

LLRF CONTROLLER UPGRADE FOR THE J-PARC 400 MeV LINAC

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Abstract

The output energy of the J-PARC proton LINAC will be upgraded from 181 to 400 MeV in the next two years by adding high- β acceleration sections. The upgrade of the FPGA-based digital LLRF controller for the 400 MeV LINAC will be presented in this paper. This new LLRF controller works for both the 324-MHz low- β and 972-MHz high- β sections. Many functions have been added into the LLRF controller, such as 1) working for different RF systems, 2) gradually increasing the feedback gains in the feedback loop instead of fixed ones, 3) automatic chopped beam compensation, 4) automatically switching the beam loading compensation in accordance with different beam operation mode, 5) input RF-frequency tuning to match the RF cavities during RF start-up, and 6) auto-tuning of the RF cavity tuner by detecting the phase curve of the RF cavity during the field decay instead of the phase difference between the cavity input and output signals.

have been developed and tested. A very good stability of the accelerating fields has been successfully achieved about $\pm 0.2\%$ in amplitude and ± 0.2 degree in phase, much better than the requirements of $\pm 1\%$ in amplitude and ± 1 degree in phase. This paper mainly describes progresses of the LLRF controller for the J-PARC LINAC, especially for the 972-MHz high- β systems.

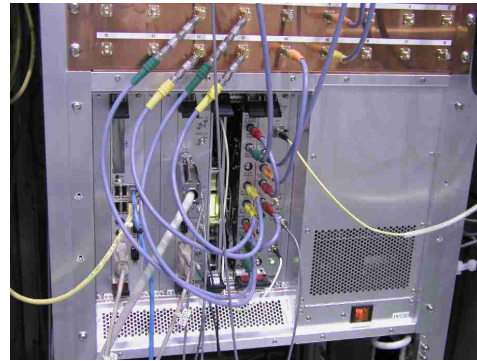


Figure 2: Digital feedback control system installed in a compact PCI.

INTRODUCTION

The energy of the J-PARC proton LINAC will be upgraded from 181 to 400 MeV, by adding 972-MHz high- β acceleration sections. The layout of the RF systems of the J-PARC 400 MeV LINAC is shown in Fig. 1. For both the 324-MHz low- β and 972-MHz high- β sections, the RF signals are controlled by the FPGA-based digital feedback control systems installed in a compact PCI (cPCI), as shown in Fig.2. It consists of the CPU, IO, DSP with FPGA, Mixer & IQ modulator, and RF & CLK boards [1-4]. The hardware for the 324 and 972 MHz systems is basically the same, except the RF board and Mixer & IQ board, working for different frequency [5]. The software for the two systems is completely the same. Both the hardware and software

LLRF SOFTWARE FOR THE WHOLE 400 MeV LINAC

During the development of the LLRF software for the 400 MeV LINAC, the different facility conditions and operation requirements between the 324-MHz low- β and 972-MHz high- β sections have been considered, and a uniform LLRF software is designed to apply for the whole 400 MeV LINAC. In the LLRF controller, all of the different conditions between the two sections are just set as input parameters of the controller, so that the software could run for different conditions.

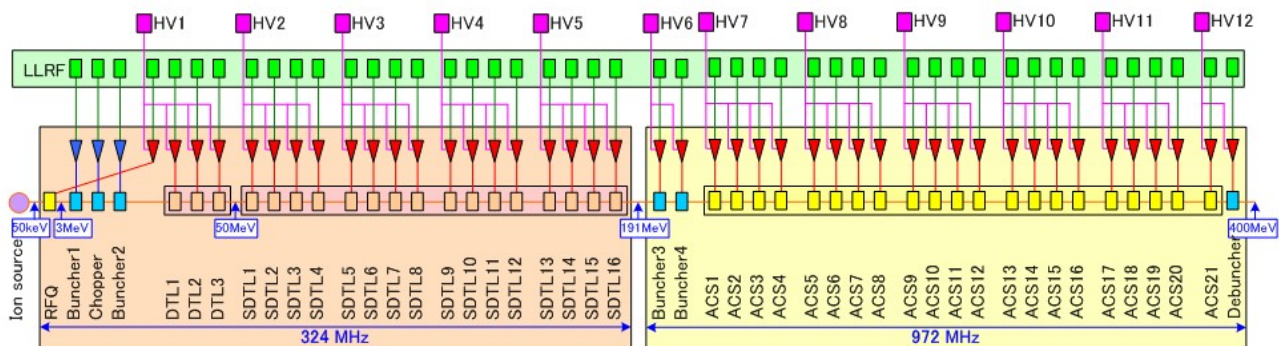


Figure 1: Layout of the RF systems of the J-PARC 400 MeV LINAC.

In the 972-MHz sections, there are chopping signal (shown in Fig.4) lines connected to the digital feedback systems. While in the 324-MHz sections, there are not such lines. The uniformed LLRF software is designed to work for both the conditions. In the 972-MHz sections, chopped-beam compensations are fed forward to the RF cavities. While in the 324-MHz sections, beam compensations just corresponding to the macro-pulse, namely the Beam Gate shown in Fig.4, are fed forward to the RF cavities. Another simple example of the difference between the two systems is operation frequency. This will be used in the calculation of Q-value and detuned phase of the RF cavities by measuring the RF waveform during the cavity field decay [6]. The operation frequency is set as an input parameter of the LLRF systems, so that the LLRF software could work for any frequencies.

By using the uniformed LLRF software, it is convenient to maintain and improve the software for all the RF systems, and we could always apply the newest software to the operation of the whole 400 MeV LINAC.

GRADUALLY INCREASED FEEDBACK GAINS

In the old LLRF controller, the feedback Proportional Gain (P) and Integral Gain (I) in the feedback loop are fixed during the whole RF pulse. In the new controller, the feedback gains, P and I, have been modified with a rising time as shown in Fig. 3. The parameters of feedback-start time and PI-rising time, as well as the maximum values of P and I, could be adjusted through the PLC touch panel. By using this method, the RF waveforms with feedback ON are expected to become much smoother than before, especially during the RF rising time of the RF cavity.

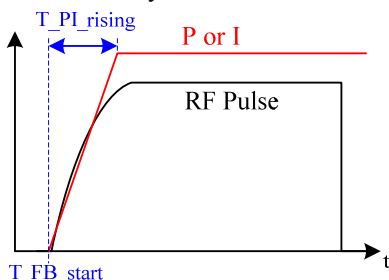


Figure 3: Gradually increased feedback gains used in the feedback loop.

CHOPPED BEAM COMPENSATION

For the 972-MHz high-β sections, the operation frequency is three times of that of the low-β section, and the decay time of the RF field becomes quite shorter. For the chopped beam operation, a chopped beam compensation is required for the 972-MHz sections, instead of a macro-pulse compensation used for the 324-MHz sections.

In the chopped beam operation, the beam will be modulated by a chopping signal as shown in Fig. 4. The frequency of chopping signal is about 1 MHz. We connect this chopping signal to the IO board of the cPCI control

system. Then in the FPGA control program, the FF_beam is fed forward when the logical AND with inputs of the beam gate and chopping signal has the value 1. Also, in order to adjust the timing between the chopping signal and beam pulse, a delay is added to the chopping signal before the logical AND operation. This delay could be exactly adjusted in a clock of 48 MHz in the FPGA.

A test result for the chopped beam compensation is shown in Fig. 5 by using a cavity simulator [5]. A stability of the accelerating fields has been successfully achieved about ±0.4% in amplitude and ±0.3 degree in phase.

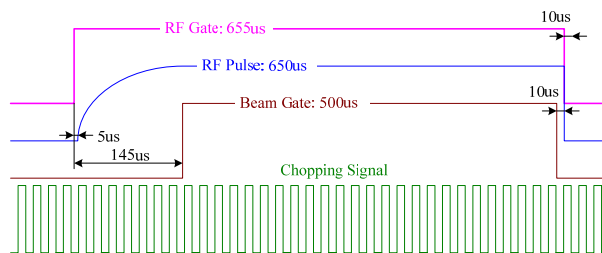


Figure 4: Chopping signal and timing of the LLRF system.

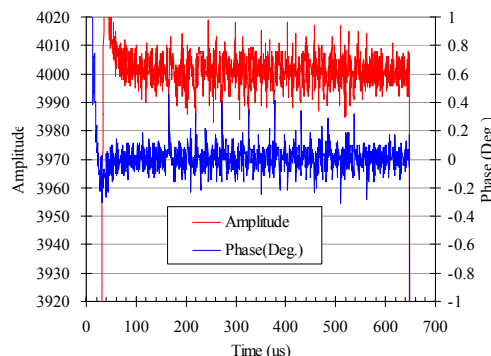


Figure 5: Test result for the chopped beam compensation.

BEAM LOADING COMPENSATION SWITCHING

Different beam operation modes with different beam loading are considered for the J-PARC LINAC. A control system with automatically switching the beam loading compensation is designed. We add a mode-exchanging signal to the LLRF control system, which is called as FF_Beam_Mult gate with a different pulse width, corresponding to the different beam operation mode. The timing of the LLRF system is shown in Fig. 6. The pulse width of the FF_Beam_Mult could be from 1 μs to 50 μs. This signal is connected to the IO board of the cPCI and will be detected by the FPGA. Then in the FPGA control program, the different value of the feeding forward for the beam loading compensation (FF_beam) will be applied corresponding to the pulse width of the FF_Beam_Mult gate. Since the pulse width of the FF_Beam_Mult gate is detected before each pulse of FF_beam, switching the beam loading compensation will also be realized before each pulse, without any delay. This function has been successfully applied in the

operation of the J-PARC LINAC.

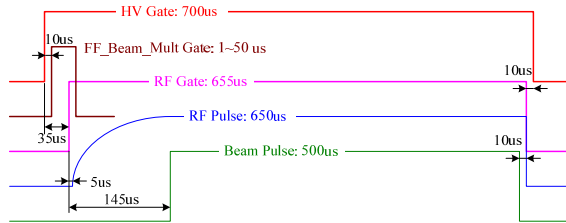


Figure 6: Timing of the LLRF system.

INPUT RF-FREQUENCY TUNING

During the RF start-up, besides the RF-cavity mechanical tuning method, the input RF-frequency tuning method has been added to the new controller.

At first, the detuned frequency ($\Delta\omega$) of the RF cavities from the operation frequency will be detected from the cavity phase decay curve [6],

$$\Delta\omega = \frac{d\theta}{dt}$$

Then the input RF-frequency will be controlled by the FPGA to match the RF cavities. The input feeding forwards of I and Q to the IQ modulator are calculated in the FPGA as the following.

$$FF_I = FF_base_amp \times \cos(\Delta\omega \cdot t),$$

$$FF_Q = FF_base_amp \times \sin(\Delta\omega \cdot t).$$

Both of the two tuning methods have been successfully performed in the operation of the present J-PARC LINAC. We prefer to use the input RF-frequency tuning method, since the RF start-up of the cavities could be realized quickly and smoothly, without a long-time tuning of the mechanical tuner. Figure 7 shows an example of the waveforms of RF cavity and DAC during the RF start-up at the DTL03. Furthermore, because the input RF-frequency is always matched to the cavity resonance frequency during the RF start-up, the probability of the interlock due to reflection or VSWR will be reduced apparently.

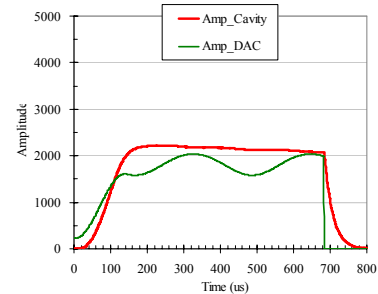
AUTO-TUNING OF RF CAVITY TUNER

After the RF start-up, when the full power is fed to the RF cavity, the auto-tuning of RF cavity tuner is performed by the LLRF controller to keep the detuned phase of RF cavity within 1 degree. There are two methods to judge whether the RF cavity is close to the resonance state or not. The first method is to detect the phase difference between the cavity input and output signals and to see whether it's the same as that for resonance state. The second method is to detect the phase curve of the RF cavity during the field decay and to see whether the phase is a constant. Now, the second method is used in the operation of J-PARC LINAC, since it's the absolute criterion for resonance state, and it has a higher precision.

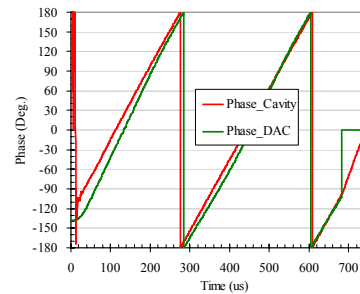
SUMMARY

The LLRF controller has been successfully upgraded for the J-PARC 400 MeV LINAC, by adding many

functions, such as gradually increasing the feedback gains, automatic chopped-beam compensation, automatically switching the beam loading compensation, input RF-frequency tuning during RF start-up, auto-tuning of the RF cavity tuner by detecting the phase curve of the RF cavity during the field decay, and so on. The new controller has been successfully applied in the operation of the present J-PARC LINAC.



1) amplitude during RF start-up.



2) phase during RF start-up.

Figure 7: Waveforms of RF cavity and DAC during the RF start-up at the DTL03.

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