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 $8.33 \times 10^{13}$ 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 related 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 a half of the designed 1 MW beam power when the chromaticity ($\xi$) is corrected for the entire acceleration cycle up to 3 GeV, but no beam instability occurs if the $\xi$ 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.

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 $\xi$ is corrected to zero.
throughout the acceleration cycle by using sextupole with ac fields (SX ac), but the beam is stable if the $\xi$ 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 $E_{\text{inj}}$ of 0.4 GeV, which from the experimental data for 0.5 MW beam power is estimated to be $900 \, \text{s}^{-1}$, as compared to 759 $\, \text{s}^{-1}$ for the $E_{\text{inj}}$ 0.181 GeV case. The Landau damping effect of the nonlinear SC force is smaller for higher $E_{\text{inj}}$, resulting an enhancement of the beam instability as compared to that with lower $E_{\text{inj}}$ case. We have done detailed and unique studies for the SC effects on the beam instability as given in the next section.

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 $\beta$ and $\gamma$ are the relativistic parameters of the beam [11]. Moreover, we increased the SC force by applying only fundamental rf voltage ($V_{1\text{rf}}$) and also without applying longitudinal injection painting (LP), which numerically gives a significantly strong SC regime with $\Delta \nu/\nu_s >> 1$ ($\sim 80$) 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 $V_{1\text{rf}}$, 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 latter 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 $V_{1\text{rf}}$ 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 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 ($\rho$) 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 $\rho$ 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 $\rho$.

**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, $\Delta p/\langle p \rangle$ (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 enhances the beam instability (Fig. 3).

Although no beam instability occurs up to 0.5 MW beam power when $\xi$ 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 $\xi$ correction at all. We have studied the possible manipulation of the horizontal betatron tune, $\nu_x$, during the acceleration cycle. The $\nu_x$ 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 $\nu_x$ as a function of acceleration time to stabilize the beam at 1 MW power. The $\nu_x$ 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 $\nu_x$ even without any manipulation (red line).

Figure 5 shows comparison of the simulation (left) and measurement (right) results of beam instability mitigation at 1 MW beam power. No correction of the $\xi$ and a proper $\nu_x$ 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 $\xi$ 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.
REFERENCES


