BEAM INSTABILITY SUPPRESSION IN THE 3-GeV RCS OF J-PARC

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Abstract

In the 3-GeV Rapid Cycling Synchrotron (RCS) of Japan Proton Accelerator Research Complex, significant beam instability is caused by the transverse impedance of the extraction kicker magnets. The hardware measures to reduce the kicker impedance are in progress slowly, which needs extensive R&D studies for practical implementation. In order to study a detail beam instability nature we used ORBIT code by successfully introducing all realistic time dependent machine parameters including the impedance. We studied a detail of the parameter dependence such as the degree of chromaticity correction, choice of betatron tunes as well as momentum spread of the injected beam in order to determine realistic parameters to suppress the beam instability at 1 MW. The simulation results are well reproduced in the measurements, while an acceleration of 1 MW beam has also been successfully accomplished. The beam instability scenarios at high intensities and measures to accomplish 1 MW beam acceleration based on the 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 intensity proton accelerator, designed for 1 MW beam power 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 at a repetition rate of 25 Hz. The extracted beam is simultaneously delivered to the MLF as well as inject into the MR. The beam power for the user operation so far reached to half of the designed 1 MW but systematic studies have already been reached to the designed beam power [2].

Table 1 gives a list of RCS key parameters, especially those are strongly connected to the beam growth occurred due to the beam instability. The time independent parameters are given in the upper part, where the time dependent ones are listed in the lower part of the table. The nominal ν_x and ν_y set at injection are usually varied throughout the acceleration in order to mitigate the beam losses as well as the beam instability. The ξ_x, ξ_y are thus being slightly changed accordingly but those can be corrected to any degrees by using Sextupole magnets.

Similar to any such high intensity machines, the beam instability at 1 MW beam power was also a concern in the RCS [3]. The impedance sources throughout the machine were controlled to be as minimum as possible but unfortunately the impedances of RCS 8 extraction kicker magnets (KM) remains as significant beam instability sources.

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Table 1: Main Parameters of the RCS [1]

Name	Value
Circumference [m]	348.333
Transition energy [GeV]	9
Repetition rate [Hz]	25
Harmonic number (h)	2
Number of bunches	2
Output beam power [MW]	1
Number of particles per bunch	4.165×10^{13}
$\Delta p/p$ acceptance [%]	1

Name	Injection	Extraction
Kinetic energy [GeV]	0.4	3
Rev. frequency (f_0) [MHz]	0.614	0.84
Bunching factor (B_f)	0.45	0.2
Slippage factor (η)	-0.48	-0.047
Bunch length [m]	160	60
Betatron tune (ν_x, ν_y)	6.45, 6.42	variable
Natural chromaticity (ξ_x, ξ_y)	-8.5, -8.8	variable
Synchrotron tune (ν_s)	0.0058	0.0005

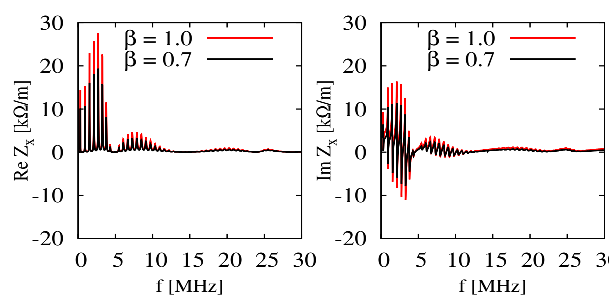

Figure 1: Real (left) and imaginary (right) parts of the transverse horizontal impedance of one extraction KM for injection (β=0.7) and extraction (β=1.0) energy regions.

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 impedance strongly depends on the Lorentz β, where sharp peaks are the characteristic RCS kicker impedances due to cable resonances of the beam induced currents in the kicker magnets.

The beam instability caused by the KM impedance are studied in detail in the simulation by using ORBIT 3D space charge code in order to determine realistic parameters to suppress the beam instability at the designed 1 MW beam power. A detail of the simulation strategies and the corresponding measurement results are reported in this paper.

ORBIT SIMULATION BACKGROUND

Although a direct measure in order to reduce the KM impedance has already been proposed and also experimentally demonstrated, but there needs much efforts and time for detail R&D studies for the real implementation [5]. It was therefore very important to study the beam instability in details by simulations in order to determine realistic parameters to suppress the beam instability. In this study we used ORBIT simulation code which was recently available for beam simulations in synchrotrons [6]. At first we concentrated on a very precise space charge simulation as theoretically the space charge effect on the beam instabilities are intensively discussed recently [7–10]. For that purpose, all realistic time dependent machine parameters were first introduced and later the code was made capable of taking into account a time or β dependent impedance namely, turn-by-turn. We have confirmed and reported ORBIT capabilities of realistic space charge and beam instability simulations up to the then maximum 0.5 MW beam power [11, 12].

Figure 2 shows sextupole (SX) strength factor versus lattice chromaticity (ξ) as function of time. A strength factor 1 for the entire cycle with AC field of the SX makes a full correction of the ξ, while it is not corrected at all for a 0 strength factor (OFF). A DC SX field guaranties a full ξ correction only at injection energy but the strength factor decreases with sinusoidal beam energy increase, resulting a time dependent or naturally modulated ξ correction and 70% of the ξ remains uncorrected 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. In the ORBIT code we have introduced any variations of the SX fields in order to study the beam instability on the degree of ξ correction pattern.

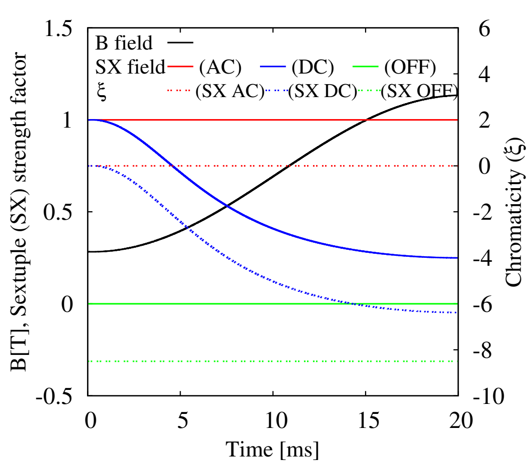

Figure 2: SX field strength versus ξ as function of beam energy ramp up in the RCS. A careful SX pattern is needed to mitigate the beam loss and beam instability at the lower and higher energies, respectively.

Up to around 0.5 MW beam power, we found in both simulations and the measurements that the beam instability occurs only when ξ is fully corrected for the entire acceleration cycle by SX AC field but no beam instability occurs for ξ fully corrected only at injection energy and naturally reducing the correction factor as a function of time by SX DC field also named as DC ξ correction. However, the simulation shows very critical beam instability scenario beyond 0.5 MW beam power. We take into accounts many measures to stabilize 1 MW beam power as presented in detail in the following section.

BEAM INSTABILITY MITIGATION AT 1 MW BEAM POWER

In order to stabilize 1 MW beam power, the following three measures we studied in detail in the simulation.

- A careful betatron tune variation throughout the acceleration cycle.
- Further reduction of the degree of DC ξ correction.
- Reduction of the momentum spread (Δp/p) of the injected beam.

Figure 3 shows a typical betatron tune manipulation that was found to be one good candidate to successfully stabilize the beam instability at 1 MW. The horizontal and vertical tunes, ν_x and ν_y) are typically set to be 6.45 and 6.42 respectively but they are manipulated and set to be almost same of 6.40 for both planes.

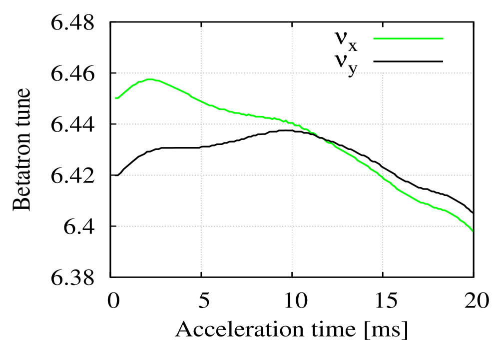

Figure 3: Realistic time dependent betatron tunes obtained from the measured data were applied for the present study.

The advantage of realistic tune tracking has been observed even at 0.75 MW beam power. Figure 4 shows such a comparison of the simulated results to those of measurements for a beam power of 0.75 MW. The horizontal axis the acceleration time, where vertical axis is the turn by turn beam position measured by a beam position monitor (BPM) located at the RCS injection region. The beam position offset at the beginning is due to the time dependent transverse injection painting orbit, where beam instability is observed at the later of the cycle when no manipulation of ν_x and ν_y are applied (red). In this case, ν_x and ν_y at injection are set to be 6.45 and 6.42 are kept same over time until the end of the cycle. As expected in the simulation, the beam instability can be successfully suppressed and completely stabilized also in the corresponding measurement (green) by utilizing ν_x and ν_y manipulations as shown in Fig. 3.

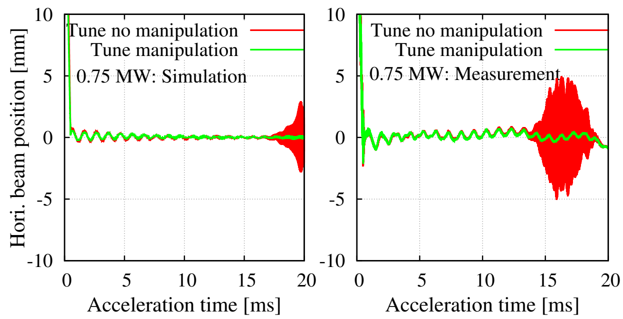

Figure 4: Simulation (left) and measurement (right) of beam growth due to beam instability caused by the transverse impedance of the extraction kicker magnets at 0.75 MW beam power. A proper tune manipulation as proposed in the simulation (see Fig. 3) to stabilize the beam is found to be consistent with measurement result.

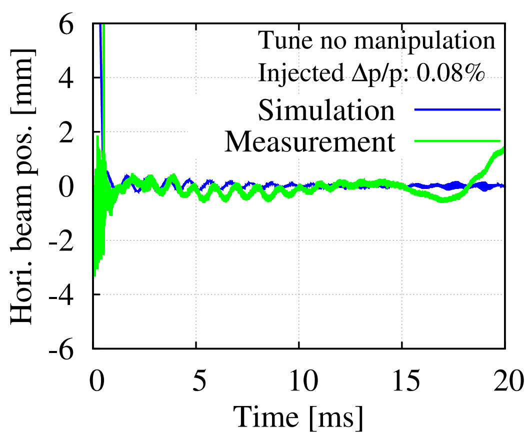

Figure 5: A narrower Δp/p is also an useful way to utilize space charge damping in order to stabilize the beam.

The rms Δp/p of the injected beam was 0.18% for both cases, where DC ξ correction (blue dotted line in Fig. 2) was applied. The transverse injection painting area was 100π mm mrad, where a maximum longitudinal injection painting were applied. The measured B_f was obtained to be same as given in the Table 1.

An alternate way as we also proposed was to choose a narrower Δp/p of the injected beam. We studied for a case when Δp/p is nearly half (0.08%) from that of typical (0.18%). Figure 5 shows a comparison between simulation (blue) and measurement results for the same 0.75 MW beam power. The beam instability which occurred for an wider Δp/p (0.18%) of the injected beam (red in Fig. 4) can be successfully suppressed by using a narrower Δp/p (0.08%) of the injected beam. The B_f by using a narrower Δp/p was obtained to be 15~20% lower as compared to that of using an wider one. As a result, the space charge damping becomes more effective in this case to stabilize the beam.

However, in contrast to the beam instability issues, an wider Δp/p is more suitable in order to minimize the space charge effect at lower energy for 1 MW beam power. Although, beam instability up to 0.75 MW can be suppressed by a given tune manipulation even if a DC ξ correction is applied but that does not confirm the beam instability suppression at 1 MW for any available manipulation patterns. A further reduction, specifically a quarter of the degree of DC ξ correction is a must in order to accomplish 1 MW beam power without any beam instability.

Figure 6 shows 1 MW simulation results for the beam instability dependence on the degree of ξ correction controlled by the SX DC fields. The data in red color corresponds to a full ξ 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 ξ correction. The green color data shows for a case of no ξ 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 ξ correction to half at injection and it shows further reduction of the ξ correction is needed for a complete suppression of the beam instability. A quarter of the DC ξ correction (by DC ×0.25) or even no ξ correction (by SX OFF) gives a complete suppression of the beam instability at 1 MW.

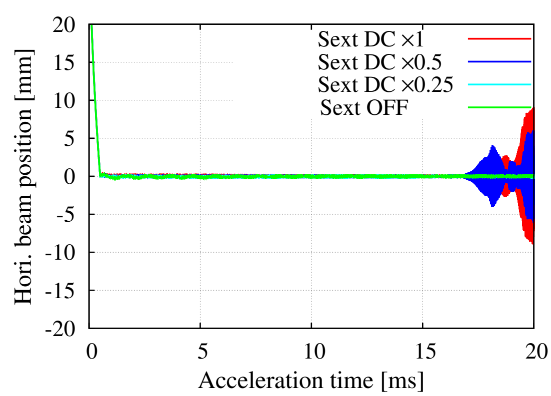

Figure 6: Simulation results of beam instability at 1 MW for different degrees of ξ correction. A quarter of the full ξ correction at injection is at least necessary in order to suppress the beam instability completely.

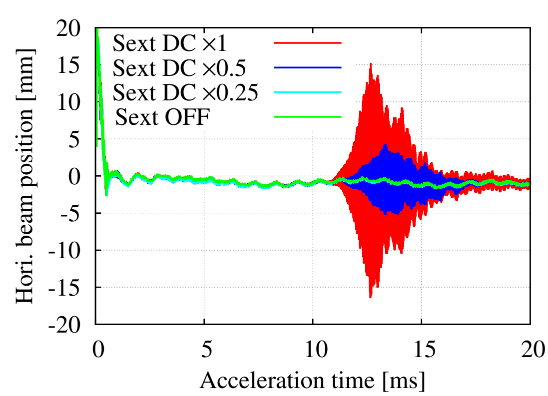

Figure 7: Measurement results of beam instability at 1 MW for different degrees of ξ correction. The measurement results well reproduced the simulated beam instability scenarios as shown in Fig. 6.

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. We made further efforts in addition to those reported earlier [12] but no significant improvement is achieved yet. The difference at 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 KM 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 KM location. It is thus planed to use newly developed PyOrbit code [13], which is free from defining the number of such impedance nodes.

RECENT STUDIES

Recently, we have also studied the beam instability dependence on the transverse painting area as well as further dynamic variation of the ξ during acceleration by updating the SX power supplies. Those are necessary for further improvement of the extracted beam quality, especially for the MR. For a particular choice of the betatron tunes, a DC ξ correction gives a better quality of the beam up until the beam instability occurs at the later period. In order to suppress the beam instability in such a case, we have introduced rather an extra ξ, nearly 1.4 times higher than natural ξ from the mid of the acceleration cycle by dynamically varying the SX fields.

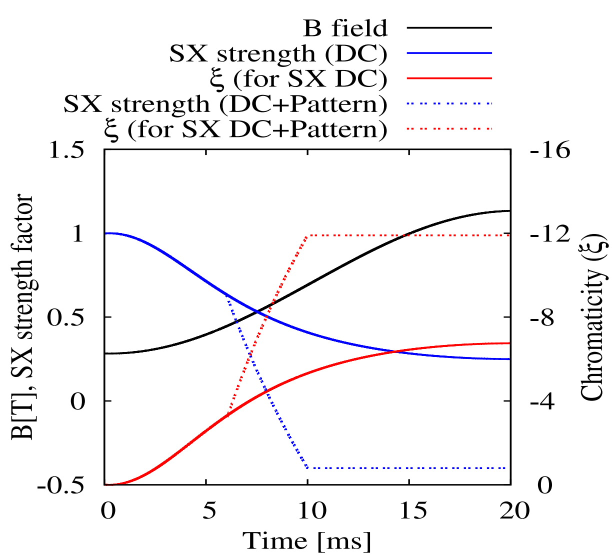

Figure 8: A dynamic change of the SX field to utilize ξ correction at lower energy but to introduce an extra ξ at higher energy in order to further suppression of the beam instability in a wider choice of the parameter space.

Figure 8 shows such dynamically varied SX pattern (dashed blue curve) and the corresponding calculated lattice ξ (broken red curve) along with as usual SX DC field pattern (solid blue curve) and the ξ (solid red curve). In the new pattern, SX with DC field is kept up to 6 ms, linearly varied to be -1.4 times reverse strength factor from that required for full ξ correction at 12 ms and the strength factor is kept constant throughout the rest of the cycle. The ξ at 12 ms becomes -12 and becomes constant up to the end of 20 ms. The simulation studies shows that a beam position growth of even more than ±5 mm can be successfully stabilized by using such a pattern, where no extra beam losses appears at the later cycle even with such a large ξ. Detail experimental studies will be carried out in October, 2016, when SX power supply system will be upgraded capable of operation for such a purpose.

SUMMARY AND OUTLOOK

In order to study the beam instabilities caused by the transverse impedance of the RCS extraction kicker magnets, the ORBIT space charge code was used by introducing all realistic time dependent machine parameters including the kicker impedance itself. The main motivation was to determined a realistic parameter set in order to accomplish the designed 1 MW beam power. Based on the detail systematic studies we have found that a proper manipulation of the betatron tunes and a quarter of the DC ξ correction are at least necessary in order to stabilize 1 MW beam. The detail beam instability nature as obtained in the simulation are nicely reproduced in the measurements and a successful acceleration of 1 MW beam has also been achieved. However, for detail comparison of the beam growth rate and time structure of the beam instability, further efforts in the simulation are in progress.

We have also discussed further dynamic change of the Sextupole field in order to introduce an extra ξ in the later half of the acceleration cycle. One can have at least two benefits by such a ξ variation as a function of time. The ξ, if required can be applied at the lower energy but reversely an extra ξ can be introduced later in order to avoid any beam instability occurs at the later cycle. The corresponding detail experimental studies are planned to be carried out in the next beam study at the end of 2016.

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 but the beam instability is one of the most concerning issues for such a higher beam power. It is very important to seriously consider an ultimate measures to reduce the kicker impedance itself.

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