High intensity single bunch operation with heavy periodic transient beam loading in wide band rf cavities

Fumihiko Tamura,* Hideaki Hotchi, Alexander Schnase,† Masahito Yoshii, Masanobu Yamamoto, Chihiro Ohmori, Masahiro Nomura, Makoto Toda, Taihei Shimada, Katsushi Hasegawa, and Keigo Hara

J-PARC Center, KEK & JAEA, 2-4 Shirakata, Tokai, Naka, Ibaraki 319-1195, Japan

(Received 21 July 2015; published 29 September 2015)

The rapid cycling synchrotron (RCS) in the Japan Proton Accelerator Research Complex (J-PARC) was originally designed to accelerate two high intensity bunches, while some of neutron experiments in the materials and life science experimental facility and a muon experiment using main ring beams require a single bunch operation mode, in which one of the two rf buckets is filled and the other is empty. The beam intensity in the single bunch operation has been limited by longitudinal beam losses due to the rf bucket distortions by the wake voltage of the odd harmonics ($h = 1, 3, 5$) in the wide band magnetic alloy cavities. We installed an additional rf feedforward system to compensate the wake voltages of the odd harmonics ($h = 1, 3, 5$). The additional system has a similar structure as the existing feedforward system for the even harmonics ($h = 2, 4, 6$). We describe the function of the feedforward system for the odd harmonics, the commissioning methodology, and the commissioning results. The longitudinal beam losses during the single bunch acceleration disappeared with feedforward for the odd harmonics. We also confirmed that the beam quality in the single bunch acceleration are similar to that of the normal operation with two bunches. Thus, high intensity single bunch acceleration at the intensity of 2.3×10^{13} protons per bunch has been achieved in the J-PARC RCS. This article is a follow-up of our previous article, Phys. Rev. ST Accel. Beams 14, 051004 (2011). The feedforward system extension for single bunch operation was successful.

DOI: 10.1103/PhysRevSTAB.18.091004 PACS numbers: 29.20.−c, 29.27.−a

I. INTRODUCTION

The 3 GeV rapid cycling synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC) is a high intensity pulsed proton driver [1,2]. The RCS delivers proton beams to the materials and life science experimental facility (MLF) and the main ring synchrotron (MR). At present, the RCS provides 4.5×10^{13} protons per pulse (ppp), which corresponds to the beam power of 500 kW at the repetition rate of 25 Hz, to the MLF and MR. During the high intensity test performed in January 2015 [3], 8.3×10^{13} protons were successfully accelerated with a low beam loss below 0.2%. This demonstration was performed in the single shot mode, where a beam macro pulse is injected from the linac to the RCS on demand.

The RCS normally accelerates two bunches in the high intensity user operation as the original design. However, a single bunch operation mode, in which one of the two rf buckets is filled and the other is empty, is required by the COMET (COherent Muon to Electron Transition) experiment [4] using the beam from the MR and some of the neutron experiments in the MLF. The COMET phase-I experiment will start with low intensity proton beams from the MR, however, the output beam power of 56 kW is required in the phase-II experiment. To achieve that, the RCS must accelerate a very high intensity proton beam, more than 2.5×10^{13} protons per bunch (ppb), in the single bunch operation.

An example in the MLF which prefers the single bunch operation is the Accurate Neutron-Nucleus Reaction Measurement Instrument (ANNRI) [5]. The neutron energy resolution of the ANNRI determined by the time-of-flight technique depends on the time structure of the neutron pulse. It is reported that the energy resolution deteriorates above about 10 eV because the time structure of the neutron pulse splits into two peaks in the two bunch operation, while the energy resolution better than 1% is obtained in the single bunch operation.

The parameters of the J-PARC RCS and its rf system are listed in Table I. In the summer shutdown of 2013, the output energy of the J-PARC linac was upgraded from 181 MeV to the design energy of 400 MeV [6]. The RCS accelerates the beams from 400 MeV to the output energy of 3 GeV.

The magnetic-alloy (MA) loaded cavities are employed in the RCS to generate high accelerating voltages. The maximum accelerating voltage is 440 kV with twelve cavities. The Q value of the MA cavity is set to 2 by using an external

*fumihiko.tamura@j-parc.jp
†Present address: GSI Helmholtzzentrum für Schwerionenforschung GmbH Planckstraße 1, 64291 Darmstadt, Germany.

TABLE I. Parameters of the J-PARC RCS and its rf system after the linac upgrade was finished in summer 2013.

circumference	348.333 m
energy	0.400–3 GeV
beam intensity	(design) 8.3×10^{13} ppp
	(achieved) 8.3×10^{13} ppp
accelerating frequency	1.227–1.671 MHz
harmonic number	2
maximum rf voltage	440 kV
repetition rate	25 Hz
No. of cavities	12
Q-value of rf cavity	2

inductor [7], so that the frequency response covers the frequency sweep from 1.227 to 1.671 MHz, to follow the velocity change during acceleration. The MA cavity does not require a tuning bias loop, which is necessary in case of ferrite loaded cavities. The wide band frequency response also enables the dual-harmonic operation, in which each cavity is driven by the superposition of the fundamental accelerating harmonic ($h = 2$) and the second harmonic ($h = 4$) [8]. The bunch shape control by the dual-harmonic operation during the injection period is a key for mitigation of the space charge effects to reduce the beam losses [9,10].

For acceleration of high intensity beams, the beam loading in MA cavities is a key issue. The wake voltage in the wide band MA cavity contains not only a component of the fundamental accelerating rf, but also the higher harmonics. A multiharmonic beam loading compensation system using the rf feedforward method was developed and commissioned as described in our previous article [11]. For two bunch operation on harmonic number $h = 2$, only even harmonics have relevant amplitude in the beam spectrum. Hence the multiharmonic feedforward system compensates the most important three harmonics ($h = 2, 4, 6$) and the impedance seen by the beam is significantly reduced. The beam loss in the high dispersion area due to the bucket distortion is reduced by the feedforward. The feedforward compensation for even harmonics ($h = 2, 4, 6$) is required for the normal high power beam operation.

However, the beam intensity in the single bunch operation, in which one of the two rf buckets is filled and the other is empty, has been limited due to the heavy periodic transient effects, i.e., wake voltages of the odd harmonics ($h = 1, 3, 5$). The rf bucket distortion due to the wake voltages of the odd harmonics causes longitudinal beam losses in the middle of the accelerating period.

Therefore, we installed an additional feedforward system to compensate the beam loading of the odd harmonics ($h = 1, 3, 5$) aiming at accelerating a single bunch with comparable protons per bunch to that of the two bunch operation.

In this article, we describe the system configuration of the feedforward system for the odd harmonics and the commissioning of the system. Finally, we report the results of the beam quality measurements with high intensity beams.

II. ADDITIONAL FEEDFORWARD SYSTEM FOR THE ODD HARMONICS

The feedforward system extension for the odd harmonics ($h = 1, 3, 5$) was considered when the system for the even harmonics ($h = 2, 4, 6$) was developed. As described in our previous article [11], the in-phase/quadrature-phase (I/Q) vectors of the beam signal are distributed via a specialized backplane. The number of the backplane pins is not enough to distribute the I/Q vectors of six harmonics. Furthermore, finite impulse response (FIR) filters, which consume a large number of logic cells and multipliers in the field programmable gate array (FPGA), are used in the I/Q detection block. At the time of the development of the system, no FPGAs that can handle six harmonics were available. Therefore, we decided that the feedforward system for the even and odd harmonics are separated. The system is designed and built so that the operation modes for the even ($h = 2, 4, 6$) or odd ($h = 1, 3, 5$) harmonics can be selected by an on-board switch. We describe the detail of the extension of the feedforward system for the odd harmonics as follows.

The configuration of the feedforward system with the additional system for the odd harmonics is illustrated in Fig. 1. The beam signal from the wall current monitor (WCM) is digitized by an analog-to-digital converter (ADC) in the system for the even harmonics ($h = 2, 4, 6$). The digital signal is transferred to the system for the odd harmonics ($h = 1, 3, 5$) via a high speed serial data connection.

The function of the feedforward system for the odd harmonics is similar to that of the even harmonics [11] except the target harmonics. The I/Q vectors of the beam signal for the selected harmonics ($h = 1, 3, 5$) are picked up by using the I/Q detection technique. The I/Q vector of the selected harmonic, $(I_{\text{out}}, Q_{\text{out}})$ is obtained as

$$I_{\text{out}} = A(h,t)\sin[\phi(h,t)], \quad (1)$$

$$Q_{\text{out}} = A(h,t)\cos[\phi(h,t)], \quad (2)$$

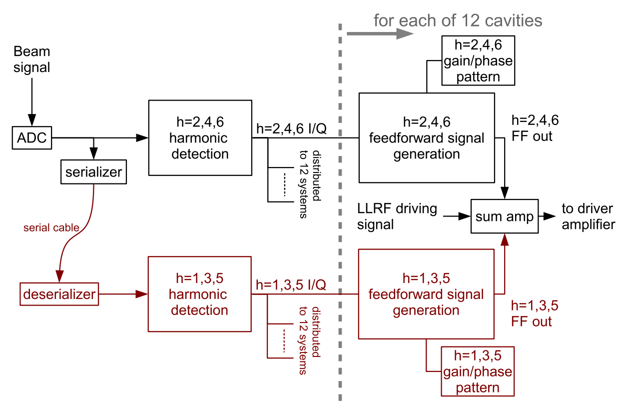

FIG. 1. The configuration of the additional feedforward system for the odd harmonics ($h = 1, 3, 5$).

where h is the selected harmonic, t the time, $A(h,t)$ and $\phi(h,t)$ are the amplitude and the phase of the selected harmonics, respectively.

The I/Q vectors are distributed to the modules for all cavities. By using I/Q modulation, feedforward compensation signal is generated with the gain and phase patterns for the selected harmonic as

$$\begin{aligned}&(\mathrm{I/Q\,modulation\ output})\\&\quad= G[I_{\mathrm{out}}\cos(\omega_h t+\psi)+Q_{\mathrm{out}}\sin(\omega_h t+\psi)]\\&\quad= GA(h,t)\sin[\omega_h t+\phi(h,t)+\psi],\end{aligned} \tag{3}$$

where G and ψ are the gain and phase patterns and ω_h is the angular frequency of the selected harmonic, $\omega_h = h\times\omega_{\mathrm{rev}}$ (revolution frequency). The feedforward compensation signals of $(h=1,3,5)$ are summed up and the multiharmonic compensation signals are generated by a digital-to-analog converter (DAC). As described in our previous article [11], the system works as a tracking bandpass filter, whose passbands at the odd harmonics $(h=1,3,5)$ follow the change of the revolution frequency with programmed gain and phase patterns.

Finally, the feedforward signals from the systems for even and odd harmonics and the driving rf signal are summed up by the summation amplifier. The cavity is driven by these signals.

III. COMMISSIONING OF THE FEEDFORWARD SYSTEM

A. Commissioning methodology

The commissioning methodology, which is used for the even harmonics $(h=2,4,6)$, is applied to the odd harmonics $(h=1,3,5)$. The details of the methodology are described in our previous article [11]. Here, we briefly describe the commissioning methodology.

The commissioning is performed in frequency domain. Since the cavity is not driven by the odd harmonics $(h=1,3,5)$, the cavity voltage $V_{\mathrm{cav}}(h,t)$ is a superposition of the wake voltage $V_{\mathrm{cav,wake}}(h,t)$ and the feedforward voltage $V_{\mathrm{cav,FF}}(h,t)$, where h is the selected harmonic, and t the time. The superposition is expressed as

$$\begin{aligned}V_{\mathrm{cav}}(h,t) &= V_{\mathrm{cav,wake}}(h,t)+V_{\mathrm{cav,FF}}(h,t)\\&= Z'_{\mathrm{cav}}(h,t)\cdot I_{\mathrm{beam}}(h,t)+Z_{\mathrm{FF}}(h,t)\cdot I_{\mathrm{beam}}(h,t),\end{aligned} \tag{4}$$

where $I_{\mathrm{beam}}(h,t)$ is the harmonic component of the beam current, and $Z'_{\mathrm{cav}}(h,t)$ the cavity impedance obtained by accelerating a beam without feedforward. $Z_{\mathrm{FF}}(h,t)$, which is the transfer function from the beam current to the feedforward gap voltage, is obtained by using (4) and the measured voltage and beam current, $V_{\mathrm{cav}}(h,t)$ and $I_{\mathrm{beam}}(h,t)$.

To minimize the impedance seen by the beam $Z'_{\mathrm{cav}}(h,t)+Z_{\mathrm{FF}}(h,t)$, the gain and phase patterns are modified so that

$$Z_{\mathrm{FF}}(h,t) = -Z'_{\mathrm{cav}}(h,t), \tag{5}$$

assuming a linear response of the feedforward voltages. Applying several iterations, one can minimize the impedance seen by the beam.

B. Commissioning results

Commissioning of the feedforward system for the odd harmonics $(h=1,3,5)$ was performed by using high intensity single bunch beams, 2.3×10^{13} ppb, which corresponds to 280 kW at the repetition rate of 25 Hz. As of February 2014 when the system was commissioned, 2.3×10^{13} ppb was the maximum intensity with the linac peak current of 25 mA. The feedforward system for the even harmonics $(h=2,4,6)$ was fully set up in advance.

The harmonic components of the gap voltage of cavity #5 without feedforward for the odd harmonics are plotted in the upper left in Fig. 2. The cavity is driven by the accelerating harmonic $(h=2)$ and the second harmonic $(h=4)$. The second harmonic voltage $(h=4)$ is applied from start until 5 ms to improve the bunching factor. Thanks to the feedforward compensation of the even harmonics, the wake voltage of the second harmonic is suppressed after 5 ms as well as the third harmonic $(h=6)$ throughout the accelerating period.

Without feedforward for the odd harmonics, the odd harmonic components $(h=1,3,5)$ of the wake voltage are observed as shown in the plot. The $(h=3)$ component is most significant. The amplitude of the $(h=3)$ component at the middle of acceleration is one sixth of the accelerating harmonic $(h=2)$, and the ratio reaches 50% near the extraction, where the accelerating voltage is reduced. The revolution harmonic $(h=1)$ of the wake voltage has a comparable amplitude to the $(h=3)$ component and the amplitude of the $(h=5)$ component is relatively small.

These wake voltage of the odd harmonics causes strong voltage distortions. The gap voltage waveforms of cavity #5 without feedforward for the odd harmonics at the middle of acceleration (10 ms) and just before extraction (19.9 ms) are plotted in the upper middle and upper right in Fig. 2, respectively. The waveforms are far from a sinusoidal waveform, while the cavity is driven by a single accelerating harmonic $(h=2)$. The gap voltage is strongly modulated by the beam pulse. Clearly this shows the periodic transient effect of a high intensity beam in a wide band cavity. At 10 ms, one can observe that the bunch is accelerated by the voltage near the lower peaks. Due to the distortion by the wake voltage of the odd harmonics, the rf bucket shrinks and beam losses occur. The voltage

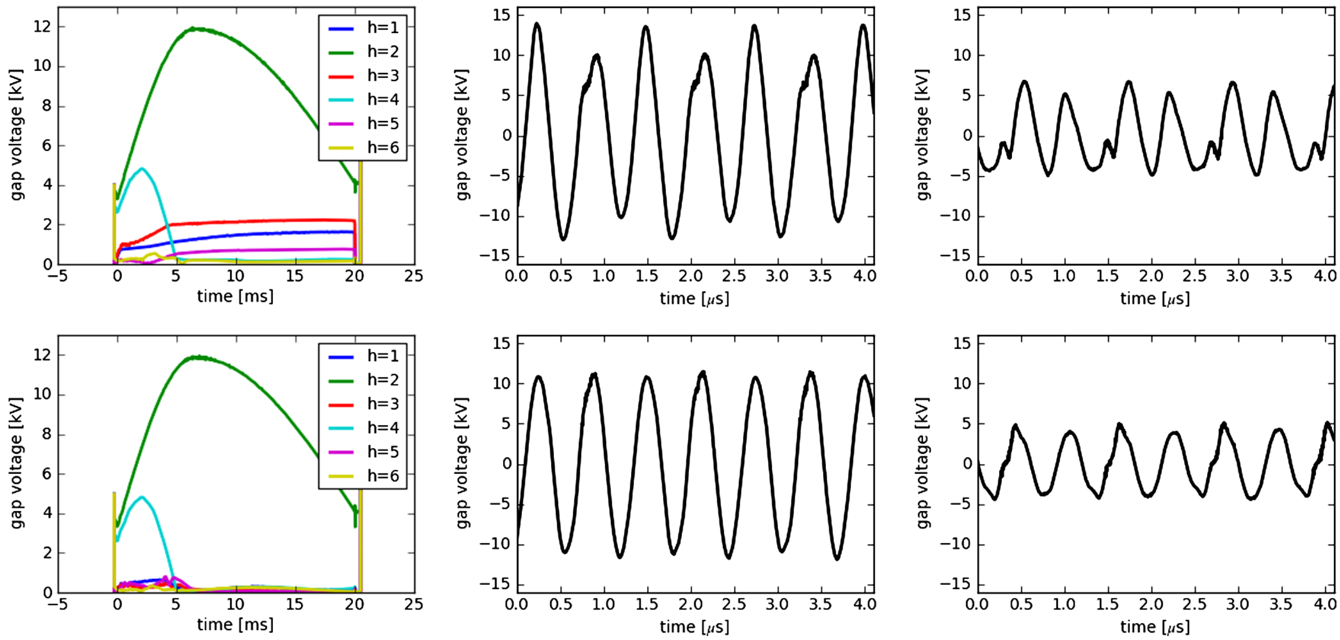

FIG. 2. Left: the harmonic components of the gap voltage of cavity #5 and the gap voltage waveforms at (middle) middle of acceleration (10 ms) and (right) just before extraction (19.9 ms). Upper plots are without feedforward and the lower plots are with feedforward after commissioning.

distortion is even severer at 19.9 ms, near the extraction, where the accelerating voltage is reduced.

The harmonic components of the gap voltage of cavity #5 with feedforward for the odd harmonics after commissioning are plotted in the lower left in Fig. 2. The odd harmonics components ($h = 1, 3, 5$) of the wake voltage are substantially reduced. After 7 ms, a significant attenuation better than 20 dB for the odd harmonics is achieved with feedforward. The gap voltage waveforms of cavity #5 with feedforward for the odd harmonics at the middle of acceleration (10 ms) and just before extraction (19.9 ms) are plotted in the lower middle and lower right in Fig. 2, respectively. The voltage distortions are reduced with feedforward and the waveforms are much closer to sinusoidal ones.

On can define a figure of merit (FOM), which is derived from the definition of the total harmonic distortion (THD), to characterize the distortion as

$$(\mathrm{FOM}) = \frac{\sqrt{V_{\mathrm{h1}}^2 + V_{\mathrm{h3}}^2 + V_{\mathrm{h4}}^2 + V_{\mathrm{h5}}^2 + V_{\mathrm{h6}}^2}}{V_{\mathrm{h2}}}, \qquad (6)$$

where V_{h2} is the amplitude of the fundamental accelerating harmonic ($h = 2$), and $V_{\mathrm{h1}}, V_{\mathrm{h3}}, V_{\mathrm{h4}}, V_{\mathrm{h5}}, V_{\mathrm{h6}}$ are the components of the harmonics of ($h = 1, 3, 4, 5, 6$) related to distortions. For a pure sine wave, the FOM is zero like the THD. The FOMS from injection to extraction with and without feedforward are compared in Fig. 3. Note that the FOM does not characterize the distortion very well until 5 ms, because the cavity is driven by dual harmonic. After 5 ms, one can clearly see that the FOM is reduced by the feedforward. Without feedforward, the FOMs are 23.7% and 67.9% at 10 ms and 19.9 ms, respectively. The FOMs are greatly improved to 3.9% and 6.3% at 10 ms and 19.9 ms, respectively, with feedforward for the odd harmonics.

Thus, the feedforward system of cavity #5 for the odd harmonics was successfully commissioned by using the commissioning methodology described in the previous subsection.

Due to the limitation of the commissioning time, we did not have enough time to adjust the feedforward patterns for the odd harmonics of all other cavities, #1–4 and #6–12.

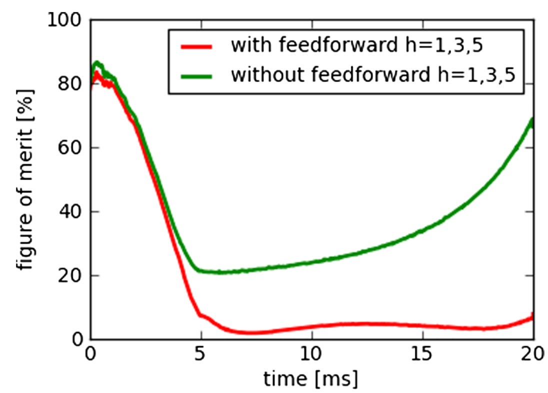

FIG. 3. A comparison of the FOM from injection to extraction with and without feedforward for the odd harmonics. Note that the FOM does not characterize the distortion very well until 5 ms, because the cavity is driven by dual harmonic.

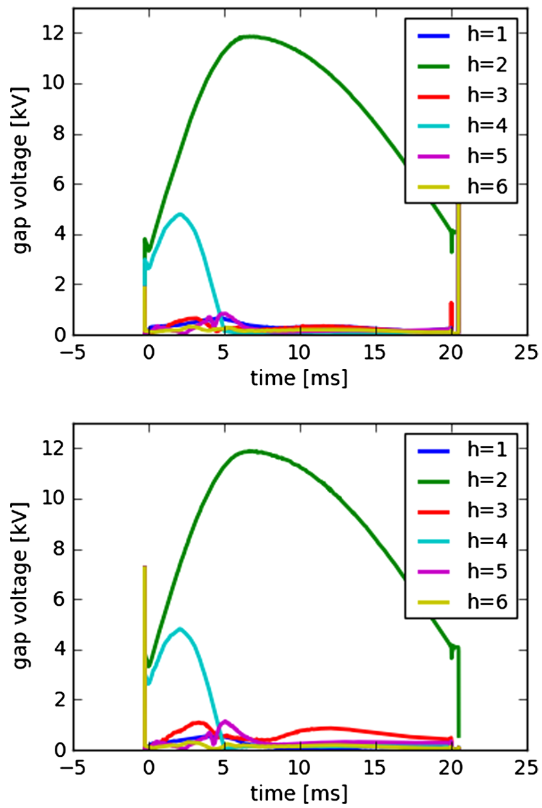

FIG. 4. The harmonic components of the gap voltage of (top) cavity #1 and (bottom) cavity #12 with feedforward for the odd harmonics with the modified phase patterns.

Since the RCS cavity systems have similar impedances and frequency responses, one can consider applying the feedforward patterns of cavity #5 to the other cavities. The gain patterns can be used as is. The phase patterns for the harmonics ($h = 1, 3, 5$) must be shifted according to the cavity position in the ring as follows.

$$\Delta\phi(h,t) = \frac{\Delta s}{(\text{ring circumference})} \cdot 360 \cdot h \text{ [deg]}, \quad (7)$$

where $\Delta\phi(h,t)$ is the phase shift for the harmonic h at the time t, and Δs is the distance from cavity #5. Δs and hence $\Delta\phi(h,t)$ are positive for the upstream cavities (#1–4) and negative for the downstream cavities (#6–12).

The harmonic components of the gap voltage of cavity #1 and #12 with feedforward for the odd harmonics with the modified phase patterns using (7) are plotted in Fig. 4. The suppression of the odd harmonics components of the wake voltage is fairly good in case of cavity #1. One can observe that the ($h = 3$) component remains with feedforward in case of cavity #12, while the ($h = 1, 5$) components are reduced fairly well. This implies that the transfer function of the rf system #12 is slightly different from the other systems, but the limited reduction is still acceptable.

IV. ACHIEVEMENT OF HIGH INTENSITY SINGLE BUNCH OPERATION

The single bunch acceleration test was performed with feedforward for the odd harmonics ($h = 1, 3, 5$). The feedforward patterns for cavity #5 were adjusted by using the commissioning methodology, and the phase shifted patterns were used for the other cavities, as described in the previous section.

The beam intensities from injection to extraction measured by a slow current transformer with and without feedforward are plotted in Fig. 5. A significant intensity loss is observed without feedforward for the odd harmonics from 10 to 13 ms, where the synchronous phase is high and the rf bucket is small. The rf bucket distortion due to the wake voltage of the odd harmonics ($h = 1, 3, 5$) is more critical during this period. Most of such a longitudinal beam loss occurs in the high dispersion area due to large momentum excursions. The beam loss monitor signals near the dispersion peak in the arc section are plotted in Fig. 6, in which a more detailed time structure of beam loss can be observed. Also, the calculated synchrotron frequency without the second harmonic is plotted. As shown in Fig. 6, beam losses already start from 6 ms before the beginning of the major intensity loss observed in Fig. 5. Though the beam loss monitor signal is saturated at 10 ms just after the beginning of the major intensity loss, one can clearly find the oscillation of the beam loss monitor signal until 10 ms, which is related to the synchrotron motion. The synchrotron frequency changes from 3 kHz at 7 ms to 1.9 kHz at 10 ms. There is a clear correlation between the synchrotron frequency and the oscillation period of the loss monitor signal.

With feedforward for the odd harmonics ($h = 1, 3, 5$), no intensity losses are observed and the longitudinal beam losses disappear. The beam loss monitor signals until 5 ms come from transverse beam losses leaked from the beam collimator, but not from longitudinal beam losses.

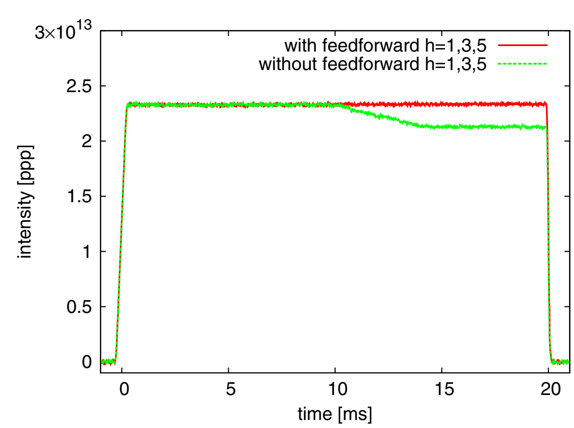

FIG. 5. Beam intensities from injection to extraction with and without feedforward for the odd harmonics.

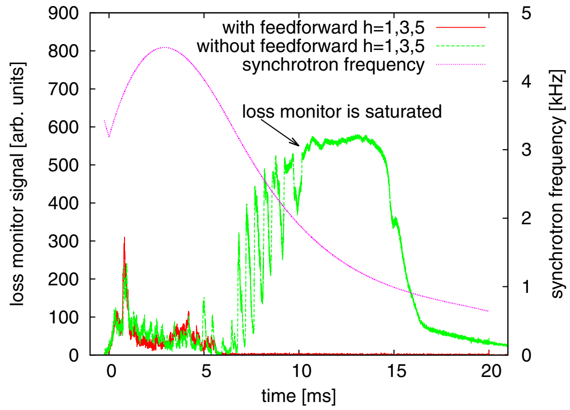

FIG. 6. Beam loss monitor signals near the dispersion peak in the arc section from injection to extraction with and without feedforward for the odd harmonics. The bunch intensity is 2.3×10^{13} ppb. Also, the calculated synchrotron frequency without the second harmonic is plotted.

Thus, high intensity single bunch operation of 2.3×10^{13} ppb, which corresponds to 280 kW at the repetition rate of 25 Hz, was achieved by mitigating the periodic transient effects due to the wake voltage of the odd harmonics ($h = 1, 3, 5$) by feedforward compensation.

Next, we investigate the beam quality of the high intensity single bunch operation.

The bunching factors from injection to extraction in cases of acceleration of single bunch with and without feedforward for the odd harmonics and two bunches are compared in Fig. 7. The bunch intensity is 2.3×10^{13} ppb in both cases, therefore the total intensity is 4.6×10^{13} ppp for acceleration of two bunches. The bunching factors are very similar throughout the accelerating period in cases of acceleration of single bunch with additional feedforward for the odd harmonics and two bunches. In contrast, the bunching factor without feedforward for the odd harmonics shows a significant difference. It means that the bunch

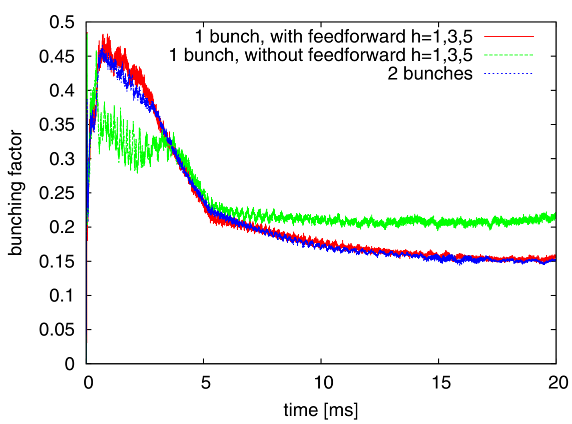

FIG. 7. The bunching factors from injection to extraction in cases of acceleration of a single bunch with and without feedforward for the odd harmonics, and two bunches of 2.3×10^{13} ppb with standard $h = 2, 4, 6$ feedforward.

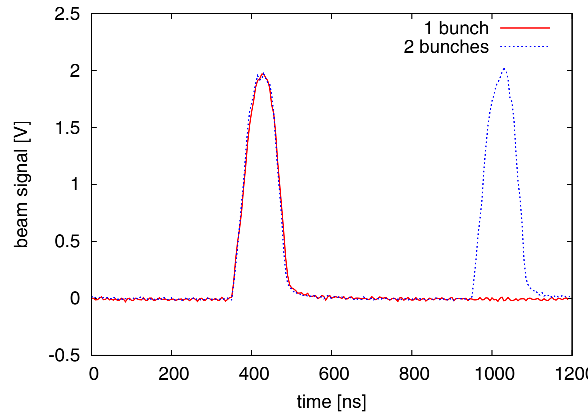

FIG. 8. A comparison of the WCM beam signals just before extraction in cases of acceleration of a single bunch and two bunches of 2.3×10^{13} ppb.

shape is strongly affected by the rf voltage distortion due to the wake voltage of the odd harmonics.

The WCM beam signals just before extraction in cases of acceleration of a single bunch with feedforward for the odd harmonics and two bunches at the bunch intensity of 2.3×10^{13} ppb are compared in Fig. 8. In the plot, negative offsets of the WCM signals due to the AC coupling circuit are removed. One can clearly observe that the bunch shapes in both cases are very similar, almost identical.

These results show that the longitudinal beam quality for the acceleration of a single bunch throughout the cycle is kept similar to the case of two bunches, thanks to the compensation of the odd harmonics.

The main source of the transverse emittance growth and beam losses is the space charge effect, which depends on bunching factors. Since the bunching factors are similar, it is expected that the beam loss ratios are also similar in both cases of acceleration, single bunch or two bunches. The beam loss monitor signals near the primary collimator measured with various bunch intensities of a single bunch and two bunches are plotted in Fig. 9. The bunch intensity is varied from 0.43×10^{13} to 2.3×10^{13} ppb by thinning the number of intermediate pulses while keeping the injection macro pulse of 500 μs [6]. The condition of injection painting [12] and the foil hitting rate [10] during the injection period are not changed by this intensity variation using thinning. For all intensities, the beam loss signals in single bunch acceleration are half of that of two bunches. The beam loss ratio in case of the single bunch acceleration is similar to the case of two bunches.

Transverse beam profiles of extracted beams, measured by a multiwire profile monitor at the beam dump located in the beam transport to the MLF, are plotted in Fig. 10. The bunch intensity is again 2.3×10^{13} ppb. In case of two bunches, the charge density is twice high corresponding to the total beam intensity. In both transverse directions, the profiles are nicely fitted by Gaussian distribution as plotted in the figure. The measured horizontal rms beam widths

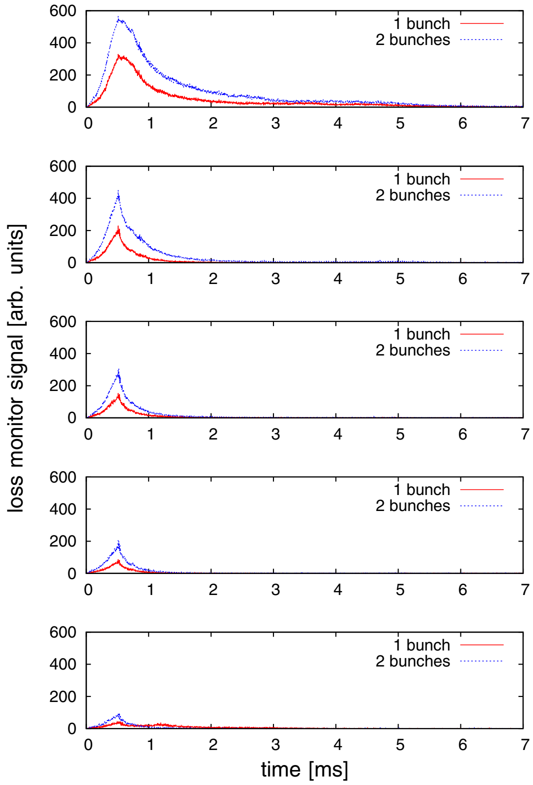

FIG. 9. Comparisons of the beam loss monitor signals near the primary collimator in cases of acceleration of a single bunch and two bunches with various beam intensities. The beam intensities are 2.3×10^{13} ppb, 1.7×10^{13} ppb, 1.3×10^{13} ppb, 0.86×10^{13} ppb, and 0.43×10^{13} ppb, from top to bottom.

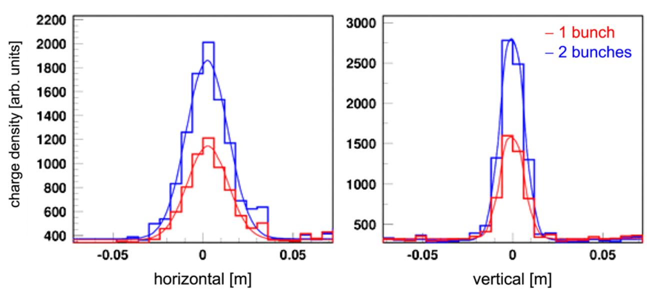

FIG. 10. Transverse beam profiles of extracted beams at the intensity of 2.3×10^{13} ppb, measured by a multiwire profile monitor at the beam dump located in the beam transport to the MLF. Left: horizontal. Right: vertical.

are 11.31 ± 0.16 mm and 11.54 ± 0.10 mm in the cases of acceleration of a single bunch and two bunches, respectively. The vertical widths are 6.27 ± 0.06 mm and 6.33 ± 0.04 mm, respectively. Thus, the beam profiles of the extracted beams are very close in both cases.

All measurements above confirm that the beam qualities in cases of acceleration of a single bunch and two bunches are similar, thanks to the beam loading compensation of the odd harmonics with additional feedforward.

V. CONCLUSION

We summarize the article as follows. (i) For the high intensity single bunch operation of the J-PARC RCS, beam loading compensation of the odd harmonics in addition to the even harmonics is necessary. (ii) An additional feedforward system for the odd harmonics ($h = 1, 3, 5$) was installed. The system has a similar architecture to that of the even harmonics ($h = 2, 4, 6$). (iii) The commissioning methodology of the feedforward used for the even harmonics is applied to the odd harmonics. Commissioning of a system for one of the cavities was successfully performed. The odd harmonic components of the wake voltage in the cavity and the voltage distortions due to the wake voltage were substantially reduced with feedforward. (iv) For other cavities, phase shifted patterns are applied to save the commissioning time. The reductions of the wake voltage in the cavities are fairly good. (v) The longitudinal beam losses, which limited the intensity of the single bunch operation, disappeared with additional feedforward. The beam quality in the single bunch operation is similar to that of acceleration of two bunches.

For acceleration of a single bunch at the designed value, 4.15×10^{13} ppb with linac peak current of 50 mA, the phase shifted pattern might be insufficient. In such case, we consider to adjust the feedforward patterns for all cavity systems. The commissioning of the feedforward system is time-consuming. A few days are expected for commissioning of the feedforward patterns for the even and odd harmonics of twelve cavity systems. However, the digital feedforward system and the high power rf system including the MA cavity are stable for a long period as reported in our previous article [11]; the interval of the setting of the feedforward patterns is expected to be long.

The achieved beam intensity, 2.3×10^{13} ppb, is comparable to the requirement of the COMET phase-II experiment.

The feedforward system for the odd harmonics does not affect the acceleration of two bunches, because the harmonic components of the beam for the odd harmonics are negligibly small with acceleration of two bunches. In the normal two bunch operation, the feedforward for odd harmonics is activated. The rf systems of the J-PARC RCS are now operated with beam loading compensation for six harmonics, $h = 1, 2, 3, 4, 5, 6$.

ACKNOWLEDGMENTS

We would like to thank Professor E. Ezura, Professor K. Takata, and Professor E. Takasaki for fruitful discussions and comments. We also thank the beam commissioning group of the RCS for providing the beam time for commissioning of the feedforward systems. We appreciate the J-PARC writing support group, which continuously encouraged us to write up this article. Also, we would like to thank all the members of the J-PARC.

[1] KEK-Report No. 97-16, 1997.
[2] JAERI-TECH Report No. 2003-044, 2003.
[3] H. Hotchi, Recent progress of J-PARC RCS beam commissioning–toward realizing the 1-MW output beam power, in *International Particle Accelerator Conference 2015 (IPAC 15)* (JACOW, Richmond, VA, 2015), p. 1346.
[4] Y. Kuno, A search for muon-to-electron conversion at J-PARC: The COMET experiment, Prog. Theor. Exp. Phys. (**2013**) 022C01.
[5] K. Kino *et al.*, Energy resolution of pulsed neutron beam provided by the ANNRI beamline at the J-PARC/MLF, Nucl. Instrum. Methods Phys. Res., Sect. A **736**, 66 (2014).
[6] H. Hotchi, Commissioning the 400 MeV linac at J-PARC and high intensity operation of the J-PARC RCS, in *International Particle Accelerator Conference 2014 (IPAC 14)* (JACOW, Dresden, Germany, 2014), p. 899.
[7] A. Schnase *et al.*, MA cavities for J-PARC with con-trolled Q-value by external inductor, in *Proceedings of the 22nd Particle Accelerator Conference, PAC-2007, Albuquerque, NM* (IEEE, New York, 2007), p. 2131.
[8] F. Tamura, A. Schnase, and M. Yoshii, Dual-harmonic auto voltage control for the rapid cycling synchrotron of the Japan Proton Accelerator Research Complex, Phys. Rev. ST Accel. Beams **11**, 072001 (2008).
[9] F. Tamura *et al.*, Longitudinal painting with large amplitude second harmonic rf voltages in the rapid cycling synchrotron of the Japan Proton Accelerator Research Complex, Phys. Rev. ST Accel. Beams **12**, 041001 (2009).
[10] H. Hotchi *et al.*, Beam commissioning and operation of the Japan Proton Accelerator Research Complex 3-GeV rapid cycling synchrotron, Prog. Theor. Exp. Phys. (**2012**) 02B003.
[11] F. Tamura *et al.*, Multiharmonic rf feedforward system for beam loading compensation in wide-band cavities of a rapid cycling synchrotron, Phys. Rev. ST Accel. Beams **14**, 051004 (2011).
[12] H. Hotchi *et al.*, Beam loss reduction by injection painting in the 3-GeV rapid cycling synchrotron of the Japan Proton Accelerator Research Complex, Phys. Rev. ST Accel. Beams **15**, 040402 (2012).