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Consideration for improving the longitudinal beam matching between RCS and MR at the J-PARC

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Abstract. The J-PARC 3 GeV Rapid-Cycling Synchrotron (RCS) delivers a high intensity proton beam to the 30 GeV Main Ring (MR). The improvement of longitudinal beam matching between RCS and MR is desired to suppress the beam loss in the MR. A scenario to improve the longitudinal beam matching between RCS and MR is designed. For the RCS, the bunch lengthening scheme using the unstable fixed point generated by the second harmonic is considered. For the MR, the RF voltage pattern is adjusted to match the longitudinal beam emittance of the RCS. The details of the scenario for improving the longitudinal beam matching between RCS and MR and the results of beam simulation studies are reported.

1 INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) has two high intensity proton synchrotrons: 3 GeV Rapid Cycling Synchrotron (RCS)[1, 2] and Main Ring (MR)[3]. RCS delivers 3 GeV proton beam to MR. MR accelerates the proton beam from 3 GeV to 30 GeV. One of the operation modes of MR is the fast extraction (FX) for the neutrino experimental facility. MR has achieved the design beam power of FX mode of 750 kW, and plans to upgrade the beam power toward 1.3 MW[4].

The space charge effect (SC) is a significant issue to cause the beam loss in MR[5]. The SC becomes pronounced when the bunching factor (BF) is low. In the current MR FX mode, the BF of MR (BF_{MR}) reaches low values at specific timings immediately after injection, during which beam loss occurs. Initially, the BF_{MR} at the injection point is low of 0.2, since the bunch shape of the extraction beam from RCS is not flat. After the injection, the BF_{MR} oscillates and degrades transiently due to the longitudinal beam mismatch between RCS and MR[6]. To reduce the beam loss in MR immediately after injection, it is required to flatten the RCS extraction beam and to improve the matching.

In this study, a scenario to improve the longitudinal beam matching between RCS and MR is designed, aiming to increase the BF_{MR}. For RCS, a longitudinal beam manipulation technique is considered to flatten the extraction beam distribution that matches the dual harmonic RF bucket of MR. For MR, the dual harmonic RF voltage pattern is adjusted to accommodate the flattened beam from RCS.

By optimizing the RF gymnastics for both RCS and MR, results of longitudinal beam tracking simulations show that the BF_{MR} can be increased to 0.4 without significant oscillations. The details of scenario for improving the longitudinal beam matching between RCS and MR, and the results of beam simulation studies are described.

2 Mismatch between RCS and MR

The primary parameters of RCS and MR at MR 800 kW FX mode are listed in Table 1. Hereafter, all discussions refer to MR 800 kW FX mode. The RF voltage patterns of RCS and MR are shown in Fig. 1. Both RCS and MR employ the dual harmonic operation using the fundamental and second harmonic at the beginning of acceleration to alleviate the SC. The fundamental and second harmonic RF voltages are denoted as V_{h2} and V_{h4} for RCS, and as V_{h9} and V_{h18} for MR, respectively. RCS extracts 3 GeV beam at 20 ms. The latter part of acceleration in RCS is the single harmonic operation using only $V_{\rm h2}$. For MR, the beam is injected four times from RCS between 10 ms and 130 ms. During the injection period of MR, the dual harmonic operation is applied. $V_{\rm h9}$ and $V_{\rm h18}$ during the injection are constant at 140 kV and 110 kV, respectively. Acceleration up to 30 GeV is carried out from 140 ms to 790 ms.

Table 1: Parameters of RCS and MR at MR 800 kW FX Mode

	RCS	**MR**
Proton Energy [GeV]	0.4–3	3–30
Repetition Period [s]	0.04	1.36
Intensity [ppp]	5.6E+13	2.2E+14
# of Bunches	2	8
Harmonic Number h	2	9

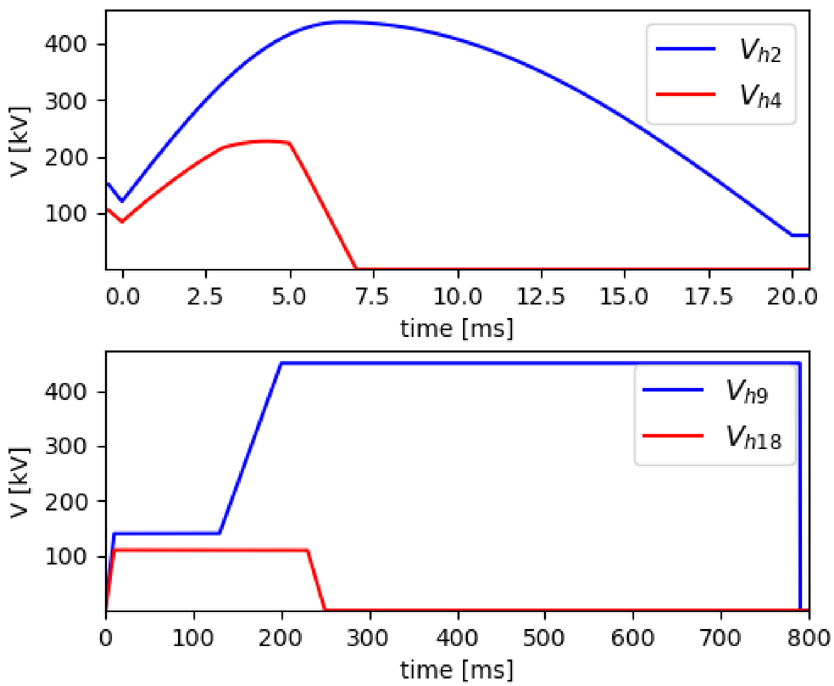

Figure 1: RF voltage patterns of RCS (top) and MR (bottom) in the current MR 800 kW FX mode.

The current MR FX operation has a longitudinal beam mismatch between RCS and MR. Figure 2 is the longitudinal phase space distribution of the injection beam into MR, i.e., the extraction beam from RCS. The RF bucket and contour lines in Fig. 2 are for MR. The distribution was measured by the tomography[7]. The longitudinal phase space distribution of extracted beam from RCS and RF bucket shape of MR are completely mismatched as shown in Fig. 2.

The measured $\rm BF_{MR}$ after the injection is shown in Fig. 3. The initial $\rm BF_{MR}$ is quite low of 0.2. This is because the latter part of acceleration in RCS is the single harmonic, and the beam width is shrunk due to the adiabatic damping through the acceleration in RCS. Until 1500 turns, the $\rm BF_{MR}$ oscillates in the process that the mismatched beam is diluted in the dual harmonic RF bucket. After 1500 turns, the

BF_{MR} settles around 0.35. In general, the dual harmonic operation with the synchronous phase ϕ_s of 0 deg., as is the case during the MR injection period, can achieve the BF of 0.4.

This study aims to both reduce the oscillation in BF_{MR} and increase the BF_{MR} by improving the matching between the RCS and MR. To improve the matching, for RCS side, the extraction beam needs to be flattened and shaped to fit into the dual harmonic RF bucket of MR. For MR side, the shape and area of the dual harmonic RF bucket need to be adjusted to match the flattened RCS beam.

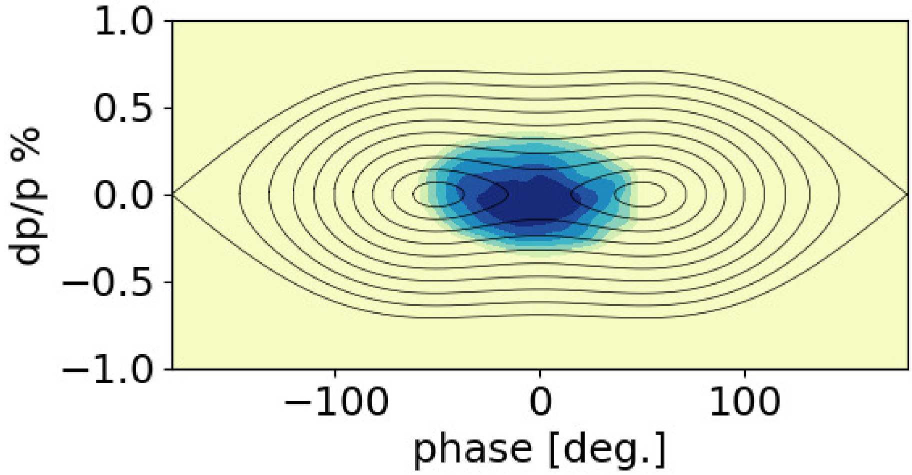

Figure 2: The measured phase space distribution of injection beam of MR at 800 kW FX mode. The RF bucket shape and contour lines are for MR.

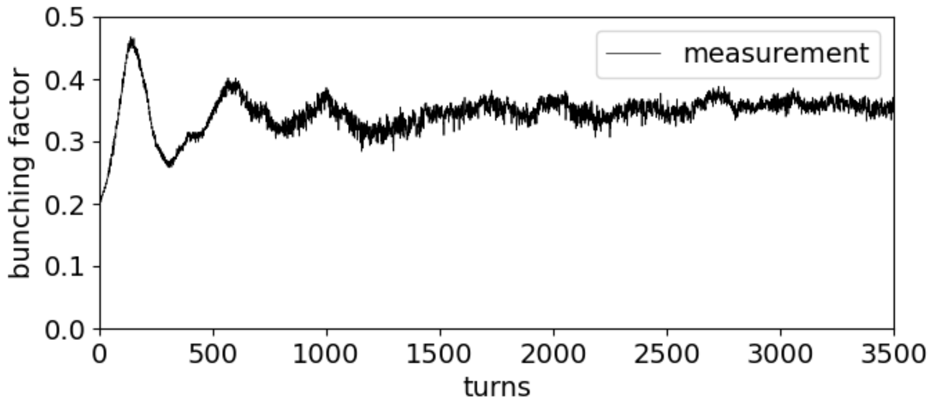

Figure 3: The measured BF_{MR} after the injection at 800 kW FX mode.

3 RF gymnastics of RCS

A task of RCS is to flatten and shape the extraction beam to fit into the dual harmonic RF bucket of MR. A typical method for flattening the extraction beam is to apply the dual harmonic at the latter part of acceleration. In this method, the RF voltage waveform around ϕ_s is smoothed out, and stretch the beam with the adiabatic process. However, this method is not effective for RCS. Figure 4 is the behavior of the slippage factor η, ϕ_s and synchrotoron oscillation period T_{syn} during the acceleration in RCS. Since η approaches zero toward the end of acceleration, the synchrotron oscillation period becomes beyond 1000 turns, which is very slow compared to the entire RCS acceleration period of 15500 turns. Additionally, the variations in ϕ_s is fast after 12000 turns. Within a few synchrotron oscillation cycles, ϕ_s changes approximately 40 deg. Thus, the latter part of acceleration in RCS is quite severe condition to introduce adiabatic longitudinal beam manipulations.

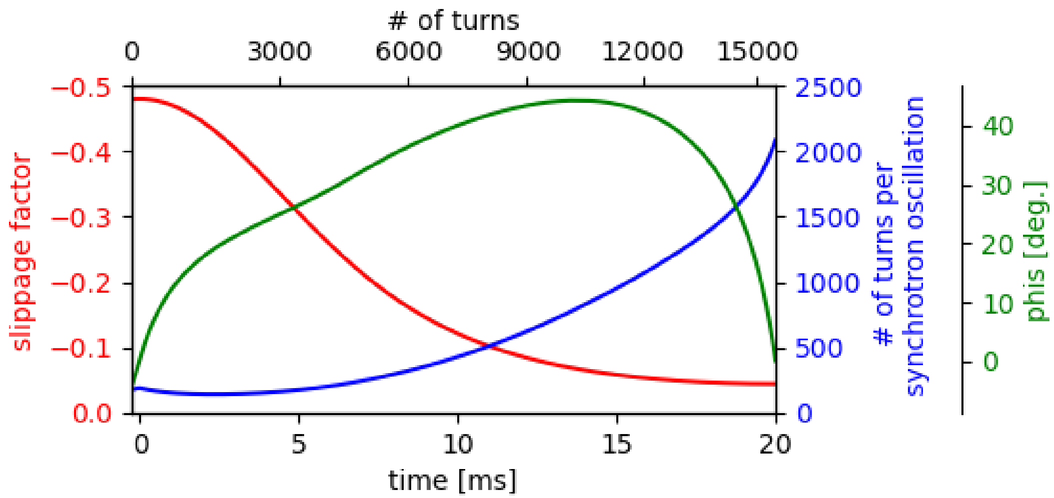

Figure 4: The variations in η, ϕ_s, and T_{syn} in RCS.

In this study, a beam manipulation technique using the unstable fixed point (UFP) is considered. The advantage of this scheme is that can stretch the beam with the nonadiabatic process using where the RF voltage waveform has a large gradient. Hence, the beam can be flattened in a short period even under low η conditions.

We use the second harmonic V_{h4} to generate the UFP. For RCS, the manipulation using the UFP must be performed where $\phi_s \neq 0$ deg. as shown in Fig. 4. Where $\phi_s \neq 0$ deg., the RF bucket shape has an asymmetry around the UFP. The asymmetry around the UFP can be adjusted by using the second harmonic phase. In addition, the shorter wavelength of second harmonic allows for finer deformation of the phase space distribution. The experimental demonstration and optimization studies of the UFP manipulation using the second harmonic in RCS are reported in [8].

Here, we describe an example of the UFP manipulation in RCS. The designed RF voltage pattern of RCS introducing the UFP manipulation is shown in Fig. 5. V_{h4} is turned on from 19.475 ms to 19.825 ms to generate the UFP. The second harmonic phase is set to $\pi - 2\phi_s$. The ratio of V_{h4}/V_{h2} is constant at 1.2. After V_{h4} is turned off, V_{h2} is raised up to 150 kV to reduce the variations in ϕ_s.

Simulated phase space distributions during the UFP manipulation using the designed RF voltage pattern shown in Fig. 5 are depicted in Fig. 6. The initial conditions and machine parameters used in the simulation are the same as the actual MR FX 800 kW mode. As shown in Fig. 6, through the UFP manipulation, the bunch shape is finally flattened at the extraction timing. The BF of RCS (BF_{RCS}) can be increased from 0.2 to 0.4 at the extraction timing.

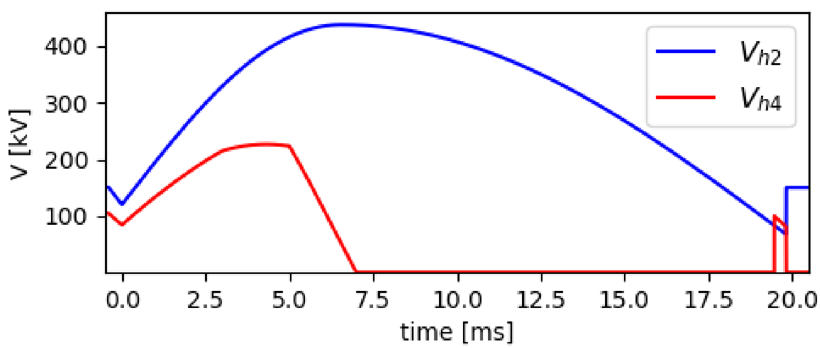

Figure 5: The designed RF voltage pattern of RCS introducing the UFP manipulation.

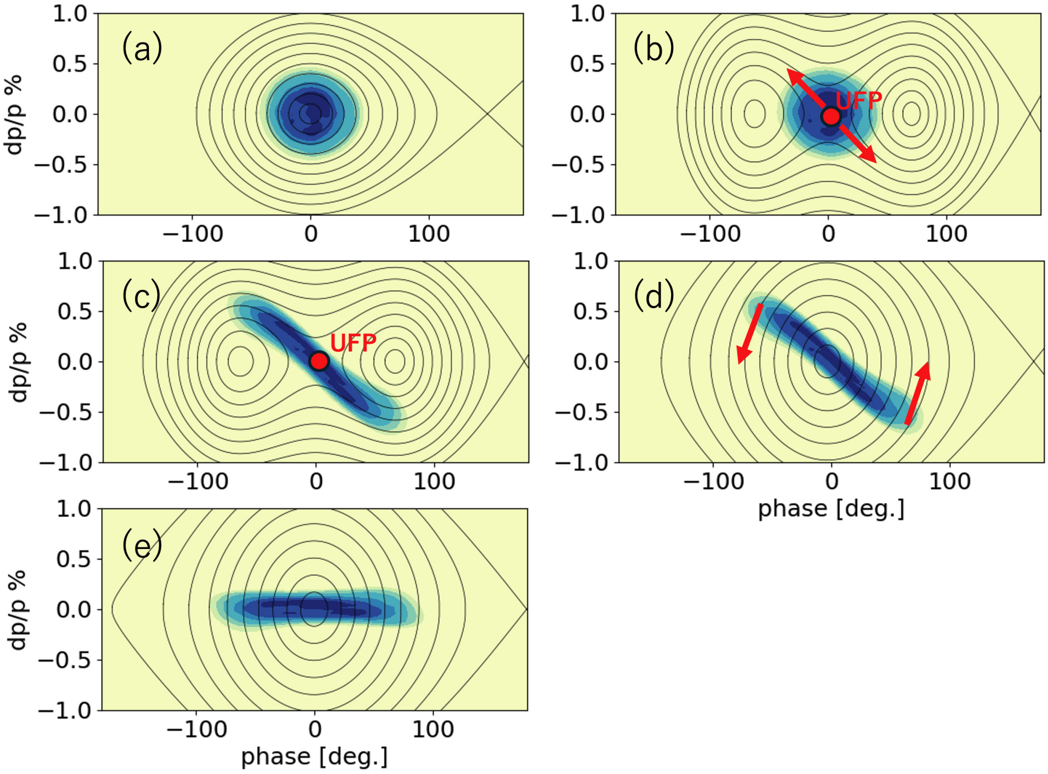

Figure 6: The change of phase space distribution during the UFP manipulation in RCS. (a) Before the UFP manipulation. (b) After turning on V_{h4}. (c) Before turning off V_{h4}. (d) After turning off V_{h4}. (e) Distribution at the extraction timing.

4 RF gymnastics of MR

A task of MR is to adjust the shape and area of the dual harmonic RF bucket to accommodate the RCS beam flattened by the UFP manipulation. The area of dual harmonic RF bucket of MR formed during the injection is large compared to the RCS beam, which has an emittance of 5 eVs. In the dual harmonic RF bucket of the MR, the area corresponding to the momentum filling factor (MF) of 0.8 is 15 eVs. Hence, the dual harmonic RF voltage of the MR should be lowered.

Note that lowering the RF voltage increases ϕ_{s} during acceleration of MR, and the effect of beam loading should be considered. $d\phi_{\mathrm{s}}/dt$ also increases, and a filamentation of longitudinal phase space distribution may occur. In addition, a decrease of longitudinal focusing force with respect to the longitudinal SC is also a concern.

In this study, V_{h9} and V_{h18} at the injection are reduced to 59 kV and 48 kV, respectively. In the dual harmonic RF bucket generated by the lowered RF voltage, the area corresponding to MF of 0.8 is reduced to 10 eVs. This voltage is set with a margin to avoid the negative influence described above. Figure 7 is generated dual harmonic RF bucket of MR with V_{h9} =59 kV and V_{h18} =48 kV. The simulated longitudinal phase space distribution flattened by the UFP manipulation in RCS is also depicted in Fig. 7. Compared to the current FX operating condition shown in Fig. 2, the matching between the RF bucket shape and longitudinal phase space distribution is clearly improved.

The simulated $\mathrm{BF}_{\mathrm{MR}}$ is shown in Fig. 8. For reference, the simulation result using the current 800 kW FX mode is also shown. The simulation reproduces the measured $\mathrm{BF}_{\mathrm{MR}}$ well and is reliable. The red line in Fig. 8 is the simulation result using the flattened distribution by the UFP manipulation and the lowered dual harmonic RF voltage pattern of MR. The $\mathrm{BF}_{\mathrm{MR}}$ of improving the matching between RCS and MR can be increased to 0.4 without significant oscillations. Simulation studies show that the occurrence of filamentation and longitudinal SC in MR are negligible even with lowered dual harmonic RF voltage pattern. The results of this study indicate that the designed scenario to improve the matching between RCS and MR is feasible. Beam simulation studies suggest that increasing the $\mathrm{BF}_{\mathrm{MR}}$ to 0.4 can almost completely eliminate the beam loss currently caused immediately after injection.

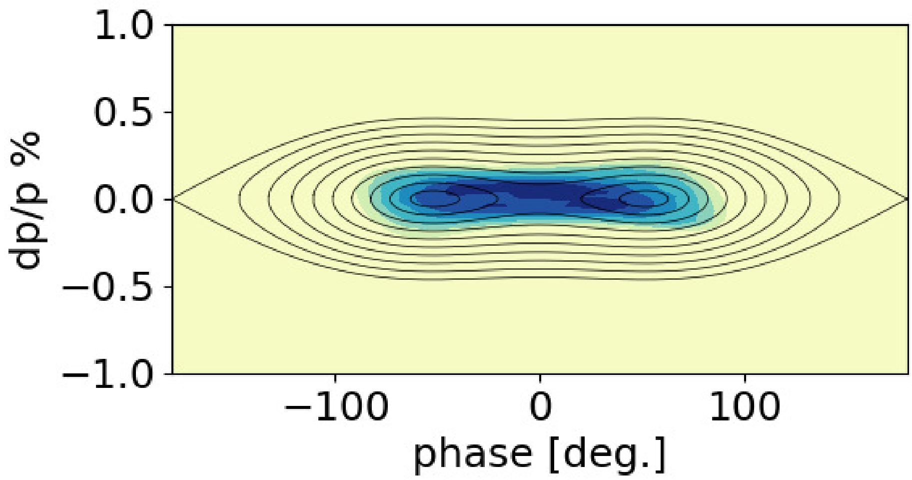

Figure 7: RF bucket and injection beam distribution of MR after improving the matching between RCS and MR. The dual harmonic RF bucket shape of MR is at $V_{\mathrm{h9}} = 59$ kV and $V_{\mathrm{h18}} = 48$ kV. The beam distribution is the result of the UFP manipulation in RCS.

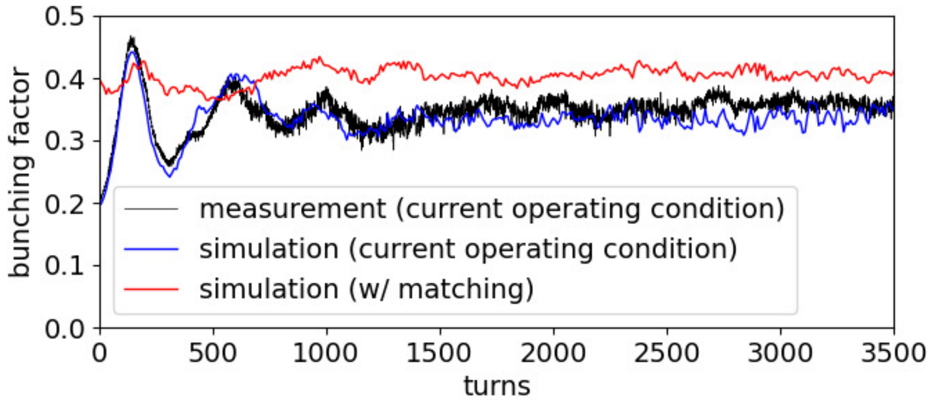

Figure 8: The $\mathrm{BF_{MR}}$ after improving the matching.

5 Summary

In this study, we design the scenario to improve the longitudinal beam matching between RCS and MR for the purpose of increasing the $\mathrm{BF_{MR}}$ and of reducing the beam loss in MR. For RCS, the bunch flattening scheme using the UFP is considered, and the $\mathrm{BF_{RCS}}$ of extraction beam can be increased from 0.2 to 0.4. For MR, the shape and area of the dual harmonic RF bucket is adjusted to accommodate the flattened RCS beam by the UFP manipulation. Consequently, the matching between RCS and MR is improved, and the $\mathrm{BF_{MR}}$ is increased to 0.4 without significant degradations.

We have been demonstrating the proposed method with beam experiments. For RCS side, the beam experiment applying the UFP manipulation has been carried out, and demonstrated that the extraction beam is flattened as expected[8]. In parallel, the microwave instability and beam loading in MR under improved matching conditions will be discussed.

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