MITIGATION OF BEAM INSTABILITY DUE TO SPACE CHARGE EFFECTS AT 3 GeV RCS IN J-PARC

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Abstract

In order to accomplish high intensity proton beams, it is important to identify impedance sources in accelerators. At 3 GeV rapid cycling synchrotron (RCS) in Japan Proton Research Complex (J-PARC), the kicker impedance is the most dominant among such impedance sources. Beam instability can be observed by correcting chromaticity during the acceleration. Growth rate of the beam instability can be reduced by increasing peak current (reducing bunching factor). In other words, it is experimentally found that space charge effects mitigate the beam instability.

INTRODUCTION

J-PARC [1], which is composed of 181MeV linac, 3 GeV RCS and 30 GeV main ring, is the proton accelerator, that aims to accomplish MW-class proton beam in the future. In order to achieve the purpose, it is very important to identify the impedance sources in the rings. In the RCS, the kicker impedance has been considered to be the most dominant among such impedance sources. However, in 300 kw-equivalent intensity beam operation, the beam instability was not observed in the RCS. This is because sextupole magnets were supplied by DC electric power. In other words, chromaticity was corrected to zero only at the injection energy. The beam has tune spread due to the momentum spread during the acceleration.

Since last summer, the electric power source has been upgraded to AC power. The chromaticity is able to be handled in the entire acceleration region. Further, 420 kW-equivalent intensity beam at low level intensity loss of less than 1% is now achieved in the RCS. Using the high intensity beam, the beam instability can be investigated by changing several parameters in the RCS (for example, chromaticity, bunching factor etc). In this report, we experimentally demonstrate that space charge effect mitigates the beam growth rate of the beam instability.

TRANSVERSE BEAM INSTABILITIES

The impedance budget of the transverse impedance shows that the kicker impedance is the dominant source in the RCS. Actually, the measurement results show that there are sharp peaks in the RCS kicker impedances (see Fig. 1.)[2, 3, 4, 5]. They are about 10 times larger than those of SNS kickers [6]. The sharp peaks are due to cable resonances of beam-induced currents in the kicker magnet.

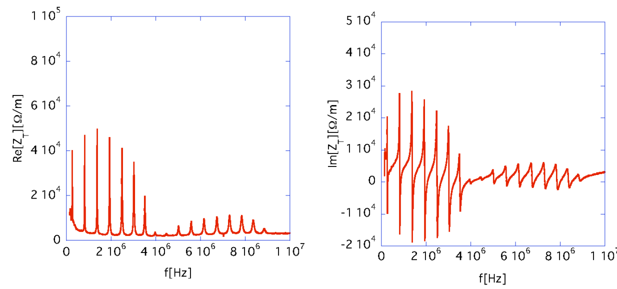

Figure 1: The measurement results of a kicker impedance of the RCS. The left and the right figures show the real and the imaginary parts, respectively. The total number of the kicker magnets n_k is eight in the RCS.

There is a conventional formula for estimate of the growth rate of beam positions, using the impedance Z_T as input data [7, 8]:

$$\tau_m^{-1} = -\frac{I_c c n_k}{(1+m)4\pi Q_T E/c} \sum_{p=-\infty}^{\infty} Z_T(\omega_p) F_m(\omega_p - \omega_\xi), \quad (1)$$

$$F_m = \frac{h_m(\omega)}{B_f \sum_{q=-\infty}^{\infty} h_m(\omega_q - \omega_\xi)}, \quad (2)$$

$$h_m(\omega) = \frac{\tau_L^2 (m+1)^2 [1 + (-1)^m \cos(\omega\tau_L)]}{2\pi^4 [(\omega\tau_L/\pi)^2 - (m+1)^2]^2}, \quad (3)$$

$$\omega_\xi = 2\pi f_0 \xi Q_T/\eta, \tau_L = \frac{B_f}{h f_0}, \quad (4)$$

$$\omega_p = 2\pi f_0 (ph + \mu + Q_T + m\nu_s), \quad (5)$$

where E is the beam energy, ξ is the chromaticity, μ is the coupled bunch mode number $\mu = 0...h-1$, h is the harmonic number, m is the head-tail mode number. The main parameters for the 420 kW-equivalent intensity beam in the RCS are summarized in Table 1.

Using the measured kicker impedance, the highest growth rate among different head-tail modes during the acceleration was calculated, assuming that the chromaticity is corrected to zero in the whole energy. The results are shown in Fig. 2. We can see that the sharp impedances of kicker magnets produce intolerable growth rate. This may be a significant constraint to increase the beam intensity.

Measurement for the 420 kw-equivalent intensity beam is done for the case that the chromaticity is corrected to zero only at the injection energy. The emittance growth is mitigated by applying both longitudinal and transverse paintings. The results are shown in Fig. 3. Beam instability

Table 1: Parameter List of RCS (C = 348.333, h=2, Repetition rate = 25 Hz)

T(kinetic energy, GeV)	0.181		3
f_0 (revolution freq., MHz)	0.47		0.84
η(slippage factor)	-0.69		-0.047
$Q_x/Q_y(=Q_T)$(tune)		6.45/6.42	
B_f(bunching factor)	0.374		0.185
N_b(proton/bunch)/10^{13}	1.74		1.74
I_c(average current, A)	2.62		4.68
I_p(peak current, A)	7		25
$\Delta p/p(\%)$	0.85		0.38
τ_z(half bunch length, m)	55		20
ν_s(synchrotron tune)	0.0058		0.0005

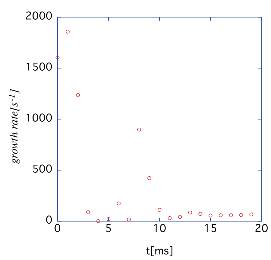

Figure 2: Horizontal instability due to the kicker magnets at 420 kW-equivalent beam operation in the RCS. The chromaticity is corrected to zero in the entire energy.

is not observed both in the horizontal and the vertical directions. Formula (2) is derived from the linear theory where no betatron tune spread, no space-charge effects nor Landau damping effects are considered. Without space charge, it was predicted that the beam instability would occur in the 420 kw high intensity beam. However, the beam instability does not occur. Landau damping may stabilize the beam instability not only through the momentum spread, but also through the space charge effect.

In order to isolate the space charge effect from the momentum spread, the chromaticity is corrected to zero in the entire energy. As we find in afterwards (shown in Fig. 6), the beam instability is observed only in the horizontal direction. Now, let us investigate the mitigation of beam instability due to space charge effect by changing some machine parameters. Bunching factor (average current/peak current) is one of the important parameters, which is related to the space charge effect. In order to mitigate emittance growth due to the space charge effect, the bunching factor is enlarged by applying second harmonic of rf-cavity during the injection period. The left figure in Fig. 4 shows the bunching factor during the acceleration both for the cases that only fundamental harmonic is applied and that the second as well as the fundamental harmonics are applied. The corresponding bunch shapes at 10ms is represented in the

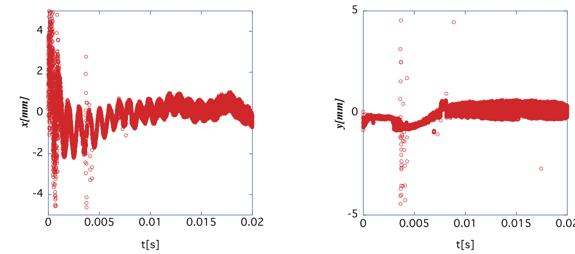

Figure 3: The measurement results for 420 kW-equivalent intensity beam operation. The left and the right figures show the horizontal and the vertical beam positions, respectively. The chromaticity is corrected to zero only at the injection energy.

right figure of Fig. 4.

In order to investigate the Landau damping due to space charge effect, it is important to ensure that the momentum spreads are almost identical both for two cases. Figure 5 shows simulation results for the momentum spread. Before 3ms, the momentum spread for the case that only fundamental harmonic is applied is larger than that for the case that the second harmonic is applied, as well. However, except the injection period, the momentum spreads for both two cases are almost identical.

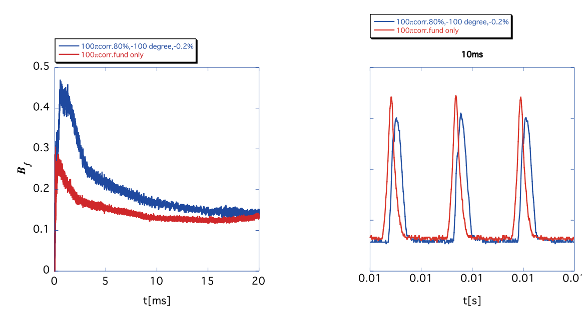

Figure 4: The left and the right figures represent the bunching factor during the acceleration period and the bunch shape at 10 ms, respectively.

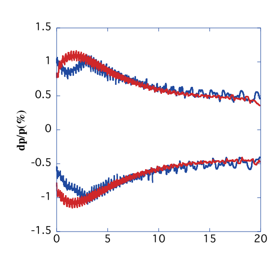

Figure 5: Simulation results of the momentum spread during the acceleration period.

Now, let us measure the beam positions by changing the bunching factor. The results for 420 kW-equivalent intensity beam are shown in Fig. 6. The left and the right figures show the horizontal and the vertical beam positions, respectively. The chromaticity is fully corrected to zero during the entire energy region. In the measurement, the second harmonic as well as fundamental harmonic are applied. The bunching factor is larger. On the other hand, Figure 7 shows the horizontal beam positions when the only fundamental harmonic is applied. Comparison between both two results teaches us that the beam growth rate is lower as the bunching factor is smaller (the peak current is larger). Naively thinking, the bigger bunching factor should give a smaller growth rate, because of smaller peak current. However, the measurement result is opposite. Incoherent tune spread due to space charge is about 0.45 at 1ms in 420kw operation. According to Sacherer, the stability condition in the existence of betatron tune spread is given by:

$$|\text{ Full-spread at half-height of } 2\pi Q_T f_0| > \text{growth rate}, \quad (6)$$

where Q_T is transverse tune and f_0 is the revolution frequency. The experimental results suggest that the suppression of the growth rate by the space charge effect is significant.

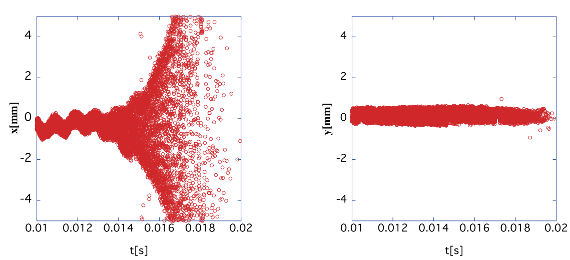

Figure 6: The measurement results for 420 kW-equivalent intensity beam. The left and the right figures show the horizontal and the vertical beam positions, respectively. The chromaticity is fully corrected to zero during the entire energy region.

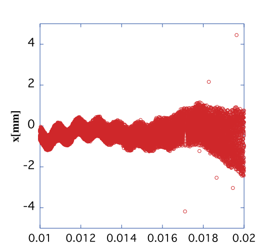

Figure 7: The measurement results for 420 kW beam operation. The only fundamental rf voltage is applied.

The measurement of beam positions, where the chromaticity is corrected to +1, is also done. The results are shown in Fig. 8. The mitigation of growth rate is observed in this case, as well.

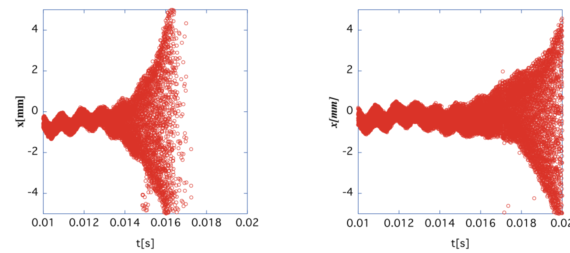

Figure 8: The measurement results for 420 kW beam operation. The chromaticity is fully corrected to +1 in the entire energy region. The left and the right figures show the horizontal beam positions for the cases that the second harmonic is applied as well (peak current is smaller) and that only fundamental frequency is applied (peak current is larger), respectively.

SUMMARY

By using the beam of the RCS of J-PARC, we experimentally demonstrate that the beam instability is mitigated due to space charge effects. From the beam instability point of view, it is preferable not to introduce second harmonic RF frequency as well as not to correct chromaticity. However, the application of both the second harmonic and the chromaticity correction are indispensable to reduce the beam loss at the injection period. Toward PMW operation, it is planned that the chromaticity correction and the application of the second harmonic will be done only at the injection period.

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