

RECENT PROGRESS OF J-PARC RCS BEAM COMMISSIONING - TOWARD REALIZING THE 1-MW OUTPUT BEAM POWER

Hideaki Hotchi for the J-PARC RCS beam commissioning group
 J-PARC center, Japan Atomic Energy Agency, Tokai, Naka, Ibaraki, 319-1195 Japan

Abstract

J-PARC RCS is now in the final beam commissioning phase aiming for the design output beam power of 1 MW. This paper presents our approaches to beam loss issues that we faced on the process of the beam power ramp-up toward 1 MW.

INTRODUCTION

The J-PARC 3-GeV Rapid Cycling Synchrotron (RCS) is the world's highest class of high-power pulsed proton driver aiming at the output beam power of 1 MW [1]. The injector linac delivers a 400-MeV H^- beam to the RCS injection point, where it is multi-turn charge-exchange injected through a 350- $\mu\text{g}/\text{cm}^2$ -thick HBC stripping foil over a period of 0.5 ms. RCS accelerates the injected protons up to 3 GeV with a repetition rate of 25 Hz, alternately providing the 3-GeV proton beam to the Material and Life Science Experimental Facility and to the 50-GeV Main Ring Synchrotron by switching the beam destination pulse by pulse.

Recently the hardware improvement of the injector linac has been completed, by which the injection energy was upgraded from 181 MeV to the design value of 400 MeV in 2013, and then, the injection peak current was upgraded from 30 mA to the design value of 50 mA in 2014. In October, 2014 after completing these series of injector linac upgrades, RCS started the final stage of beam commissioning aiming for the design output beam power of 1 MW. This paper presents our approaches to beam loss issues that we faced on the process of the beam power ramp-up toward 1 MW.

550-kW BEAM TEST CONDUCTED AFTER THE INJECTION ENERGY UPGRADE (RUN#54)

In April, 2014 (Run#54), RCS conducted a 550-kW high intensity beam test with the upgraded injection energy of 400 MeV, using a 0.5 ms-long injection pulse with a peak current of 24.6 mA and a chopper beam-on duty factor of 60%. In this beam test, the operating point was set at (6.45, 6.42), where systematic beam loss measurements were performed with various injection painting parameters, and compared with the old data taken with the lower injection energy of 181 MeV.

In order to minimize space-charge induced beam loss, RCS employs injection painting for both transverse and longitudinal phase spaces [2]. On the transverse plane, correlated painting with a painting emittance of 100π mm mrad (ϵ_{tp}) was applied in this beam test. On the other

hand, for longitudinal painting [3,4], the momentum offset injection of 0.0, -0.1 and -0.2% ($\Delta p/p$) was tested in combination with superposing a 2nd harmonic rf with an amplitude of 80% (V_2/V_1) of the fundamental rf. As an additional control in longitudinal painting, the phase sweep of the 2nd harmonic rf was also employed during injection from -100 to 0 degrees (ϕ_2) relative to that of the fundamental rf.

Painting parameter ID

Parameter ID	ϵ_{tp} (π mm mrad)	V_2/V_1 (%)	ϕ_2 (degrees)	$\Delta p/p$ (%)
1	—	—	—	—
2	100	—	—	—
3	—	80	-100	—
4	—	80	-100	-0.1
5	—	80	-100	-0.2
6	100	80	-100	—
7	100	80	-100	-0.1
8	100	80	-100	-0.2

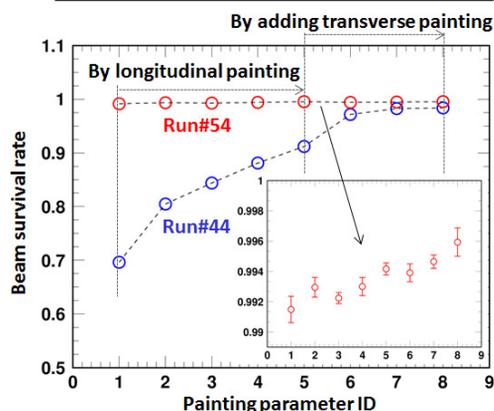


Figure 1: Beam survival rates measured with various combinations of transverse and longitudinal painting (IDs 1 to 8), where the red circles correspond to the data taken with the upgraded injection energy of 400 MeV with a beam intensity of 553 kW, while the blue ones are the old data taken with the lower injection energy of 181 MeV with a similar beam intensity of 539 kW.

Figure 1 shows the beam survival rates measured with various combinations of transverse and longitudinal painting (IDs 1 to 8). In this figure, the red circles correspond to the data taken in this beam test with a beam intensity of 553 kW (4.60×10^{13} ppp), while the blue ones are the old data (Run#44 in November, 2012) taken with the lower injection energy of 181 MeV with a similar beam intensity of 539 kW (4.49×10^{13} ppp). As shown by the blue circles, the larger parameter dependence was observed for the lower injection energy of 181 MeV, since the space-charge effect is more critical. In this case, 30%-big beam loss appeared with no painting. But, this beam loss was drastically decreased from ID 1 to ID 5 by longitudinal painting, and from ID 5 to ID 8 by adding

transverse painting. This situation was further improved, as shown by the red circles. This reflects the further space-charge mitigation by a factor of 0.34 achieved by the injection energy upgrade from 181 MeV to 400 MeV. The parameter dependence for the red circles is nearly flat, but it also has a similar dependence to that for the blue circles, as shown in the inset in Fig. 1.

These experimental data clearly shows the enormous gain from the injection energy upgrade as well as the excellent ability of injection painting.

1-MW BEAM TESTS CONDUCTED AFTER THE INJECTION PEAK CURRENT UPGRADE (RUN#57 & #60)

In October, 2014 (Run#57), RCS conducted the first 1-MW trial with the upgraded injection peak current of 50 mA at the same operating point of (6.45, 6.42) and with the injection painting parameter of ID8. As already reported in Ref [5], the beam acceleration of up to 773 kW was achieved with no significant beam loss, but the 1-MW beam acceleration was not reached in this beam test due to the over current of the anode power supply of the RF system; the RF system suddenly tripped when the beam intensity got to over 800 kW.

After this beam test, several quick measures were taken against the RF trip. The resonant frequency of the RF cavity was shifted by removing a capacitor, by which the anode current required for the 1-MW beam acceleration was reduced. In addition, the interlock level was turned up to use all of margin of the anode power supply. In January, 2015 (Run#60) after taking these quick measures, we successfully achieved the 1-MW beam acceleration. As shown in Fig. 2, there is no terrible beam loss, but some un-localized beam loss still remains at the arc sections.

The upper plot in Fig. 3 shows the BLM signals at the high dispersion area in the arc section measured over the full acceleration time of 20 ms for various beam intensities from 568 kW to 1010 kW. As shown in the figure, there is no significant beam loss for the beam intensity of up to 825 kW, but the beam loss appeared for the 944-kW and 1010-kW intensity beams, as shown by the blue and red plots. These beam losses, the blue and red ones, can be interpreted as longitudinal beam loss arising from beam particles leaking from the RF bucket. Such beam particles suffer from large momentum excursions and most of them are lost at the high dispersion area, not at the collimator located in the dispersion-free straight section. This type of beam loss should be cured by adjusting the RF voltage. But now the anode power supply of the RF system reaches the limit, and there is no margin at all. For this issue, we plan to increase the anode power supply using this summer maintenance period [6]. This longitudinal beam loss will be suppressed by this hardware improvement.

On the other hand, the lower plot in Fig. 3 shows the similar BLM signals at the collimator section. As shown in the figure, the beam loss at the collimator section

appears only for the first 1-ms region. This remaining beam loss is mainly from foil scattering during charge-exchange injection. As to the other beam loss, such as space-charge induced beam loss, it was well minimized by injection painting even for the 1-MW beam. The remaining beam loss at the collimator for the 1-MW beam was estimated to be 0.17%. This corresponds to 240 W, which is much less than the collimator limit of 4 kW.

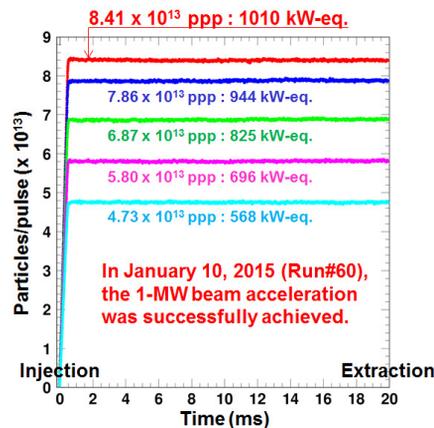


Figure 2: DCCT data over the full acceleration time of 20 ms for various beam intensities from 568 kW to 1010 kW.

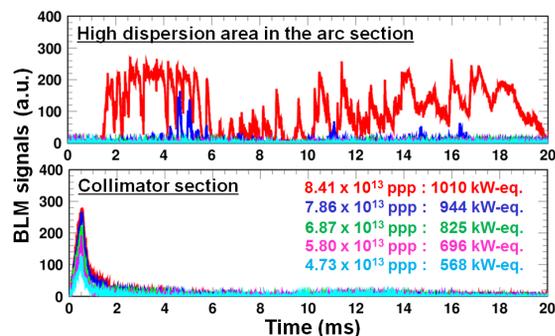


Figure 3: BLM signals at the arc and the collimator sections measured over the full acceleration time of 20 ms for various beam intensities from 568 kW to 1010 kW.

RECENT EFFORTS FOR FURTHER BEAM LOSS MITIGATION (RUN#62)

As mentioned above, the beam loss other than foil scattering beam loss was well minimized. Thus the next issue is to further reduce the remaining foil scattering beam loss. Most of the foil scattering beam loss is well localized at the collimators, but some of them with large scattering angles cause un-localized beam loss, making relatively high machine activations near the charge-exchange foil. It was around 15 mSv/h on the chamber surface for the 400-kW routine beam operation. This machine activation is expected to be within the permissible level even if assuming the 1-MW routine beam operation, but we tried further beam loss mitigation to keep the machine activation as low as possible.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2015). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI.

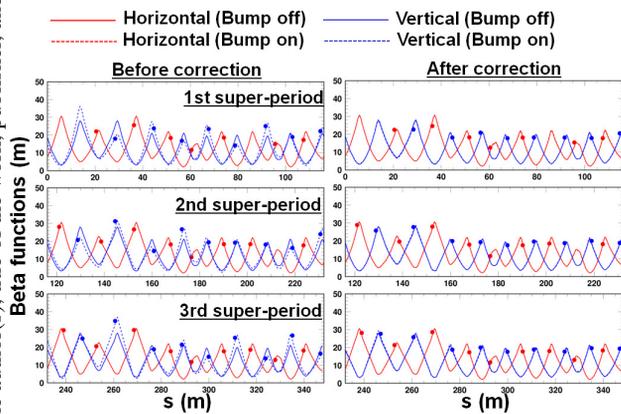


Figure 4: Beta functions measured without (left) and with (right) the addition of the quadrupole correctors.

The foil scattering beam loss can be reduced by larger transverse painting, especially on the horizontal plane. As described in Ref. [2], horizontal painting is performed by closed orbit variation. Thus the circulating beam more rapidly escapes from the foil in going to larger horizontal painting. But such a large transverse painting had not been realized until recently due to beta function beating caused by the edge focus of the injection bump magnets.

In RCS, beam injection is performed with a time dependent horizontal local bump orbit by using 8 sets of rectangular pulse dipole magnets, where the edge focus is generated at the entrance and exit of each injection bump magnet. As shown in the left plot in Fig. 4, the edge focus makes 30% big beta function beating on the vertical plane during injection. This beta function beating causes a distortion of the lattice super-periodicity and additionally excites various random betatron resonances. These random resonances cause an additional shrinkage of the dynamic aperture during injection, and lead to extra beam loss when applying large transverse painting.

In order to solve the above issue, we have recently installed 6 sets of pulse type quadrupole correctors, to compensate beta function beating and to minimize the effect of the random resonances through the recovery of the super-periodic condition [7]. As shown in Fig. 4, vertical beta function beating was successfully corrected by the quadrupole correctors, while keeping the super-periodic condition on the horizontal plane. Figure 5 shows the BLM signals at the collimator section. The top plot is for the original transverse painting with the painting emittance of 100π mm mrad. On the other hand, the middle plot is for the larger horizontal painting area of 150π mm mrad. In this case, significant extra beam loss appeared. But this beam loss was well mitigated as expected by introducing the quadrupole correctors, as shown by the bottom plot.

The 500-kW routine beam operation is now conducted using large transverse painting achieved with the addition of the quadrupole correctors. By the large transverse painting and also by re-optimizing the foil position, the foil hitting rate was drastically reduced; the number of foil hits per particle was reduced by a factor of 0.69 by re-

optimizing the foil position, and it was further reduced by a factor of 0.59 by expanding horizontal painting area. By these attempts, the residual dose level near the charge exchange foil was decreased to less than half as expected.

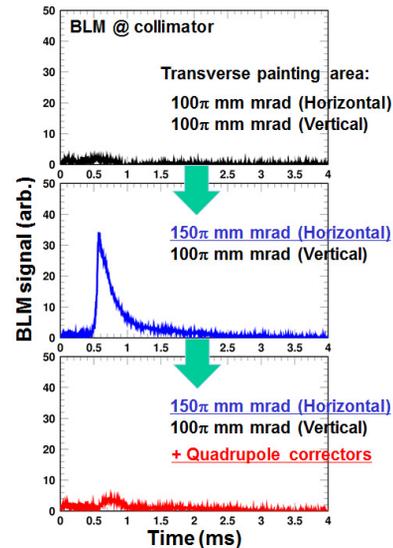


Figure 5: BLM signals at the collimator section measured with a 670-kW intensity beam.

SUMMARY

We started 1-MW beam tuning from October, 2014, and successfully achieved 1-MW beam acceleration in January, 2015. Major part of beam loss, such as space-charge induced beam loss, was well minimized by the injection painting technique. The remaining beam loss is mainly from foil scattering during charge-exchange injection. In addition, very recently, the transverse painting area was successfully expanded by correcting beta function beating caused by the edge focus of the injection bump magnets, by which the foil scattering beam loss was further reduced. By such efforts, the beam loss is now at the permissible level for the 1-MW routine beam operation, except for the longitudinal beam loss appearing for the higher intensity beam of > 900 kW.

The 1-MW routine beam operation will be ready after this summer maintenance period, namely by solving the remaining longitudinal beam loss after completing the RF anode power supply upgrade. The output beam power for users is now gradually increased by a 100-kW step every one month. If this scenario is going well, the 1-MW routine beam operation is to start up from the next spring via the summer maintenance period.

REFERENCES

- [1] H. Hotchi et al., PRST-AB **12**, 040402 (2009).
- [2] H. Hotchi et al., PRST-AB **15**, 040402 (2012).
- [3] F. Tamura et al., PRST-AB **12**, 041001 (2009).
- [4] M. Yamamoto et al., NIM, A **621**, 15 (2010).
- [5] H. Hotchi, Proc. of HB2014, MOXLR02 (2014).
- [6] M. Kinsho, in These Proceedings, THPF044.
- [7] H. Hotchi et al., NIM, A **778**, 102 (2015).