15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-TUAN1

BEAM LOSS AND BEAM EMITTANCE MINIMIZATION AT J-PARC RCS FOR SIMULTANEOUS OPERATION TO THE MLF AND MR

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Abstract

The 3 GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex) simultaneously delivers high intensity proton beam to the MLF (Material and Life Science Experimental Facility) and MR (50 GeV Main Ring). The beam power to the MLF has been increased to the designed 1 MW. In addition to the beam loss mitigation in the RCS for a stable operation by keeping a lower machine activation, it is also highly required to ensure a high-quality beam having a lower emittance and less beam halos for the users. Numerical simulations and systematic beam studies have been carried out to minimize the beam loss and the beam emittances by reducing the foil scattering uncontrolled beam losses and mitigating the space charge effect by optimizing longitudinal and transverse injection paintings, betatron tune, resonance corrections, chromaticity (ξ) manipulation as well as using a higher energy spread of the injection beam. The beam loss and the beam emittances are significantly reduced minimizing beam halos for both MLF and the MR. The residual radiation in the RCS at 0.95 MW operation has been one order of magnitude reduced to achieve a stable operation with more than 98% availability.

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 as well as beam injection to the MR [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. Multi turn charge-exchange injection of H^- beam has been utilized to inject 8.33×10^{13} protons for achieving 1 MW beam power. Figure 1 shows a history of RCS beam power to the MLF so far. The net beam power to the MLF is reached to 0.95 MW at a routine operation since April 2024, while is nearly 700 kW or 200 kW equivalent beam power to the MR depending on the MR operational mode of fast extraction (FX) or slow extraction (SX). The beam sharing ratio between MLF and MR is 88:12 or 96:4 for the MR FX or SX mode. The machine activation at the RCS is thus mainly determined by the beam loss for beam operation to the MLF. The beam loss reduction in the RCS operating in this mode is a first priority, but we also have to ensure a significantly smaller beam emittance with less beam halos for the MR.

To reduce the space charge (SC) effect, both transverse painting (TP) and longitudinal injection painting (LP) have been adopted in the RCS [2–4]. The TP area is simultaneously varied to control transverse emittance of the extracted beam between MLF and the MR [5]. A large TP of 200 πmm−mrad is applied for the MLF beam to minimize circulating beam hitting on the foil to reduce foil scattering uncontrolled beam losses and also for a longer foil lifetime [6–12]. It is also essential to minimize beam density on the Mercury target to reduce its pitting damage. On the other hand, a relatively smaller TP of 50 πmm−mrad is used for the MR to realize a smaller emittance to minimize beam loss at the beam transport and also in the MR. However, it gives one order of magnitude higher average foil hitting of 62 for each injected proton as compared to that only 6.5 for the MLF as can be realized from the simulated beam distribution on the foil at the end of injection shown in Fig. 2 [13]. In this research, we first studied to reduce the foil hitting and the corresponding foil scattering beam losses and then for mitigation of the SC effect by taking into account several measures to minimize additional beam losses and beam emittance.

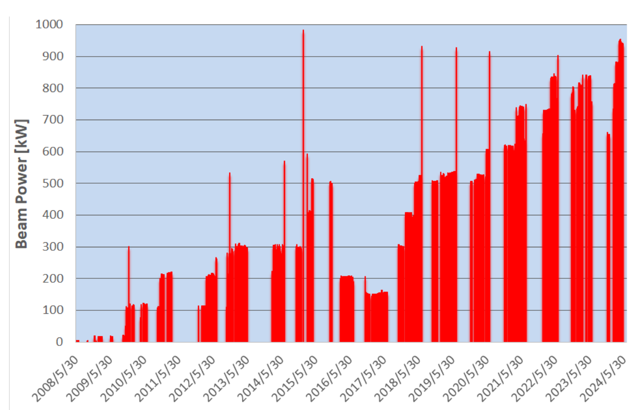

Figure 1: History of RCS beam power delivery to the MLF. A routine operation with a beam power of 0.95 MW to the MLF has been started since April 2024.

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REDUCTION OF THE FOIL SCATTERING BEAM LOSSES

To reduce the foil scattering beam losses, we reduced vertical foil size from its 20 mm to 14 mm. The vertical size of the injection beam was also optimized by reducing its rms size to 0.9 mm from 2 mm so far. Figure 3 shows photograph of the foils with 20 mm (top) and 14 mm (bottom) used in this study. Such a reduction of the foil size gives a nearly 30% reduction of the foil hitting and the corresponding foil scattering beam loss for the MLF beam, which is quite consistent between simulation and measurement results as reported earlier [14].

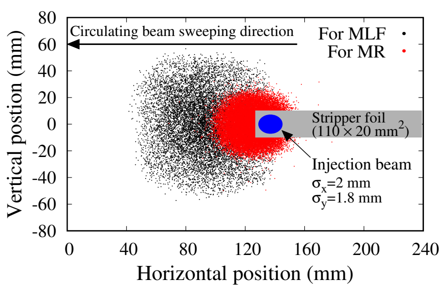

Figure 2: Simulated transverse beam distribution on the foil at the end of injection for the MLF (black) and MR (red).

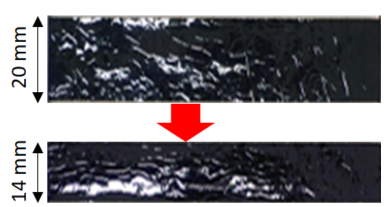

Figure 3: Photographs of the stripper foil with a vertical size of 20 mm (top) and 14 mm (bottom) used in this study.

Figure 4 shows simulation results of average foil hits of each injected proton in the RCS for the MR beam. The black and red colors are with 50 πmm−mrad for both horizontal and vertical planes, where vertical foil size is 14 mm for the latter case. The blue line is for a horizontal TP of 100 πmm−mrad keeping the vertical TP unchanged. The average foil hits of 62 for a foil of 20 mm is about 15% reduced to 52 by reduced the size to 14 mm, but it is further 50% reduced by enlarging the horizontal TP from 50 to 100 πmm−mrad. Figure 5 shows the measurement results of foil scattering beam losses corresponding to the parameters as used in the simulation. The measurement was done by using a plastic scintillator counter beam loss monitor (BLM) placed 90^o above the foil in the horizontal direction. Secondary particles such as, γ rays generated from the lost primary protons and any secondary particles at the nearby beam pipe due to large angle scattering and interaction at the foil. A reduction of the foil size from 20 mm to 14 mm gives more than 10% foil scattering beam loss mitigation, while enlarging horizontal TP to 100 πmm−mrad gives another ~50% mitigation, consistent with a reduction of the foil hitting as obtained in the simulation.

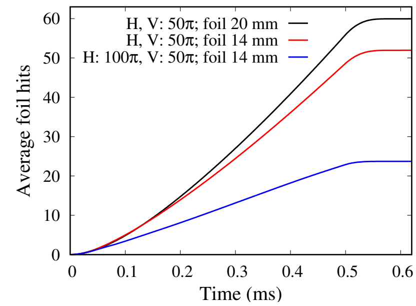

Figure 4: Simulation results of minimizing foil hits by reducing the foil size and also extending TP for the MR beam.

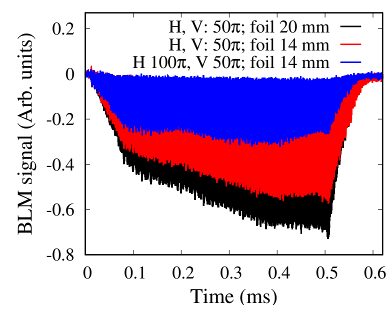

Figure 5: Measurement results of foil scattering beam loss minimization by using reducing the foil size and also extending the TP for the MR beam.

BEAM LOSS AND BEAM EMITTANCE MITIGATION

Next we tried to minimize the beam loss and beam emittances at high intensities for simultaneous operation to the MLF and MR. Due to a big difference of the TP and also the beam intensity, the beam loss and the beam emittance optimization scheme significantly differs between MLF and MR. Table 1 shows key parameters of the RCS optimized individually to change pulse-to-pulse. Recently, in addition to a momentum offset ($\Delta p/p = 0.15\%$) of the injection beam, a higher momentum spread ($\Delta p/p = 0.2\%$ in rms from 0.15% so far) is implemented for further SC mitigation, but those cannot be changed pulse-to-pulse.

The beam loss for the MLF at 1 MW has been well minimized by taking into account several measures such as resonance corrections, optimization of both TP and LP as can be found in Ref. [15]. The beam loss in this mode has been reduced to more than 80% as compared to that in a trail operation at 1 MW in 2020. The rms emittance of the extracted beam has also been more more than 30% reduced. The beam loss and beam emittance mitigation for the MR obtained until recently are mainly presented in this paper.

Figure 6 shows measurement results of the beam loss throughout the RCS at 0.78 MW equivalent beam power for the MR. The integrated beam loss signal of each BLM for

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Table 1: Key Parameters of the RCS Changed Pulse-to-pulse for Beam Operation to the MLF and MR

Parameter	For MLF	For MR
Intensity	8.33×10^{13}	6.5×10^{13}
Tune at inj.	(6.46, 6.36)	(6.42, 6.46)
Tune at ext.	(6.38, 6.35)	(6.38, 6.35)
TP (πmm-mrad)	(H,V): (200, 200)	(H,V): (100, 50)
TP type	Anti-correlated	Correlated
LP (RF voltage)	Dual harmonic	Dual harmonic
RF 2nd harmonic	up to 6 ms	up to 7 ms
Δf RF at inj.	600 Hz	0.0
Sextupoles	Resonance corr.	Bipolar
	($\nu_x - 2\nu_y = -6$)	ξ manipulation

the entire cycle of 20 ms is used. A beam loss mitigation of 40% in average at the collimator to the 1st arc section has been achieved mainly by applying a TP of 100 πmm–mrad (horizontal) and an optimization of the tune at injection as compared to that of 50 πmm–mrad as shown by the red and black colors, respectively. An enlarged TP not only significantly reduced the foil hitting, but also the SC effect to minimize the beam loss. It is worth mentioning that the TP function for the red case is modified to make a slower time variation of the painting kickers [15,16]. This gives a slightly lower painting area than 100 πmm–mrad, but produces a lower spatial charge concentration to reduce the SC effect for beam loss and beam emittance mitigation as compared to an ordinary TP pattern.

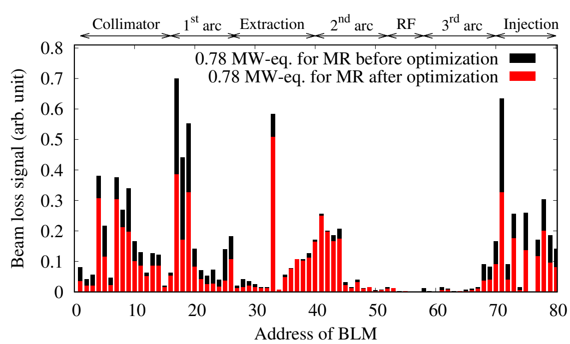

Figure 6: Measurement result of beam loss mitigation by optimizing the TP and betatron tune for the MR.

Figure 7 shows measurement results of the rms emittance of the extracted beam as a function of the 2nd debuncher (DB2) amplitude of the linac used to control momentum spread of the injection beam. The DB2 amplitude of 6000 for a momentum spread of 0.2% (rms) has been implemented to the operation as compared to that of 3600 (0.15%) so far. The rms emittance of the extracted beam is nearly 15% reduced by applying a higher amplitude of the DB2, which gives less beam halos at the 3-50BT (3 GeV to 50 GeV beam transport) as well as in the MR.

Figure 8 shows a significant reduction of the residual radiation (measured in contact) in the RCS at a routine operation with nearly 1 MW beam power (red) as compared to 0.6 MW routine operation (cyan) and a trail 1 MW operation (black) in 2020. The noted measurement places are at the hottest spot in collimator area (#1), collimator exit (#2) and the dispersion peaks (#3~ #8). The present effort of beam loss mitigation gives a significant reduction of the machine activation which in the collimator area is 1 order of magnitude lower and also several times lower at other areas noted as uncontrolled beam losses.

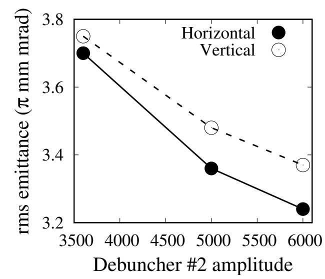

Figure 7: Beam emittance reduction for the MR by using a higher momentum spread of the injection beam with a higher DB2 amplitude.

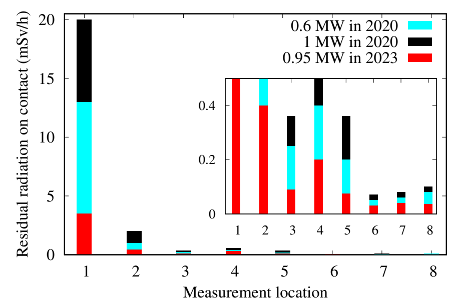

Figure 8: The residual radiation in the RCS has been significantly reduced recently by minimizing the beam losses.

SUMMARY

The uncontrolled beam loss caused by the foil scattering in the RCS has been significantly reduced by using a smaller size foil and implementing a higher transverse painting area, especially for the MR beam. The space charge effect has also been well mitigated to minimize the beam losses and the beam emittance for both MLF and the MR by taking into account several measures such as, optimizing transverse and longitudinal paintings, betatron tune at injection, manipulating chromaticity as well as implementing a higher energy spread of the injection beam. The optimized parameters are changed pulse-to-pulse for simultaneous beam operation to the MLF and MR. The improvements in the RCS also give beam loss reduction at both facilites. The simulation and measurements are found to be quite consistent to each other. As a result, the residual radiation in the RCS has also been sufficiently reduced to realize a stable operation with a higher of more than 98% availability.

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