ACHIEVEMENT OF LOW BEAM LOSS AT HIGH-INTENSITY OPERATION OF J-PARC 3 GeV RCS

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Abstract

The beam power 3-GeV RCS of J-PARC for operation to the MLF has been increased to 800 kW recently. The total beam loss even at the designed 1 MW beam power has been well controlled. However, the residual radiation at the injection area caused by the uncontrolled beam loss occurred by foil scattering of the circulating beam is a serious issue for regular maintenance works. To minimize the beam loss further but for further, especially the uncontrolled beam losses caused by the foil scattering, recently we have implemented a new approach by minimizing the injection beam size and using a smaller size stripper foil. A foil hitting of the circulating beam is reduced so as the foil scattering uncontrolled beam losses mainly at the injection area. In addition, an optimized transverse painting area matching with a smaller injection beam gives a smaller circulating beam emittance to reduce the beam loss at the collimator section and its downstream. The corresponding residual radiation for operation at 700 kW beam power was measured to be significantly reduced as compared to that with an original bigger injection beam size and a bigger foil. A smaller injection beam size including other potential optimizations were also extensively tested at 1 MW beam power and obtain a residual beam loss of nearly 0.05%, which is nearly 3/4 reduction as compared to the previous 1 MW test operation done in 2020.

INTRODUCTION

The 3-GeV RCS (Rapid Cycling Synchrotron) at J-PARC (Japan Proton Accelerator Research Complex) delivers high intensity proton beam to both MLF (Materials and Life Science Experimental Facility) and the MR (30-GeV Main Ring Synchrotron) [1]. The injection beam energy is 400 MeV, which is accelerated to 3 GeV at repetition rate of 25 Hz and simultaneously delivered to the MLF and MR. The designed beam power is 1 MW (8.33×10^{13} protons/pulse), while at the latest it is 800 kW to the MLF and also nearly 800 kW equivalent beam power to the MR. Figure 1 shows the history of the beam power to the MLF. The beam power to the MLF is gradually approaching to the designed 1 MW by carefully investigating the neutron production target. Meanwhile we have conducted 1 MW test operation several times to check the feasibility of continuous operation.

Usually, a more than 90% of the beam from the RCS is delivered to the MLF. A beam loss reduction in the RCS for operation to the MLF is highly important. Based on the detailed studies and numerical simulations, The beam loss at the RCS has been well controlled even at the designed 1 MW beam power [2]. Recently, we have achieved further beam loss mitigation by optimizing the betatron tune as well as adopting a momentum offset ($\Delta p/p$) of the injection beam itself instead of RF bucket offset as a process of longitudinal painting. However, the uncontrolled beam loss caused by the foil scattering of the circulating proton beams during multi-turn charge-exchange injection of H^- and the corresponding residual radiation at the injection area is still considerably high. It is thus a serious concern at 1 MW regular operation in a near future [3,4]. A large transverse painting (TP) at injection is adopted for the MLF to reduce average foil hits of the circulating beam to only 7 [5], but it is not sufficient to keep the residual radiation at the injection area to a permissible level. A further technique for foil hit reduction is thus highly essential.

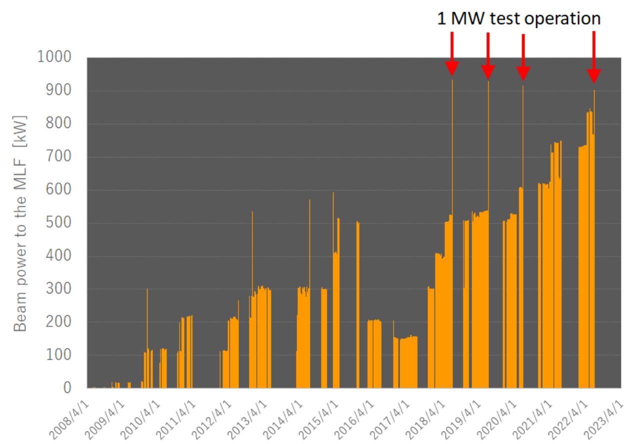

Figure 1: History of RCS beam power to the MLF.

To further reducing the foil hits of the circulating beam and the corresponding foil scattering beam losses, we have implemented a smaller size foil by minimizing the injection beam size at the 1st stripper foil. This was done by manipulating vertical twiss parameter (β_y) of the injection beam. As a result, a significant reduction of the uncontrolled beam losses at the injection area and the corresponding foil hit reduction were obtained. In addition, an optimized transverse painting area matching with a smaller injection beam gives a smaller circulating beam emittance for further reducing the beam loss also at the collimator section and its downstream.

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PRESENT APPROACH

Figure 2 shows a schematic view of the present approach to reduce foil hits of the circulating beam by minimizing vertical size of the injection beam and using a smaller size foil. This allows us to reduce both sides of the vertical foil instead of a single side if it is done for the horizontal size, as the foil is horizontally mounted. The vertical twiss parameter (β_y) of the injection beam is minimized to 2.4 m from its typical value of 8 m by using 4 quadrupole magnets located at the upstream of the stripper foil.

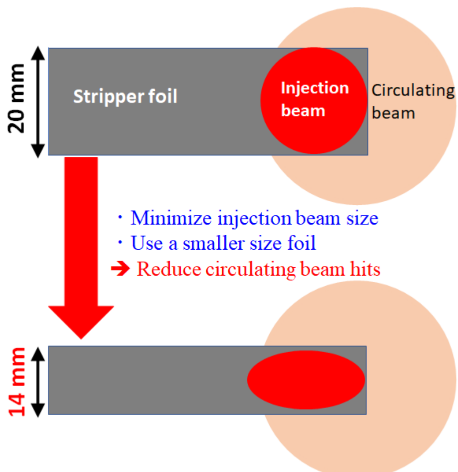

Figure 2: Schematic view of the present approach to reduce circulating beam hits on the foil and the corresponding foil scattering beam losses by minimizing vertical size of the injection beam to place a smaller size foil.

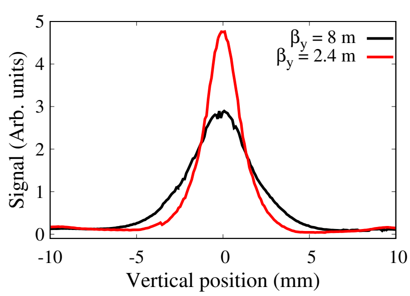

Figure 3: Measured vertical profiles of the injection beam at a location of the foil. A profile of 2 mm (in σ) was minimized to nearly half of 1.1 mm.

Figure 3 shows the measured vertical profiles of the injection beam at the 1st foil location for an original β_y of 8 m and minimized one of 2.4 m depicted by the black and red lines, respectively. The profile width (σ) of 2 mm has been reduced to nearly half of 1.1 mm.

Figure 4 shows a schematic demonstration of vertical transverse painting (TP) done by changing vertical angle (y') of the injection beam by using two vertical painting magnets placed the beam transport, upstream of the injection point. The edge of the injection beam determines the maximum painting area, where a y' of -3.4 mrad gives a

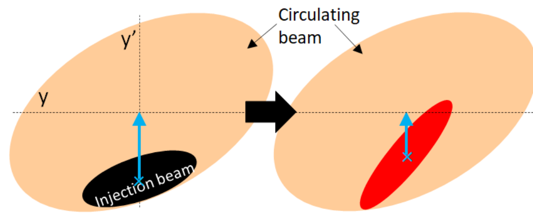

Figure 4: Schematic view of vertical TP done by varying y' of the injection beam. The y' for a smaller β_y can be minimized while keeping a same painting area to reduce large amplitude particles in the circulating beam.

painting area of 200π mm for the MLF. As emittance of the injection beam is unchanged, then the beam ellipse for a smaller β_y is changed as shown in the right figure. The angle of the injection beam can be thus minimized to keep the painting area unchanged. Such an optimization of the vertical painting improves vertical beam distribution by minimizing the number of large amplitude particles as compared to that with a bigger β_y of the injection beam. While due to space charge effect the maximum beam emittance goes beyond 200π mm at high intensity, the beam loss caused by the large amplitude particles at the collimator and its downstream sections can also be further mitigated by minimizing β_y of the injection beam for a smaller vertical beam size.

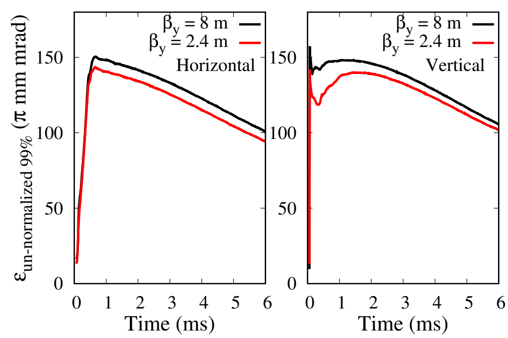

Figure 5: Reduction of circulating beam emittances obtained in the simulation by using a smaller injection β_y and optimizing the painting area.

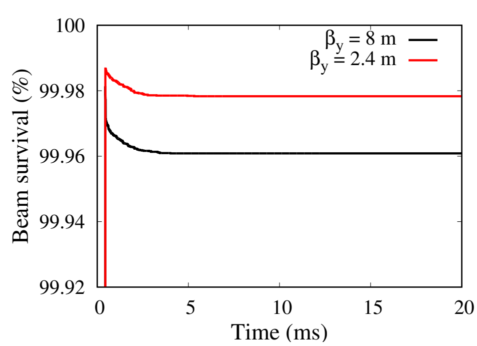

Figure 6: Simulation results of beam survival improvement at 700 kW by minimizing injection β_y 8 m to 2.4 m and reducing the foil size 20 mm to 14 mm, respectively.

Figure 5 shows 99% unnormalized emittances of the circulating beam obtained in the numerical simulations for β_y of 8 m (black) and 2.4 m (red), where left plots are for the horizontal and right plots are for vertical emittances, respectively. In this simulation, is it found that a smaller β_y with an optimized painting area (shown in Fig. 4) gives a reduction of the circulating beam emittances.

Figure 6 shows numerical simulation results of beam survival for β_y of 8 m (black) and 2.4 m (red). The simulation was done for a beam power of 700 kW by taking into account measured twiss parameters of the injection beam and realistic machine parameters including foil scattering. The vertical foil size for a bigger and smaller β_y was 20 mm and 14 mm, respectively. A smaller β_y gives a significant improvement of the beam survival by reducing the total beam loss as much as 45%. The corresponding average foil hits was also estimated to be reduced 30%. The simulation results thus indicate that the present approach can reduce the uncontrolled foil scattering beam losses at the injection area while reducing the overall beam loss at the collimator section and its downstream.

EXPERIMENTAL RESULTS AT 700 KW BEAM POWER

Figure 7 shows the beam losses at 700 kW equivalent beam power measured by the beam loss monitors (BLM) at the collimator and the 1st arc sections. Each BLM signal is integrated over the whole cycle of 20 ms (injection to extraction). A smaller β_y (red) gives 42% beam loss reduction in average as compared to a bigger β_y (black), where more than 50% reductions have also been obtained at several points. It is worth mentioning that the absolute beam losses at the 1st arc section is comparatively much lower than the collimator section. The high voltage of the BLM devices are set higher to measure even a lower beam loss signal. The measurement result is quite consistent with simulation result as shown a beam survival improvement (Fig. 6). The rms emittances of the extracted beam for both horizontal and vertical planes were measured to be more than 10% reduced by applying a smaller β_y of the injection beam.

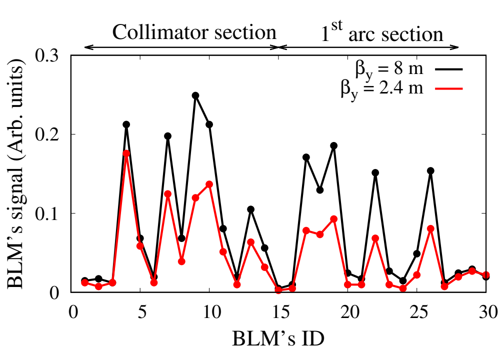

Figure 7: Measured beam loss as a function of BLM IDs at a beam power of 700 kW. A beam loss reduction of 42% (in average) is obtained by minimizing the injection β_y.

As for the beam loss reduction at the injection section, it was separately measured by using a small plastic scintillator counter type BLM placed 90^o above the foil in the horizontal direction. In this measurement, secondary charged particles such as, γ rays generated by large angle foil scattering primary protons lost at the nearby beam pipe. A 30% reduction of such a beam loss was measured corresponding to a same reduction of foil hits obtained with a smaller β_y as compared to that with a bigger one [6], and was consistent with 27% reduction estimated from the numerical simulation.

A smaller injection β_y and a smaller vertical size foil of 14 mm were tested for RCS operation at 700 kW beam power. Figure 8 shows a comparison of the measured residual radiation (on contact and after 4 hours cooling from beam stop) between two β_ys used each for 1 month operation. Similar to the measured beam loss, the residual radiation was also successfully reduced significantly by implementing a minimized injection β_y, where reductions at the injection and 1st arc sections have significant importance due frequent access on these areas for regular maintenance works. As a result, a smaller injection β_y and a smaller foil were implemented for RCS routine operation, and there is no issues so far even at the present beam power of 800 kW. They were also been successfully tested for several hours operation at 1 MW beam power in June 2022.

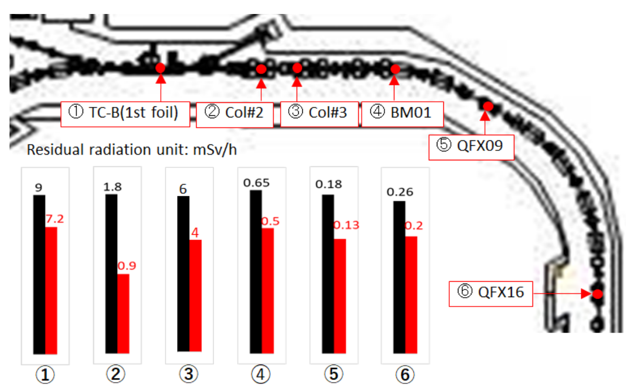

Figure 8: Comparison of residual radiation (on contact) at the injection, collimator and 1st arc sections with a bigger (black) and smaller (red) β_y measured after 1 month operation at 700 KW beam power. The residual radiation was significantly reduced by implementing a smaller β_y and a smaller size foil.

BEAM LOSS MITIGATION AT 1 MW BEAM POWER

We have also carried out detail studies at 1 MW beam power by using a smaller β_y and a smaller size foil. In addition, we have applied following several other parameters step by step to for beam loss at 1 MW.
Parameter ID #1: Original with β_y = 8 m.
Parameter ID #2: Optimization of betatron tune and $\Delta p/p$ offset by the injection beam instead of RF bucket offset.
Parameter ID #3: β_y = 2.4 m and optimization of horizontal

transverse painting to produced more uniform distribution. Details can be found in Ref. [7].

Parameter ID #4: Reduction of chicane bump height (20%) mainly to suppress their non vanished sextupole field component that excites the $3\nu_x = 19$ resonance causing a horizontal emittance growth.

Parameter ID #5: Application of 1 ms longer 2nd harmonic RF voltage to 7 ms for further mitigation of the space charge effect producing more uniform longitudinal beam distribution and achieving a higher bunching factor [8].

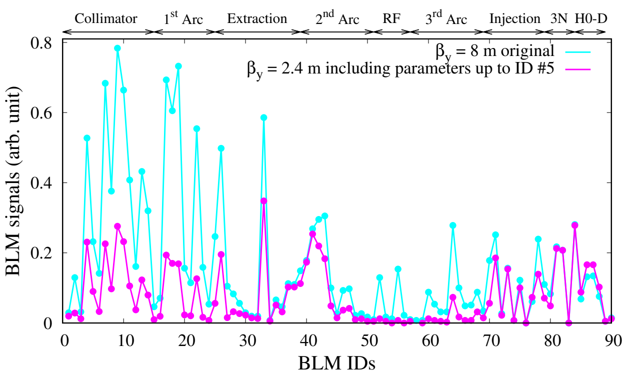

Figure 9: Measurement of beam loss mitigation at 1 MW beam power by using a smaller injection β_y of 2.4 m and applying measures taken by parameter IDs #2 through #5 as compared to the original one with a larger β_y of 8 m.

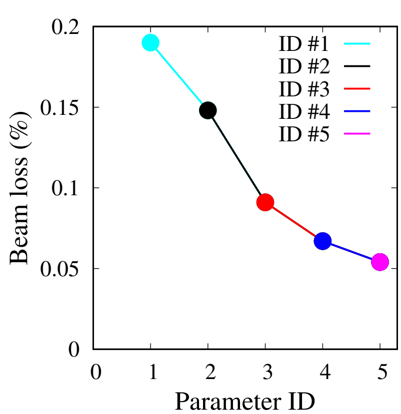

Figure 10: Reduction of the residual beam loss at 1 MW in the collimator through 1st arc sections as a function of the applied parameter ID.

Figure 9 shows the measured beam losses 1 MW beam power throughout the RCS. The beam loss has been significantly mitigated by using a smaller injection β_y of 2.4 m and applying all parameters mentioned in IDs #2 through #5 as compared to that of original one with using a β_y of 8 m. An average beam loss reduction of more than 70% has been obtained at the collimator through 1st arc section. Figure 10 shows a step by step reduction of the residual beam loss estimated from measured BLM signals at the collimator through 1st arc section as a function of the parameters applied. The residual beam loss at the latest remains only around 0.05%, obtained by mitigating nearly 3/4 from an original beam loss of 0.2% at the previous 1 MW test operation in 2020.

It is thus can be noted that the remaining beam loss is dominated by the foil scattering ones and a complete mitigation is practically impossible as long a stripper foil is used. The additional beam losses even at 1 MW beam power has been well mitigated. In the next beam study, we will test a little further smaller size foil of 12 mm for another at least 10% reduction of the foil scattering beam losses. To eliminate the foil scattering beam losses as well as to avoid issues associated with a stripper foil short lifetime and failures, we are developing a foil-less H^- charge-exchange injection by using only lasers [9]. One can thus expect an achievement of MW level beam power essentially without almost any beam losses.

SUMMARY

To reduce the residual radiation at the injection area of J-PARC RCS caused by the uncontrolled foil scattering beam losses, we have implemented a smaller size foil for RCS operation by minimizing the injection beam size. The vertical beam size (σ) at the foil from 2 mm was minimized to 1.1 mm by reducing a β_y of 8 m to 2 m and replace a foil size of 20 mm to 14 mm, respectively. The beam loss at the injection area and the corresponding average foil hits of the circulating beam was measured to be 30% reduced, consistent with an expectation of 27% reduction. In addition, an optimized vertical transverse painting area matching for a smaller injection beam reduces the circulating beam emittance to mitigate the beam losses at the collimator and its downstream sections. The residual radiation at 700 kW beam power operation with a smaller β_y was measured to be significantly reduced as compared to that with a bigger one used so far. A smaller injection beam with other potential optimizations have also been extensively tested at 1 MW beam power. The residual beam loss at the latest beam test is minimized to nearly 0.05%, which is nearly 3/4 reduction from that of 0.2% beam loss at the previous 1 MW test operation done in 2020. The remaining beam losses are mainly dominated by the foil scattering, which can be further mitigated by reducing the foil size to 12 mm in the next beam test. A foil-less charge-exchange injection of H^- by using lasers, which we are developing at J-PARC can eliminate realistic issues and limitations associated with a stripper foil including foil scattering uncontrolled beam losses.

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