Beam commissioning and operation of the Japan Proton Accelerator Research Complex 3-GeV rapid cycling synchrotron

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The 3-GeV rapid cycling synchrotron (RCS) of the Japan Proton Accelerator Research Complex (J-PARC) is a high-power pulsed proton driver aiming at 1 MW output beam power. The RCS was beam commissioned in October 2007 and made available for user operation in December 2008 with an output beam power of 4 kW. Since then, the output beam power of the RCS has been steadily increasing following progressions in beam tuning and hardware improvements. So far, the RCS has successfully achieved high-intensity beam trials of up to 420 kW at a low-level intensity loss of less than 1%, and the output beam power for the routine user program has been increased to 210 kW. The most important issues in increasing the output beam power are the control and minimization of beam loss to maintain machine activation within the permissible level. This paper presents the current status of the RCS beam power ramp-up, with particular emphasis on our approach to beam loss issues. The future prospects of RCS beam commissioning and operation are also described.

1. Introduction

The Japan Proton Accelerator Research Complex (J-PARC) is a multi-purpose high-power proton accelerator facility [1,2], comprising a 400-MeV linac, a 3-GeV rapid cycling synchrotron (RCS), a 50-GeV main ring synchrotron (MR), and three experimental facilities—a materials and life science experimental facility (MLF), a hadron experimental hall (HD), and a neutrino beam line to Kamioka (NU). In this chain of accelerators, the RCS has two functions: one as a proton driver to produce pulsed muons and neutrons at the MLF, and the other as an injector to the MR, aiming at 1 MW output beam power.

The J-PARC beam commissioning began in November 2006 from the linac to the downstream facilities. The RCS was beam commissioned in October 2007. Following the initial beam tuning and the underlying beam studies [3], the RCS was made available for user operation in December 2008 with an output beam power of 4 kW. Since then, efforts have been made to increase the output beam power. Figure 1 shows the history of the RCS output beam power: the beam power ramp-up of the RCS has steadily proceeded to the design beam power to date. Although the East Japan earthquake
Fig. 1. History of the RCS output beam power for the MLF since the start-up of the user program.

on March 11, 2011 caused considerable damage to the J-PARC site [4], we resumed beam operation for the user program in January 2012 after nine months of recovery work and a one-month beam test. The current output beam power for the routine user program is 210 kW, which is the same beam power as just before the earthquake.

At high-power accelerator facilities such as the RCS, beam loss is always a key issue. A large fraction of the beam commissioning group’s effort is focused on reducing and managing the beam loss associated with the beam power increase, to maintain machine activation within the permissible level and to preserve a hands-on-maintenance environment. In this paper, we present our approach to beam loss issues observed in high-intensity beam trials of up to 420 kW, and summarize the current status and future prospects of the RCS beam power ramp-up.

2. Layout and design parameters of the RCS

Figure 2 shows a schematic of the RCS, and the design parameters are listed in Table 1. As shown in Fig. 2, a H\(^{-}\) beam from the linac is delivered via the linac-to-3-GeV beam transport line (L-3BT) to the RCS injection point, where it is multi-turn charge-exchange injected through a 200–300 \(\mu\)g/cm\(^2\)-thick hybrid-type boron-mixed carbon stripping foil—HBC foil [5]—over a period of 0.5 ms. In order to avoid longitudinal beam loss during injection, the H\(^{-}\) linac beam is equipped with a chopped bunch structure in synchronization with the ring RF frequency at the time of injection, where the chopper beam-on duty factor is typically 56%. The current injection energy is 181 MeV. The RCS accelerates the injected protons up to 3 GeV at a repetition rate of 25 Hz. Most of the time, the 3 GeV beam from the RCS is transported via the 3-GeV-to-neutron-target beam transport line (3-NBT) to the MLF, while only a portion of the RCS beam (typically four pulses every several seconds) is transported via the 3-GeV-to-50-GeV beam transport line (3-50BT) to the MR.

Figure 3 shows the optical functions along the ring. As shown in Figs. 2 and 3, the RCS has a three-fold symmetric lattice over its circumference of 348.333 m. Each superperiod consists of two 3-DOFO arc modules and one 3-DOFO long straight insertion, where DOFO describes a defocusing–focusing periodic cell. Each arc module has a missing-bend cell, where the horizontal dispersion is at a maximum (6 m). Such a lattice structure gives a high transition energy (\(\gamma_t = 9.2\) GeV), which is sufficiently far from the extraction energy. This high-\(\gamma_t\) lattice obtained by the missing-bend technique is a unique feature of the RCS optics design. Three families of sextupole magnets for chromatic correction and a longitudinal primary collimator (scatterer) are installed in the high-dispersion areas.
Fig. 2. Schematic of the RCS.

Table 1. RCS design parameters, where the values in brackets correspond to the final design parameters to be achieved after upgrading the linac.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
<td>348.333 m</td>
</tr>
<tr>
<td>Superperiodicity</td>
<td>3</td>
</tr>
<tr>
<td>Injection energy</td>
<td>181 MeV [400 MeV]</td>
</tr>
<tr>
<td>Injection period</td>
<td>0.5 ms</td>
</tr>
<tr>
<td>Peak current of the injection beam</td>
<td>15–30 mA [50 mA]</td>
</tr>
<tr>
<td>Chopper beam-on duty factor of the injection beam</td>
<td>56%</td>
</tr>
<tr>
<td>Unnormalized transverse emittance of the injection beam</td>
<td>$6\pi$ mm mrad [4$\pi$ mm mrad]</td>
</tr>
<tr>
<td>Momentum spread of the injection beam</td>
<td>$\pm 0.1%$</td>
</tr>
<tr>
<td>Extraction energy</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>25 Hz</td>
</tr>
<tr>
<td>Ramping pattern</td>
<td>Sinusoidal</td>
</tr>
<tr>
<td>Transition energy</td>
<td>9.2 GeV</td>
</tr>
<tr>
<td>Harmonic number</td>
<td>2</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>2</td>
</tr>
<tr>
<td>Number of particles per pulse</td>
<td>$2.5-5.0 \times 10^{13}$ [8.3 $\times 10^{13}$]</td>
</tr>
<tr>
<td>Output beam power</td>
<td>0.3–0.6 MW [1 MW]</td>
</tr>
<tr>
<td>Momentum acceptance</td>
<td>$\pm 1%$</td>
</tr>
<tr>
<td>Ring acceptance</td>
<td>$486\pi$ mm mrad</td>
</tr>
<tr>
<td>Collimator aperture</td>
<td>$324\pi$ mm mrad</td>
</tr>
<tr>
<td>Collimator capability</td>
<td>4 kW</td>
</tr>
</tbody>
</table>

Fig. 3. Beta (upper) and dispersion (lower) functions along the ring, where the red curves are the horizontal ones, the blue curves the vertical ones, and the open circles show the measured results.
On the other hand, the straight insertions have zero dispersion. Injection and collimation systems are installed in the first straight section. The injection system uses the first 1.5 cells, while the transverse primary collimator (scatterer) and secondary collimators (absorbers) use the remainder of the cells. Extraction and RF systems are located in the second and third straight sections.

The ring acceptance of the RCS is $486\pi$ mm mrad for a possible momentum spread of $\pm 1\%$, for which the primary collimator aperture is set at $324\pi$ mm mrad. Such a large ring acceptance is essential for maintaining particle losses within the permissible level. Moreover, such a large ratio of ring acceptance to collimator aperture (1.5) is necessary for localizing the residual particle losses in the collimator section and minimizing the irradiation of the rest of the ring [6].

With the current injection energy of 181 MeV, the RCS aims at providing more than 300 kW output beam power. The linac will be upgraded in the 2013 summer–autumn period; the output energy will be improved to 400 MeV with the addition of an annular coupled structure (ACS) linac [7], and the maximum peak current will be increased from 30 to 50 mA by replacing the front-end system (the ion source and the RF quadrupole linac). After that, the RCS will aim at our final goal of 1 MW output. It is well known that the direct space-charge effect in the low-energy region imposes a major performance limit on high-power proton synchrotrons. The above two operations give an equivalent space-charge effect at each injection energy as per the $\beta^2\gamma^3$ scaling law, where $\beta$ and $\gamma$ are the Lorentz factors. The allowable intensity loss for 1 MW output operation with 400 MeV injection energy is 3% at injection, determined on the basis of the current collimator capability (4 kW). Therefore, achieving more than 300 kW output with 181 MeV injection energy at less than 3% intensity loss will serve as a benchmark for realizing 1 MW output with 400 MeV injection energy.

Details of the distinctive features of the RCS devices are described in [8].

3. Lattice property and operating point

Before beginning high-intensity beam experiments, we performed thorough investigations of the basic lattice property, looking, in particular, for intrinsic lattice imperfections in the ring, and to find better operating points for high-intensity beams.

In the RCS, beam injection is performed with a horizontal local bump orbit formed by four sets of rectangular pulse dipole magnets (SB1–4 in the upper plot in Fig. 16 given later). This method generates edge focus at the entrance and exit of each SB, causing beta function beating during injection. Figure 4 shows the results of beta beating measurement (the technical details of optics measurement in the RCS are described in [3]). As shown in the figure, this four-bump method causes beta function beating only in the vertical plane, since the horizontal edge focus effect is compensated by another horizontal focusing property produced by bending. From this measurement, the strength of the edge focus was evaluated to be $-0.0067$ T per edge, which corresponds to around 1% of the main quadrupole field strength at injection.

Another major lattice imperfection was found in the extraction section, which arises from the leakage of static magnetic fields generated by the extraction beam line DC magnets into the ring. In order to reduce the leakage field, we installed additional magnetic shields. Although this achieved a 40% reduction [9], there is still significant leakage field remaining. Figure 5 shows a closed orbit distortion (COD) caused by the leakage field. From this COD, the dipole field component in the leakage field was evaluated to be 0.0022 (normal component) and 0.0002 (skew component) Tm. Because the COD can be corrected sufficiently by steering magnets, the COD itself does not lead to serious issues. However, such a leakage field generally includes higher-order field components.
Fig. 4. Horizontal (red) and vertical (blue) beta functions along the ring, where the circles show those measured when the injection bump is active, while the solid curves correspond to the beta functions when the injection bump is inactive.

Fig. 5. Horizontal (upper) and vertical (lower) COD caused by the leakage field from the extraction beam line DC magnets, where the circles show measurements, and the squares are calculated values.

Fig. 6. Horizontal (upper)–vertical (lower) coupling caused by the leakage field from the extraction beam line DC magnets; orbit leak to the vertical plane by a horizontal single kick, where the circles show measurements, and the squares are calculated values.

In fact, we confirmed in the tune survey that the leakage field enhances half-integer and linear coupling resonances. This implies that the leakage field includes significant normal and skew quadrupole field components. The normal quadrupole field component was evaluated to be 0.0098 T from a tune change caused by the leakage field. On the other hand, the skew quadrupole field component was estimated to be $-0.0022$ T from a horizontal–vertical coupling measurement, namely by observing an orbit leak to the vertical plane by a horizontal single kick, as shown in Fig. 6.

Figure 7 shows tune diagrams obtained from single-particle tracking simulations at the injection energy with different combinations of the lattice imperfections. The left plot in this figure (a) shows a tune diagram calculated with only field and alignment errors of the ring magnets. Since the lattice
Fig. 7. Tune diagrams obtained from single-particle tracking simulations at the injection energy with different combinations of the lattice imperfections, where (a) corresponds to a tune diagram calculated with only field and alignment errors of the ring magnets, (b) adds the leakage field, and (c) adds the edge focus.

superperiodicity in this case is still sufficiently maintained, almost all the resonances observed in this plot are the systematic ones: they are third- and fourth-order systematic resonances excited chiefly by chromatic correction sextupole fields, a sextupole field component in the main dipole magnets and their second-order effects. The middle plot (b) shows a similar result calculated with the addition of the leakage field. The leakage field, which includes normal and skew quadrupole field components, strongly excites half-integer and linear coupling resonances. In addition, one can see that it slightly excites several third-order random resonances through a distortion of the lattice superperiodicity. The right plot (c) represents the result obtained by further adding edge focus. The edge focus makes a relatively large distortion of the superperiodicity on the vertical plane. Thus it enhances various random resonances related to the vertical motion. The state of the lattice property gradually changes from (c) to (a) as the acceleration progresses. Plot (c) corresponds to the tune diagram when the injection bump is active for injection, while plot (b) represents the situation when the injection bump is inactive just after injection. Then plot (b) gradually changes to (a) as the acceleration progresses, because the effect of the static leakage field gradually fades out with the acceleration.

On the basis of the above investigation of the basic lattice property, and taking into account space-charge induced resonances such as fourth-order systematic resonances, we searched possible operating tunes for high-intensity beams. High-intensity beam trials of up to 420 kW, which will be described in the following sections, were performed at (6.45, 6.42). This operating point allows the space-charge tune shift to avoid serious multipole resonances.

4. Measures against beam loss in the low-energy region

In January 2011, we performed a high-intensity beam trial using a 0.5 ms linac pulse with a peak current of 20 mA and a chopper beam-on duty factor of 56%, where the number of particles per pulse totaled $3.5 \times 10^{13}$, corresponding to 420 kW output beam power.

In high-power proton machines such as the RCS, the direct space-charge effect in the low-energy region is one of the most crucial sources of beam loss, setting a strong limit on the achievable beam intensity. To alleviate this, the RCS adopts a multi-turn charge-exchange injection painting scheme. This approach permits the control of the charge density distribution of the circulating beam in the transverse and the longitudinal phase spaces, resulting in space-charge mitigation and beam loss reduction. In the present high-intensity beam trial, we investigated the effect of the transverse and
Fig. 8. Schematic of the injection painting in the transverse plane, where the upper plot is for the horizontal phase space, while the lower one is for the vertical one.

longitudinal injection painting on beam loss reduction in the low-energy region [10]. In this work, the operating point was set at (6.45, 6.42) to avoid the possible effects of strong betatron resonances, as discussed in Section 3.

In this section, the experimental results are discussed with the corresponding numerical simulation results obtained with a three-dimensional particle-tracking code, SIMPSONS [11]. Details of the numerical simulation, such as the modeling of the lattice and handling of the space-charge potential calculation, are described in [10] and [11].

4.1. Transverse painting in the RCS

Figure 8 shows the transverse painting scheme applied in the present beam experiment. As shown in the figure, the transverse painting makes use of a controlled phase-space offset between the centroid of the injection beam and the ring closed orbit to form a different particle distribution of the circulating beam from the multi-turn injected beam. On the horizontal plane, the injection beam was filled from the center to the border of the circulating beam ellipse along its major axis by a horizontal closed orbit variation, while, on the vertical plane, it was painted from the center to the border by a vertical injection angle change. In the present experiment, the painting emittance was set to $100\pi \text{ mm mrad}$, and a square-root-type function for the phase-space offset of the injection beam relative to the ring closed orbit was chosen for the painting process:

$$
\begin{align*}
    x_{\text{paint}} &= x_{\text{max}} \sqrt{t/T}, \\
    x_{\text{paint}}' &= -x_{\text{max}}' \sqrt{t/T}, \\
    y_{\text{paint}} &= 0, \\
    y_{\text{paint}}' &= -y_{\text{max}}' \sqrt{t/T},
\end{align*}
$$

where $(x_{\text{max}}, x_{\text{max}}') = (27.1 \text{ mm}, 3.8 \text{ mrad})$ and $(y_{\text{max}}, y_{\text{max}}') = (0.0 \text{ mm}, 2.3 \text{ mrad})$ are the maximum phase-space offsets for the horizontal and vertical planes, respectively, corresponding to the border of the circulating beam ellipse with the required painting emittance of $100\pi \text{ mm mrad}$. Other parameters are $T$, representing an injection duration of 0.5 ms, and $t$, indicating a time step.
Fig. 9. Schematic of the longitudinal motion for the multi-turn injection process without (left) and with (right) a momentum offset, where the boxes represent the injection bunch train from the linac.

from 0 through the end of injection $T$. This type of transverse painting is known as correlated painting [12,13].

In this experiment, we investigated the effectiveness of this correlated painting for beam loss reduction in combination with longitudinal painting. Details of the beam-based adjustment procedure of the transverse painting are described in [14] and [15].

4.2. Longitudinal painting in the RCS

The longitudinal painting makes use of a controlled momentum offset to the RF bucket in combination with superposing a second harmonic RF voltage to obtain a uniform particle distribution in the longitudinal direction after the multi-turn injection. Figure 9 shows the momentum offset injection scheme. As shown in the figure, a flat beam bunch is formed through emittance dilution by the large synchrotron motion excited by the momentum offset. In this method, the superposition of the second harmonic RF voltage fills the role of shaping a flatter and wider RF bucket potential (compare the blue and red solid curves in Fig. 11 given later), which leads to better longitudinal motion to make a flatter bunch distribution. As an additional control in the longitudinal painting, a phase sweep of the second harmonic RF voltage relative to the fundamental one was applied. This second harmonic phase sweep method enables further bunch distribution control through a dynamical change of the RF bucket potential shape, including a position change of the stable fixed points during injection (see the red curves in Fig. 11 given later).

The RF voltage $V_{\text{rf}}$ applied in the present experiment is expressed as

$$V_{\text{rf}} = V_1 \sin \phi - V_2 \sin(2(\phi - \phi_s) + \phi_2),$$

where $V_1$ is the amplitude of the fundamental RF voltage, $V_2$ is the amplitude of the second harmonic RF component, $\phi_s$ is the synchronous phase, $\phi$ is the phase of the RF voltage, and $\phi_2$ is the phase offset of the second harmonic RF voltage. In the present beam experiment, the second harmonic RF voltage with an amplitude of 80% ($V_2/V_1$) of the fundamental was employed during the first 1 ms, as shown in Fig. 10. Also, its phase was linearly swept from $-100$ to 0 degrees ($\phi_2$) over an injection duration of 0.5 ms. In this case, the shape of the RF bucket potential gradually changes during injection, as shown by the red curves in Fig. 11. For such a dynamically controlled RF bucket potential, the momentum offset injections of 0, $-0.1$ and $-0.2\%$ ($\Delta p/p$) were performed.
In this experiment, we investigated the influence of the longitudinal painting on the transverse motion and the combined effect of the transverse and longitudinal painting on beam loss reduction. Further details of RF parameter dependence on the longitudinal motion are described in [16] and [17].

4.3. Experimental results and discussion with numerical simulations

The injection painting parameters tested in the present beam experiment are listed in Table 2. With these systematic combinations of transverse and longitudinal painting, we surveyed their effectiveness for beam loss reduction.

Figure 12 shows the time dependence of the circulating beam intensity from injection through extraction, measured with a DC current transformer (DCCT) installed in the ring for the painting parameter IDs 1–8 in Table 2, where the ramp-up slope of the beam intensity from 0 to 0.5 ms corresponds to the beam accumulation process. In the figure, it is confirmed that the major beam loss appears only for the first several milliseconds in the low-energy region, where the space-charge effect is most serious. For data ID 1, the injected beam was accumulated at the center region in the transverse and the longitudinal phase spaces with no charge density manipulation (called center injection). The beam survival rate with center injection was measured to be 83%, while it was gradually improved...
Table 2. Injection painting parameters applied in the present beam experiment: ID 1, no painting (center injection); ID 2, transverse painting only; IDs 3–5, longitudinal painting only; and IDs 6–8, combinations of transverse and longitudinal painting.

<table>
<thead>
<tr>
<th>Parameter ID</th>
<th>$\epsilon_{tp}$ ($\pi$ mm mrad)</th>
<th>$V_2/V_1$ (%)</th>
<th>$\phi_2$ (deg)</th>
<th>$\Delta p/p$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>100</td>
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<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>—</td>
<td>80</td>
<td>-100 to 0</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>—</td>
<td>80</td>
<td>-100 to 0</td>
<td>-0.1</td>
</tr>
<tr>
<td>5</td>
<td>—</td>
<td>80</td>
<td>-100 to 0</td>
<td>-0.2</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>80</td>
<td>-100 to 0</td>
<td>—</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>80</td>
<td>-100 to 0</td>
<td>-0.1</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
<td>80</td>
<td>-100 to 0</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

Fig. 12. Time dependence of the circulating beam intensity from injection through extraction, measured with the DCCT installed in the ring for the painting parameter IDs 1–8 in Table 2, where the ramp-up slope of the beam intensity from 0 to 0.5 ms corresponds to the beam accumulation process. In the figure, the corresponding numerical simulation results are plotted as black curves.

for data IDs 1 to 8 by introducing transverse painting, longitudinal painting, and their combination. The best beam survival rate obtained for parameter ID 8 was measured to be better than 99%, where the highest output intensity, corresponding to 420 kW output beam power, was obtained. With this measurement in particular we confirmed the powerful ability of longitudinal painting for beam loss
In order to investigate more detailed time structure of the beam loss, we employed a scintillation-type beam loss monitor (BLM) with a photomultiplier, because the use of this BLM helps in obtaining excellent time response and resolution. The top plots in Fig. 13 show the time structure of the scintillation-type BLM signal for the first 6 ms measured in the collimator section for data IDs 3 to 8, while the middle plots in Fig. 13 show the corresponding simulated result plotted as the number of lost macro-particles per turn. The measured and simulated beam loss patterns are in good agreement. In these figures, the contribution of the transverse painting to the beam loss reduction, in addition to that of the longitudinal painting, can be clearly observed; by comparing the left (IDs 3–5) and right (IDs 6–8) sides of the top and middle plots in Fig. 13, it is confirmed that transverse painting effectively decreases the beam loss mainly in the first 1 ms region. The beam loss in this period includes a component arising from foil scattering during the charge-exchange injection process. The foil-scattering beam loss is essentially proportional to the foil-hitting probability during injection. While longitudinal painting hardly changes the number of foil hits during injection, transverse painting reduces it due to the horizontal closed orbit variation in the painting process and the excited betatron amplitudes that are larger than the foil size. In this case of transverse painting, the number of foil hits per particle during injection is reduced from 90 to 20. Therefore, the beam loss reduction by transverse painting includes the effect of the foil-hitting rate reduction as well as that of the charge density control. In order to distinguish the two contributions, we performed additional numerical simulations with no foil scattering, as shown in the bottom plots in Fig. 13. By comparing the left and right sides of the middle and bottom plots in Fig. 13, we can separately confirm...
the significant beam loss reduction by charge density control in the transverse painting, in addition to that by its resultant decrease in the foil-hitting rate. In addition, this comparison shows that the remaining small beam loss of less than 1% observed for painting parameter ID 8 is mainly caused by foil scattering during the charge-exchange process. This indicates that the space-charge induced beam loss for the 420 kW-intensity beam is mostly minimized through the charge density control in the transverse and the longitudinal painting with parameter ID 8.

Figure 14 shows the time evolution of the horizontal and the vertical normalized emittances over an injection duration of 0.5 ms calculated for parameter IDs 1, 2, 6, 7, and 8, where different emittances encircling 38%, 68%, 95%, and 99% of the macro-particles are plotted for each parameter ID. In the figure, similar results calculated with no foil scattering are also plotted as dashed curves for reference. This figure shows the characteristic features of the transverse and the longitudinal painting. As shown by the emittance change from data IDs 1 to 2, transverse painting increases the beam emittances for 38% and 68%, while it decreases those for 95% and 99%. In the transverse painting, the beam is widely distributed directly in the transverse phase space following the painting functional form. Therefore, the basic function of the transverse painting is to widen the core part of the beam and to decrease its tail. On the other hand, the emittance variations from data IDs 2 to 8 show that longitudinal painting acts to decrease all 38–99% emittances. Figure 15 shows the calculated two-dimensional plot of the longitudinal phase space ($\phi$, $\Delta p/p$) at the end of injection and its projection to the $\phi$ axis for parameter IDs 2, 6, 7, and 8. In this figure, the corresponding longitudinal beam profile measured with a wall current monitor (WCM) is also plotted as a red curve, and this is well reproduced by the calculated profile. This figure clearly indicates that the flatness level of the beam bunch is improved significantly with progression of the longitudinal painting. The transverse emittance reduction for both core and tail parts obtained by longitudinal painting is led through such a significant charge density mitigation in the longitudinal direction. The above analyses of the calculated particle distributions conclude that the significant beam loss reduction observed in Figs. 12 and 13 is led through beam halo/tail reduction by the charge density control in the transverse and the longitudinal directions and its resultant space-charge mitigation.

5. Measures against foil-scattering beam loss during injection

The above comparison of the empirical and numerical simulation results shows that the space-charge induced beam loss is mostly minimized for beam intensities of up to 420 kW by the combination of transverse and longitudinal painting, and that the remaining small beam loss of less than 1% arises mainly from foil scattering during the charge-exchange injection process.

Although most of the foil-scattering beam loss is well localized on the ring collimator section, a part of it ($10^{-4}$–$10^{-3}$ of the injected beam) generated several hot spots ($\sim$6 mSv/h on the chamber surface in the 210 kW routine user operation) between the foil and the ring collimator. The charge-exchange injection scheme with a foil inevitably involves foil-scattering beam loss, which cannot be completely eliminated. Therefore, as for the foil-scattering beam loss, the localization, as well as the minimization of the foil-hitting rate during injection by introducing transverse painting and by adjusting the position and dimension of the foil, are key issues.

The upper plot in Fig. 16 shows a schematic of the RCS injection section, where (A) and (B) correspond to the hot spots observed downstream of the foil. The BLM signals at the hot spots measured as a function of the average number of foil hits per particle during injection are given in the lower plot in Fig. 16, where the foil-hitting rate was varied by adjusting the transverse painting and the foil position relative to the injection beam. As shown in the figure, the BLM signals show a
**Fig. 14.** Time evolution of the horizontal (left) and vertical (right) normalized emittances over an injection duration of 0.5 ms calculated for parameter IDs 1 (black), 2 (gray), 6 (green), 7 (blue), and 8 (red) in Table 2, where different emittances encircling 38%, 68%, 95%, and 99% of the macro-particles are plotted for each parameter ID. In the figure, similar results calculated with no foil scattering are also plotted as dashed curves for reference.

**Fig. 15.** Calculated two-dimensional plot of the longitudinal phase space ($\phi$, $\Delta p/p$) at the end of injection and its projection to the $\phi$ axis for parameter IDs 2, 6, 7, and 8 in Table 2, where the red solid curve in the projection plot shows the corresponding distribution measured with the WCM.
Fig. 16. Top: Schematic of the RCS injection section, where (A) and (B) correspond to the hot spots downstream of the foil. Bottom: Scintillation-type BLM signals at the hot spots, (A) and (B), measured as a function of the average number of foil hits per particle during injection, where the foil-hitting rate was varied by adjusting the transverse painting and the foil position relative to the injection beam.

A linear response for the foil-hitting rate, and the extrapolated lines have a practically zero intercept. This is clear evidence that the machine activations downstream of the foil arise mainly from the foil-scattering beam loss. The upper plot in Fig. 17 shows the result of a tracking simulation for scattered particles on the foil. In this simulation, the scattered particles were generated on the foil with the scattering angle distribution calculated with GEANT [18], assuming both the Coulomb and hadronic interactions beforehand. As shown in the figure, this particle-tracking simulation well reproduces the locations of the observed machine activations, and shows that the Coulomb scattering events with scattering angles of 20–25 mrad produce horizontal particle losses there. This situation was in good agreement with that of the actual machine activations; the radiation level in the horizontal direction was significantly higher than that in the vertical direction. A horizontally defocusing quadrupole magnet (QDL in Figs. 16 and 17) is placed downstream of the foil. This is the reason why the beam loss occurs mainly in the horizontal direction.

In order to localize the uncontrollable beam loss component, we introduced a new collimation system [19] during the period of recovery from the damage caused by the East Japan earthquake. The location of the new collimation system is shown by red boxes in Figs. 16 and 17. The lower plot in Fig. 17 corresponds to the tracking simulation result obtained with the new collimation system. This collimation system consists of two copper blocks (absorbers) 200 mm long along the beam, which provide sufficient stopping power for protons in the injection energy region. The copper blocks are installed horizontally in the vacuum chamber covered with a 450-mm-thick iron radiation shield. The unique feature of this collimation system is that the position and angle of the absorbers are independently adjustable. This function is essential for obtaining sufficient collimation efficiencies for large-angle events scattered on the foil. Figure 18 shows the BLM signal at the hot spot (B) observed both without and with the new collimator; the new collimation system decreased the integrated value of the BLM signal by an order of magnitude from the original value, as expected. This
collimation system has already been introduced to the current 210 kW routine user operation, and has been proven to be effective in preventing machine activation downstream of the foil. The current residual radiation is maintained within a sufficiently permissible level of $\sim 0.5$ mSv/h on the chamber surface, which corresponds to less than one-tenth of the previous level. Details of the new collimation system, its design, and the adjustment procedure for the position and angle of the absorbers, are described in [20].

6. Measures against beam loss in the middle stage of acceleration

High-intensity beam accelerations generally involve an RF bucket distortion arising from the beam loading. In the initial beam tuning phase for high-intensity beams, a small portion of the beam particles ($\sim 10^{-5}$ of the injected beam), which escaped from the distorted RF bucket, were lost at the
high-dispersion area because of large excursions from the synchronous momentum. The left plot in Fig. 19 shows the BLM signal at the high-dispersion area observed for a 300 kW-intensity beam with painting parameter ID 8 in Table 2. As shown in the figure, this beam loss appears at the middle stage of the acceleration process, where the synchronous phase reaches its maximum (50 deg). Consequently, the beam loading effect also worsens the flexibility of the longitudinal painting, especially that of the momentum offset employed for exciting large synchrotron motions.

In order to get stable longitudinal motions for high-intensity beams, beam loading compensation for the RF accelerating cavities was performed. In the RCS, magnetic alloy (MA) loaded cavities, which have a wide-band frequency response, are employed. The wake voltage in this wide-band MA cavity includes the higher harmonics as well as a component of the fundamental accelerating RF. Therefore, in the RCS, the multi-harmonic RF feedforward method, which handles the three most significant harmonics \( h = 2, 4, \) and \( 6 \), was developed for beam loading compensation [21]. Via the thorough methodology with 300–420 kW high-intensity beams, this multi-harmonic RF feedforward method was introduced for routine user operation. Currently, the beam loading effect is stably well compensated by this method, and the beam feels the accelerating RF voltage as programmed. As shown in the right plot in Fig. 19, the beam loss arising from the RF bucket distortion disappears by introducing the beam loading compensation. This method also restores a sufficient variable range of the momentum offset in the longitudinal painting. The beam experiment described in Section 4 was performed with the beam loading compensation.

7. Considerations on beam loss in the L-3BT

Another beam loss to be solved is observed at the exit of the first injection septum magnet located furthest downstream of the L-3BT—(C) in the upper plot in Fig. 20. The residual radiation level at that point in the current 210 kW routine user operation is \( \sim 1 \) mSv/h on the chamber surface. The corresponding beam loss fraction is estimated to be \( 10^{-4} \) from this machine activation level. This residual dose is observed only at the opposite side to the bending direction of the septum, as if the beam loss component is insensitive to the magnetic field. In fact, the BLM signal at the hot spot shows no significant response to orbit changes by the septum. On the other hand, the BLM signal clearly shows a linear response to the peak current variation of the injection beam, as shown in the lower plot in Fig. 20. These aspects imply that the main cause of this beam loss is the \( H^0 \) component neutralized by charge stripping from the \( H^- \) injection beam. There are three possible mechanisms for charge stripping: Lorenz stripping, intra-beam stripping, and residual gas stripping. The former two can be rejected because of the following reasons. The production rate of Lorenz stripping is less
than $10^{-14}$ for the present set-points of the magnetic fields. Such a small fraction cannot explain the observed residual dose level. In the case of intra-beam stripping, the peak current dependence of beam loss should have a quadratic response [22], not a linear response as observed. Thus, the most probable cause of this particle loss is the $H^0$ component arising from residual gas stripping. At the bending magnet furthest downstream, positioned upstream of the first injection septum, namely at (D) in the upper plot in Fig. 20, no significant residual dose has been observed so far. Therefore, it is highly possible that the vacuum pressure in the straight section between (C) and (D) is worse locally than that in other places. While the current residual dose level is still within the permissible level, this beam loss has to be solved to achieve the design goal of 1 MW beam operation. There are no pressure gauge and vacuum pump in this section at present. Therefore, our first step for this concern will be to install pressure gauges in this section and measure the vacuum pressure. Then we plan to introduce vacuum pumps for beam loss reduction, if the pressure measurement indicates that this is necessary.

8. Current beam power ramp-up status and the next target

The beam loss in the RCS has been minimized to less than 1% for beam intensities of up to 420 kW by making use of the injection painting technique and beam loading compensation. Also, most of the remaining beam loss, which arises mainly from foil scattering during the charge-exchange injection, is well localized at the collimator sections in the ring. The beam loss of 1% during injection corresponds to 250 W in power if assuming a 420 kW output beam operation, which is still much less than the current ring collimator capability of 4 kW. This achievement in the high-intensity trial means that the 1 MW design output with the higher injection energy of 400 MeV is reachable within the permissible beam loss level in terms of the direct space-charge effect at the injection energy region, as mentioned in Section 2.
Fig. 21. Residual dose levels (μSv/h) in the RCS injection and collimator sections observed five hours after beam shutdown of the three-week 210 kW routine beam operation, where the values correspond to the radiation levels measured at 30 cm from the chamber surface.

Fig. 22. Top: Proportional-type BLM signals observed along the ring for 210 (black), 300 (blue), and 420 (red) kW intensity beams. Bottom: Similar BLM signals normalized by beam intensity and the foil-hitting rate during injection.

In the above process, the output beam power of the RCS for the routine user program has been increased to 210 kW to date. The current residual activation in the RCS is primarily in the injection and the collimator sections (no significant residual dose has been detected in other locations of the RCS). Figure 21 shows the residual dose levels observed there five hours after beam shutdown of the three-week 210 kW routine beam operation, where the values correspond to the radiation levels measured at 30 cm from the chamber surface. After a day’s cooling, the radiation levels decreased further to less than half of these values. As shown in the figure, machine activation in the RCS has still been kept at a sufficiently low level to date.

The next target in the RCS beam power ramp-up scenario is to run a 300 kW routine beam operation. The upper plot in Fig. 22 shows proportional-type BLM signals observed along the ring for 210, 300, and 420 kW intensity beams, while the lower one in Fig. 22 is a similar plot normalized by beam intensity and the foil-hitting rate during injection. The average numbers of foil hits per particle during injection here were 11.5 (210 kW), 12.5 (300 kW), and 20 (420 kW), depending on the injection pulse length, transverse painting, and foil position. The normalized BLM signal distributions are nearly the same for the different beam intensities. This is further evidence that the beam loss in the RCS is mostly minimized up to a beam intensity of 420 kW, and that the remaining beam loss arises mainly from foil scattering during injection. The BLM signal ratio in the upper plot in Fig. 22 predicts a dose level around two times higher for the coming 300 kW routine beam operation than the present one, but it is still within a sufficiently acceptable level. We plan to carry out the 300 kW routine beam operation as soon as the new mercury target system is available for neutron production at the MLF (probably from the middle of October 2012).
9. Realizing low-halo/tail beams

As mentioned above, we have so far made steady progress on the beam loss issues in the RCS. Another main issue for the RCS is to improve the quality of the extraction beam, namely to realize high-power low-halo/tail beams. This is essential particularly for beam injection to the MR, since the MR has a relatively small physical aperture (81π mm mrad) compared to that of the 3-NBT (324π mm mrad, which is similar to the RCS ring collimator aperture).

For the MR, the 3 GeV beam from the RCS is transported via the 3-50BT to the injection point, as shown in Fig. 2. In the 3-50BT, a collimation system is installed. The aperture of the 3-50BT collimator is typically set at 54–60π mm mrad, where a tail component of the RCS beam is removed. Therefore, the first matter for the MR injection is to pass the beam through the 3-50BT collimator within the acceptable beam loss level.

Figure 23 shows the time evolution of the transverse normalized emittance for the first 6 ms calculated for a 420 kW-intensity beam with injection painting parameter ID 8 in Table 2. This painting parameter gives the minimum beam loss in the RCS, as mentioned above. In this figure, one can see remarkable emittance growth after 1 ms. Although this emittance growth contributes very little to the beam loss in the RCS, it causes a major part of the beam loss at the 3-50BT collimator. Figure 24 shows the corresponding calculated time dependence of the bunching factor, where the bunching factor is defined as the ratio of the average current to peak current of the circulating beam; namely it reflects the flatness-level of the beam bunch. By comparing Figs. 10, 23, and 24, one can find how emittance growth proceeds following the decrease of the bunching factor after 1 ms, and this decrease of the bunching factor corresponds to the fall time of the second harmonic RF voltage after 1 ms. If the bunching factor decreases in this low-energy region, a portion of the beam particles reaches the integer lines of νx,y = 6 (see Fig. 30 given later). On these integer lines, there exist all-order systematic resonances, by which the beam particles suffer from emittance dilution. If this consideration is correct, the emittance growth can be suppressed by minimizing the effects of the integer lines through further charge density control after 1 ms as well as during injection.

We have recently performed numerical simulations and experiments for a 420 kW-intensity beam (3.5 × 10^{13} particles per pulse), using the improved injection painting on the basis of the above consideration. Figure 25 shows the second harmonic RF voltage patterns used for the longitudinal painting in the present work. They have different durations (3–5 ms), where the shorter pattern (3 ms duration) corresponds to the original one used in Section 4. In this work, the behavior of the emittance growth in the low-energy region and its contribution to the extraction beam halo were systematically investigated for longitudinal painting with the two types of second harmonic RF durations shown in Fig. 25 and their combinations with transverse painting. The injection painting parameters tested in the present work are summarized in Table 3, where parameter IDs 5 and 8 are identical to those in Table 2, and the phase sweep of the second harmonic RF (φ2) and momentum offset (Δp/p) applied in the longitudinal painting are all the same as those for IDs 5 and 8 described in Section 4.

The left plot in Fig. 26 shows a painting parameter dependence of beam loss at the 3-50BT collimator measured for a 420 kW-intensity beam extracted from the RCS, where the horizontal axis corresponds to the painting parameter IDs in Table 3. In this measurement, the 3-50BT collimator aperture was set at 54π (horizontal) and 60π (vertical) mm mrad. Thus, the vertical axis in this plot corresponds to the amount of beam halo component with larger transverse emittances than the collimator aperture. The absolute value of the beam halo component was evaluated with a 43 m-long air-ionization type BLM covering the entire 3-50BT collimator area [23].
Fig. 23. Time evolution of the horizontal (left) and vertical (right) normalized emittances calculated for the first 6 ms with parameter ID 8 in Table 2, where different emittances encircling 68%, 90%, 95%, and 99% of the macro-particles are plotted.

Fig. 24. Time evolution of the bunching factor calculated for the first 6 ms with parameter ID 8 in Table 2.

by making various intentional beam losses at the 3-50BT collimator, where the BLM signals detected for the lost particles of \((0.5–8.5) \times 10^{11}\) had a linear response. The measurement was performed within the linear range, the precision of which was estimated to be less than ±7% by considering a pulse-by-pulse deviation and a beam loss position dependence of the BLM signal. On the other
Fig. 25. Second harmonic RF voltage patterns with different durations (a) and (b) used for the longitudinal painting in the present work, in which the shorter pattern (a) corresponds to the original one used in Section 4.

Table 3. Injection painting parameters applied in the present work, where parameter IDs 5 and 8 are identical to those in Table 2, and the phase sweep of the second harmonic RF ($\phi_2$) and momentum offset ($\Delta p/p$) applied in the longitudinal painting are all the same as those for IDs 5 and 8 described in Section 4.

<table>
<thead>
<tr>
<th>Parameter ID</th>
<th>$\epsilon_{tp}$ ($\pi$ mm mrad)</th>
<th>$V_2/V_1$ (%)</th>
<th>$\phi_2$ (deg)</th>
<th>$\Delta p/p$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>100</td>
<td>80 [(a) in Fig. 25]</td>
<td>-100 to 0</td>
<td>-0.2</td>
</tr>
<tr>
<td>5</td>
<td>—</td>
<td>80 [(a) in Fig. 25]</td>
<td>-100 to 0</td>
<td>-0.2</td>
</tr>
<tr>
<td>5'</td>
<td>—</td>
<td>80 [(b) in Fig. 25]</td>
<td>-100 to 0</td>
<td>-0.2</td>
</tr>
<tr>
<td>8'</td>
<td>100</td>
<td>80 [(b) in Fig. 25]</td>
<td>-100 to 0</td>
<td>-0.2</td>
</tr>
</tbody>
</table>

Fig. 26. Left: Painting parameter dependence of beam loss at the 3-50BT collimator measured with the air-ionization type BLM for a 420 kW-intensity beam extracted from the RCS, where the horizontal axis corresponds to the painting parameter IDs in Table 3. Right: Similar dependence of the RCS output intensity measured upstream of the 3-50BT collimator in parallel with the above beam loss measurement. That is, it reflects the state of the beam survival or beam loss in the RCS. Figure 27 shows the bunching factor for the first 6 ms measured with the WCM for painting parameter IDs 5 and 5', where the corresponding numerical simulation results are plotted as black curves, which are in good agreement with the measured ones. As shown by data IDs 5 and 5' in Figs. 26 and 27, the longitudinal painting with the longer-duration second harmonic RF improved the bunching factor after 1 ms, and significantly decreased the beam halo component, as expected. The transverse painting also displayed the ability to reduce the beam halo in combination with longitudinal painting with the longer-duration second harmonic RF, as evident in the comparison of data IDs 5' and 8' in the left plot in Fig. 26.
Fig. 27. Bunching factor for the first 6 ms measured with the WCM for painting parameter IDs 5 (light blue) and 5′ (pink) in Table 3, where the corresponding numerical simulation results are plotted as black curves.

A similar situation was also obtained in the corresponding numerical simulations. Figure 28 shows the time evolution of the transverse normalized emittances calculated for the first 6 ms with the painting parameter IDs in Table 3, in which the normalized emittances obtained at 6 ms are plotted in Fig. 29 as a function of the painting parameter ID. The longitudinal painting with the longer-duration second harmonic RF acts to maintain a large bunching factor over the first several milliseconds, and to reduce the tune depression after 1 ms as shown in Fig. 30. This process alleviates the influence from the integer lines, leading to the significant emittance growth mitigation observed for the data IDs 5 to 5′ in Figs. 28 and 29. This process also enhances the effect of transverse painting on the emittance growth mitigation. The transverse painting well suppresses emittance growth during charge accumulation, but this effect vanishes following the decrease of the bunching factor after 1 ms, as shown by data ID 8 in Fig. 28, because of the influence from the integer lines. The longer-duration second harmonic RF improves this situation, as shown by data ID 8′ in Fig. 28. It is inferred that the empirical painting parameter dependence of the extraction beam halo in the left plot in Fig. 26 reflects such a behavior of the emittance growth in the low-energy region in Figs. 28 and 29. In fact, the calculated dependence in Fig. 29 qualitatively reproduces well the trend of the measurements in the left plot in Fig. 26.

As shown in Fig. 26, the highest output intensity from the RCS, namely the lowest beam loss in the RCS, was obtained both for parameter IDs 8 and 8′, while beam loss at the 3-50BT collimator was reduced to 0.8% by parameter ID 8′, which corresponds to less than half of the original value of 2% measured for parameter ID 8. As a result of this improved injection painting, the extraction beam halo is maintained at a sufficiently low level for beam intensities of up to 420 kW. If the RCS delivers the 420 kW-intensity beam to the MR with a typical operation cycle (4 pulses per 2.56 s), the beam loss of 0.8% at the 3-50BT collimator corresponds to 208 W in power, which is much less than the present capability of the 3-50BT collimator (2 kW).

The beam halo reduction will be a major issue in aiming at the 1 MW design beam operation, when the injection energy is upgraded to 400 MeV. Though the higher injection energy gives a significant advantage in terms of the space-charge effect at injection, it causes a lower adiabatic damping rate (two-thirds of that for the current injection energy of 181 MeV). Such a slower adiabatic damping over the acceleration process can enhance the beam halo formation in different mechanisms from that discussed above, such as the emittance growth caused by resonance crossing at the middle and second halves of the acceleration. In that case, dynamic tune manipulations in the acceleration process
Fig. 28. Time evolution of the horizontal (left) and vertical (right) normalized emittances calculated for the first 6 ms with parameter IDs 8 (red), 5 (light blue), 5’ (pink), and 8’ (blue) in Table 3, where different emittances encircling 68%, 90%, 95%, and 99% of the macro-particles are plotted for each parameter ID.

Fig. 29. Horizontal (circle) and vertical (square) normalized emittances obtained at 6 ms in Fig. 28, plotted as a function of the painting parameter ID in Table 3.
Fig. 30. Space-charge tune depressions calculated at 3 ms for parameter IDs 5 (left) and 5’ (right) in Table 3, where the bare tunes are set at (6.45, 6.42).

for avoiding resonance crossing would be necessary for emittance growth suppression. Our efforts hereafter will be to establish such further beam halo reduction schemes, that is, to obtain high-quality beams that meet the MR requirements, as well as to minimize beam loss in the RCS for MW-class high-intensity beams.

10. Summary and future plans
The RCS beam power ramp-up has proceeded well since the start-up of the user program. The major beam loss issues observed in high-intensity beam trials of up to 420 kW have been solved. The beam loss for a 420 kW-intensity beam was successfully minimized to less than 1% by introducing the injection painting technique and beam loading compensation. Also, the remaining beam loss, which arises mainly from foil scattering during the charge-exchange injection, was localized by installing the new collimation system. In this process, the output beam power for the routine user program has been increased to 210 kW to date. The machine activation in the RCS for this routine beam operation is still maintained at a sufficiently low level. The next target in the RCS beam power ramp-up scenario is to run a 300 kW routine beam operation. We plan to perform this as soon as the new mercury target system for neutron production at the MLF is available (probably from the middle of October 2012).

The direct space-charge effect in the low-energy region generally imposes a major performance limit on high-power proton synchrotrons. The above result achieved for beam intensities over 300 kW with an injection energy of 181 MeV indicates that the 1 MW design output with the higher injection energy of 400 MeV is achievable within the permissible beam loss level in terms of the direct space-charge effect, since the above two operations give an equivalent space-charge effect at each injection energy. That is, it means we have arrived at an important milestone on the road to the final goal of 1 MW output beam power.

The next major issue in the RCS is to improve the quality of the extraction beam, namely to realize high-power low-halo/tail beams. The extraction beam halo significantly decreased through the suppression of emittance growth in the low-energy region by the combination of improved longitudinal painting with a longer-duration second harmonic RF and transverse painting. Though the amount of extraction beam halo is maintained at a sufficiently low level for beam intensities of up
to 420 kW thanks to this manipulation, further efforts towards beam halo reduction, such as dynamic tune control over the acceleration process to suppress emittance growth in the middle and late stages of acceleration, would be necessary in aiming at the 1 MW design output, especially for beam injection to the MR. Our efforts hereafter will be focused on achieving high-quality beams that satisfy the downstream facilities, as well as on minimizing beam loss in the RCS for MW-class high-intensity beams.

The linac will be upgraded in the 2013 summer–autumn period; the output energy will be improved from 181 to 400 MeV with the addition of the ACS linac section, and the maximum peak current will be increased from 30 to 50 mA by replacing the front-end system. With this upgrade of the linac, several hardware improvements will also be performed in the RCS [24]. The power supplies of the RCS injection magnet system will be upgraded for higher injection energy. In addition, another RF cavity will be installed for MW-class high-intensity beam accelerations. One of the important issues that we face at present is to establish a solution to damp the impedance of the RCS fast extraction kickers [25,26], which may be an obstacle when aiming for the 1 MW design output. For this concern, we plan to take several possible measures, such as the introduction of matching resistor and diode to the power supplies for damping beam-induced currents in the kicker magnets, and modification of the coaxial cable lengths for reducing a pile-up of beam-induced currents among the kickers. We also plan to install quadrupole correctors for compensating the beta function beating during injection caused by the edge focus of the injection bump magnets, and add magnetic shields for reducing the leakage field from the extraction beam line DC magnets. Following these hardware upgrades and improvements, the beam commissioning of the upgraded linac will start at the beginning of November 2013. Then, the RCS will start beam test and tuning with the upgraded injection energy of 400 MeV in December 2013, aiming at our final goal of the 1 MW output beam power.

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