ORBIT SIMULATION, MEASUREMENT AND MITIGATION OF TRANSVERSE BEAM INSTABILITY IN THE PRESENCE OF STRONG SPACE CHARGE IN THE 3-GeV RCS OF J-PARC

P.K. Saha*, Y. Shobuda, H. Hotchi, H. Harada,
N. Hayashi and F. Tamura, J-PARC Center, KEK & JAEA, Tokai, Japan

Abstract

The transverse impedance of eight extraction pulse kicker magnets (KM) is a strong beam instability source in the 3-GeV RCS (Rapid Cycling Synchrotron) at J-PARC (Japan Proton Accelerator Research Complex). Significant beam instability occurs even at a half of the designed 1 MW beam power when the chromaticity (ξ) is fully corrected for the entire acceleration cycle up to 3 GeV, but no beam instability occurs if the ξ is fully corrected only at the injection energy of 0.4 GeV. To realize the designed 1 MW beam power, collective beam dynamics with including the space charge effect for the coupled bunch instabilities excited by the KM impedance and associated measures were studied by incorporating all realistic time-dependent machine parameters in the ORBIT 3-D particle tracking code. The simulation results for systematic beam instability studies and its mitigation measures were found to be very consistent with measurements and, as a consequence, an acceleration of 1 MW beam power has been successfully achieved.

INTRODUCTION

The 3-GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex (J-PARC) is designed for 1 MW beam power. A total of 8.33×10^{13} protons in 2 bunches is accelerated from 0.4 GeV to the 3 GeV at a repetition rate of 25 Hz [1]. The extracted beam is simultaneously delivered to the MLF (Material and Life Science Experimental Facility) and the MR (Main Ring Synchrotron). Table 1 gives a list of RCS key parameters, especially those, which are strongly connected to the beam instabilities.

Similar to any such high intensity machines, the beam instability at 1 MW beam power was also a concern in the RCS [2]. The impedance sources throughout the machine were controlled to be as minimum as possible but unfortunately the impedances of RCS 8 extraction kicker magnets (KM) remains as significant beam instability sources [3]. The head-tail coupled bunch beam instability occurs even at beam power exceeding 0.25 MW when the chromaticity (ξ) (defined by the betatron tune variation with the beam momentum) is fully corrected for the entire acceleration cycle. The beam instability up to 0.5 MW beam power can be mitigated by ξ fully corrected only at the injection energy, but significant beam instability occurs at 1 MW beam power, even at no ξ correction at all for the entire acceleration cycle.

The hardware measure to reduce the KM impedances is under study, which needs extensive R&D works for practical

implementation. In order to study the detailed beam instability caused by the KM impedance and to determine realistic parameters to suppress the beam instability at 1 MW, we used ORBIT 3D space charge code [4]. We introduced numerous enhancements to the code to cope with all relevant time-dependent machine parameters, error sources, and also realistic transverse and longitudinal injection painting [5]. We have also upgraded the impedance model to incorporate realistic time-dependent impedances for the beam instability simulation. The space charge (SC) effect on the beam instability, especially the suppression of the beam instability by the SC is intensively discussed in theoretical works [6–9]. At first, we have done a precise SC simulation as RCS is a SC dominated machine not only because of high intensity beam but also for its lower injection energy. The ORBIT code takes indirect SC into account in the simulation. The radius of the conducting wall boundary is used to 0.145 m in the simulation. Then, we studied a detailed of beam instability dependence on many parameters such as momentum spread ($\Delta p/p$) of the injected beam, the degree of ξ correction and the choice of betatron tunes to stabilize 1 MW beam power.

Table 1: Time dependent main parameters of the RCS, especially those related to the beam instabilities are given [1].

Name	Injection	Extraction
Kinetic energy [GeV]	0.4	3
Rev. frequency (f_0) [MHz]	0.614	0.84
Bunching factor (B_f)	0.47	0.21
Slippage factor (η)	-0.478	-0.047
Bunch length [m]	160	60
Synchrotron tune (ν_s)	0.0053	0.0005
Betatron tune (ν_x, ν_y)	(6.45, 6.42)	(6.399, 6.405)
Natural chromaticity (ξ_x, ξ_y)	-10, -7	variable

BEAM INSTABILITY UP TO 0.5 MW BEAM POWER

Figure 1 shows simulation (top) and measurement (bottom) results of coupled bunched beam instability dependence on the beam intensity. The RCS injection energy ($E_{inj.}$) in the left and right plots were 0.181 GeV (until 2013) and 0.4 GeV, respectively, while the extraction energy was always 3 GeV. The horizontal axis is the time, where vertical axis is the turn-by-turn horizontal position of the circulating beam for a BPM (Beam Position Monitor) located at the RCS injection area [10]. The beam instability occurs for the beam power exceeding 0.25 MW when the ξ is corrected to zero

---
* saha.pranab@j-parc.jp

05 Beam Dynamics and EM Fields
D07 High Intensity Circular Machines Space Charge, Halos

This is a preprint — the final version is published with IOP

throughout the acceleration cycle by using sextupole with ac fields (SX ac), but the beam is stable if the ξ is corrected to zero for only at the injection energy by using SX with dc fields (SX dc). The simulation and measurement results are found to be consistent with each other. Both simulation and measurement results show that the beam instability occurs at higher energy, which means that the beam is stabilized by the SC at lower energy. Furthermore, the growth rates are slightly higher for higher $E_{inj.}$ of 0.4 GeV, which from the experimental data for 0.5 MW beam power is estimated to be 900 s^{-1}, as compared to 759 s^{-1} for the $E_{inj.}$ 0.181 GeV case. The Landau damping effect of the nonlinear SC force is smaller for higher $E_{inj.}$, resulting an enhancement of the beam instability as compared to that with lower $E_{inj.}$ case. We have done detailed and unique studies for the SC effects on the beam instability as given in the next section.
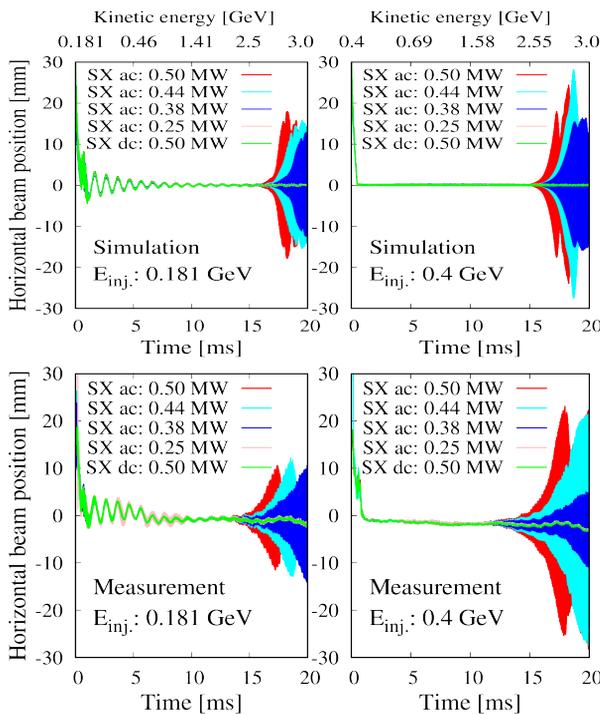

Figure 1: Simulation (top) and measurement (bottom) results of beam instability growth dependence on the beam power.

BEAM INSTABILITY SUPPRESSION BY THE SPACE CHARGE EFFECT

The significance of the SC effect for the beam instability suppression has been intensively discussed in many recent theoretical works [8, 9]. The Landau damping effect is more enhanced due to larger tune spread caused by the SC to suppress the beam instability. Differing from the present beam instability in the RCS, although the transverse mode coupling impedance (TMCI) is considered in the later article [9], the important point is that the stability exists even at an extremely high SC regime defined by the parameter as the ratio of the SC tune shift to the synchrotron tune ($\Delta\nu/\nu_s$) far exceeding the unity ($>> 1$).

In this study we consider the lower injection energy of 0.181 GeV as for example, the incoherent betatron tune shift, $\Delta\nu$ is inversely proportional to $\beta^2\gamma^3$, where β and γ are the relativistic parameters of the beam [11]. Moreover, we increased the SC force by applying only fundamental rf voltage (V_{1rf}) and also without applying longitudinal injection painting (LP), which numerically gives a significantly strong SC regime with $\Delta\nu/\nu_s >> 1$ (~ 80) for 0.5 MW beam power.

Figure 2 shows simulation (left) and experimental (right) results of time dependent beam intensity with SC force controlled by the rf voltages and LP for 0.5 MW beam power. Due to the strong SC effect when applying only V_{1rf}, the beam intensity drops by about 15% (black) at lower energy, as compared to that well mitigated by applying dual harmonic rf voltages and LP (red) [12, 13]. The bunching factor (B_f) at the end of injection is obtained to be only 0.27 for the former case, as compared to it twice higher (0.45) for the later case, where the $\Delta\nu$ is also inversely proportional to the B_f. The data in red are same as those shown by the plots with same color in the left of Fig. 1.

In contrast to the beam survival, beam instability occurs for the lower SC condition in both simulation (left) and measurement (right) in shown in Fig. 3. It is worth mentioning that the beam instabilities with applying dual harmonic rf voltages and LP occur (Fig. 1) even for much lower intensity than survived intensity with applying V_{1rf} only. The beam instability is suppressed due to enhancement of Landau damping effect by the strong SC force. The simulation and measurements are very consistent with each other.
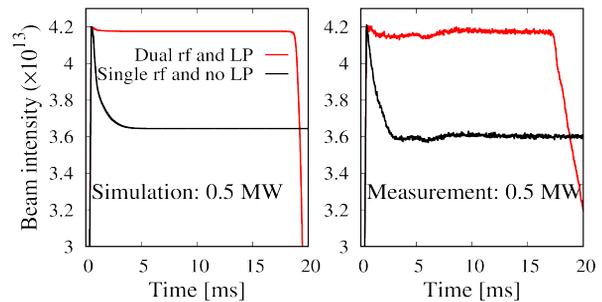

Figure 2: Simulated and measured time dependent beam intensity for two different SC conditions.
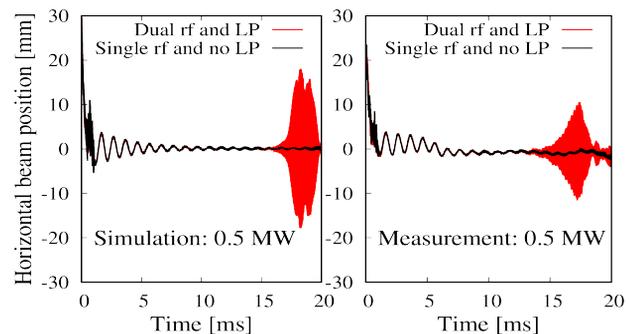

Figure 3: Simulation and measurement results of beam instability suppression by the SC effect.

In the simulation, we also studied the effect of indirect SC by changing radius (ρ) of the vacuum chamber (conducting wall boundary) [13]. The beam which is stable by applying single rf system (for example Fig. 3) tends to unstable with a lower SC effect if the value of ρ is enlarged from its actual value of 0.145 m. On the other hand, the stability condition naturally doesn't change for a reduction of the ρ.

ACCOMPLISHMENT OF 1 MW BEAM POWER

In 2014, the peak current of the H$^-$ beam in the Linac was upgraded to the designed 50 mA to achieve 1 MW beam power in the RCS. We performed detailed simulation studies for the beam instability scenarios beyond 0.5 MW beam power to prepare realistic guidelines to accomplish 1 MW beam power. In order to achieve 1 MW beam power, a reduction of the SC effect is very essential to mitigate the beam losses, especially at lower energy. For that purpose, an wider momentum spread, $\Delta p/p$ (rms 0.18%) of the injected beam in addition to the dual harmonic rf voltages at lower energy and also full LP injection were applied. The beam losses can be well mitigated, but a reduction of the SC effect enhanced the beam instability (Fig. 3).

Although no beam instability occurs up to 0.5 MW beam power when ξ is corrected only at the injection energy by SX dc (Fig. 1), the simulation results shows that beam is unstable at 1 MW beam power even if the SX is kept off for no ξ correction at all. We have studied the possible manipulation of the horizontal betatron tune, ν_x during the acceleration cycle. The ν_x is particularly important, as the transverse horizontal impedance of the RCS KM excites only horizontal beam instability [8].

The green line in Fig. 4 shows a realistic manipulation of ν_x as a function of acceleration time to stabilize the beam at 1 MW power. The ν_x at injection is typically set at 6.45 but it is manipulated to finish at 6.40. The tracking errors between bending and quadrupole magnets lead to a temporal variation of ν_x even without any manipulation (red line).
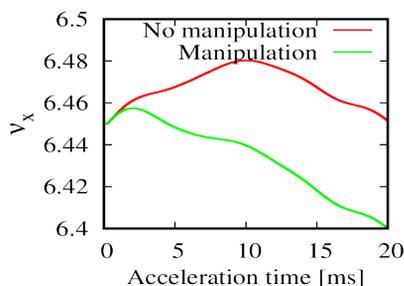

Figure 4: Simulation result of realistic manipulation of ν_x (green) to mitigate the beam instability at 1 MW beam power.

Figure 5 shows comparison of the simulation (left) and measurement (right) results of beam instability mitigation at 1 MW beam power by utilizing a proper ν_x manipulation. The SX are turned off for no ξ correction throughout the acceleration cycle (keep the natural ξ for the entire energy range), but the beam instability occurs for ν_x without any

manipulation. However, such a beam instability can be well mitigated and stabilized by utilizing a proper ν_x manipulation. A minimal ξ correction to ensure Landau damping to be more effective and to avoid characteristics (resonance lines) of the impedance [3] of the extraction kicker magnets, a proper manipulation of the betatron tune were employed together to mitigate the beam instability and accomplished the designed 1 MW beam power successfully [14]. More detailed results with ξ variation and ν_x manipulations can be found in our earlier articles [8, 13].
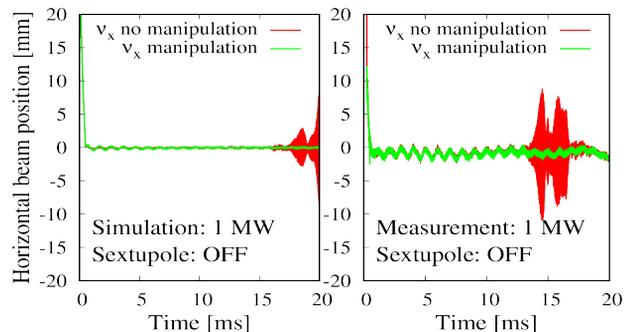

Figure 5: Comparison of simulation (left) and measurement (right) results of beam instability mitigation at 1 MW beam power. No correction of the ξ and a proper ν_x manipulation was determined to stabilize the beam (green). The simulation results are well confirmed in the measurements.

SUMMARY

The transverse impedance of the extraction kicker magnets in the 3-GeV RCS of J-PARC is a significant beam instability source and also the biggest issue to realize the designed 1 MW beam power. The ORBIT code was highly enhanced by introducing all time dependent machine parameters, error sources, transverse and longitudinal injection painting processes as well as the KM impedances for realistic beam instability studies considering including the space charge to determine measures for beam instability mitigation. The beam instability suppression by the space charge effect has been observed in both simulations and measurements. The indirect space charge effect taking into account by a perfectly conducting boundary wall is very important to understand the realistic beam instability nature in the RCS. A reduction of the space charge effect is very important for beam losses mitigation at lower energy, but beam tends to be unstable in that case. To make Landau damping more effective a minimal correction of the ξ and a proper manipulation of the betatron tune to avoid characteristics of the KM impedance were employed to mitigate the beam instability at 1 MW. The simulation results are well reproduced by the measurements, and acceleration of the designed 1 MW beam power has been successfully accomplished. However, such a huge impedance of the KM restricts on the choice of flexible and simultaneous operation of the RCS with dynamic variation of the parameters requested by the users. A reduction of the KM impedance is therefore highly desirable.

This is a preprint — the final version is published with IOP

REFERENCES

[1] High-intensity Proton Accelerator Project Team, "Accelerator technical design report for J-PARC", JAERI-Tech 2003-044 and KEK Report 2002-13.

[2] Y.H. Chin *et al.*, "Impedance and beam instability issues at J-PARC Rings", in Proc. HB'06, Tsukuba, Japan (2006), p. 125.

[3] Y. Shobuda *et al.*, Nucl. Inst. and Meth. A **713**, 52 (2013).

[4] J.A. Holmes *et al.*, in The ICFA Beam Dynamics Newsletter, Vol. 30, (2003).

[5] P.K. Saha *et al.*, in Proc. of IPAC'13, Shanghai, China (2013), pp. 521-523.

[6] M. Blaskiewicz, Phys. Rev. ST Accel. Beams **4**, 044202 (2001).

[7] Y.H. Chin *et al.*, Phys. Rev. Accel Beams **19**, 014201 (2016).

[8] Y. Shobuda *et al.*, Prog. Theor. Exp. Phys. **2017**, 013G01 (2017).

[9] V. Balbekov, Phys. Rev. ST Accel. Beams **20**, 114401 (2017).

[10] N. Hayashi *et al.*, "Beam position monitor system of J-PARC RCS", Nucl. Instr. and Meth. A **677**, 94 (2012).

[11] L.J. Laslett, BNL Report 7534, pp. 325-367 (1963).

[12] F. Tamura *et al.*, Phys. Rev. Accel. Beams **12**, 041001 (2009).

[13] P.K. Saha *et al.*, Phys. Rev. Accel. Beams **21**, 024203 (2018).

[14] H. Hotchi, in Proc. IPAC'15, IPAC'15, Richmond, VA, USA (2015), pp. 1346-1348.