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DEVELOPMENT AND INTEGRATION OF A NEW LOW-LEVEL RF SYSTEM FOR MEDAUSTRON

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Abstract

The MedAustron Ion Therapy Centre is a synchrotron-based particle therapy facility, which delivers proton and carbon beams for clinical treatments. Currently, the facility treats 40 patients per day and is improving its systems and workflows to further increase this number. Although MedAustron is a young and modern center, the life-cycle of certain crucial control electronics is near end-of-life and needs to be addressed. This paper presents the 216MHz injector Low-Level Radio Frequency (iLLRF) system with option of use for the synchrotron Low-Level Radio Frequency (sLLRF - 0.4-10MHz). The developed system will unify the cavity regulation for both LLRFs and will also be used for beam diagnostics (injector/synchrotron) and RF knock-out slow extraction. The new LLRF system is based on a µTCA platform which is controlled by the MedAustron Control System based on NI-PXIe. Currently, it supports fiberoptics links (SFP+), but other links (e.g. EPICS, DOOCS) can be established. The modular implementation of this LLRF allows connections to other components, such as motors, amplifiers, or interlock systems, and will increase the robustness and maintainability of the accelerator.

INTRODUCTION

The MedAustron Therapy accelerator contains a linear accelerator [1] and a synchrotron to accelerate particles for medical treatment. The most important radio frequency components are the linear accelerator RF systems working at 216.816MHz and and the synchrotron RF systems [2] working at 0.4-10MHz. Till now, both accelerator parts use different components to control the RF amplifiers and monitor the cavities and the beam. Unfortunately end of life notifications were received already for most of these components and updates will be necessary in the near future. A common solution for all replaced components is foreseen to reduce the needed implementation effort and user training. To develop this common solution, efforts of MedAustron and Instrumentation Technologies are bundled in a joint project.

SYSTEM ARCHITECTURE

Requirements

The analog conversion requirements are summed up in Table 1. To allow fast frequency changes for the synchrotron a direct sampling solution is required and the LLRF shall

Table 1: Analog Conversion Requirements for the LLRF Systems

	Injector	Synchrotron
Frequency Range	216.816 ± 1 MHz	0.4 – 10 MHz
Frequency Error	<10 kHz	<100 Hz
Sample Jitter	<1 ps	<27 ps
Channel Jitter	<6 ps	<125 ps
Amplitude Stab.	<0.2 %FS	<0.2 %FS
Phase Stab.	<0.1°	<0.1°
Group Delay	<500 ns	<500 ns

provide CW and Pulsed operation modes. Furthermore, the LLRF shall allow connection to different supervising systems and subcomponents like plunger motors for cavity tuning or the RF amplifiers. If used as a beam diagnostic backend, only the analog input channels are used.

Hardware Architecture

Limited resources are available for hardware development and testing at MedAustron. Therefore only off-the-shelf (COTS) hardware was selected. For expected long term availability and easy replacement of single components, the µTCA architecture was chosen. The most important components of the hardware are:

- Vadatech AMC560 [3]: Base board providing the computing power to connect to the supervision systems and to provide a local control interface. The FPGA is used for baseband conversion and cavity regulation.
- Vadatech FMC231 [4]: ADC/DAC extension board for the AMC560. Provides 4 channels of 16bit 1GSps ADC and 4 channels of 16bit 2.5GSps DAC.
- Vadatech FMC105 [5]: High speed connection to the MedAustron Control System (supervising system) via SFP+.
- Vadatech FMC155 [6]: GPIO for Interlocks and Modbus for plunger motor communication.
- Vadatech UTC004 [7]: µTCA management and 10MHz reference clock distribution.

Firmware Architecture

The firmware architecture, seen in Fig. 1, was designed having reusability in mind. The goal was to have an unified firmware, which can support all applications planned in the future. All building blocks of the firmware can be configured

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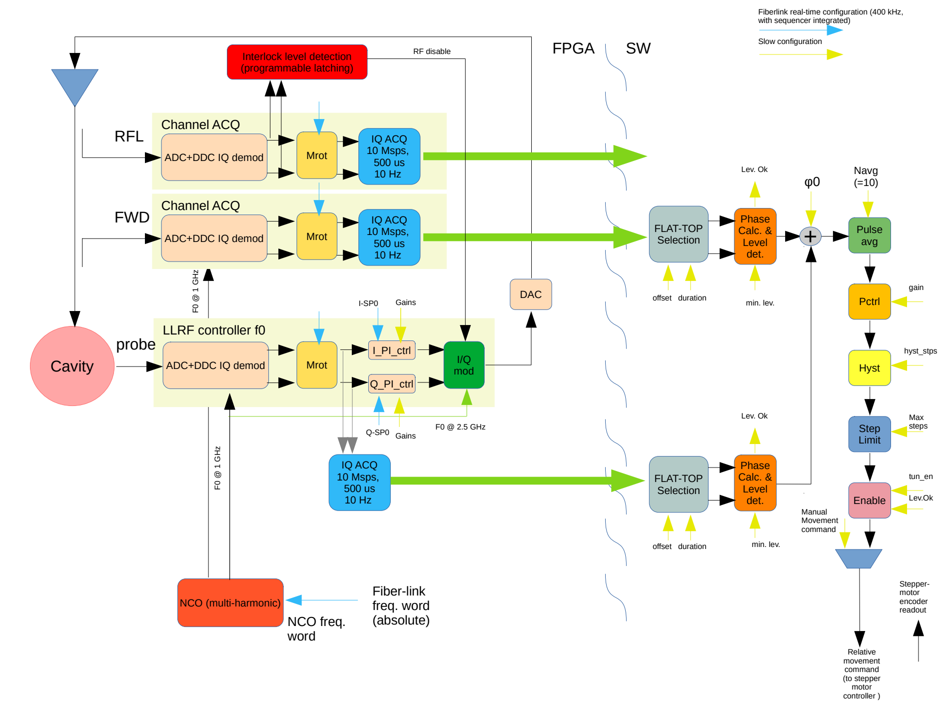

Figure 1: Firmware Architecture used for the µTCA LLRF.

to the needed application or can be disabled if not needed. The most important building blocks are:

- **Numerically Controlled Oscillator:** The NCO is used for the demodulation and modulation of the RF signals. With the fixed sampling frequency of the analog converters and the necessity to support different frequencies, a cordic based implementation is used. The requested frequency can be updated with 10 MHz using predefined sequences. Multiple NCOs are available in the current design and each of them provides the first 4 harmonics of the requested frequency.
- **Digital Down Conversion / Demodulation:** The DDC block includes multistage filtering and demodulation using cascaded CIC and IIR filters, allowing coefficient updates at runtime. The DDC block provides in phase and quadrature signal components at a rate of 10 MHz.
- **Matrix Rotation:** The matrix rotation block allows to apply phase and gain corrections on the input signal to compensate for cable and input stage delays and attenuation. The matrix rotation can be set up to apply a compensation dependant on the frequency defined by the NCO.
- **PI Regulation:** The PI controller supports setpoint and feed forward signal inputs and can be enabled and disabled with high precision timing events. The regulation coefficients can be configured during runtime and independently for the in phase and quadrature signal components.
- **Direct Digital Synthesis / Modulation:** The DDS block generates the RF signals from the baseband input provided by the PI controller. Multiple DDS outputs can be added up to generate signals containing multiple frequency components.
- **Sequencers:** Sequencers will provide setpoints for the NCOs (tuning the frequency) and the cavity controllers (I and Q or Amplitude and Phase setpoints) with a maximum rate of 10 MHz. These sequencers can be used to program any frequency, amplitude or phase waveform into the LLRF to generate any RF pulse shape requested.

RESULTS

In the first stages of the development the hardware was tested against the analog requirements mentioned in Table 1.

Table 2: Analog Conversion Results for the µTCA LLRF

	Measurement
Frequency Range	0.3-400 MHz
Frequency Error	locked to GPS clock - < 10^{-10}
Sample Jitter	0.9 ps
Channel Jitter	5 ps
Amplitude Stability	0.1 %FS at controlled temperature
Phase Stability	0.07° @ 216 MHz
Group Delay	450 ns from DAC to ADC

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The results in Table 2 fulfill and partially exceed the given requirements which was the first important milestone to start the development of the LLRF.

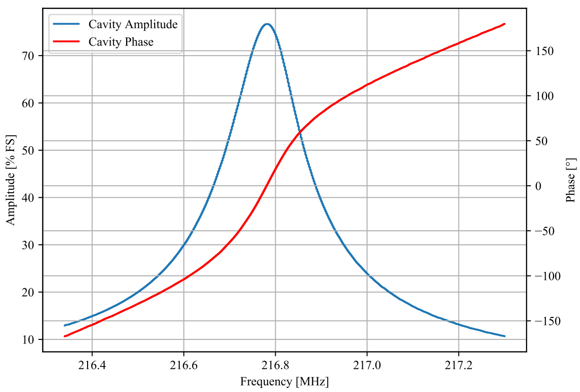

Figure 2: Using the µTCA LLRF as Signal Analyzer to find the Cavity Resonance.

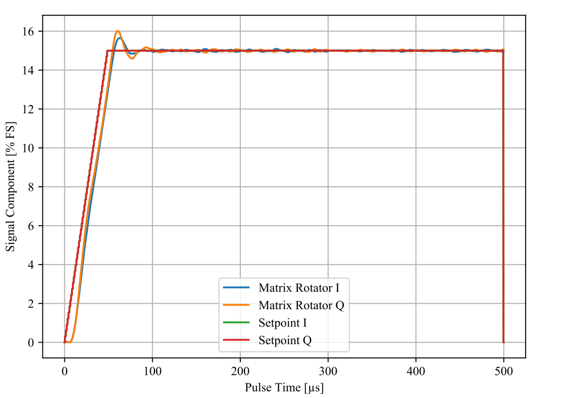

Figure 3: Generating a regulated RF Pulse at 216.772 MHz.

At the current point of development, cavity regulation is possible for multiple parallel cavities connected to one or multiple AMC560 cards. This project milestone was tested with a dummy cavity, as direct access to the medical accelerator at MedAustron is difficult and testing times would be limited. To find the resonance frequency of the dummy cavity, the NCO was set up to sweep through the frequency range of 216.3 – 217.3 MHz using a static feed forward signal in the PI controller. In Fig. 2 the expected resonance peak of the cavity can be seen at 216.772 MHz. With this information, the LLRF could be reconfigured to use a static frequency and to generate an RF Pulse of 500 µs with a ramp up of 50 µs and a stable time of 450 µs. The PI controllers were only configured preliminarily and introduced an overshoot at the end of the ramp time, as it can be seen in Fig. 3. Nonetheless, this measurement shows stable RF signals can be generated as needed for the linear accelerator. These presented configurations and measurements were done with a local control interface on the AMC560 card, because the connection to the MedAustron control system is not finalized yet.

OUTLOOK

At the current state of the development, cavity regulation is already possible and ready to be used in the linear accelerator at MedAustron. This will happen as soon as all the necessary safety (external interlocks) and auxiliary systems are implemented and tested. Most important here are the reflected power measurement and the resulting interlock. To keep the reflected power low, the implementation of the cavity tuning via plunger motors has to be finalized in the next months. In the further future it is also planned to implement a particle energy measurement system, based on the time of flight of the particles in the transfer line from the linear accelerator to the synchrotron. After finishing the linear accelerator applications, the focus will be switched to applications in the synchrotron. Most important to mention here is the synchrotron LLRF, which will not only regulate the cavity in the synchrotron, but will regulate on multiple beam parameters as the beam phase compared to the cavity phase and the beam radial position. In the synchrotron, the µTCA LLRF shall also provide the regulation of the RF-Knockout cavity responsible for the slow extraction of particles from the synchrotron to the treatment rooms.

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