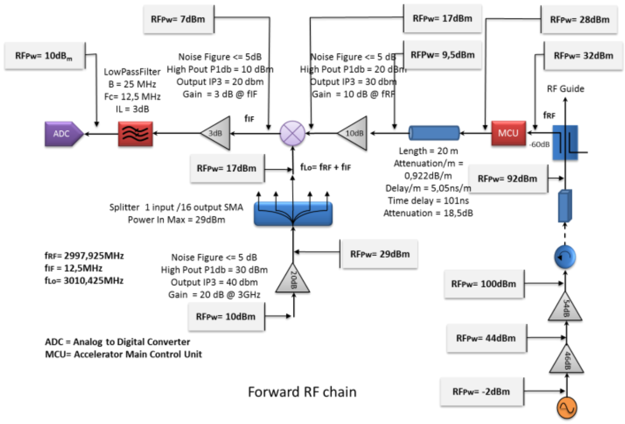

Figure 4: Signal conditioning and frequency down-conversion of the forward RF signal.

The local oscillator f_{LO} employed to obtain the intermediate modulation is synthesized by PXI-express 5651. This module is phase locked to the bus PXI_CLK10 which is routed to the external 10 MHz Reference Clock IN. The synthesizer module has good stability in frequency and adequate resolution: in fact on board the main synthesizer circuit is phase-locked to the Direct Digital Synthesizer (DDS) output signal and this DDS reference signal delivers the necessary fine-tuning steps of the synthesizer.

The demodulated analog signals are sampled at 50MS/s by the 14-bit ADC of the FlexRIO Adapter Module (NI5751). The digital I/Q baseband demodulation is performed by FPGA Virtex-5 SX50T of the module FlexRIO PXI-e7962R. This module mounts on board two DDR2 memory banks of 256MB and has 16 DMA channels that can transfer peer to peer at high-speed data stream up to 800 MB/s. Figure 5 shows the relationships between the channel bandwidth in input and in output to the IQ demodulator and the RF frequency, the sampling frequency and the macro pulse parameters.

Demodulation & Sampling Parameters			Macro Pulse Parameters		
f_{RF}	RF Power Frequency	2997,925MHz	T	Pulse Period	1÷10 ms
f_{IF}	Intermediate frequency	12,5MHz	τ	Pulse width	4 µs
Dw	Down conversion	≈ 240	τ / T	Duty cycle	$4\ 10^{-4} \div 4\ 10^{-3}$
f_{LO}	Local oscillator frequency	3010,425MHz	S_τ	Samples for macro pulse $S_\tau = f_{IF}\ \tau$	50
f_s	Sampling frequency	50MHz			
Data flow parameters			B_{wi}	Istantaneous Bandwidth B_{wi} = NBits Nch fs	1,6GB/s
			B_{wa}	Aggregate Bandwidth $B_{wa} = B_{wi}\ \tau / T$	640 kB/s÷ 6,4 MB/s

Figure 5: Sampling & demodulation parameters, macro pulse parameters and the DMA channel bandwidth.

RF Control Loops

Figure 6 shows the two RF control loops with their actuators: the first one (LLRF Mod Phase), whose measuring system has already been described, ensures amplitude and phase to be kept at the prescribed values at predetermined points in the RF distribution chain, the second one (MCU) allows the tuning of the individual accelerating structures.

The LLRF amplitude and phase control loop acts on the power balancer and phase trimmer; the law implemented by the controller is of the type Proportional Integral Derivate (PID), the actuators are controlled by Ethernet port and the controller is a module PXI-express 8135 RT.

Each accelerating structure is tuned by a Main Control Unit (MCU). The MCU implements an automatic frequency control loop that detects structures detuning caused by thermal drifts and produce an error signal fed to the tuning motor.

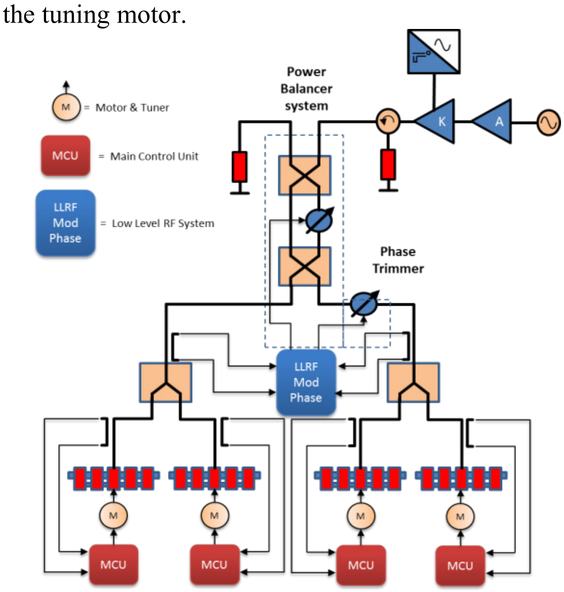

Figure 6 : Control Loops of first LLRF module.

The accelerator structures have typical a Q_{Load} factor between 3500 and 5000, therefore a ±2 degrees phase tolerance corresponds to a request of frequency stability within ±10 kHz.

The action of each MCU varies only slightly the reflection coefficient at the mouths of the hybrid dividers when the detuning is contained within the prescribed tolerances and the insulation coefficient (S14) of the hybrid is a typical value [7][8][9][10]. Therefore in typical operation conditions each MCU loop can be considered independent.

CONCLUSIONS

This paper shows the solutions adopted by the TOP-IMPLART accelerator to implement a control system that respects the design specification :

- scalable and modular LLRF in terms of beam energy,
- phase and amplitude settable pulse by pulse,
- independent tuning system of the accelerator structures.

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