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# 1-MW BEAM OPERATION AT J-PARC RCS WITH MINIMUM BEAM LOSS

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*Abstract*

We have achieved a routine operation of the 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex) at a beam power close to the designed value of 1 MW. Based on the numerical simulations and experimental studies, the beam loss has been well minimized to a sufficiently low level and also controlled to occur only at lower beam energy localizing almost at the collimator section to realize a stable operation with less machine activation. We have optimized both longitudinal and transverse injection paintings and obtained as much as more than 60% beam loss mitigation. The beam intensity for operation to the muon and neutron production target at the MLF (Material and Life Science Experimental Facility) is now about 8.0 × $10^{13}$ ppp (proton per pulse) with respect to the required 8.33 × $10^{13}$ for 1-MW beam power. This corresponds to 960 kW equivalent beam power, which is just 4% less than 1 MW due to absence of one failure RF cavity out of 12 in total. The RF cavity is under repair and will be back in service at the beginning of April 2024 to realize the user operation with a full beam intensity.

## INTRODUCTION

The 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex) is a high intensity proton driver of 1-MW beam power for the pulsed muon and neutron productions at the MLF (Materials and Life Science Experimental Facility) as well as an injector to the MR (30-GeV Main Ring Synchrotron) [1]. The beam sharing ratio between MLF and the MR from the RCS is 88:12 or 97:3 depending on the fast or slow operation cycle of the MR. The injected 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.

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 extraction section is placed the 2nd straight section, while the RF cavities are placed at the 3rd straight section. The collimator limit is 4 kW, which means a maximum 3% of 133 kW injected beam power can be lost if the beam loss occurs at around the injection energy. In addition, the beam loss localization at the collimator section is also highly necessary for a regular accelerator maintenance works and to realize a stable operation.

Figure 2 shows RCS beam power history for beam operation to the MLF so far. We have demonstrated 1-MW operation at 25 Hz several times, where the latest longer one

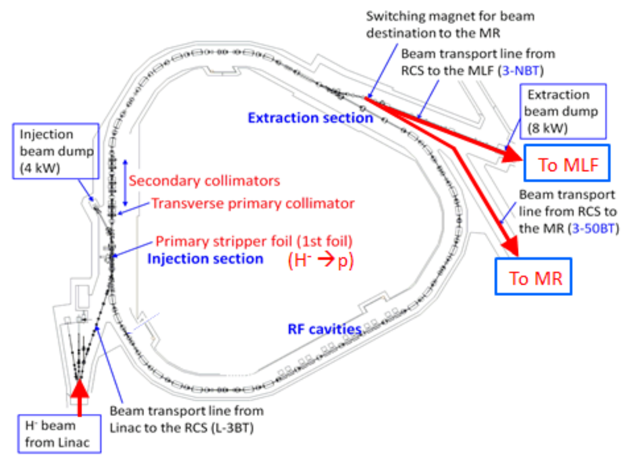


Figure 1: A schematic view of the 3-GeV RCS at J-PARC. The CEI system followed by the collimation system are placed at the first straight section. The extracted beam is simultaneously delivered to the MLF and MR.

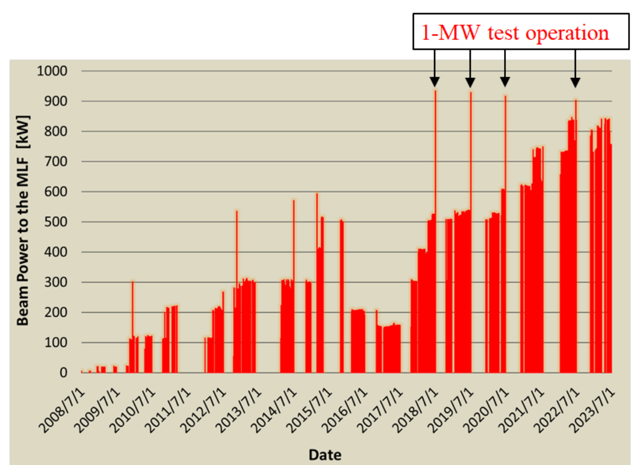


Figure 2: History of RCS beam power to the MLF. The beam power is reached almost to the designed value of 1 MW with 0.1 MW step per year recently according to the operation strategy of the neutron production target.

was done for about 1.5 days in 2020. At present the beam power for operation to the MLF is set to be nearly 850 KW at maximum. The number of particles per pulse (ppp) is about 8.0×$10^{13}$, which is equivalent to 960 kW beam power, but the net beam power becomes 950 kW at 88% duty factor to the MLF when the MR operates for the fast extraction mode. On the other hand, it gives 930 kW net beam power with 97% duty factor when MR operates for the slow extraction mode.

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The beam studies are always conducted at the designed beam intensity of $8.33\times10^{13}$ ppp at beam-on-demand single-shot mode or a lower repetition rate.

The beam loss is one of the key issues to realize a stable and high availability at such a high intensity beam power of 1 MW. A mitigation of the beam loss is thus high essential. As most of the RCS beam is delivered to the MLF, a beam loss mitigation for beam operation to the MLF is highly important. 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 [2–5]. 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 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 200 π mm mrad 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, 8–12].

To further reducing the foil scattering beam losses by reducing foil hitting of the circulating beam, recently we have implemented a minimized vertical size of the injected beam by manipulating its vertical beta of the twiss parameter together with reducing a vertical size of the stripper foil. The rms size of the injected beam at the foil location has been minimized to less than 1 mm from that of its nearly 2 mm. As a result, the vertical size of the foil has also been reduced to 14 mm from its original size of 20 mm. We have measured nearly 30% reduction of average foil hitting of the circulating beam by minimizing the sizes of both injected beam and the stripper foil. We also obtained a significant mitigation of the beam losses at the injection area, collimator section and its downstream by optimizing transverse vertical painting matching with the minimized vertical size of the injected beam. The beam loss at the collimator and first arc section at an equivalent beam power of 770 kW ($6.4\times10^{13}$ ppp) was measured to be as much as 40% reduced in average. As a result, the residual radiation at those areas was also thus measured to be significantly reduced [5].

However, due to a nonlinear effect of the space charge (SC), the beam loss beyond 700 kW beam power was measured to be several times higher than a beam intensity increase. Figure 3 shows a comparison of the intensity dependence beam losses measured by the proportional counter beam loss monitor called (P-BLM) placed throughout the RCS. The horizontal axis is the address of the P-BLM, where vertical axis is the integrated beam loss signal for whole period of beam injection to the extraction in 20 ms. It is important to note that the BLM ID of 33 is placed on contact to the beam duct at the extraction area, which gives a high signal for the extracted beam, but the beam loss rate is quite small and there has no any significant machine activation. In addition, the beam loss signals at BLM IDs around 40 and also for 81-84 mainly occur just after the beam extraction due to the beam is extracted to the beam dump nearby as they are placed at the extraction beam transport (BT) and the 3rd arc section, close to the beam dump. There has thus almost no beam loss signal from those monitors during user operation.

In general, the beam loss has been well controlled to localized mainly at the collimator section, but the intensity dependence of the beam loss is found to be too strong. The integrated beam loss at the collimator and the first arc section at 1-MW beam power is measured to be as much as 4 times higher as compared to only 30% increase of the number of particles from 770 kW beam power. A further beam loss mitigation at 1 MW is therefore essential.

In this research for the last couple of years we have carried out systematic experimental studies and numerical beam simulations for beam loss mitigation at 1 MW. We have optimized both longitudinal and transverse injection paintings to mitigate the beam loss to an extremely low level as presented in this paper.

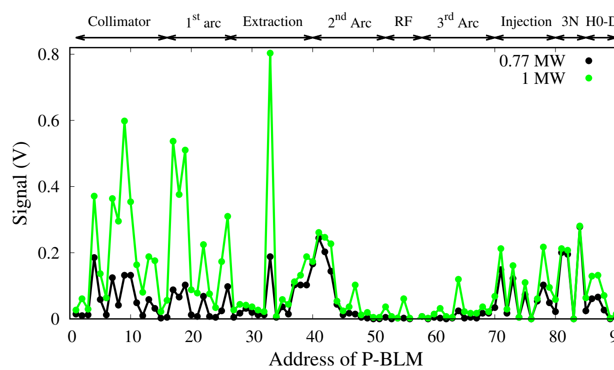


Figure 3: Measurement results of intensity dependence beam loss at 0.77 MW and 1 MW shown by the black and green colors, respectively. Due to the SC effect, the beam loss at the collimator and first arc section at a beam power 1 MW is measured to be as much as 4 times higher than that at 0.77 MW.

## BEAM LOSS MITIGATION AT 1 MW BEAM POWER

To mitigate the beam loss at 1 MW, we have done systematic beam studies and numerical simulations by taking into all realistic machine parameters. In this course of beam loss mitigation, an optimization of the longitudinal painting (LP) and the transverse paintings (TP) at injection were the most significant measures for beam loss mitigation at 1-MW beam power.

### *Optimization of the Longitudinal Painting*

The LP applied at the injection period plays a dominant role for mitigating the space charge (SC) effect at lower beam

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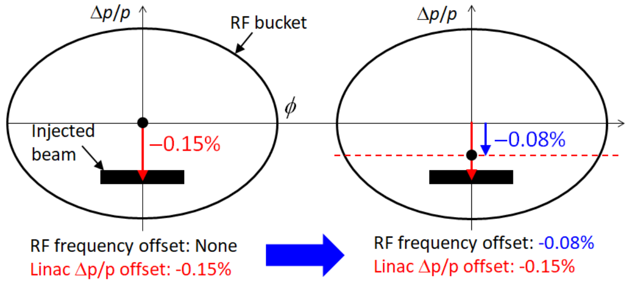


Figure 4: A schematic view of the LP in an original method (left) and the present optimized one (right) applied for beam loss mitigation for a beam power beyond 0.7 MW.

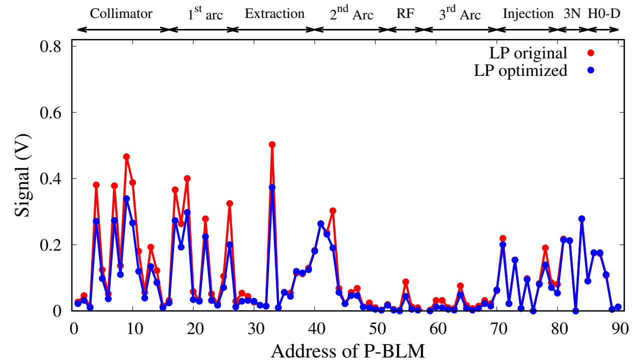


Figure 5: Measurement results of the beam loss at 1 MW throughout the RCS for an original and the present optimized LP painting methods depicted by the red and blue colors, respectively. A nearly 30% beam loss mitigation in average throughout the collimator and the first arc sections has been obtained by applying an optimized LP method.

energy by producing a uniform beam distribution in the longitudinal phase space [7, 13, 14]. One of the parameter of the LP is a momentum offset of the injected beam in the RCS RF bucket. The value of the offset is -0.15% as compared to the bottom energy of 400 MeV and also from the reference RF frequency. In the optimized pattern, the injection beam offset is kept same, but we added a RF frequency offset equivalent to -0.08% for a resultant momentum offset of -0.07% with respect to the center of the RF bucket. Figure 4 shows a schematic view of the original and present optimized LP in the left and right plots, respectively.

Figure 5 shows the measurement result of a significant beam loss mitigation at 1-MW beam power by applying an optimized LP depicted by the blue color with respect to that with for an original LP depicted by the red color. The beam loss throughout the collimator section including the first arc section is significantly reduced by using a modified LP method. The beam loss in average at the collimator and the first arc section is obtained to be 30% reduced by applying a modified LP method. A combination of momentum offset of the injection beam and a RF frequency offset improves longitudinal motion of the beam to reduced the number of off momentum particles lost due chromaticity effect as the betatron tune at injection (6.45) is close to the horizontal half integer resonance. Such an optimization of the LP method also allows us a further fine tuning of the betatron tune, which is current under study.

### *Optimization of the Transverse Painting*

In the next step, we considered an optimization of the transverse painting (TP) applied during injection [15], which was proposed to be an essential way to control the transverse beam density distribution for beam loss mitigation at high-intensity. We realized that at a high intensity of 1 MW a larger painting area bigger than 150 $\pi$ mm mrad causes a significant beam loss due to the beam emittance growth caused by the SC effect and generates halo particles beyond the aperture limit. However, a design TP area of 200 $\pi$ mm mrad is essential to minimize the foil hitting of the circulating beam as well as to maintain lower density beam profile to reduce a pitting damage of the neutron production target.

Figure 6 shows an illustration of the present approach for optimizing the TP to control the transverse beam density

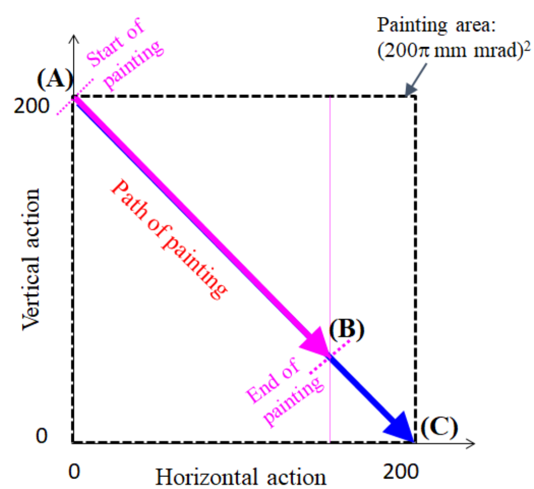


Figure 6: Schematic representation of the anti-correlated TP applied during injection period, where a horizontal and vertical action start from a minimum and maximum amplitudes, respectively. In contrast to the original approach shown by the blue arrow, the range of the beam painting is optimized to be shortened shown by the pink arrow to avoid high spatial charge concentration at high-intensity.

distribution by adjusting the range of the beam painting for both horizontal and vertical directions as shows by the pink arrow as compared to an ordinary one shown by the blue arrow. The horizontal and vertical axes represent a horizontal and vertical actions, respectively. The injection painting is performed by phase space offset of the injection beam relative to the closed orbit, which for an anti-correlated painting the injection beam is usually painted from (A) to (C), but it is modified to paint from (A) to (B) by introducing a scaling factor for a slow variation of the phase space offset. A high spatial charge concentration at the end of injection at high-intensity can be avoided by adjusting the range of the beam painting in such a way.

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Figure 7 shows the optimized painting patterns in broken lines for this purpose plotted together with the ordinary patterns in solid lines. Instead of the painting magnets collapse at the end of the injection pulse duration of 0.5 ms shown by the rectangular box, they are extended to 0.6 ms for the present purpose. As a result, the phase space offset of the injection beam in the new method ends at (B) (Fig. 6), which is less than a usual full painting offset continued up to (C). The unpainted region (B) to (C) is filled by the SC effect and emittance exchange at high intensity, and thus it reduces the large amplitude particles or beam halos beyond the boundary of the painting emittance of 200 $\pi$ mm mrad.

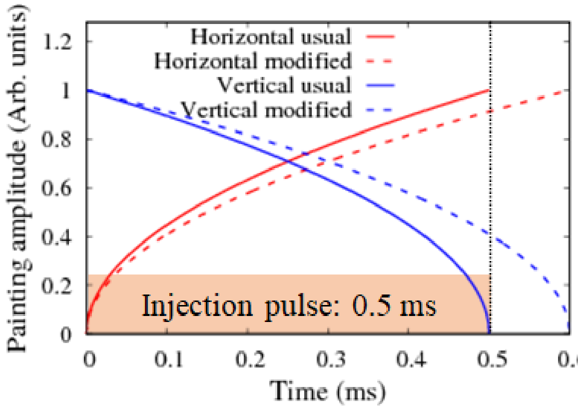


Figure 7: Horizontal (red) and vertical (blue) painting patterns for an anti-correlated TP. The solid lines are the original patterns where both patterns collapse at the end of injection duration of 0.5 ms. The broken lines are optimized patterns and both collapse at 0.6 ms to control the beam painting as shown by the pink arrow in Fig. 6.

Figure 8 shows measurement result of beam loss mitigation by applying a modified TP at 1-MW beam power. An optimized TP (pink) gives a further nearly 35% beam loss mitigation in average at the collimator through the first arc section as compared to that for using an original TP (blue).

Figure 9 shows a comparison of the beam loss at a beam power of 1 MW before and after applying the optimized LP and TP patterns in this study depicted by the green and pink colors respectively. One can see that the beam losses not only the collimator and the first arc sections but throughout the RCS have been significantly mitigated. The beam loss at the collimator and the first arc sections has been mitigated to be more than 60% by optimizing both LP and TP in this study. It is worth mentioning that the rms emittance of the extracted beam, especially the horizontal one has also been nearly 25% reduced and thus beam halos as well, which also gives much less machine activations at the beam transport until the neutron production target.

Figure 10 shows a comparison of the time structure of the beam loss at 1 MW measured by a plastic scintillator placed at the collimator section. The additional beam loss appeared after the injection period of 0.5 ms without any optimization of the paintings (green) has been almost mitigated by applying an optimized LP together with the TP (pink).

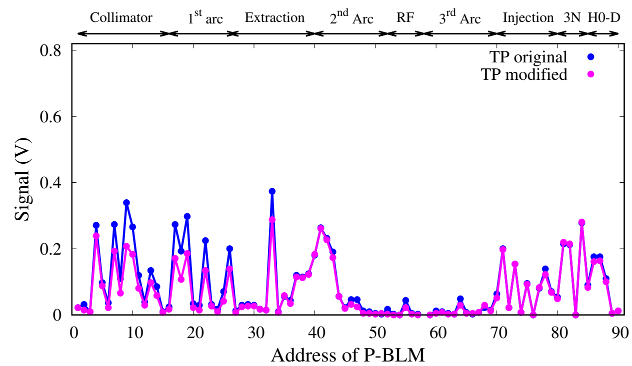


Figure 8: Comparison of the measured beam loss by applying a modified TP (pink) to control the range of beam painting to that with using an original TP (blue). A modified TP gives a further nearly 35% beam loss mitigation in average in the collimator and the first arc section as compared to the original TP.

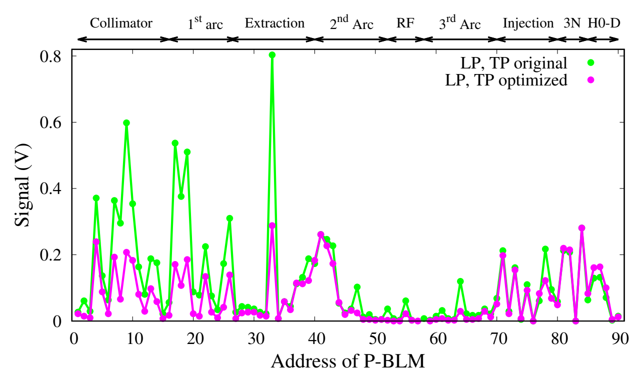


Figure 9: Comparison of the measured beam loss before and after optimizing the LP and TP depicted by the green and pink colors, respectively. An optimization of LP and TP together gives more than 60% beam loss mitigation in the collimator through the first arc section as compared to those without modifications.

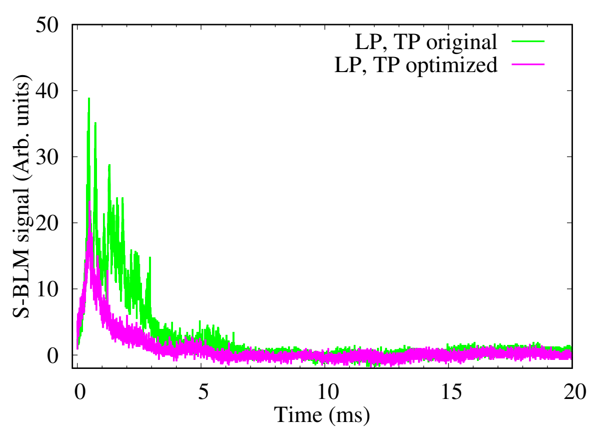


Figure 10: Measured time structure of the beam loss at 1 MW. The additional beam loss appeared using original LP and TP (green) has been well mitigated by optimizing those (pink) in the present study.

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The residual beam loss has been estimated to be well below than 0.1% dominated by the remaining foil scattering of the circulating beam. A further beam loss mitigation, especially the foil scattering one can be obtained by further reducing vertical size of the foil to 12 mm as the injected beam has been well minimized.

We have already implemented the present optimized longitudinal and transverse injection paintings for RCS beam operation to the MLF at beam power nearly 1 MW and obtained a stable operation with low beam loss and less machine activation.

## NUMERICAL SIMULATION RESULTS

In this section the simulation results of beam loss mitigation obtained by applying an optimized TP are presented. The simulations were done by using ORBIT 3D code for the RCS designed 1-MW beam power [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]. The present simulation has also been performed by introducing almost all machine parameters as presented the experimental results in the previous section.

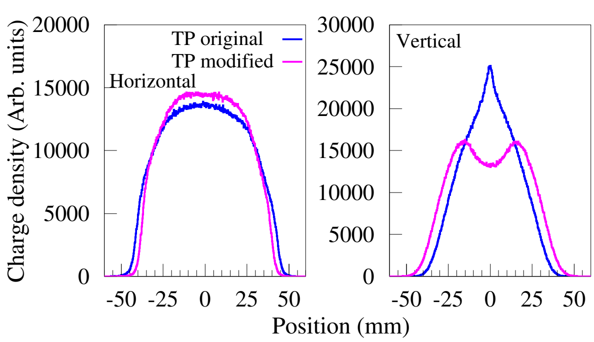


Figure 11: Simulation results of transverse beam distributions obtained at the end of injection for a beam intensity of 1 MW. A high spatial charge concentration in the vertical plane occurred for an original TP can be mitigated to produce a uniform distribution by optimizing the range of beam painting with a modified TP.

Figure 11 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 beam profiles obtained for original painting patterns (solid lines in Fig. 7) and the present modified patterns (dashed lines in Fig. 7) are depicted by the blue and pink colors, respectively. The simulation results shows that a high spatial charge concentration, especially in the vertical plane has been well mitigated producing a uniform distribution by applying a modified TP.

Figure 12 shows the simulation results of beam survival as a function of acceleration time done by using the original and modified TP patterns depicted by the blue and pink colors, respectively. At this moment, the simulations were carried out until 6 ms as the beam survival has already been saturated. The beam survival is significantly improved to more than 40% by applying a present modified TP pattern and is consistent with the measurement result.

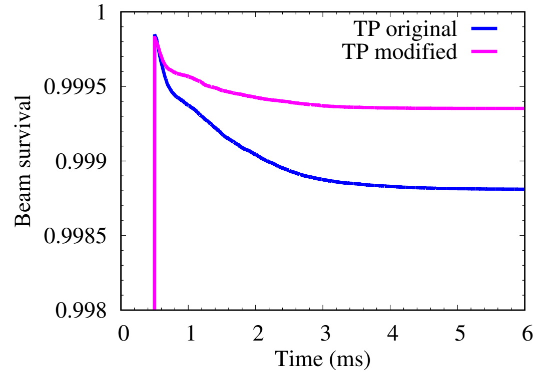


Figure 12: Simulation results of beam survival at a beam intensity of 1 MW obtained for an original (blue) and the modified (pink) TP. A modified TP gives a significant beam survival consistent to that obtained in the measurement.

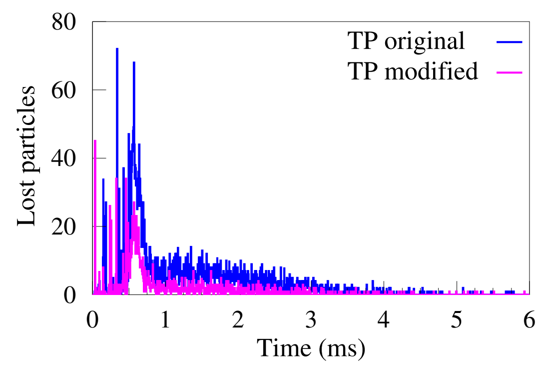


Figure 13: Simulation results of time structure of the beam losses depending on the TP. Additional beam losses (blue) appeared for an original TP have been well mitigated by applying a modified TP (pink). The residual beam losses is mainly caused by the foil scattering of the circulating beam.

The time structure of the beam loss distributions at the primary collimator is shown in Fig. 13. The beam loss is well controlled occurring mainly at injection energy caused by the foil scattering of the circulating beam during injection period, but there appears some additional beam losses for an original TP. Such an additional beam losses are well mitigated by reducing the space charge effect controlling the range of the beam painting in an optimized TP. The residual beam loss is dominated by the foil scattering beam losses occurring during injection period and for some additional time until the beam is sweep away from the foil. The time structure of the beam loss obtained in the simulation is also consistent with the experimental results.

## SUMMARY

In the 3-GeV RCS of J-PARC, we have obtained a significant beam loss mitigation at a designed beam power of 1 MW by systematic experimental studies and numerical beam simulations. In this study, we have optimized both longitudinal painting (LP) as well the transverse painting (TP) applied during the injection period. The optimization of the LP is done by applying a momentum offset of -0.15% the injection beam together of the with RCS RF frequency offset corresponds to -0.08%, instead of momentum offset of the injection beam only so far. On the other hand, the TP is optimized by extending painting magnets patterns beyond the injection pulse duration for a slow variation of the phase space offset to adjust the range of the beam painting that ensures a uniform spatial charge distribution of the transverse beam profile at the end of injection.

The beam loss applying these changes was measured to be significantly reduced to more than 60% as compared to that without any optimization of either LP or TP. The measured time structure of the beam loss was found to be occur mainly during injection period. The residual beam loss is estimated well below than 0.1% and dominated by the beam losses caused by foil scatting of the circulating beam, while the most of the additional beam losses have been mitigated. The rms emittance of the extracted beam, especially the horizontal one was also measured to nearly 25% reduced by applying the present optimized parameters.

The numerical beam simulation results studied for the TP dependence have also been presented. A modified TP ensures a uniform spatial charge distribution of the transverse beam profile at the end of injection. As a result, the beam survival is significantly improved by successfully reducing the additional beam losses. The beam loss occurs mostly during injection period caused by the foil scattering of the circulating beam.

The optimized longitudinal and transverse injection painting at injection has already been implemented to the RCS beam operation to the MLF at a beam power nearly 1 MW. We obtained a stable operation with low beam loss and less machine activation.

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