RF FEEDBACK CONTROL SYSTEMS OF THE J-PARC LINAC

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Abstract

The J-PARC 181-MeV proton linear accelerator (LINAC) was commissioned in October 2006. The RF sources of the LINAC consist of 4 solid-state amplifiers and 20 klystrons. In each RF source, the RF fields are controlled by a digital RF feedback (FB) system installed in a compact PCI (cPCI) in order to realize an accelerating field stability of ±1% in amplitude and ±1° in phase [1][2]. In this paper, the performance of the RF feedback control systems will be reported in detail.

INTRODUCTION

In the J-PARC 181-MeV proton linear accelerator (LINAC), the RF sources consist of 4 solid-state amplifiers and 20 klystrons. In each RF source, the RF fields are controlled by a digital RF feedback system installed in a compact PCI, which consists of the CPU, IO, DSP with FPGA, Mixer & IQ modulator, and RF & CLK boards [3][4]. The block diagram of the RF feedback control system is shown in Fig. 1.

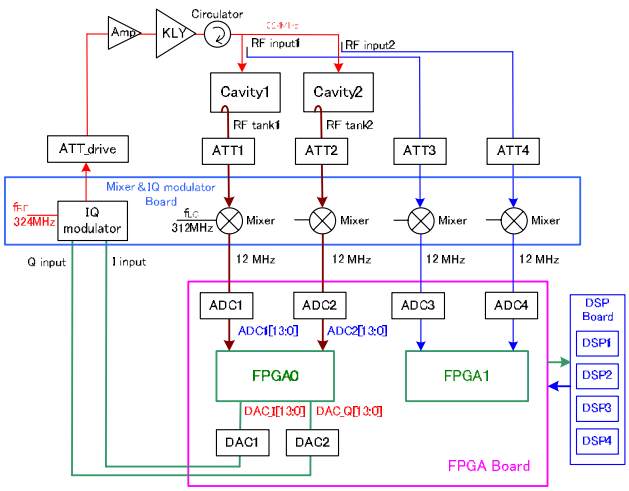

Figure 1: Block diagram of the RF feedback control system.

As shown in Fig. 1, each klystron drives two cavities. The RF signals from two cavity input power monitor signals (RF input) and two cavity monitor signals (RF tank) are down-converted to 12-MHz IF signals by mixers, and connected to 14-bit ADCs in a FPGA board. In the FPGA board, there are two FPGAs (Xilinx XC2V2000) [5]. FPGA0 is used for the real-time-feedback processing of cavity accelerating fields. FPGA1 is used only for measuring the I and Q components of the cavity input power, and the data is used in the DSP board for cavity tuner control calculation. After real-time-feedback processing in FPGA, which will be described in the next section, the FPGA outputs of the I and Q components are sent to 14-bit DACs, and the outputs of the DACs are connected to the inputs of the IQ modulator, which produces 324-MHz RF signals to drive the RF cavities through the klystron amplifier systems.

DIGITAL FEEDBACK CONTROL

The block diagram of the digital feedback control in FPGA0 is shown in Fig. 2. First, the I and Q components of the 12-MHz down-converted ADC signals of the cavity fields (RF tank) are produced by sampling them with a 48-MHz clock. Subsequently, after the phase rotation with amplitude calibration, the I and Q components of the cavity fields are measured. The calibration parameters of the amplitude factor and loop phase for each cavity is determined in advance by measuring the cavity monitor signals (RF tank) with a required power fed to the cavities with the FB OFF. A selector is used to select which one of the cavity fields—cavity 1 or 2 or an average of these fields—must be applied in the feedback calculation loop. For usual operations, the selector for the average fields of cavities 1 and 2 is adopted. A reference table (REF) is used for feedback setting. The general FB ON/OFF function is controlled by the PLC and DSP. Further, a feedback switch in the waveform is designed, which is turned ON between the start and stop times.

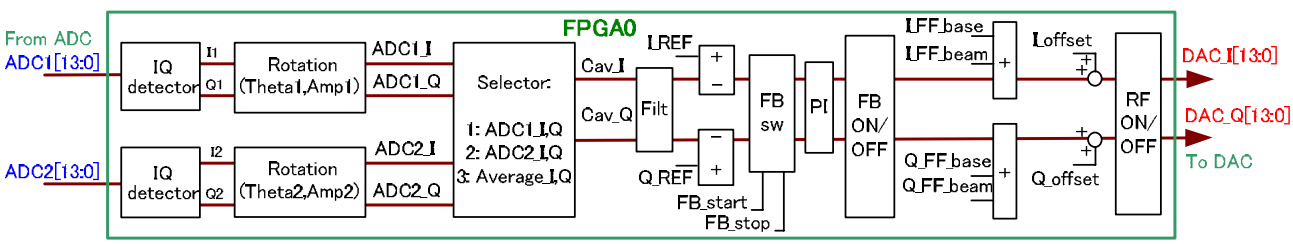

Figure 2: Block diagram of the digital feedback control in FPGA0.

A PI controller is used in the feedback loop. Two control parameters, PROPORTION and INTEGRAL, are adjusted through the PLC touch panel. Two feedforward tables, FF_base and FF_beam, independently triggered by the RF and BEAM gates, are provided for the excitation compensation of accelerating fields and beam loading, respectively. Thus, we were able to obtain a flat-top for the RF pulse of the cavity fields even with beam loading by adjusting the timing of the feedforward compensation, namely, the start time of the BEAM gate pulse signal. The general RF ON/OFF function is controlled by both the PLC and RF gate. The FPGA outputs of the I and Q components will be sent to the two 14-bit DACs if the RF is ON. Then, the DAC outputs are connected to the IQ modulator, as shown in Fig. 1.

IQ OFFSETS OF RF CONTROL SYSTEM

During the experiments on the RF control system with FB OFF, we found that even with the FPGA outputs of the I and Q components set to 0, the IQ modulators in the RF control systems still produce a considerable output power. In order to cancel this undesired output, we added the I and Q offsets to the feedback calculation loop in front of the DACs in the RF control system, as shown in Fig. 2, and each I and Q offsets for the 24 RF control systems of the J-PARC LINAC were measured and set accurately.

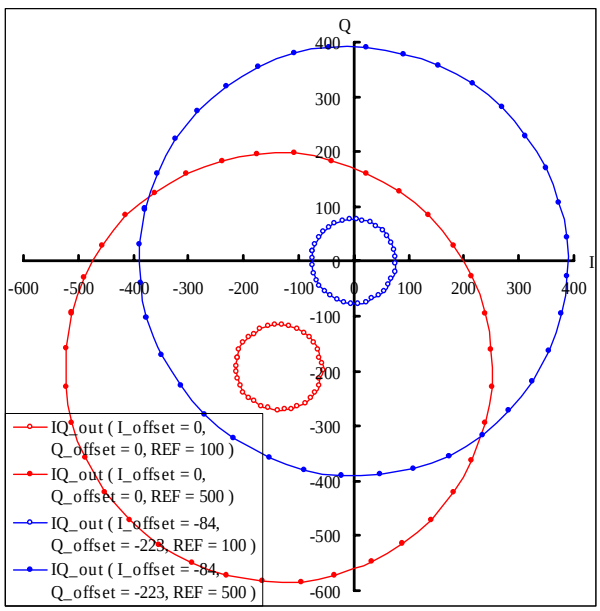

Figure 3: IQ modulator outputs at SDTL13 with or without IQ offsetting.

Fig. 3 shows the experimental results of the IQ modulator outputs at SDTL13 with or without IQ offsetting. The experiment data were obtained with constant RF amplitude setting and phase scanning of 360°. It can be observed that with IQ offsetting, the performance of the IQ modulator outputs with FB OFF is improved significantly 1) almost no output power is delivered when I and Q are se to 0; 2) with phase scanning, the amplitude of the IQ modulator outputs vary by less than 1%. t

FEEDBACK PERFORMANCE

High-power tests were performed for the 24 RF systems of the J-PARC LINAC. Figs. 4 and 5 show an example of the cavity outputs with FB ON at SDTL7 with full power operation. The RF amplitude is set to 4000 and the phase is set to 0°. From Fig. 4, it can be observed tha the variation in the cavity amplitude in the flat-top is less than 0.1%. Similarly, from Fig. 5, the variation in the cavit phase is less than 0.1°.

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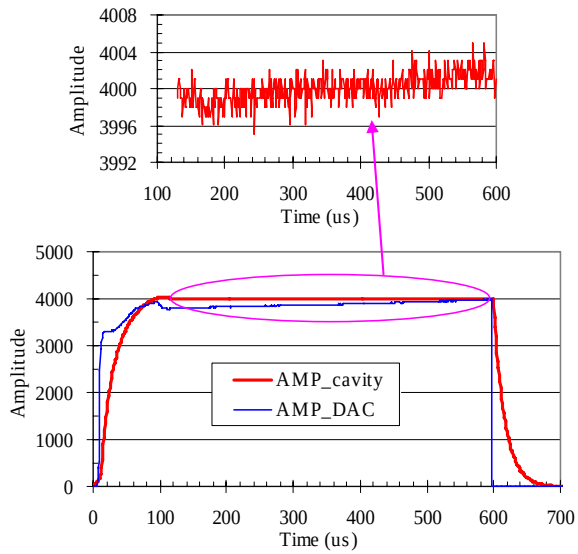

Figure 4: Amplitudes of the cavity and DAC output at SDTL7.

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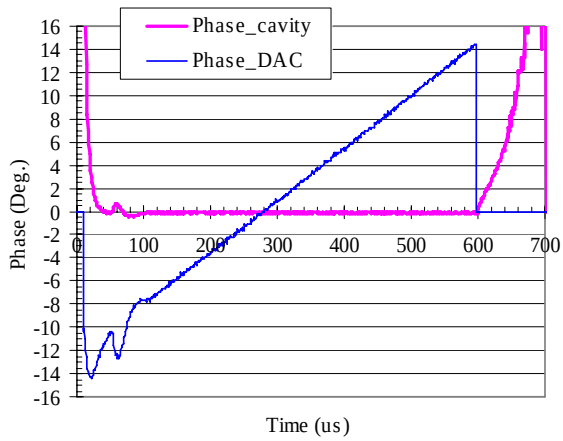

Figure 5: Phase of the cavity and DAC outputs at SDTL7.

FEEDBACK WITH BEAM LOADING COMPENSATION

The J-PARC 181-MeV proton LINAC was commissioned in October 2006, and a proton beam was successfully accelerated to 181 MeV on January 24, 2007. After beam study, a proton beam with a peak current of 26 mA and a pulse width of 50 μs was successfully achieved in May 2007. In order to obtain a flat-top for the cavity accelerating fields even with beam loading, a beam feedforward table for the compensation of the beam loading was added to the feedback loop of the RF feedback control system corresponding to the beam pulse ranging from 200 to 250 μs. Fig. 6 shows an example of the cavity fields at SDTL3 with the loading beam of 26 mA and 50 μs. It shows that in the case of beam loading, the variations in the amplitude and phase of the cavity fields are successfully maintained within 0.3% and 0.2°, respectively, by means of beam feedforward compensation.

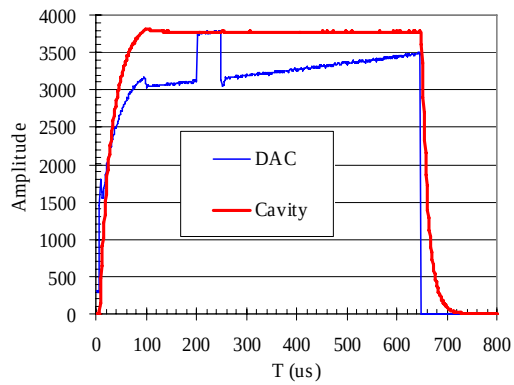

Figure 6: Amplitudes of the cavity and DAC outputs at SDTL3 with beam feedforward compensation.

STABILITY OF RF FEEDBACK SYSTEM

The stability of the RF feedback system during a long-duration operation was measured through an external monitor [6]. Fig. 7 shows an example of the test results at DTL3. From this figure, it can be observed that during the 48-hour operation from May 21–23, 2007, the peak-to-peak amplitude error in the pulse is approximately 0.1% without beam loading or 0.3% with beam loading. The absolute drift of the amplitude is maintained within approximately 0.2%. Similarly, the peak-to-peak phase error in the pulse is approximately 0.1° without beam loading or 0.2° with beam loading. Almost no absolute drift of the phase is observed.

SUMMARY

The 24 sets of FPGA-based RF feedback control systems were developed and applied to the J-PARC 181-MeV proton LINAC, and the high-power tests were performed successfully. In case of FB OFF, the amplitude of the RF systems varies less than 1% with a phase scanning of 360°. For FB ON, the variations in the cavity amplitude and phase are less than 0.1% and 0.1° without beam loading, or 0.3% and 0.2° with beam loading, respectively. Moreover, the RF feedback systems exhibited a considerably high stability for a long-duration operation.

Basing on the developed RF feedback systems mentioned above, a proton beam of 181 MeV with a peak current of 26 mA and a pulse width of 50 μs was successfully achieved in May 2007. Further beam study for a peak current of 50 mA and a pulse width of 500 μs will be continued in the coming months by adjusting the beam loading compensation in the RF feedback control systems.

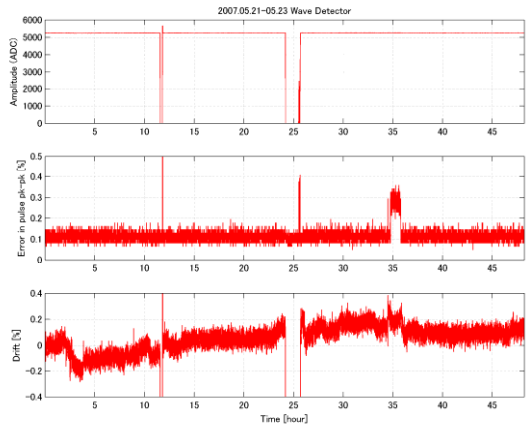

Figure 7: Stability of the RF feedback control system at DTL3.

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