BEAM LOSS MITIGATION FOR OPERATION BEYOND 1 MW BEAM POWER OF THE J-PARC RCS

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Abstract

The 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex) simultaneously delivers high intensity beams to both neutron and muon production targets at the material and life science experimental facility (MLF) as well to the main ring synchrotron (MR). Recently, routine operation with the designed 1 MW beam power to the MLF has been started. However, to cope with a faster operation cycle of the MR and beam sharing by the under construction 2nd neutron production target at the MLF, RCS has to achieve far beyond the designed 1 MW to ensure net 1 MW beam power to the present MLF targets. For this purpose, we tested RCS possibility for achieving 1.5 MW beam power injecting more particles by increasing both peak current and injection pulse length of the Linac beam. Based on the series of systematic beam tests and numerical simulations, we have obtained a sufficient beam loss mitigation by keeping the beam loss rate even lower than an intensity increase from that of 1 MW.

INTRODUCTION

The 3-GeV RCS of J-PARC has already been achieved the designed operation at high intensity proton beam of 1 MW to pulsed muon and neutron production targets at the MLF as well as more than 700 kW equivalent beam power to the MR [1, 2]. In the RCS, the proton beam injecting at 0.4 GeV by utilizing multi-turn charge-exchange injection is accelerated up to 3 GeV at a repetition rate of 25 Hz and simultaneously delivered to the MLF and MR, which is 8.33×10^{13} protons per pulse at 1 MW beam power [3].

The net beam power to the MLF depends on the beam sharing by the MR determined by the MR operation cycle, which is gradually getting much faster than the designed value, currently operating at 1.36 s cycle in the fast extraction (FX) mode for the neutrino facility. The ultimate goal of the FX cycle is 1.16 s, resulting a beam sharing between MLF and MR reach to 84:16 [4]. In addition, a 2nd neutron production target at the MLF is also currently under construction [5]. As a result, RCS duty to the present MLF targets will be further reduced. Given these updates of the user facilities, RCS beam power should be increased to 1.5 MW or even 2 MW to ensure net 1 MW beam to the present targets at the MLF. As RCS extraction beam energy as well as repetition rate are kept unchanged, the only way to increase the injected beam particles.

However, the primary challenge hindering effective beam loss mitigation and its control is the nonlinear increase of the beam loss primarily caused by the space charge (SC) effect at high-intensity. Other key issues are to overcome the limitation of increasing the injection painting area to the designed value of 200π mm mrad to minimize the foil scattering uncontrolled beam losses as well as to ensure the beam instability mitigation enhances as the beam increases. Since early stage of the RCS beam commissioning until to date we kept achieving improvement of the beam loss mitigation by systematic beam tests and the corresponding numerical simulations, which at the recent 1 MW operation is managed to keep to an extremely low level [2, 6]. Figure 1 shows temporal structures of the beam loss at 1 MW measured by a beam loss monitor (BLM) at the collimator region of the RCS, where the remaining additional beam losses in 2020 were almost mitigated [2]. The residual beam loss rate is estimated to be even less than 10^{-3} corresponding to a loss power of less than 0.1 kW, which is sufficiently smaller than the collimator capacity of 4 kW.

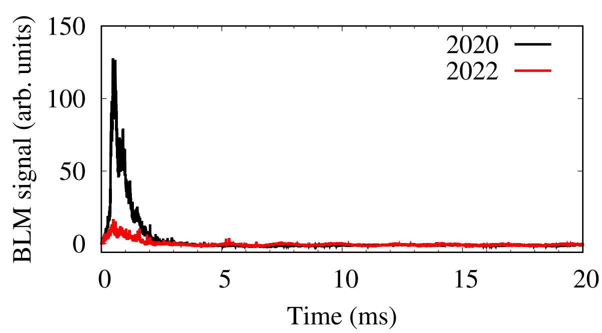

Figure 1: Temporal structure of the measured beam loss at 1 MW. The beam loss at the RCS is continuously improved, which is well minimized in 2022.

Such a beam loss mitigation at 1 MW is one of the key factor to consider for achieving far beyond the designed 1 MW beam power in the RCS. Recently we have performed detail systematic beam studies and numerical simulations for beam loss mitigation at 1.5 MW. We have obtained a sufficiently low beam loss occurring only at lower beam energy by well controlling at the collimator area. The transverse injection painting area has also been enlarged to an expected value of 200π mm mrad. The total beam loss at 1.5 MW is measured to be nearly identical to that at 1 MW, thus giving a smaller beam loss rate at 1.5 MW from that at 1 MW.

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KEY PARAMETERS AND STRATEGY FOR 1.5 MW BEAM TEST

Figure 2 shows a schematic view of the way and key parameters to increase the beam power in the RCS by increasing both peak current and pulse length of injection beam. Those were increased by 20% and 25%, respectively for 1.5 MW from those at 1 MW case. Table 1 summarizes the injection beam parameters corresponding the the desired beam power in the RCS.

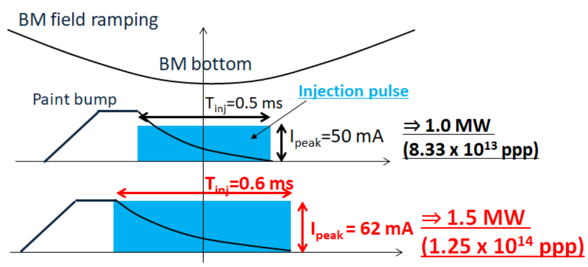

Figure 2: Schematic view illustrating the way and key parameters to achieve 1.5 MW beam power in the RCS by increasing peak current and pulse length of the injection beam.

Table 1: Injection Beam Parameters (Peak Current and Pulse Length) for Desired Beam Power in the RCS

Peak current (mA)	Pulse length (ms)	Injected particles	Beam power (MW)
50	0.5	$8.33{\times}10^{13}$	1.0
62	0.5	$1.00{\times}10^{14}$	1.2
62	0.6	$1.25{\times}10^{14}$	1.5
70	0.7	$1.67{\times}10^{14}$	2.0

However, to accelerate 1.5 MW beam up to the final energy of 3 GeV in the RCS it is necessary to replace all existing RF cavities, where half of the 12 cavities have been replaced to new ones so far [7]. This is needed to overcome the significant unbalance of the vacuum tubes caused by the anode voltage swing due multi-harmonic operation and beam loading compensation of the existing RF system, especially at high-intensity operation. As a result, the beam tests were performed by accelerating up to 0.8 GeV and then extracted the beam by the kickers before RF trips occurs as depicted in the Fig. 3. The beam is thus extracted at 5.54 ms from the B field at bottom corresponds to $t = 0$. It is worth mentioning that the main purposes of this study is beam loss mitigation, which occurs only at lower beam energies as we have already investigated in the previous studies [8]. It is therefore meaningful the present strategy of 1.5 MW beam tests for beam loss mitigation.

Figure 4 shows simulated tune footprints studied for optimizing the bare point at injection. The ν_x and ν_y are the horizontal and vertical tunes, respectively. The green color represents the current operation at 1 MW setting the bare tune at (6.45, 6.36). However, at 1.5 MW the SC effect is more pronounced affecting the tune spread crossing the integer resonance, particularly $\nu_y = 6$ and resulting additional beam losses as depicted in red. As showing in black, the ν_y is thus set to 6.42. However, further increase of the ν_y is limited due to vertical half-integer resonance $\nu_y = 6.5$ and the coupling resonance $2\nu_x - 2\nu_y = 0$. The bare tune at injection for 1.5 MW beam test is thus set at (6.45, 6.42).

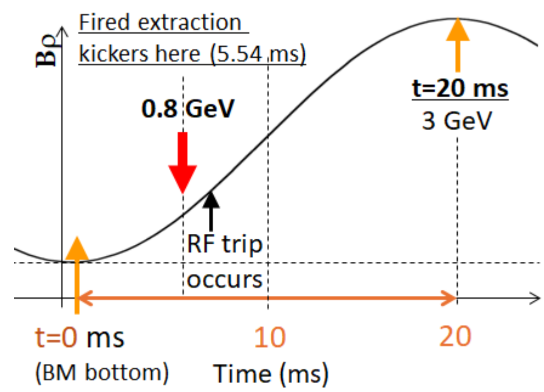

Figure 3: Present scheme for beam acceleration up to 0.8 GeV and then extraction for 1.5 MW beam test.

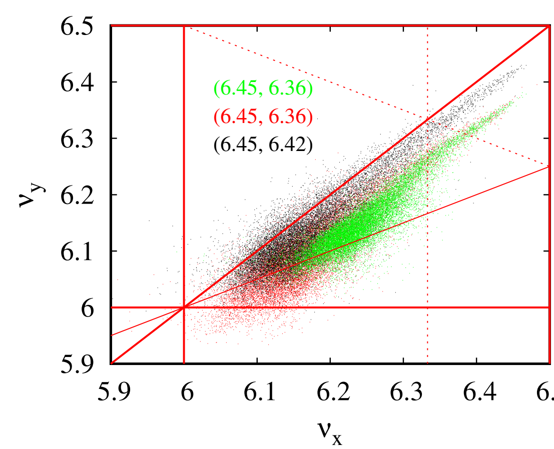

Figure 4: Simulation results of tune footprints at the end of injection for 1.5 MW (red), while keeping the bare tune unchanged from that at 1 MW (green). The ν_y for 1.5 MW is changed from 6.36 to 6.42 to keep away the beam from the $\nu_y = 6$ resonance (black).

Unfortunately, the beam instability we cannot check at this stage as it occurs at higher energy due to transverse impedance of the extraction kicker magnets (KM) [9, 10]. However, we have installed 4 diodes to 4 KMs out of 8 in total and also studied the beam instability up to 1 MW [11]. The impedance is significantly reduce so does the beam instability. Based on the such studies and simulations we have estimated that at the present condition there occurs no beam instability at 1.5 MW. As a result, we can determine the RCS parameters for 1.5 MW beam operation based on the present strategy of accelerating the beam up to 0.8 GeV.

BEAM TEST RESULTS AT 1.5 MW

Figure 5 shows circulating beam intensities in the RCS measured by a DCCT up to 1.5 MW beam intensity. The horizontal and vertical axes are the acceleration time and the number of particles, respectively. The injection pulse length is only changed by keeping other parameters unchanged for changing the beam intensity. The maximum pulse length was 0.6 ms giving a beam intensity of 12.5×10^{13} corresponding to 1.5 MW beam power. There has no visible beam intensity loss can be seen at any intensity up to 1.5 MW throughout injection to the extraction at 5.54 ms. This means that the space charge effect has been well controlled to mitigate the beam loss even at 1.5 times higher beam intensity than that of the designed value.

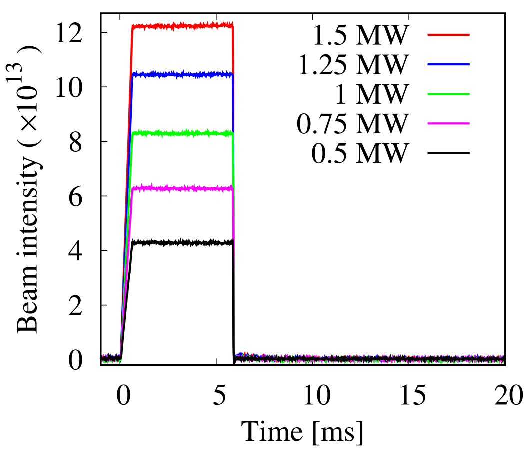

Figure 5: Circulating beam intensity measured by a DCCT in the RCS. The beam is extracted at 5.54 ms after accelerating to 0.8 GeV, where no intensity loss can apparently be seen up to the highest 1.5 MW beam power.

In the latest beam test in March 2025, we made several optimizations of the injection beam as well as in the RCS. Those includes improvement of the transverse emittance of the injection beam, optimization vertical Twiss parameter α_y of the injection beam to avoid Twiss mismatch with the circulating beam, application of higher momentum spread of the injection beam for SC mitigation, precise injection error corrections as well as optimization of the phase feedback parameters of the RCS RF.

The beam loss throughout the RCS is measured by using nearly 100 beam loss monitors (BLM) [12, 13]. Figure 6 shows the measurement results of the beam loss throughout the RCS. The horizontal axis is the BLM ID, where vertical axis is the integrated beam loss for the whole period of injection through extraction. In any case, the beam loss is almost localized at the collimator section giving significantly less beam loss at other sections. It has to be noted that the BLMs at the 2nd arc section (ID 35-45) mostly count the signal from the beam dump as the beam is transported to a beam dump located near the 2nd arc section. These signals are mostly vanished at user operation when the beam is delivered to the users. The optimizations of many parameters in March 2025 gives significant beam loss mitigation (red) as compared to that in December 2024 (black), which is even reduced to be almost same level to that at 1 MW. Among many other optimizations, an optimization RCS parameters, especially for the phase feedback plays an important role for such an improvement of the beam loss mitigation in the latest beam test [14].

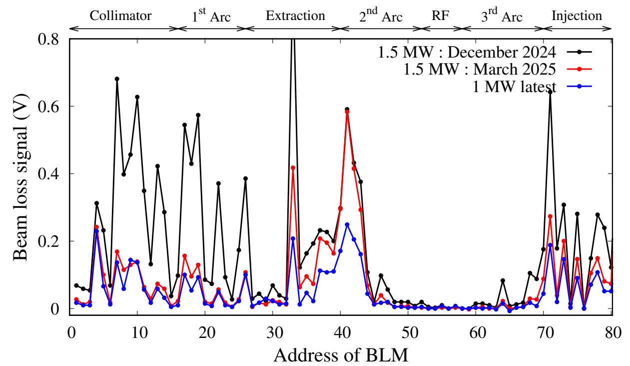

Figure 6: Measured beam loss throughout the RCS and comparison between recent two measurements done in 2024 (black) and 2025 (red) at 1.5 MW. The beam loss distribution at 1 MW beam power (blue) is also shown for comparison.

Figure 7 shows a temporal structure of the beam loss as a function of the beam intensity. One can see that the beam loss occurs only at lower beam energies, linearly increase with beam intensity peaking at the end of injection. Such a beam loss is caused by the foil scattering of the circulating beam during multi-turn injection period and until the closed orbit is moved away from the foil after the injection is finished. The means that the beam loss even up to the maximum beam intensity of 1.5 MW is dominated by the unavoidable foil scattering of the circulating beam with almost no additional beam losses occurring after the injection period. The residual beam loss rate at 1.5 MW is estimated to be 0.04% corresponding to a power loss of only 70 W, which is thus kept significantly lower than the collimator capacity of 4 kW. The beam loss is also well localized at the collimator section, while beam loss at other section are negligibly small (see Fig. 6). The measurement results show that RCS can operate at least at 1.5 MW beam power keeping a minimum machine activation level.

It is also important to mention in this beam time we could enlarge the transverse painting (TP) area to the designed value of 200π mm mrad from that of one of the serious issue limiting to 200π mm mrad so far. Figure 8 shows a comparison of the beam loss throughout the RCS at 1.5 MW beam depending on the TP of 150π mm mrad (black) and 200π mm mrad (red), while the beam loss is kept unchanged by enlarging the TP to the designed value. It is worth mentioning again that the higher the TP area, the lower the foil hitting rate of the circulating beam so does the foil scattering beam loss [15, 16]. An implementation the designed TP area 200π mm mrad is thus one of the most significant improvement among many others in this beam test.

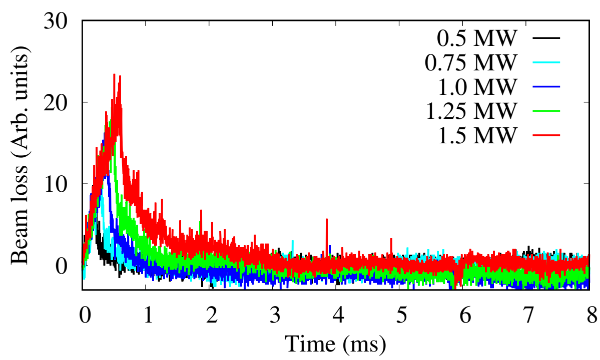

Figure 7: Measurement results of temporal structure of the beam loss at the collimator section depending on the beam intensity. The beam loss is measured to be almost linear with the beam intensity occurring only at injection energy mainly caused by foil scattering of the circulating beam.

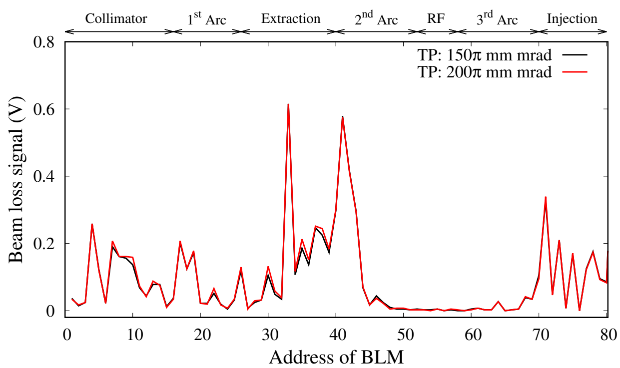

Figure 8: Measurement results of the beam loss depending on the TP area at 1.5 MW. The beam loss is kept unchanged by applying a designed TP area of 200π mm mrad, which was limited to 150π mm mrad.

Figure 9 shows numerical simulation result of temporal structure of the beam loss at 1.5 MW. Beam loss occurs only at lower energies and the beam loss profile is quite consistent with the measurement. The beam loss rate is estimated to be around 0.03%, which is also almost aligned with the measurement result.

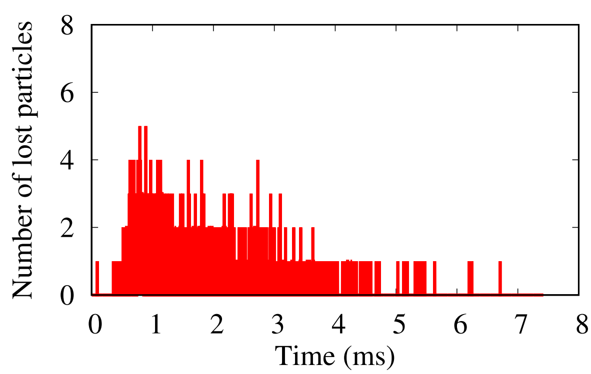

Figure 9: Simulation result of temporal structure of the beam loss at 1.5 MW. Beam loss occurs only at lower energy.

SUMMARY

The 3-GeV RCS of J-PARC has already been started routine operation at the designed 1 MW beam power by keeping the beam loss and the corresponding machine activation minimum. To cope with continuous upgrades of the user facilities, RCS beam power should be upgraded to 1.5 MW or more. To adopt such a big change, we have conducted beam studies for beam loss mitigation in the RCS at 1.5 MW by increasing both peak current and the pulse length of the Linac beam. In the latest beam test done in March 2025, by optimizing many parameters of the Linac as well as in the RCS, we have achieved a significant beam loss mitigation giving 0.04% beam loss rate corresponding to a loss power of only 70 W, which sufficiently lower than 4 kW capacity of the collimator. The transverse painting applied at at injection has also been enlarged to the designed value of 200π mm mrad, which was limited up to 150π mm mrad so far. The simulation results were also shown to be well consistent to those with measurements. The present results thus ensure that RCS beam power can be ramp-up to 1.5 MW while keeping a minimum machine activation level.

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