

State-of-the-art beam loss minimization at high-intensity beam operation of the 3 GeV rapid cycling synchrotron at the Japan Proton Accelerator Research Complex

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(Received 4 October 2024; accepted 20 June 2025; published 25 July 2025)

At the 3-GeV rapid cycling synchrotron (RCS) of the Japan Proton Accelerator Research Complex, we have minimized the beam loss at high-intensity beam operation up to the designed beam power of 1 MW. This was accomplished through systematic numerical simulations and experimental studies conducted over 2 years from 2020 and 2022. We first focused on mitigating uncontrolled beam losses originating from the foil scattering of the circulating beam, which results in high residual radiation levels, particularly in the injection area. These uncontrolled beam losses were well mitigated by reducing the stripper foil size and optimizing the injection beam size. Subsequently, we attempted to minimize the space charge effects and the associated beam losses at 1 MW by implementing several measures, such as refining both longitudinal and transverse injection paintings, correcting betatron resonances, and optimizing betatron tunes at injection. Consequently, we reduced beam losses throughout the RCS, including the collimator area, by 80% as compared to those observed at 1-MW trial operation in 2020. The residual beam loss at 1 MW is now estimated to be well below 10^{-3} , which is primarily attributed to residual foil scattering-induced beam losses. Notably, beam losses in areas other than the collimator section are uncontrolled and required to be well minimized to ensure stable operation and regular accelerator maintenance. We have considerably reduced the machine activation, achieving a 1-order-of-magnitude decrease at the collimator compared to that in 2020. This improvement has enabled the RCS to maintain more than 98% availability for user operation recently. The simulation and measurement results, demonstrating good agreement, provide a detailed understanding of the beam loss mechanism at each step and guide the implementation of effective optimizations.

DOI: [10.1103/tyh-jcq3](https://doi.org/10.1103/tyh-jcq3)

I. INTRODUCTION

The 3-GeV rapid cycling synchrotron (RCS) at the Japan Proton Accelerator Research Complex (J-PARC) is designed to produce a high-intensity proton beam of 8.33×10^{13} protons per pulse (ppp) at a repetition rate of 25 Hz for achieving a beam power of 1 MW. This high-intensity beam serves various experimental purposes, including the generation of pulse neutrons and muons at the Material and Life Science Experimental Facility (MLF)

and beam injection into the 30-GeV main ring synchrotron (MR) [1].

Figure 1 represents a schematic view of the RCS. Notably, the RCS utilizes multiturn charge-exchange injection of H^- (negative hydrogen), wherein a 0.4-GeV H^- beam from the Linear accelerator (LINAC) is stripped to a proton beam by using a stripper foil before injecting into the RCS. The protons are then accelerated up to 3 GeV and simultaneously delivered to the MLF and MR at a repetition rate of 25 Hz. The beam tuning and the beam studies are typically conducted by beam-on-demand single-shot mode or a lower repetition rate of less than 1 Hz, as the beam directed to the extraction beam dump, which has a capacity of only 8 kW located near the RCS extraction area (circle in Fig. 1). Currently, the RCS beam sharing ratio between the MLF and MR is generally 88.2%:11.8% or 96.2%:3.8%, depending on MR operating mode of fast extraction (FX) or slow extraction (SX), respectively. Given that the major proportion of the

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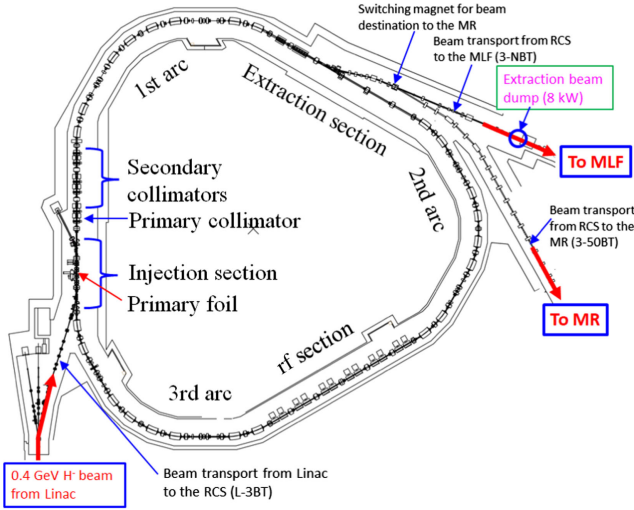


FIG. 1. Schematic view of the 3-GeV RCS at the J-PARC. The 0.4-GeV injection H^+ beam from the LINAC is stripped to proton beam using the primary stripper foil (also called first foil) and subsequently injected into the RCS. The injected protons are then accelerated up to 3 GeV and delivered simultaneously to the MLF and MR. The beam tests are conducted by transporting the beam to the extracted beam dump located one floor down near the second arc section of the RCS.

beam is delivered to the MLF, minimizing the beam loss for beam delivery to the MLF is particularly crucial to ensure RCS operation stable and sustainable, while reducing the machine activation to a sufficiently low level.

TABLE I. Typical designed parameters of the RCS, specifically for beam operation to the MLF.

Name	Value
Circumference	348.333 m
Injection energy	0.4 GeV
Extraction energy	3 GeV
Transition energy	9 GeV
Repetition rate	25 Hz
Harmonic number	2
Number of bunches	2
Number of protons per pulse	8.33×10^{13}
Output beam power	1 MW
Normalized transverse emittance of the injection beam (rms)	$0.25 \text{ } \mu\text{m mrad}$
Momentum spread of the injection beam (rms)	$\pm 0.15\%$
Transverse painting emittance	$200 \text{ } \mu\text{m mrad}$
Ring acceptance	$486 \text{ } \mu\text{m mrad}$
Primary collimator aperture	$324 \text{ } \mu\text{m mrad}$
Collimator capability	4 kW
Momentum acceptance	1%
Betatron tune at injection	(6.46, 6.36)
Betatron tune at extraction	(6.38, 6.35)
Natural chromaticity (ξ_x, ξ_y)	-10, -7

Table I presents the key operational parameters of the RCS, specifically pertaining to the beam operation for the MLF. Notably, most RCS parameters, except properties of the injection beam, are separately optimized for the MLF and MR and adjusted on a pulse-to-pulse basis. Additional details regarding the RCS can be found in the J-PARC technical design report [1].

Figure 2 illustrates historical RCS beam power data for beam delivery to the MLF up to recent times. The ramp-up in beam power primarily follows the operational strategy adopted for the neutron production target, which typically involves an annual increase of 0.1 MW. Recently, we have reached the designed beam intensity of 8.33×10^{13} ppp, which gives 0.88 or 0.96 MW net beam power when approximately 12% or 4% of the RCS pulses are delivered to the MR for FX or SX operation, respectively. To date, we have demonstrated test operation at approximately 1 MW beam power a couple of times, each for a short duration. In particular, the most recent test conducted in 2020 recorded an equivalent beam power of approximately 1 MW for 1.5 days. As it was the first run for both accelerator and the target to test with a designed beam power for a longer period than previously tested for 1 h or less, it was scheduled at the end of user operation, which was just before the 3 months long summer shutdown period for yearly maintenance works in 2020.

In high-intensity particle accelerators such as the RCS of J-PARC, mitigating beam loss is crucial for achieving stable and sustainable operation, while minimizing machine activation is essential to facilitate regular maintenance of accelerator components. However, the primary challenge hindering effective beam loss control is the nonlinear increase in beam emittance caused by the space

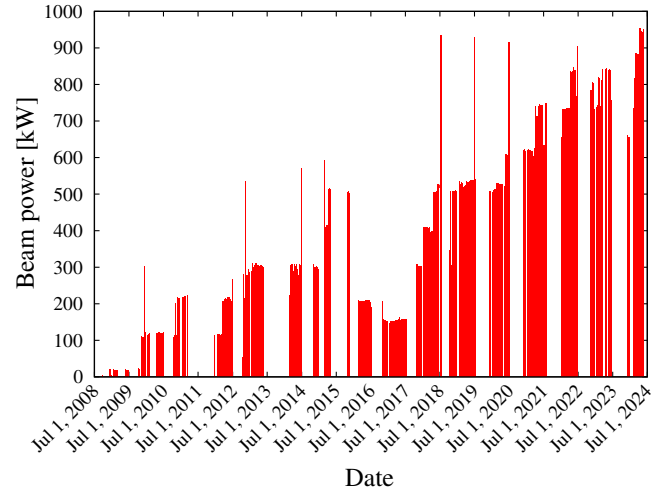


FIG. 2. Historical RCS beam power data for beam delivered to the MLF. The equivalent beam power for routine operation of the RCS has reached the designed value of 1 MW, resulting in a net beam power of 0.95 MW when approximately 4% of the RCS pulses are delivered to the MR for SX operation.

charge (SC) effect prevalent at high intensities. This non-linear increase leads to beam loss due to beam emittance blowup and beam halo generation and represents the primary issue hindering adequate beam loss and control [2–10]. Effective strategies to address this issue primarily include carefully selecting the betatron tune, correcting lattice imperfections and optimizing the beam distribution to minimize SC-induced resonance excitation and shrinkage of the dynamic aperture [8,11–14]. Given that more than 90% of the beam is delivered to the MLF, the residual radiation in the RCS predominantly originates from beam loss associated with MLF-directed beam operation. Hence, the beam loss reduction in the RCS for this mode is highly important. However, residual radiation levels, particularly at the injection area, are considerably high even at low beam intensity owing to uncontrolled beam losses resulting from the foil scattering of the circulating beam, longitudinal beam losses at arc sections (dispersion peaks), and beam losses occurring downstream of the collimator section due to leakage from the collimator because of excess beam loss at the collimator section [15–19]. Notably, beam losses at locations other than the collimator section represent uncontrolled losses, and their associated residual radiations are substantial challenges for beam operation at high intensities. Hence, the effective mitigation of such beam losses, especially the uncontrolled ones, is vital for beam power ramp-up to the designed value of 1 MW.

One of the primary motivations for this study was to minimize uncontrolled beam losses in the RCS caused by the foil scattering of the circulating beam while also addressing additional beam losses originating from the SC effect at the designed beam power of 1 MW. To this end, extensive numerical beam simulations and systematic beam studies were conducted over nearly 2 years from 2020 to 2022. These studies primarily focused on minimizing the rate at which the circulating beam hits the foil, correction of the betatron resonances, optimizing longitudinal painting (LP) and transverse painting (TP) applied during injection, as well as fine-tuning of the betatron tunes at injection. These optimizations considerably reduced beam losses throughout various sections of the RCS, including the injection area, collimator section, and arc sections. In particular, the beam loss at the highest beam power of 1 MW was reduced up to 80% as compared to the level achieved for the previous operation conducted in 2020. Currently, the rate of the residual beam loss at a beam power of 1 MW is estimated to be considerably low, only about 5×10^{-4} . Such a reduction in beam loss has led to a substantial decrease in residual radiation levels in the RCS, making routine operation at 1 MW more sustainable. The operational availability has improved to more than 98%, where the downtime periods mostly attributed to hardware failures and their repair or replacement rather than beam loss or residual radiation issues [20,21].

This paper is organized as follows. In the following section, we briefly review the beam loss situation during

the previous operation with 1-MW beam power in 2020. The present research conducted from 2020 to 2022 are presented in Secs. III–V, where numerical simulation and experimental results of foil scattering beam loss reduction conducted at 0.77-MW beam power are presented in Sec. III, experimental results of beam loss minimization at 1 MW beam power in Sec. IV, numerical simulation results at 1-MW beam power in Sec. V. Finally, a summary is given in Sec. VI.

II. BEAM LOSS MITIGATION RESULTS AT 1 MW UNTIL 2020

Figure 3 shows measurement results of the circulating beam intensities in the RCS recorded by a slow current transformer (SCT), as a function of acceleration time. Each color in the figure represents a different beam intensity achieved by varying the injection pulse length from 0.1 ms to a maximum of 0.5 ms while keeping all other parameters unchanged. A linear relationship is observed between beam accumulation and injection pulse duration, with no apparent reduction in beam intensity. This indicates that the beam loss is effectively managed for any intensity up to the designed maximum of 1 MW.

In the RCS, beam loss is measured by two types of more than a hundred beam loss monitors (BLMs) positioned around the ring. Among these, proportional counter type BLMs, called P-BLMs, are the most predominant and are used for the machine protection system [22–24]. The P-BLMs are filled mostly with Ar and a little additive gas mixture produced by Toshiba Electron Tube Company Limited [25]. The integrated signal of each P-BLM is collected in real time and the interlock system is activated

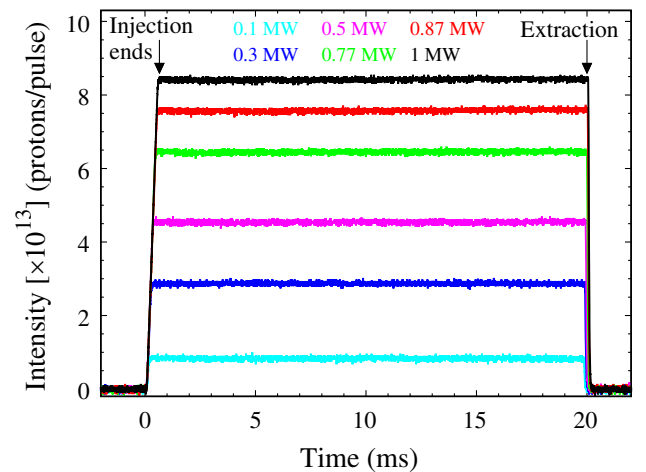


FIG. 3. Temporal variation of the measured circulating beam intensity. Different colors represent various beam intensities controlled by the injection pulse length. No significant beam intensity loss is observed at any beam intensity up to the maximum of 1 MW.

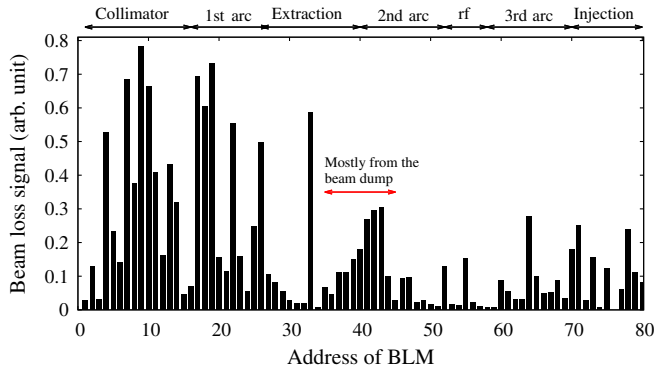


FIG. 4. Beam losses at 1 MW measured by P-BLMs installed throughout the RCS. The BLM signals are integrated over the complete cycle from injection to extraction. Beam losses are observed to be primarily localized at the collimator section, but additional non-negligible beam losses occurring, especially at the downstream of the collimator section throughout the first arc section and partly at the second and third arc sections.

to stop the beam if any P-BLM signal crosses the preset value.

In addition to P-BLMs, we have also another type of BLMs with plastic scintillator called S-BLMs used for measuring the detail temporal structure of the beam loss [23,24]. The type of the plastic scintillator is BC-400 produced by Bicron, and the photomultiplier type is H3164-10 produced by Hamamatsu photonics [26]. The S-BLM has a good time resolution of less than 100 ns in FWHM.

Figure 4 shows the measured beam loss distribution throughout the RCS at a beam power of 1 MW. The horizontal axis in this figure represents the IDs of the P-BLMs, while the vertical axis represents the integrated beam loss measured over 20-ms period from injection to extraction. The beam loss has been almost localized at the collimator section, but substantial beam losses are apparent in the first arc section, with non-negligible beam losses in other arc sections, including injection area. The operating voltages of the P-BLMs differ across different sections of the RCS. In particular, in sections other than the collimator, these voltages are maintained at higher levels to detect even minimal fractions of beam losses. Consequently, the machine activation is the highest and almost entirely localized in the collimator section, although it is also notably high, particularly in the injection and first arc sections. Furthermore, the machine activations at the second and third arc sections are also non-negligibly high. Notably, the beam losses for the P-BLMs positioned between the latter part of the extraction and second arc sections (P-BLM IDs between 35 to 45 as indicated by the red arrow in the figure) correspond to signal from the extraction beam dump as the beam was transported to the beam dump which is located near the second arc section (see Fig. 1). These beam losses are apparent only if the beam is transported to the beam dump for beam studies and disappear during regular beam operations when the beam is directed to user facilities. In addition, it is also important to

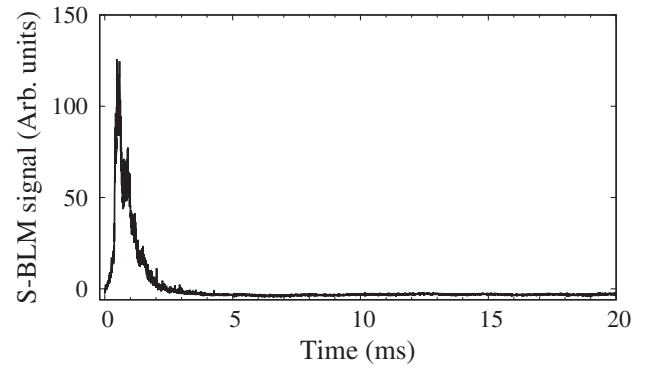


FIG. 5. Temporal structure of the beam loss at 1 MW measured by an S-BLM installed within the collimator section. The beam loss is almost managed occurring at lower energies but there still has additional beam losses continued up to later periods.

mention that in contrast to most of the P-BLMs put at around 1 m distance from the beam chamber, a few of them, such as the P-BLM ID of 33 is put almost on contact to the beam duct for measuring even a tiny fraction of the beam halos at the extraction branch. The signal of this BLM thus shows a higher beam loss rate among others nearby, but the machine activation at that location remains negligibly small [27].

Figure 5 shows the temporal beam loss distribution measured by an S-BLM placed in the collimator section. The beam loss is almost well controlled, occurring only during the early acceleration period, i.e., the first few milliseconds of the cycle characterized by the lower beam energy, while no beam losses are observed at higher beam energies throughout the remainder of the cycle until the final extraction at 20 ms. Notably, higher energy protons lost contribute to greater machine activation rates owing to the increased production of secondary particles and hadronic showers [28]. However, in the present scenario, significant beam loss occurs during the injection period and persists for approximately 5 ms, leading to considerable residual radiation, especially in the injection area, collimator section, and the first arc section. The residual radiation levels measured on contact after 5 h cooling of RCS operation at a beam power of 1 MW for 1.5 days during the operation conducted in 2020 were as high as 9, 20, and 2 mSv/h at the hottest spots in the injection area, collimator section and the first arc section, respectively. Furthermore, other areas, such as the second and third arc sections, presented non-negligible residual radiation levels up to several hundred μ Sv/h. More details on the machine activations around the ring at 0.6 MW routine operation in 2020, including 1-MW test operation, can be found in our another article [27].

Notably, the beam losses observed in sections other than the collimator represent uncontrolled beam loss. Such a beam loss results in a high residual dose level, which poses considerable challenges for stable routine operation at high intensity and regular maintenance of accelerator

components. The machine activation throughout the RCS, even at a routine beam power of only 0.6 MW, was also considerably high. In particular, beam losses observed in the injection area caused by uncontrolled foil scattering of the circulating beam during multiturn injection and in the first arc section largely attributed to the excess beam loss in the collimator and also the beam loss leakage or hadronic showers from the collimator were serious concern to ramp up the beam power. Hence, further mitigation of the beam loss at the collimator section is essential to reduce the beam loss and the corresponding residual radiation level downstream of the collimator section including all arc sections. Concurrently, minimizing the uncontrolled beam loss at the injection area is also necessary. The primary motivation of the present research was thus to reduce the uncontrolled beam losses throughout the RCS, including injection area, caused by the foil scattering of the circulating beam at a routine beam power of 0.7 MW for the MLF in 2020 and also eventual ramp-up operation to the designed beam power of 1 MW.

III. MINIMIZATION OF THE FOIL SCATTERING BEAM LOSS

The foil scattering of the circulating beam primarily results in uncontrolled beam losses in the injection area. Such beam losses are attributed to the large-angle scattering particles from the injected and circulating beams, caused by nuclear reactions and Rutherford scattering during each foil traversal in the injection period [18,19,28]. Foil scattering also results in beam emittance growth, leading to the formation of unexpected beam halos owing to multiple traversals of the circulating beam during the multiturn injection process. Moreover, foil scattering-induced uncontrolled beam losses at the injection area result in high residual radiation levels even at moderate beam powers [16–19]. Consequently, during long shutdown periods, particularly in summer, the exposure dose rate to accelerator maintenance workers is the highest in the injection area compared to any other area in the RCS [20]. This poses a serious challenge for regular maintenance and presents a major concern for the planned beam power ramp-up to 1 MW.

Figure 6 illustrates a schematic layout of the RCS injection area, also demonstrating the transverse painting (TP) process during the injection period. The injection scheme employs a primary carbon stripper foil, named the first foil has a thickness of $333 \mu\text{g}/\text{cm}^2$ to strip 99.7% of the H^- beam originating from the LINAC to proton beam for injecting into the ring. The remaining 0.3% of H^- beam, mostly partially (single electron) stripped H^- known as neutral hydrogen H^0 , and any unstripped H^- are ideally negligibly small [29]. The H^0 and any unstripped H^- are further stripped to protons by secondary foils (second and third foils, respectively) and are directed to the injection beam dump. To reduce the foil scattering-induced beam losses, reducing the number of foil traversals of the

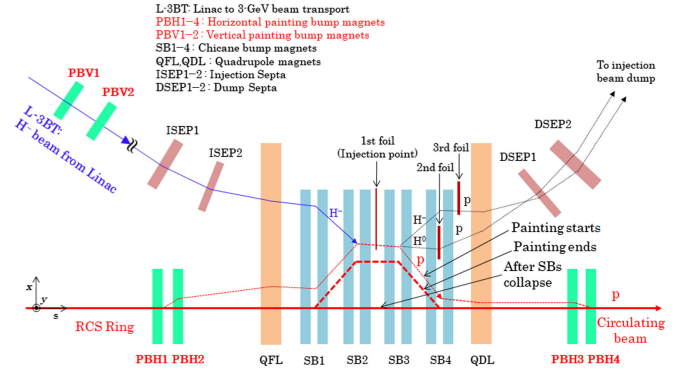


FIG. 6. Layout of the RCS injection area and a schematic view of the TP process at injection. The horizontal TP magnets (PBH1-4) are installed in the injection area, while vertical TP magnets (PBV1-2) are placed at the injection beam transport.

circulating beam is essential. For that purpose, a TP scheme with large emittance, especially for beam operation to the MLF has been adopted [12,30,31]. The TP scheme induces a controlled, time-dependent phase space offset between the injection beam and circulating closed orbit, thereby creating a different particle distribution within the circulating beam during the multiturn charge-exchange injection process. The TP scheme serves two key purposes. First, it ensures a uniform beam distribution, which is essential for suppressing space charge (SC) effects at high intensities. Second, by varying the closed orbit, the TP scheme induces large betatron oscillations in the circulating beam, thereby reducing its frequency of foil traversal. The TP in the horizontal plane is performed by sweeping the horizontal closed orbit along the major axis of the circulating beam ellipse using four horizontal painting magnets (PBH1-4) placed within the injection straight section of the injection region, while vertical angle of the injection beam at the first foil (injection point) is varied by keeping its position unchanged by using two vertical painting magnets (PBV1 and PBV2), placed at the end of the injection beam transport called L-3BT (Linac to the 3-GeV Beam Transport). The PBVs are about 10 m upstream from the first foil and have a 180° vertical betatron phase advance from PBV1 to the first foil. The time-dependent waveforms of the painting magnets are typically produced by a square-root function exciting only during the injection period of 0.5 ms, which can be found in detail in our earlier articles [12,30–32]. For a painting area of $200 \pi \text{mm mrad}$, the phase space offset (position and angle) for painting in the horizontal plane is typically 42.6 mm and -6.1 mrad , while those are 0 and -3.4 mrad in the vertical plane. The foil hitting rate decreases with increasing TP area. Hence, a TP area of $200 \pi \text{mm mrad}$ is adopted for the MLF beam [32], which also ensures the requirement of a large beam emittance for reducing pitting damage of the neutron production target.

Although the average number of foil hits per injected particle for MLF beam remains around 7, a further reduction

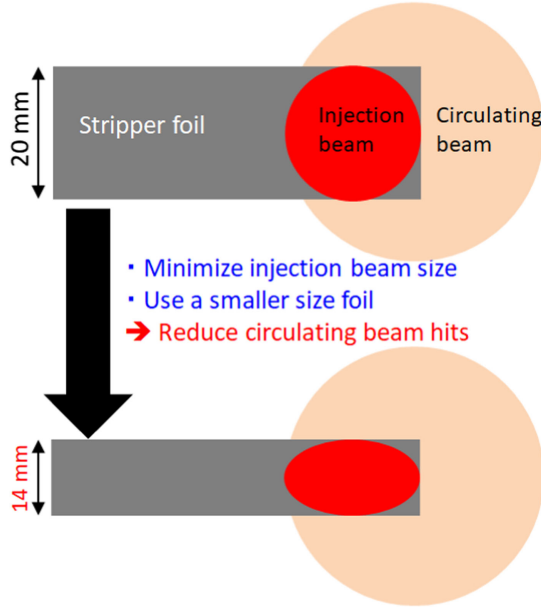


FIG. 7. Schematic view of the approach currently adopted to reduce foil traversal rate of the circulating beam by decreasing the vertical size of the injection beam, thereby confining it to a smaller vertical portion of the foil.

is essential owing to the extremely high machine activation at the injection area, collimator region, and downstream of the collimator region in the first arc section. One straightforward way to reduce the number of foil hits of the circulating beam particles involves minimizing the size of the stripper foil itself. However, doing only this poses a risk of increasing the number of missing injection H^- , leading to an increase in the amount of unstripped waste beam at the injection beam dump. To address this, our approaches also focus on minimizing the size of the injection beam at the foil. Figure 7 demonstrates this approach, wherein the injection beam size is reduced to occupy a smaller vertical size of the foil, reduced to 14 mm, compared with the original of 20 mm. This reduction in the vertical size of the injection beam is achieved by manipulating the vertical Twiss parameter (β_y) of the injection beam at the foil using four quadrupole magnets positioned along the L-3BT line. Reducing the vertical beam size of the injection beam is particularly effective because it allows us to reduce horizontally oriented foil from both its top and bottom edges, rather than just one side, as in the case of horizontal beam size reduction [32]. The β_y from its original value of 8.2 m is reduced to 2.2 in this study. A further reduction of the β_y limits the aperture of the injection beam transport (BT) at the upstream of the injection point, where β_y is once defocused for a maximum focusing at the injection point. Furthermore, vertical painting magnets are also located at the injection BT for making a vertical bump orbit for vertical painting. Damaging the stripper foil by a further smaller size of the injection beam size is also a concern. Notably, a simultaneous manipulation of the injection beam in both horizontal and vertical planes is

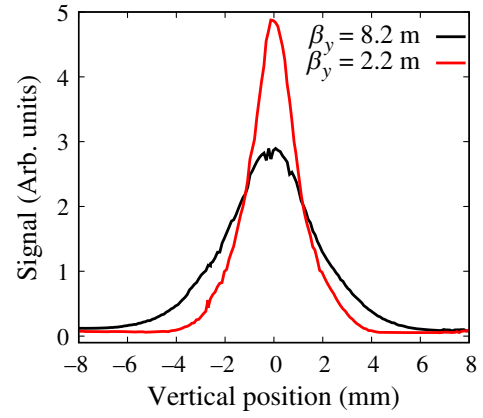


FIG. 8. Measured vertical profiles of the injection beam at the first foil location under the application of the original and reduced β_y values of 8.2 (black) and 2.2 m (red), respectively. The original profile width of the injection beam (in σ) is reduced from 1.8 to 0.92 mm, halving its size.

challenging owing to the designed beam line configuration and the aperture limit of the L-3BT line.

Figure 8 shows the vertical profiles of the injection beam measured by a multiwire profile monitor installed just upstream of the first foil [33,34]. The depicted profiles with an original β_y of 8.2 m and the reduced one of 2.2 m are indicated by the black and red colors, respectively. This results in a reduction in the original profile width (σ) of the injection beam from 1.8 to 0.92 mm, halving its size. Table II lists the measured Twiss parameters of the injection beam at the first foil, considering both the original and the optimized β_y . These Twiss parameters were obtained by model fitting of the H^- beam profiles measured by four MWPMs installed upstream of the injection point (first foil).

Minimizing the vertical beam size also offers an additional advantage as it results in a nearly zero value for the inclination (α_y) of the injection beam ellipse, crucial for optimizing the vertical TP, as demonstrated in Fig. 9. The edge of the injection beam determines the maximum vertical painting area that can be filled. The vertical

TABLE II. Twiss parameters of the injection beam measured at the location of the first foil under the application of the original and optimized β_y of the injection beam. The horizontal and vertical un-normalized rms transverse emittances are denoted as ϵ_x and ϵ_y , respectively.

Parameter (unit)	Original value	Optimized value
α_x	-0.50	-0.50
α_y	-1.57	-0.20
β_x (m)	6.2	5.7
β_y (m)	8.2	2.2
ϵ_x (π mm mrad)	0.48	0.45
ϵ_y (π mm mrad)	0.40	0.39

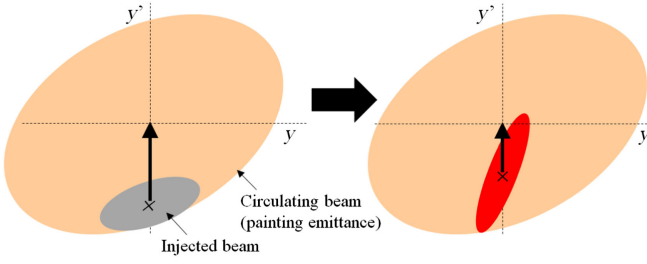


FIG. 9. Schematic view of the vertical TP implemented by varying y' of the injection beam. For a smaller β_y , the y' can be reduced to -2.8 mrad from its original value of -3.4 mrad with a larger β_y , reducing the number of large-amplitude particles within the circulating beam while maintaining the same painting area.

centroid angle (y') of the injection beam for a larger β_y is calculated to be -3.4 mrad for a painting area of $200 \pi \text{ mm mrad}$ as illustrated in the left plot. In the vertical plane, the injection beam angle is swept from the outside to the center of the circulating beam ellipse for an anticorrelated painting, whereas it is swept from the center to the outside for a correlated painting [12,30,31]. Under a constant emittance of the injection beam, reducing β_y while maintaining α_y at approximately zero changes the shape of the injection beam ellipse, as depicted by the red ellipse in the right plot of Fig. 9. This adjustment reduces the centroid y' of injection beam to -2.8 mrad, while maintaining the maximum painting area unchanged. Optimizing vertical TP in this manner improves the vertical beam distribution by reducing the number of large amplitude particles compared with a larger β_y of the injection beam. Owing to the SC effect at high intensities, the maximum beam emittance far exceeds $200 \pi \text{ mm mrad}$. Thus, reducing the β_y value of the injection beam helps mitigate the beam loss induced by large amplitude particles.

Figure 10 shows numerical simulation results of the average number of foil hits per injected proton at a beam intensity of 1 MW obtained for the original injection β_y of 8.2 m and the reduced one of 2.2 m depicted by black and red lines, respectively. The vertical foil sizes are 20 and 14 mm for the original and optimized configurations, respectively, with a painting area of $200 \pi \text{ mm mrad}$ applied in both cases. The average number of foil hits is calculated by integrating the number of particles hitting the foil over each turn and dividing by the total number of injected particles. The simulation results reveal that in the current operational setup, the average number of foil hits per injected proton is 6.7, which can be 27% reduced to 4.9 by reducing the β_y value of the injection beam and adopting a smaller vertical size of the stripper foil.

The numerical simulations were performed using the ORBIT SC code [35–38], by incorporating a realistic multi-turn injection process, longitudinal and transverse injection paintings, and realistic time-dependent machine parameter and errors to simulate actual conditions. Notably, the

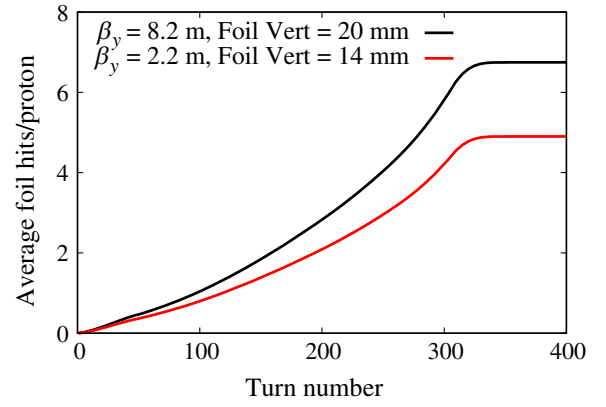


FIG. 10. Numerical results of the average number of foil hits per injected proton as a function of the turn number. Minimizing the injection β_y and foil size results in an approximately 30% reduction (red) in the number of foil hits compared to that in the original configuration (black).

simulation results of the ORBIT code have been previously demonstrated to closely align with the experimental observations at the J-PARC [31,39].

Figure 11 displays images of the two foils utilized for our experimental studies and later implemented in actual operations. The top image depicts a foil with a vertical size of 20 mm, which adopts the original injection β_y value of 8.2 m. The bottom image depicts a foil with a vertical size of 14 mm, which adopts the reduced injection β_y value of 2.2 m. The horizontal size of both foils is the same (100 mm).

Figure 12 presents the measured foil scattering-induced beam losses corresponding to the original injection β_y value of 8.2 m and reduced β_y value of 2.2 m depicted by black and red colors, respectively. The measurements were performed by a small plastic scintillator counter BLM positioned at 90° above the foil along the horizontal direction. This BLM was set to detect secondary particles, such as gamma rays, generated primarily by the large-angle foil scattered protons that strike the beam pipe and are

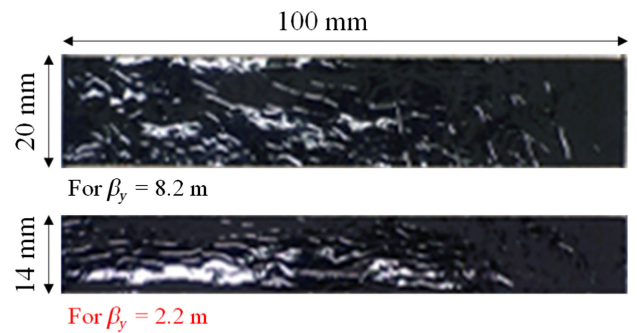


FIG. 11. Photographs of the foils with two different vertical sizes, 20 mm (top) and 14 mm (bottom) used for experimental studies with injection β_y values of 8.2 and 2.2 m, respectively.

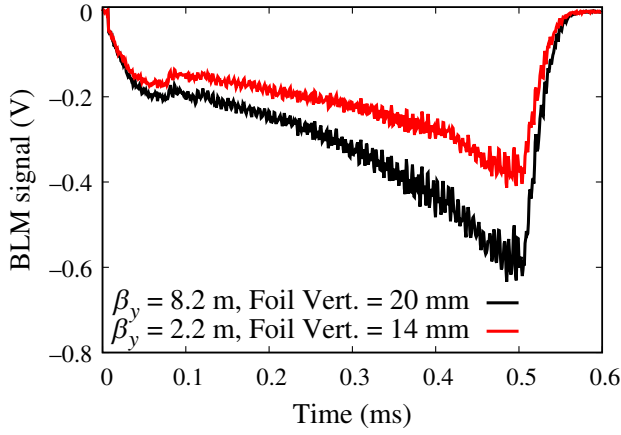


FIG. 12. Measurement results of foil scattering-induced beam loss. This loss is minimized by reducing the injection β_y and using a smaller foil (red) as compared to that with an original configuration of a larger β_y and using a bigger size foil (black).

instantly lost. Furthermore, the position of the BLM was set to avoid any direct interaction of the primary proton beam. Unlike any other BLMs, the raw signal from the monitor head is recorded in this case without using any preamplifier, which gives a negative signal. The BLM signal for the smaller size foil, corresponding to the reduced injection β_y , was considerably reduced compared with that for the bigger size foil with large injection β_y . The reduction rate in the number of foil hits was computed by integrating each signal and calculating the ratio of the red signal (smaller β_y) to the black signal (original β_y). This integrated beam loss signal for a smaller β_y of the injection beam was calculated to be 30% reduced as compared to that with the original β_y , which corresponds to a 30% reduction in the number of average foil hits. This finding is consistent with the results of the numerical estimation.

Figure 13 plots the simulated and measured foil hit reduction rates as functions of injection β_y using open squares and filled circles, respectively. Both sets of results for the original β_y of 8.2 m were utilized as a reference to calculate the foil hit ratio for the minimized β_y of 2.2 m. The arrow in the figure indicates a reduction in the average number of foil hits, as demonstrated by the simulation and measurement results.

Figure 14 shows numerical simulation results assessing the dependence of the beam survival rate on injection β_y at a beam power of 0.7 MW, which was set for MLF user operation in 2021. The beam survival rate for each turn was calculated by dividing the number of circulating particles by the total number of injected particles. Both configurations, with the original and reduced β_y , demonstrate beam survival rates well above 99%. However, a decrease in beam survival rates is observed during the initial few ms at low beam energies. Such a beam loss is significantly improved, reducing nearly 40% using a smaller injection

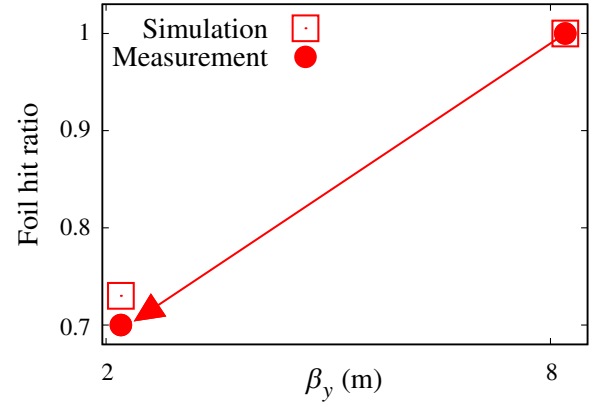


FIG. 13. Summary of simulation (empty square) and measurement results (solid circle), depicting the reduction in the number of foil hits achieved by minimizing β_y value of the injection beam.

β_y , along with a smaller size foil and adjusting the vertical TP area by optimizing the vertical angle of the injection beam (see Fig. 9), thus yielding a substantial improvement of the beam survival rate.

Figure 15 shows a comparison of the simulated temporal evolution of the beam loss at the collimator section for original and reduced β_y values of the injection beam depicted by black and red colors, respectively. The simulation was done by injecting a total of 4×10^6 macro-particles for each case, where number of lost particles were nearly 1250 and 750 for the original and reduced β_y , respectively. Compared with the configuration with original larger β_y and bigger foil size, the reduced β_y and smaller foil size considerably reduces beam losses occurring during and after injection. Figure 16 shows simulation results of normalized 99% beam emittance for the original and reduced β_y values of the injection beam depicted by black

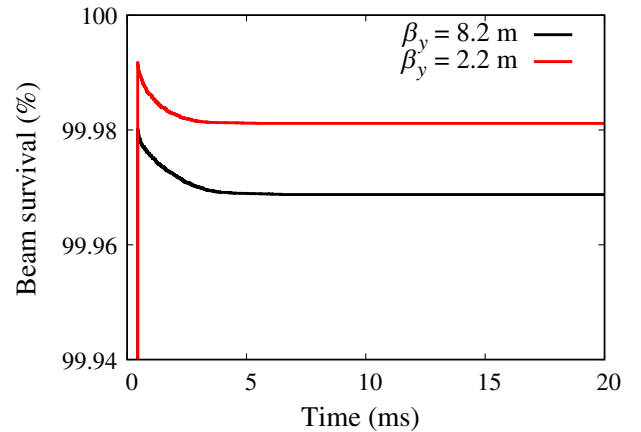


FIG. 14. Simulation results demonstrating the improvement in beam survival achieved through the minimization of injection β_y and using a smaller size foil together with optimizing the vertical TP.

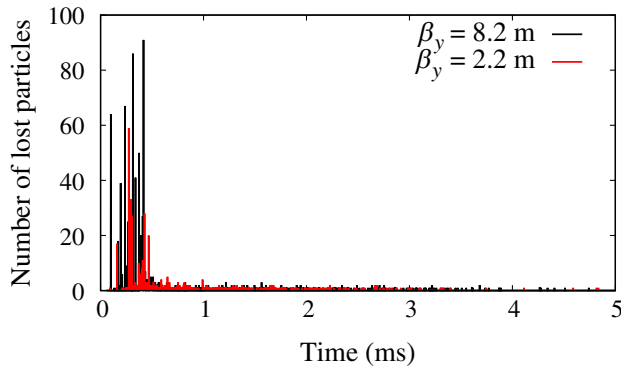


FIG. 15. Simulation results illustrating the temporal structure of the beam loss reduction achieved by minimizing the injection β_y and using a smaller size foil together with optimizing the vertical TP.

and red colors, respectively. The horizontal and vertical beam emittances are plotted in the left and right panels, respectively. Optimizing the vertical TP when using a reduced β_y (Fig. 9) results in a notable reduction of vertical beam emittance during the injection period. This reduction contributes to considerably improved beam survival by mitigating the beam loss.

Figure 17 shows a comparison of the measured beam losses corresponding to the original and reduced β_y of the injection beam at a beam power of 0.77 MW depicted by black and red colors, respectively. The peak current of the LINAC beam was set to 50 mA, with a chopper beam-on duty of 54% for an injection pulse length duration of 0.385 ms. The beam intensity at the extraction instant was 6.4×10^{13} ppp recorded by an SCT, corresponding to 0.77-MW beam power, which indicates a net beam power of 0.72 MW for an operational duty factor of 0.94 for the MLF operation at that time. The horizontal axis is this

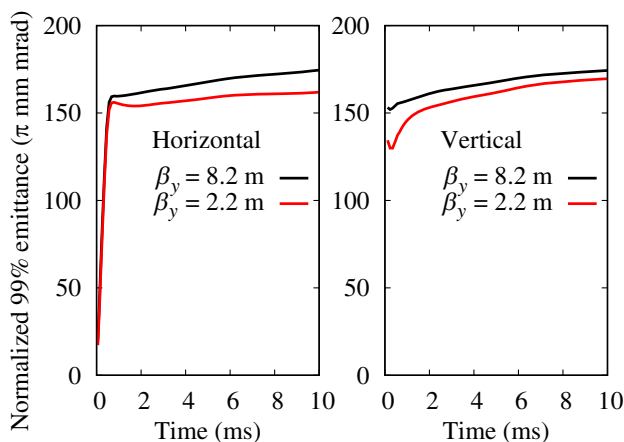


FIG. 16. Simulation results of the normalized 90% beam emittances for the two injection β_y values of 8.2 and 2.2 m. The beam emittance, particularly the vertical one at low energy, is significantly improved with a smaller injection β_y , along with a smaller foil and optimizing the vertical TP.

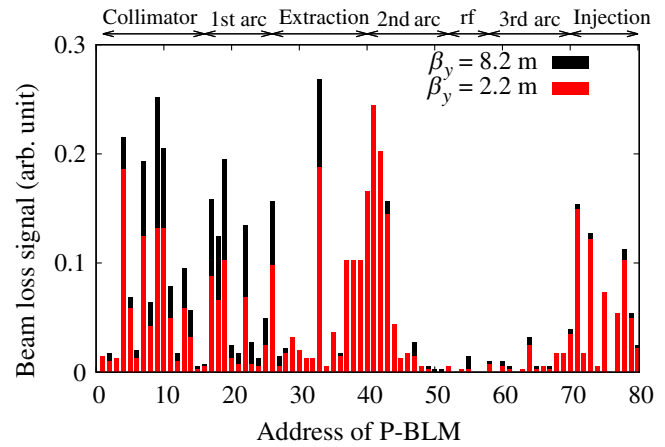


FIG. 17. Measurement results of beam loss throughout the RCS when using the original and minimized injection β_y values of 8.2 and 2.2 m, depicted in black and red, respectively. The beam loss throughout the collimator region and the first arc section is significantly reduced with the minimized injection β_y .

figure denotes P-BLM ID, while the vertical axis represents the integrated signal of each BLM over the complete 20-ms period between injection and extraction. Compared with the configuration, with the original β_y of 8.2 m and larger foil size, the configuration with a reduced β_y of 2.2 m and smaller foil size, along with optimized vertical TP, results in a considerable reduction of 39% in beam losses at the collimator and first arc sections, which is in good agreement with the outcome of the numerical simulation. Figure 18 shows a comparison of the temporal beam loss distribution at the collimator section measured by an S-BLM before and after minimizing the injection β_y depicted by the black and red colors, respectively. A smaller injection β_y gives nearly 40% reduction from that with original parameters, which is aligned with the average beam loss reduction at the collimator and first arc sections obtained from the P-BLMs data.

Furthermore, the root-mean-square (rms) emittances of the extracted beam for both horizontal and vertical planes are also measured to be nearly 15% reduced by applying the reduced injection β_y , confirming an improvement in beam quality for the users. Beam losses throughout the beam transport from RCS extraction to the neutron target are also substantially reduced, not only owing to lower beam emittances, but also because of suppressed beam halos achieved by decreasing the foil hitting rate and optimizing the vertical TP. Consequently, the resulting beam was effectively utilized for transverse beam broadening using octupole magnets placed upstream of the neutron production target, which is otherwise challenging with a beam featuring excess beam halos or long tails, thus minimizing pitting damage to the target [40].

In May 2021, we conducted a month-long test using the reduced injection β_y with a smaller foil size for RCS user

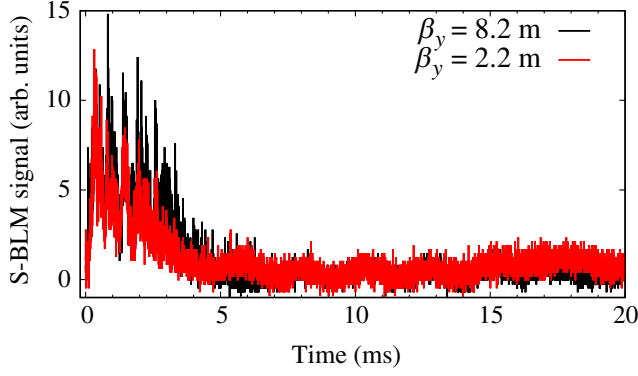


FIG. 18. Temporal structure of the beam loss measured by an S-BLM at the collimator section for an original injection β_y of 8.2 m and the minimized one of 2.2 m depicted in black and red, respectively. The beam loss by implementing a minimized β_y in this study is 40% reduced.

operation at a net beam power of 0.72 MW. One of the primary purposes of this investigation was to assess whether these changes could reduce residual radiation doses compared with the previously used configuration with the original, large injection β_y and bigger foil size. Another important objective was to evaluate the performance of smaller size foil under regular operating conditions. Figure 19 shows a comparison of the residual doses at various locations in the RCS, including the injection region, collimator, and first arc sections, measured on contact after 4-h cooling from the beam stop. In this figure, the circled numbers 1 to 6, respectively, correspond to the following measurement locations: first foil chamber, second absorber of the collimator, third absorber of the collimator, first bending magnet just after the collimator

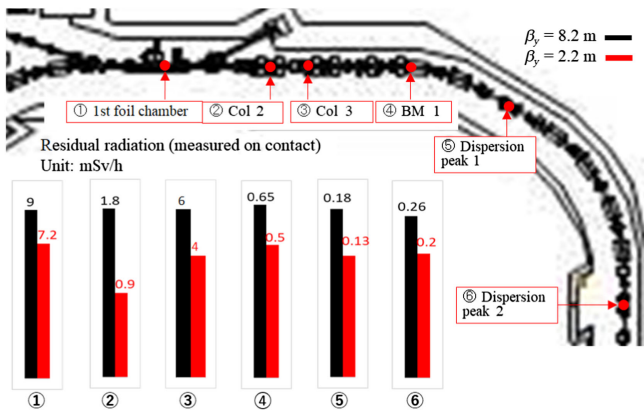


FIG. 19. On-contact measurement results demonstrating a significant reduction in residual doses at the RCS injection and collimator sections and dispersion peaks in the first arc section, achieved by implementing the reduced injection β_y and smaller foil (red) for the routine operation at 0.7 MW beam power.

section, first dispersion peak, and the second dispersion peak, respectively. The bar plots displayed in the figure show a comparison of the residual radiation doses measured on contact at the aforementioned six locations after a month-long operation, each for the two values of the injection β_y . The black bars represent the residual radiation doses recorded under the larger injection β_y and bigger foil size, while the red bars denote corresponding data under the reduced injection β_y and smaller foil size. Compared with the larger injection β_y and bigger foil size, the reduced injection β_y and smaller foil size result in considerable reductions in residual radiation doses at the injection, collimator, and the first arc sections. This reduction of residual radiation dose mirrors the observed decrease in beam loss. Furthermore, the smaller size foil results in no significant degradation in stripping efficiency throughout the test. Consequently, starting from autumn 2021, RCS user operations have been conducted using the reduced injection β_y value of 2.2 m and a vertically smaller foil size of 14 mm at a beam power of 0.7 MW. These operational settings are still used at the designed beam power of 1 MW.

IV. BEAM LOSS MITIGATION AT THE DESIGNED 1 MW BEAM POWER

The next phase of the research focused on minimizing beam loss at the highest RCS beam intensity of 1 MW. To this end, the beam intensity was increased to 1 MW by extending the injection pulse length to 0.5 ms while maintaining the chopper beam on duty at 54%. This adjustment resulted in 8.33×10^{13} ppp, representing only a 30% increase from 6.4×10^{13} ppp used for RCS operation at 0.77 MW so far. Despite the effectiveness of the optimized parameters in reducing beam loss at 0.77 MW, their application at 1 MW resulted in a fourfold increase in beam loss compared with that at 0.77 MW.

Figure 20 shows a comparison of the beam losses measured at beam intensities of 0.77 and 1 MW depicted by the red and black colors, respectively. Notably, the SC effect intensifies beyond 0.77 MW, leading to a large tune

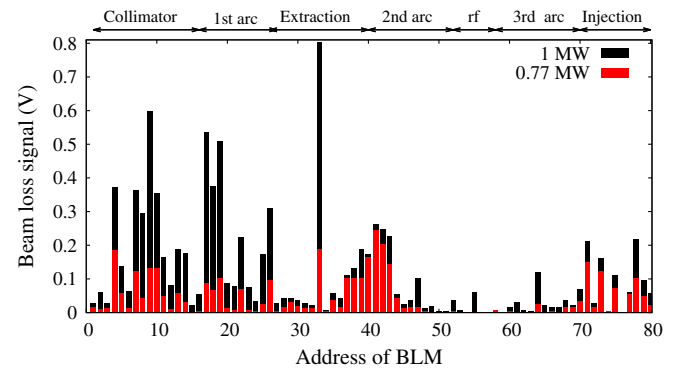


FIG. 20. Measurement results comparing intensity-dependent beam losses at 0.77 and 1 MW.

spread and enhanced resonance effects, particularly at lower beam energies [39]. To address these issues, we performed systematic beam studies and numerical simulations to determine the root causes of the increased beam loss and identify appropriate practical measures for beam loss suppression. These measures are as follows: (i) Partial correction of the $3\nu_x = 19$ resonance, which is excited by the sextupole field component intrinsic in the injection chicane magnets, called as shift bump magnet (SB), to minimize horizontal beam emittance growth, where ν_x is the horizontal betatron tune [41,42]. (ii) Optimization of the longitudinal painting (LP) at injection by adjusting the momentum offset of the injection beam and the rf frequency offset (Δf rf) of the RCS rf to improve longitudinal beam behavior and minimize longitudinal beam halos by propagating the beam close to the center of the rf bucket. (iii) Optimization of the transverse painting (TP) at injection to reduce transverse beam emittances and beam halos induced by the SC effect. (iv) Optimization of the betatron tune at injection to enhance resonance separation and increase the dynamic aperture of the beam.

A. Beam loss and beam emittance mitigation by partial correction of the $3\nu_x = 19$ resonance

Figure 21 shows the tune footprint at the end of beam injection obtained in the numerical simulation at 1-MW beam intensity. The horizontal axis is the horizontal betatron tune (ν_x), while the vertical axis is the vertical betatron tune (ν_y). The red dot marks the bare operating point at injection, which is set at (6.45, 6.36). The red lines indicate the major resonances responsible for beam losses under the current operating conditions. Among these resonances, the third-order structure resonance $\nu_x - 2\nu_y = -6$ is the strongest

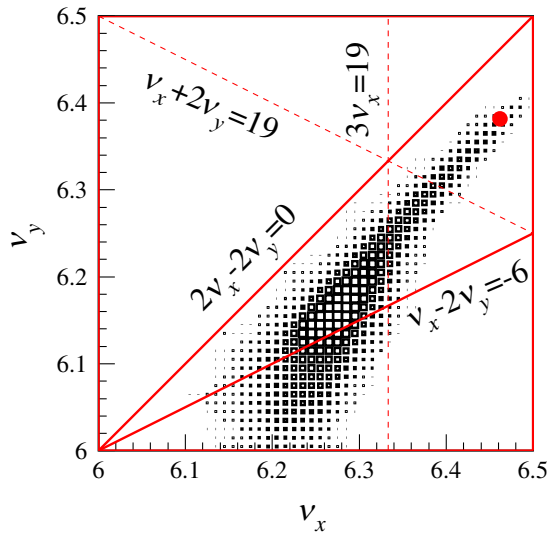


FIG. 21. RCS tune diagram and the simulated tune footprint at the end of injection for 1 MW beam intensity. The red circle represents the bare operating point set at injection.

one, which is primarily excited by the sextupole field components intrinsic in the bending magnets and the sextupole magnets if they are ON for chromaticity (ξ) correction. This resonance causes substantial beam loss due to a large tune depression, particularly at high beam intensities. However, the ξ is not usually corrected for beam operation to the MLF, making the sextupole field in the bending magnets the primary contributor to this resonance. Notably, the $\nu_x - 2\nu_y = -6$ resonance is originally corrected by the sextupole magnets.

In addition to the aforementioned resonance, we focused on another uncorrected third-order betatron resonance, $3\nu_x = 19$, which is excited by the sextupole field components intrinsic in four injection chicane magnets (SB1–SB4 in Fig. 6) [41,42]. Ideally, the SBs are utilized for multiturn beam injection, each producing a constant magnetic field distribution except for polarity variation [43,44]. However, owing to varying distances between the SBs and adjacent quadrupole magnets positioned beyond the SB1 and SB4, each SB experiences different magnetic interferences, resulting in nonidentical magnetic field distributions. Although the effect of dipole field components is accounted for by integrating over SB1–SB4 to ensure a constant horizontal injection orbit bump of the desired height, a similar compensation for higher-order field components remains inadequate owing to magnetic interferences. The residual sextupole field component characterized by $K_2 = 0.012 \text{ m}^{-2}$ remains uncanceled and thus excites the $3\nu_x = 19$ resonance. Given the lack of additional sextupole magnets to correct this resonance, we adopted an alternative partial correction approach, wherein the SB field strength was 20% reduced, ensuring that the SB operated at 80% of its designed strength. Further reduction in the SB field strength is constrained by factors, such as the aperture limitation of injection beam transport, the capacity of the injection septa needed to match the injection beam with the circulating beam.

Figure 22 shows a comparison of the beam losses at 1 MW measured for SBs operating at their designed and

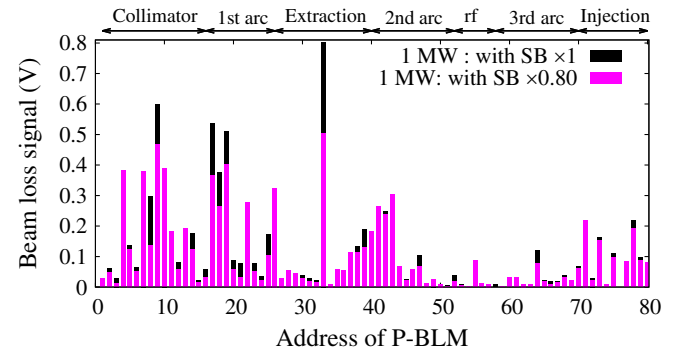


FIG. 22. Measurement results of beam losses at 1 MW, depending on the magnetic fields of the SB. The integrated beam loss at the collimator and the first arc sections is nearly 20% reduced by reducing 20% magnetic fields of the SB.

80% of their designed magnetic field strengths, depicted by the black and pink colors, respectively. Partially correcting the $3\nu_x = 19$ resonance by reducing magnetic field strength of the SB magnets results in substantial beam loss mitigation nearly 20% at the collimator and first arc sections. This adjustment also results in a 10% decrease in the horizontal rms emittance of the extracted beam, while vertical emittance remains unchanged as expected. This is because this resonance excites only the horizontal betatron motion, causing beam emittance growth and beam halo generation in the horizontal plane [42].

Notably, reducing the 20% field strength of the SB results in nearly 40% reduction in the vertical beta function beating caused by the edge focusing effect of the SB. The beta beating is known to excite betatron resonances by distorting the lattice superperiodicity during active operation of the SBs over a 0.5-ms beam injection period and their subsequent collapse over an additional period of 0.35 ms. Under the current operating tune, the third-order nonlinear sum resonance $\nu_x + 2\nu_y = 19$ is concerned, which affects twice the larger beam emittance growth in the vertical plane as compared to that in the horizontal plane. However, the current vertical tune is set quite far from the vertical half integer ($\nu_y = 6.5$), where beta function beating effects are less severe, typically only around 10% and it is further suppressed by reducing the magnetic field strength of the SB.

Furthermore, reducing the SB magnetic field helps lowering the decay (stripping to proton) rates of excited partially stripped (neutral) H^0 noted as H^{0*} (produced at the first foil) before reaching the second stripper foil. Under normal conditions, the H^{0*} decays in flight in the magnetic field of the SB in between the first and second foils often fall outside the machine aperture and contribute to uncontrolled beam losses at the injection area [32,45,46]. Primarily, due to lower injection beam energy and higher stripping efficiency of 99.7%, the H^0 beam power is only 400 W (injection beam power is 133 kW). Then, the H^{0*} states with principle quantum number $n > 4$ are susceptible to stripping, giving an upper limit of the beam power loss of 8 W corresponding to a loss rate of less than 10^{-4} level as we estimated earlier [45–48]. In a similar way, we have now estimated that a 20% reduction in the SB magnetic field slightly extends the lifetime of the H^{0*} species, resulting in a 5% reduction in their stripping probability and the corresponding uncontrolled beam losses.

B. Optimization of the longitudinal painting scheme at injection

To mitigate the space charge (SC) effects at high intensity, the longitudinal painting (LP) at injection is utilized in the RCS [12,39,49]. At the designed beam intensity of 1 MW, the LP scheme plays a dominant role in mitigating the SC effect at lower beam energies by

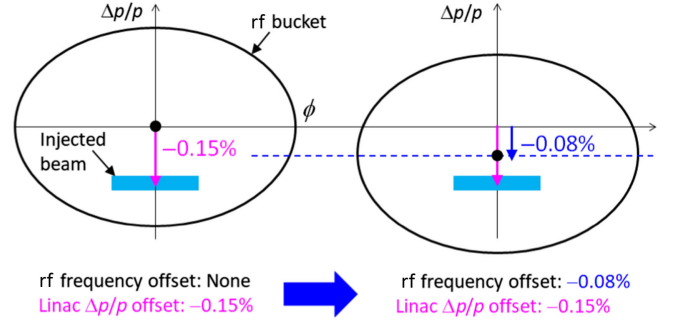


FIG. 23. Schematic views of the LP schemes at injection. In addition to only an injection beam offset in the original scheme (left), the frequency offset of the rf during injection is additionally applied in the optimized scheme for beam loss mitigation at 1 MW.

producing a uniform longitudinal beam distribution. One key parameter of the LP scheme is a momentum offset of the injection beam in the rf bucket of the RCS to enhance synchrotron oscillation in the longitudinal phase space. Notably, the momentum offset of the injection beam, expressed in $\Delta p/p$ (p is the reference momentum of the injection beam), is set to -0.15% relative to its value at the reference energy of 400 MeV, which corresponds to the bottom of the sinusoidal magnetic field of the RCS bending magnet and the reference frequency of the rf. In the optimized pattern, the momentum offset of the injection beam is kept unchanged, but an additional offset of the rf frequency (Δf_{rf}) equivalent to -0.08% in $\Delta p/p$ is adopted. Figure 23 schematically illustrates the original and optimized LP schemes in the left and right plots, respectively.

Figure 24 shows a comparison of beam losses measured under LP optimization (green) and no LP optimization (pink). LP optimization achieves up to 30% beam loss mitigation within the collimator and first arc sections.

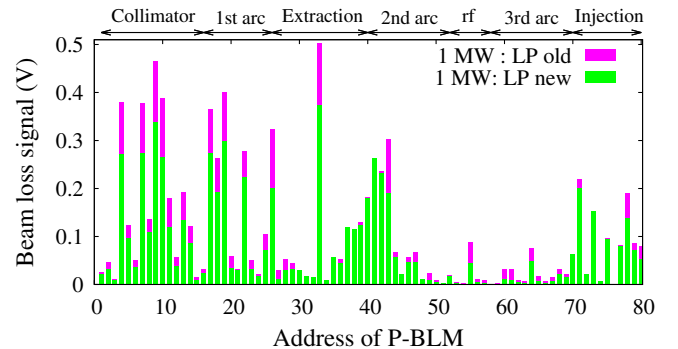


FIG. 24. Comparison of beam loss at 1 MW beam for the original and optimized LP methods, depicted by the pink and green colors, respectively. The integrated beam loss at the collimator and first arc sections is reduced by 30% when using the optimized LP method at injection, and the beam loss throughout all arc sections is also significantly reduced.

Furthermore, beam losses across all arc sections are considerably suppressed owing to improved longitudinal motion of the beam in the rf bucket, which is achieved by incorporating the momentum offset of the injection beam and shifting the bucket toward the injection beam. In the original LP scheme, beam losses in regions with dispersion peaks at the arc sections are attributed to particles leaking from the rf bucket. Furthermore, beam losses in the collimator region (dispersion free) originate from chromatic tune shifts affecting the horizontal tunes of highly deviated momentum (high $\Delta p/p$) particles in the rf bucket and large amplitude particles in the transverse plane near the bare operating point, which is close to the horizontal half integer resonance. The considerable reduction in these losses is attributed to the optimized LP method, which effectively minimizes longitudinal beam halos and enhances beam stability in the rf bucket.

C. Optimization of the transverse painting scheme at injection

The transverse painting (TP) is also utilized in the RCS at injection for mitigating the SC effects and reducing the foil hitting rate of the circulating beam by introducing large betatron oscillations during multiturn injection [12,30,32]. A large TP area is desirable to reduce the foil traversal rate of the circulating beam induced by large betatron oscillations of the circulating beam, thus lowering the density for producing a wider and uniform transverse beam distribution, which is also essential to minimizing pitting damage of the neutron production target. The designed TP area for the MLF beam is $200\pi\text{mm mrad}$. However, at the beam power of 1 MW, this area leads to additional beam losses because of beam halos caused by the SC effect, resulting in the beam emittance growth far beyond the $200\pi\text{mm}$ and exceed physical aperture of the machine. To reduce beam losses beyond those presented in Fig. 24 (green), we attempted to optimize the TP pattern during injection. The TP optimization approach is similar to that recently discussed as an essential way to control the transverse beam distribution in the presence of strong SC effect [8]. In this optimized method, a high spatial charge concentration is managed by modifying the time dependence of painting magnets to achieve an appropriate balance between horizontal and vertical transverse emittances. This balance helps minimize emittance exchange and emittance growth at high intensities.

Figure 25 illustrates the current approach adopted for optimizing the TP scheme to control transverse beam density distribution. The optimization method involves adjusting the beam painting range along the horizontal and vertical directions, as indicated by the blue arrow in the figure, relative to the original one indicated by the green arrow. The horizontal and vertical axes in this figure represent horizontal and vertical actions, respectively. The injection painting is performed by a phase space offset

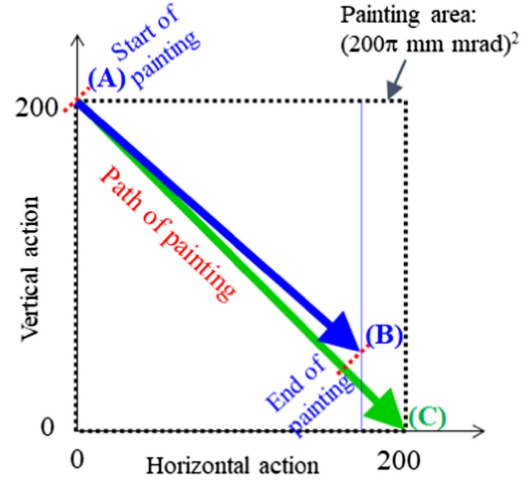


FIG. 25. Schematic view of optimization of the TP at injection. The ranges of beam painting along both the horizontal and vertical directions are optimized, as indicated by the blue arrow, compared to the original scheme indicated by the green arrow.

of the injection beam relative to the closed orbit. For an anticorrelated painting scheme, the injection beam is originally painted from (A) to (C). However, this process is modified to paint the injection beam from (A) to (B) by introducing a scaling factor to account for the gradual variation in phase space offset. This adjustment helps avoid high spatial charge concentration at the end of injection, particularly at high intensities.

Figure 26 shows the time-dependent square root patterns of the painting magnets, normalized to one corresponding to the maximum painting amplitude. The horizontal and vertical patterns are indicated by the solid and broken lines, respectively. The blue lines indicate the optimized painting patterns, while the green lines indicate the original patterns. The injection pulse duration is set to 0.5 ms, as indicated by the pink rectangular box. In contrast to the original scheme,

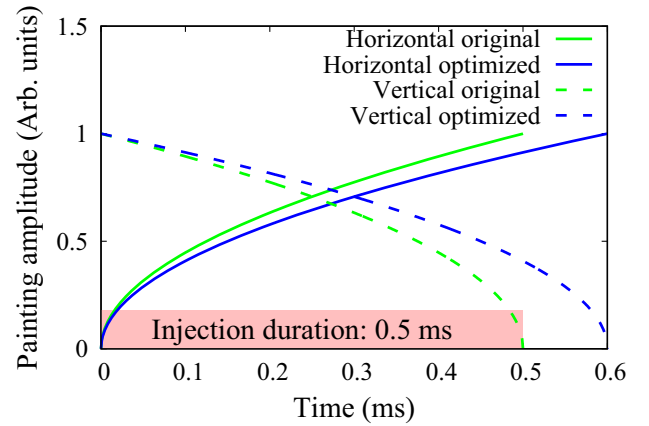


FIG. 26. Time-dependent square root patterns of the painting magnets normalized to one for maximum painting amplitudes, comparing the original and a slowly varying optimized TP method, indicated using green and blue lines, respectively.

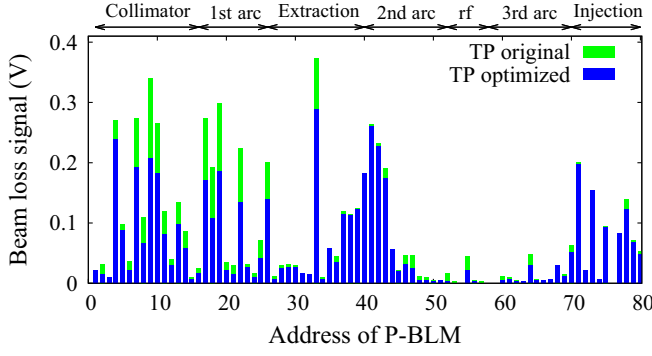


FIG. 27. Comparison of the beam loss at 1 MW beam obtained after implementing the original and new TP methods, indicated by the green and blue colors, respectively. Optimization of the TP at injection results in a 33% reduction in beam loss mitigation at the collimator and the first arc sections compared to the original TP.

wherein the painting magnets collapse right after the end of the injection period of 0.5 ms, they are kept for an additional 0.1 ms in the optimized scheme for gradually occurring the beam painting over a period of 0.6 ms instead of 0.5 ms [12,30]. This adjustment leads to the phase space offset of the injection beam for the painting to end at (B) (Fig. 25), which occurs slightly earlier than the originally continuing up to (C). The unpainted region (B) to (C) is filled by SC effects, the emittance growth, and emittance exchange at high intensities, which helps reducing the number of large amplitude particles or beam halos beyond the boundary of the TP area.

Figure 27 shows a comparison of the beam losses at 1 MW measured under the original (green) and optimized (blue) TP schemes. Compared with the original TP, the optimized TP scheme achieves a 33% reduction in beam loss. Figure 28 shows a corresponding comparison of the TP for the temporal structure of the beam loss measured by

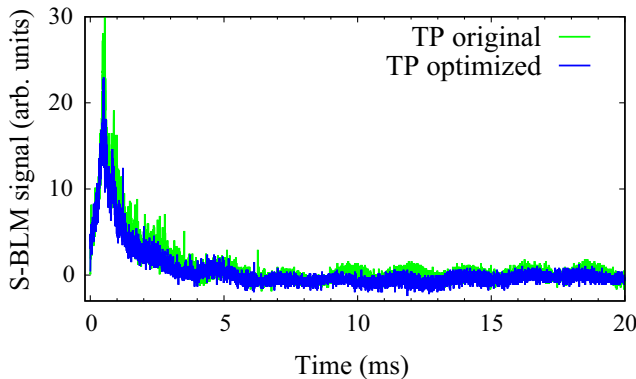


FIG. 28. Temporal structure of the beam loss at 1 MW measured by an S-BLM at the collimator section with and without TP optimization depicted by the green and blue colors, respectively. An implementation of the present optimized TP yields nearly a 35% reduction in beam losses, which is also consistent with the results obtained from the P-BLMs data.

an S-BLM at the collimator section. Similar to the P-BLM, the S-BLM also gives more than 30% beam loss mitigation for an optimized TP. Furthermore, the rms emittance of the extracted beam, particularly in the horizontal direction, is nearly 25% reduced. The optimized TP by gradually varying the painting patterns achieves a balanced distribution of the horizontal and vertical emittances. This balance is crucial for controlling the growth of beam emittance caused by the SC effect and emittance exchange to achieve considerable beam loss and beam emittance mitigation.

D. Optimization of betatron tunes at injection

The optimization of betatron tunes, particularly at lower beam energy (injection energy), plays an important role in mitigating beam loss and beam emittance growth originating from the SC effects and the related resonances. Following the above optimizations, where beam loss and beam emittances were well suppressed, we conducted a detailed examination of betatron tunes by making small adjustments (in steps of 0.01) near the current horizontal tune (ν_x) and vertical tune (ν_y) setting of (6.45, 6.36).

Figure 29 shows measurement results of beam loss depending on the betatron tunes setting at injection. The horizontal and vertical axes are denoted by ν_x and ν_y , respectively. As depicted, the beam loss increases for any change of either ν_x or ν_y in any direction. The only exception here is a minor increase of 0.01 in the ν_x to 6.46, made while maintaining the ν_y unchanged as depicted by the red bar. As shown in Fig. 21, this change in the horizontal tune from 6.45 to 6.46 helps the beam avoid the coupling resonance ($2\nu_x - 2\nu_y = 0$), also known as the Montague resonance [50]. This mitigates emittance growth and emittance exchange. Furthermore, the adjustment in the ν_x alerts

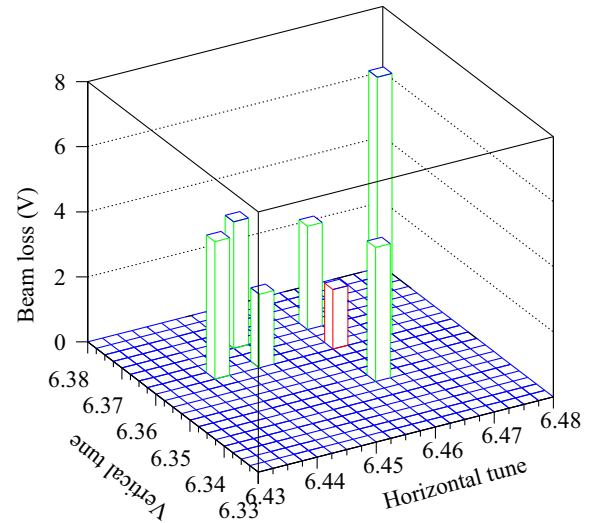


FIG. 29. Measurement results demonstrating the beam loss depending on the betatron tunes at injection surveyed around the current setting at (6.45, 6.36). The tune setting at (6.46, 6.36) gives a minimum beam loss as depicted by the red bar.

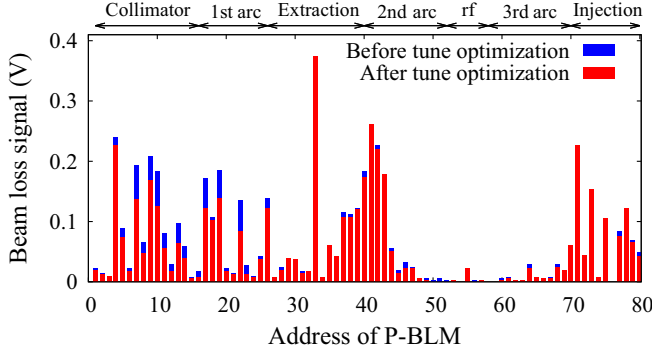


FIG. 30. Comparison of measured beam loss throughout the RCS at 1 MW beam intensity using the current and optimized betatron tunes at injection, indicating in blue and red colors, respectively. Optimizing the tune for setting at (6.46, 6.36) results in a 20% reduction in beam loss at the collimator and first arc sections as compared to the current setting at (6.45, 6.36).

the number of particles interacting with other nearby resonances, further reducing beam loss. However, increasing the ν_x further to 6.47 results in a considerable increase in beam loss owing to the effect of the half integer resonance, $2\nu_x = 13$.

Figure 30 shows a comparison of the beam losses at 1 MW measured under the current (6.45, 6.36) and optimized (6.46, 6.36) tune settings, depicted in blue and red colors, respectively. The data indicate that optimizing the ν_x by just 0.01 reduces nearly 20% integrated beam loss at the collimator and first arc sections.

Figure 31 shows a comparison of the beam loss distribution measured at 1 MW before and after implementing all optimizations outlined in this section. The nonlinear increase in additional beam loss originating from strong SC effects and the corresponding secondary effects at 1 MW beam intensity have been well mitigated by adopting appropriate optimization measures to reduce the beam loss as much as 70% as compared to that observed by implementing even all optimized parameters determined at 0.77 MW (Fig. 20).

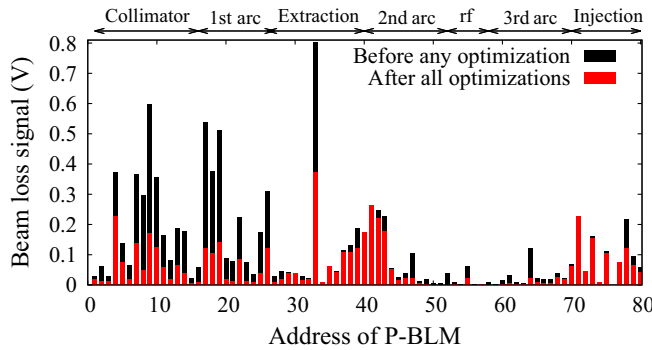


FIG. 31. Comparison of the measured beam loss at 1 MW before any optimization (black) and following the optimizations of SB, LP, TP, and betatron tunes at injection (red).

TABLE III. IDs of optimized parameters implemented and the corresponding integrated beam loss within the collimator and the first arc sections at 1 MW.

ID	Parameter/optimization	Beam loss (V)
1	Tune: (6.45, 6.32), injection β_y : 8.2 m	9.04
2	Tune: (6.45, 6.36), LP optimization [Injection beam momentum ($\Delta p/p$) offset instead of rf frequency offset (Δf rf)]	7.05
3	Injection β_y : 2.2 m, Foil size: 20 $\rightarrow$ 14 mm	5.5
4	SB: $\times 0.8$ for $3\nu_x = 19$ partial correction	4.6
5	LP optimization ($\Delta p/p$ offset + (Δf rf))	3.28
6	TP modification	2.22
7	Tune optimization: (6.46, 6.36)	1.82

E. Summary of the beam loss mitigation at 1 MW achieved during 2020 to 2022

This section summarizes the beam loss mitigation achieved at 1 MW during the 2-year study period from 2020 to 2022. Table III lists the parameters involved in the corresponding optimizations, including their ID, descriptions, and corresponding integrated beam losses at the collimator region and the first arc section. The ID1 represents the parameters optimized until 2020, including the injection β_y of 8.2 m and a bigger size vertical stripper foil of 20 mm. The IDs 2–7 correspond to the optimized parameters introduced in the current study starting with a preliminary optimization of the betatron tune at injection and introduction of momentum offset of the injection beam instead of rf frequency offset in the LP scheme. The smaller injection β_y of 2.2 m, the smaller foil size of 14 mm, and subsequent optimizations presented in this section have been implemented starting from ID 3. Figure 32 graphically represents the step-by-step reduction in beam

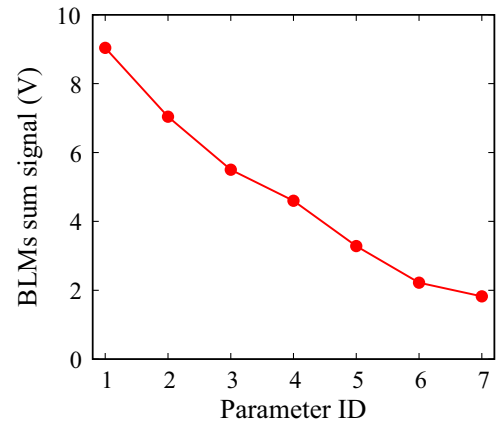


FIG. 32. Step-by-step beam loss reduction at 1 MW relative to the implementation of the optimized parameters listed in Table III.

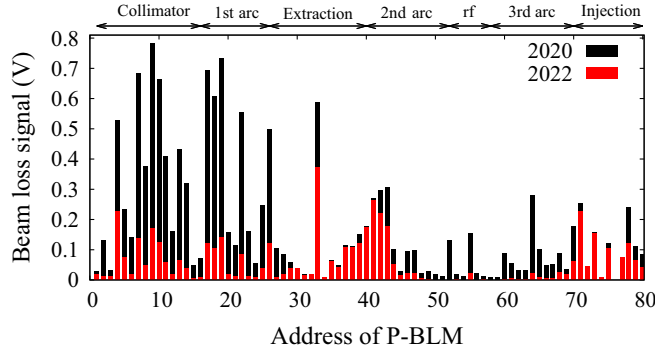


FIG. 33. Comparison of the measured beam loss at 1 MW in 2020 using a larger injection β_y (black) and in 2022 using a smaller β_y (red), including all optimizations detailed in Sec. IV.

loss achieved at 1-MW beam by implementing the optimized parameters detailed in Table III.

Figure 33 shows a comparison of the beam losses throughout the RCS measured at 1 MW following the application of 2022 (indicated by IDs 2–7 in Table III) and 2020 (ID 1) optimizations, depicted by the red and black colors, respectively. A considerable reduction in beam loss is obtained throughout the RCS, with a notable decrease of 80% in integrated beam loss in the collimator and first arc sections. The reduction rate of the beam loss at most of the straight sections is even more pronounced. Although the beam loss in the collimator region is treated as manageable, beam losses in other sections of the ring are totally uncontrolled. These uncontrolled beam losses must be particularly minimized to ensure stable operation of the accelerator and to reduce personal dose for radiation workers during regular accelerator maintenance. The optimizations introduced in this study not only minimize the substantially high beam loss in the collimator region but also considerably mitigate uncontrolled beam losses throughout various sections of the RCS, particularly at the arc sections. The residual beam loss rate is estimated to be even lower than 10^{-3} , which is only around 0.1-kW power loss in the collimator as compared to the 4-kW capacity of the collimator.

Figure 34 shows a comparison of the temporal structure of beam loss at the collimation region measured at 1 MW following the application of the 2022 and 2020 optimizations depicted in red and black colors, respectively. The data are recorded by the S-BLM over the complete 20-ms period between injection and extraction. Compared with optimization up to 2020, those introduced in 2022 demonstrate a more substantial reduction in residual beam loss. Following the implementation of the 2022 optimizations, residual beam loss is only restricted to the injection period and is primarily attributed to the foil scattering of the circulating beam. This indicates that any additional beam losses at 1 MW resulting from the SC effect are effectively minimized by appropriate optimization measures detailed in Table III.

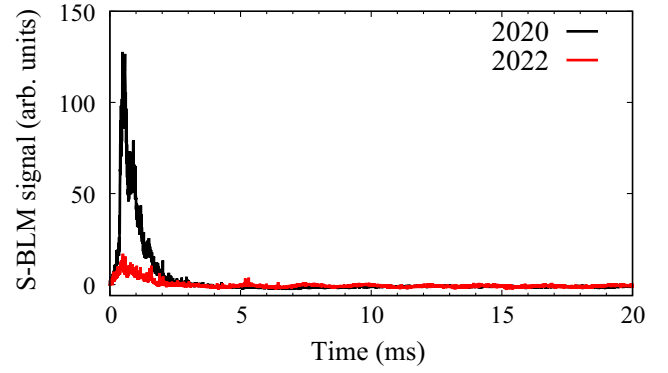


FIG. 34. Measurement results of the temporal structure of the beam loss at 1 MW, comparing 2020 and 2022 data. The beam loss is primarily localized around the injection period, while additional beam loss caused by the SC effects has been well mitigated in 2022. The residual beam loss is mostly attributed to foil scattering of the circulating beam.

Figure 35 illustrates the intensity dependence of the beam loss measured at 0.6 and 1 MW. The symbols in black colors are the beam losses at 0.6 and 1 MW measured in 2020. While the integrated beam loss in the collimator and first arc sections was 2.25 V at 0.6 MW routine operation in 2020, it increased fivefold to 9.04 V at 1 MW operation, despite only a 1.67-fold increase of the beam intensity. On the other hand, a linear extrapolation of the beam loss at 1 MW estimated from the beam loss at 0.6 MW operation in 2020 is 3.74 V, as shown by the cyan line. However, the optimizations introduced in this study reduce the beam loss

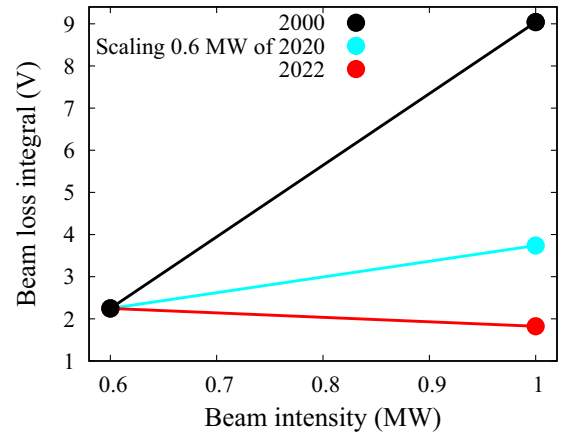


FIG. 35. Intensity-dependent beam loss before and after optimization. The beam loss at 1 MW after the current optimizations is 80% reduced (red) compared to that of 1-MW operation in 2020 (black). In addition, the current beam loss is even 20% lower than that of 0.6-MW operation in 2020 as well as more than 50% lower from that of an estimated beam loss at 1 MW obtained by a linearly approximated beam loss at 0.6-MW operation in 2020 (cyan).

at 1 MW to 1.82 V (red), which is even less than a half from that of the linearly approximated value from the beam loss at 0.6 MW in 2020. Furthermore, the current beam loss at 1 MW represents as much as an 80% reduction compared with the beam loss at 1 MW operation in 2020 and even a 20% reduction with the beam loss only at 0.6-MW operation in 2020.

In 2023, the current optimized parameters were incorporated into the routine operation of the RCS at a beam power of approximately 1 MW. As anticipated from the results of beam loss mitigation, the optimized parameters led to a considerable reduction in machine activation. Figure 36 represents a comparison of residual dose levels at various key locations within the RCS. The horizontal axis in this figure indicates key measurement locations, while the vertical axis represents the on-contact measured residual radiation in mSv/h. The measurement locations include the hottest spots at the collimator section (1); exit of the collimator section (2); and dispersion peaks at the first (3, 4), second (5, 6), and third (7, 8) arc sections. A magnified views of the latter measurement locations are presented in the inset for clarity. Measurements are usually recorded after 4-h cooling period following beam operation, but it was after 5-h cooling for 1-MW test operation in 2020. The residual dose within the collimator section decreased by an order of magnitude compared with that in 2020, despite operating at almost the same beam power. In addition to the collimator section, the residual dose levels in other key regions throughout the RCS were also considerably suppressed, as indicated by the black and red colors, respectively. Furthermore, current machine activation levels are considerably lower than those recorded during operation at only 0.6 MW in 2020 (cyan). This reduction

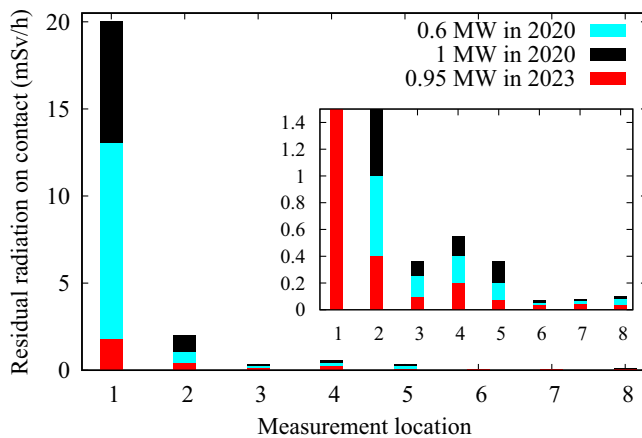


FIG. 36. Comparison of on-contact measured residual radiation at major hot spots in the RCS (see text for location) in 2020 and 2022. The current optimizations at approximately 1-MW beam power results in a significant reduction in residual radiation throughout the RCS, which is much lower than that operating even at 0.6 MW beam power in 2020.

in machine activation not only supports more stable operation of the RCS but also allows for regular maintenance of the accelerator components. Notably, in recent years, the availability of the RCS for user operation has reached a record high of over 98%. The primary sources of downtime at present include rf and kicker magnet failures as well as their recovery and replacement [20,21]. Furthermore, the downtime attributed to the machine protection system (MPS) of the BLMs is negligible. For example, in 2022 fiscal year run, the RCS achieved 98.4% availability for beam operation to the MLF. The downtime caused by the MPS of BLM was only 2 h as compared to the entire downtime of 52 h mostly caused by the failures of rf (25 h) and kicker magnets (11 h).

V. NUMERICAL SIMULATION RESULTS OF BEAM LOSS MITIGATION AT 1 MW

In addition to the beam tests, we conducted systematic numerical beam simulations at 1 MW to acquire a detailed understanding of beam loss mechanisms and to evaluate realistic optimizations for the machine. The beam survival simulation results depicted in Fig. 37 indicate improvements following the application of each optimization step. The horizontal axis in this figure represents time, while the vertical axis denotes the beam survival rate, obtained by normalizing the circulating beam with the total injected beam. Similar to the experimental results, the simulation results also reveal a reduction in beam loss at each optimization step, ultimately achieving a beam survival rate of 99.96%, corresponding to a 70% reduction in beam loss compared with the scenario without optimizations.

Figure 38 shows the simulation results of un-normalized horizontal beam emittance distributions, which are plotted for above $200 \pi \text{ mm mrad}$ obtained at the end of the

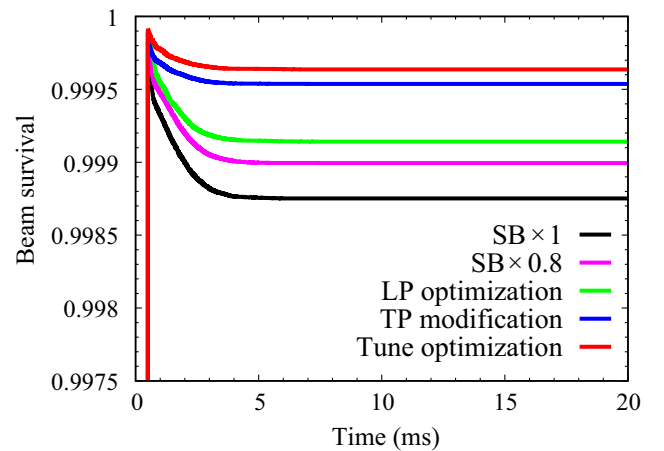


FIG. 37. Simulation results depicting improved beam survival at 1 MW owing to the implementation of four optimizations. Beam loss is significantly reduced, improving beam survival as high as to approximately 99.96%.

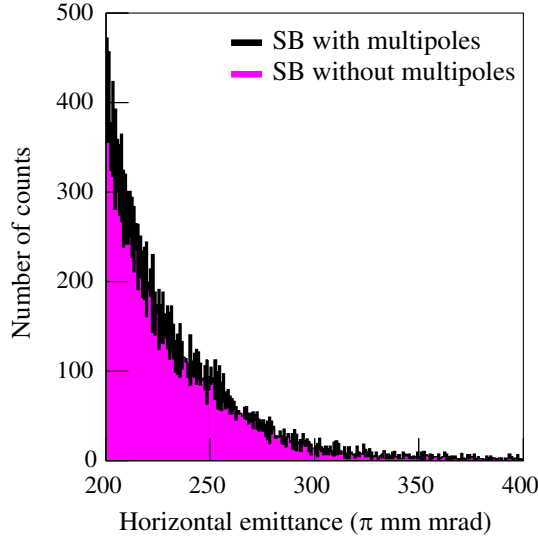


FIG. 38. Simulation results of horizontal beam emittance growth due to the $3\nu_x = 19$ resonance, considering SB multipoles (black) versus without SB multipoles (pink). The presence of SB multipoles results in more pronounced emittance growth.

injection process. These distributions are plotted with and without consideration of the multipoles intrinsic in the injection chicane magnets, SB [41,42], depicted in black and pink, respectively. When considering SB multipoles, the growth of the horizontal beam emittance significantly surpasses the painting emittance of $200 \pi \text{ mm mrad}$ owing to the excitation of the $3\nu_x = 19$ resonance by SB multipoles. Conversely, the beam loss is approximately 20% reduced, resulting in an improvement in beam survival mitigating the resonance effect partially by reducing 20% magnetic field of the SBs, as presented in Fig. 37.

Figure 39 illustrates the improvement in longitudinal beam characteristics achieved by optimizing the LP

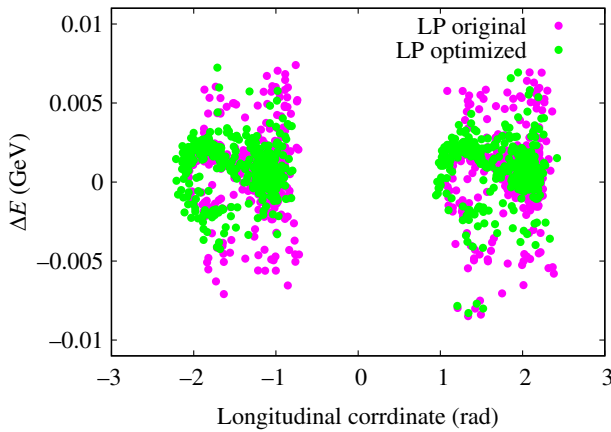


FIG. 39. Simulation results of longitudinal beam distribution of lost particles without (pink) and with (green) LP optimization at 1-MW beam intensity. The left and right plots represent the lost particles from two bunches in the ring. The particle losses are more than 10% reduced by optimizing the LP at injection.

scheme as depicted in Fig. 23. The longitudinal beam distributions of the lost particles without and with LP optimization are indicated in pink and green, respectively. The left and right plots represent the lost particles from two circulating bunches in the ring. The horizontal axis in this figure represents the longitudinal coordinate in radians (π), corresponding to 2π is the ring circumference. Meanwhile, the vertical axis represents the energy deviation of the lost particles. Optimizing the LP scheme by applying an rf frequency offset, along with a momentum offset of the injection beam, reduces the energy spread of the beam compared to that observed when using only momentum offset of the injection beam. The optimization of the LP gives more than 10% less particle losses (green) as compared to that of using an original LP scheme (pink). The rf offset helps retain the beam near the center of the rf bucket, thus minimizing longitudinal beam halos reducing the beam losses.

Figure 40 shows the transverse beam profiles obtained at the end of the injection process without and with modification of the transverse painting (TP) scheme as depicted by the green and blue lines, respectively. Optimizing the TP pattern by adjusting the speed and range of painting, as depicted in Figs. 25 and 26, results in a more uniform beam distribution, particularly in the vertical plane. This modification reduces the high spatial charge concentration caused by the SC effect when using the original TP pattern. The corresponding tune footprints are shown in Fig. 41, where the higher spatial charge concentration observed under the original TP scheme leads to an asymmetric tune distribution, trapping numerous particles within the third-order resonances, $3\nu_x = 19$ and $\nu_x - 2\nu_y = -6$. Such trappings result in a higher beam loss compared to a symmetric tune distribution obtained by applying a modified transverse beam painting for achieving a considerable beam loss mitigation, as depicted by the green and blue colors, respectively.

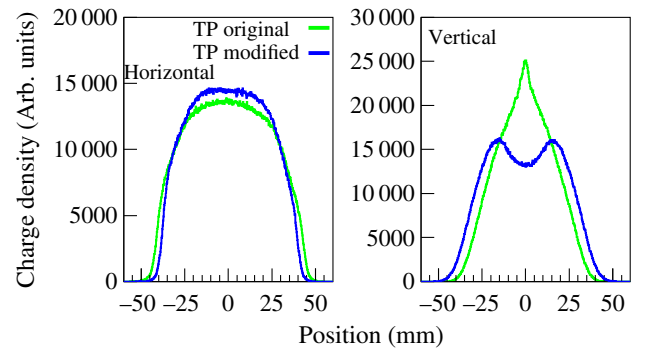


FIG. 40. Simulation results of transverse beam profiles at the end of injection for horizontal (left) and vertical (right) planes. High spatial charge concentration in the vertical plane (green) is significantly reduced, achieving a more uniform beam distribution with modified TP (blue) optimized to reduce the beam loss.

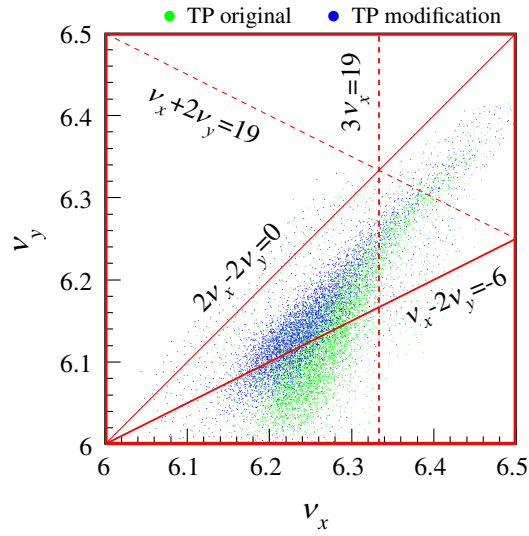


FIG. 41. Simulation results of tune footprint at 1 MW with (blue) and without (green) TP modification at injection.

Figure 42 shows simulation results for the temporal structure of beam loss at the collimator obtained under the application of the original and modified TP schemes as depicted by the green and blue colors, respectively. The additional beam losses observed after the injection period when using the original TP scheme are considerably reduced by optimizing the TP scheme. The optimized scheme gives nearly 40% beam loss mitigation, which aligns well with the measurement result.

Finally, we numerically simulated the optimization of the betatron tune similar to that done for the beam tests. A little increase of only the horizontal tune to 6.46 from 6.45 gives

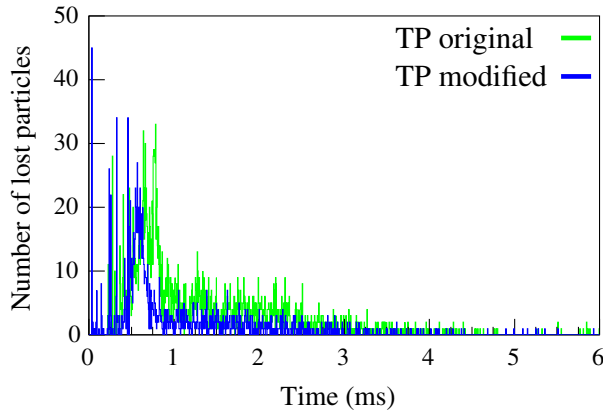


FIG. 42. Simulation results of the temporal structure of beam loss with the original (green) and modified (blue) TP schemes optimized to reduced the beam loss. Additional beam losses, other than those caused the foil scattering, which appeared after injection and continued at least up to 5 ms with the original TP, are significantly mitigated by optimizing the TP patterns in this study.

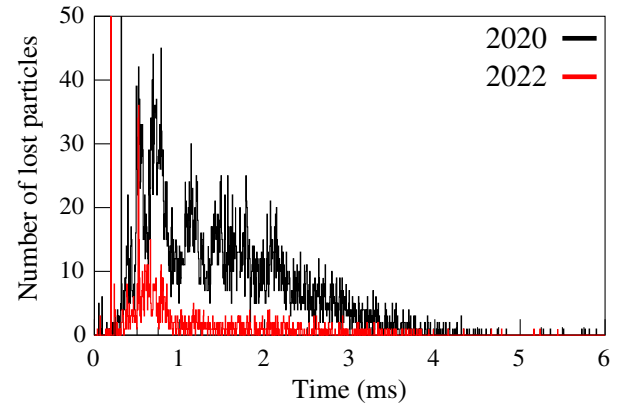


FIG. 43. Simulation results comparing the temporal structure of the beam loss at 1 MW between 2020 (black) and 2022 (red) using larger and smaller injection β_y , respectively. The beam loss is sufficiently minimized by reducing the β_y and using a smaller stripper foil with appropriate optimizations. The beam loss occurs only around the injection period mainly due to the foil scattering of the circulating beam.

a beam loss mitigation of approximately 15% by improving the beam survival as illustrated in Fig. 37, which is also quite consistent with the measurement result.

Figure 43 represents the temporal structures of beam loss at 1 MW, comparing the results obtained after the implementation of all optimizations introduced between 2020 and 2022 (red) with those obtained after the implementation of optimizations introduced until 2020 (black). As depicted, the SC effect at 1 MW is significantly suppressed, substantially reducing the beam loss to an extremely low level. The residual beam loss is minimized to 0.04%, and this loss is primarily attributed to the foil scattering of the circulating beam during injection. The beam loss peaks at the end of the injection period at 0.5 ms.

Overall, the optimizations introduced in this study successfully mitigate the SC effect and the corresponding sources of the beam loss to sufficiently minimize the beam loss and beam emittance at the designed beam power of 1 MW. The numerical simulation results are consistent with the measurement results, highlighting their importance and utility in guiding the beam tests.

VI. SUMMARY

In the study focused on the 3-GeV RCS of the J-PARC, we initially aimed to minimize uncontrolled beam losses in the injection region attributed to foil scattering of the circulating beam during multiturn injection. This was achieved by reducing the vertical size of the stripper foil to 14 mm from its original size of 20 mm and the injection beam size. The vertical Twiss parameter of the injection beam at the foil (injection point) was optimized to minimize the vertical rms beam size of 1.8 to 0.92 mm. Furthermore, we optimized vertical transverse painting (TP) to match the upright smaller injection beam size. Consequently, the

average foil hitting of the circulating beam was reduced by 30%, leading to a corresponding decrease in uncontrolled beam loss in the injection region occurring due to foil scattering of the circulating beam. The integrated beam loss at the collimator and the first arc section (downstream of the collimator) was also reduced up to 40% for a beam intensity of 0.77 MW. Simulation results of the above tests demonstrated good agreement with the measurement results. Furthermore, using a smaller foil and reduced injection beam size for 0.77-MW beam operation of the RCS considerably reduced machine activations, mirroring the beam loss mitigation achieved at the injection, collimator, and first arc sections.

However, the designed 1-MW beam power results in beam losses up to 4 times higher than those observed at 0.77 MW, even after applying all optimized parameters derived at 0.77 MW and only a 30% increase in beam intensity. This increase in beam loss is primarily attributed to the stronger space charge (SC) effects and corresponding betatron resonances at the higher beam intensity. To address this, the second part of our research focused on minimizing beam loss at 1 MW by suppressing the SC effects and associated beam losses.

Initially, we partially mitigated the effect of the horizontal beam emittance growth and the resulting beam loss caused by the third-order betatron resonance, $3\nu_x = 19$, which is excited by multipole field components intrinsic in the injection chicane magnets (SB). This was achieved by reducing the SB magnetic field by 20% (maximum permissible reduction without affecting beam injection) as no additional sextupoles were available to correct this resonance. This reduction resulted in a 20% decrease in beam loss and a 10% decrease in the horizontal rms beam emittance. Furthermore, we estimated that such a reduction of the SB fields led to a 40% decrease in the vertical beta function beating caused by the edge focusing effect of the SB, resulting in a partial reduction of the third-order betatron resonance, $\nu_x + 2\nu_y = 19$ excited when the super-periodicity of the RCS is distorted during beam injection. Moreover, the lower value of the SB field is also estimated to reduce the decay rates of partially stripped (neutral) excited H^0 species stripping to proton before they reached to the downstream second stripper foil, thus reducing losses.

Next, we optimized the longitudinal painting scheme at injection by introducing an offset of the rf frequency in addition to only the momentum offset of the injection beam currently used. This adjustment positioned the injection beam closer to the rf bucket center, improving longitudinal beam behavior by reducing longitudinal beam halos (large $\Delta p/p$) and leakage from the bucket. This modification resulted in a 30% reduction in beam loss at the collimator and arc sections.

In the next step, we modified the transverse painting at injection involving a gradual variation of the painting

magnets. This adjustment helped to reduce high spatial charge concentrations and the asymmetric tune distribution that traps numerous particles on the third-order betatron resonances, $3\nu_x = 19$ and $\nu_x - 2\nu_y = -6$ owing to the SC effect. This approach strikes a proper balance between horizontal and vertical painting emittances, thus minimizing the emittance exchange and emittance growth. This optimization also resulted over 30% reduction in beam loss at the collimator and first arc sections, including a 25% decrease in the rms emittance of the extracted beam.

Finally, betatron tunes during injections were optimized based on the tune survey conducted around the current operating point of (6.45, 6.36). By slightly (0.01) adjusting the horizontal tune ν_x to 6.46 while maintaining the vertical one unchanged at 6.36, we achieved nearly 20% beam loss mitigation. This adjustment was the most effective among the investigated tunes, most probably improved the separation of the tune distribution from the Montague resonance $2\nu_x - 2\nu_y = 0$, resulting in beam loss mitigation. However, increasing the ν_x further was not feasible owing to the second-order resonance, $2\nu_x = 13$, which induces additional beam losses. Approaches involving the use of trim quadrupoles installed in the RCS for correcting this resonance are currently under investigation.

Thus, our optimization efforts significantly reduced beam loss at the designed 1-MW beam power by addressing the foil scattering effect and mitigating SC effects. Compared with the situation in 2020, the beam loss at 1 MW in 2022 is reduced by 80%, along with a 40% reduction of the transverse rms emittances of the extracted beam. Similar to the beam loss optimization obtained for RCS operation at 0.7 MW, the simulation results at 1 MW also demonstrate good agreement with measurement results, providing a detailed understanding of the underlying beam physics and effective strategies for beam loss and beam emittance minimization. The residual beam loss rate at 1 MW is estimated to be well below than 10^{-3} , which is primarily attributed to the foil scattering of the circulating beam. Furthermore, the measured beam loss at 1 MW is even 20% lower than that recorded at 0.6 MW in 2020 and less than half of the scaled beam loss derived from the loss at 0.6 MW. The beam power loss at the collimator is estimated to be around 0.1 kW, which is only approximately 3% of the 4-kW capacity of the collimator. This significant reduction in beam loss demonstrates the potential for achieving far exceeding the designed beam power of 1 MW in the RCS, with the next target set at 1.5 MW.

The optimized parameters introduced in this research have been incorporated into the routine operation of RCS at an approximately 1-MW beam power in 2023. As expected, this implementation has considerably reduced machine activation compared with the operation at a beam power of 1 MW in 2020. The residual dose measured at the prime spot of the collimator is an order of magnitude lower,

while the uncontrolled machine activations throughout the ring are also reduced several times. Currently, the residual doses throughout the RCS are even considerably lower than those that occurred at 0.6-MW routine operation in 2020. Consequently, we have achieved stable and sustainable operation of the RCS with more than 98% availability. Furthermore, beam loss throughout the beam transport process to the neutron production target is considerably reduced, reflecting not only a reduction of rms emittance of the beam but also an improvement in beam quality, with less beam halos. This is essential for broadening the beam using octupole magnets placed upstream of the neutron production target, crucial for preventing pitting damage to the target.

The present optimization measures, which were considered in the simulations and applied in practice, accomplished the goal of minimizing beam loss and achieving negligible machine activation in the 3-GeV RCS at the J-PARC. Furthermore, these measures can be easily adapted for any similar accelerators to achieve effective beam loss minimization at high-intensity operations.

ACKNOWLEDGMENTS

The authors highly acknowledge entire J-PARC accelerator colleagues for their kind support and cooperation on the present study. We would like to express our gratitude to the assistant director of J-PARC Dr. Michikazu Kinsho for his continuous support and encouragement of this research. We also extend our special thanks to the entire group of the beam transport for measuring extracted beam emittance and beam halos, which were highly essential in this study.

DATA AVAILABILITY

The data that supports the findings of this article are available from the corresponding author upon reliable request.

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