# SHORT-BUNCH EXTRACTION IN J-PARC RCS

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*Abstract*

The 3 GeV Rapid-Cycling Synchrotron (RCS) at J-PARC supplies the proton beam to the Materials and Life Science Experimental Facility (MLF), where it is utilized for the production of secondary particle beams such as muons and neutrons. Secondary particle beams are used in experiments in condensed matter physics, polymer chemistry, biophysics, and other fields. Experiments requiring high time resolution demand an RCS extraction beam with a short-bunch width. The RCS extraction beam is shortened through bunch rotation driven by a manipulation of the fundamental RF voltage. The present study investigated the optimization of this method. In addition, the effectiveness of employing a second harmonic RF voltage in combination was evaluated. Detailed results on short-bunch extraction in the RCS are reported in this presentation.

## INTRODUCTION

The 3 GeV Rapid-Cycling Synchrotron (RCS) at J-PARC accelerates a 400 MeV proton beam up to 3 GeV and delivers a high power proton beam of up to 1 MW to the Materials and Life Science Experimental Facility (MLF) [1, 2]. At MLF, this proton beam produces secondary beams such as neutrons and muons, which serve experiments in materials science, life sciences, and fundamental physics. The time structure of these secondary beams depends strongly on the bunch structure of the proton beam delivered by RCS.

In μSR (muon Spin Rotation/Relaxation/Resonance) experiments, the time evolution of muon spin polarization is measured; therefore, the time width of incident muons (bunch width) directly determines the experimental time resolution [3]. Short-bunch are thus critical for high-resolution time measurements.

To deliver short-bunch beams to MLF, RCS shortens the bunches by manipulating the fundamental RF voltage immediately before beam extraction. RCS operates under the constraint $\Delta p/p < 1\,\%$. Because emittance is conserved, shortening the bunch width increases the momentum spread $\Delta p/p$. Thus, efficient bunch shortening means reducing the bunch width while suppressing the increase in $\Delta p/p$.

The current short-bunch voltage pattern is shown in Fig. 1. The blue line shows the fundamental RF voltage (h = 2) and the red line the second harmonic RF voltage (h = 4). By raising the fundamental voltage to +90 kV after 19.6 ms, the bunch width is reduced. Figure 2 shows beam profiles before and after bunch shortening with 800 kW operation. With the present voltage pattern, the extraction beam for MLF is shortened to about 120 ns.

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The present voltage pattern is not fully optimized and offers potential for further improvement. This study evaluates the effectiveness of superimposing a second harmonic RF voltage for more efficient bunch shortening and verifies its efficacy. The results are presented here.

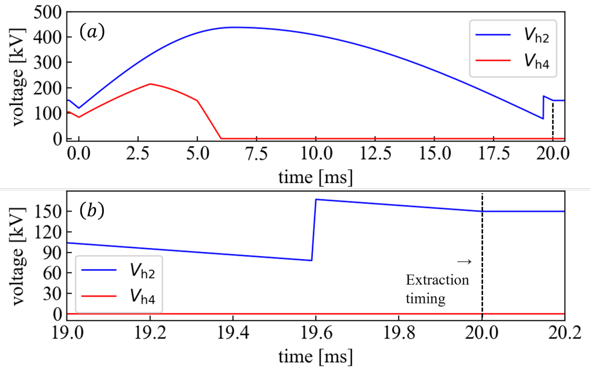


Figure 1: Current short-bunch voltage pattern. The blue line denotes the fundamental RF voltage and the red line the second harmonic RF voltage. The horizontal axis is time; (a) shows the full acceleration period and (b) is an enlarged view just before extraction.

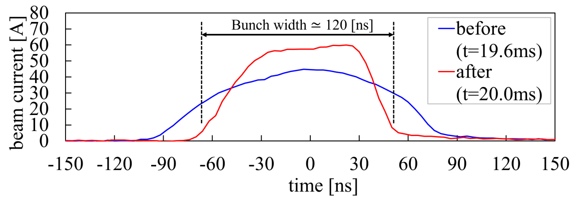


Figure 2: WCM measurements before the bunch shortening operation (blue) and of the shortened extraction beam (red).

## PRELIMINARY SIMULATION WITH A SIMPLIFIED LONGITUDINAL MODEL

To assess the effectiveness of superimposing a second harmonic RF voltage for efficient bunch shortening, a simplified simulation was performed and compared with the case using only the fundamental RF voltage.

### *Construction of Short-Bunch Voltage Pattern*

Table 1 lists the combinations of formulas used to generate the short-bunch voltage patterns for the fundamental only case and for the case with a superimposed second harmonic RF voltage. The parameter $t$ denotes the RCS acceleration time (0–20 ms), while $t_s$ denotes the time at which the voltage manipulation for bunch shortening is initiated. The quantity $V_0$ is the fundamental RF voltage in the pattern without bunch shortening operation. The phase of the second harmonic RF voltage is set as given in the table so that the superposition does not affect the acceleration of the reference-particle. The synchronous phase is denoted by $\varphi_s$. The parameter $A, B$ are a parameter that determines the degree of bunch shortening. The values of $t_s$, $A$ and $B$ were chosen so that the desired bunch width is obtained at the extraction timing (20 ms).

Table 1: Short-bunch Voltage Patterns Used for Bunch Shortening for $t < t_s$ and $t \geq t_s$

| | $\mathbf{t < t_s}$ | $\mathbf{t \geq t_s}$ |
|---|---|---|
| Fundamental only | $V_0 \sin\varphi$ | $AV_0 \sin\varphi$ |
| With 2nd harmonic | $V_0 \sin\varphi$ | $V_0 \sin\varphi$ $+BV_0 \sin 2(\varphi - \varphi_s)$ |

Figure 3 shows the voltage waveforms and the corresponding Hamiltonian contour plots for the following cases, both before bunch shortening ($t < t_s$) and during the bunch-shortening process ($t \geq t_s$). In these plots $\varphi_s = 0$ is assumed. The red line denotes a separatrix.

Increasing the fundamental RF voltage cause the separatrix to expand in the momentum direction. In contrast, when the second harmonic RF voltage is superimposed, the separatrix narrows in the phase direction. Therefore, for identical initial bunch sizes, the separatrix with the superimposed second harmonic RF voltage is expected to experience stronger nonlinear effects.

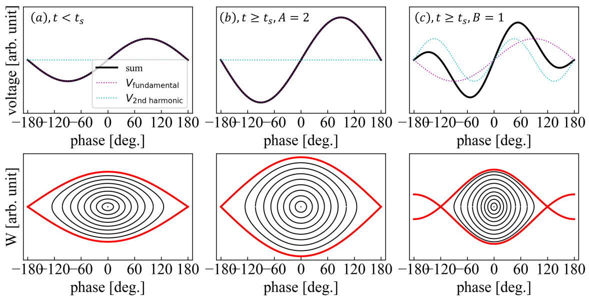


Figure 3: Comparison of voltage waveforms and separatrix shapes during the bunch shortening operation. (a) before the operation, (b) with the fundamental RF only, (c) with the second harmonic RF voltage superimposed.

## Bunch Shortening Simulation

Figure 4 shows the initial bunch normalized to a diameter of 1. The ratio of the bunch area to the separatrix area in the normalized phase space is equivalent to that at J-PARC RCS extraction. Using this initial bunch, the temporal evolution of the bunch shape was simulated for the case with only the fundamental RF voltage and for the case with a superimposed second harmonic RF voltage.

The results are presented in Fig. 5. Time progresses from top to bottom, and each plot shows the bunch shape and its projections onto the momentum axes at successive times. The left column shows the results using the fundamental RF voltage, while the right column shows the results with the second harmonic RF voltage superimposed.

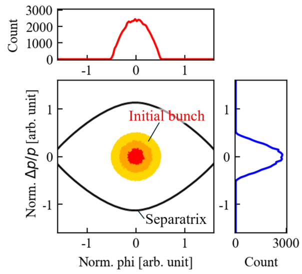


Figure 4: Initial bunch for simplified simulations. Condition $\varphi_s = 0$; the bunch size follows the current RCS extraction beam size. The red and blue lines show projections of the phase and momentum distributions, respectively.

With only the fundamental RF voltage, particles move predominantly in a region where the linear approximation holds; consequently, the phase space contour is largely preserved while the bunch elongates in the momentum direction. When the second harmonic RF voltage is superimposed, some particles experience strong nonlinear effects, producing marked differences in particle trajectories. As a result, the momentum direction projection deforms to a more uniformly broadened profile, and the bunch shape shows nonlinear distortions such as S-shaped curvature at the upper and lower edges. These effects depend on the initial bunch size and become more pronounced for larger initial sizes.

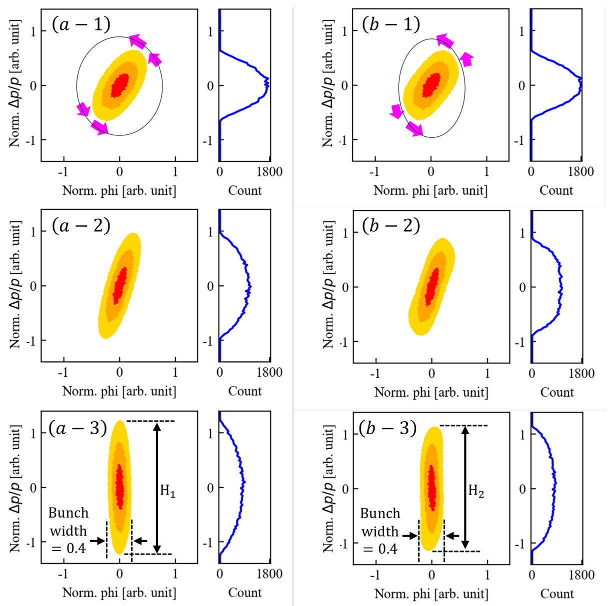


Figure 5: Comparison of the bunch shortening process using the fundamental RF only (left column) and with second harmonic superposition (right column). Time progresses from top to bottom.

Figure 6 shows the reduction rate of the $\Delta p/p$ peak for final bunch widths (0.90, 0.85, 0.80, …, 0.30; 0.05 increments). The reduction rate on the vertical axis was calculated as

$$\Delta p/p \text{ Peak Reduction [\%]} = 100\left(1 - \frac{H_2}{H_1}\right) \quad (1)$$

where $H_1$ denotes the bunch height after bunch shortening using only the fundamental RF voltage, and $H_2$ denotes the bunch height after bunch shortening with the second harmonic RF voltage superimposed. For the same final bunch width, superimposing the second harmonic RF voltage was found to suppress the peak of $\Delta p/p$ by up to approximately 7.5 %, demonstrating more efficient bunch shortening.

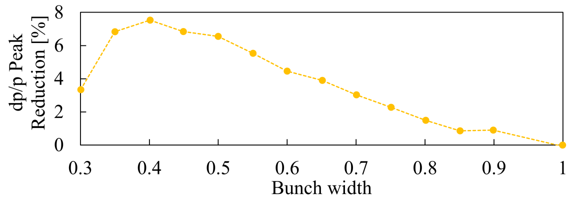


Figure 6: Reduction rate of the $\Delta p/p$ peak for final bunch widths (0.90, 0.85, 0.80, …, 0.30; 0.05 increments).

## APPLICATION TO J-PARC RCS

Longitudinal beam simulations of the RCS, including short-bunch extraction for MLF, were performed using BLonD [4]. The calculation conditions for RCS are listed in Table 2. The method for generating the short-bunch voltage patterns follows the procedure described in subsection "Construction of Short-Bunch Voltage Pattern".

Table 2: RCS Operation Parameters (MLF 800 kW eq.)

| | |
|---|---|
| Linac $\Delta p/p$ offset | -0.15 % |
| $f_{rf}$ offset | -588 Hz (-0.1 %) |
| Intermediated pulse width | 394 ns |
| Macro pulse width | 460 µs |
| Thining | 128/128 |
| harmonic number | 2 |

Figure 7 shows the reduction rate of the peak of $\Delta p/p$ when bunch width at the RCS extraction was varied from 90 to 150 ns. It was confirmed that, for the RCS extraction beam, superimposing the second harmonic RF voltage suppresses the peak of $\Delta p/p$ by up to approximately 10 %.

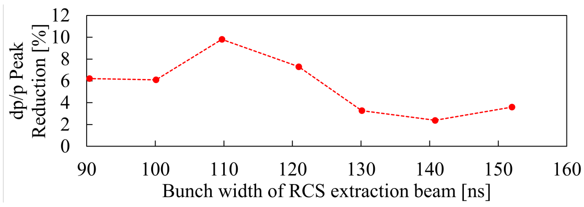


Figure 7: Reduction rate of the $\Delta p/p$ peak for final bunch widths of 150, 140, 130, …, 90 (i.e., 10 ns increments) at RCS extraction.

Figure 8 presents the peak of $\pm\Delta p/p$. It is seen that using only the fundamental RF voltage allows a bunch width of about 100 ns, whereas superimposing the second harmonic RF voltage enables a bunch width of about 95 ns. The corresponding voltage patterns are shown in Fig. 9. The fundamental RF voltage reached up to 300 kV, and the second harmonic RF voltage up to 160 kV.

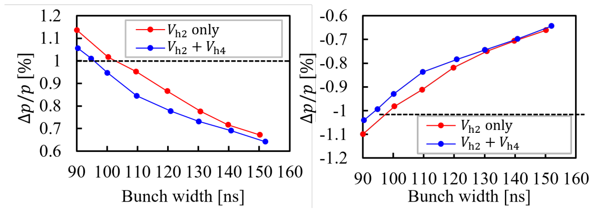


Figure 8: The peak of $\pm\Delta p/p$ for final bunch widths of 150, 140, 130, …, 90 (i.e., 10 ns increments) at RCS extraction.

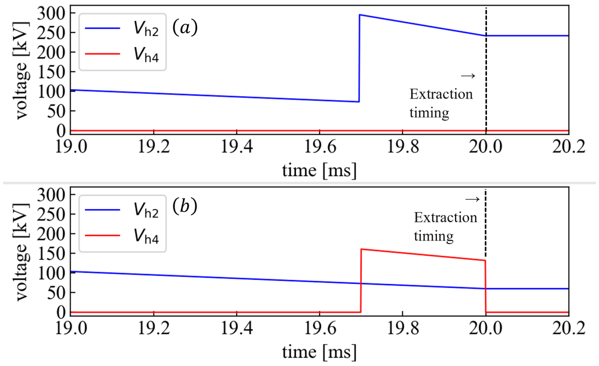


Figure 9: Voltage patterns that minimize the bunch width while keeping the $\pm\Delta p/p$ peak below the limit ($\simeq$ 1 %). (a) fundamental RF only; (b) with second harmonic RF superimposed.

## SUMMARY

The present study investigated a method of combining a second harmonic RF voltage with the fundamental RF voltage to achieve bunch shortening in the J-PARC RCS. Simplified simulations showed that superimposing the second harmonic enhances nonlinear effects during bunch rotation, enabling shorter bunches while broadening the profile of $\Delta p/p$ to a more uniformly. For the same width of the shortened bunch, longitudinal simulations for J-PARC RCS show that second harmonic RF voltage superposition can reduce the $\Delta p/p$ peak by up to 10 %, suggesting improved short-bunch extraction efficiency. Future work will focus on optimizing the voltage patterns and experimentally demonstrating the effectiveness of second harmonic RF voltage superposition.

## REFERENCES


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