SIMULATION STUDIES AND MEASUREMENTS OF BEAM INSTABILITIES CAUSED BY THE KICKER IMPEDANCE AT HIGH INTENSITIES IN THE 3-GeV RCS OF J-PARC

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Abstract

The transverse impedance of the extraction kickers is a significant beam instability source in the 3-GeV Rapid Cycling Synchrotron of Japan Proton Accelerator Research Complex. The ORBIT code was used for the space charge and beam instability simulations by successfully introducing realistic time dependent machine parameters. The beam instability near the designed 1 MW beam power was found be very critical. As there was no practical measure yet to reduce the kicker impedance itself, a detail simulation studies were done in order to determine realistic machine parameters to suppress the beam instability. The simulation results were found to be consistent with measurements and 1 MW beam acceleration has also been successfully accomplished. The beam instability scenarios, especially at high intensities based on simulation and experimental studies are presented in this paper.

INTRODUCTION

The 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex) is a high power of 1 MW proton beam source for the MLF (Material and Life Science Facility) as well as for the MR (Main Ring Synchrotron) [1]. The beam energy at injection is 400 MeV, while it is accelerated up to 3-GeV and simultaneously delivered to the above two facilities at a repetition rate of 25 Hz. The beam power for the user operation so far reached to half of the designed 1 MW but systematic studies have already been done up to the designed beam power [2].

The beam instability in the RCS at 1 MW was a big concern due to the significant impedance, especially the transverse ones of 8 pulse kicker magnets used for the beam extraction. The direct measures to reduce the impedance has already been proposed but there needs much time for detail R&D studies for the real implementation [3]. It was therefore very important to study the beam instability by simulations in order to determine realistic parameters to suppress the beam instability.

Figure 1 shows theoretically given transverse horizontal impedance of one kicker magnets for injection (β=0.7) and extraction (β=1.0) energy regions [4]. The real and imaginary parts of the impedance are shown in the left and right plots, respectively. The revolution frequency of RCS at 400 MeV injection and 3 GeV extraction are 0.614 and 0.84 MHz, respectively. The Lorentz β dependence of the impedance is very strong, where sharp peaks are the characteristic RCS kicker impedances due to cable resonances of the beam induced currents in the kicker magnets.

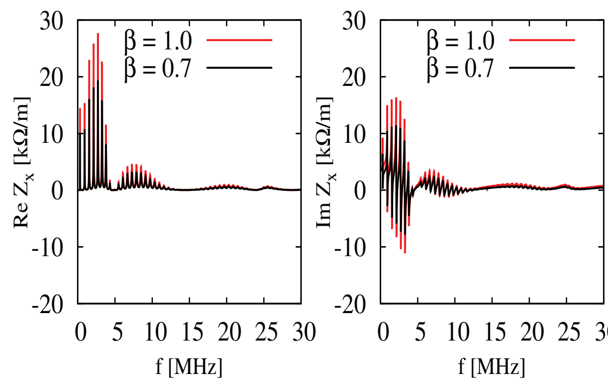

Figure 1: Real (left) and imaginary (right) parts of the measured transverse horizontal impedance of one extraction kicker magnet for injection (β=0.7) and extraction (β=1.0) energy regions.

In order to study beam instability in the RCS, we used ORBIT code that was given new enhancements for beam simulations in synchrotrons [5]. We introduced all realistic time dependent machine parameters including an implementation of the kicker impedance too [6, 7]. We confirmed and reported ORBIT capabilities of realistic space charge and beam instability simulations up to the then maximum 500 kW beam power [6, 7]. In this paper systematic beam instability studies at high intensities, especially 1 MW accomplishment strategy based on simulations and the corresponding measurement results are reported.

In the simulation, we studied in detail the dependence of growth rate on the choice of betatron tune, momentum spread (Δp/p) of the injected beam as well as degree of lattice chromaticity (ζ) correction. Figure 2 shows sextupole (SX) strength factor versus lattice chromaticity as function of time. A strength factor 1 for the entire cycle with SX AC field makes a full correction of the ζ, while it is not corrected at all for a 0 strength factor (OFF). A DC SX field guaranties a full ζ correction only at injection energy but the strength factor decreases with sinusoidal beam energy increase, resulting a time dependent or naturally modulated ζ correction and it makes almost no correction at the top energy. The beam loss at lower energy and beam instability at higher energy can be controlled by using such a SX pattern, especially at high intensity.

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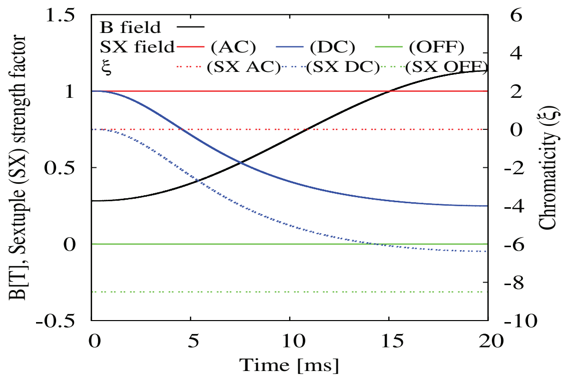

Figure 2: Sextupole field strength versus lattice chromaticity as function of beam energy ramping in the RCS. A careful SX pattern is needed to suppress the beam loss at lower energy and the beam instability at higher energy.

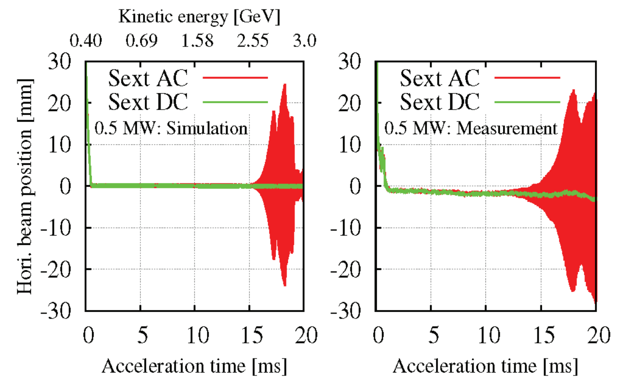

Figure 3: Simulation (left) and measurement (right) of beam growth due to beam instability caused by the transverse impedance of the extraction kicker magnets at 500 kW beam power. The simulation results are found to be consistent with measurements, where beam instability occurs only when ζ is fully corrected throughout the acceleration cycle.

BEAM INSTABILITY UP TO 500 kW AND SCENARIO AT 1 MW BEAM POWER

Figure 3 shows a comparison of the simulation and measurements results for beam growth at 500 kW beam power as reported earlier [7]. The injection energy was 400 MeV for both cases. The horizontal and vertical axes are the acceleration time and the turn-by-turn horizontal beam position at a beam position monitor located few meter upstream of the injection point. The beam instability occurs only when ζ is fully corrected for the entire acceleration cycle by SX AC field but no beam instability occurs for ζ fully corrected at injection energy and naturally reducing the correction factor as a function of time by SX DC field.

We have also reported that the situation changes at 1 MW beam power. Namely, we have found that a careful betatron tune manipulation as a function of time in addition to the reduction of ζ correction as less as possible are required in order to suppress the beam instability at 1 MW. In the mean time many parameters of the machine were also changed for the beam power ramp up. As a result, the simulation was also updated with time to time realistic machine parameters to study the beam instability at 1 MW and possible mitigation.

BEAM INSTABILITY AT 1 MW BEAM POWER AND MITIGATION

In our previous report we presented a possible way to suppress the beam instability at 1 MW by a proper tune manipulation during acceleration even if a full ζ correction (blue dotted line in fig. 2) is applied only at injection [7]. However, in that simulation we used comparatively a narrower $\Delta p/p$ of the injected beam but recently it has been enlarged more than twice (0.18% in rms) than that of previous value. In the updated simulation we realized that a tune manipulation of any pattern is not enough to suppress the beam instability at 1 MW if the above ζ correction is applied. There needs further reduction of the degree of ζ correction, where at best a quarter of the full correction at injection gives complete suppression of the beam instability.

Figure 4 shows a realistic betatron tune manipulation applied for the present study. As betatron tunes are important parameters for the present study, a time dependent tunes for each turn were precisely determined from the measured ones. The horizontal and vertical betatron tunes, ν_x and ν_y at injection are set to be 6.45 and 6.42, respectively, which are then manipulated during acceleration process to be around 6.40 for both planes.

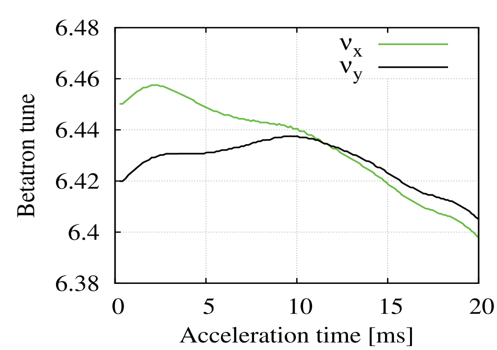

Figure 4: Realistic time dependent betatron tunes obtained from the measured data were applied for the present study.

Figure 5 shows 1 MW simulation results for the beam instability dependence on the degree of ζ correction controlled by the SX fields. The data in red color corresponds to a full ζ correction at injection energy (blue dotted line in fig. 2) by SX DC ×1, where other colors correspond for further scaling down the SX field to reduce the degree of ζ correction. The green color data shows for a case of no ζ correction at all (green dotted line in fig. 2) by keeping the SX off for the entire cycle. Significant beam instability occurs even reducing the degree of ζ correction to half at injection and it shows further reduction of the ζ correction is needed for a complete suppression of the beam instability. There has no significant difference on the results between a quarter and no ζ correction.

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Figure 6 shows the corresponding experimental results at 1 MW beam power. The simulation results are well reproduced in the measurements. An acceleration of 1 MW beam has been successfully achieved by a proper betatron tune manipulation and sufficiently reducing the degree of ζ correction. Enough wider longitudinal injected beam, maximum longitudinal and moderate transverse injection painting make sufficient reduction of the space charge at lower energy. A careful choice of the betatron tunes guaranties beam loss mitigation at lower energy even for no ζ correction at all. On the other hand, in this case one can also minimize the 3rd order resonances further excited by the SX fields.

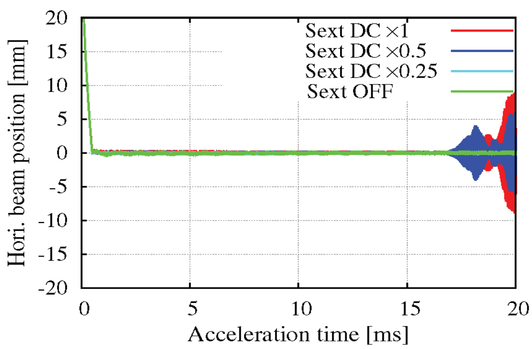

Figure 5: Simulation results of beam instability at 1 MW for different degrees of ζ correction. A quarter of full ζ correction at injection is necessary in order to suppress the beam instability completely.

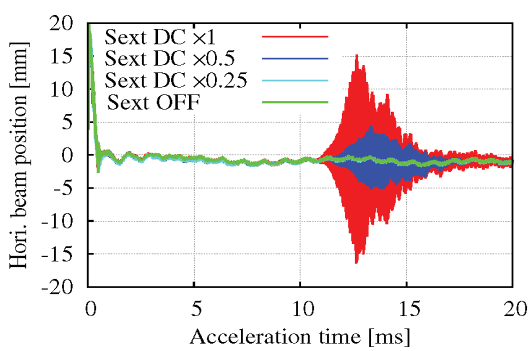

Figure 6: Measurement results of beam instability at 1 MW for different degrees of ζ correction. The measurement results well reproduced the simulated beam instability scenarios as shown in Fig. 5.

The difference the simulation and the measurement can be noticed on the growth rate and its appearance. The measured growth rate is stronger and also the beam instability occurs much earlier as compared to those in simulation. The difference is bigger than it was up to 500 kW beam power as shown in Fig. 3. We made further efforts in addition to those reported earlier [7] but no significant improvement is achieved yet. The difference for such high intensity may comes from the less reproducibility of the measured longitudinal bunch size in the simulation, especially in the later half of the acceleration cycle. Further efforts are on going to improve the bunching factor similar to that obtained in the measurement. Moreover, in the present ORBIT code only one impedance node can be defined, while there are a total of 8 kicker magnets placed in about 8 meter long space and there exists also one quadrupole magnet in between the 3rd and 4th kicker magnets. The kicker impedance for 1 magnets is multiplied by 8 and applied at a place where horizontal optical beta function (β_x) has an average value in kicker location. It is thus planed to use newly developed PyOrbit code [8], which is free from defining the number of such impedance nodes.

SUMMARY AND OUTLOOK

The beam instabilities caused by the transverse impedance of the extraction kicker magnets in the 3-GeV RCS J-PARC are studied up to the designed 1 MW beam power. For realistic simulations, the ORBIT code was used by introducing all relevant time dependent machine parameters. The simulation set the degree of chromaticity correction in order to suppress the beam instability and was successfully reproduced in the measurements later. A successful acceleration of 1 MW beam has been achieved by a quarter of the ζ correction at injection energy. The simulation gives very similar beam instability scenarios as confirmed in the measurements but for detail comparison of the beam growth rate and time structure of the beam instability, efforts are ongoing to improve the simulation results.

It has been realized that kicker impedance in the RCS puts a lots of constraint on the choice of beam parameters. The RCS operation with 1 MW beam power has not yet been started but in order to meet the requirements of the downstream multi-users facilities there should have enough flexibility on the parameter space. Further more than the designed 1 MW beam power in the RCS is also under study. Naturally, such a beam instability issue becomes more serious for higher beam power as we have also understand by some preliminary simulations. It is very important to seriously consider an ultimate measures to reduce the kicker impedance itself.

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