RECENT RESULTS OF BEAM LOSS MITIGATION AND EXTREMELY LOW BEAM LOSS OPERATION OF J-PARC RCS

P. K. Saha*, K. Okabe, T. Nakanoya, Y. Shobuda, H. Harada,
F. Tamura, H. Okita, M. Yoshimoto
J-PARC Center, JAEA and KEK Joint Project, Tokai-mura, Naka-gun, Ibaraki-ken, Japan
Hideaki Hotchi, KEK, Tokai, Ibaraki-ken, Japan

Abstract

In the 3-GeV RCS (Rapid Cycling Synchrotron) at J-PARC (Japan Proton Accelerator Research Complex), multi-turn H^- charge-exchange injection is performed by using a thin stripped foil. 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. In addition, the beam loss at the collimator section and its downstream caused for a large emittance beam also should be reduced, especially at high intensity operation. For that purpose we have minimized injection beam size and implemented a smaller size stripper foil. The circulating beam hitting rate is reduced by using a smaller foil, while an optimized vertical angle of the smaller injection beam for vertical transverse painting also gave a reduction of the circulating beam emittances and resulted a further significant beam loss mitigation at the collimator section and its downstream. As a result, the residual radiation after user operation at 700 kW beam power was also measured to be significantly reduced.

INTRODUCTION

The 3-GeV RCS at J-PARC 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 nearly 800 kW equivalent beam power to the MR. As more than 90 % of the beam is delivered to the MLF, a beam loss reduction in the RCS for operation to the MLF is highly important.

Due to multi-turn (307 turns in 0.5 ms) charge-exchange injection of H^- performed by using a stripper foil, the foil scattering beam losses of the circulating beam is the dominant uncontrolled beam loss and high residual radiation sources at injection area. Figure 1 shows a layout of the RCS injection area and a schematic view of the transverse painting (TP) process performed at injection. The TP at injection is adopted to produce a wider beam profile required by MLF to minimize beam density on the neutron production target as well as to reduce circulating beam hitting rate on the foil by large betatron oscillation occurred by varying horizontal closed orbit with 4 horizontal painting magnets (PBH1-4) and varying vertical angle of the injection beam by using two vertical painting magnets (PBV1,2) placed at the injection beam transport (BT) [2, 3]. The average foil hits of the circulating beam at a painting area of 200 π mm mrad for the MLF 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 [4–7]. The foil thickness is 333 $\mu g/cm^2$ to achieve a stripping efficiency of 99.7 %, while the un-stripped beams are further stripped to protons by secondary foils and disposed at the injection beam dump (I-Dump) [8]. Due to nonlinear nature of the space charge (SC) effect, the beam loss at high-intensity also increases non-linearly, especially at the collimator section and affects the downstream 1st arc section. The beam loss reduction at the collimator section is also highly important for stable operation at 1 MW beam power in a near future. In this research we have succeeded to reduce both uncontrolled beam losses at the injection area caused by the foil scattering of the circulating beam as well as the beam losses caused by the beam halos at the collimator section and its downstream.

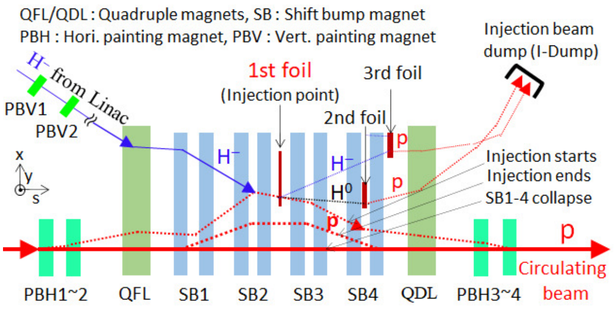

Figure 1: Layout of the RCS injection area and a schematic view of the TP process at injection. The PBH1-4 and PBV1-2 are used for horizontal and vertical painting, respectively.

PRESENT APPROACH AND NUMERICAL SIMULATION RESULTS

Figure 2 shows a schematic view of our present approach. We minimized vertical size of the injection beam at the 1st stripper foil by manipulating its vertical twiss parameter (β_y) to reduce vertical size of the foil. The foil hitting rate of the circulating beam and the corresponding beam losses caused by the foil scattering can be thus reduced. A smaller vertical size of the injection beam allows us to reduce both sides of the vertical foil instead of a single side if done for the

---

[*] saha.pranab@j-parc.jp

horizontal size, as the foil is horizontally mounted. 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 original width of 2 mm (σ) was reduced to nearly half of 1.1 mm to cover well by a vertical foil size of 14 mm. There was no missing H^- measured at the I-Dump. It is worth mentioning that the existing magnet configuration and the aperture of the BT gives a β_y minimization of around 2m.

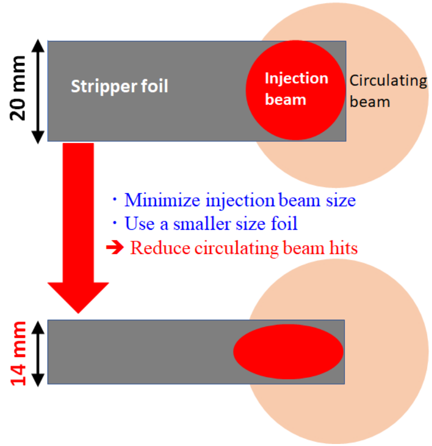

Figure 2: Present approach to reduce circulating beam hits on the foil by minimizing vertical size of the injection beam at the foil and using a smaller size vertical foil.

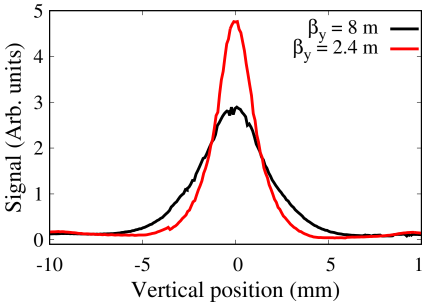

Figure 3: Measured vertical profiles of the injection beam at the foil. The profile width (σ) by manipulating β_y was reduced to 1.1 mm from that of its original 2 mm.

Figure 4 shows a schematic demonstration of vertical TP done by changing vertical angle (y') of the injection beam by using VPB1 and VPB2. The edge of the injection beam determines the maximum painting area, where a y' of −3.4 mrad gives a painting area of 200 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 SC effect the maximum beam emittance goes beyond 200 mm mm at high intensity, the beam loss caused by the large amplitude particles at the collimator section can also be reduced with a smaller injection β_y.

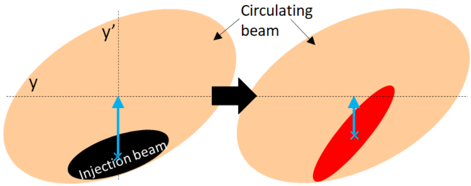

Figure 4: Schematic view of vertical TP done by varying y' of the injection beam. The y' can be minimized for a smaller β_y while keeping a same painting area to reduce large amplitude particles in the circulating phase space.

Figure 5 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 including foil scattering of the beam passing through the foil and all realistic machine parameters. The vertical foil size for a bigger and smaller β_y was 20 mm and 14 mm, respectively. A significant beam survival can be improved with a smaller β_y by reducing the total beam loss as much as 45 %. In this simulation the average of foil hits of each injected particle for a smaller β_y and a smaller foil was also estimated to be nearly 30 % reduced as compared to that for a bigger β_y with a bigger foil. A reduction of the foil hits would thus reduce the uncontrolled beam loss and the corresponding residual radiation at the injection area caused by the large angle foil scattering of the beam.

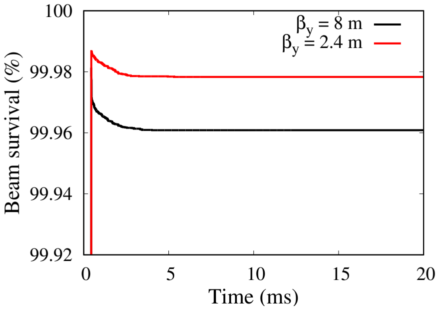

Figure 5: Simulation results of beam survival improvement at 700 kW by minimizing injection β_y from 8 m to 2.4 m and reducing the foil size 20 mm to 14 mm, respectively.

EXPERIMENTAL RESULTS

Similar to the simulations, we also performed experimental studies for beam loss and foil hit measurements by using two β_y of the injection beam. Figure 6 shows measured signals of the beam loss monitors (BLM) placed at the collimator and the 1st arc sections. Each BLM signal is integrated for the whole cycle of 20 ms (injection to extraction). The measurement was done an equivalent beam power of 700 kW. The beam loss with a minimized β_y of 2.4 m (red) was measured to be 42% reduced in average as compared to that with an original β_y of 8 m (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 for a beam survival improvement (Fig. 5).

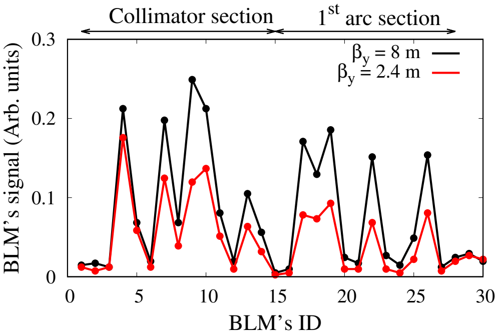

Figure 6: Measured beam loss as a function of BLM's ID at a beam power of 700 kW. A beam loss reduction of 42 % (in average) is obtained by minimizing the injection β_y.

We have also measured a reduction of circulating beam hitting rate on the foil for a smaller β_y and a smaller foil at 1 MW beam power. The measurement was done by using a plastic scintillator counter type BLM placed 90° above the foil in the horizontal direction. Secondary particles such as, γ rays were measured, generated from the lost primary protons at the nearby beam pipe due to large angle scattering at the foil. The measurement result is shown in Fig 7. A reduction of the signal intensity for a smaller β_y (red) as compared to that for a bigger β_y reflects a reduction of the foil hits, which was obtained to be 30% from a ratio of the integrated signals, and was also consistent with an expected reduction of 27%. A similar reduction of the residual radiation at the injection area can be thus expected.

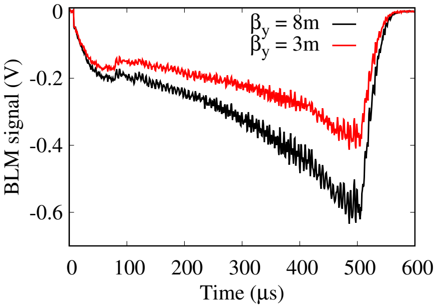

Figure 7: Measured signals of secondary particles generated from the lost primary protons caused to large angle foil scattering during injection period. A foil hit reduction of 30% was achieved with a smaller β_y.

We have implemented a smaller injection β_y and a smaller vertical size foil of 14 mm for RCS operation at 700 kW beam power. Figure 8 shows a comparison of the measured residual radiation (on contact) at the injection, collimator and 1st arc sections after operation with a bigger (black) and smaller (red) injection β_y. For each case, the operation was performed for 1 month and measurement was done after 4 hours cooling from beam stop. Similar to the measured beam loss, the residual radiation was also successfully reduced significantly by implementing a minimized injection β_y. It is worth mentioning that a reduction of the residual radiation outside the collimator section, such as injection and 1st arc section have significant importance due frequent access on these areas for regular maintenance works. At present RCS beam power to the MLF is increased to more than 800 KW, and there is no issues with using a smaller size foil. A smaller size foil with a smaller injection β_y will also be tested at 1 MW beam power at the end of June 2022.

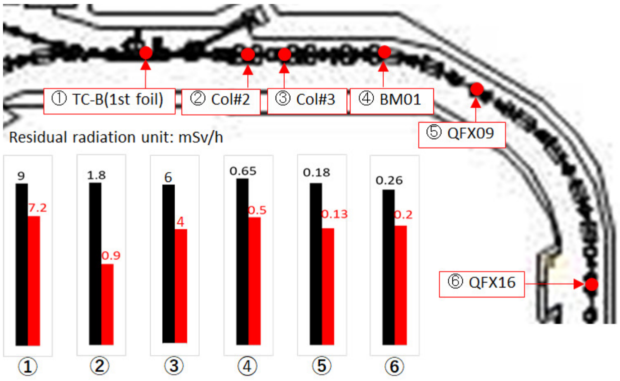

Figure 8: Comparison of residual radiation (on contact) at the injection, collimator and 1st arc sections with a bigger (black) and smaller (red) β_y measured after 1 month operation at 700 kW beam power. The residual radiation by implementing a smaller β_y was significantly reduced.

SUMMARY

We have achieved a significant reduction of the beam loss at J-PARC RCS by minimizing β_y of the injection beam and reducing vertical size of the stripper foil. The β_y was minimized to 2.4 m from 8 m and the corresponding vertical size (in σ) was reduced to 1.1 mm from 2 mm so as the vertical foil size to 14 mm from 20 mm, respectively. The average foil hits of each circulating proton was measured to be 30 % reduced and was consistent with an estimated value of 27 %. The uncontrolled beam loss at the injection area caused by foil scattering of the circulating beam as well as the beam losses at the collimator section and its downstream at a beam power of 700 kW was obtained to be 42 % reduced in average, which was also consistent to that expected in the numerical simulation. As a result, the residual radiation after 1 month operation at 700 kW beam power with a smaller β_y was measured to be significantly reduced as compared to that with a bigger β_y. A smaller β_y and a smaller size foil have been successfully implemented for the present RCS operation at 800 kW and will also be tested at 1 MW beam power operation in June 2022.

REFERENCES

[1] High-intensity Proton Accelerator Project Team, "Accelerator technical design report for J-PARC", *KEK report* 2002-13 and *JAERI-Tech* 2003-044.

[2] P.K. Saha *et al.*, "Direct observation of the phase space footprint of a painting injection in the Rapid Cycling Synchrotron at the Japan Proton Accelerator Research Complex", *Phys. Rev. ST Accel. Beams*, vol. 12, p. 040403, 2009. `doi:10.1103/PhysRevSTAB.12.040403`

[3] H. Hotchi *et al.*, "Beam loss reduction by injection painting in the 3-GeV rapid cycling synchrotron of the Japan Proton Accelerator Research Complex", *Phys. Rev. ST Accel. Beams*, vol 15, p. 040402, 2012. `doi:10.1103/PhysRevSTAB.15.040402`

[4] J.A. Holmes and M.A. Plum, "Beam loss due to foil scattering in the SNS accumulator ring", *in proceedings of the 52nd ICFA Advanced Beam Dynamics Workshop, (HB2012)*, Beijing, China, 2012, paper TUO1B01, pp. 254-258.

[5] M.Y. Huang, N. Wang, S. Wang, S.Y. Zu, "Beam loss due to the foil scattering for CSNS/RCS", *in proceedings of the 52nd ICFA Advanced Beam Dynamics Workshop (HB2012)*, Beijing, China, 2012, paper MOP213, pp. 78-80.

[6] B. Goddard, M. Aiba, C. Bracco, C. Carli, M. Meddahi, W. Weterings, "Stripping foil issues for H- injection into the CERN PSB", *in proceedings of international particle accelerator conference (IPAC'10)*, Kyoto, Japan, 2010, paper THPFB030, pp. 3951-3953.

[7] Shinichi. Kato, Kazami Yamamoto, Masahiro Yoshimoto, Hiroyuki Harada and Michikazu Kinsho, "Localization of the large-angle foil-scattering beam loss caused by multi-turn charge-exchange injection", *Phys. Rev. ST Accel. Beams*, vol. 16, p. 071003, 2013. `doi:10.1103/PhysRevSTAB.16.071003`

[8] P.K. Saha *et al.*, "First measurement and online monitoring of the stripper foil thinning and pinhole formation to achieve a longer foil lifetime in high-intensity accelerators", *Phys. Rev. Accel. Beams*, vol. 23, p. 082801, 2020. `doi:10.1103/PhysRevAccelBeams.23.082801`