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 near to 1 MW beam power. The beam loss and the corresponding residual radiation are key issues for beam intensity ramp up. Based on detail numerical simulations and 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 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.

1. 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 the equivalent beam power to the MR in fast extraction mode is also nearly 800 kW. 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 H^- 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, 3, 4, 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 the 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 200π mm mrad can be

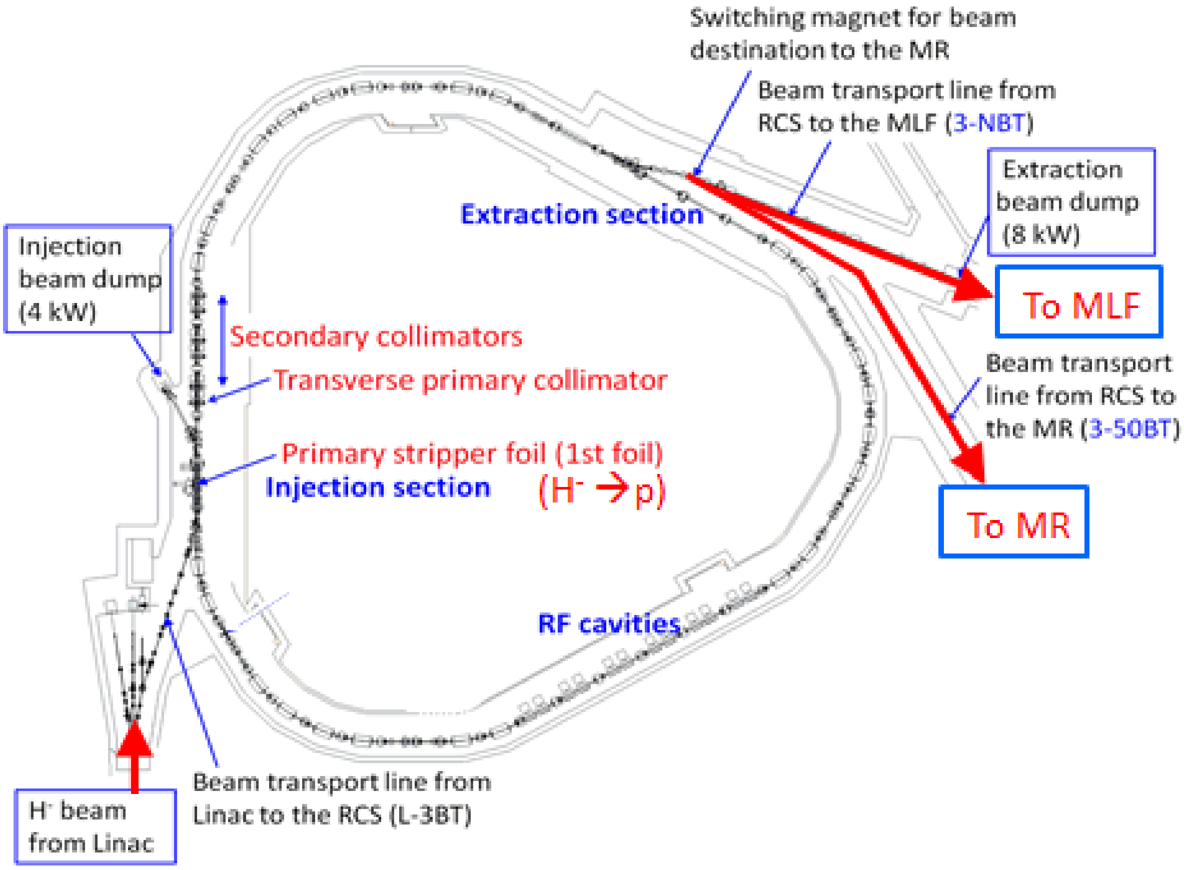

Figure 1. A schematic view of the 3 GeV RCS at J-PARC. The CEI system followed by the collimation system are placed at the 1st straight section. The extracted beam is simultaneously delivered to the MLF and MR.

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, 9, 10, 11, 12]. To further reduce 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 times higher than the beam intensity increase. When increasing the beam power from 700 kW to 800 kW, the beam losses increased 3 times stronger than the associated 14% increase in beam intensity. Our 2nd phase of beam loss mitigation studies covered beam intensities from 800 kW 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.

2. 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 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, 14, 13]. 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 -0.1% 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 kW without optimization is more than 40% higher as compared to that at 700 kW, even though the beam intensity is increased only by 14%. With the optimized LP, the beam loss is decreased significantly as shown in blue color, reaching even lower levels as compared to 700 kW operation at almost all BLMs. A combination of linac momentum offset together with RF frequency offset improves longitudinal beam properties by reducing the number of off momentum particles resulting in significant beam loss mitigation.

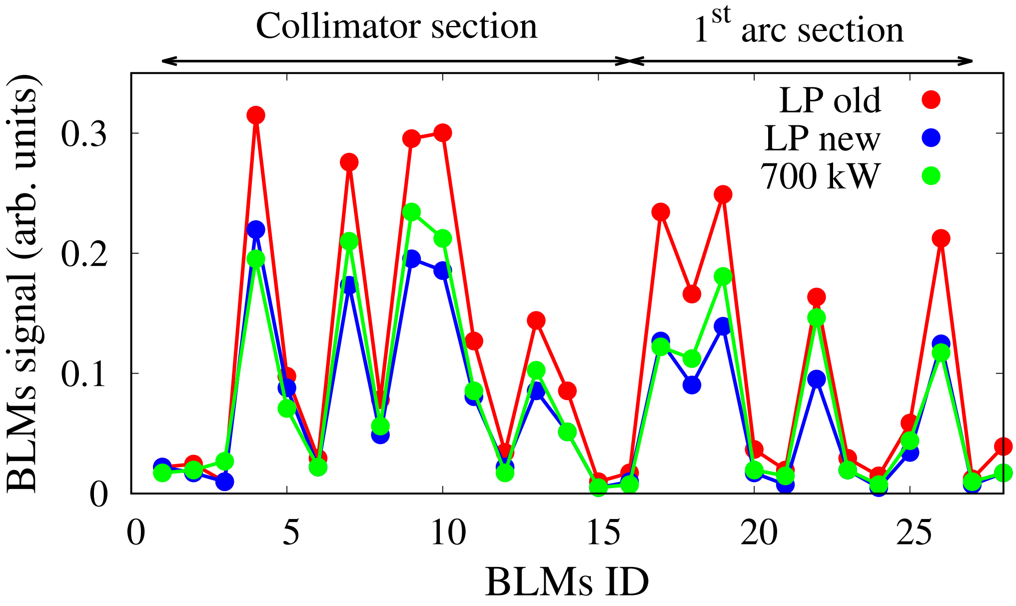

Figure 2. Measured beam losses as a function of BLMs ID at the collimator and 1st arc sections. The beam loss at 800 kW (red) has been significantly mitigated (blue) by an optimized LP and is kept even lower than at 700 kW (green).

Next, we applied a modified 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 horizontal and vertical action coordinates can be interpreted as the average single particle emittances of injected protons due to the phase space offsets between the injected and stored beams ellipses. The fact that, during painting, the horizontal offset increases, while the vertical one decreases is referred to as anti-correlated painting [15]. During our optimization, the painting path during the injection pulse was changed from (A)-(C) to (A)-(B). 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 (B) in Fig. 3, which is less than a usual full painting offset continued up to

(C). 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 200π mm mrad.

Figure 5 shows measurement result of beam loss mitigation with regard to the modified TP at 800 kW. The integrated beam loss from collimator through the 1st arc section has been reduced by more than 30% with respect to the old TP as shown by the pink and blue 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.

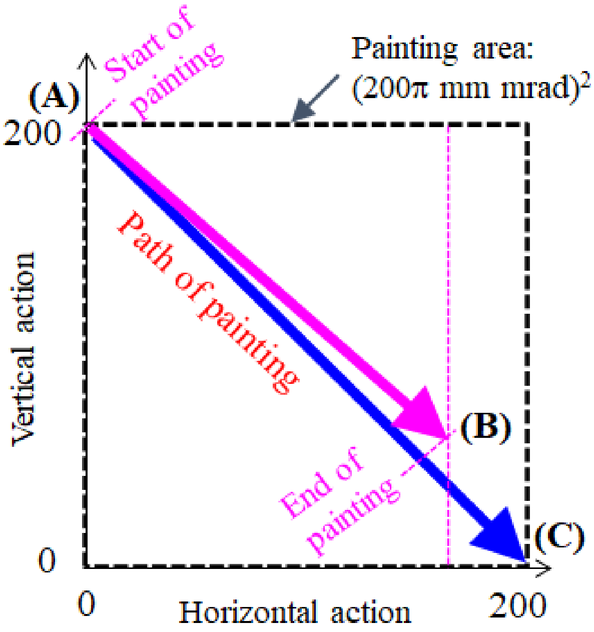

Figure 3. Schematic presentation of the anti-correlated TP and a modified approach (pink) to avoid high spatial charge concentration at high-intensity.

3. NUMERICAL SIMULATION RESULTS

In this section the simulation results, especially by applying the modified TP are presented. The simulations were done by using ORBIT 3D code for the RCS design beam power of 1 MW [16]. The ORBIT code has been well adopted for J-PARC RCS beam simulations by incorporating all realistic machine parameters and it has been demonstrated to well reproduce the measurements [14]. Figure 6 shows transverse beam profiles obtained at the end of injection painting for the horizontal and vertical planes in the left and right plots, respectively. The profiles obtained with original painting patterns (solid lines in Fig. 4) and the present modified patterns (dashed lines in Fig. 4) are depicted by the blue and pink colors, respectively. The simulation results show that a high spatial charge concentration in the vertical plane has been well mitigated producing a more uniform distribution by applying the present modified TP. In the horizontal space, no change of the distribution is observed.

Figure 7 shows the simulation results of beam survival as a function of acceleration time again comparing the old and new TP patterns depicted by the blue and pink colors, respectively. The beam survival is significantly improved by applying a present modified TP pattern. The simulations were ended at 6 ms, where the beam loss is saturated. The time structure of the beam loss distributions at the primary collimator are shown in Fig. 8. For both TP schemes,

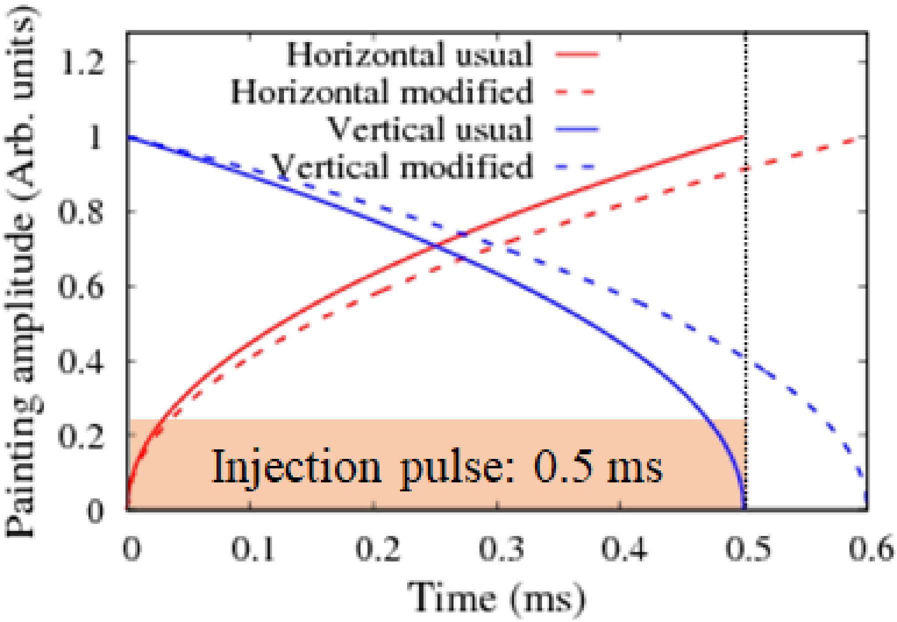

Figure 4. Original and modified TP patterns are shown by the solid and broken lines, respectively.

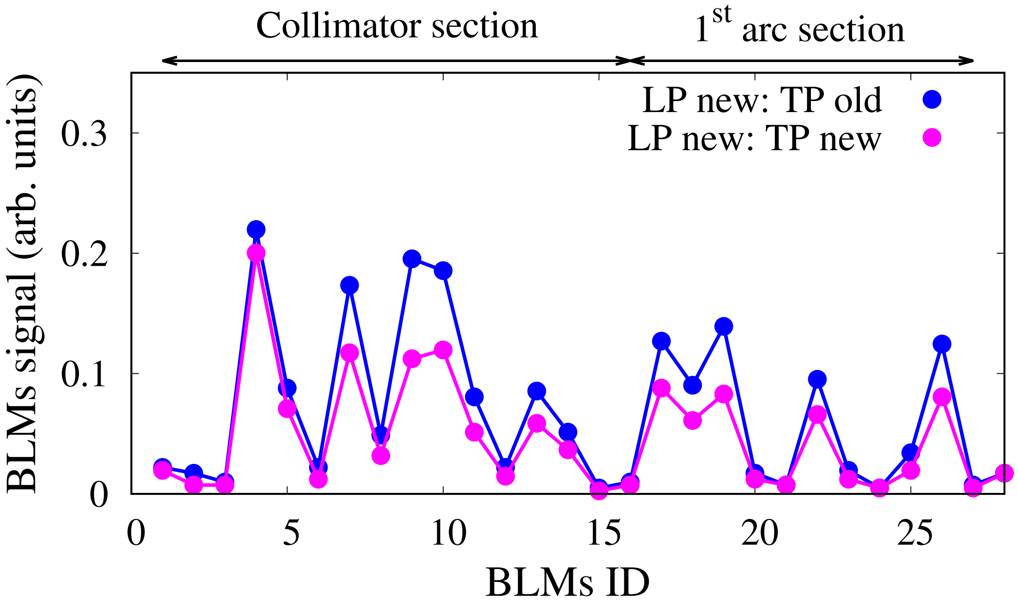

Figure 5. Measured beam loss as a function of BLMs ID at the collimator and 1st arc sections of the RCS. The beam loss at 800 kW (red) has been significantly mitigated (blue) by an optimized LP, which is kept even a lower level that at 700 kW (green).

most of the residual beam loss occurs mainly at injection energy caused by the foil scattering of the circulating beam during injection period, while for the original TP, also significant additional loss at later times is observed. Those additional beam losses are well mitigated by reducing the space charge effect when applying the 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.

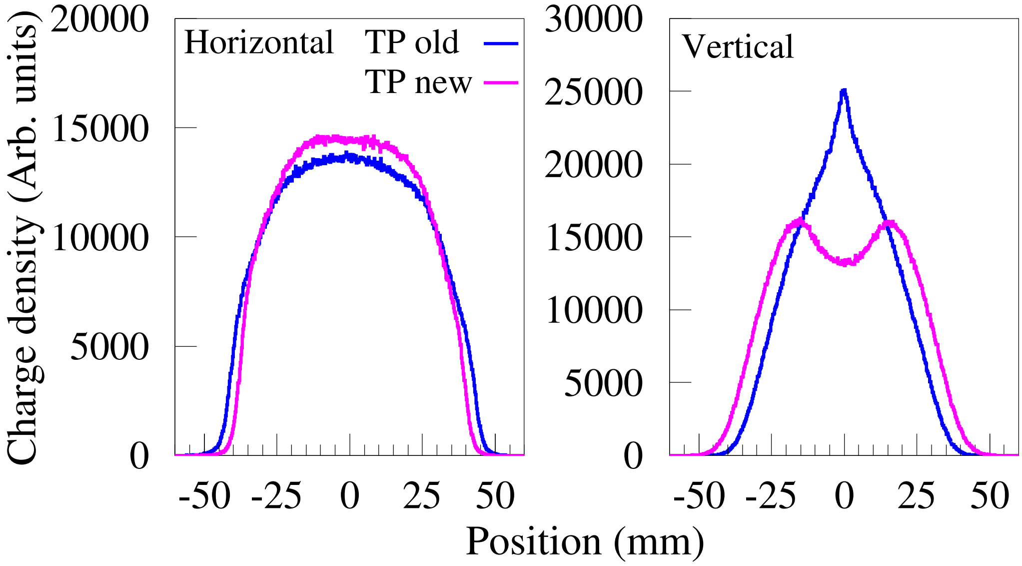

Figure 6. Simulation results of transverse beam distributions obtained at the end of injection. A high spatial charge concentration in the vertical plane occurred for an old TP can be mitigated to produce a uniform distribution by applying a modified TP.

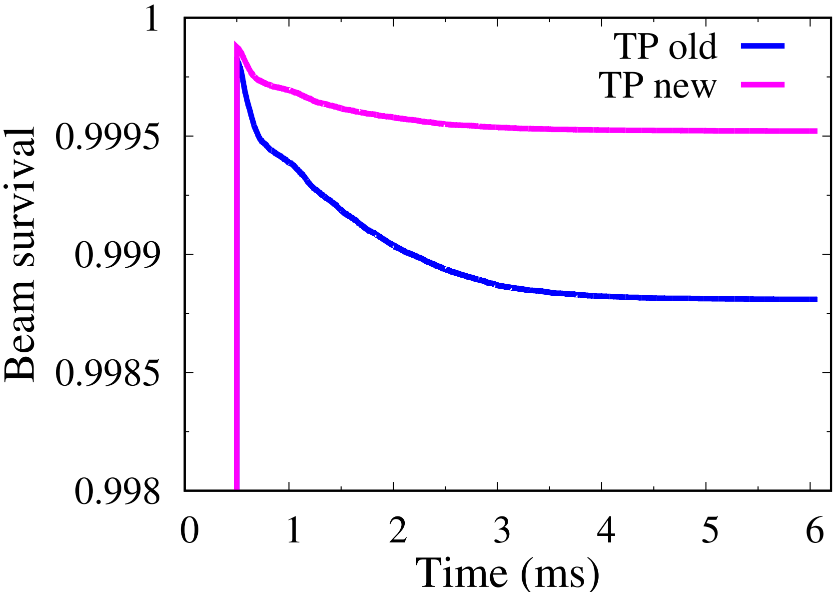

Figure 7. Simulation results of beam survival improvement (pink) by applying a modified TP.

4. SUMMARY

To mitigate the beam loss at J-PARC RCS, we have done systematic studies by optimizing both longitudinal and transverse paintings 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, effectively reducing the range of the beam painting. The beam loss after applying these changes was measured to be significantly reduced, where the residual beam loss is estimated to only around 0.05% and dominated by the foil scattering beam loss. The new LP and TP parameters have been

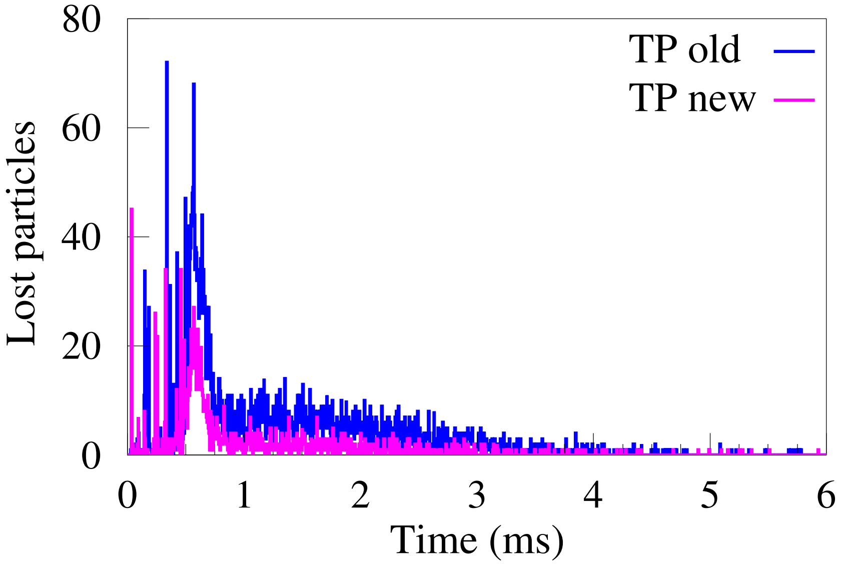

Figure 8. Simulation results of time structure of the beam losses. The additional beam losses (blue) appeared for the old TP have been well mitigated by applying a modified TP (pink) to remain mainly the foil scattering beam losses.

implemented to the present RCS operation at 800 kW beam power. We have also studied the new injection settings using numerical simulations and confirmed that a modified TP ensures a uniform distribution of the beam. The simulation reflects the much-improved observed beam survival and confirms the interpretation that residual beam loss occurs mostly during injection due to foil scattering.

In this study, we have identified almost all remaining sources of the beam loss and sufficiently minimized the beam loss to achieve a stable operation of the RCS at a beam power of more than 800 kW.

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