LONGITUDINAL PARTICLE TRACKING OF J-PARC RCS FOR SYNCHRONIZATION

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

Abstract

We have performed particle tracking simulation of J-PARC RCS to study the synchronization process. A frequency offset is added to the original rf frequency pattern to shift the bunch center, under the condition that the offset value should be 'adiabatic' with respect to the synchrotron motion. Since the synchrotron frequency of the J-PARC RCS is substantially changed during acceleration, the particle tracking simulation helps to decide the limit of the frequency offset which can be employed.

INTRODUCTION

The J-PARC Rapid Cycling Synchrotron (RCS) provides a high intensity proton beam for neutron experiments and also for the Main Ring (MR). The RCS is operated at 25 Hz repetition rate, and the MR is operated at 3.64 sec period. The neutron experiment uses 'Fermi chopper', which rotates at 600 Hz revolution frequency to get fine energy resolution. The timing system generates precise timing signal and delivers it to the extraction kicker, which is synchronized with the Fermi chopper and MR [1, 2, 3].

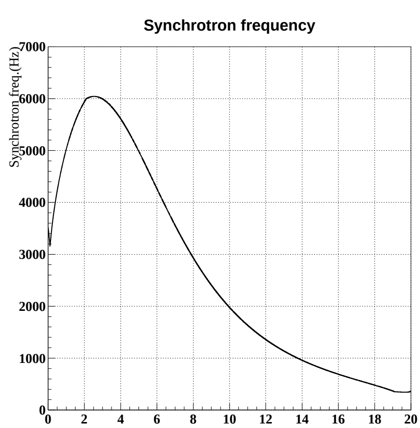

Figure 1: The synchrotron frequency of the RCS.

We can realize the synchronization in RCS by adding a frequency offset to the rf frequency pattern, but it is very difficult to know by simple calculation how much offset is allowed in RCS, because the synchrotron frequency is changed widely during the acceleration period as shown in Fig. 1. So, we investigate the suitable parameter of the synchronization by particle tracking simulation.

SIMULATION METHOD

We have been developing the particle tracking code for the longitudinal motion [4]. This code is also very useful to evaluate the synchronization process. In order to get the phase shift of the bunch center at the extraction, the frequency offset Δf is added to the original rf frequency pattern during the acceleration as follows:

$$\omega_{\mathrm{rf}}^{\mathrm{actual}} = h\omega_{\mathrm{revs}} + \Delta\omega, \tag{1}$$

where h is the harmonic number, ω_{revs} is the revolution frequency of the synchronous particle and $\Delta\omega = 2\pi\Delta f$, respectively.

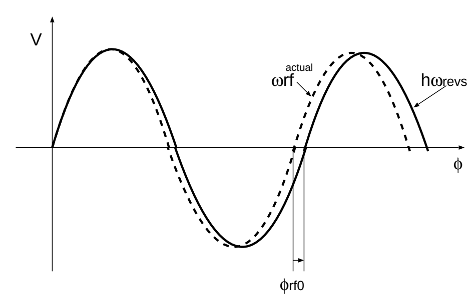

Figure 2: The phase relation between 'actual rf' and 'reference rf'.

Then, the phase shift ϕ_{rf0} of the actual rf voltage pattern from the original rf voltage pattern becomes as follows:

$$\phi_{\mathrm{rf0}} = 2\pi\left(\frac{\omega_{\mathrm{rf}}^{\mathrm{actual}}}{h\omega_{\mathrm{revs}}} - 1\right) = \frac{2\pi\Delta f T_{\mathrm{revs}}}{h} \tag{2}$$

or

$$= 2\pi h\left(\frac{\omega_{\mathrm{rf}}^{\mathrm{actual}}}{h\omega_{\mathrm{revs}}} - 1\right) = 2\pi\Delta f T_{\mathrm{revs}}, \tag{3}$$

where T_{revs} is the revolution period of the synchronous particle. The eq. (2) is the case that the frequency offset Δf is added for each rf wave and the eq. (3) is the case that it is added for each revolution.

The requirement from the synchronization is that the bunch center should be shifted over one rf wave length forward and backward. Since the RCS has a harmonic number

* masanobu.yamamoto@j-parc.jp

of 2, we can replace the position of each bunch, then we can manage any request from the synchronization. This means:

$$\sum_n 2\pi\Delta f \cdot T^n_{\mathrm{revs}} = \pm 2\pi, \tag{4}$$

where n means the n-th turn from the beginning of the acceleration. For example, if we perform the phase shift during 10 msec, this means $\sum_n T^n_{\mathrm{revs}} = 10$ msec, then Δf should be ± 100 Hz in the case of eq.(3).

However, the eq.(4) shows the shifting of the 'rf bucket center', not the 'bunch center'. The bunch is shifted according to the slippage of the synchrotron motion as follows:

$$\frac{\Delta\omega_{\mathrm{rev}}}{\omega_{\mathrm{revs}}} = \eta_s \frac{\Delta p}{p_s}, \tag{5}$$

where $\Delta\omega = \omega^{\mathrm{actual}}_{\mathrm{rev}} - \omega_{\mathrm{revs}}$, $\omega^{\mathrm{actual}}_{\mathrm{rev}}$ is the revolution frequency of the bunch center, η_s is a slippage factor of the synchronous particle, p_s is a momentum of the synchronous particle $\Delta p = p - p_s$ and p is the momentum of the bunch center, respectively.

If the phase shift rate is so called 'adiabatic', the bunch center follows the rf bucket center, and the synchronization is performed well. Otherwise, the difference between the rf bucket center and the bunch center becomes larger and larger, then the particle will be lost during the phase shift by the filamentation of the longitudinal beam emittance. We should avoid such beam losses. Since the synchrotron frequency of the RCS is very low near the extraction as shown in Fig. 1, the slippage of the bunch center also becomes small.

SIMULATION RESULTS FOR SYNCHRONIZATION

We perform the simulation for two cases:

1. The case that the phase shift starts at 10 msec after beginning of the acceleration and continues until 20 msec, then the frequency offset is $\Delta f = 100$ Hz.

2. The case that the phase shift starts at 15 msec after beginning of the acceleration and also continues until 20 msec, then the frequency offset is $\Delta f = 200$ Hz.

Figure 3 shows the beam emittance at the extraction in the case that the phase shift is not applied. The horizontal axis shows the phase in the rf wave for the synchronous particle, 0 nsec means that the bunch center equals to the synchronous particle. This is the reference beam emittance.

Figure 4 shows the case 1. The phase shift becomes around -600 nsec, this means that the bunch center is shifted by 2π, because the rf wave length is 598 nsec at extraction in RCS. Figure 5 shows the case 2. The phase shift also becomes around -600 nsec. Figure 6 shows a plot of the phase shift of the bunch center during the synchronization. It seems that the phase is shifted monotonously and finally it reaches -600 nsec for both cases. However, the momentum dispersion becomes very large in the case of 200 Hz frequency offset as shown in Fig. 7, this causes the filamentation and the beam losses of 0.7 % happen during the phase shift. This means that the case 2 is not adiabatic for the RCS synchronization. From these results, we should employ the case 1.

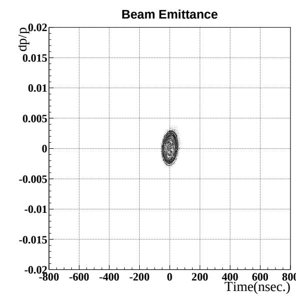

Figure 3: The beam emittance at the extraction for the reference rf pattern.

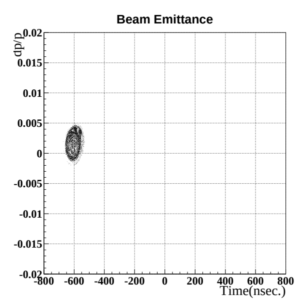

Figure 4: The beam emittance in case 1.

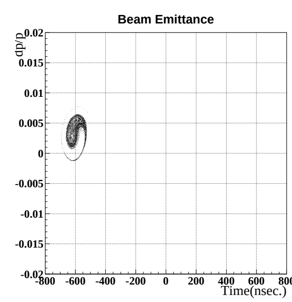

Figure 5: The beam emittance in case 2.

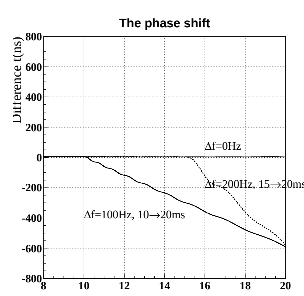

Figure 6: The simulation results of the phase shift.

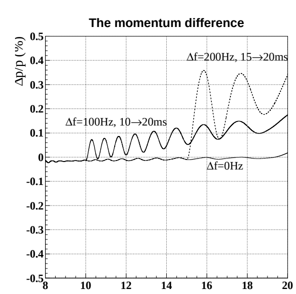

Figure 7: The simulation results of the momentum shift.

EVALUATION OF BENDING FIELD ERROR

It is very important to know how much influence is occurred on the longitudinal bunch motion if the bending field has some errors from the designed value. This can be evaluated by same method as for the synchronization.

Supposing a 'nominal particle' which is synchronized with the design bending field, it obtains the energy from the 'reference rf' voltage as shown in Fig. 2. On the other hand, there is a 'synchronous particle' which is synchronized with the bending field with some errors, and affected by the 'actual rf' voltage also as shown in Fig. 2. Then, the frequency offset Δf arises between the nominal particle and the synchronous particle.

In the practical method of the particle tracking, we prepare two rf voltage patterns, one is for the nominal particle and the other is for the synchronous particle. Then, we calculate the frequency difference turn by turn. After that, the particle tracking is performed including the frequency offset in same way as the synchronization case.

We evaluate the effect from the bending field error under the condition that the bending field always has a offset of 10^{-4}, that is, the bending field$B$ is $B = B_0 + B_0 \cdot 10^{-4}$, where B_0 is the design value. Of course, the error of the real bending field is random, but we can get the knowledge how much frequency offset corresponds to the error of 10^{-4}.

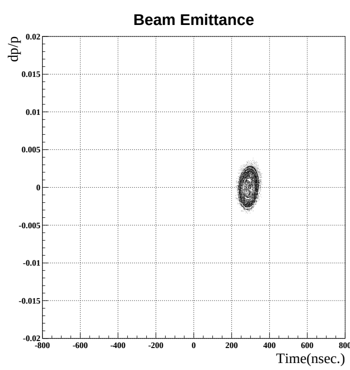

Figure 8: The beam emittance in the case of the bending field error of 10^{-4}.

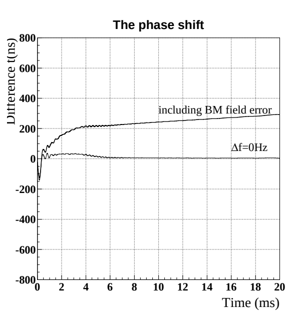

Figure 9: The phase shift in the case of the bending field error of 10^{-4}.

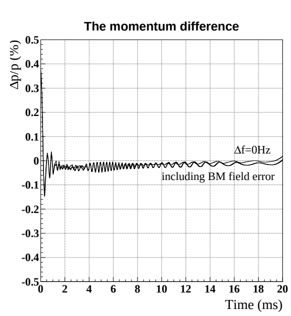

Figure 10: The momentum shift in the case of the bending field error of 10^{-4}.

Figure 8 shows the beam emittance at the extraction, and Figure 9 shows the phase shift, the thick line is the case with the bending field error. The bending field error of 10^{-4} also causes the phase shift around 300 nsec, but the momentum difference does not become large as shown in Fig. 10 because the constant error affects the beam adiabatically. Figure 11 shows the calculation result of the frequency offset, the error of 10^{-4} corresponds to a frequency offset of 10∼65 Hz in RCS.

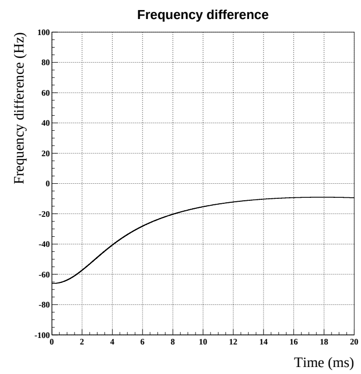

Figure 11: The frequency offset caused by the bending field error of 10^{-4}.

SUMMARY

We perform the particle tracking simulation for the synchronization, then we find that the frequency offset of 100 Hz is suitable in the RCS operation. Furthermore, we evaluate the effect of the bending field error to the longitudinal bunch motion, then we find that the error of 10^{-4} corresponds to the frequency offset of 10∼65 Hz in RCS.

REFERENCES

[1] F. Tamura *et al*, "Synchronization system for J-PARC RCS", Proc. 3rd annual meeting of particle accelerator society of Japan and 31th Linac accelerator meeting in Japan, 2006

[2] F. Tamura *et al*, "Timing System for J-PARC", Proc. of PAC2005, p3853

[3] F. Tamura *et al*, "J-PARC Timing System", Proc. of ICALEPCS2003, p247

[4] M. Yamamoto *et al*, "Longitudinal Beam Dynamics on 3 GeV PS in JAERI-KEK Joint Project", Proc. of EPAC 2002, p.1073