LLRF CONTROL SYSTEM OF THE J-PARC LINAC

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Abstract

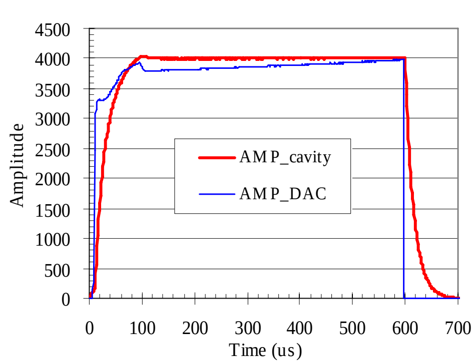
In the J-PARC proton LINAC, each klystron drives two RF cavities. The RF amplitude and phase of the cavities are controlled by an FPGA-based digital feedback control system. The test results show that the variations in the cavity amplitude and phase are less than 0.1% and 0.1° without beam loading, or 0.3% and 0.2° with beam loading. The tuning of each cavity is also controlled by a DSP of this control system. The cavity auto-tuning is successfully controlled to keep the detuned phase within ±1 degree. In our RF system, the tuning information including detuned frequency and phase, and Q-value of each cavity are measured in real-time and displayed in the PLC touch panel of the control system.

INTRODUCTION

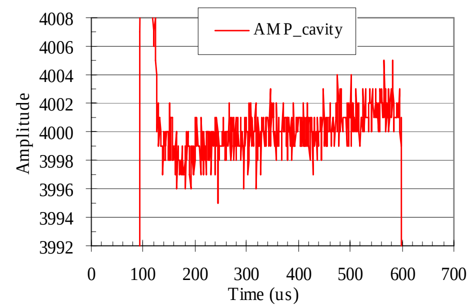
The RF sources of the J-PARC 181-MeV proton LINAC consist of 4 solid-state amplifiers and 20 klystrons with operation frequency of 324 MHz. The RF fields of each RF source are controlled by an FPGA-based digital RF feedback system installed in a compact PCI, which consists of the CPU, IO, DSP with FPGA, Mixer & IQ modulator, and RF & CLK boards [1-5]. Besides, the tuning of each accelerator cavity including 3 DTLs and 15 SDTLs is also controlled by this feedback system through a cavity tuner.

FEEDBACK PERFORMANCE

High-power tests were performed for the 24 RF systems of the J-PARC LINAC. A very good stability of the accelerating fields has been successfully achieved about ±0.1% in amplitude and ±0.1° in phase without beam loading, or ±0.3% in amplitude and ±0.2° in phase with beam loading, much better than the requirements of ±1% in amplitude and ±1° in phase. Fig. 1 shows an example of the cavity outputs with FB ON at SDTL7 with full power operation, when the RF amplitude is set to 4000 and the phase is set to 0°.



a) full scale of cavity and DAC amplitude waveform.



b) expansion of flat top of cavity amplitude.

Figure 1: Amplitudes of cavity and DAC outputs with FB ON at SDTL7.

THREE METHODS OF F_0 SETTING

By adjusting the tuner position, we tune the RF cavity with a resonant frequency of 324 MHz, and register the phase difference between picked-up signal from cavity and cavity input signal, which will be used in the auto-tuning control of the RF cavity. This process is called as f_0 setting of RF cavity.

We have investigated three methods of f_0 setting of RF cavity with FB OFF. With the cavity tuner moved, we take data of 1) cavity amplitude, 2) reflection from cavity, and 3) phase slope during field decay. Then the tuner positions for 1) the maximum cavity amplitude, 2) the minimum reflection, and 3) the flat cavity-phase decay, are obtained, which correspond to the positions for f_0 setting of the three methods.

Figure 2 shows an example of f_0 setting data by the three methods at S1A; cavity amplitude normalized by input signal (red curve), reflection amplitude from cavity (green curve), and cavity phase slope during field decay (blue curve), as function of tuner position. We can see that, the f_0 setting tuner positions of the three methods are different from each other.

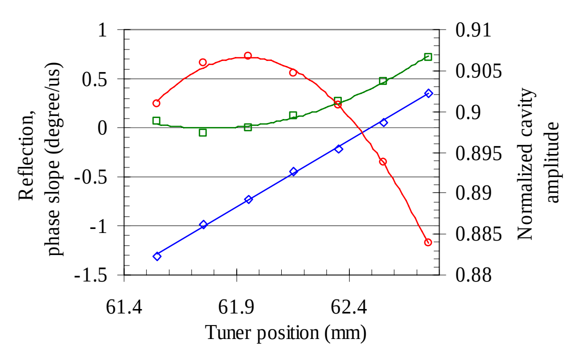


Figure 2: Cavity amplitude (red curve), reflection from cavity (green curve), and cavity phase slope during field decay (blue curve), as function of tuner position for S1A.

AFFECTING BETWEEN TWO CAVITIES

At the SDTLs of the J-PARC LINAC, one klystron drives two cavities, as shown in Fig. 3. However each component in the waveguide systems is not an ideal device. For examples, there are reflections from cavities and dummy loads; the hybrid has a finite isolation between the two outputs; and also the direction couplers have a finite directivity. Due to the hybrid isolation and dummy reflection, the reflection from one cavity will affect the RF amplitude and phase of the other cavity.

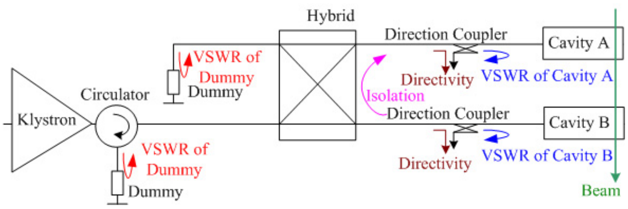
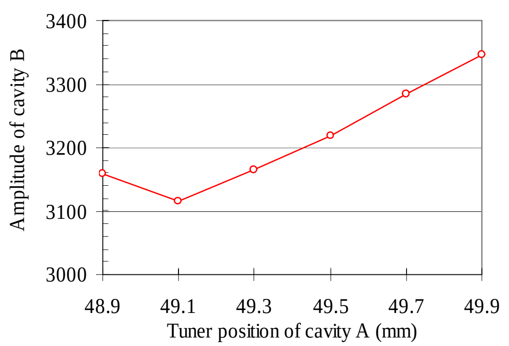
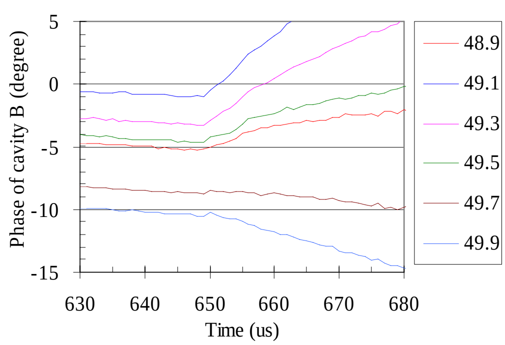


Figure 3: Setup of RF systems at the SDTLs of the J-PARC LINAC.



(a) Amplitude of cavity B



(b) Phase of cavity B

Figure 4: Amplitude and phase of cavity B as function of tuner position of cavity A.

Figure 4 shows an example of test results of affecting between the two cavities at S14. We can see that, when the tuner of cavity A is moved, both the amplitude and phase of cavity B change much.

The maximum amplitude method for f_0 setting is not good in the case with large affecting between the two cavities, since it will result in a large system error. On the other hand, the minimum reflection method by using a directional coupler is not good either. Two reasons, the affecting between the two cavities and directivity (about -35dB) of directional coupler, will result in a worse system error.

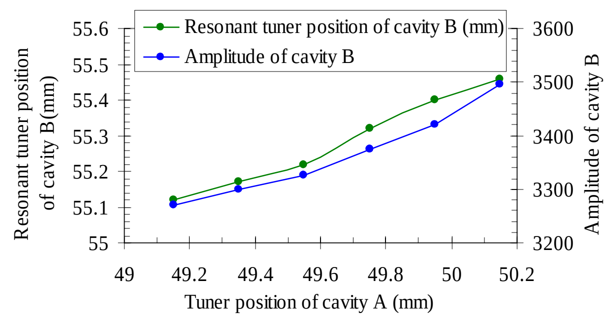
Only by using the method with flat cavity-phase decay, the cavity will be exactly tuned at 324 MHz, because the phase decay is just determined by the frequency difference of the cavity itself from the sampling frequency (324 MHz).

However, with FB OFF, the cavity power will be affected when the other cavity tuner is moved, so the resonant tuner position will be changed too. Therefore we should take the data of the resonant tuner position corresponding to a fixed cavity power with FB ON.

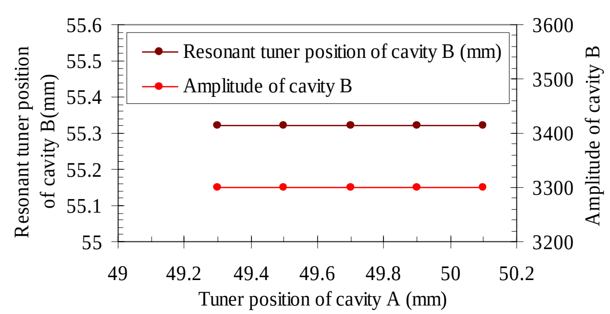
CORRECT F_0 SETTING METHOD

From the above discussion of f_0 setting by the three methods, we know the correct method is the flat phase decay method with FB ON. This conclusion has been proved by late experiments, in which it was confirmed that the cavity resonant tuner position by flat phase decay method is only dependent on cavity power, even with interactions between cavities.

Figure 5 shows the test results of resonant tuner position of cavity B at S14 with flat phase decay method, when the tuner of cavity A is moved to change the interactions between the two cavities.



(a) Cavity A and B are set with FB OFF.



(b) Only Cavity B is set with FB ON.

Figure 5: Resonant tuner position of cavity B as function of tuner position of cavity A at S14.

From the above experiments, we can see that, 1) in case of FB OFF, both the cavity power and the resonant tuner position are changed when the other cavity tuner is moved; and 2) in case of FB ON, both the cavity power and the resonant tuner position are fixed even when the other cavity tuner is moved.

Finally, the f_0 setting method using flat phase decay with FB ON is adopted in the actual operation of the J-PARC LINAC. We pre-defined the cavity resonant states with the tuner adjusted to obtain a constant phase during the cavity field decay. The cavity auto-tuning is successfully controlled to keep the detuned phase within ±1 degree.

GENERAL DISCUSSION ON F_0 SETTING

From the above analysis and experiments, it is concluded that:

1) In case of one cavity without cavity interactions, both the maximum amplitude method and flat phase decay method should be correct, and the results from the two ways should be same. This point has been confirmed by experiments at BUN1, BUN2, and DEB2. The resonant tuner positions from the two methods are exactly same as shown in Fig. 6.

2) In case of two cavities with cavity interactions, the maximum amplitude method is not good, while only the flat phase decay method is correct.

3) In any cases, due to the directivity of directional coupler, the minimum cavity input method with FB ON is not good.

4) Again, in any cases, due to the directivity of directional coupler, the minimum cavity reflection method is not good either.

The f_0 setting methods for different cases of cavity interactions are summarized in Table 1.

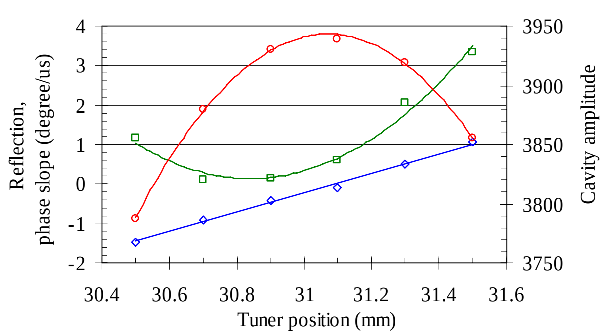


Figure 6: Cavity amplitude (red curve), reflection from cavity (green curve), and cavity phase slope during field decay (blue curve), as function of tuner position for BUN2.

Table 1: F_0 Setting Methods for different Case of Cavity Interaction

Case of cavity interaction	Maximum amplitude method	Flat phase decay method
one cavity without cavity interactions	Correct	Correct
two cavities with cavity interactions	Not good	Correct

For the maximum amplitude method, it can only be used in case of one cavity with FB OFF. For the flat phase decay method, it can be used in any cases, one or two cavities, with FB ON or FB OFF. We just need to take care of the cavity power at the moment of resonance measuring. The flat phase decay is the absolute standard of cavity resonance.

AUTO-TUNING AND Q-VALUE MONITORING

In our RF system, the detuned phases of RF cavities are successfully controlled within ±1 degree, and the tuning information including detuned frequency and phase, and Q-value of each cavity are measured in real-time and displayed in the PLC touch panel.

From the amplitude waveform during the cavity field decay, the time constant of decay is calculated out by measuring the amplitude at two sampling points:

$$T_d = \frac{t_2 - t_1}{\ln(AMP_1) - \ln(AMP_2)} \cdot$$

Then, the Q-value of cavity is carried out:

$$Q_L = \frac{\omega_{rf}}{2} \times T_d \quad \cdot$$

In the meantime, from the phase waveform during the cavity field decay, the detuning frequency and phase of each cavity are calculated out:

$$\Delta f = \frac{d\theta}{2\pi \times dt} \;, \quad \Delta\varphi = \tan^{-1}(2Q_L \frac{\Delta f}{f_0}) \quad \cdot$$

All of those parameters are monitored in real-time in the PLC touch panel of the control system.

SUMMARY

By using developed FPGA-based RF feedback control systems, a very good stability of the accelerating fields has been successfully achieved about ±0.2% in amplitude and ±0.2 degree in phase.

The three methods of f_0 setting of RF cavity, 1) maximum cavity amplitude, 2) minimum reflection, and 3) flat cavity-phase decay, have been discussed. Finally, the f_0 setting method using flat phase decay with FB ON is adopted in the actual operation of the J-PARC LINAC. The cavity auto-tuning is successfully controlled to keep the detuned phase within ±1 degree.

The tuning information including detuned frequency and phase, and Q-value of each cavity are measured in real-time and displayed in the PLC touch panel in our RF system.

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