BEAM HALO REDUCTION IN THE J-PARC 3-GeV RCS

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Abstract

The RCS beam power ramp-up has well proceeded since the start-up of user program in December 2008. So far the RCS has successfully achieved high intensity beam trials 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 to date. Recently our effort has also been made to improve the quality of the extraction beam, namely to realize low-halo high-power beams. In this paper, recent effort for beam halo reduction in the RCS will be presented.

INTRODUCTION

The J-PARC is a multi-purpose high-power proton accelerator facility [1], 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 as a proton driver to produce pulsed muons and neutrons at the MLF and as an injector to the MR, aiming at 1 MW output beam power.

A negative hydrogen ion beam from the linac is delivered to the RCS injection point, where it is multi-turn charge-exchange injected through a HBC foil over a period of 0.5 ms. The RCS accelerates the injected beam up to 3 GeV at a repetition rate of 25 Hz. With the current injection energy of 181 MeV, the RCS aims at providing more than 0.3 MW output beam power. The linac energy will be upgraded to 400 MeV with the addition of an ACS linac section in 2013 summer-autumn period. After that, the RCS will aim at our final goal of the 1 MW output.

The RCS was beam commissioned in October 2007. Via the initial beam tuning and underlying beam studies [2], the RCS made available for user operation in December 2008 with an output beam power of 4 kW. The RCS beam power ramp-up has well proceeded since the start-up of user program. So far the RCS has successfully achieved high intensity beam trials up to 420 kW at a low-level intensity loss of less than 1% [3], and the output beam power for the routine user program has been increased to 210 kW to date.

Recently our effort has also been made to improve the quality of the extraction beam, namely to realize low-halo high-power beams. This is essential matter especially for the beam injection to the MR, since the MR has a relatively small physical aperture (81π mm mrad) compared with that of the beam transport line to the MLF (324π mm mrad, which is the same as the RCS ring collimator aperture). In the beam transport line to the MR (3-50BT), the collimation system is installed. The aperture of the 3-50BT collimator is typically set at 54$-$60π mm mrad, where a halo 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. In this paper, our effort for beam halo reduction in the RCS will be presented.

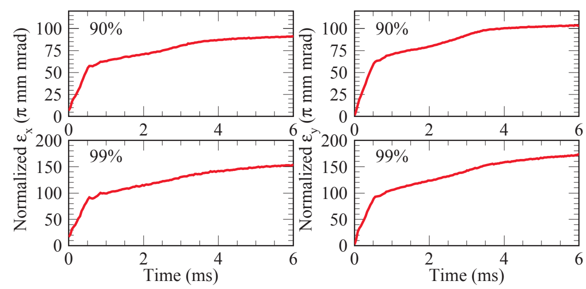

Figure 1: Time evolution of the horizontal (left) and vertical (right) normalized emittances calculated for the first 6 ms, where different emittances encircling 90 and 99% of the macro-particles are plotted.

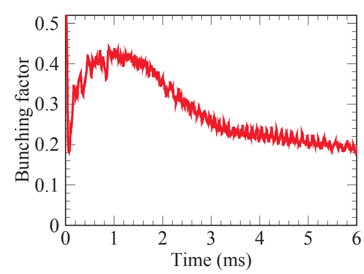

Figure 2: Time evolution of the bunching factor calculated for the first 6 ms.

EMITTANCE GROWTH IN THE LOW ENERGY REGION

The beam loss in the RCS up to 420 kW intensity beam was successfully minimized to less than 1% by making use of transverse and longitudinal injection painting [3]. In transverse painting, 100π-mm-mrad correlated painting (ϵ_{tp}) was applied here. On the other hand, in longitudinal painting [4, 5], the momentum offset injection of -0.2% ($\Delta p/p$) was employed in combination with the superposition of the second harmonic rf with an amplitude of 80% (V_2/V_1) of the fundamental one. The phase sweep from

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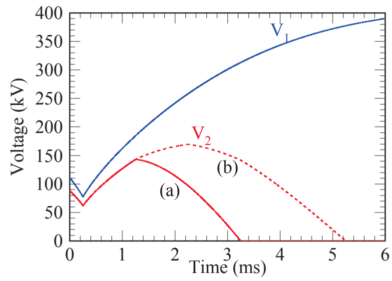

Figure 3: Second harmonic rf voltage patterns with different durations (a) and (b) used for longitudinal painting in the present work.

Table 1: Injection painting parameters applied in the present work

ID	ϵ_{tp} (π mm mrad)	V_2/V_1 (%)	ϕ_2 (degrees)	$\Delta p/p$ (%)
1	100	80 [(a)]	-100 to 0	-0.2
2	–	80 [(a)]	-100 to 0	-0.2
3	–	80 [(b)]	-100 to 0	-0.2
4	100	80 [(b)]	-100 to 0	-0.2

-100 to 0 degrees (ϕ_2) of the second harmonic rf was also applied during injection, which enabled further bunch distribution control through a dynamical change of the rf bucket potential.

Figure 1 shows the time evolution of transverse normalisd emittance for the first 6 ms calculated for a 420 kW intensity beam with the above injection painting parameter. In this figure, one can see remarkable emittance growth after 1 ms. Though this emittance growth hardly contributes to the beam loss in the RCS, it makes a major part of the beam loss at the 3-50BT collimator. Fig. 2 shows the corresponding calculated time dependence of the bunching factor, where the bunching factor is defined as a ratio of (average current/peak current) of the circulating beam, namely it reflects the flatness-level of the beam bunch. By comparing Figs.1 and 2, one can find the emittance growth proceeds following the decrease of the bunching factor after 1 ms. If the bunching factor decreases in this low energy region, a part of the beam particles reaches to the integer lines of $\nu_{x,y} = 6$ (see Fig. 8 given later). On these integer lines, there exist all-order systematic resonances, by which the beam particles suffer from the emittance dilution. If this consideration is right to the point, the emittance growth can be suppressed by minimizing the effects from the integer lines through further charge density control after 1 ms as well as during injection.

BEAM HALO REDUCTION BY IMPROVED INJECTION PAINTING

We have recently performed numerical simulations and experiments for a 420 kW intensity beam, using improved injection painting on the basis of the above consideration. Fig. 3 shows second harmonic rf voltage patterns (a) and (b) used for longitudinal painting in the present work. They have different durations (3−5 ms), in which the shorter pattern (3-ms duration) corresponds to the original one used in Sec. 2. 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 kinds of second harmonic rf durations in Fig. 3 and their combinations with transverse painting. Injection painting parameters tested in the present work are summarized in Table 1, where the parameter ID 1 corresponds to the original one used in Sec. 2.

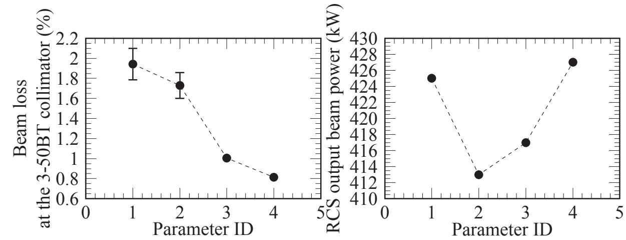

Figure 4: [Left] Painting parameter dependence of the beam loss at the 3-50BT collimator measured for the extracted beam from the RCS, where the horizontal axis corresponds to the painting parameter IDs in Table 1. [Right] Similar dependence of the RCS output intensity measured upstream of the 3-50BT collimator in parallel with the above beam loss measurement.

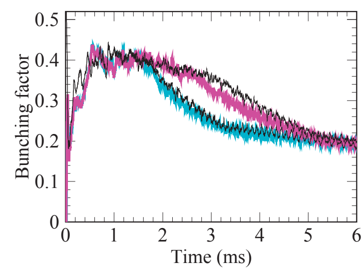

Figure 5: Bunching factor for the first 6 ms measured for the painting parameter IDs 2 (light blue) and 3 (pink) in Table 1, where the corresponding numerical simulation results are plotted by black curves.

The left plot in Fig. 4 shows a painting parameter dependence of the beam loss at the 3-50BT collimator measured for the extracted beam from the RCS, where the horizontal axis corresponds to the painting parameter IDs in Table 1. In this measurement, the 3-50BT collimator aperture was set at 54π (horizontal) and 60π (vertical) mm mrad. That is, 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 whole 3-50BT collimator area [6]. On the other hand, the right plot in Fig. 4 is a painting parameter dependence of the RCS output intensity measured upstream of the 3-50BT collimator in parallel with the beam halo measurement. That is, it reflects the state of the beam survival or beam loss in the RCS. Fig. 5 shows the bunching factor for the first 6 ms mea-

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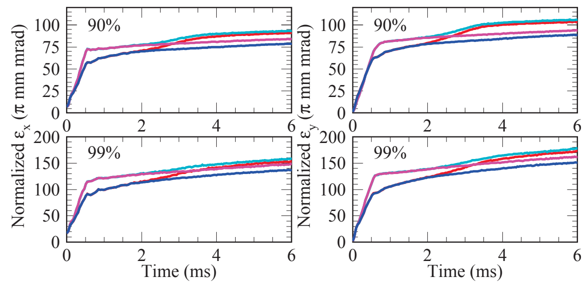

Figure 6: Time evolution of the horizontal (left) and vertical (right) normalized emittances calculated for the first 6 ms with the parameter IDs 1 (red), 2 (light blue), 3 (pink) and 4 (blue) in Table 1, where different emittances encircling 90 and 99% of the macro-particles are plotted for each parameter ID.

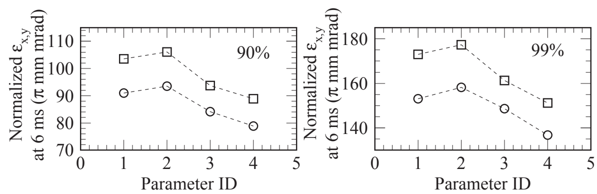

Figure 7: Horizontal (circle) and vertical (square) normalized emittances obtained at 6 ms in Fig. 6, plotted as a function of the painting parameter ID in Table 1.

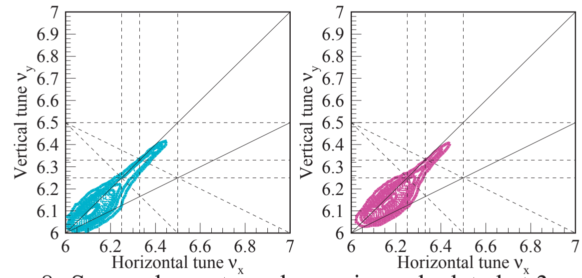

Figure 8: Space-charge tune depression calculated at 3 ms for the parameter IDs 2 (left) and 3 (right) in Table 1, where the bare tunes are set at (6.45, 6.42).

sured for the painting parameter IDs 2 and 3, where the corresponding numerical simulation results are plotted by black curves, which are in good agreement with the measured ones. As shown by the data IDs 2 and 3 in Figs. 4 and 5, longitudinal painting with the longer second harmonic rf duration improved the bunching factor after 1 ms, and significantly decreased the beam halo component, as expected. Transverse painting also displayed the ability to the beam halo reduction in combination with longitudinal painting with the longer second harmonic rf duration, as is evident in the comparison of the data IDs 3 and 4 in the left plot of Fig. 4.

The similar situation was also obtained in the corresponding numerical simulations. Fig. 6 shows the time evolution of transverse normalized emittance calculated for the first 6 ms with the painting parameter IDs in Table 1, in which the normalized emittances obtained at 6 ms are plotted in Fig. 7 as a function of the painting parameter ID. Longitudinal painting with the longer second harmonic rf duration acts to maintain large bunching factor over the first several ms, and to reduce the tune depression after 1 ms as shown in Fig. 8. This process alleviates the influence from the integer lines, leading to the significant emittance growth mitigation observed for the data IDs 2 to 3 in Figs. 6 and 7. This process also assists the effect of transverse painting to the emittance growth mitigation. Transverse painting well suppresses the emittance growth during charge accumulation, but this effect vanishes following the decrease of bunching factor after 1 ms, as shown by the data ID 1 in Fig. 6, because of the influence from the integer lines. The longer second harmonic rf improves this situation, as shown by the data ID 4 in Fig. 6. It is interpreted the empirical painting parameter dependence of the extraction beam halo in the left plot of Fig. 4 reflects such a behavior of the emittance growth in the low energy region in Figs. 6 and 7. In fact, the calculated dependence in Fig. 7 qualitatively well reproduces a trend of the measured one in the left plot of Fig. 4 within the quoted errors.

As shown in Fig. 4, the highest output intensity from the RCS, namely the lowest beam loss in the RCS was obtained both for the parameter IDs 1 and 4, while the beam loss at the 3-50BT collimator was decreased to 0.8% by the parameter ID 4, which corresponds to less than half of the original value of 2% measured for the parameter ID 1. The amount of the extraction beam halo is maintained at sufficiently low level up to 420 kW intensity beam thanks to this improved injection painting. If the RCS delivers the 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).

SUMMARY

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 longer second harmonic rf duration and transverse painting. Though the amount of the extraction beam halo is maintained at sufficiently low level up to 420 kW intensity beam thanks to this manipulation, further effort for beam halo reduction, such as a dynamical tune control over the acceleration process to suppress the emittance growth in the middle and late stage of acceleration, would be necessary in aiming at the 1 MW design output, especially for the beam injection to the MR. Our effort hereafter will be made to get high-quality beams that satisfy the downstream facilities, as well as to minimize the beam loss in the RCS for MW-class intensity beams.

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