PERFORMANCE OF A DIGITAL LLRF FIELD CONTROL SYSTEM FOR THE J-PARC LINAC

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Abstract

Twenty high-power klystrons are installed in the J-PARC linac. The requirements for the rf field stabilities are +-1% in amplitude and +-1 degree in phase during a 500 μs flat-top. In order to satisfy these requirements, we have adopted a digital feedback and feed-forward system with FPGAs and a commercially available DSP board. The FPGAs (Virtex-II 2000) enable fast PI control for a vector sum of two cavity fields. The measured stability during an rf pulse was +-0.06% in amplitude and +-0.05 degree in phase. The tuner control was successively operated by way of the DSP board by measuring the phase difference between the cavity input wave and the cavity field. Beam loading effects were emulated using a beam-loading test box. By proper feed-forward, the rf stability was less than +-0.3% and +-0.15 degree.

INTRODUCTION

We have installed 20 high-power klystrons (324 MHz, max. 3 MW) in the J-PARC linac. These klystrons drive RFQ, DTLs and SDTLs [1]. The required stabilities of the rf outputs are less than +-1% in amplitude and less than +-1 degree in phase. In order to satisfy these requirements, a digital feedback system using a compact PCI (cPCI) has been developed. The system consists of a FPGA board, a DSP board, a mixer and down-converter, an rf&clock generator and an I/O board [2,3]. The FPGA board has two FPGAs (VirtexII2000), four 14-bit ADCs (AD6644) and four 14-bit DACs (AD9764), which works as a mezzanine card of a commercially available DSP board (Barcelona by Spectrum). The DSP board is used as a tuner control of the cavities and communication between the FPGAs and the local host [4].

Intermediate-frequency (IF; 12 MHz) signals from pick-ups are directly detected by ADCs with 48 MHz sampling. Two cavity pick-ups are processed in FPGA1 and the forward powers are processed in FPGA1. Cavity signals are separated into I and Q components, and a feedback (FB) algorithm (PI-control) is operated with a vector sum of two cavities. A feed-forward table is added in order to compensate for any transient behaviour and/or beam-loading.

VECTOR SUM CONTROL

A klystron drives two cavities in the case of the SDTL module, and the vector sum of two cavity signals is calculated. The operated vector sum control at a SDTL is shown in Fig. 1. The set-values are 6,000 in amplitude and 0 degree in phase. Since the FPGA handles integer

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numbers, the integer set-value is used. The proportional and integral gains are 4 and 0.01, respectively. The stability of the vector sum during the flat-top is less than +-0.06% in amplitude and +-0.05degree in phase.

EXTERNAL MONITOR

In order to confirm the stability of the feedback, we measure the amplitude and the phase with an external monitor. Figure 2 shows a schematic of the external monitor. The amplitudes are measured by diodes, and the phases are measured with two mixers. The signals are stored in a computer by way of a commercially available FPGA board (Xilinx XtremeDSP) with two 14-bit ADCs. Data acquisitions are carried out every 1 μs. The obtained data are shown in Fig. 3. The set-values are 6,000 in amplitude and 0 degree in phase, respectively and stability is less than +-0.2% and +-0.2 degree. Since the band-width of the cavity is less than 20 kHz, the fast noises in Fig. 3 are included in the monitor. It is considered that better stabilities would be accomplished in the cavities.
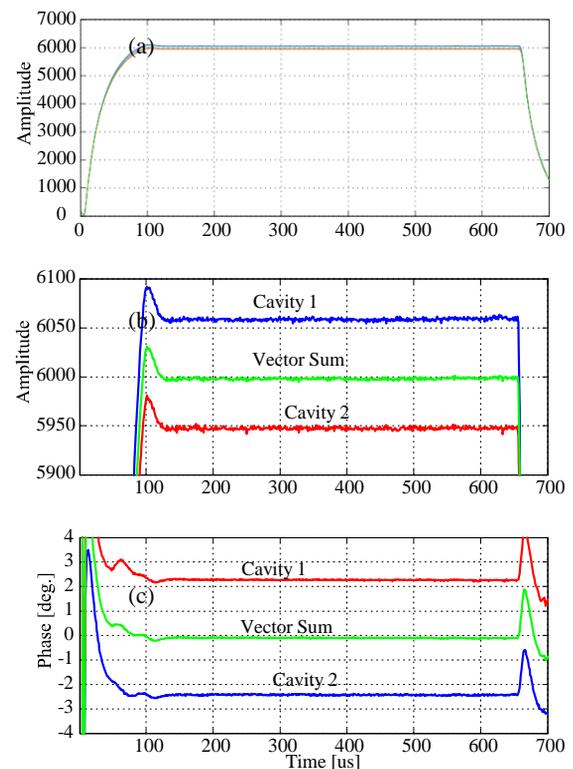
Figure 1: Performance of the vector sum FB control. (a) and (b), amplitude; (c) phase. Set-values are 6,000 in amplitude and 0 degree in phase. The proportional gain of 4 and integral gain of 0.01 for a 48 MHz clock accumulation are applied.

Figure 2: Schematic of the external monitor system.

TUNER CONTROL

The phase difference between the forward rf power and the cavity is related to cavity tuning. Tuner control is carried out by monitoring the phase difference in order to maintain the set-tuning angle. The measured phase difference is compared with the set-detuning angle. These calculations are made by one of the four DSPs on Barcelona. When the measured tuning is different from set-value, for example, by more than 1 degree, tuner-control starts. The control continues until the difference becomes less than 0.2 degree. An example of the tuner controls is shown in Fig. 4. In this example, we changed the tuner position by about +1 mm (cavity 1 at around 1 min.) and -1 mm (cavity 2 at around 4 min.), manually. The corresponding detuning was about 15 degrees. This detuning was much larger than the expected value during operation (typically around 1 degree), but the tuner position stabilized. During the tuner control, the vector sum was still stable owing to the cavity feedback control even though the amplitudes and phases of two cavities were different due to the detuning.
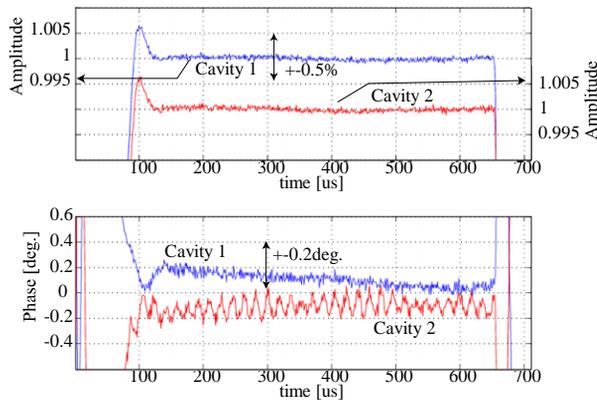
Figure 3: Amplitude and phase stability during an rf pulse monitored with an external monitor.(a):normalized amplitude and (b) phase. The FB parameters are same to Figure 1.
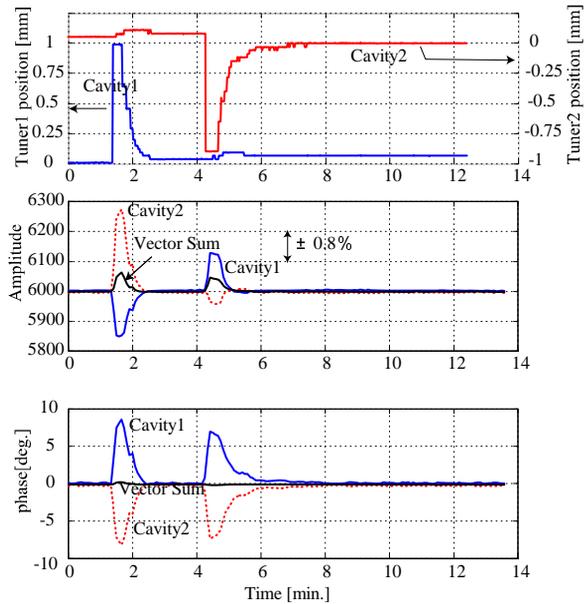
Figure 4: Tuner position, amplitudes and phases of cavity 1 and 2 during the tuner control test. The tuner positions are changed +-1 mm (corresponding +-15 degree detuning) manually and these returned in 2 minutes by tuner control.

BEAM LOADING COMPENSATION

In order to examine the beam-loading effects on the feedback, we introduced a beam-loading test box [1]. A schematic of the beam-loading test is shown in Fig. 5. The test-box consists of phase-shifter and a mixer. The beam-loaded cavity signal without FB is shown in Fig. 6. About a 15% decrease in amplitude is observed by the test-box in this case. The stabilities during feedback operation at the beginning and end of the beam pulse were around +-5% in amplitude and +-2 degree in phase because the feedback algorism can not follow completely due to the loop delay. By adding the proper feed-forward synchronized with the beam pulse, the stabilities were improved drastically to +-0.3% in amplitude and +-0.15 degree in phase, respectively, as shown in Fig. 7. It is confirmed that the feed-forward is effective for a constant disturbance.
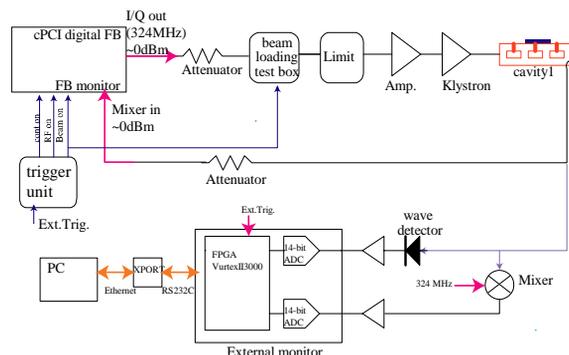
Figure 5: Schematic of beam loading compensation examination.
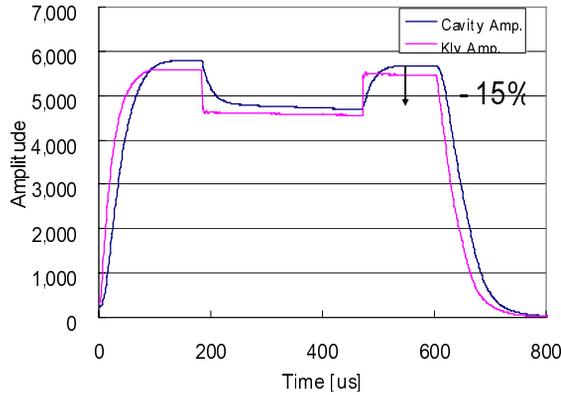
Figure 6: Effects of the beam-loading test box. Beam loading of 15% is generated by the test box. This signal is obtained at the cavity without any feedback (only feed-forward).
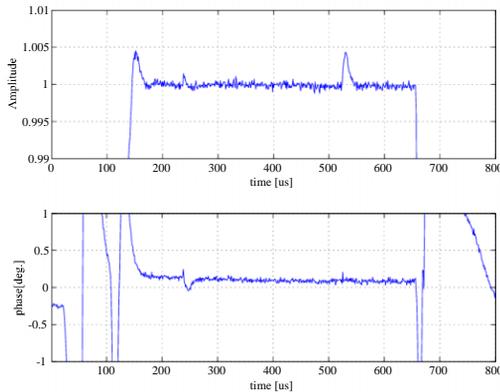
Figure 7: Beam-loading compensation by FB with proper feed forward. The stability is +-0.3% in amplitude and +-0.15 degree in phase during the flat top.

LINEARITY FOR PHASE-SCAN

In commissioning the J-PARC linac, first of all, the accelerated beam characteristics were compared with the calculation under various rf parameters (phase-scan under a constant amplitude set-level). Thus, amplitude stability is required for the various set-phases. Since a distortion of the IF signal (Mixer output) results in phase and amplitude errors, the amplitude is measured with a diode
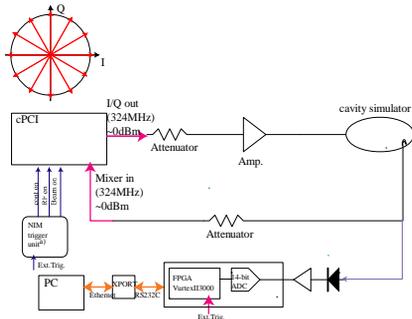
Figure 8: Schematic of the linearity test.
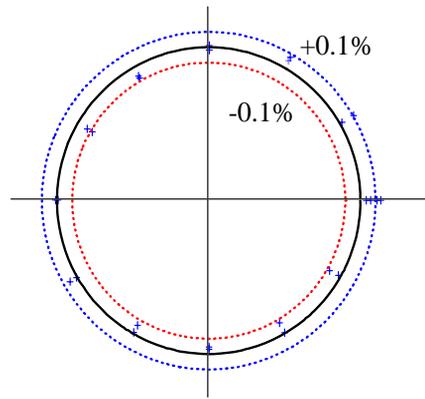
Figure 9: Results of the amplitude errors with various phases. The stabilities in amplitude are less than +-0.15%, the comparable to the pulse-to-pulse stability.

detector under various set-phases with feedback. If a distortion of the mixers and/or non-linearity of the ADCs exist, a difference in amplitude between the external monitor and the internal FB monitor should appear. A schematic of the linearity test is shown in Fig. 8. Figure 9 shows the results of the phase-linearity. The obtained stability is less than +-0.15% under the various set-values. This error is the same as the pulse-to-pulse amplitude errors, and thus the linearity is satisfied during the phase-scan.

SUMMARY

The performance of the digital FB system used at the J-PARC linac satisfies the requirements, and a stability of less than +-0.06% in amplitude and +-0.05 degree are obtained in the internal monitor. The external monitor, where the amplitude and phase are measured by diode-detectors and mixers, show a stability of less than +-0.2% in amplitude and +-0.2 degree. The tuner control is calculated in DSP, and reaches its goal of within 0.2 degree in detuning within 2 min. of operation. It was shown that the beam loading can be compensated with proper feed forward. The linearity of the IF signals was confirmed by a comparison between external and FB monitors. The conditioning of the cavities in the J-PARC linac will start this September, and beam commissioning will start this year.

REFERENCES

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