

BEAM TEST OF CHOPPED BEAM LOADING COMPENSATION FOR THE J-PARC LINAC 400-MEV UPGRADE

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Abstract

A new function of the chopped beam loading compensation was implemented into the digital feedback/feed-forward control system of the J-PARC Linac LLRF system to stabilize the ACS cavity fields for the 400-MeV upgrade.

The first beam test of the chopped beam loading compensation was performed with the present 324-MHz cavity system. As the result, the chopped beam loading was successfully compensated and the validity of this function was confirmed.

INTRODUCTION

J-PARC will be one of the highest intensity proton accelerators, which consists of a 181 or 400-MeV Linac, a 3-GeV, 1-MW rapid-cycling synchrotron (RCS) and a 50-GeV synchrotron (main ring, MR) [1]. The beam is applied to several experimental facilities, for example, the Materials and Life Science Facility (MLF), the Hadron Physics Facility and the Neutrino Facility.

The linac has the RFQ, 3 DTL cavities and 32 SDDL cavities to accelerate the beams up to 191 MeV. They are driven by 324-MHz RF systems. And, 21 ACS cavities will be installed to accelerate the beams from 191 MeV up to 400 MeV [2]. The RF frequency of the ACS is 972 MHz. The maximum peak current of the linac will be 50 mA for the RCS injection.

In the present phase, the ACS cavities are not installed yet, and the linac provides 181-MeV beam to the RCS. In this case, the last 2 cavities of the SDDL are applied as debunchers. The 400-MeV upgrade is now in progress.

The RF deflector (RF chopper) [3], which is located between two bunchers in the medium energy beam transport line (MEBT), chops the 500- μ s long macro-pulse beam into the medium-bunches at the RCS RF frequency of 1-MHz for the RCS injection. The chopped beams (medium bunches) in the linac vibrate the ACS cavity field widely because of the lower Q-value of the ACS cavity. Therefore the function of the chopped beam loading compensation was implemented into the digital feedback/feed-forward control system of the J-PARC Linac LLRF system to stabilize the ACS cavity fields for the 400-MeV upgrade.

The first beam test of the chopped beam loading compensation was performed with the present 324-MHz cavity system. The result will be presented in this paper.

For high quality and high intensity beam acceleration, the stability of the accelerating field is one of the most important issues. Because the momentum spread ($\Delta p/p$)

of the RCS injection beam is required to be within 0.1%, the accelerating field error of the linac must be maintained within $\pm 1\%$ in amplitude and ± 1 degree in phase. To realize this stability, a digital feedback (FB) control is used in the low level RF (LLRF) control system, and a feed-forward (FF) technique is combined with the FB control for the beam loading compensation [4]. In the 181-MeV acceleration of the linac, the 24 LLRF systems are operated in a frequency of 324 MHz and the stability of $\pm 0.2\%$ in amplitude and ± 0.2 degree in phase is achieved including the beam loading [5].

BEAM STRUCTURE

The beam structure of the J-PARC linac is shown in Fig. 1. Maximum peak current will be 50 mA. Macro-pulses of 500- μ s widths are accelerated in 25-Hz repetition. The macro-pulse is chopped by a RF-chopper into medium pulses as synchronized with the RCS RF frequency of about 1 MHz. In the present operation the macro-pulse beam is 200- μ s width and 15-mA peak current.

The harmonic number of the RCS is 2 ($h=2$). Figure 1 shows the medium pulses for two-bunch (full bucket) acceleration in the RCS. In this case, the beam is distributed to the MLF. On the other hand, when the beam is distributed to the MR, the RCS operation changes to the one-bunch acceleration. In this case, the train of the medium pulses is alternative (thinned) as shown in Fig 2; the macro pulse is chopped at about 500 kHz

The chopper cavity is driven by a 30-kW solid-state amplifier and the TE₁₁-like mode field kicks the macro pulse beam to make the medium pulses. The LLRF for the chopper driving generates the chopped RF pulse as synchronizing with the RCS injection RF signal, which is received from the RCS through an optical link. This

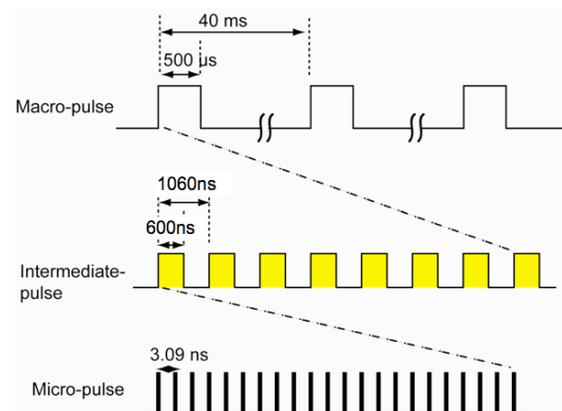


Figure 1: Linac beam structure.

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chopping frequency (1 MHz or 500 kHz) depends on the beam destination (the MLF or the MR). Accordingly, the beam loading changes twice when the beam is distributed to the MLF.

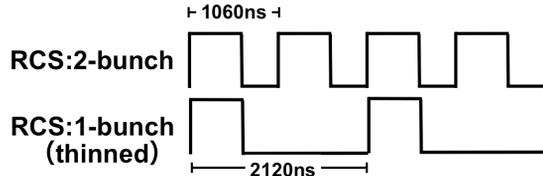


Figure 2: Medium Pulses of two-bunch operation and one-bunch operation in the RCS.

CHOPPED BEAM LOADING

Acceleration field in the cavity is vibrated by the chopped beam as shown in Fig. 3. The amplitude and phase variation of an optimum-tuned cavity field can be estimated with following equations,

$$\frac{\Delta V_c}{V_c} = (1-\eta) \frac{T_0}{T_{f0}} b, \quad \Delta\phi = (1-\eta) \frac{T_0}{T_{f0}} b \cdot \tan\phi, \quad (1)$$

respectively, where η is duty factor of the medium pulse beam, T_0 is medium pulse period T_0 is filling time of the cavity corresponding to unloaded Q-value (Q_0), b is loading factor (P_b/P_c) and ϕ is acceleration phase. Table 1 shows the estimations of the field variation due to the chopped beam loading for the ACS cavity and the debuncher in the case of 54-mA peak current and $\eta=56\%$ (average current is 30 mA). From Eq. 1 and Table 1, it is found that the field variation of the one-bunch (thinned) operation is larger than that of two-bunch (full duty) operation even though the average loading is smaller.

Figure 4 shows the time-domain simulation result of the amplitude and phase change in the ACS cavity for the one-bunch operation. This simulation result agrees well with the estimation from Eq. 1 as shown Table 1. Furthermore, Fig. 4 shows that the phase shift furthers the

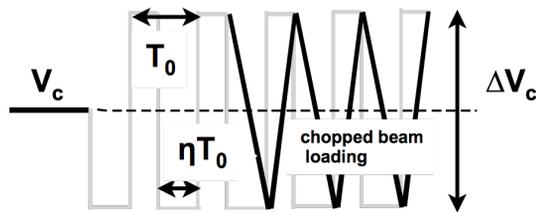


Figure 3: Acc. field vibration due to chopped beam.

Table 1: Estimation of Filed Variation due to Chopped Beam Loading

RCS	A C S		(de) buncher	
	Amp.	Phase	Amp.	Phase
2-bunch acc.	$\pm 0.8\%$	± 0.3 度	$\pm 0.2\%$	± 0.5 deg
1-bunch acc.	$\pm 2.8\%$	± 0.9 度	$\pm 0.5\%$	± 1.7 deg

amplitude change as shown Fig. 5. In other words, the phase change does not cancel the amplitude change.

In consideration of the estimation and simulation results, the field vibration due to the chopped beam is not negligible for the requirements of the field stability. Therefore the compensation system will be needed for the 400-MeV upgrade using the ACS cavities.

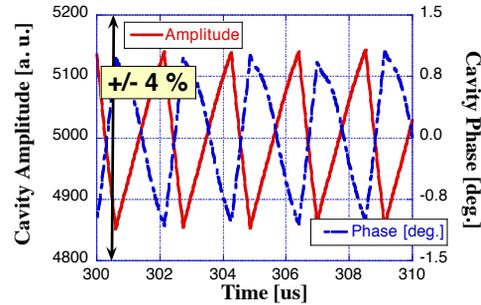


Figure 4: Time domain simulation result of the amplitude and phase for the one-bunch operation.

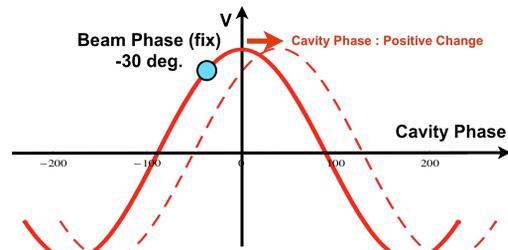


Figure 5: Phase definition in the simulation of Fig. 4. The accelerating phase is fix ($\phi=-30$ deg.).

BEAM LOADING COMPENSATION

The digital FB and FF control basically stabilize the cavity field with compensation of the macro-pulse beam loading, but it cannot compensate the field vibration caused by chopped beam. Therefore additional FF control function, which synchronizes with the chopped beam (medium pulses), is needed as shown in Fig. 6. As shown in the figure, the digital LLRF system receives the chopping pulse signal (medium beam pulse) externally, then it performs the FF control synchronizing with the medium beam pulse to compensate the chopped beam loading. The FF control output timing is adjustable with the chopped beam by changing the delay in the FPGA. The external medium pulse signal is distributed to all the LLRF control stations from the chopper LLRF control as shown in Fig. 7. At the chopper LLRF, the medium pulse signal, which is transferred from the RCS RF system, is used for making chopping RF pulse to drive the chopper cavity as shown in the figure.

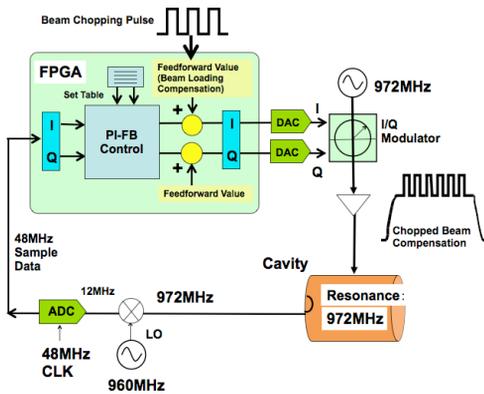


Figure 6: Illustration of the digital FB/FF control. External signal, which is synchronizing with chopping pulse, is received to compensate the chopped beam loading.

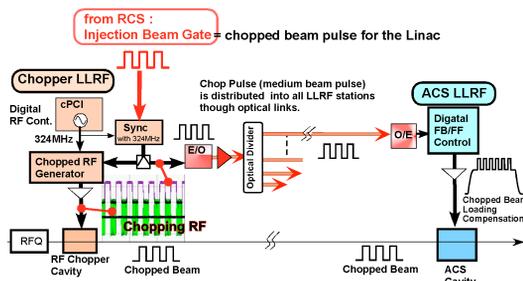


Figure 7: Distribution of the chopping pulse signal to the LLRF control systems for the chopped beam loading compensation.

BEAM TEST OF THE COMPENSATION

In this chapter, the beam test result of the chopped beam loading compensation is shown. In the present operation, there are no ACS cavities, and only the 324-MHz RF systems are working. The beam current is 15-mA peak. In this case, the field vibration in the Debuncher2 is observed most clearly because the driving power of the DB2 is only 2 kW. But in the debuncher, the phase change is bigger than amplitude change. Figure 8 shows the measured phase variations and the simulation in the DB2 cavity for the both case of the one-bunch and two-bunch operation. In the figure, the solid line indicates the measured phase and the dashed line indicates the simulation. In the one-bunch operation, the phase change of about ± 0.5 degrees is observed. The simulation result is slightly different from the measurement, but it depends on operation parameters of the cavity in the calculation.

Figure 9 shows the chopped beam compensation result at the DB2. The solid line indicates the result of the compensation, and the dashed line indicates the no-compensation case. As the result, the chopped beam loading successfully compensated and the phase change vanished completely.

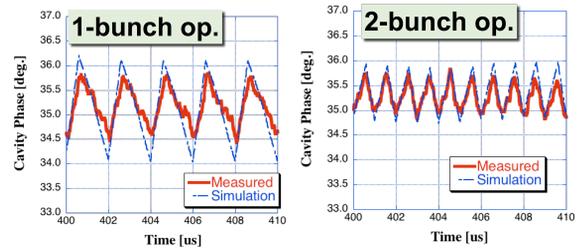


Figure 8: The phase variations in the Debuncher2 caused by the chopped beam of the one-bunch and two-bunch operation, respectively.

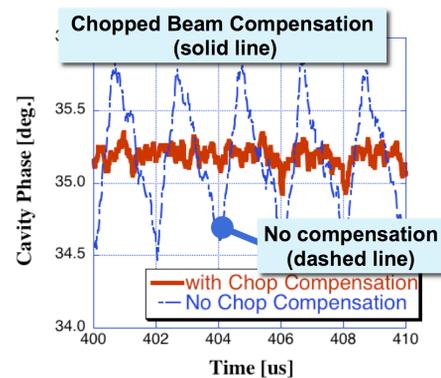


Figure 9: The chopped beam compensation result. The solid line shows the result of the compensation and the dashed line shows the case without the compensation.

SUMMARY

In order to compensate the chopped beam loading, additional function was implemented into the digital FB/FF control system of the J-PARC Linac LLRF system to stabilize the ACS cavity fields for the 400-MeV upgrade.

The first beam test of the chopped beam loading compensation was performed with the present 324-MHz cavity system. As the result, the chopped beam loading was successfully compensated and the validity of this function was confirmed.

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