LOW-LEVEL RF CONTROL AT LIGHT IONS INJECTOR FOR NICA

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Abstract

Light ion injector for future NICA project contain several resonator: buncher, RFQ, Alvarez-type linac LU-20, and possibly debuncher, that all work on same resonant frequency 145.2 MHz. Base frequency for all resonators in injector produced by LU-20 linac, worked in self-excited loop mode. Low-level RF control system of injector should capture RF signal from LU-20 linac within front of signal and generate output RF signals with same frequency on others resonators, with regulated phase difference between channels. Additionally, low-level RF control system should tune resonant frequencies of RFQ, buncher and debuncher. Presented LLRF system was successively work within several years. LLRF controllers design, possibilities, and key stabilization techniques are presented.

INTRODUCTION

The NICA (Nuclotron-based Ion Collider fAcility) is accelerator facility, which is now under construction at Joint Institute for Nuclear Research (JINR, Dubna) [1]. It was used the Alvarez-type linac LU-20 as an injector for light ions, polarized protons and deuterons. Old HV fore-injector of the LU-20, which operated from 1974, was replaced by the new RFQ accelerator, which was commissioned in spring 2016 [2] and successfully works within 2016-2018 years.

Light Ions Injector RF Control

An injector for light ions, polarized protons and deuterons consists from next main parts [2]: SPI or LIS ion source, Low Energy Beam Transport (LEBT) Channel, 4-wane 3-section RFQ, Buncher, LU-20 and possibly Debuncher.

In 2016-2018 years Radio Frequency (RF) system of light-ion injector of Nuclotron was successfully work with Low-Level RF (LLRF) controller, developed in ITEP in 2015-2016. Figure 1 shows second generation of RF system of injector, with new LLRF Controller.

The RF power system is designed to excite an electromagnetic field in the accelerating structure at a frequency of 145.2 MHz, stable in amplitude, frequency and phase. RF amplifier stages and anode voltage modulator operate in a pulsed mode, with a maximum pulse repetition rate of 1 pulse/sec, and with more frequently used repetition rate of 7-10 sec/pulse. The duration of the RF pulse is about 150 μs.

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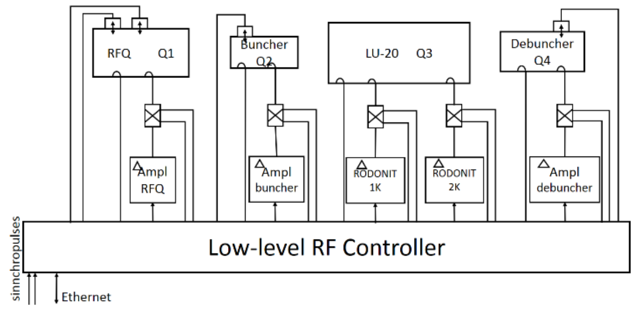

Figure 1: Injector of Nuclotron RF system.

In main mode the Alvarez-type linac LU-20 works in self-excited loop (SEL) mode, and his resonant frequency, equal to 145.2±0.1 MHz, and relative phase slowly changed from pulse to pulse. In the new proposed mode of operation, the LU-20 linac also should be excited from external RF generator. Accordingly, second generation LLRF controller should:

- Generate RF signals to the amplifiers of RFQ, buncher and debuncher resonators, whose frequency should be equal to the natural frequency of LU-20, if LU-20 works in SEL mode; additionally to generate RF signals to LU-20 resonator, if LU-20 works in external generation mode.
- In the commissioning mode, provide independent excitation of the LU-20, RFQ, buncher and debuncher with independent phasing of the channels and the possibility of simultaneous setting of different excitation frequencies for each of the channels.
- Synchronize the high-frequency fields in the resonators and to measure and control the phase difference in the resonators.
- Automatically adjust the own frequency of RFQ, buncher and debuncher resonators; in the case that the resonator LU-20 operates in the external excitation mode, determine the value of the resonant frequency of the resonator LU-20.
- Synchronize the operation of the controller by an external timer signal.
- Receive commands from the high-level control system and transmit diagnostic information via the Ethernet interface.

The differences between the frequencies of the RF field in the resonators and the resonator's natural frequencies are measured by the phase differences method, for the input and output signals of the resonators. For each resonator, three input RF signals are required: from the resonator loop, and also from the pin and from the loop of the input reflectometers. The own resonance frequency of RFQ,

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buncher and debuncher resonators is adjusted by changing the position of the mechanical tuners, which are controlled by stepping motors.

LLRF CONTROLLER DESIGN

The LLRF controller consists of three 19-inch racks with 3U height each. The main rack contains a module for controlling, generating and digitizing of RF signals, containing the central processing unit (CPU) of the LLRF controller – the CPU rack. The other two crates contain stepper motor controllers for resonator tuners – a self-made crate for RFQ and debuncher tuners and phyMOTION-21SL-R-p [3] controller for a buncher tuner. The CPU module transmits the control signals to the rack with the RFQ and debuncher stepper motor controller via the serial interface, as well as the buncher tuner controller via the Ethernet interface.

CPU Module of LLRF Controller

Figure 2 shows main CPU module of LLRF controller, mounted inside 19-inch 3U rack.

Figure 2: CPU module of LLRF controller.

The CPU rack is the basic module of the LLRF controller, which performs the main tasks of the high-frequency signal control system of the Nuclotron accelerator injector. The CPU module:

- Digitizes the input RF signals.
- Calculates the required parameters of output high-frequency signals, determined by the results of measurements and the specified mode of operation.
- Produces RF signals to resonator amplifiers.
- Gives commands to control the stepper motor controllers, by an external command from the control panel, or with automatic frequency control.

Figure 3 shows a simplified diagram of the CPU module.

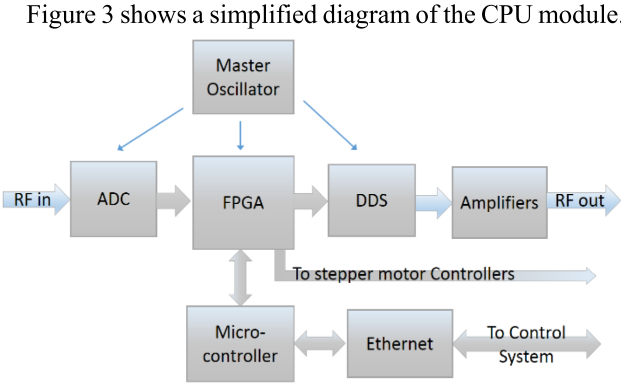

Figure 3: CPU module.

The main parts of the CPU module are Analog-to Digital Converters (ADC) that digitizes the input RF signals, Direct Digital Synthesizers (DDS) that generates output RF signals to the preamplifiers, and Micro Controller Unit (MCU), which through Ethernet module communicate with the main control system. The Field Programming Gate Array (FPGA) module is a base module of the entire LLRF controller. This module:

- Receives and processes digitized RF signals from the ADC.
- Detects RF pulses, by the signal level or from an external timer, and transfers the recorded amplitudes and phases of high-frequency pulses to the microcontroller.
- Generates control signals to the DDS unit.
- Provides capture of the reference RF signal from the LU-20, adjusting the frequency and phase of the output RF signals on the leading edge of the high-frequency pulse with LU-20.
- Generates control signals to the controllers of stepper motors of tuners.

Figure 4 shows simplified FPGA module scheme.

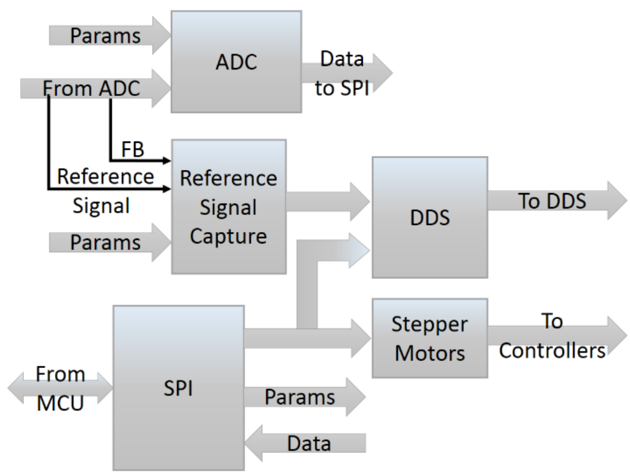

Figure 4: FPGA scheme.

The purpose of most modules inside the FPGA is evident from the previous description. Commands and data between the FPGA and the MCU are transmitted via the serial interface SPI. The capture module of reference signal is the main module in the FPGA. It must synchronize the frequency and phase of the output RF signals with the input reference RF signal from the LU-20 cavity. The maximum allowable synchronization time is determined by the position of the accelerated beam with respect to the rising edge of the reference RF signal from the LU-20, and it should be no more than 100 µs. Figure 5 shows a simplified scheme of the capture module of reference signal.

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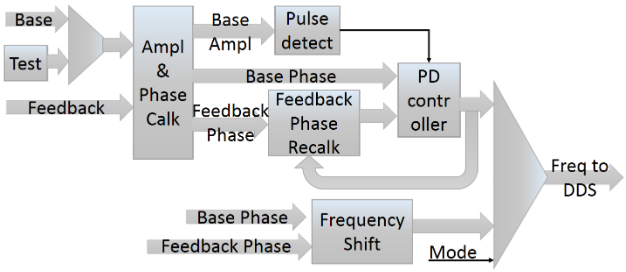

Figure 5: Reference signal capture module.

The digitized data of the input RF signals are fed to the two channels of the capture module: 'Base' (reference signal from LU20) and 'Feedback' (feedback signal - directly from one of the outputs of the RF generator). For the reference signal channel, as an additional option, the modulation mode of the input continuous sinusoidal signal is provided by means of a pulse generated in the FPGA, the shape of which is similar to the shape of the reference pulse from the resonator LU20. This allows you to test the operation of the capture module without a real RF pulse in the 'Base' channel. A modulating pulse is generated using the IIC filter. Amplitudes and phases of the two input signals are calculated in the 'Ampl & Phase Calk' module. The parameters of the output RF signals are corrected in accordance with the measured phases of the reference signal and the feedback signal. Tuning is initialized, when the RF reference pulse is detected by the 'Pulse detect' module.

There are two modes for capturing the reference signal. The main is phase stabilization mode, in which the frequency of the reference signal is not exactly known. In this case, a proportional-differentiating controller in the module ‘PD controller’, which has proportional and differential feedback components, adjusts the phases of the output RF signals. To reduce the delay in the feedback loop and to minimize the error in calculating the phase difference, the phase of the feedback signal is not used as a feedback signal, but the signal phase calculated by integrating the output frequency value on the DDS chip is used. The phase is recalculated in the 'Feedback Phase Recalk' module: the initial value of the phase is fixed when the pulse is detected, and then it is updated at each step of the feedback algorithm operation.

Another mode of capturing the phase of the reference signal can be used only after stabilizing the frequency of the RF signal from the LU20. In this mode, the required value of the frequency of the output signals is known with acceptable accuracy, and to adjust the phase of the output RF signals to the phase of the reference, it is sufficient:

- Measure the phase difference between the input signals at the time of detection of the RF pulse from the LU20.
- In the 'Frequency Shift' module, shift the frequency of the output RF signals with respect to the known value of the reference signal frequency for a predetermined period sufficient to reduce the phase difference to zero.

The frequency of the reference signal is measured in each pulse, and the frequency shift mode is allowed to use if the difference between the minimum and maximum frequency values for the last n pulses is less than the specified value.

RF SYSTEM CONTROL PROGRAM

Figure 6 shows a screenshot of the RF system control program, during one of the working sessions.

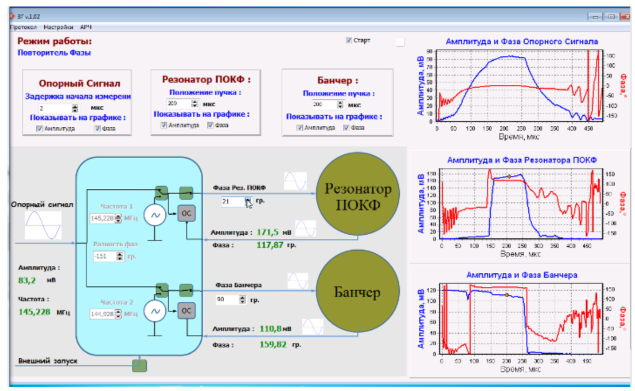

Figure 6: RF system control program.

As can be seen, the control program allows to:

- Control the generation of output RF signals, with the same or different frequencies of the output RF signals.
- Control the phase between the output RF signals.
- Select between the mode of independent generation of output RF signals and the mode of capture of the reference signal.
- Control the phases of the output RF signals with respect to the reference signal with LU-20 in the capture mode.
- Detect and show the measured input signals. Detection is possible both from the external signal from the timer and from the front of one of the measured signals.
- Calculate a mean amplitudes, phase and frequencies of all measured signals. It is possible to adjust the time range of averaging.
- All parameters of operation modes are saved and restored upon power-up.
- In addition, all recorded signals, parameters and calibration values are stored in the archive database.

REFERENCES

[1] G. Trubnikov *et.al.*, “Project of the Nuclotron-based ion collider facility (NICA) at JINR”, in *Proc. EPAC’08*, Genoa, Italy, June 2008, pp. 2581-2583.

[2] G. V. Trubnikov *et.al.*, “Comissioning of New Light Ion RFQ LINAC and First Nuclotron Run with New Injector”, in *Proc. RUPAC’16*, St.Petersburg, Russia, Sep. 2016, pp. 153-155.

[3] PhyMOTION controller; https://www.phytron.eu/products/driver-controller/phymotiontm/

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