SIMULATION OF LONGITUDINAL EMITTANCE CONTROL IN J-PARC RCS

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 beam commissioning and user operation have been going at the J-PARC RCS. For high intensity operation the longitudinal beam gymnastics has been successfully optimized. We have developed the longitudinal particle tracking code with beam loading and space charge effects to evaluate the longitudinal beam emittance. We describe the relation between the acceleration voltage pattern and the beam emittance with the dual harmonic rf in the high intensity operation.

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]. The maximum operation beam power is 300 kW (2.5×10^{13} ppp). The maximum accelerating voltage for the normal operation is 400 kV, which is provided by 11 rf cavities.

The accelerating voltage pattern is controlled to minimize the beam loss. Adding the second harmonic rf with a momentum offset and a phase sweep techniques are adopted to alleviate the space charge effect near the injection [2]. Furthermore, the extraction voltage is adjusted to prevent the beam loss.

We have investigated the longitudinal beam emittance by a particle tracking code. We found that the beam emittance is conserved in the dual harmonic rf because the adiabaticity parameter is enough small in the RCS. Furthermore, we found that the rf bucket should have a margin to avoid the beam loss in the high intensity operation.

LONGITUDINAL BEAM EMITTANCE

The acceleration voltage pattern of the fundamental harmonic rf is basically chosen to preserve the beam emittance during the whole acceleration period while keeping the momentum filling factor constant [3]. The momentum filling factor is the ratio of the maximum momentum difference from the synchronous particle with given beam emittance to the bucket height.

The RCS rf system employs the dual harmonic rf with the fundamental rf and second harmonic one to alleviate the space charge effect near the injection region. The rf voltage is written as

$$\begin{aligned} V_{\rm rf} &= V_1 \sin\phi + V_2 \sin\left\{2(\phi-\phi_{\rm s})+\phi_2\right\} \\ &= V_1 \left[\sin\phi + a_2 \sin\left\{2(\phi-\phi_{\rm s})+\phi_2\right\}\right] \ , \end{aligned} \quad (1)$$

where V_1 is the amplitude of the fundamental rf voltage, V_2 is the amplitude of the second harmonic rf, a_2 is the voltage ratio of V_2/V_1, ϕ is the phase of the rf voltage, $\phi_{\rm s}$ is the phase of the synchronous particle, and ϕ_2 is an arbitrary phase offset to improve the bunching factor at the beginning of the injection [4].

When the upper limit phase of the particle trajectory in a phase space with given beam emittance is $\phi_{\rm b2}$, the beam emittance $\varepsilon_{\rm L}$ is calculated as

$$\begin{aligned} \varepsilon_{\rm L} &= 2\sqrt{\frac{eV_1\beta_{\rm s}^2E_{\rm s}}{\pi h^3\omega_{\rm revs}^2\eta_{\rm s}}} \\ &\times \int_{\phi_{\rm b1}}^{\phi_{\rm b2}} \Bigg[\cos\phi - \cos\phi_{\rm b2} + (\phi-\phi_{\rm b2})\sin\phi_s \\ &+\frac{a_2}{2}\left[\cos\left\{2(\phi-\phi_{\rm s})+\phi_2\right\} - \cos\left\{2(\phi_{\rm b2}-\phi_{\rm s})+\phi_2\right\}\right]\Bigg]^{\frac{1}{2}} d\phi \end{aligned} \quad (2)$$

where $\beta_{\rm s}$ is the ratio of the velocity of the synchronous particle to the speed of light c, $E_{\rm s}$ is the total energy of the synchronous particle, h is the harmonic number, $\omega_{\rm revs}$ is the angular revolution frequency of the synchronous particle, and $\eta_{\rm s}$ is the slippage factor. $\phi_{\rm b1}$ is the lower limit phase of the particle trajectory with given beam emittance which satisfies

$$\begin{aligned} &\cos\phi_{\rm b1} - \cos\phi_{\rm b2} + (\phi_{\rm b1}-\phi_{\rm b2})\sin\phi_{\rm s} \\ &+\frac{a_2}{2}\Bigg[\cos\left\{2(\phi_{\rm b1}-\phi_{\rm s})+\phi_2\right\} \\ &-\cos\left\{2(\phi_{\rm b2}-\phi_{\rm s})+\phi_2\right\}\Bigg] = 0 \ . \end{aligned} \quad (3)$$

The momentum filling factor $P_{\rm f}$ is calculated as

$$\begin{aligned} P_{\rm f} &= \sqrt{\frac{W_{\rm b}}{W_{\rm bk}}} \quad (4) \\ W_{\rm b} &= \cos\phi - \cos\phi_{\rm b2} + (\phi-\phi_{\rm b2})\sin\phi_{\rm s} \\ &+\frac{a2}{2}\left[\cos\left\{2(\phi-\phi_{\rm s})+\phi_2\right\} - \cos\left\{2(\phi_{\rm b2}-\phi_{\rm s})+\phi_2\right\}\right] \\ W_{\rm bk} &= \cos\phi - \cos\phi_{\rm bk2} + (\phi-\phi_{\rm bk2})\sin\phi_{\rm s} \\ &+\frac{a2}{2}\left[\cos\left\{2(\phi-\phi_{\rm s})+\phi_2\right\} - \cos\left\{2(\phi_{\rm bk2}-\phi_{\rm s})+\phi_2\right\}\right] \ , \end{aligned}$$

* masanobu.yamamoto@j-parc.jp

where $W_{\rm b}$ is proportional to the maximum $\Delta p/p_{\rm s}$ of the beam at ϕ, $W_{\rm bk}$ is proportional to the bucket height at ϕ, $\phi_{\rm bk2}$ is the upper limit phase of the rf bucket, which satisfies

$$\sin\phi_{\rm s} - \sin\phi_{\rm bk2} - a_2 \sin\{2(\phi_{\rm bk2} - \phi_s) + \phi_2\} = 0\ . \quad (5)$$

The normal acceleration pattern in the RCS is defined by the condition that the rf bucket accepts the beam emittance of 1.94 eVs with 70 % momentum filling factor. In this case the maximum accelerating voltage becomes 400 kV at 7.6 ms from the injection as shown in Fig. 1. The extraction voltage is set to 150 kV, whereas it becomes 2 kV as shown in Fig. 1 from the condition to keep the beam emittance and the momentum filling factor constant. The reason why we set the extraction voltage to 150 kV is that beam loss was observed at the beam experiment when the extraction voltage was set below 120 kV.

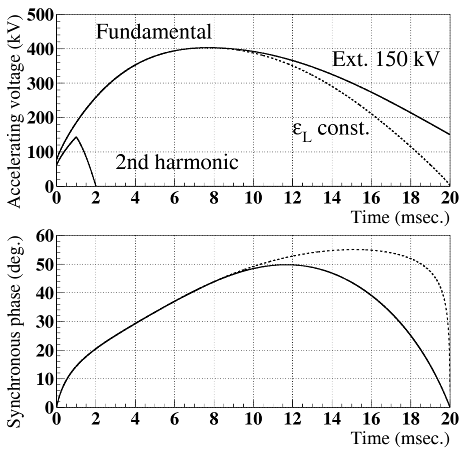

Figure 1: The accelerating voltage pattern and the synchronous phase. The thick lines show the case that the extraction voltage is 150 kV, and the dotted lines show the case that ε and $P_{\rm f}$ are constant.

The voltage ratio a_2 is set to 80 % at the normal operation, and it is kept until 1 ms and gradually decreased toward 2 ms as shown in Fig. 1.

We have performed the particle tracking simulation to calculate the beam emittance by eq.(2). First of all, the space charge effect and the beam loading effect are not included to evaluate the nature of the bucket and the beam emittance. We calculate for the cases (a) only fundamental rf, (b) fundamental rf with the momentum offset of $\Delta p/p = -0.2\%$, (c) including the second harmonic rf with case (b), and (d) including the phase sweep of $\phi_2 = -100$ degrees with case (c). The initial condition of the injected beam is that the chopping width is 560 ns and the momentum spread is ± 0.05 %. The beam is injected into the RCS by the multi-turn injection scheme.

Figure 2 shows the calculation results, the upper graph shows the beam emittance, the middle graph shows the momentum filling factor, and the bottom graph shows the so called 'adiabaticity parameter'. The adiabaticity $\epsilon_{\rm a}$ is calculated as

$$\epsilon_{\rm a} = \frac{1}{\omega_{\rm s}} \left| \frac{d\omega_{\rm s}}{dt} \right| , \quad (6)$$

where $\omega_{\rm s}$ is the angular synchrotron frequency. When $\epsilon_{\rm a} \ll 1$, typically $\epsilon_{\rm a} < 0.1$, the change of the accelerating voltage is considered as enough adiabatic in comparison with the synchrotron motion [5].

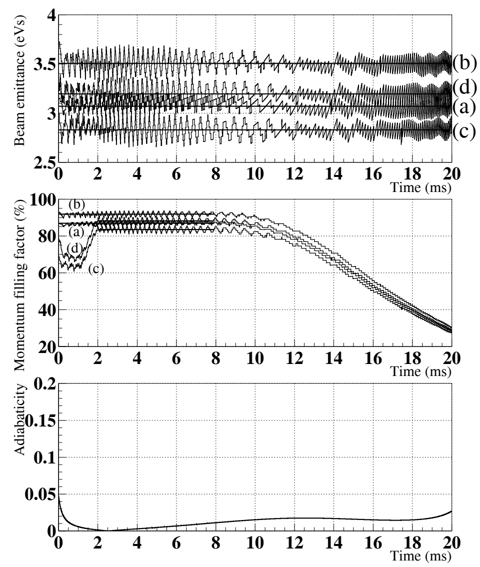

Figure 2: The beam emittance, the momentum filling factor, and the adiabaticity. (a) Only fundamental rf, (b) fundamental rf with the momentum offset, (c) dual harmonic rf with the momentum offset, and (d) dual harmonic rf with the momentum offset and the phase sweep.

Table 1: The Simulation Results of the Beam Emittance, the Momentum Filling Factor, and the Adiabaticity

	$\varepsilon_{\rm L}$	$P_{\rm f}$ with V_1	$P_{\rm f}$ with V_1 and V_2
(a)	3.1 eVs	87 %	
(b)	3.5 eVs	92 %	
(c)	2.8 eVs	83 %	63 %
(d)	3.2 eVs	88 %	68 %

The simulation results are summarized in Table 1. In all conditions, the beam emittance is constant because the $\epsilon_{\rm a}$ is small enough. It does not depend on whether the second harmonic rf is turned on or off. Comparing case (b) with (c), the beam emittance and the momentum filling factor with the second harmonic rf becomes smaller than that of only fundamental one. From the results, an initial rf bucket shape determines the beam emittance over the whole acceleration period. The second harmonic rf improves not only the bunching factor but also the momentum filling factor.

The simulation results for different extraction voltages from 150 kV are shown in Fig. 3. The initial rf condition is same as in case (d). In the case of (e), the extraction voltage is set to 60 kV. In the case of (f), the accelerating voltage pattern completely follows to keep the beam emittance and the momentum filling factor constant over the whole period. In the case of (f), since the adiabaticity is larger than 0.1 after 18.4 ms, the emittance growth occurs, thus the momentum filling factor becomes more than 100 % in the end. In the case of (e), since the adiabaticity is larger than 0.1 just before the extraction, small emittance growth is observed. The extraction voltage of 60 kV is the lower limitation to keep the beam emittance constant in the RCS.

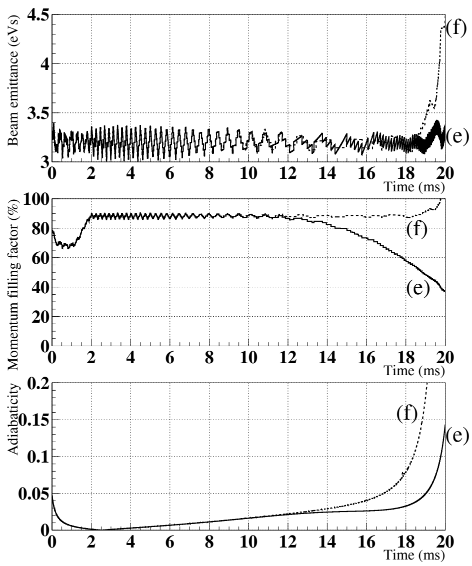

Figure 3: The simulation results of the beam emittance, the momentum filling factor, and the adiabaticity. (e) The extraction voltage is set to 60 kV, and (f) The voltage pattern keeping the beam emittance and the momentum filling factor constant.

From the results, it is not necessary to take care of keeping the target value of the beam emittance and the momentum filling factor constant unless the adiabatic condition is broken. Once the initial beam emittance is determined by the initial rf bucket shape, it is conserved.

Figure 4 shows the simulation results including non-adiabatic terms such as the space charge effect and the beam loading effect. The condition of the number of particles with 2.5×10^{13} ppp is simulated. In the case of (g), the space charge effect is included in case (d). From the result, since the beam emittance is 3.26 eVs, the difference from the case without the space charge effect is very small. In the case of (h), the beam loading effect and the space charge effect are included in case (d), and the beam loading compensation method is adopted for the fundamental and second higher harmonic components. In the case of (i), the extraction voltage is set to 60 kV and the other conditions are same as in case (h).

From the results, the emittance growth is observed at high intensity operation due to the beam loading effect. If the rf bucket does not have enough margin such as in case (i), the momentum filling factor almost reaches 100 % from 10 to 14 ms. This means the beam tends to be spilled out from the rf bucket. In order to prevent the beam loss, it is necessary to increase the accelerating voltage around such region. At present, since the maximum rf voltage is limited at 400 kV, it is better to choose a higher extraction voltage such as in case (h). In future, adding the 12^{th} rf cavity helps to enlarge the rf bucket margin.

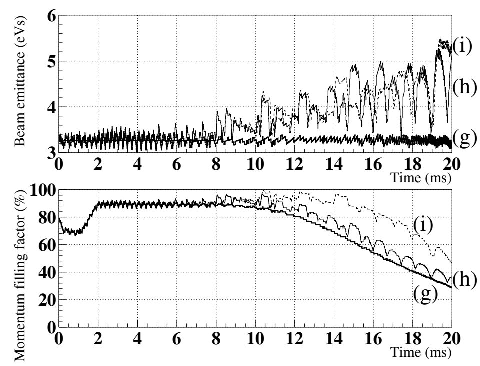

Figure 4: The simulation results of the beam emittance and the momentum filling factor. (g) Only space charge effect is included, (h) the beam loading effect and space charge effect are included. The beam loading effect is compensated for the fundamental and the second harmonic components, and (i) the extraction voltage is set to 60 kV in addition to case (h).

SUMMARY

We have evaluated the longitudinal beam emittance by the particle tracking simulation in J-PARC RCS. We found the beam emittance is conserved under the dual harmonic rf when the adiabatic condition is satisfied. The beam emittance is defined by the initial rf bucket shape.

Since the beam loading effect causes the emittance growth, the momentum filling factor almost reaches 100 % around the middle of the acceleration period. The accelerating voltage should be kept high enough to avoid the beam loss.

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