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DYNAMIC VARIATION OF CHROMATICITY FOR BEAM INSTABILITY MITIGATION IN THE 3-GeV RCS OF J-PARC

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Abstract

To mitigate transverse beam instability caused by the extraction kicker magnets in the 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex), we have implemented dynamic variation of chromaticity (ξ) by using bipolar sextupole magnetic fields. The method includes a partial ξ correction at lower beam energy to reduce the chromatic tune spread ($\Delta\nu_{chro.}$) required to minimize the beam loss and the beam emittance, while introducing an excess of ξ at higher beam energy to utilize larger $\Delta\nu_{chro.}$ to enhance the Landau damping for beam instability mitigation. We first carried out detail numerical simulations by using ORBIT code for a beam intensity as high as 830 kW, then established the method by experimental verification and has already been implemented for the RCS operation.

INTRODUCTION

The 3-GeV RCS (Rapid Cycling Synchrotron) at J-PARC (Japan Proton Accelerator Research Complex) delivers high intensity proton beams to both MLF (Materials and Life Science Experimental Facility) and the MR (30-GeV Main Ring) [1]. In the RCS, the injected 400 MeV protons are accelerated up to 3 GeV at a repetition rate of 25 Hz and simultaneously delivered to the MLF and MR. The designed beam power is 1 MW (8.33×10^{13}/pulse), but at present the beam power to the MLF is 500 kW, while it is nearly 750 kW equivalent beam power to the MR. Figure 1 shows a schematic view of the RCS extraction region and 8 pulse kicker magnets (KM) used for the fast extraction of two circulating bunches in a pulse [2]. However, the transverse impedance of the extraction kicker magnets (KM) are the most dominant beam instability source in the 3-GeV RCS [3]. The beam instability excited by the transverse horizontal impedance of the KMs causes the circulating beam centroid evolution in the transverse horizontal plane.

Figure 2 shows sinusoidal ramping pattern of the B field (B) and the corresponding kinetic energy (T) of the circulating beam. The beam instability due to the KM impedance occurs at the later half of the acceleration cycle, namely at relativistic energy rather than the non-relativistic energy. The space charge effect plays a significant role on the beam instability, which we have detailed studied in theory, simulations and experiments as reported earlier [4–6]. The hardware measures to reduce the KM impedance itself is in progress, but it requires detail R&D studies for the real implementation [7].

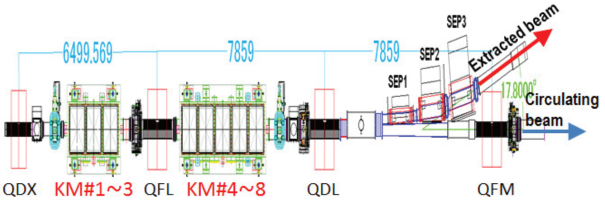

Figure 1: Schematic view of the RCS extraction area with 8 pulse KMs used for fast beam extraction. The KMs are the most dominant beam instability sources in the in the RCS.

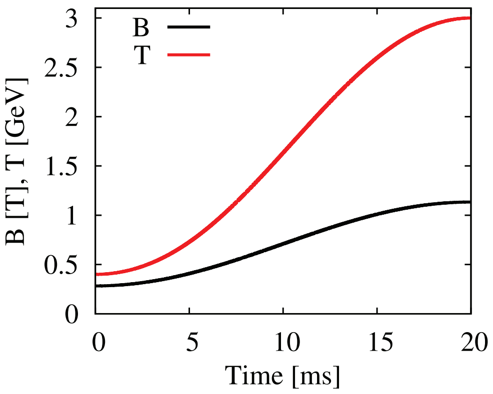

Figure 2: Sinusoidal B field and the corresponding kinetic energy. The beam instability due to the KM impedance occurs at relativistic energy.

In order to mitigate the beam instability, especially for the MLF beam we have carefully determine the betatron tune manipulation during the acceleration cycle in addition to a minimum or no uses of the Sextupole magnets (SX) to keep the lattice chromaticity (ξ), especially the horizontal one with the natural value of -9. However, for the MR beam which requires to ensure a comparatively smaller enough transverse emittances as compared to those for the MLF beam, the beam instability growth rate is significantly higher for the MR beam. The transverse emittances in the RCS can be controlled pulse-by-pulse by the choice of injection painting area, the betatron tunes can also be accordingly manipulate. In this work, we consider further dynamic variation of the SX field, so does the ξ to mitigate the beam instability for the MR beam. The dynamic variation includes introduction of an excess ξ over its natural value from mid acceleration cycle by reversing the SX fields. Here we take the advantages of chromatic tune spread ($\Delta\nu_{chro.}$) (expressed by a product of beam momentum spread and the ξ) in two ways. The beam losses and mostly the emittance growth are minimized by keeping the beam away from crossing many resonances due to a smaller $\Delta\nu_{chro.}$ is obtained by a smaller ξ at lower energy [8], while the beam instability is mitigated

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by enhancing the Landau damping due to a larger $\Delta\nu_{chro.}$ obtained by introducing a higher ξ at higher beam energy.

It is worth mentioning that we first carried out detail numerical simulations by implementing all realistic machine parameters in the ORBIT code [9], then established the method by experimental verification finally implemented for the RCS operation.

CHROMATICITY VARIATION BY SX OFF TO REVERSE

The SX power supplies (PS) were originally unipolar and thus those were needed to upgrade to bipolar for dynamic variation of the ξ. In the meantime, we studied to demonstrate the effect of higher ξ for beam instability mitigation by varying SX off to reverse. Figure 3 shows a variation of the SX strength factor (green solid line) and the corresponding ξ (green dash line), which was nearly 20% increased in the reverse way to that used for ξ correction in order to have a ξ of about -11 as compared to -9 with SX off and keep it constant for the later half of the cycle by using AC SX fields.

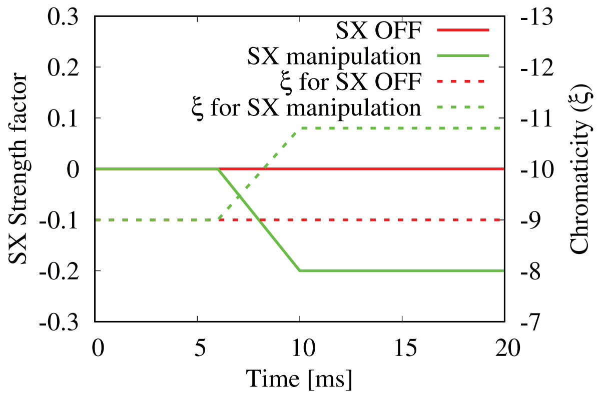

Figure 3: Variation of the SX strength factor to introduce 20% excess ξ from mid acceleration cycle to the end.

Figure 4 shows simulation (top) and experimental (bottom) results of beam instability mitigation by introducing an excess of ξ by varying SX from off to reverse field. The horizontal axis the time where vertical axis is the time and turn-by-turn horizontal beam centroid position at a beam position monitor (BPM) located in the injection area.

The study was done for 830 kW equivalent beam power and for the MR beam condition, where a minimum transverse injection painting area of 50π mm mrad and dual harmonic rf cavity voltages with maximum longitudinal injection painting were applied. The horizontal betatron tune (ν_x) was 6.45 at injection which is usually manipulated to a lower value for beam instability mitigation, but it was kept unchanged for this particular study. The beam instability occurs even when the ν_x is kept to its natural value, the beam can be fully stabilized by introducing ν_x 20% by using SX reverse fields. The simulation and measurement results were consistent each other. However, to minimize the beam losses as much as possible in the RCS, SX uses at least for partial ξ correction at lower energy is required. For that purpose

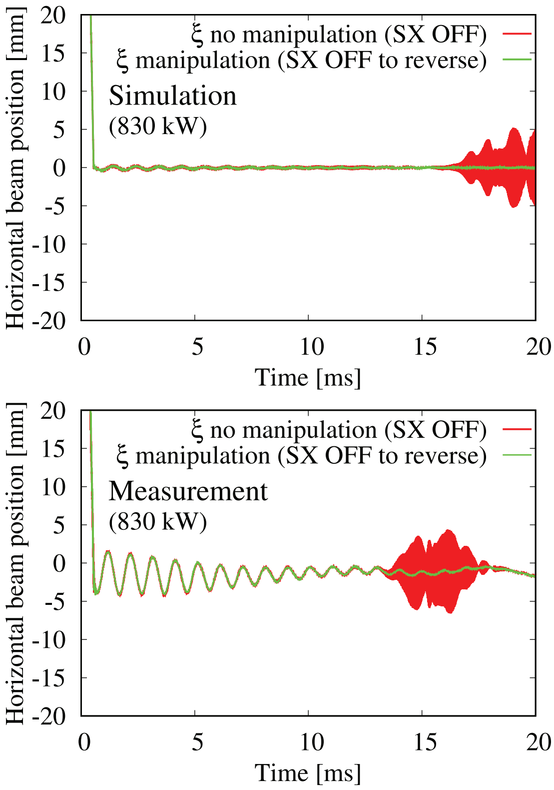

Figure 4: Simulation (top) and measurement results of beam instability mitigation for a high intensity beam of 830 kW with an excess of ξ by manipulating SX fields off to reverse.

the SX PS were upgraded for bipolar uses, namely, for ξ correction at lower energy, and for introducing excess ξ at higher energy by zero crossing and reversing the SX fields.

APPLICATION OF DYNAMIC VARIATION OF THE CHROMATICITY

We have applied the dynamic variation of ξ by using bipolar SX fields for minimizing the beam loss and beam emittance at lower beam energy, while for beam instability mitigation at higher beam energies. Figure 5 shows a typical bipolar uses of the SX fields (green solid line) and the corresponding ξ variation (green dash line) as a function of beam acceleration time. The SX DC fields with 60% of its full strength (SX DC ×0.6) was used for up to 6 ms, it was then zero crossed by another 4 ms for about 20% reverse field and keep it same by the AC fields for rest of the cycle. As the beam energy increases, the SX strength factor drops (solid red line) when used as DC fields and almost the natural ξ (red dash line) remains at the end of the cycle, where a bipolar excitation of the SX fields gives nearly 20% more ξ (-11) from that of its natural value (-9) for the later half of the acceleration cycle.

Figure 6 shows the simulation (top) and measurement (bottom) results of the beam instability mitigation by dynamic variation of the ξ_x by using bipolar SX fields. The beam intensity in this case is same as in the previous section

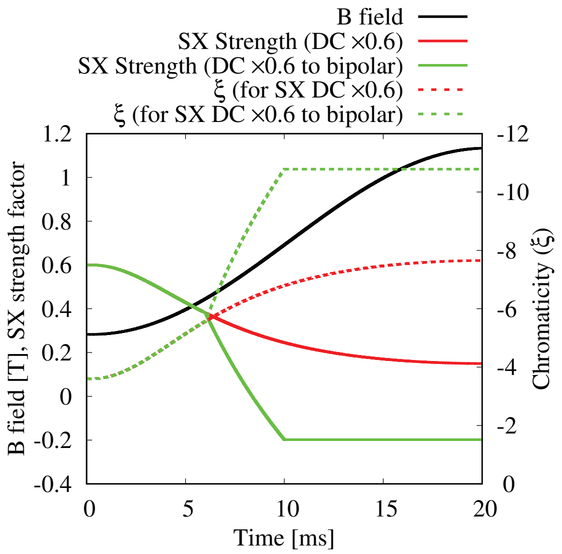

Figure 5: Dynamic variation of the ξ (green dash line) by using bipolar SX fields (green solid line).

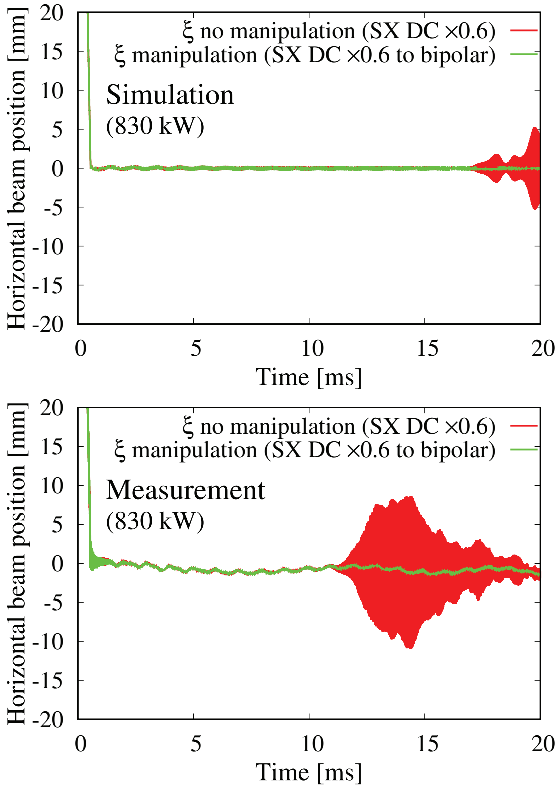

Figure 6: Simulation (top) and measurement results of beam instability mitigation for a high intensity of beam 830 kW by dynamic variation of the ξ.

(830 kW), but the ν_x was manipulated to 6.37 at the end of the cycle to minimize the beam loss and beam emittance and also to reduce the beam instability growth rate, which is the strongest for ν_x with no manipulation. A partial DC SX fields (SX DC ×0.6) for partial ξ correction is essential for beam loss minimization at lower beam energy, but it gives beam instability at higher energy. However, such a beam instability can be fully mitigated to stabilize the beam by dynamic variation of the ξ with bipolar SX fields.

The advantages of such a dynamic variation of the ξ are twofolds. The $\Delta\nu_{chro.}$ due to a smaller ξ is reduced to keep beam away from many resonance including the integer resonances, namely, $\nu_{x,y} = 6$. The beam loss and mostly the beam emittance growth are well controlled to obtain a lower beam emittance for the MR injection. Due to RCS large momentum acceptance of maximum $\pm 1\%$, the $\Delta\nu_{chro.}$ itself is estimated to be as high as nearly ± 0.1. In an opposite way, a larger $\Delta\nu_{chro.}$ is obtained by increasing the ξ, which is essential to enhance the Landau damping for beam instability mitigation at higher energy. Due to momentum spread gets smaller as beam energy increases, such an introduction of the excess ξ at higher energy does not either lead to any additional beam losses or significant increase of the beam emittances. We have already successfully implemented such a dynamic variation of the ξ by using bipolar SX fields for the RCS beam delivered to the MR.

SUMMARY

The transverse beam instability caused by the transverse impedance of the J-PARC RCS extraction kicker magnets has been successfully mitigated by introducing dynamic variation of the ξ by using bipolar SX magnetic fields. The method has been established based on detail numerical simulations by using ORBIT code and the corresponding experimental studies. The simulation results were well reproduced by the measurement results. The beam loss and mostly the beam emittance were minimized by using partial ξ correction at lower beam energies while beam instability was well mitigated by introducing an excess of ξ controlled by bipolar SX magnetic fields. The method has already been successfully implemented for the RCS beam operation to the MR.

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