HIGH INTENSITY BEAM OPERATION OF J-PARC RCS WITH MINIMUM BEAM LOSS

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Abstract
The 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex) at present operates at a high intensity beam nearly to its designed beam power of 1 MW. The beam loss and the corresponding residual radiation are key issues and limitations for beam intensity ramp up. Based on detail numerical simulations and recent systematic beam studies the beam loss has been well mitigated to a minimum level. The residual beam loss at 1 MW beam power is mostly due to unavoidable foil scattering of the circulating beam during multi-turn injection. We have identified almost all major beam loss sources and optimized to minimize the beam loss for achieving a stable operation at 800 kW beam power since April 2022.

INTRODUCTION
The 3-GeV RCS of J-PARC is designed for high intensity proton beam of 1 MW for pulsed muon and neutron productions at the MLF (Materials and Life Science Experimental Facility) as well as beam injection to the MR (30-GeV Main Ring Synchrotron) [1]. The injection beam energy is 400 MeV, which is accelerated to 3 GeV at a repetition rate of 25 Hz and simultaneously delivered to the MLF and MR. The beam power to the MLF is 800 kW at present, while is also nearly 800 kW equivalent beam power to the MR at FX mode. The beam sharing between MLF and MR is typically 9:1. The machine activation is thus mainly determined by the beam loss for beam operation to the MLF. As a result, a beam loss reduction in the RCS for operation in this mode is highly important.

Figure 1 shows a schematic view of the RCS. The $^-$charge-exchange injection (CEI) system followed by the beam collimation section is placed at the first straight section. The beam loss in the RCS has been well mitigated and controlled, occurring only at injection energy and localized mostly in the collimator region. However, the residual radiation at the injection area due to uncontrolled beam losses caused by foil scattering of the circulating beam during multi-turn charge-exchange injection is one of the most concerning issues to ramp up the beam power [2–5]. To reduce the circulating beam hitting rate on the foil, a large transverse painting (TP) at injection for both horizontal and vertical planes are adopted [6, 7]. This is done by varying horizontal closed orbit with 4 horizontal painting magnets and varying vertical angle of the injection beam by using two vertical painting magnets placed at the injection beam transport (BT) [5]. The average foil hits at a maximum painting area of 200\(\pi\) mm mrad can be kept to only 7, but similar to other facilities the residual radiation at the injection area caused by the foil scattering beam losses is very high even at a lower beam power [4, 8–12]. To further reducing the foil scattering beam losses, recently we have minimized the injection beam size and implemented a smaller size foil. We obtained a significant reduction of the beam losses at the injection area, collimator section and its downstream. The residual radiation at those areas for RCS operation at 700 kW beam power was also measured to be significantly reduced [5]. However, due to a nonlinear effect of the space charge (SC), the beam loss beyond 700 kW was measured to be several factors higher than a beam intensity increase. The beam loss at 600 kW increased 3 times higher than an intensity increase of only 14% from 700 kW. We started our 2nd phase of beam loss mitigation at this intensity including up to 1 MW by systematic experimental studies and numerical beam simulations. We have optimized both longitudinal and transverse injection paintings to mitigate the beam loss to an extremely low level, which is presented in this paper.

EXPERIMENTAL RESULTS OF BEAM LOSS MITIGATION
To mitigate the beam loss at 800 kW, at first we adopted an optimized longitudinal painting (LP) done at injection. The

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LP plays a dominant role to mitigate the space charge (SC) effect at lower beam energy by producing a uniform beam distribution in the longitudinal phase space [7, 13, 14]. The present optimization is a combination of momentum offset of the Linac beam and a frequency offset of the RCS RF. The Linac momentum offset of -0.15% and RF frequency offset for a momentum offset of -0.05% are applied, resulting in an offset of the injection beam from the RF bucket.

Figure 2 shows measured signals of the beam loss monitors (BLM) placed at the collimator and the 1st arc sections of the RCS. The horizontal axis is the BLMs ID, where vertical axis is the integrated beam loss over the whole cycle of 20 ms. The beam loss at 700 kW is shown by the green color, where the red and blue colors are measured at 800 kW without and with an optimization of the LP, respectively. The integrated beam loss at 800 without optimization is more than 40% higher as compared to that at 700 kW, while only a 14% increase of the beam intensity. However, such an additional beam loss has been well mitigated by applying an optimized LP as shown by the blue color, which is kept even a lower level as compared to the beam loss at 700 kW. A combination of Linac momentum offset together with RF frequency offset improves longitudinal beam properties to reduce the number of off momentum particles for achieving such a significant beam loss mitigation.

Next, we applied a modified transverse painting (TP), which was proposed as an essential way to control the transverse beam density distribution for beam loss mitigation at high-intensity [15]. In this approach, a high spatial charge concentration at high-intensity can be avoided by adjusting the range of the beam painting for both horizontal and vertical directions as illustrated in Fig 3. The injection painting is performed by phase space offset of the injection beam relative to the closed orbit, which for an anti-correlated painting the injection beam is usually painted from (A) to (C), but it is modified to paint from (A) to (B) by introducing a scaling factor for a slow variation of the phase space offset. Figure 4 shows the optimized patterns of the painting magnets (broken lines) for this purpose, which collapse at 0.6 ms instead of usual 0.5 ms (solid lines). The injection pulse length, which is 0.5 ms long is shown by the rectangular box. As a result, the phase space offset of the injection beam in the new method ends at (C) in Fig. 3, which is less than a usual full painting offset continued up to (B). At high-intensity, the unpainted region in Fig. 3 for a new method is automatically filled by the SC effect and emittance exchange, and thus reduces the large amplitude particles or beam halos beyond the painting emittance of 200\(\pi\) mm mrad.

Figure 5 shows measurement result of beam loss mitigation by applying a modified TP at 800 kW. The integrated beam loss from collimator through the 1st arc section has been reduced to more than 30% from that with an old TP as shown by the pink and red lines, respectively. These new LP and TP parameters are implemented to the RCS operation at the present 800 kW beam power, where the beam loss is estimated to be as low as 0.05% dominated by the foil scattering of the circulating beam.
To mitigate the beam loss at J-PARC RCS, we have done systematic studies by optimizing both longitudinal painting (LP) as well as the transverse painting (TP) at injection. An optimized LP by a combination of the Linac beam momentum offset and RCS RF bucket offset are applied. A modified TP is done by extending painting magnets patterns beyond the injection pulse duration for a slow variation of the phase space offset to adjust the range of the beam painting. The beam loss applying these changes was measured to be significantly reduce, where the residual beam loss is estimated only around 0.05% and dominated by the foil scattering beam loss. The new LP and TP parameters have been implemented to the present RCS operation at 800 kW beam power. We have also studied the dependence in the numerical simulations and confirmed that a modified TP ensures a uniform spatial distribution of the beam painting. The beam survival is significantly improved by successfully reducing the additional beam losses. The beam loss occurs mostly during injection period, but there appears some additional beam losses for an original TP. Such an additional beam losses are well mitigated by reducing the space charge effect when applying a new TP. The residual beam loss is dominated by the foil scattering beam losses. The simulation results of beam loss mitigation by applying a modified TP is quite consistent with measurement result shown in Fig. 5.

SUMMARY

To mitigate the beam loss at J-PARC RCS, we have done systematic studies by optimizing both longitudinal painting (LP) as well the transverse painting (TP) at injection. An optimized LP by a combination of the Linac beam momentum offset and RCS RF bucket offset are applied. A modified TP is done by extending painting magnets patterns beyond the injection pulse duration for a slow variation of the phase space offset to adjust the range of the beam painting. The beam loss applying these changes was measured to be significantly reduce, where the residual beam loss is estimated only around 0.05% and dominated by the foil scattering beam loss. The new LP and TP parameters have been implemented to the present RCS operation at 800 kW beam power. We have also studied the dependence in the numerical simulations and confirmed that a modified TP ensures a uniform spatial distribution of the beam painting. The beam survival is significantly improved by successfully reducing the additional beam losses. The beam loss occurs mostly during injection period, but there appears some additional beam losses for an original TP. Such an additional beam losses are well mitigated by reducing the space charge effect when applying a new TP. The residual beam loss is dominated by the foil scattering beam losses. The simulation results of beam loss mitigation by applying a modified TP is quite consistent with measurement result shown in Fig. 5.

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