EXPERIENCE WITH J-PARC RCS INJECTION AND EXTRACTION SYSTEMS

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Abstract

The 3 GeV RCS (rapid cycling synchrotron) of J-PARC (Japan proton accelerator research complex) is in the beam commissioning stage at present. In order to achieve 1 MW output beam power, the injection and extraction systems play two major roles in RCS. At the injection RCS is designed to utilize the painting injection process in both transverse and longitudinal planes so as to mitigate the space-charge force, while the whole extraction channel with enough wider aperture is considered for not to lose even a single particle during extraction period. In the recent beam commissioning of RCS, we have started studying the painting injection, especially in the transverse plane. This paper summarizes the experience with RCS injection and extraction systems with the results obtained so far in the commissioning stage, where a comparison of the design parameters of all magnets to that with the commissioning parameters, the beam loss issues in the injection and extraction areas are also discussed.

INTRODUCTION

Starting from the end of year 2007, the beam commissioning of RCS is in good progress [1]. The design goal of RCS is to achieve a output beam power of 1 MW with the injection and extraction energy of 0.4 and 3 GeV, respectively, and with 8.3×10^{13} protons per pulse at a repetition rate of 25 Hz [2]. However, the injection energy at this stage is 181 MeV and the output beam power at 3 GeV extraction is expected to be 0.6 MW. Fig. 1 shows the general layout of the RCS, which is a three-fold symmetric lattice with a circumference of 348.333 meters. Each super-period consists of two 3-DOFO arc modules with missing bends and a 3-DOFO insertion. The three insertions are named as I, E and R and are dispersion free. The injection and the transverse collimation systems are located in the I insertion, extraction system in the E insertion and RF cavities is in the R insertions. The H^- charge-exchange injection system occupies the first and a quarter of the 2nd cell, where the collimation system occupies the rest of the I insertion. The detail of the RCS collimation system including the commissioning results can be found in Ref. [3]. In order to reduce the effect of space charge, the beam density at the low energy is controlled by utilizing painting injection in the transverse direction and a RF operation in the longitudinal direction, where the nominal painting area is 216π.mm.mrad. Recently, beam commissioning of RCS with painting injection has been started. In this paper together with the experience with RCS injection and extraction systems, the preliminary result with painting injection study is also reported.

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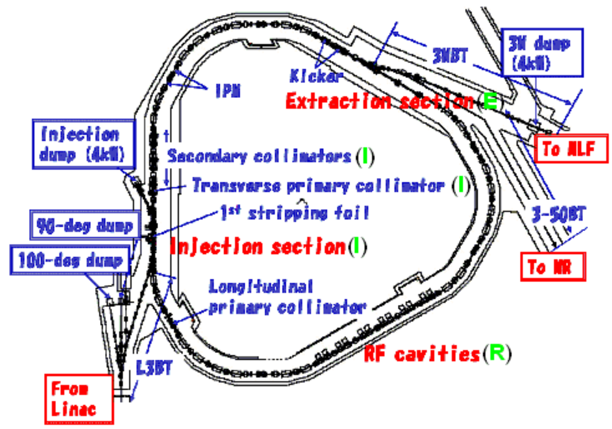

Figure 1: Layout of RCS. The injection and the transverse collimation system are located in the I insertion, extraction in the E insertion and RF cavities are in the R insertion.

RCS INJECTION AND EXTRACTION SYSTEMS

Fig. 2 shows the general layout of RCS injection and the successive H^0 dump line. The total length of this transport line starting from the end of L3BT (Linac-to-3GeV-Beam-Transport) line (QM79) to the entrance of the H0 beam dump is about 26 m. The design H^- injection system in RCS comprises eight closed-orbit bump magnets in the horizontal direction (SB1∼4,PB1∼4) and two bump magnets in the vertical direction (VB1∼2). Among eight closed-orbit bump magnets, four are the horizontal bump magnets (SB1∼4) and called the shift bump magnets. They are placed in an uninterrupted drift space between two quadrupole magnets (QFL and QDL) and have the role to form a constant closed bump orbit during injection. The other four (PB1∼4) are used for the painting injection to sweep the closed-orbit in the horizontal plane by using the decay pattern of the magnetic field of these magnets and thus called the paint bump magnets. First two of them are located at the upstream QFL and the other two are at the downstream of the QDL. Painting in the vertical plane is done by sweeping directly injection beam angle with two vertical paint bump magnets (VPB1∼2) placed in the L3BT line. The first one (VPB1) is a main painting magnet located at the phase difference of π from the charge-exchange foil, where the 2nd one (VPB2) is auxiliary type and used to adjust the phase difference from the main

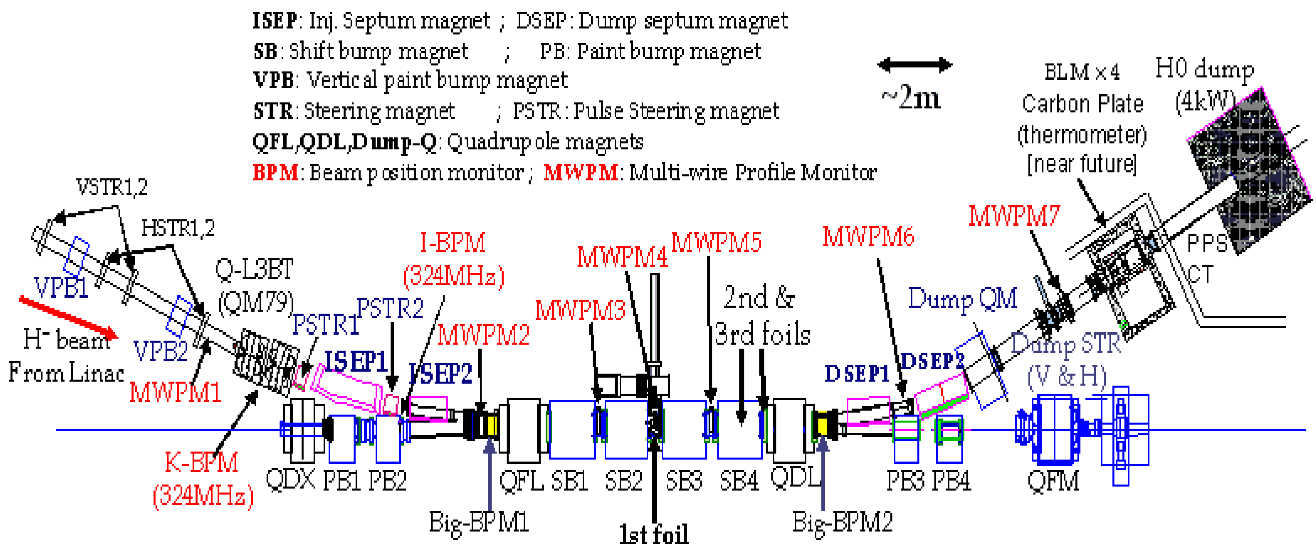

Figure 2: Layout of the RCS injection and the successive H0 dump line. Four horizontal shift bump magnets (SB1∼4) produce a constant closed-orbit, while in addition, another four paint bump magnets (PB1∼4) in the horizontal direction and two vertical paint bump magnets (VPB1∼2) in the vertical direction produce time dependent fields for the painting injection.

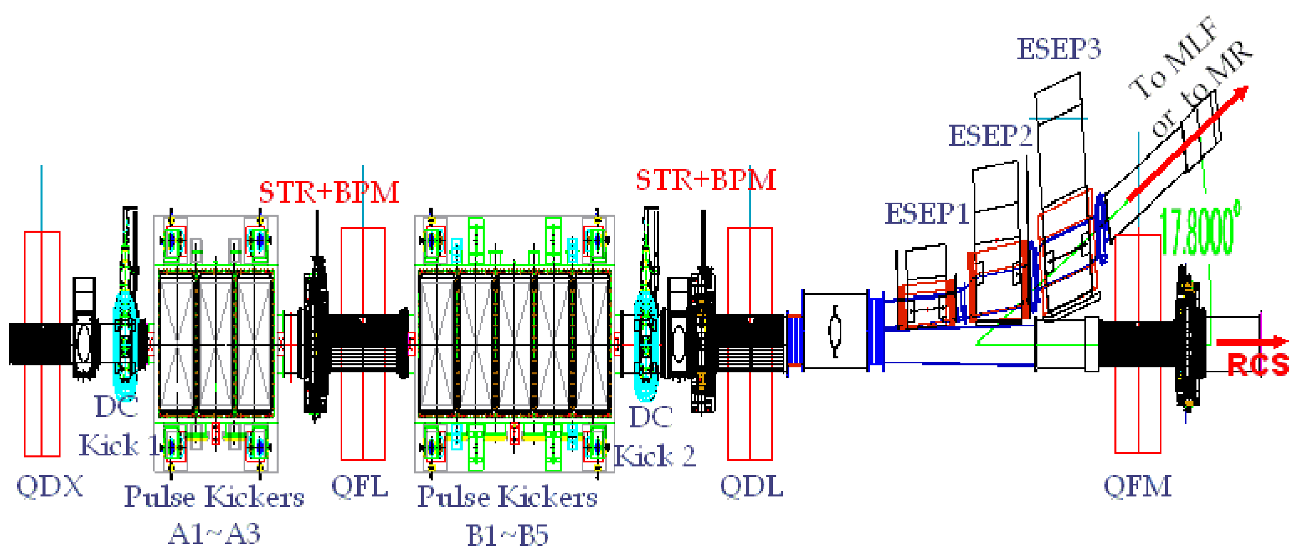

Figure 3: Layout of the RCS extraction system. Extracted beam of energy 3 GeV is delivered to the spallation neutron target or to the MR. A set of eight pulse kickers (A1∼A3,B1∼B5) together with three DC septum magnets (ESEP1,2,3) perform the beam extraction at the 3 GeV.

painting magnet to the foil position. In RCS, so-called both correlated and anti-correlated painting can be done by changing the excitation pattern of the vertical painting magnets [4]. There are also two septum magnets in the injection line (ISEP1,2) and two other in the H0 dump line (DSEP1,2), several DC steering magnets for the beam orbit control and a focusing quadrupole in the dump line (Dump-QM). The purpose of two pulse steering magnets (PSTR1,2) in the injection line is to change the painting area (smaller) for the MR beam (144π.mm.mrad) as compared to that for the neutron target beam (216π.mm.mrad) by changing angle of the injection beam at the foil and will be available in the next phase. By changing the excitation level of shift bump magnets, the beam position at the foil can be kept unchanged so as the foil position will also be unchanged from the optimum size. As for the beam diagnostic system in the injection and H0 dump line, it is mainly consists of a set of seven MWPMs (multi-wire profile monitor) placed almost between magnets. There are also four BPMs (beam position monitors) (I-BPM, K-BPM, Big-BPM1,2). The advantage of the using MWPM is that both the beam position and profile can be known at the same time.

There are three charge-exchange foils in the RCS injection. The main (1st) carbon foil with a thickness of 200 μg/cm^2 is located almost at the center of the four shift bump magnets. The charge-exchange efficiency at the present beam energy of 181 MeV is estimated to be 99.6%. The rest of 0.4% is mainly the partially stripped H^0, which are then stripped further to H^+ by the 2nd foil placed in the middle of SB4 and driven to the H0 dump. The fraction of the unstripped H^- beam is expected to be negligibly small. But for any unstripped H^- beam, the 3rd foil is placed at the exit of SB4 so as to be converted to H^+ and driven to the H0 dump. The thickness of both 2nd and 3rd foil are designed to be 500 μg/cm^2. The thickness of the 1st foil will be changed to 300 μg/cm^2 at the injection beam energy of 400 MeV, where the stripping efficiency is estimated to be 99.7%. In the design estimation, unless any damage of the 1st stripping foil or any fault, the main component of the waste beam that goes to this dump is the partially stripped H^0 one (after converting to H^+ by the 2nd foil). The name of the dump is thus called the H0 dump. The overall aperture of the injection and the H0 dump line is kept as 30π.mm.mrad with additional 9 mm considering several effects like, the modulation of beta function, dispersion function and the orbit distortion, where injection beam emittance (4σ) with 181 MeV injection is expected to be 6π.mm.mrad.

Fig. 3 shows the general layout of RCS extraction system. As the extracted beam energy is as high as 3 GeV, much attention was paid for designing the extraction system so as to have no uncontrolled loss in practical. The overall extraction system has an aperture of 324π.mm.mrad (same as the primary collimator) plus additional 9 mm considering several factors as also considered for the injection-H0 dump line. The extraction of the 3 GeV beam is performed by a set 8 pulse kicker system (A1$\sim$A3,B1$\sim$B5) and a set of 3 DC septum magnets (ESEP1$\sim$3). The two DC kickers (DC KICK1,2) seen in fig. 3 are used together with 3 septum magnets for the beam extraction with no circulation (so-called 1/3 mode) for various beam studies in the commissioning stage. As seen in the figure, there is almost no beam diagnostic system in the extraction systems mainly due to the space limitation. Two BPMs seen in the figure are mainly to measure the circulating orbit and are not so effective for the extraction orbit measurement as the extracted orbit passes through very off-center of the beam duct. The extraction orbit control is then considered to be done with beam positions measured by BPMs in the 3NBT (3GeV-to-Neutron-Beam-Transport) line. During the beam commissioning of RCS, the extracted beam is driven to the so-called 3NBT dump located at about 40 m far from the exit of RCS last extraction septum magnet.

BEAM COMMISSIONING RESULTS OF RCS INJECTION AND EXTRACTION

The beam commissioning of RCS was started with the injection and the successive H0 dump line and was called as the H0 dump mode. The incoming H^- beam from the Linac of energy 181 MeV was converted to H^+ by the 3rd foil and driven to the H0 dump. The injection and the H0 dump line beam orbit was clearly established from the position information of 3 BPMs (I-BPM,Big-BPM1,2) and mean positions of the beam profiles measured by the 6 MWPMs. The hardware configurations and properties of these MWPMs as well as the profile reconstruction method can be found in ref. [5, 6]. Fig. 4 shows the horizontal and vertical beam profiles measured by the MWPM4 along the wire directions (u and v). The mean positions and widths in both planes were then converted to the x (horizontal) and y (vertical) directions by using equations 1 and 2 as,

$$\begin{bmatrix} u \\ v \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \tag{1}$$

and

$$\begin{bmatrix} \sigma_u^2 \\ \sigma_v^2 \end{bmatrix} = \begin{bmatrix} \cos^2\theta & \sin^2\theta \\ \sin^2\theta & \cos^2\theta \end{bmatrix} \begin{bmatrix} \sigma_x^2 \\ \sigma_y^2 \end{bmatrix} \tag{2}$$

where, u and v are the mean positions measured along the wire directions, σ_u and σ_v are their widths (1σ), respectively. The mean positions in the horizontal and vertical planes are represented by x and y, respectively, where σ_x and σ_x are their widths (1σ). The wire inclination is represented by θ, which is 17.7°.

The profile widths (1σ) in the horizontal and vertical plane were found be 1.4 mm and 1.7 mm, respectively. The geometrical position of the MWPM4 is just 56 mm upstream from the 1st foil and thus the beam profile measured at the MWPM4 was considered as the beam profiles at the 1st foil, whereas the beam directions or derivatives at the

1st foil was extracted from the measured beam positions at MWPM3 and 5. Fig. 5 shows the simulated (design) together with the measured (red circles) beam orbit of the injection to the H0 dump line in the horizontal direction for the so-called center injection mode. The measurement was done with six MWPMs and three BPMs. The simulation was done based on a model using SAD (Strategic Accelerator Design) [7], where in the injection line, ISEP1 and ISEP2 were adjusted in order to get the measured beam position and inclination at the foil and in the dump line, DSEP1 and DSEP2 were adjusted so as to get the beam positions measured at MWPM6 and MWPM7, respectively. However, the measured orbit was found to match in all 9 measured location as seen in the figure. The parameters used in the real beam commissioning gives here the difference with the design stage parameters. Table 1 represents a comparison of the design stage and the beam commissioning parameters of four septum magnets in the RCS injection-H0 dump line. Except ISEP2, the difference with all other 3 septum magnets are found to be acceptable by considering several points like, the uncertainty of the measurement of injection beam position and inclination at the initial point (upstream of ISEP1, which can't be measure directly with present monitor's availability), the fluctuation of the shift bump flat-top ($\pm 1\%$) and the resolution of monitors. Concerning the big discrepency with ISEP2, the detail study is on going including the field calculation along the present center injection orbit, which could't be measured because the orbit passes through the very off-center of ISEP2 as unfortunately two other magnets (PSTR1,2) were not available at the present stage. A bit more detail experimental data also necessary for the final conclusion.

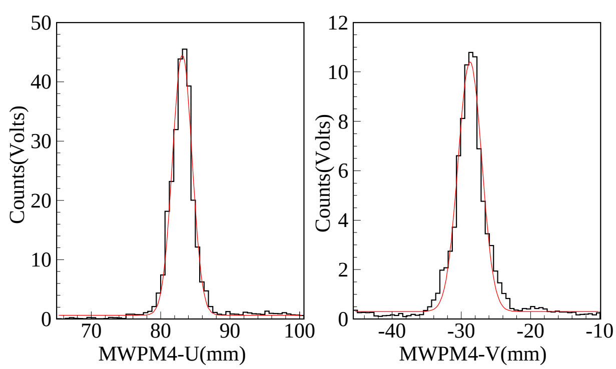

Figure 4: Beam profiles at the RCS injection point measured by MWPM4 along the wire directions (u and v plane). The mean positions and profile widths were then converted to the horizontal (x) and vertical (y) planes taking into account of the wires inclination of 17.7° and by using equations 1 and 2. The profile widths (1σ) were found to be 1.4 mm and 1.7 mm for the horizontal and vertical planes, respectively.

Unlike injection, there are practically no monitors in the extraction system for the extraction orbit measurement and

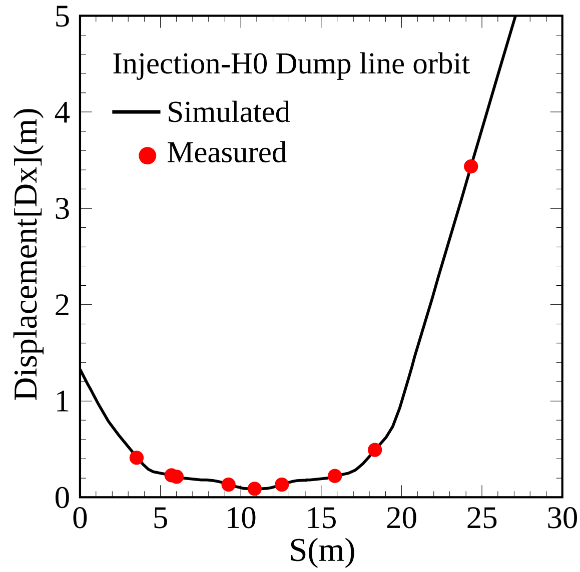

Figure 5: Measured injection and the H0 dump line orbit (red dots) on the top of the simulated one (solid line). The orbit was measured with six MWMPs and three BPMs as located in fig. 2. See text for detail.

Table 1: Comparison of the design (θ_{Degn}) and the beam commissioning (θ_{Comm}) parameters (bending angle) of four septum magnets in the RCS injection-H0 dump line for the present center injection orbit. A comparatively big difference concerning with ISEP2 is under study. See text for detail.

Magnet	θ_{Degn}[mrad]	θ_{Comm}[mrad]	**Diff** [%]
ISEP1	107.0	110.0	2.80
ISEP2	160.4	173.8	8.35
DSEP1	146.4	144.0	-1.66
DSEP2	311.4	317.4	1.93

thus may be one major difficult part for the orbit control in a small step. In the present beam commissioning of RCS, the extraction orbit is controlled by looking the beam positions measured by the BPMs in the 3NBT line. Although detail comparison same as the injection system cannot be done here, the overall agreement with the design stage parameters were found to be quite consistent with the beam commissioning parameters. The extraction orbit control for any change of the RCS parameters was done using only with the extraction septum 2 and 3. As for the beam stability, all three DC septum magnets were found exactly stable. The fluctuation of the pulse kickers flat-top was found to be as low as $\pm 0.2\%$, for which the orbit distortion at the exit of ESEP3 can be ± 0.1 mm at maximum and is negligible. A detail commissioning result with RCS extraction kicker system can be found in Ref. [8]. The stability of the extraction orbit even with present comparatively low intensity beam was found to be quite good as seen in figure 6, where the extraction obit was measured by several BPMs for a couple of hours [9]. The mean position of the beam center was found be to within ± 1 mm with a maximum standard deviation (σ) of 0.67 mm and 0.69 mm in the horizontal and vertical planes, respectively.

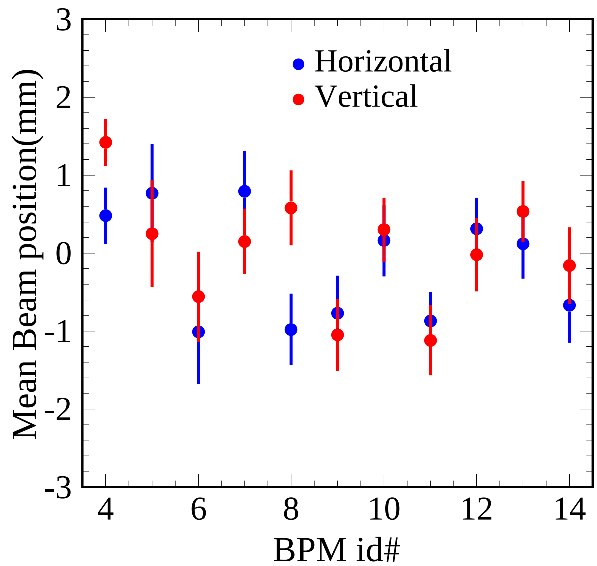

Figure 6: Stability of the extracted beam by measuring the mean of the beam center positions (blue: horizontal, red: vertical) so as the standard deviations (solid lines) as a function of several BPMs in the extraction line. The standard deviation (σ) of the mean position at maximum even with present low intensity beam was 0.67 mm and 0.69 mm in the horizontal and vertical planes, respectively First 4 BPMs were noisy and thus excluded from the analysis.

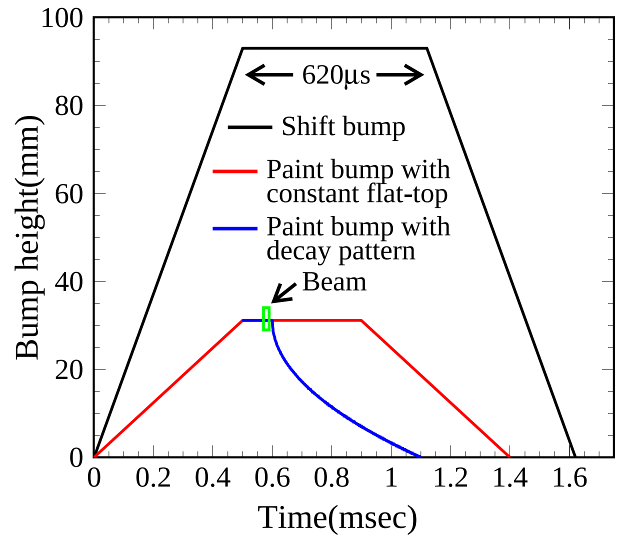

Figure 7: Schematic view of the bump patterns used for the RCS injection. The black line is for the shift bump magnets produce always a constant flat-top and used for the center injection, where on the top shift bump magnets, paint bump magnets were excited for both constant flat-top (red) and decay pattern (blue curve) according to the painting injection study. The sum of the height of shift bump and paint bump was 124 mm for a painting area of 100 π.mm.mrad. The footprint of the painting injection using the decay pattern of the paint bump was done at six different timing by delaying (or shifting) the pattern with a step of 100 μs, where a single pulse beam from the Linac was injected. The timing of the beam with respect to the shift bump was unchanged during the painting injection study as shown in the figure.

PAINTING INJECTION STUDY

Recently we have started studying the painting injection in RCS. As stated earlier, in order to realize a high output beam power, the beam density at the injection energy is controlled by utilizing a painting injection [500μs (235 turns with 181 MeV injection)] in the transverse plane and a RF operation mode in the longitudinal plane so as to defuse the space charge effect. In the first stage, the response and the balance adjustment of all horizontal and vertical paint bump magnets with beam were studied. In the horizontal plane, the balance adjustment were done by measuring the closed-orbit distortion (COD) caused by the imbalance of four paint bump magnets during the time they are on. If the bump orbit is closed perfectly, there will not be distortion of the closed-orbit outside the bump orbit. As for the vertical plane, the balance of two paint bump magnets were done by measuring the injection beam position and inclination at the foil using MWPM 3 and 4. The next stage was to reconstruct so as to identify the phase space coordinate of the injection beam relative to the closed-orbit at the injection point for the painting injection. It was done at first with paint bump of constant flat-top pattern with several painting area and then with a design decay pattern. Fig. 7 shows a demonstration of such patterns of the paint bump magnets together with the shift bump magnets. An accurate reconstruction of the phase space coordinate during the painting injection period allows one to optimize and control the painting area so as for a deep understanding of the painting process as well. To do so, we have developed two independent methods in RCS. The first method (method 1) using a BPM pair in the ring located completely in the drift space and with a single pass (turn-by-turn) mode. In RCS, there are such two pairs of BPMs; the first pair (pair 1) is located in the extraction straight section, while the second pair (pair 2) is located in the RF straight section. Two BPMs in each pair are located at a distance of about 5.5 m. After subtracting the ring COD at each BPM, the measured phase space coordinate from each pair were transferred to the injection point (1st foil) using a calculated transfer matrix so as to get the initial phase space coordinate at the injection point as demonstrated by the equation 3,

$$\begin{bmatrix} X_{BPM} \\ \\ X'_{BPM} \end{bmatrix} = \begin{bmatrix} \mathbf{M}^n \end{bmatrix} \begin{bmatrix} \mathbf{M}_{1stFoil \rightarrow BPM} \end{bmatrix} \begin{bmatrix} X_{Foil} \\ \\ X'_{Foil} \end{bmatrix} \quad (3)$$

where X_{BPM} and X'_{BPM} are the phase space coordinates of the circulating beam center measured with a pair of BPM. X_{Foil} and X'_{Foil} are the initial phase space coordinates of the injection beam at the injection point and has to be obtained. $\mathbf{M}_{1stFoil \rightarrow BPM}$ is a transfer matrix from the injection point to the 1st BPM of each pair and can be express as

$$\mathbf{M}_{Foil \rightarrow BPM} = \begin{bmatrix} \mathbf{a}_{11} & \mathbf{a}_{12} \\ \\ \mathbf{a}_{21} & \mathbf{a}_{22} \end{bmatrix} \quad (4)$$

$\mathbf{M}^n$ is a transfer matrix for n turns in the ring starting from the 1st BPM of each pair, which can be express by the following equation,

$$\mathbf{M}^n = \begin{bmatrix} \mathbf{cos}(\phi) + \alpha \mathbf{sin}(\phi) & \beta \mathbf{sin}(\phi) \\ \\ -\gamma \mathbf{sin}(\phi) & \mathbf{cos}(\phi) - \alpha \mathbf{sin}(\phi) \end{bmatrix} \quad (5)$$

where, $\phi = 2\pi n \Delta\mu$, n corresponds to the turn number and $\Delta\mu$ is the fraction of betatron tune. α, β and $\gamma (= \frac{1+\alpha^2}{\beta})$ are called as twiss parameters. As for the transfer matrices, a calculated model which found to reproduce well the measured optics was used.

As for the 2nd method (method 2), phase space coordinates at the injection point was extracted by measuring betatron response matrix and by detecting the real and imaginary part of the betatron sideband peak measured with a tune BPM spectrum placed at the end of extraction straight section [10]. In this paper, results obtained mainly by using method 1 has been discussed.

The data was taken simultaneously for both methods with RCS of DC storage mode and only a single pulse from the Linac was injected to the RCS. As the beam position measured by BPM gives only the beam center of the whole bunch, the multi-turn injection is thus gives a collective information and almost impossible to extract the correct information needed for this purpose. Injecting only a single pulse was also needed for the 2nd method in order to clearly observe the betatron oscillation. The peak current of the Linac beam was as high as 30 mA in order to gain the signal over the noise as only a single pulse was injected. As for the 1st method, two BPMs completely in the drift space give an accurate and direct phase space information of the beam center and turn-by-turn information allows one to trace for every single turn. Once the ring optics is measured, this method is very fast and straight forward in addition to the accuracy.

In order to check the validity as well as consistency of both methods the first trial was made to correct the injection error. The injection error means here the offset of the injection beam with respect to the closed-orbit at the injection point and thus the correction means a matches of the injection to closed-orbit at the injection point in both horizontal and vertical directions so as the betatron oscillation gets smaller. Both methods gave very similar results for both horizontal and vertical offsets of the injection beam so as well corrected by using septum and vertical steering magnets in the horizontal and vertical directions, respectively. The betatron oscillations were reduced to be minimum in both directions, which was then also confirmed by looking mountain views of the beam profiles measured by ionization profile monitors (IPM) as can be seen in ref. [1].

Although the design painting area in RCS is 216 π.mm.mrad but for the systematic understanding in the beginning, we choose to study for three different painting areas of 100, 150 and 200 π.mm.mrad, where the painting areas of the beam center trajectory were expected to be 75, 124 and 175 π.mm.mrad, respectively by considering the calculated circulating beam twiss parameters at the foil. At first in order to fix the top excitation level of paint bump magnets for the desired painting injection area, the horizontal and vertical paint bump magnets were studied separately and excited with a constant flat-top (Fig. 7). Once a top of the excited level is fixed, the decay pattern for the painting injection time of 500μs can easily be made using design functions, which are basically a square root function of time [2] (Fig. 7, blue curve). Fig. 8 shows normalized phase space plots of the horizontal beam center measured with BPM turn-by-turn mode, where the plotted data were for first 30 turns. In this mode, the injection beam was on the center injection orbit but the horizontal paint bump magnets were excited with a constant flat-top on the top of the shift bump magnets for painting areas of the beam center trajectory with 75(black), 124(red) and 175(green) π.mm.mrad, respectively, which can be considered as an equivalent to the horizontal offset injection. As expected, each plot looked like a circle and thus the emittance of the beam center trajectory was extracted from the area of each circle. From a statistical analysis, the emittances for three cases were found to be 78.8$\pm$2.1 (black), 113.3$\pm$3.2 (red) and 159.0$\pm$4.3 π.mm.mrad (green),respectively, and were almost consistent with expectation. The phase space coordinate of the center of the injection beam at the injection point was then extracted by using equation 3. Those were also found to be consistent by comparing with the phase space coordinates for which the paint bumps were excited in each case. It is thus reflects the accuracy of the present method together with the calculated transfer matrix which was used. The injection septum magnets parameters were then determined for each measured painting injection coordinates and the orbit was measured with MWPM 3 and 4. From the relative difference of the beam orbits for the painting and center injection measured at MWPM3 and MWPM4, the relative inclination of the injection beam was calculated, where the beam position at the injection point was calculated by using measured position at MWPM4 and the inclination. It is important to note here that the injection beam inclination at the injection point for the center injection orbit was adjusted almost to zero (match with the closed-orbit). The direct measurement of the injection beam position and inclination at the injection point with MWPM3 and 4 gave very consistent result as compared to what was reconstructed with using equation 3 (method 1) from BPM turn-by-turn data. The results are summarized in table 2. As for the vertical plane, phase space coordinates of the injection beam were determined by measuring directly with MWPM as two vertical paint bump magnets are located in the injection line (Fig. 2).

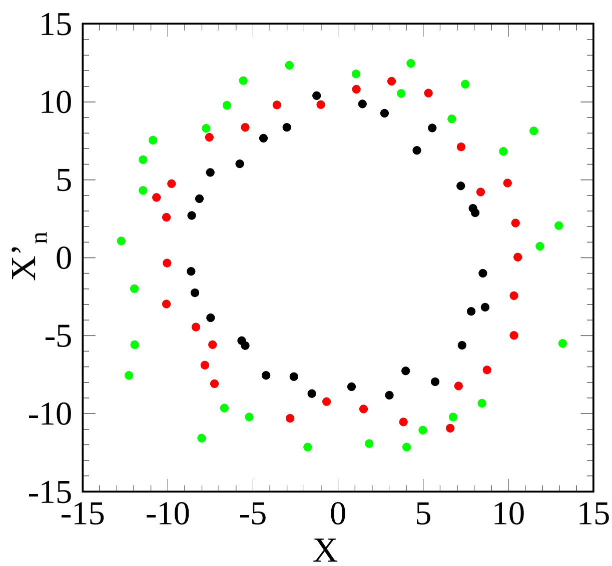

Figure 8: Normalized horizontal phase space plots of the beam center measured by the BPM turn-by-turn mode for the first 30 turns. The paint bump magnets were excited with a constant flat-top for painting areas of the beam center trajectories with 75(black), 124(red) and 175(green) π.mm.mrad, respectively. As expected, each phase space plot looked like a circle, where emittances were calculated from the circle area. From a statistical analysis, the emittances for three cases were found to be 78.8$\pm$2.1 (black), 113.3$\pm$3.2 (red) and 159.0$\pm$4.3 π.mm.mrad (green),respectively, and were almost consistent with expectation.

The decay patterns of the paint bump magnets for both horizontal and vertical planes were then made, where in both planes a center to outside painting in the phase space of circulating beam (so-called correlated painting) was performed. It was done by sweeping the circulating beam orbit with horizontal paint bump magnets in the horizontal direction and by sweeping directly the injection beam in the vertical plane with vertical paint bump magnets. In order to reconstruct the intermediate footprint of the painting injection during 500 μs, the data was taken at six different timing (t0$\sim$t5) by delaying (or shifting) the decay pattern with a step of 100 μs, where a single pulse from the Linac was injected. The time t0 corresponds to the start of the painting (center) and t5 thus corresponds to the end of painting (outside). From the phase space information of the circulating beam center measured by the BPM pairs with turn-by-turn mode, the reconstructed phase space footprint of the injection beam using equation 3 is shown in fig. 9 for a correlated painting of 100 π.mm.mrad in both horizontal and vertical planes. The measured linac beam emittance at the injection point was used and was 3.6 π.mm.mrad in both horizontal and vertical planes with 3σ cut. Results from the both pair were found consistent to each other, where the footprints especially in the horizontal plane were found to reproduce well the expected linear red line. On the other hand, reconstructed footprints in the vertical plane for intermediate time scale were found a bit zigzag but finally reach to the expected goal at t5. The reason may be due to fluctuation of the vertical paint bump pattern, especially the 2nd vertical paint bump, which was operated comparatively with a low current as compared to its maximum capability. The 2nd vertical paint bump magnet is used as an auxiliary one in order to adjust the phase difference from the 1st painting magnet to the injection position. A fine tuning while making the bump patterns could improve the fluctuation and remains as a next challenge. Results obtained with same procedure for different painting areas of 150 π.mm.mrad and 200 π.mm.mrad although performed only in the horizontal plane were also found consistent to the expectation. The present decay patterns were then used for the design painting injection study in the transverse direction with multi-turn injection. The beam profiles with painting injection study measured by the IPM for both horizontal and vertical planes can be seen in refs. [1, 11]. The present method is found to be a very powerful and accurate for reconstruction of the phase space footprints during the painting injection, which would be very useful for a precise understanding of the painting injection process in the transverse direction so as to feedback towards RCS power up ramping from now in a transition of commissioning to the operation stage.

Table 2: Reconstructed phase space coordinates of the injection beam obtained from the BPM turn-by-turn data (method 1) and using equation 3, which was found to be very consistent with the direct measurement with MWPM. The expectation was as shown by the target.

Paint area (π.mm.mrad)	**Injection**(X, X') (mm, mrad)	**Comment**
100	(31.1, -4.4)	Target
	(30.6, -4.69)	with pair 1(equn.3)
	(30.1, -4.52)	with pair 2(equn.3)
	(31.2, -4.61)	with MWPM

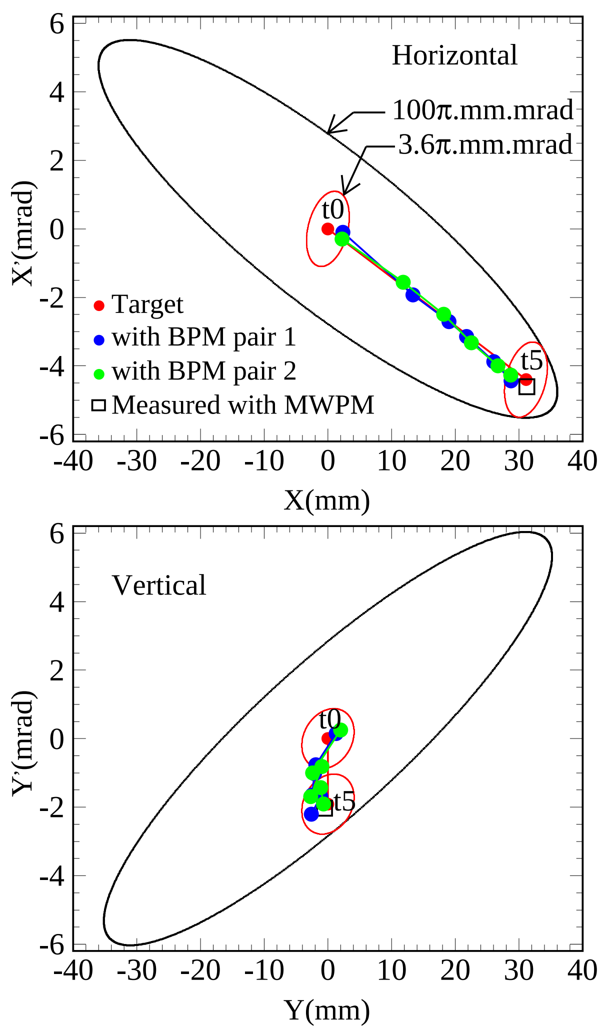

Figure 9: Reconstructed phase space footprint obtained by using using equation 3 for a painting injection of 100 π.mm.mrad done in both horizontal and vertical plane simultaneously, where a correlated painting was performed. The measurement was done for six different timing of the paint bump decay pattern covering the whole period of 500 μs by delaying (or shifting) the bump patterns with a step of 100 μs. Legends are same for both horizontal and vertical planes. Results from both pair were found very consistent to each other and especially in the horizontal plane, each points were found to sit just on expected linear red line.

BEAM LOSS STUDY IN THE INJECTION AND EXTRACTION

Like any other high power machine, RCS of J-PARC also deeply concerns the beam loss issues. In most cases, the beam loss issues, especially the uncontrolled beam losses become major obstacle in achieving the design power in a similar machine. The injection and extraction periods come with major sources of the uncontrolled beam losses. In RCS, the uncontrolled beam loss of less than 1 Watt/meter is required for the hands-on-maintenance, which corresponds to an integrated uncontrolled beam loss in the ring should be less than 3.5×10^{-4} for 1 MW. The controlled beam loss in the collimation area is acceptable to a maximum of 4kW [3]. As seen in fig. 2, the injection area of RCS is very complicated and there are many sources of both uncontrolled and controlled beam losses. These are 1) the Lorentz stripping of the incoming H^- beam in the magnetic field before reaching to the charge-exchange foil, 2) excited states decays of the partially stripped H^0 before reaching to the 2nd charge-exchange foil and 3) nuclear scattering together with the multiple Coulomb scattering due to the multi-turn injection. All these sources were studied in detail in the design stage as can be found in refs.[4, 12]. The estimated beam losses caused by the first two sources were found to be negligible and is confirmed from the beam commissioning data so far, where the injection line as well as the shift bump region were practically clean as found from the residual survey after each beam cycle. The third one is the major source of the uncontrolled beam in the injection area as also realized from the beam commissioning experience. At present, significant amount of uncontrolled beam losses during the injection period were observed near the H0 branch and upstream of the primary collimator, where physical apertures were slightly smaller. Those were probably due to the large angle events caused by the nuclear together with multiple coulomb scattering at the charge-exchange foil during the multi-turn injection. At present the beam commissioning of RCS is mainly done with so called center injection. As a result, the foil traversal rate of the circulating beam increases significantly as compared to the painting injection. Due to numerous beam study, the foil size as well as the position were not optimized precisely and finally, the falling time of shift bump magnets at the end of injection was as long as 500μs. These two reasons independently also contribute to the increase of foil traversal rate. All these three sources together can increase the foil traversal rate nearly an order of magnitude higher as compared to the design painting injection with design system. As the first stage of tuning has already been finished successfully, the foil size as well as the position can now be optimized. The shift bump falling time also succeeded to reduce down to 250μs. It is thus hope that the uncontrolled beam loss at the injection area will reduce significantly.

As for the extraction, the beam energy is as high as 3 GeV. An extra care was taken in the design stage for not to lose practically even a single particle through the extraction channel. From the loss monitors and even with residual survey after each beam study cycle, the extraction area always found to be clean as expected. However, more study especially with comparatively bigger emittances at the extraction due to the design painting injection in the beginning as well as with high duty operation are needed for the detail comparison.

SUMMARY

The experience with J-PARC RCS injection and extraction systems from nearly a year beam commissioning results has been summarized. Starting very smoothly in the beginning, both the injection and extraction systems are found very stable and in full cooperation with overall beam commissioning of RCS. A comparison of the design stage parameters with the present beam commissioning parameters was also done. Except one magnets in the injection line (ISEP2), the rest all were found acceptable in agreement. A comparatively large discrepancy with ISEP2 is under study and will be reported elsewhere. The extracted orbit even with present low intensity beam was found to be stable. As a result, the beam commissioning of the successive beam lines were proceeded very smoothly. Recently aiming for high beam power at the output, painting injection study in both transverse and longitudinal planes has been started. For a precise understanding of the painting process in the transverse plane, two independent methods have been established in RCS, where results obtained by utilizing BPM turn-by-turn data were reported here and was found to be very efficient and accurate. A precise understanding of the painting process in such a way can lead one to control the transverse phase space so as a direct feedback towards achieving high output power through painting injection. The beam loss issues in both injection and extraction were also found to be consistent with the design stage estimation. The two hot points near the injection area might be due to the large angle events caused by the nuclear scattering together with the multiple Coulomb scattering as the circulating beam heat the foil during multi-turn injection. Due to the present operation with center injection mode, comparatively large foil size and slow falling time of the shift bump magnets (500μs) together cause a significant increase of foil traversal rate and was estimated nearly a magnitude higher than the design painting injection with the design system. The foil size as well as the position can be now optimized and the shift bump falling time has also been succeeded to reduce down to 250 μs. The uncontrolled beam loss is thus hope to be reduced further even with the center injection.

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