

# BUNCH LENGTHENING OF THE EXTRACTION BEAM USING SECOND HARMONIC IN J-PARC RCS

K. Adachi\*, H. Okita, F. Tamura, M. Nomura, T. Shimada, R. Miyakoshi, M. Yoshii, C. Ohmori, K. Seiya, K. Hara, K. Hasegawa and Y. Sugiyama, J-PARC Center, Tokai, Ibaraki, Japan

## Abstract

3GeV Rapid-Cycling Synchrotron (RCS) at J-PARC supplies a high-intensity beam to the Main Ring (MR). Under current operating conditions, there is a longitudinal mismatch between the RCS extraction beam and the MR RF bucket. To improve the RCS-MR longitudinal matching, a method for bunch lengthening of the RCS extraction beam is proposed. The proposed method is based on driving a second harmonic RF voltage just before the beam extraction and the placing the beam at the unstable fixed point (UFP). The consideration of bunch lengthening in RCS is described in this paper. The focus is on optimizing the condition for driving a second harmonic RF voltage. Furthermore, the demonstrations of driving a second harmonic RF voltage and beam experimental results are discussed.

## INTRODUCTION

J-PARC is a high-intensity proton accelerator facility consisting of 400 MeV linear accelerator (LINAC), 3 GeV rapid cycling synchrotron (RCS), and main ring (MR). RCS has achieved stable acceleration of high-intensity beams with a design beam intensity of  $8 \times 10^{13}$  ppp, exhibiting minimal beam loss. RCS provides proton beams for Materials and Life Science Experimental Facility (MLF) and MR. MR is one of the world's most powerful accelerators with a beam intensity of  $2 \times 10^{14}$  protons per pulse (ppp). MR achieved 800 kW user operation in 2024. Upgrade activity is underway to realize further high-intensity beams up to 1.3 MW [1].

In the acceleration of high-intensity proton beams, such as in the MR, mitigation of space charge effects is crucial for reducing beam loss. The bunching factor  $B_f$  is one of the indicators used to evaluate the space charge effect.  $B_f$  is defined as the ratio of the average current to the peak current and takes values from 0 to 1, being equal to 1 in the case of a coasting beam. Increasing  $B_f$  of the beam mitigates space charge effects. Under the current operating conditions,  $B_f$  of the RCS extraction beam is low, which causes beam loss after MR injection.

In order to reduce beam loss at MR, a  $B_f$  increasing method has been proposed [2]. The proposed method in RCS is based on driving a second harmonic RF voltage just before the beam extraction and the placing the beam at the unstable fixed point (UFP). This method lengthens the bunch while keeping the emittance, thereby reducing the peak current and increasing the  $B_f$  just before the beam extraction.

This paper discusses the simulations and experiments conducted to demonstrate the proposed bunch lengthening

method. In addition, the optimization of the bunch lengthening method is also discussed.

## BUNCH LENGTHENING USING SECOND HARMONIC

### Concept

The schematic view of the bunch lengthening method using the UFP generated by second harmonic RF voltage is shown in Fig. 1. The UFP is generated at the bunch center position by superimposing the second harmonic RF voltage ( $V_2$ ) on the fundamental RF voltage ( $V_1$ ). As shown by the red arrows, the beam is stretched in the direction along the contour line around the UFP. After stretching, the beam is rotated while keeping its shape by applying only the fundamental RF voltage.

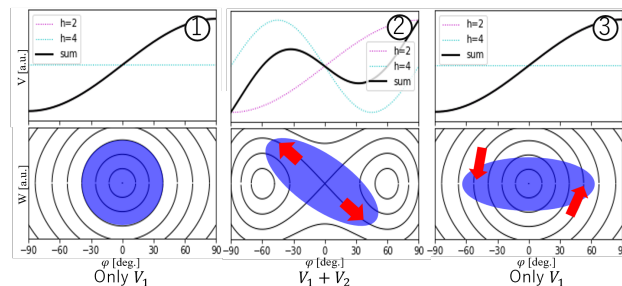


Figure 1: The illustration shows the scheme of bunch lengthening using the UFP. (first row) The fundamental and second harmonic RF voltages, as well as their superimposed voltage waveforms. (second row) Contour lines of the hamiltonian and the direction of bunch shape change.

### Simulation

The purpose of the simulations in this study is to investigate the applicability of the bunch lengthening to RCS extraction beam. The simulations were executed using BLoND (Beam Longitudinal Dynamics), a longitudinal beam simulation code developed at CERN [3]. The simulation conditions are listed in Table 1. A low-intensity beam was used to neglect the influence of the collective effect.

The acceleration pattern of RCS RF voltages is shown in Fig. 2. Figure 2 on the right shows the pattern of the second harmonic RF voltage that is driven to generate the UFP, hereafter referred to as the UFP pattern. The timing of the beam extraction was set to 15450 turns, and the timing to apply the second harmonic RF voltage is chosen so that a lengthy beam is formed at 15450 turns. The parameters are shown in Table 2.

\* kyosuke.adachi@j-parc.jp

Table 1: Simulation Conditions based on RCS Operation Parameters

Intermediated pulse width	456 ns
Macro pulse width	400 $\mu$ s
Thinning	32/128
$f_{rf}$ offset(injection/extraction)	0.0 % / 0.0 %
Linac momentum offset	-0.15 %

The results are shown in Fig. 3.  $B_f$  increased from less than 0.2 to about 0.4. Figure 3 on the right shows bunch shape at 15450 turns. The vertical axis show momentum spread ( $\Delta p/p$ ) and the horizontal axis shows phase ( $\phi$ ). It is shown that the bunch shape of RCS extraction beam becomes longer by the proposed methods from results of simulation.

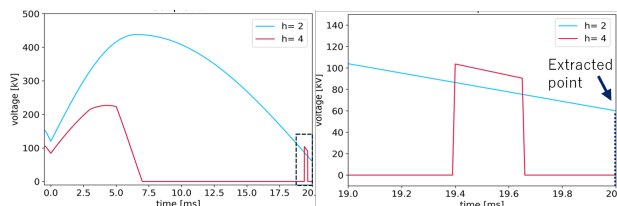


Figure 2: The left graph shows the acceleration pattern in which the second harmonic RF voltage is applied at the end of the acceleration. The right graph shows an expanded view of left graph.

Table 2: Parameters of the UFP Pattern

Time	19.4 - 19.65 ms
Ratio ( $V_2/V_1$ )	1.2
Rise and fall time	0.01 ms

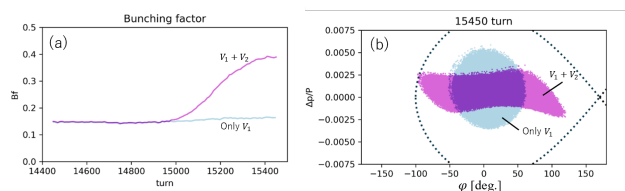


Figure 3: The comparison of the  $B_f$  (left) and bunch shape (right) with and without application of the second harmonic RF voltage.

### Experimental Demonstration

The beam experiments are carried out using the operating parameters shown in Table 1 and the UFP pattern shown in Fig 2. The experimental results are shown in Fig. 4 for the mountain plot,  $B_f$  and beam profiles (at 15000 and 15450 turns). Simulation results for same conditions are also shown for comparison. The experimental results demonstrate the feasibility of bunch lengthening using the second harmonic RF voltage.

Measured voltages generated in the RF cavity are shown in Fig. 5. It has been ascertained that the timing and amplitude of generated second harmonic RF voltage are as programmed. Some distortion of the voltage waveform was observed during the rise and fall periods. This distortion shortens the effective lengthening time due to the UFP, decreasing the bunching factor by few percent. The decrease is negligible compared to the increase caused by bunch lengthening method.

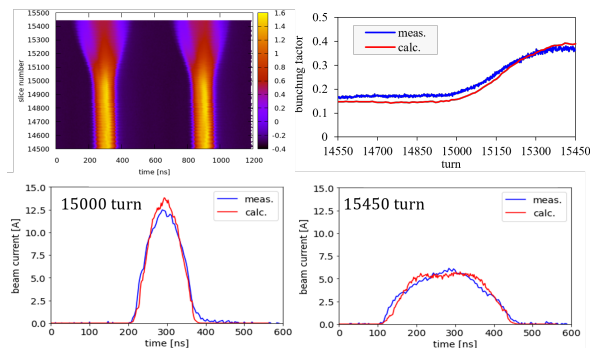


Figure 4: The upper left graph is a mountain plot of the experimental results. The comparison of simulated and experimental results for  $B_f$  (top right) and beam profiles (bottom left: 15000 turns before application of the second harmonic RF voltage, bottom right: 15450 turns at the extraction position).

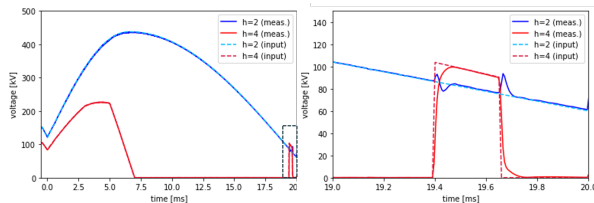


Figure 5: The comparison of the measured voltage generated in the RF cavity with the acceleration pattern. The right graph shows the UFP pattern, an expanded view of left graph.

## SHAPE OPTIMIZATION

### Concept

As shown in Fig. 3, the phase space distribution lengthened by the second harmonic RF voltage has a shape similar to a parallelogram. The sharp corners of the parallelogram distribution are predicted to induce filamentation in MR.

The formation of parallelograms is in the process of bunch rotation, as shown on the right side of Fig. 1. This is caused by the difference in the angular velocity and direction of rotation. In order to eliminate the sharp corners, the UFP pattern is investigated in which the second harmonic RF voltage is applied again. The concept is shown in Fig. 6. This idea is that the twice application of the second harmonic RF voltage will change the formation process, thus eliminating the acute angles.

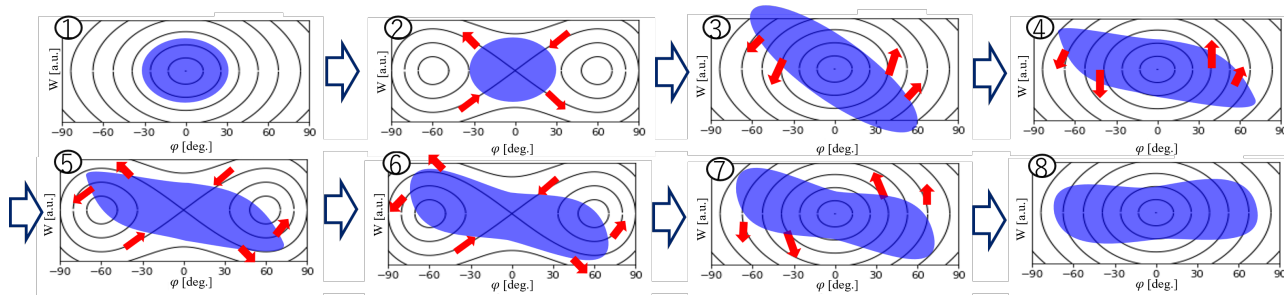


Figure 6: The schematic view of the change in bunch shape when second harmonic RF voltage are applied twice. The process is repeated twice: stretching by the UFP generated by second harmonic RF voltage and rotation by fundamental RF voltage.

### Parameter Optimization

When the second harmonic RF voltage is applied twice, determining the UFP pattern of the second harmonic RF voltages becomes difficult. Therefore, nonlinear least-squares method, one of the numerical optimization methods, is used to determine the UFP pattern.

An error function is set based on the six geometric parameters ( $\Delta_1, \Delta_2, \dots, \Delta_6$ ). The six geometric parameters are shown in Fig. 7 on the (a). From the  $\varphi$ -coordinates of the intersection of two lines parallel to the  $\varphi$ -axis, which pass through the point  $\pm\Delta p/p$  and the bunch contour line, the following quantities are obtained:  $\Delta_1$ , defined as the distance between the  $\varphi$ -coordinates of the intersection of the first and fourth quadrants; and  $\Delta_2$ , defined as the distance between the  $\varphi$ -coordinates of the intersection of the second and third quadrants.  $\Delta_3$ , define as the difference in the lengths of the two line segments. By replacing  $\Delta p/p$  and  $\varphi$  we get  $\Delta_{4,5,6}$ . In the six geometric parameters ( $\Delta_1, \Delta_2, \dots, \Delta_6$ ), if zero, the bunch shape is circumscribed by two rectangles, as shown in Fig. 7 on the (b).

The bunch of the extracted beam was calculated by BLonD and this was incorporated into the numerical optimization routine. The least\_square function from Scipy, Python's scientific computing library, was utilized [4].

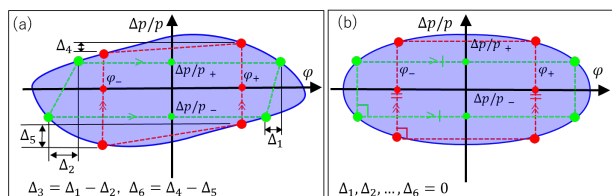


Figure 7: Geometric parameters of the extracted bunch targeted for optimization. (a) shows before and (b) after optimization.

### Shape Optimization Results

The result of optimization are shown in Table 3. The UFP pattern determined by the least squares method and bunch shape of extraction beam are shown in Fig. 8. The driving of the second harmonic RF voltage on twice resulted in the formation of bunches without sharp edges. Moreover,

it has been shown that the UFP pattern can be determined by a parameter optimization method using the least squares method.

Table 3: Parameters of the UFP Pattern determined by the Least Squares Method

Time (a)	19.31 - 19.56 ms
Time (b)	19.83 - 19.93 ms
Ratio (a) ( $V_2/V_1$ )	0.92
Ratio (b) ( $V_2/V_1$ )	0.79
Rise and fall time ((a) and (b))	0.01 ms

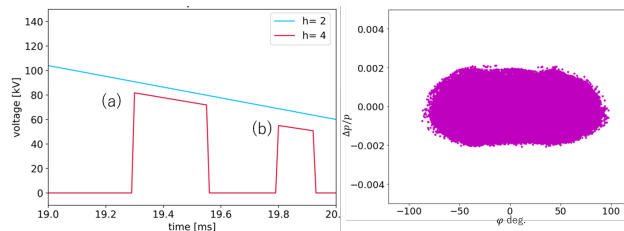


Figure 8: The left graph shows the UFP pattern in which second harmonic RF voltages are applied twice. The right graph shows a bunch shape of the optimized extraction beam.

## CONCLUSION

In order to improve the longitudinal beam matching between RCS and MR at J-PARC, the method was proposed to bunch lengthening of the RCS extraction beam by using the UFP generated by the second harmonic RF voltage driven just before the beam extraction. The bunch shape can be lengthened using the UFP at RCS is confirmed from the simulation and experimental demonstration results, and the proposed method has been demonstrated. Furthermore, it was suggested that applying the second harmonic RF voltage on twice can form the lengthen bunch that better matches the MR RF bucket. In the future, the effects of the generated voltage, which was not considered in this simulation, will be investigated. Additionally, the beam experiment to be injected into MR will be studied.

## REFERENCES

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