PULSE-TO-PULSE TRANSVERSE BEAM EMITTANCE CONTROLLING FOR MLF AND MR IN THE 3-GeV RCS OF J-PARC

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Abstract

The 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex) is a MW-class proton beam source for the muon and neutron production targets in the MLF (Material and Life Science Experimental Facility) as well as an injector for the 50-GeV MR (Main Ring). The RCS has to meet not only the beam power but also to ensure two different transverse sizes of the extracted beam for the MLF and MR, especially at high intensity operation. Namely, a wider one for the MLF in order to reduce damage on the neutron production target, while a narrower one for the MR in order to ensure a permissible beam loss in the beam transport line of 3-GeV to the MR and also in the MR. We proposed a pulse-to-pulse direct control of the transverse injection painting area so as to ensure a desired extracted beam emittance. For that purpose, RCS injection system was carefully designed for changing painting area between MLF and MR very accurately. The extracted beam profiles for the MR are measured to be sufficiently narrower than those for the MLF and also shown to be consistent with numerical beam simulation results. The system is already in service and plays an important role even at the present 300 kW beam operation. It is thus one remarkable progress on the RCS design goal to confirm that the beam parameters can be dynamically controlled and delivered as requested by the users even in simultaneous operation. A detail of the design strategy, painting process as well as experimental results are presented.

INTRODUCTION

The 3-GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex (J-PARC) is designed for a beam power of 1 MW [1]. A total of 8.33×10^{13} protons in two bunches is accelerated to 3 GeV at a repetition rate of 25 Hz and simultaneously delivered to the neutron and muon production targets in the MLF (Material and Life Science Experimental Facility) as well as to the MR (50-GeV Main Ring synchrotron). Figure 1 shows a schematic view of the RCS, which is a three-fold symmetric lattice having a circumference of 348.333 m. The injected beam energy is recently upgraded to the designed 400 MeV from the 181 MeV so far. The RCS beam power at present for the operation is 300 KW, while a beam power of nearly 800 kW with sufficiently low loss has already been demonstrated in a recent beam study [2]. A pattern dipole magnet named Pulse Bending magnet (PB) located downstream of the RCS extraction beam transport (BT) line is used to switch the beam destination to the MR according to the operation strategy. At present for the MR with fast extraction operation, RCS beam delivery ratio to the MLF and MR is typically 9:1.

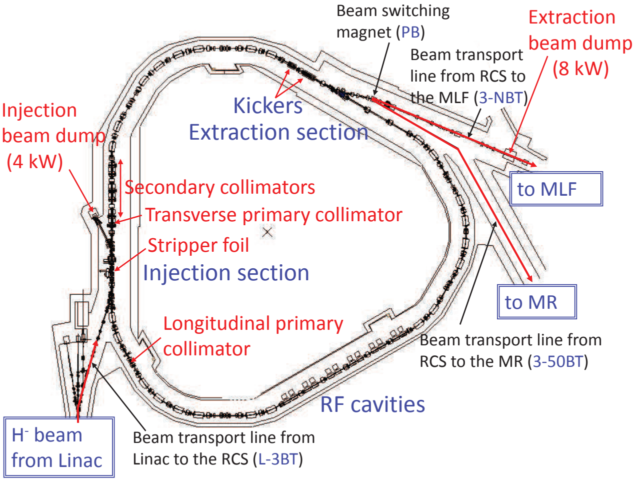

Figure 1: Schematic view of the 3-GeV RCS of J-PARC. Extracted beam is simultaneously delivered to the MLF and MR at a repetition rate of 25 Hz. A pattern dipole magnet named Pulse Bending magnet (PB) located downstream of the RCS extraction line acts as a switching magnet for changing beam destination MLF to MR.

However, RCS design goal is not only to achieve the beam power but also to ensure specific requirements of each downstream facility. One such an issue, especially at high intensity operation is to control transverse emittance of the extracted beam pulse-to-pulse between MLF and MR even in simultaneous operation. Namely, a wider transverse beam distribution for the MLF in order to reduce damage on the neutron production target, while a narrower one for the MR in order to ensure a permissible beam loss in the BT of 3-GeV RCS to the MR (3-50BT) as well as in the MR. The BT of RCS to the MLF targets named 3-NBT has the aperture of 324π mm mrad, same as the RCS primary collimator but 3-50BT and MR designed apertures are much smaller, 120π mm mrad and 81π mm mrad, respectively. In order to realize such a requirement, we proposed pulse-to-pulse direct control of the transverse painting area during multi-turn H^- charge-exchange injection process in the RCS so as to ensure a desired transverse beam profile or in other words, a desired transverse emittance of the extracted beam. The designed injection painting area in the RCS for the MLF and MR are 216 and 144π mm mrad, respectively. The RCS injection system was carefully designed for varying both hor-

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izontal and vertical painting areas pulse-to-pulse between MLF and MR and has also been experimentally verified through beam studies. At the present 300 kW operation of the RCS, the transverse painting areas for the MLF and MR are chosen to be 100 and 50π mm mrad, respectively.

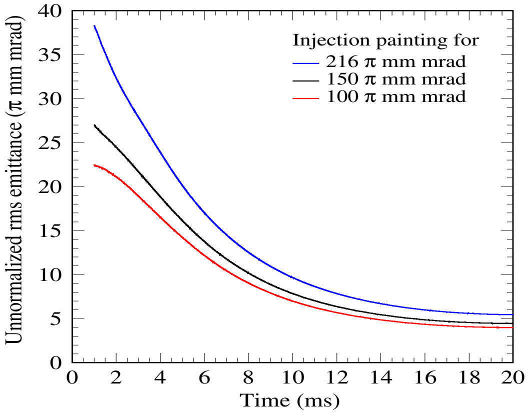

Figure 2: Estimated damping of the transverse rms horizontal emittance and dependence on the injection painting area for a beam power of 350 kW. A smaller painting area gives comparatively a smaller emittance of the extracted beam.

Figure 2 shows numerical results for expected transverse rms emittance damping and dependence on the injection painting areas of 216, 150 and 100π mm mrads as shown by blue, black and red lines, respectively. The painting emittance values are 99.7% emittance values for all cases. In this simulation injected beam energy was 181 MeV and a beam power of 350 kW at the extraction energy of 3 GeV was considered, where a full 3-D space charge effect was taken into account. It can be easily seen that a smaller initial painting area guaranties comparatively a smaller emittance of the extracted beam. One can expect nearly 25% reduction of an rms emittance for an injection painting area of 100π mm mrad as compared to that of 216π mm mrad.

RCS INJECTION SCHEME AND TRANSVERSE PAINTING PROCESS

Figure 3 shows a layout of the RCS injection area. The H^- beam from the LINAC is stripped to H^+ by the 1st stripped foil placed in the middle of 4 injection chicane magnets, also called shift bump magnets (SB), and is injected into the RCS. The transverse injection painting in the horizontal direction are performed by 4 painting bump magnets named PBH. The first two of them (PBH1~2) are place in the upstream of the SB, while the rest two (PBH3~4) are place at the downstream of the SB. The two vertical painting bump magnets (PBV1,2) are placed at the LINAC to the RCS injection beam transport (L-3BT) line. In the original design, two pulse steering magnets named PSTR1 and PSTR2 are used for changing painting area MLF to MR in the horizontal direction but recently with upgraded power supplies of the PBHs, it has also been successfully done by using only PBHs.

Figure 4 shows a schematic view of the RCS transverse injection painting process for horizontal and vertical planes in the upper and lower plots, respectively. The painting area is considered to be the design maximum of 216π mm mrad for both planes as shown by the bigger ellipses (black), where a typical injected beam emittance is considered to be 4π mm mrad (blue). In the horizontal direction, the position and angle (x and x') of the injected beam center is matched to a closed orbit offset made by the SBs together with PBHs. The horizontal phase space painting is performed by varying the closed orbit by the PBHs during 0.5 ms injection period as shown by the arrow [3, 4]. The SBs are then linearly ramped down to zero so as to move the closed orbit to the ring center. In the vertical direction, however, injected beam angle (y') at the foil is directly sweeped by the PBVs. As shown in the figure the vertical angle of the injected beam can be sweeped either center-to-outside or outside-to-center in the circulating phase space for so-called correlated or anti-correlated painting.

METHODS FOR SWITCHING PAINTING AREA BETWEEN MLF AND MR

In this section, two methods for changing injection painting area pulse-to-pulse between MLF and MR, especially for the horizontal direction are described. A change of the painting area between MLF and MR in the horizontal direction is originally performed by using PSTR magnets but recently it has also been realized by using only PBHs because of their upgraded power supplies.

Switching Horizontal Painting Area by PSTRs

Figure 5 shows a schematic view of changing transverse painting area between MLF and MR. The design painting areas for the MLF and MR are considered to be 216π mm mrad and 144π mm mrad as shown by the black and red ellipses, respectively. In order to change painting area from MLF to MR in the horizontal direction, PSTR magnets are used to change only angle of the injected beam to a smaller value by keeping its position same as that for the MLF. This is because a change of the both position and angle for a smaller painting area needs to move the foil further inside in the horizontal direction. That will significantly increase the foil hits of the circulating beam for the MLF. It is therefore a big issue for the corresponding foil scattering beam loss as well as foil lifetime as 90% of the beam is delivered to the MLF. The injected beam orbit, painting for the MLF is fixed by two DC septa, while two PSTRs are additionally used to control the injected beam orbit in such a way to realize a smaller painting area for the MR. The black and red arrows shows the amplitude and direction of closed orbit variation for the corresponding painting area performed by the PBHs. It has also to be mentioned that the chicane bump offset for the MLF and MR should be changed and it is about 11% higher for the later case. A further detail of the designed strategy as well as experimental results can be found in our separate article [5].

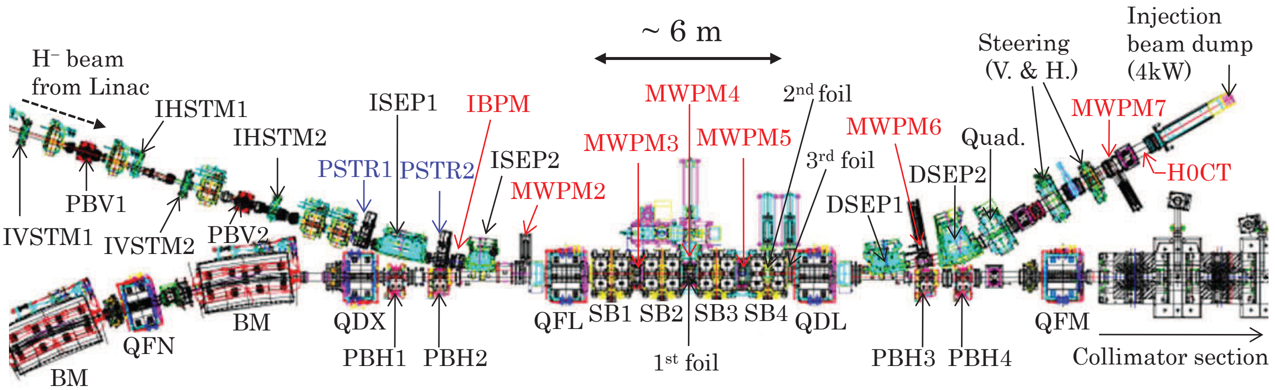

Figure 3: Layout of RCS injection area. The SB1~4 are the injection chicane magnets. The PBH1~4 and PBV1~2 (injection line) are used for transverse injection painting in the horizontal and vertical directions, respectively. The two pulse steering magnets named PSTR1 and PSTR2 (injection line) are used to control horizontal phase space coordinates of the injected beam at the 1st stripper foil in order to change horizontal painting area between MLF and MR. The PBVs are used for controlling vertical angle of the injected beam for changing vertical painting area between MLF and MR.

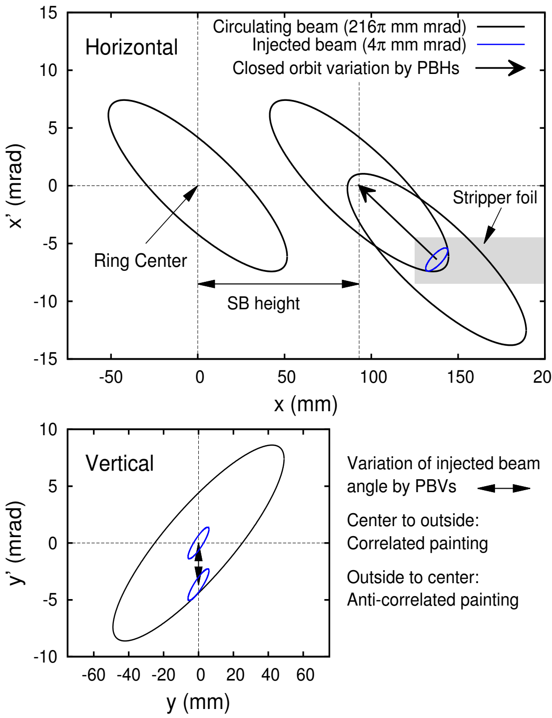

Figure 4: Schematic view of the transverse painting process in the horizontal (top) and vertical direction (bottom). A controlled closed orbit is variation is done by using PBHs for horizontal painting, while injected beam angle itself is sweeped in the vertical phase space for vertical painting.

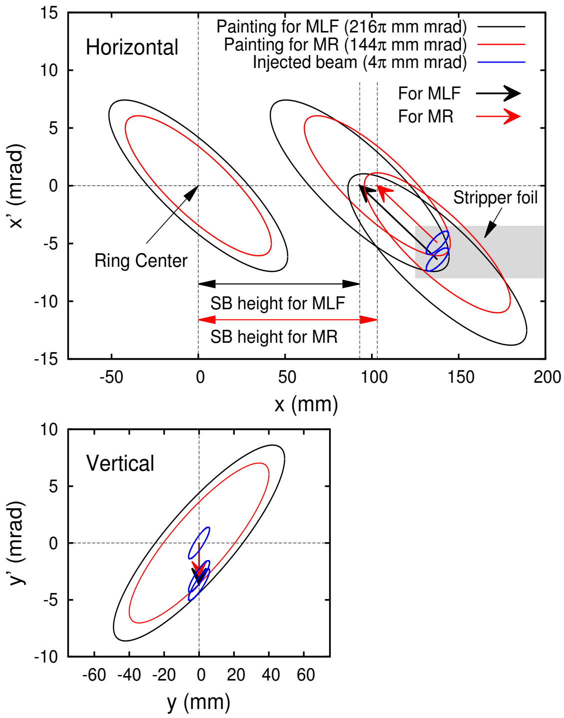

Figure 5: Schematic view of switching painting area between MLF and MR. The PSTRs are used to change angle of the injected beam by keeping its position unchanged at foil in the horizontal direction, while PBVs are used to control size of the injected beam angle in the vertical direction.

As for the vertical direction, a painting area pulse-to-pulse between MLF and MR, however, is changed by controlling the size of the injected beam angle at the foil by using two vertical painting magnets, PBV1,2. A typical case for correlated painting is shown.

Switching Horizontal Painting Area by PBHs

In stead of PSTRs, horizontal painting magnets PBHs are only used in this method for switching horizontal painting area MLF to MR. Figure 6 shows a demonstration such a process which has also been successfully introduce in the recent beam studies. In this case, injected beam position and angle are both kept same for both MLF and MR but PBHs patterns are carefully controlled for a particular closed orbit variation so as to realize a desired painting area. As the closed orbit variation at the end of injection determines the painting area, its amplitude for the MR painting is controlled as shown by the red arrow.

Figure 7 shows typical current patterns for the first painting magnets (PBH1). The solid black and red curves are typical patterns for 216 and 144π mm mrad painting area, where initial closed orbit offsets at the foil are different. However, in this method initial closed orbit offset is kept same and thus the current at the starting of 144π mm mrad is matched to that of 216π mm mrad by adding an offset between these two currents at start as shown by the red dotted curve. In stead of current being zero at the end, there has thus an offset at the end of injection, which determines the painting area for the MR. At present PBHs patterns are kept flat further 0.05 ms after injection is finished and then linearly ramped down to zero by another 0.35 ms. One big advantage with this method is that the painting area is changed by using only PBHs and injected beam orbit for both MLF and MR can be kept same. The chicane bump height is also same for both MLF and MR painting. The partially stripped and un-stripped waste beam orbits are can be thus kept same. However, an extra foil hits after the injection due to remaining offset of the PBHs can be considered as one small issue. In the vertical direction the procedure is same as done in the previous method.

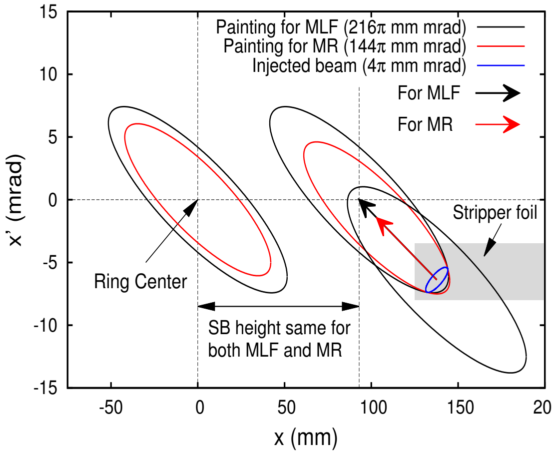

Figure 6: Schematic view of switching horizontal painting area by using only PBHs.

EXPERIMENTAL RESULTS

In order to verify a dependence of the extracted beam profiles on the RCS injection painting area, experimental studies were carried out for both 181 MeV and recently upgraded 400 MeV injection energies.

Measurement of Extracted Beam Profiles by Changing Horizontal Painting Area by PSTRs

The experimental study by using PSTRs were carried out at 181 MeV injection. For simplicity, transverse injection painting applied only for the horizontal direction and was 150 and 100π mm mrad for the MLF and MR, respectively. The extracted beam profiles were measured by a Multi-wire Profile Monitor (MWPM) placed in the 3-NBT. Figure 8 shows the measured (solid red circles) and simulated (lines) horizontal extracted beam profiles for MLF (top) and MR (bottom) for an equivalent beam power of 350 kW. As expected, the width of the extracted beam profile for the MR painting is measured to be narrower as compared to that of MLF painting and is also quite consistent with corresponding simulation results. The simulation was performed by using ORBIT code [6, 7].

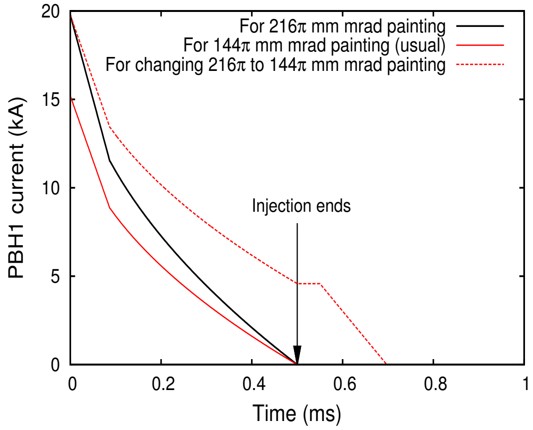

Figure 7: Typical PBH current patterns for different painting areas. The dotted line is a typical patterns for changing horizontal painting area MLF to MR by using only PBHs.

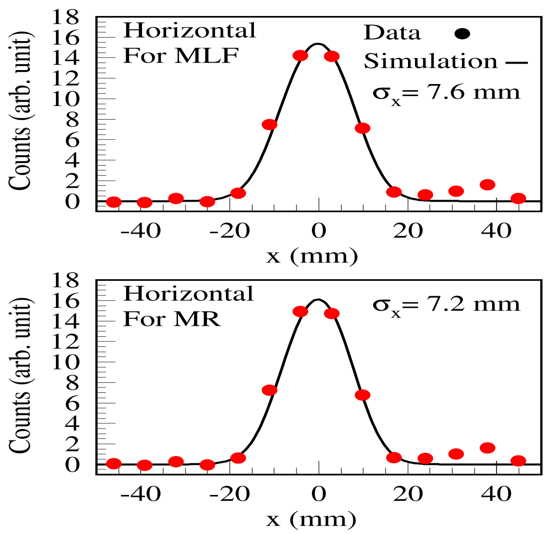

Figure 8: Comparison of horizontal extracted beam profiles for the MLF 150 and MR 100π mm mrad injection painting applied for only in the horizontal direction. The equivalent beam power was 350 kW, where red solid circles are the measured data by MWPM and lines are the corresponding simulation results. The profile width for a smaller injection painting area for the MR is confirmed to be narrower as compared to that for a larger one for the MLF.

Measurement of Extracted Beam Profiles by Changing Horizontal Painting Area by PBHs

Figure 9 shows comparisons of both horizontal and vertical extracted beam profiles between MLF and MR. The painting area between MLF and MR was changed by using PBHs and PBVs for the horizontal and vertical directions, respectively. In this experiment, the injected beam energy was 400 MeV and the extracted beam intensity was 4.6×10^{13} ppp (550 kW equivalent). The painting area for the MLF and MR was chosen to be 100 and 50π mm mrad, respectively. The top two figures are for comparison in the horizontal direction, while bottom two figures are those for the vertical direction. The measured profiles are plotted with red solid circles, where lines are corresponding beam simulations. Here also extracted beam profiles for the MR painting is measured to be significantly narrower as compared to those for the MLF painting even for an equivalent beam power of 550 kW. The simulation results are also found to be almost consistent with measured ones.

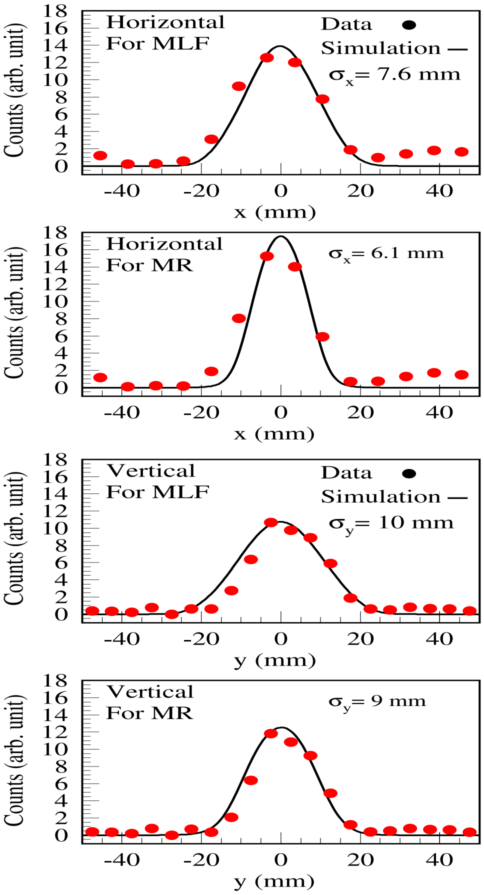

Figure 9: Comparison of the horizontal (top two) and vertical (bottom two) extracted beam profiles for the MLF 100 and MR 50π mm mrad injection painting applied for both horizontal and vertical directions. In this case painting area between MLF to MR was changed by the PBHs and PBVs for the horizontal and vertical directions, respectively. The beam profile widths for the MR are obtained to be narrower than those for the MLF.

SUMMARY

In order to control extracted beam emittance pulse-to-pulse in simultaneous operation, a direct control of the transverse injection painting is proposed and has also been successfully demonstrated through experimental studies. The extracted beam profiles for a smaller injection painting area for the MR are measured to be significantly narrower as compared to those for a larger painting area for the MLF. Two independent methods, especially for changing painting area in the horizontal direction are considered and also successfully applied in the experimental studies. The corresponding numerical simulation results are also found to be consistent with measurements. The system is already in service even at the present RCS operation with 300 kW beam, where transverse painting area for the MLF and MR are fixed to be 100 and 50π mm mrad, respectively. It is thus confirmed that in a multi user machine beam parameters can be dynamically controlled and delivered as requested by the users even in simultaneous operation. The present principle can be applicable to any similar multi user machine for controlling beam emittances in a pulse-to-pulse mode.

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