LONGITUDINAL PARTICLE SIMULATION FOR J-PARC RCS

M. Yamamoto*, M. Nomura, A. Schnase, T. Shimada, H. Suzuki and F. Tamura
Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, JAPAN
E. Ezura, K. Hara, K. Hasegawa, C. Ohmori, A. Takagi, M. Toda and M. Yoshii
KEK, Tsukuba, Ibaraki 305-0801, JAPAN
K. Horino
Nippon Advanced Technology Co. Ltd., Ibaraki 319-1112, JAPAN

Abstract

The beam commissioning has been going at the J-PARC RCS. Some longitudinal beam gymnastics and the acceleration has been successfully performed under the high intensity operation. We had developed the longitudinal particle tracking code with the beam loading and the space charge effects. The comparison between the beam test result and the particle tracking simulation is described.

INTRODUCTION

The J-PARC Rapid Cycling Synchrotron (RCS) has started beam delivery for the experimental hall and the Main Ring (MR) as an user operation, and the beam study has been also performing [1]. We have installed the 11th rf system in the RCS after the previous report [2], the maximum accelerating voltage for the normal operation becomes ∼400 kV, it is very helpful for enlarging the acceptance of the rf bucket. The parameters of the RCS are listed in Table 1.

Table 1: The parameters of the J-PARC RCS.

Injection energy	181 MeV
Extraction energy	3 GeV
Harmonic number	2
Repetition rate	25 Hz
Acceleration period	20 ms
RF Frequency range	0.939∼1.672 MHz
Momentum compaction factor	0.0119798

We have investigated the longitudinal bunch gymnastics whole acceleration period, especially at the injection and the extraction. The bunching factor should be increased as large as possible at the injection because of the alleviation of the space charge effect. Since the J-PARC RCS uses the multi-turn injection scheme with a chopped Linac beam, it is very difficult to evaluate the bunch shape analytically, because the bunch shape is not proportional to the bucket potential well shape at all. The beam tracking simulation has been performed to find the optimum injection condition.

* masanobu.yamamoto@j-parc.jp

Furthermore, we should extract several different kinds of the beam for the user operation, the short bunch for the Muon experiment or the flat bunch for the MR injection. Since the synchrotron motion becomes slower and slower at latter acceleration period, the longitudinal beam emittance tends not to catch up with the changing rf bucket. The beam tracking simulation is also helpful to evaluate the bunch shape at the extraction.

SIMULATION

We have developed the longitudinal particle tracking code based on the difference equation of the longitudinal motion. This code also calculates the wake voltage [3] and the space charge effect [4] to evaluate the high intensity operation. The synchronous particle is calculated from the bending magnetic field by the forward difference method [5], and the accelerating voltage tracking method is also adopted to simulate the momentum offset injection scheme.

Injection

In the J-PARC RCS, the H^- ions come from the Linac and the pass through a stripping foil, then the protons are injected into the RCS by the multi-turn injection scheme. The multi-turn injection continues over 234 turns in the normal operation of the Linac where the macro bunch length is 500 μsec. The bending magnetic field of the RCS has a sinusoidal wave form, and the multi-turn injection starts at 250 μsec before the bottom of the bending field and continues until 250 μsec after the bottom.

Since the chopping width, which is the ratio of the Linac intermediate bunch length to the RCS rf wave length becomes 56 % at the normal operation, there is not enough margin to paint the injected Linac macro bunch. When the macro bunch is injected at the center of the RCS rf bucket, the charge density near the center becomes very large as shown in Fig. 1, which shows the simulation result with snap shots taken every 20 turns from the beginning of the injection.

In order to make the bunching factor larger, adding the 2nd higher harmonic rf is a possible way, and we have carefully chosen the ratio of the 2nd higher harmonic to the fundamental one. From the previous calculations [6], the ratio of over 50 % has an advantage in the case of the multi-turn injection with a large chopping factor. Furthermore, adding the momentum offset with respect to the synchronous particle is also effective [6].

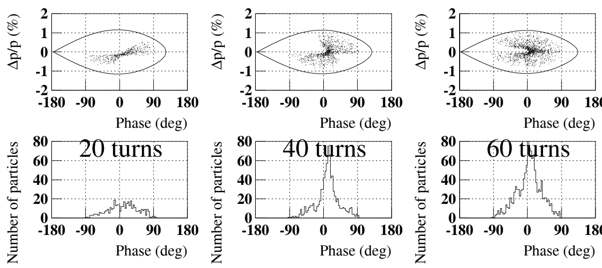

Figure 1: The simulation result of the injection transient in the rf bucket and its bunch shape. Only fundamental rf is applied.

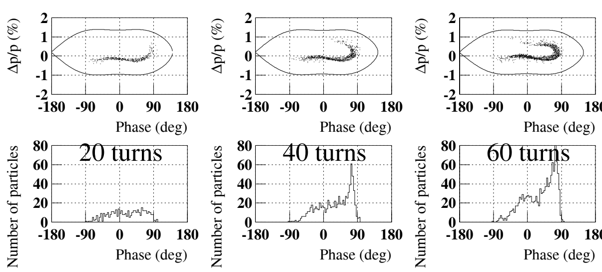

Figure 2: The simulation result of the injection transient in the rf bucket and its bunch shape. The 2nd higher harmonic rf of 80 % ratio and the momentum offset of -0.2 % are applied.

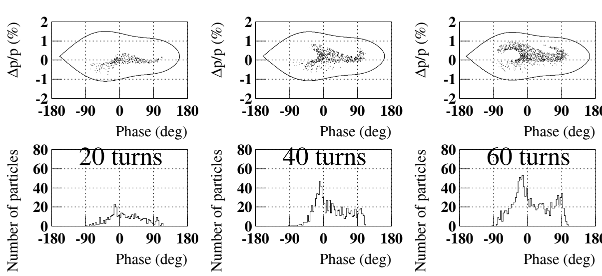

Figure 3: The simulation result of the injection transient in the rf bucket and its bunch shape. The phase sweep of the 2nd harmonic rf is applied.

Figure 2 shows the simulation result of the case with the 2nd/1st harmonic ratio of 80 % and the -0.2 % of the momentum offset. The bunch shape becomes more flat than in the case of Fig. 1. The momentum offset is realized by adding the frequency offset with respect to the synchronous particle. The frequency offset is added by -0.2 % from the beginning of the injection to the bottom of the bending field, then it gradually decreases into 0 until 1 msec.

However, the injection transient effect is still remarkable near the beginning of the injection, which is caused by the momentum offset as clearly seen in 60 turns case of Fig. 2, where the right side of the bunch has a peak. This injection transient becomes largest around the 1/4 synchrotron period, then the bunching factor becomes small. In order to avoid this, we have introduced the phase sweep of the 2nd higher harmonic against the fundamental one [7]. There is a phase offset of the 2nd harmonic one ϕ_2 at the beginning of the injection as

$$V = V_1 \sin\phi + V_2 \sin\{2(\phi - \phi_s) + \phi_2\} \ , \qquad (1)$$

where V_1 is the amplitude of the fundamental rf voltage, V_2 is that of the 2nd higher harmonic one and ϕ_s is a synchronous phase, then $\phi_2 \to 0$ gradually during the injection. The injection transient should be made smaller as shown in Fig. 3.

The beam test to improve the bunching factor at the injection has been performed at the equivalent beam power of 100 kW, that is, 8.3×10^{12} ppp. Figure 4 shows (a) the case of only fundamental rf, (b) shows the case with the 2nd higher harmonic rf and the momentum offset, and (c) shows the case with the 2nd higher harmonic rf , momentum offset and the phase sweep of 2nd higher harmonic rf. The upper graph shows the bunching factor during the injection, the vertical axis is a bunching factor and the horizontal axis is a number of turns. The thick line is the beam test result and the thin one is the simulation result. The lower graph shows the bunch shape at the end of the multi-turn injection, the shaded histogram is the simulation result and the thick line is the beam test result, respectively.

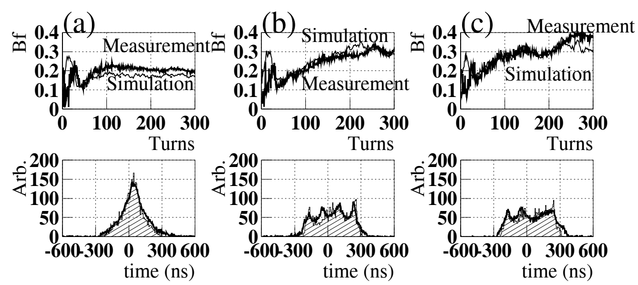

Figure 4: The comparison of the beam test with the simulation result. (a) Only fundamental rf is applied, (b) the 2nd higher harmonic rf of 80 % and the momentum offset of -0.2 % are applied, and (c) the phase sweep of the 2nd harmonic rf is applied.

The simulation results are almost same as the beam test results. However, the difference becomes larger at the beginning of the injection. It is considered that the wall current monitor which detects the bunch shape does not have enough S/N margin under the very low current at the beginning of the injection.

Furthermore, although the original concept of ϕ_2 sweep is making the injection transient smaller, it seems the bunching factor at the end of the multi-turn injection with ϕ_2 sweep becomes larger than that without ϕ_2 sweep at the beam test.

Extraction

The J-PARC RCS provides the proton beam for the experimental hall and the MR. For each beam user, we perform the longitudinal beam manipulation near the extraction with different acceleration voltage pattern from the normal one. The normal acceleration voltage pattern is defined as the beam emittance should be preserved whole acceleration period with a constant momentum filling factor [8].

The maximum acceleration voltage for the normal operation is 400 kV at present, then the condition of the beam emittance of 1.95 eVs with 70 % momentum filling factor can be used. However, if we adopt this condition near the extraction, then the acceleration voltage will be a few kV, this is too small and beam may become unstable because of beam loading. In order to avoid such condition, the extraction voltage of 60 kV is set as the design value. Figure 5 (a) shows the bunch shape at the extraction by the simulation in the case of the extraction voltage of 60 kV. Since we did not measure the bunch shape at this condition in the beam test, we only show the simulation result.

For the Muon experiment user, we demonstrate a shorter bunch than the normal operation one. In order to get the shorter bunch, we have tested the phase rotation technique near the extraction. The acceleration pattern is same as the normal one until before the last 1/4 synchrotron period from the extraction, then the acceleration voltage is suddenly increased to rotate the beam emittance in the longitudinal phase space.

Figure 5 (b) shows the comparison of the beam test result with the simulation one. The shaded histogram is the simulation result and the thick line is the beam test one, respectively. In this case, the beam test is performed with 1.64×10^{12} ppp and the Linac macro bunch length is 100 μsec. The voltage of 120 kV is added on the normal acceleration pattern 0.4 msec before the extraction. The simulation result is almost same as the beam test result, the bunch length becomes around 80 nsec by the phase rotation where it is around 120 nsec in the normal one.

For the MR injection, we provide a more flat bunch than the normal operation one, because the space charge effect is severe at the flat base of the MR. In order to get the flat bunch, the 2nd higher harmonic rf is applied again near the extraction.

Figure 5 (c) shows the comparison of the beam test result with the simulation one. In this case, the beam test is performed with 8.3×10^{12} ppp in same condition as the injection beam study. Adding the 2nd higher harmonic rf starts at 2 msec before the extraction, its amplitude gradually increases from 0 to 50 % against the fundamental one during 1 msec, then 50 % ratio is kept until the extraction.

The simulation result is slightly different from the beam test one, it is considered that the beam loading affects to the bunch shape. Although the simulation code can calculate the wake voltage, it has not included the feedback loops such as Auto Level Control and the phase feedback yet. So the beam loading effect is neglected in the simulation, only the space charge effect is included at the simulation result in Fig. 5. From the beam test result, the bunching factor becomes 0.26 with the 2nd higher harmonic rf, where it is 0.18 in the normal operation.

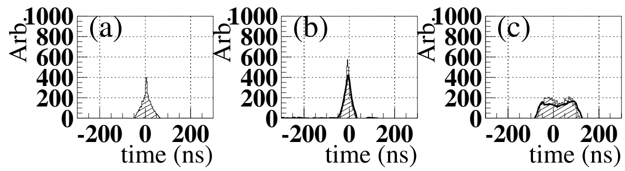

Figure 5: The comparison of the beam test with the simulation result. The 2nd higher harmonic rf is added around the extraction.

SUMMARY

We have developed the longitudinal particle tracking code which uses the acceleration pattern for the J-PARC RCS, calculates the wake voltage and the space charge effect. The comparison of the simulation result with the beam test result, it is almost same for the injection beam study. However, it is different from the beam study result at the extraction in the case of the high intensity beam. The improvement including the feedback loop should be needed for more precise simulation.

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