AUTOMATIC FREQUENCY MATCHING FOR CAVITY WARMING-UP IN J-PARC LINAC DIGITAL LLRF CONTROL

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Abstract

In the J-PARC Linac LLRF, for the cavity start-up, the cavity resonance is automatically controlled to be the accelerating frequency (324 MHz and 972 MHz) with a mechanical tuner installed on the cavity.

We are planning to introduce a new method of the cavity-input frequency matching into the digital LLRF control system instead of the tuner control for the cavity start-up. In order to match the frequency with the detuned cavity, the output RF frequency is modulated by way of phase rotation with the I/Q modulator, while the cavity tuner is fixed. The detuning of the cavity is obtained from phase gradient of the cavity field decay at the RF-pulse end and the phase rotation is automatically controlled by a FPGA and a DSP.

No hardware modification is necessary for this frequency modulation method. The cost reduction or the high durability for the mechanical tuner production is expected in the future.

INTRODUCTION

J-PARC will be one of the highest intensity proton accelerators, which consists of a 181 or 400-MeV Linac, a 3-GeV rapid-cycling synchrotron (RCS) and a 50-GeV synchrotron (main ring, MR) [1]. The beam commissioning has progressed steadily, and the 30-GeV acceleration was succeeded with the MR. Concurrently the application operation is performed and it is providing the beam to the experimental facilities, for example, the Materials and Life Science Facility (MLF), the Hadron Physics Facility and the Neutrino Facility.

In the present phase, the linac provides 181-MeV proton beam to the RCS. This linac consists of 20 accelerating cavity modules. The operation frequency is 324 MHz. The maximum RF pulse width is 620 μs, including cavity build-up time, and the repetition is 25 pps [2].

The upgrade of the linac for 400 MeV, which is the primary design, is scheduled in few years. For the additional acceleration to the 400 MeV, ACS (Annular Coupled Structure) cavity is adopted [3]. Its operation frequency is 972 MHz. Accordingly the 972-MHz low-level RF (LLRF) control system is also under development now. It will be similar to in the 324-MHz Systems: Similar electronics will be used, modified to operate at 972 MHz.

For the cavity start-up, the cavity resonance is automatically tuned to be the accelerating frequency with a mechanical tuner installed on the DTL and SDTL cavity because the source oscillator frequency is fixed. As a new method for the ACS cavity start-up, the cavity-input frequency matching will be introduced into the digital LLRF control system instead of the cavity-tuner control. This report will describe about the frequency modulation method.

DIGITAL FF/FB CONTROL SYSTEM

The momentum spread (Δp/p) of the RCS injection beam is required to be within 0.1%. Consequently the accelerating field error of the linac must be within ±1% in amplitude and ±1 degree in phase. To realize this stability, a digital feedback (FB) control is used in the LLRF control system, and a feed-forward (FF) technique is combined with the FB control for the beam loading compensation [4]. Figure 1 shows the FPAG block diagram of the digital FB/FF control system. 12-MHz IF signals are sampled by ADCs in 48 MHz, then I,Q components are directly obtained. The I,Q values are compared with set-tables and PI control is made with FF.

In the 181-MeV acceleration of the linac, the 24 LLRF systems are operated at a frequency of 324 MHz and the stability of ±0.2% in amplitude and ±0.2 degree in phase is achieved including the beam loading [2]. This RF stability makes high reproducibility of the injection beam and then contributes to the steady commissioning progress of the J-PARC

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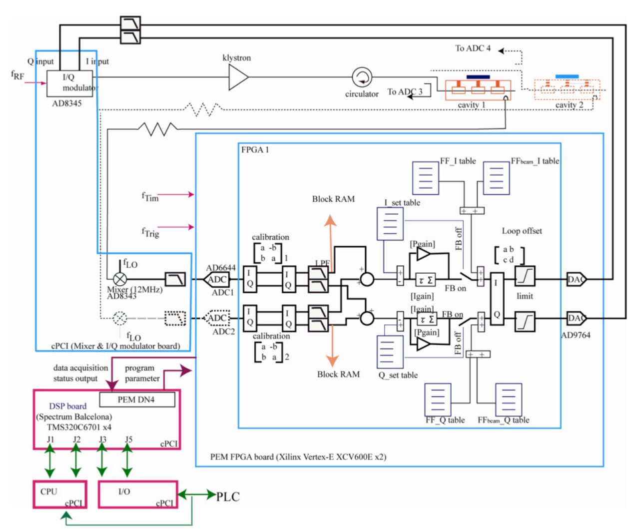

Figure 1: FPGA block diagram of the digital FB and FF control system for the J-PARC linac LLRF.

CAVITY START-UP SEQUENCE

For the cavity start-up from cold state, the input RF amplitude is slowly increased step by step to the operating level as shown in Fig.2. It takes about one minute to achieve the operating level. This sequence, which is called "Slow Start", is also performed by the DPS on Barcelona. During the slow start, the cavity tuner control is carried out as the cavity temperature rises. The cavity detuning is obtained from the phase difference between the forward RF power and the cavity. The measured phase difference is compared with the set-tuning angle then the mechanical tuner is controlled by way PLC as shown in Fig. 3 [4][5]. These calculations are made by the DSP.

In this tuner control, it is concerned that: (1) because the mechanical tuner speed is slow, it takes long time for start-up and (2) Ruggedness of the tuner would be degraded because the tuner moves quite often. Accordingly we will introduce the frequency-shift method: Cavity-input frequency is matched to the detuning.

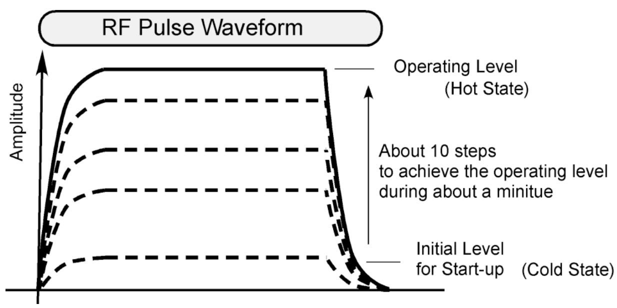

Figure 2: Amplitude is increased step by step for the cavity start-up (slow start). The tuner is controlled during this sequence.

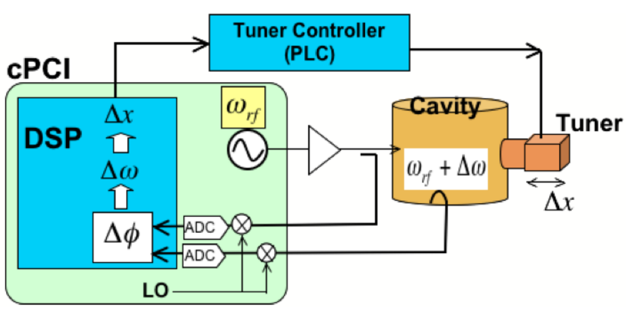

Figure 3: Cavity tuner control with DSP..

FREQUENY MODULATION METHOD

A new function of a frequency modulation was implemented in the FPGA action (Fig. 1) for the cavity start-up. The frequency of the signal source oscillator is fixed at 324 MHz or 972 MHz in our LLRF system. In order to match the frequency with the cavity detuning, the output RF is modulated by way of phase rotation with the I/Q modulator in the digital control as shown in Fig. 4. That is, during the Slow Start, the DAC outputs are switched for the rotation and the I and Q components are continuously given by

$$I = A \cdot sin(\Delta\omega \cdot t),\quad Q = A \cdot \cos(\Delta\omega \cdot t), \qquad (1)$$

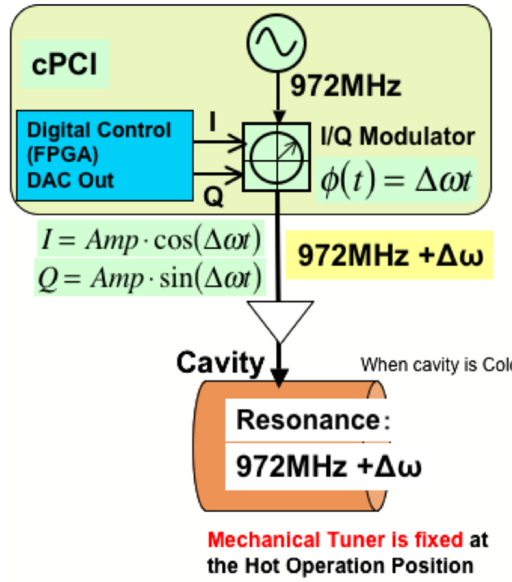

Figure 4: The phase is rotated with the IQ modulator in detuned frequency.

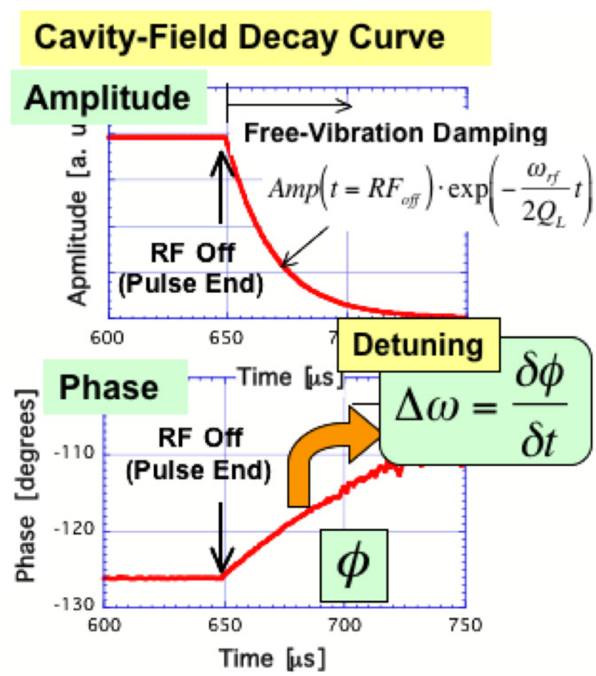

Figure 5: The Q-Value and the detuning of the cavity are obtained from the field decay curve

where A is the amplitude and Δω is the detuning frequency of the cavity. Here note that the DAC output is controlled at 48-MHz Clock. The detuned frequency of the cavity is obtained from phase gradient ($\delta\phi/\delta t$) of the cavity field decay at the RF-pulse end (See Fig. 5) as follows

$$\Delta\omega = \frac{\delta\phi}{\delta t}. \qquad (2)$$

For every pulse, the detuning is measured and the rotation is controlled.

In this sequence, the mechanical tuner is fixed at the operating option (the hot position). The initial detuning value of the cold state has to be given for the first step input with the initial RF level.

CONTROL TEST RESULT

The frequency modulation test was performed by using the 324-MHz digital system. The results are shown in Fig. 6 and 7. Figure 6 shows the plot of I and Q components of the DAC output for a 600-μs RF pulse when a 20-kHz detuning is given. The spectrum of the control RF signal is shown in Fig. 7 for the 20-kHz detuning (the upper figure). In addition, a 200-kHz modulation case is shown in the lower of Fig. 7.

High power test of the slow start was performed for the DTL cavity (324-MHz System) by using the frequency modulation method. As the result the cavity-input frequency was matched with the detuning as expected and the RF power could be fed into the detuned cavity successfully without significant reflection while the mechanical tuner was fixed at the operating position. In this case, the input RF power is about 1 MW at the operation level. The detuning is approximately 10 kHz at the cold state. This detuning requires about 20-mm tuner movement for the tuner controlling start-up.

However, it is noticed that the shorter decay time (the lower Q-value) makes the detuning measurement difficult. It is concerned issue in the future for the ACS cavities, the loaded Q-value of which will be less than 10000.

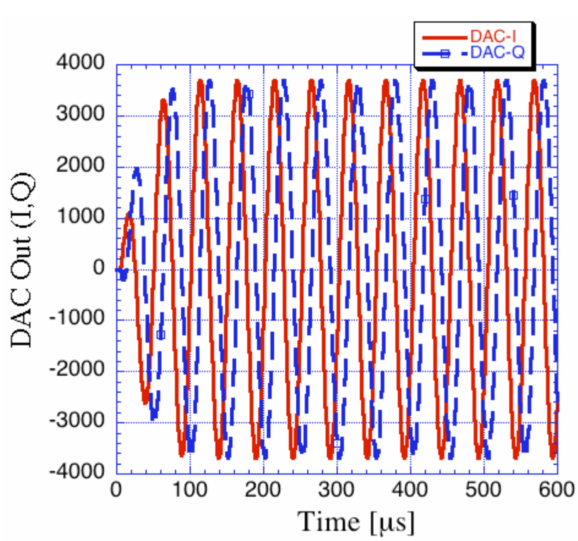

Figure 6: I and Q components of the DAC output when 20-kHz detuning is given.

SUMMARY

A new function of an automatic cavity-input frequency matching was implemented into the digital LLRF control system instead of the cavity resonance (tuner) control for the cavity start-up. For the frequency matching with the cavity detuning, the output RF is modulated by way of phase rotation with the I/Q modulator. The phase rotation is automatically controlled by the FPGA and DPS.

By using this function, the cavity start-up test was performed with the DTL cavity. It was observed that the cavity-input frequency was matched with the detuning as expected and the RF power could be fed into the detuned cavity successfully. This method will be applied for the ACS cavity operation in the 400-MeV Linac.

No special hardware modification is necessary for the implementation of this frequency modulation method. The cost reduction or the high durability for the mechanical tuner production is expected.

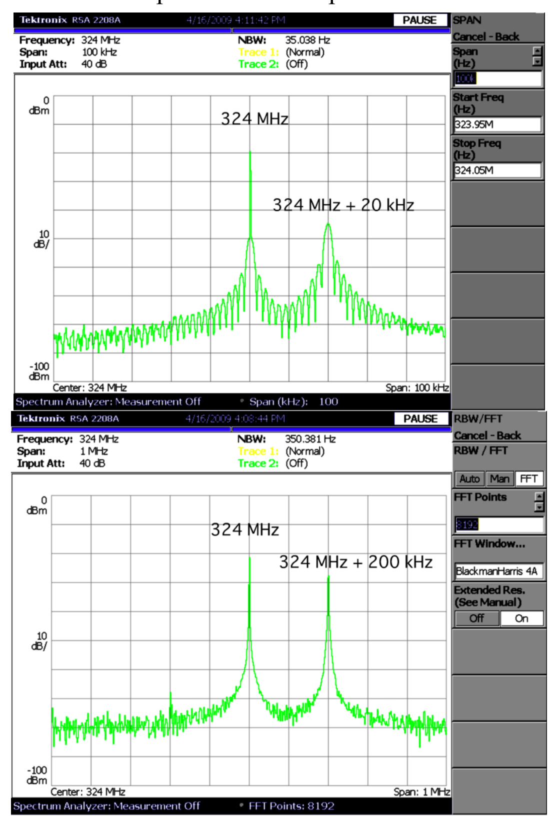

Figure 7: Measured spectrum of the modulated output signal for the 20-kHz detuning control (above) and for the case of 200-kHz detuning given (below).

REFERENCES

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