SIMULATION OF LONGITUDINAL EMITTANCE CONTROL IN J-PARC RCS FOR 400 MEV INJECTION

M. Yamamoto*, M. Nomura, A. Schnase, T. Shimada, F. Tamura
Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, JAPAN
E. Ezura, K. Hara, K. Hasegawa, C. Ohmori, A. Takagi, K. Takata, M. Toda, M. Yoshii
KEK, Tsukuba, Ibaraki 305-0801, JAPAN

Abstract

The injection energy upgrade of the J-PARC RCS from 181 MeV to 400 MeV is scheduled, this is necessary to achieve the design beam intensity. The high intensity beam is delivered to the MR, and the space charge effect at the MR injection should be alleviated by optimizing the longitudinal beam emittance at RCS extraction. This is realized by matching the shape of the beam emittance between the RCS and the MR. We describe the results of particle tracking simulation with the longitudinal emittance control.

INTRODUCTION

The beam commissioning and the beam delivery to the Material and Life science Facility (MLF) and the Main Ring (MR) have been progressing at the J-PARC Rapid Cycling Synchrotron (RCS) [1, 2]. The present injection energy is 181 MeV, the number of particles 1.7×10^{13} ppp is delivered for the MLF and 2.5×10^{13} ppp is delivered for the MR.

The injection energy upgrade from 181 MeV to 400 MeV is scheduled in 2013 to alleviate the space charge effect, the design beam power of 1 MW (8.3×10^{13} ppp) will be achieved. The parameters of the RCS in 400 MeV injection are listed in Table 1.

Injection energy	400 MeV
Extraction energy	3 GeV
Number of particles	8.3×10^{13} ppp
Harmonic number	2
Repetition rate	25 Hz
Acceleration period	20 ms
RF Frequency range	1.228∼1.672 MHz
Momentum compaction factor	0.0119798

Table 1: The parameters of the J-PARC RCS at 400 MeV injection.

Adding the second harmonic rf with a momentum offset and a phase sweep techniques [3] is adopted to alleviate the space charge effect at the RCS injection. Furthermore, the longitudinal beam emittance should be controlled at the RCS extraction to make the bunching factor high enough at the MR injection. Adding the second harmonic rf is also adopted for such purpose at the RCS extraction.

We have to take care not only of the bunch shape but also of the shape of the longitudinal beam emittance. If the emittance shape at the RCS extraction is distorted, even though the bunching factor is high enough, it is very difficult to find an appropriate MR rf bucket to capture the emittance smoothly. The bunching factor becomes worse in the MR before the emittance is diluted by the MR rf bucket.

We have investigated the longitudinal beam emittance control at the RCS extraction to find matching conditions for the MR injection by a particle tracking code.

BASIC ACCELERATION PATTERN

The acceleration voltage pattern of the fundamental harmonic rf is basically chosen to preserve the longitudinal beam emittance during the whole RCS acceleration period while keeping the momentum filling factor constant [4].

Since the multi-turn injection scheme is used in the RCS, the emittance is formed during the injection. Once the emittance is confirmed at the end of the injection, it is conserved if the changing rate of the rf voltages is adiabatic [5]. We set the target value of the emittance at 5 eVs and the momentum filling factor at 82 %. The calculation results of the acceleration pattern are shown in Fig. 1.

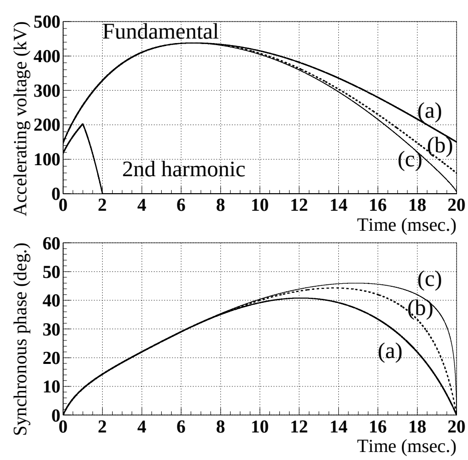

Figure 1: The accelerating voltage pattern and the synchronous phase. (a) The thick line shows the case that the extraction voltage is 150 kV, and (b) the dotted line shows the case that the extraction voltage is 60 kV. (c) The thin line shows the pattern that the emittance and the momentum filling factor is always constant.

The initial condition of the injected beam from the Linac

* masanobu.yamamoto@j-parc.jp

is that the chopping width is 435 ns and the momentum spread is ± 0.05 %. The Linac beam is injected into the RCS in 306 turns.

The thin line (c) in Fig. 1 shows the pattern that the emittance and the momentum filling factor are always constant over the whole acceleration period. In this case, the extraction voltage becomes very low, and an adiabaticity is broken near the extraction [5]. It is considered that unwanted emittance blow up occurs, and it results in the beam loss. The thick line (a) shows the case that the extraction voltage is set as 150 kV; we can avoid the beam loss by setting the extraction voltage high. The dotted line (b) shows the case that the extraction voltage is set as 60 kV to make the bunch flat at the extraction.

Without the beam loading and the space charge effect, the emittance shape is matched to the RCS rf bucket for the cases (a) and (b), they can be captured by the MR rf bucket which has same bucket height as the RCS one.

However, the beam loading and the space charge effects deform the rf bucket, and the emittance is also distorted. Figs. 2 and 3 show the simulation results with the beam loading and the space charge effect. The number of particles is 5.0×10^{13} ppp (600 kW equivalent beam) for the MR injection, and the beam loading effects up to second harmonic components are compensated by a feedforward method [6]. In these cases, we try to find the MR rf bucket to match the RCS emittance.

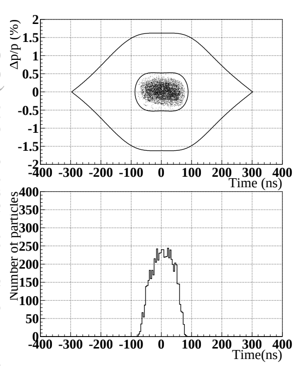

Figure 2: The phase space and the bunch shape at the RCS extraction with beam loading and space charge effect in the case that the extraction voltage is 150 kV.

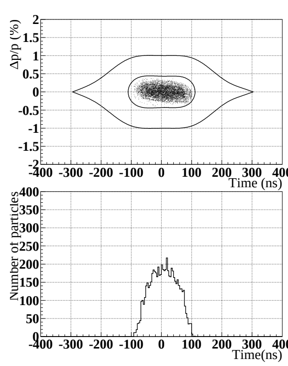

Figure 3: The phase space and the bunch shape at the RCS extraction with beam loading and space charge effect in the case that the extraction voltage is 60 kV.

EMITTANCE CONTROL FOR MR

The space charge effect is an issue in the MR injection. The bunching factor above 0.3 is needed to avoid the beam loss in the MR, but it is around 0.2 at the RCS extraction with only the fundamental rf voltage. Adding the second harmonic rf at the RCS extraction is the way to increase the bunching factor.

We have to take care not only of the bunch shape but also of the emittance shape then. For example, Fig. 4 shows the emittance and the bunch shape at the RCS extraction where the second harmonic rf is added from 19 ms to 20 ms, its amplitude increases monotonously from 0 to 80 % to the fundamental. The bunch shape gets close to flat one, but the emittance inclines. On the other hand, Fig. 5 shows the case that the second harmonic rf is added from 19 ms to 20 ms as the same pattern with Fig. 4, but the amplitude decreases by 30 % in the last 0.3 ms. The tilt of the emittance is corrected.

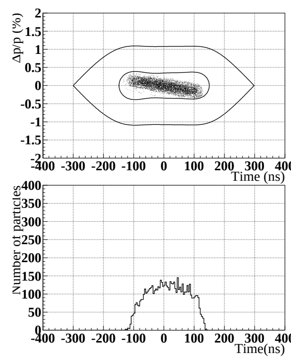

Figure 4: The phase space and the bunch shape with beam loading and space charge effect at the RCS extraction in the case that extraction voltage is 60 kV.

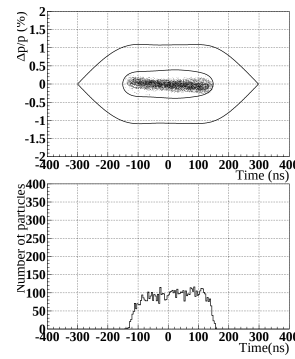

Figure 5: The phase space and the bunch shape with beam loading and space charge effect at the RCS extraction in the case that extraction voltage is 60 kV. The amplitude of the second harmonic rf is decreased in the last 0.3 ms.

Fig. 6 shows the simulation results of the bunching factor at the MR injection. In this simulation, only the space charge effect is considered at the MR injection. The thin line is the case that the emittance in Fig. 4 is captured by the MR rf where the fundamental rf voltage is 200 kV and the second harmonic one is 70 % of the fundamental one. The MR rf voltage is defined so that the trajectory in the phase space almost covers the full emittance, and the filamentation of the emittance after the MR injection seems to be small. The thick line is the case that the emittance in Fig. 5 is captured by the MR rf. The MR fundamental rf voltage is 70 kV and the second harmonic one is 70 % of the fundamental one.

It is found that the bunching factor fairly drops off just after the injection in the case that the tilted emittance is injected. The bunching factor is kept at higher value if the tilting is corrected at the RCS extraction.

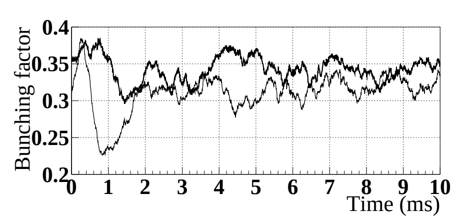

Figure 6: The simulation results of the bunching factor at the MR injection. The RCS extraction voltage is 60 kV and the second harmonic rf of 80 % to the fundamental one is added from 19 ms.

We have performed the parameter search of the matching between the RCS and the MR for various conditions. On each simulation, the tilting of the RCS emittance is corrected with an appropriate parameter. The conditions at the RCS extraction are listed in Table 2. The simulation results of the bunching factor in the MR injection are shown in Figs. 7-10. On each figure, the thin line shows the case that the second harmonic rf of 50 % to the fundamental one is added at the RCS extraction, the thick line is the case of 80 %, and the dotted line is the case of 100 %.

Figure No.	RCS ext. voltage	2^{nd} rf start
Fig. 7	150 kV	18 ms
Fig. 8	150 kV	19 ms
Fig. 9	60 kV	18 ms
Fig. 10	60 kV	19 ms

Table 2: The parameters of the simulation.

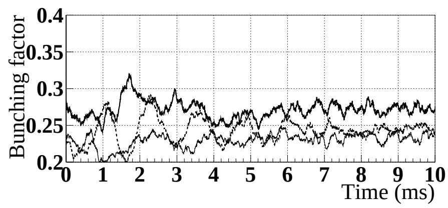

Figure 7: The simulation results of the bunching factor at the MR injection. The RCS extraction voltage is 150 kV and the second harmonic rf is added from 18 ms.

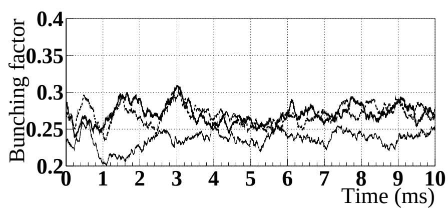

Figure 8: The simulation results of the bunching factor at the MR injection. The RCS extraction voltage is 150 kV and the second harmonic rf is added from 19 ms.

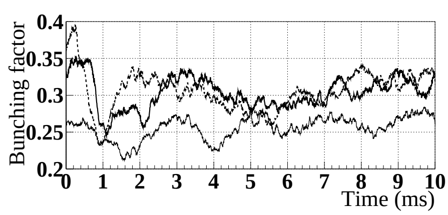

Figure 9: The simulation results of the bunching factor at the MR injection. The RCS extraction voltage is 60 kV and the second harmonic rf is added from 18 ms.

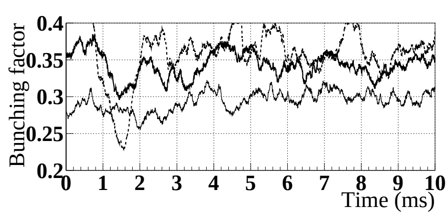

Figure 10: The simulation results of the bunching factor at the MR injection. The RCS extraction voltage is 60 kV and the second harmonic rf is added from 19 ms.

From the simulation results, it is found that the bunching factor above 0.3 can not be kept in the case that the RCS extraction voltage is 150 kV. The RCS extraction voltage should be below that. For the RCS extraction voltage of 60 kV, the bunching factor in the case that the starting time for the second harmonic rf is 19 ms becomes larger than the case of 18 ms.

From Fig. 10, the bunching factor becomes small in the case of the second harmonic rf of 50 % at the RCS extraction. Furthermore, it is very difficult to find a suitable MR rf bucket which can capture the RCS emittance smoothly in the case of the RCS second harmonic rf of 100 %. The condition of the RCS second harmonic rf around 80 % is a candidate for the high intensity operation in the MR. The MR fundamental rf voltage is 70 kV and the second harmonic one is 70 % of the fundamental.

In these simulations, since we use some test parameters for the RCS extraction voltage and the ratio of the second harmonic rf, we can also find another parameter in the RCS extraction voltage from 60 kV to 150 kV and in the ratio of the second harmonic rf from 50 % to 100 %. Furthermore, since the beam loading effect in the MR is not considered in these simulations, we have to adjust the parameters in the MR next step. But, the beam loading compensation by the feedforward in the MR should work well, and the basic scheme will be same as mentioned above.

SUMMARY

We have investigated the longitudinal emittance control for the matching between the RCS and the MR in J-PARC. It is found that the manipulation of the second harmonic rf at the RCS extraction is needed to keep the bunching factor high for the MR injection. We found that the condition that the extraction voltage of 60 kV and second harmonic rf around 80 % at the RCS is the candidate for the high intensity operation in the MR.

REFERENCES

[1] H. Hotchi *et al.*, "Beam commissioning of the 3-GeV rapid cycling synchrotron of the Japan Proton Accelerator Research Complex", Phys. Rev. ST Accel. Beams 12, 040402 (2009)

[2] H. Hotchi *et al.*, "High Intensity Beam Operations in the J-PARC 3-GeV RCS', Proc. of IPAC'10, p.624, 2010

[3] M. Yamamoto *et al.*, "Simulation of longitudinal beam manipulation during multi-turn injection in J-PARC RCS", Nucl. Instr. and Meth. A 621 (2010) p.15

[4] R. Baartman, "Efficient Numerical Technique to Find Bucket", TRI-DN-K226, 1993

[5] M. Yamamoto *et al.*, "Simulation of Longitudinal Emittance Control in J-PARC RCS", Proc. of IPAC'10, p.1940, 2010

[6] 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)