PRESENT STATUS OF J-PARC LINAC LLRF SYSTEMS

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Abstract

The low-level RF (LLRF) control systems have been successfully developed and improved for the J-PARC LINAC. In January 2014 the output proton energy of the J-PARC LINAC was upgraded to 400 MeV. In the past 8 years of the J-PARC LINAC operation, no heavy troubles occurred in the RF control systems. Every year we made improvements on the RF control systems, according to the operation experiences. In this paper, the present status of the J-PARC 400-MeV LINAC RF control systems will be described in details.

INTRODUCTION

The 400-MeV proton linear accelerator (LINAC) at the Japan Proton Accelerator Research Complex (J-PARC) consists of 324-MHz low-β and 972-MHz high-β accelerator sections, and it is operated at a repetition rate of 25 Hz with a beam pulse width of 500 μs. From October 2006 to May 2013, only the 324-MHz accelerator section was in operation with the proton beam energy of 181 MeV. In January 2014, the proton beam energy was successfully upgraded to 400 MeV after the installing the 972-MHz accelerator section. For the 400-MeV J-PARC LINAC, there are 48 RF stations and 64 cavities in total. For each RF station, one RF source is used to feed RF power to the RF cavities using a low level RF (LLRF) control system [1-2]. The RF signals including the RF amplitude and phase at the RF cavities are controlled by an FPGA (Field-Programmable Gate Array)-based digital feedback (FB) control system installed in a compact PCI (cPCI) [3-4]. Recently lots of improvements on LLRF control systems have been successfully carried out.

IMPROVEMENT OF TIMING DISTRIBUTION SYSTEM

All of the accelerator systems of the J-PARC are controlled basing a 12-MHz master clock produced at the Center Control Room (CCR). The 12-MHz output signal is connected to an E/O (Electro-Optical) converter and then sent to the J-PARC LINAC. Then it will be used in the RF reference generator system to produce phase-locked 312-MHz and 960-MHz LO (Local Oscillator) signals [5]. The 312-MHz and 960-MHz LO signals, as well as the reference 12-MHz signal, will be sent to each RF station at the J-PARC LINAC through a timing distribution system, and used for the feedback control systems in the cPCI. During the experiments on the feedback control systems at each RF station, we found that, there is a stable range of the reference 12-MHz signal delay setting from the LO (312-MHz or 960-MHz) signal for the cPCI operation, and this stable range is quite narrow especially for the 972-MHz feedback systems, since the RF frequency is 3 times of the 324-MHz RF systems. According to the measurement results, the jitter range between the reference 12-MHz signal and LO signal must be smaller than 150 ps for the J-PARC LINAC upgrade.

Then, an improvement of the timing distribution system has been successfully carried out for the whole J-PARC LINAC. Figure 1 shows the schematic diagram of the improved timing distribution system. As shown in Fig. 1, instead of an electrical fan-out used in the previous timing distribution system, the reference 12-MHz signal from CCR is divided by an optical coupler, and sent to each system at local station. Figure 2 shows an image of the timing distribution system at the LINAC after improvement. According to the measurement results, a good stability of the timing distribution has been successfully achieved as shown in Fig. 3. The jitter range between the reference 12-MHz signal and LO signal is smaller than 45 ps for all of the RF stations, satisfying our requirements. Owing to this improvement, a very good stability of the RF system has been successfully achieved for the long-term operation. We have never suffered from any problems caused by the timing instabilities up to now.

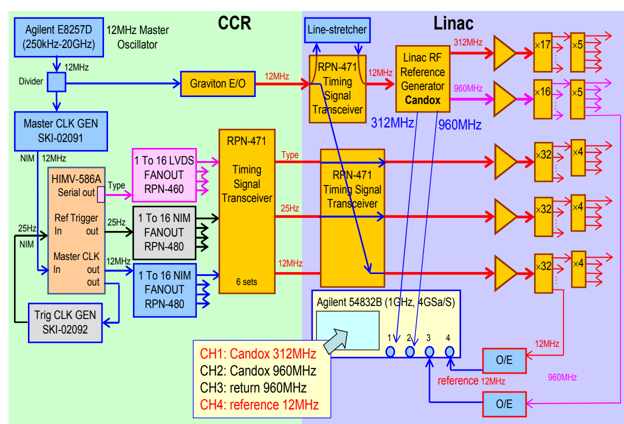

Figure 1: Schematic diagram of the improved timing distribution system.

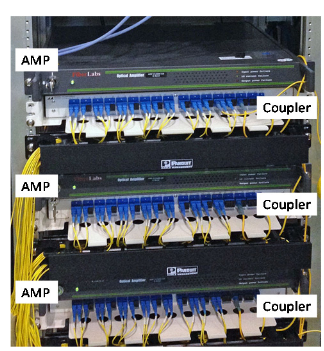

Figure 2: Timing distribution system at the LINAC after improvement.

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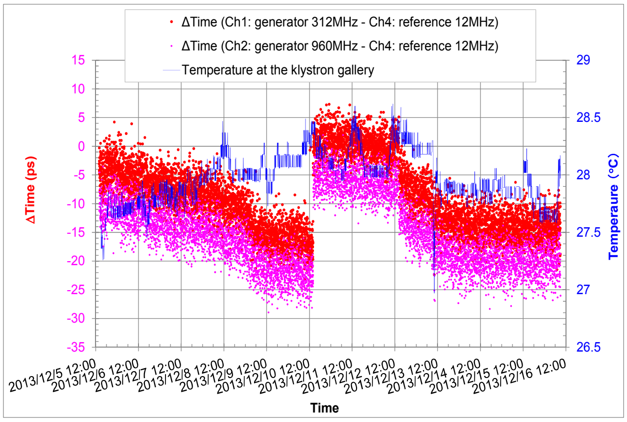

Figure 3: Measurement results of jitter between LO (312/960 MHz) and reference 12-MHz signals for the improved timing distribution systems.

IMPROVEMENT OF HARDWARE OF FEEDBACK CONTROL SYSTEM

The LLRF control systems for both the 324-MHz and 972-MHz stations are basically the same. Figure 4 shows the schematic of the digital feedback control system for the 972-MHz RF station. In the cPCI, RF (972 MHz), LO (960 MHz), and clock (48 MHz) signals are generated in the RF&CLK board with a phase-lock to both of the 960-MHz LO input signal and the 12-MHz reference input signals from the timing distribution systems. The output LO (960 MHz) signals will be used in the down-converter (Mixer) to detect the RF signals from the RF cavity. Then, an output signal with an intermediate frequency (IF) of 12 MHz from the down-converter will be acquired by the ADC in the FPGA board. The sampling frequency of the ADC is 48 MHz. After separating the I (in-phase) and Q (quadrature) components from the IF signals, a PI (Proportional-Integral) feedback control is conducted to obtain a stable RF fields at the RF cavity. The required stabilities of the RF fields at the RF cavities are less than ±1% in amplitude and less than ±1 degree in phase.

However according to our measurement results, the temperature of the klystron gallery varies approximately in a range of 27.0-28.6°C during long-term operation, although it is air-conditioned. Therefore a maximum of the temperature variation in the cPCI is considered as a level of ±1°C. In order to satisfy the requirements of the stabilities of the RF fields at the RF cavities, the stabilities of outputs from the RF&CLK boards and the down-converters is required to be less than ±0.1%/°C in amplitude and ±0.1 degree/°C in phase.

However, according to the measurement results for the first prototype of 972-MHz feedback system, we found that, the output stabilities from either the RF&CLK boards or the down-converters do not satisfy our requirement: the temperature coefficient of phase of the LO output signals from the 972-MHz RF&CLK board is near -0.2 degree/°C as shown in Fig. 5; and the temperature coefficient of amplitude of the down-converter was around -0.2%/°C as shown in Fig. 6.

Then, improvements for these boards have been successfully carried out using temperature-compensation technologies. For the RF&CLK board, a LPF (Low-Pass Filter) using a temperature-compensation capacitor is introduced into the LO output circuits. For the down-converter, a temperature-compensation attenuator is applied in the output circuit. According to the measurement results, the temperature coefficient of LO output phase from the RF&CLK board is reduced to about -0.03 degree/°C as shown in Fig. 5; and the temperature coefficient of amplitude of the down-converter is reduced to 0.01/°C in average as shown in Fig. 6.

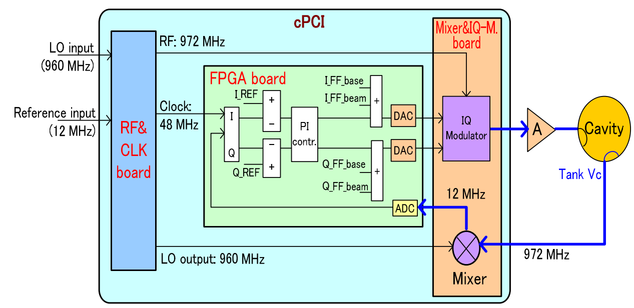

Figure 4: Schematic of the digital feedback control system for the 972-MHz RF station.

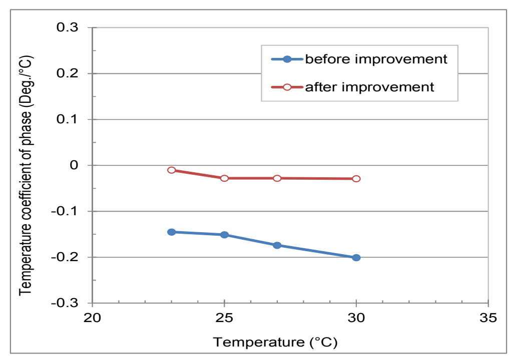

Figure 5: Temperature coefficient of the phase of the LO output signals from the prototype of 972-MHz RF&CLK board.

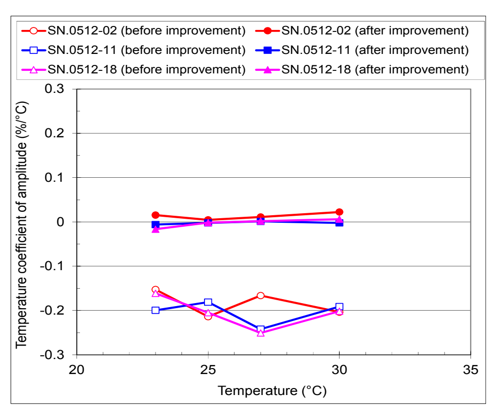

Figure 6: Temperature coefficient of the amplitude of the down-converter for three 324-MHz Mixer&IQ boards.

Owing to the improvement of the above devices, including the 972-MHz RF&CLK and Mixer&IQ boards,

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a very good stability of the accelerating fields for beam operation has been successfully achieved about ±0.2% in amplitude and ±0.2 degree in phase, much better than the requirements of ±1% in amplitude and ±1 degree in phase.

IMPROVEMENT OF AUTO-TUNING SYSTEM

In December 2013, a novel auto-tuning system was successfully carried out. Figure 7 shows an example of experimental results of the warm-up process by using the auto-tuning system after improvement at ACS01. During the RF cavity warm-up, the mechanical tuner is fixed at first, then the input RF frequency is tuned automatically by using the FPGA program to match the cavity resonance frequency. After the input power level reaches the required value at the last step of warm-up, the mechanical tuner controller starts to work at once, while the input RF frequency is still kept tuning to match the cavity resonant frequency continuously. While in the previous system, the mechanical tuner is fixed all the time to wait for cavity warming-up with a resonance close to the operation frequency. Therefore, for this improved novel auto-tuning system, during the last-step of power increasing, both mechanical tuner controller and input RF frequency tuning are working. Thus, the tuner position is controlled to adjust the cavity resonance to approach the operation frequency quickly. From Fig. 7, we can see that, the detuned RF frequency reduces quickly from 38 to 14 kHz before the last step, and continuously reduces to 3.2 kHz soon. At that moment, the input RF frequency tuning is stopped, and switched to the operation frequency of 972 MHz. Finally, only mechanical tuner controller works, and the feedback is turn on. The tuner position continues to be kept adjusting with the cavity temperature variation for long term operation. The detuned RF phase of cavity is kept within smaller than 1° in our system.

From the above experiment results, we can see that, by using this novel auto-tuning system, the required RF power will be fed to the RF cavity quickly and smoothly with a very good matching between the RF source and RF cavity during the entire operation process. Comparing with the previous auto-tuning system, the time for the warm-up process becomes much shorter; and the detuned frequency of RF cavity when input RF frequency is switched to the operation frequency is much lower, by using the improved system.

From December 2013, the improved auto-tuning system was applied to the whole RF systems of the J-PARC 400-MeV LINAC, including the 324-MHz and 972-MHz RF cavities. To the best of our knowledge, this is the first time this kind of novel auto-tuning system for the practical operation of proton linear accelerators has been successfully applied anywhere in the world. The system has operated with an excellent performance. Almost no interlock has occurred during the entire warm-up process for both of the 324-MHz and 972-MHz RF cavities. Owing to the application of this novel auto-tuning system, the operation of the 972-MHz ACS cavities has been successfully and smoothly carried out, and then the J-PARC LINAC 400-MeV upgrade has been successfully realized.

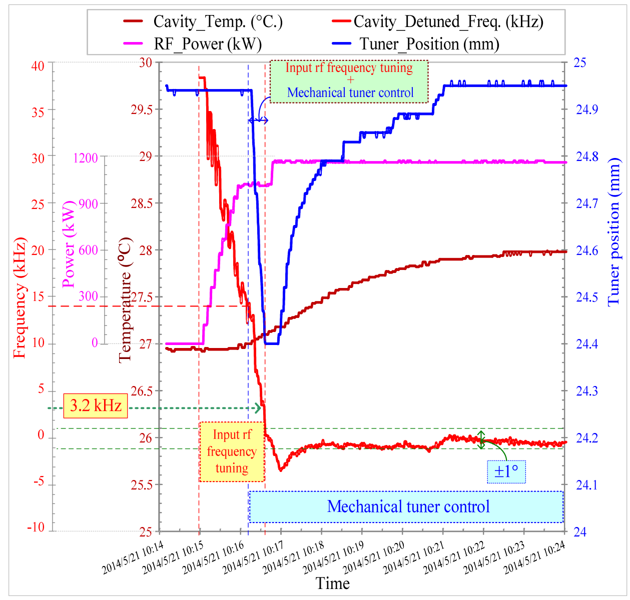

Figure 7: Experimental results of warm-up process by using the auto-tuning system after improvement at ACS01.

CONCLUSION

The improvements of the timing distribution system, the hardware of the feedback control system, and the auto-tuning system, have been successfully carried out for the J-PARC LINAC. Owing to these improvements, the operation of the 972-MHz ACS cavities has been successfully and smoothly carried out, and a very good stability of the RF system and the accelerating fields for beam operation has been successfully achieved for the J-PARC LINAC 400MeV upgrade.

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