SIMULATION FOR CONTROL OF LONGITUDINAL BEAM EMITTANCE IN J-PARC MR

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Abstract

The J-PARC MR receives a high intensity beam from the RCS. The designed longitudinal emittance of the RCS is 5 eVs, whereas the MR rf bucket has enough margin to accept up to 10 eVs. Although the RCS emittance can be increased by using phase modulation method and a large emittance is desirable to increase the bunching factor and to avoid instability, it is difficult to receive such large emittance beam in the MR because of the MR kicker performance. We have performed the particle tracking simulation of longitudinal emittance control for enlarging the beam emittance by phase modulation method and for keeping the bunching factor high using second harmonic rf during the MR injection period.

INTRODUCTION

The J-PARC MR (Main Ring) receives a high intensity proton beam of 3 GeV from RCS (Rapid Cycling Synchrotron) and accelerates it up to 30 GeV [1]. The bunching factor should be high enough to avoid the beam loss due to the space charge effect at the injection. However, the results of previous particle tracking simulation suggested that since the longitudinal beam emittance was distorted for the sake of increasing the bunching factor, it was very difficult to find an appropriate MR rf bucket to capture such distorted emittance smoothly [2]. The reason why such distortion happened is that the beam emittance at the RCS is rather small for the MR rf bucket.

We found that the controlled emittance blow-up by phase modulation) method using a HFC (High Frequency Cavity) [4, 5, 6] could be possible near the RCS extraction. It solves the emittance distortion issue, and the bunching factor at the MR injection can be kept high enough [3]. However, since the bunch length at the RCS extraction becomes longer when the emittance blow up is applied, it is difficult to extract such long bunch by the RCS extraction kicker and is also difficult to accept by the MR injection kicker.

Therefore, we consider an alternative way that the controlled emittance blow-up is applied after the injection at the MR. In this case, although a sudden drop in the bunching factor just after the capture can not be avoided [2], we can keep the bunching factor high enough at the beginning of the acceleration where the bunch width becomes narrower. Furthermore, we can mitigate a microwave instability for a slow extraction operation at the MR flat top using the large emittance.

We have investigated the controlled longitudinal beam emittance blow-up using the phase modulation at the MR injection by a particle tracking code.

EMITTANCE BLOW-UP BY PHASE MODULATION

For the emittance blow-up by the phase modulation, the HFC voltage is added to a fundamental acceleration voltage. The total rf voltage V_t is written as

$$V_\mathrm{t} = V_0 \sin h_0 \omega_\mathrm{revs} t + V_\mathrm{b} \sin(h_\mathrm{b} \omega_\mathrm{revs} t + \psi(t) + \psi_\mathrm{b}) \,, \quad (1)$$

where V_0 and h_0 are amplitude and harmonic number of the fundamental acceleration voltage, and ω_revs is the angular revolution frequency of a synchronous particle. V_b and h_b are amplitude and harmonic number of the HFC. ψ_b is the phase offset value. The phase of the HFC is modulated by

$$\psi(t) = \Delta\phi_\mathrm{mod} \sin \omega_\mathrm{mod} t \,, \quad (2)$$

where $\Delta\phi_\mathrm{mod}$ is the amplitude of the phase modulation, ω_mod is the angular modulation frequency.

The blow-up characteristics are categorized by the ratio of the modulation frequency ω_mod to the synchrotron frequency ω_s. It is called 'resonant regime [4]' in the case of $\omega_\mathrm{mod}/\omega_s < 5$, and is called 'noise regime [5, 6]' in the case of $\omega_\mathrm{mod}/\omega_s > 10$.

We have performed the particle tracking simulations for both regimes. In the simulation, beam loading effects and space charge effects are not included because we want to see the nature of the modulation effect clearly. We have performed a parameter search to investigate the correlation between the harmonic number h_b of the HFC and the modulation frequency ω_mod. The modulation amplitude $\Delta\phi_\mathrm{mod}$ has a constant value of 180 degrees. The voltage V_b of the HFC is adjusted so that the beam emittance is blown-up from 5 eVs to 10 eVs during 10 ms at the MR injection.

Fig. 1 shows the reference beam emittance and bunch shape at the MR injection without any phase modulation. In this case, only the fundamental rf voltage of V_0 = 280 kV is applied and the rf bucket completely matches the injected beam emittance. The thin line enclosing the

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emittance indicates the 5 eVs area. The harmonic number $h_0 = 9$ and the frequency of the fundamental rf is 1.672 MHz. The synchrotron frequency in the case of $V_0 = 280$ kV is 463.9 Hz.

On the other hand, Fig. 2 shows an example of the simulation result with the phase modulation. The modulation parameters are $h_\mathrm{b}/h_0 = 60$, $\omega_\mathrm{mod}/\omega_\mathrm{s} = 10$ and $V_\mathrm{b} = 220$ kV. The thin line enclosing the emittance indicates the 10 eVs area. The beam emittance is blown-up smoothly and the bunch shape becomes wider. Fig. 3 shows the variation of the beam emittance and the bunching factor. The bunching factor is also increased from 0.15 to 0.23 by the phase modulation.

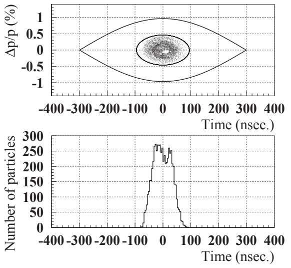

Figure 1: The longitudinal beam emittance and the bunch shape at the MR injection. No blow-up is applied.

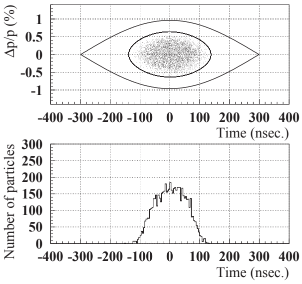

Figure 2: The variation of the longitudinal beam emittance and the bunch shape at the MR injection with the phase modulation.

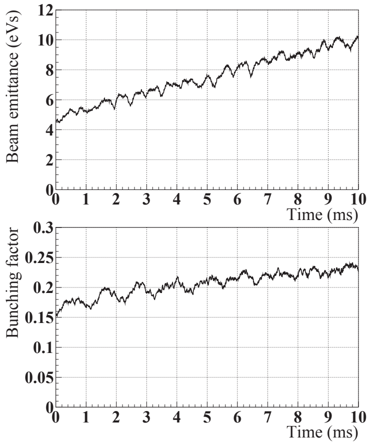

Figure 3: The increase of the beam emittance and the bunching factor during the phase modulation.

The results of the parameter search for the phase modulation are shown in Fig. 4. The evaluation ranges are $10 \leq h_\mathrm{b}/h_0 \leq 300$ and $4 \leq \omega_\mathrm{mod}/\omega_\mathrm{s} \leq 30$. The circle marks in Fig. 4 indicate the points where the beam emittance is blown-up smoothly with the minimum HFC frequency on each phase modulation frequency. In the case of a lower HFC frequency than these circle marks, the core of the emittance is hardly diluted. The square marks indicate the points where the beam emittance is blown-up smoothly with the maximum HFC frequency on each phase modulation frequency. In the case of a higher HFC frequency than these square marks, the core of the emittance is also hardly diluted.

The parameter search results suggest that the effective HFC frequency is proportional to the modulation frequency as shown in Fig. 4 (a). We can choose appropriate parameter sets of ω_mod and h_b enclosed by the upper limit and the lower limit. Furthermore, with lower modulation frequency the necessary HFC voltage is smaller for the lower limit cases as shown in Fig. 4 (b). This simply means the bucket height expressed in terms of $\Delta p/p$ is proportional to $1/\sqrt{h_\mathrm{b}}$. The bucket height from 0.09 % to 0.15 % is needed to achieve 10 eVs within 10 ms as shown in Fig. 4 (c). From these results, it seems that the HFC with small modulation frequency is an easy way to perform the controlled emittance blow-up in the MR injection because the requirement of the HFC voltage is rather small.

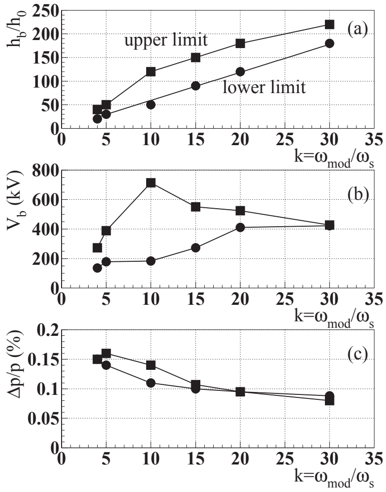

Figure 4: The correlation between the modulation frequency and the HFC frequency.

We also have performed the particle tracking simulations to check the bunching factor until the beginning of the acceleration. In these simulations, the beam loading effect and the space charge effect are included in the case of 2.5×10^{13} protons per bunch, and the beam loading compensation for $h = 8, 9, 10$ by a feedforward system [7] is applied.

The beam injection timing at the MR flat base used in these simulations is shown in Fig. 5. Two bunches are injected each 40 ms from the RCS, and 8 bunches are filled into the MR. Before the start of the acceleration, 10 ms is reserved for the phase modulation.

The simulation results of the bunching factor and the beam emittance are shown in Figs. 6 and 7. In Fig. 6, the second harmonic rf at the RCS extraction is not applied. The fundamental rf voltage is 280 kV and the second harmonic rf is 30 % to the fundamental one at the MR injection. Since the beam emittance at the RCS extraction becomes somewhat flat by the beam loading effect, the second harmonic rf is needed at the MR injection to match the RCS

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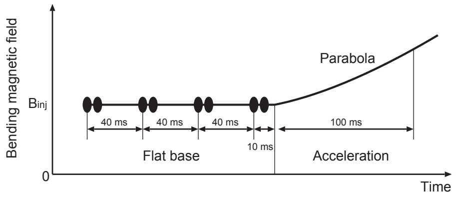

Figure 5: The beam injection timing of the MR.

emittance. After the last bunch from the RCS is injected at 0.12 s, then the phase modulation with $h_\mathrm{b}/h_0 = 60$ and $\omega_\mathrm{mod}/\omega_\mathrm{s} = 10$ is applied from 0.12 to 0.13 s in the case of the thick line. The reason why the emittance becomes larger without the phase modulation is that the beam loading effect makes a halo. The core of the emittance is not diluted without the phase modulation.

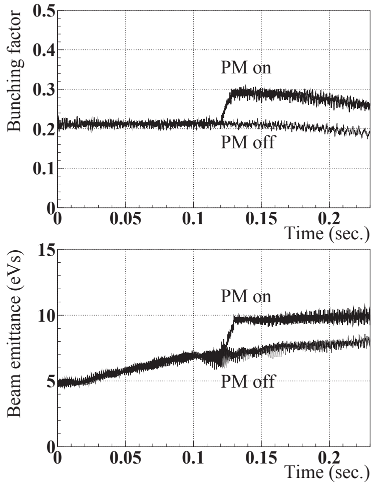

Figure 6: The simulation results of the bunching factor and the beam emittance.

In Fig. 7, the second harmonic rf of 50 % to the fundamental one at the RCS extraction is applied. The fundamental rf voltage is 150 kV and the second harmonic rf is 50 % to the fundamental one at the MR injection. In this case, the bunching factor at the injection is around 0.28. However, since the fundamental rf voltage should be increased to keep enough bucket height after the acceleration starts, the bunching factor after 0.13 s becomes smaller without the phase modulation as shown in the thin line. On the other hand, the phase modulation makes the bunching factor high enough after the start of the acceleration.

The phase modulation parameter in Figs. 6 and 7 is used as an example. Similar results can be obtained by using the parameter sets as shown in Fig. 4. We can choose the phase modulation parameters depending on the feasibility of the construction of the HFC.

SUMMARY AND DISCUSSION

We have investigated the controlled longitudinal beam emittance blow-up by the phase modulation at the the J-PARC MR injection. We found effective parameter sets for the modulation frequency and the HFC frequency. The phase modulation enlarges not only the beam emittance, but also the bunching becomes factor high enough after the start of the acceleration.

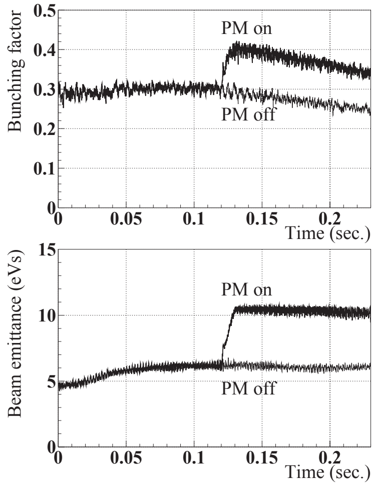

Figure 7: The simulation results of the bunching factor and the beam emittance.

Although the HFC voltage used in the simulation is optimized to achieve the 10 eVs beam emittance, a lower HFC voltage is certainly enough sufficient for improving the bunching factor. Concerning the microwave instability at the MR flat top, since the phase modulation during the acceleration period should be effective, the lower HFC voltage also offers possibility to enlarge the beam emittance until the flat top.

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