

# BEAM TEST OF THE CERN PSB WIDE-BAND RF SYSTEM PROTOTYPE IN THE J-PARC MR

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## Abstract

In the framework of the LHC Injectors Upgrade project (LIU), a complete replacement of the existing narrow band rf systems of CERN PSB with wideband magnetic alloy (MA) loaded rf systems is under consideration. A single gap MA loaded rf system prototype, which uses solid-state power amplifier and includes fast rf feedback for beam loading compensation, has been installed in the J-PARC MR to investigate the system behavior with high intensity proton beams. We report the wake voltage measurement results with and without fast rf feedback. In addition to the fast feedback, the rf feedforward method is under consideration to compensate the heavy beam loading more effectively. Preliminary beam test results with feedforward are also presented.

## INTRODUCTION

For the CERN PS booster (PSB) upgrade plan aiming at increasing the extraction energy to 2 GeV and the intensity beyond  $2 \times 10^{13}$  protons, it is now being considered replacing of the existing narrow band rf systems with wide-band magnetic alloy (MA) loaded rf systems [1]. The wide-band response covers the fundamental accelerating harmonic ( $h = 1$ ) and the second harmonic ( $h = 2$ ) range from 0.5 to 4 MHz without tuning, and allows multiharmonic operation. The MA cores have the high saturation field, which allows maintaining linear response with The new system is driven by the solid-state amplifier, which includes a fast rf feedback loop for the beam loading compensation.

In the J-PARC synchrotrons, the multiharmonic beam loading in the MA cavities is compensated by rf feedforward method [2, 3]. In case of the J-PARC synchrotrons, the impedances seen by the beam are greatly reduced by the feedforward, better than 1/20. Following the success of the J-PARC synchrotrons, it is considered to employ the rf feedforward method for the beam loading compensation of the PSB rf system in addition to the fast rf feedback.

To investigate the system behavior, a single-cell rf system prototype was installed in the J-PARC MR, where the high intensity proton beams up to  $1.4 \times 10^{13}$  ppb are available. Also, the existing multiharmonic feedforward system of the J-PARC MR was connected to compensate the wake voltages in the prototype PSB cavity.

In this article, we report the wake voltage measurement results with and without fast rf feedback and the results of the beam loading compensation by the feedforward.

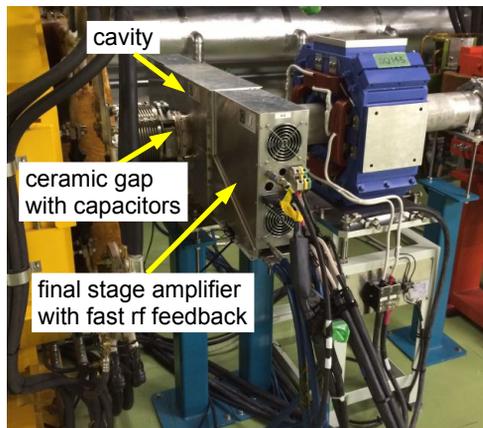


Figure 1: CERN PSB rf system prototype installed in the J-PARC MR.

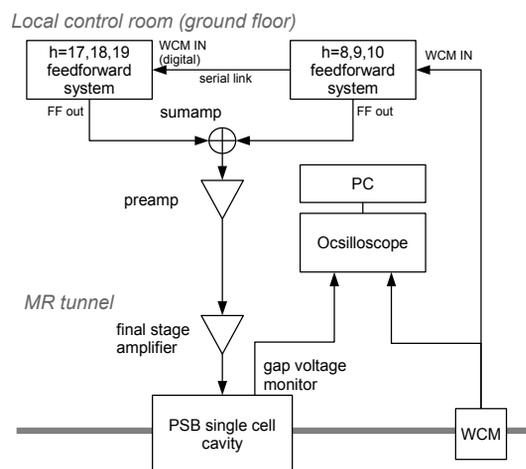


Figure 2: Schematic diagram of the beam test setup.

## TEST SETUP

The PSB prototype rf system was installed in the upstream of the straight section for the rf cavities and the fast extraction kickers. The system is located between a Q magnet and a skew-Q magnet as shown in Fig. 1. To avoid the influence of the noises from the magnets, the cavity beam duct has ceramic gaps for DC insulation. The wall currents can go through the bypass capacitors across the ceramic gaps.

A schematic diagram of the beam test setup is shown in Fig. 2. The cavity gap voltage monitor signals and the beam signals picked up by a wall current monitor (WCM) are captured by an oscilloscope. Offline harmonic analysis on the beam current and the cavity voltage signals is performed by a PC.

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## BEAM TESTS

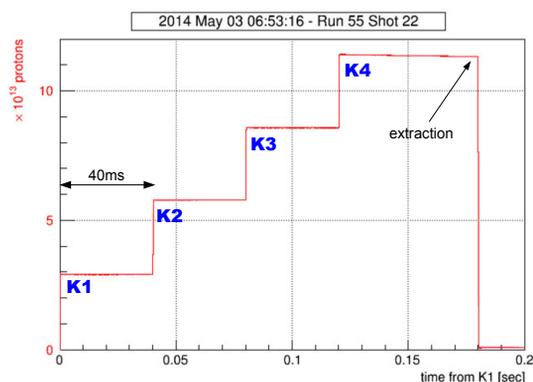


Figure 3: Typical DCCT waveform with accumulating the high intensity beam.

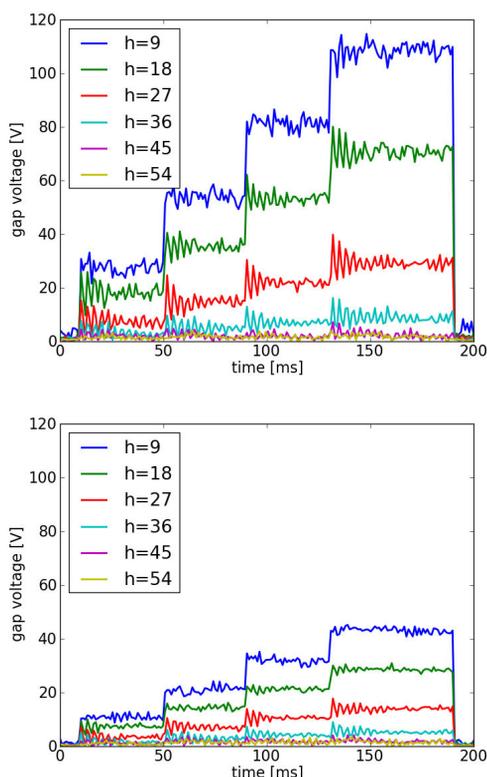


Figure 4: Harmonic components of the gap voltage, (top) without fast rf feedback and (bottom) with feedback.

The beam signals are also used as the input of the feedforward system. The feedforward systems of the J-PARC MR handle the fundamental accelerating harmonic and the neighbors ( $h = 8, 9, 10$ ), and the second harmonic and the neighbors ( $h = 17, 18, 19$ ). The beam signal is digitized by the one of the feedforward system for ( $h = 8, 9, 10$ ) and sent to the other via a high speed serial connection. The multiharmonic feedforward compensation signals of ( $h = 8, 9, 10$ ) and ( $h = 17, 18, 19$ ) are superposed by a summation amplifier. With a preamplifier, the compensation signal is sent to the final stage amplifier in the MR tunnel.

The PSB system is designed to handle the voltage level in the order of 1 kV peak. The peak beam current of the MR reaches 100 A in the end of acceleration to 30 GeV with the beam intensity of  $1 \times 10^{14}$  ppp ( $1.25 \times 10^{13}$  ppb), and the gap voltage of the PSB system may exceed 10 kV, which is not acceptable. To avoid such overvoltage issues, the beam tests were performed in the 3 GeV DC mode, where the beam is not accelerated. For the high intensity acceleration, the accelerating gap in the PSB cavity is shorted.

The harmonic number of the J-PARC MR is 9. At 3 GeV, the revolution frequency and the fundamental rf frequency are 0.186 MHz and 1.671 MHz, respectively.

During the MR injection period, four RCS beam pulses, which consist of two bunches, are transferred into the MR to accumulate eight bunches. A typical DCCT waveform with accumulating the high intensity beam is shown in Fig. 3. The injection interval is 40 ms. The four injection timings are called K1, K2, K3, and K4.

The following measurements were done without driving the cavity. Compared to the rf voltages of 160 kV generated by the J-PARC rf systems, the wake voltage is low, about 1 kV maximum. Thus, the PSB cavity impedance gave almost no effects on the circulating beam.

### RF Feedback Effectiveness

To investigate the rf feedback effectiveness on the impedance reduction seen by the beam, the measurements of wake voltages without and with fast rf feedback were performed. Note that no feedforward compensation was applied yet. This measurements were performed with relatively low intensity beams,  $2.2 \times 10^{12}$  ppb to avoid the overvoltage issues without feedback.

The harmonic components of the gap voltage up to the sixth harmonic ( $h = 54$ ) are plotted in Fig. 4, without fast rf feedback (top) and with feedback (bottom). The fundamental accelerating harmonic ( $h = 9$ ) increases with accumulating the beam, and reaches 110 V when eight bunches are in the ring. It is reduced down to 45 V with feedback. The reduction is fairly consistent with the measurements of the gap impedance by a network analyzer. Other harmonics up to the fourth harmonic ( $h = 36$ ) are also reduced with feedback. The fifth and sixth harmonics ( $h = 45, 54$ ) are already small without feedback, therefore, the reductions of the wake voltage are not visible.

### Feedforward Compensation

The feedforward patterns were adjusted by using the methodology established in J-PARC [2]. With feedforward, the cavity gap voltage is a superposition of the wake voltage and the feedforward signal. In frequency domain, the superposition at the time  $t$  for the selected harmonics  $h$  is expressed as

$$V_{\text{cav}}(h, t) = V_{\text{cav, wake}}(h, t) + V_{\text{cav, FF}}(h, t) \\ = Z_{\text{cav}}(h, t) \cdot I_{\text{beam}}(h, t) + Z_{\text{FF}}(h, t) \cdot I_{\text{beam}}(h, t), \quad (1)$$

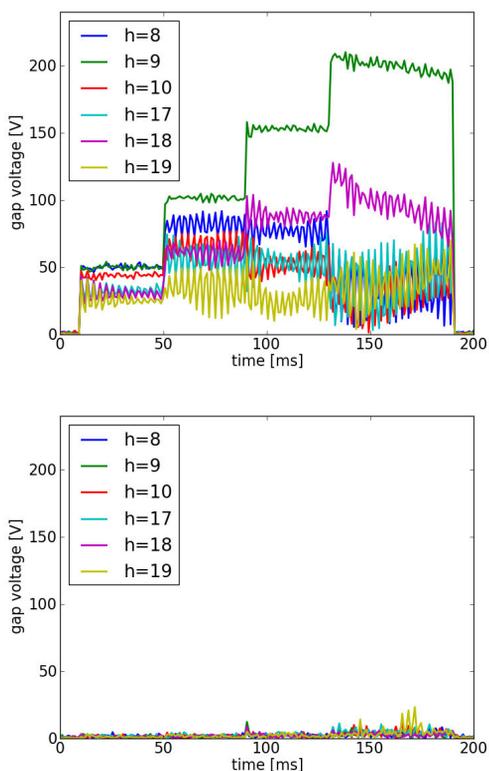


Figure 5: Harmonic components of the gap voltage, (top) without feedforward and (bottom) with feedforward.

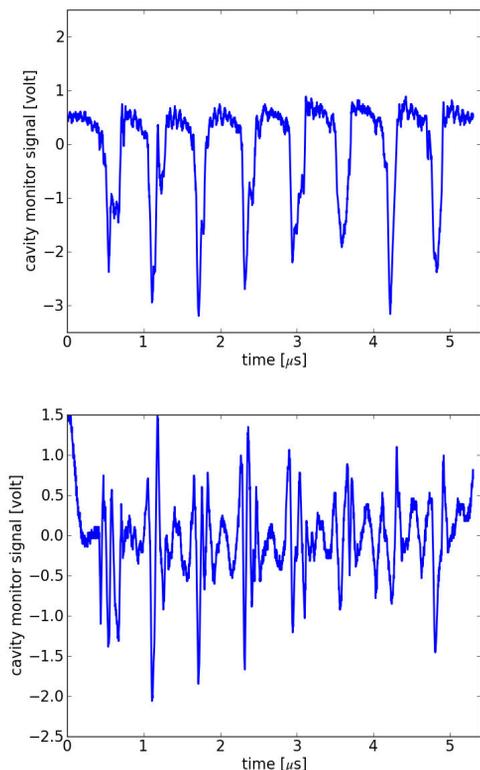


Figure 6: Gap voltage monitor waveforms, (top) without feedforward and (bottom) with feedforward.

where  $V_{cav}(h, t)$ ,  $V_{cav, wake}(h, t)$ ,  $V_{cav, FF}(h, t)$ , and  $I_{beam}(h, t)$  are the complex amplitudes of the cavity gap voltage, wake, feedforward signal, and beam current, respectively.  $Z_{cav}(h, t)$  is the impedance seen by the beam without feedforward, and  $Z_{FF}(h, t)$  is the transfer function from the beam current to the feedforward signal. The feedforward gain and phase patterns are modified so that  $Z_{FF}(h, t) = -Z_{cav}(h, t)$ . By several iterations, the impedance seen by the beam with feedforward,  $Z_{FF}(h, t) + Z_{cav}(h, t)$ , can be much reduced.

As described previous section, the feedforward compensation for the harmonics ( $h = 8, 9, 10$ ) and ( $h = 17, 18, 19$ ) were applied and commissioned with the high intensity beam of  $1.4 \times 10^{13}$  ppb. In this test, the fast rf feedback loop was closed. The harmonics components of the gap voltage on the target harmonics ( $h = 8, 9, 10, 17, 18, 19$ ) without and with feedforward are plotted in the top and bottom in Fig. 6, respectively. At this beam intensity, the fundamental component ( $h = 9$ ) of the wake voltage exceeds 200 V at K4 timing and it is suppressed by the feedforward, less than 10 V. For the other target harmonics, the wake voltages are also greatly reduced by the feedforward.

The gap voltage monitor waveforms near the extraction are shown in Fig. 6. One can see the eight major structures without feedforward. Since the PSB cavity has wideband response, the shape of the wake voltage waveform is like bunch shapes. With feedforward, the fundamental and second harmonics are compensated and only higher harmonic components remain.

## SUMMARY AND OUTLOOK

The beam tests of the PSB rf system prototype in the J-PARC MR were successfully performed and the test results are promising as following. (1) The fast rf feedback reduced the wake voltages by a factor  $\sim 2.5$ . (2) The multiharmonic feedforward compensation system of the J-PARC MR for the fundamental and the second harmonic (and their neighbors) was arranged for the PSB system tests. The feedforward patterns were successfully commissioned, and the impedance seen by the beam was reduced better than  $1/20$ , compared to the case of the rf feedback only.

The results indicate that the feedforward compensation can be used in the CERN PSB. For application to the PSB operation, the feedforward must compensate up to the fourth harmonic. Development of a new feedforward system for the PSB will be required.

## REFERENCES

- [1] M. Paoluzzi, et al., Proceedings of the 2013 International Particle Accelerator Conference, Shanghai, pp.2660–2662 (2013).
- [2] F. Tamura, et al., Phys. Rev. ST Accel. Beams, 14, 051004 (2011).
- [3] F. Tamura, et al., Phys. Rev. ST Accel. Beams, 16, 051002 (2013).