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COMPARISON BETWEEN MEASUREMENTS AND ORBIT CODE SIMULATIONS FOR BEAM INSTABILITIES DUE TO KICKER IMPEDANCE IN THE 3-GeV RCS OF J-PARC

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Abstract

The transverse impedance of the extraction kicker magnets is the most dominant beam instability source in the 3-GeV RCS of J-PARC. The beam instability occurs when the chromaticity is fully corrected during acceleration but on the other hand full chromatic correction only at the injection energy makes no instabilities at least for a beam power up to 500 kW. Recently, we have succeeded introducing realistic time dependent impedances in the ORBIT simulation code and using that the corresponding simulation results are found to be quite consistent to those with measurements. As a result, the simulation was also performed for the designed 1 MW beam in order to check beam instability scenario for such a high intensity beam. The beam instability occurs even a full chromatic correction is done only at the injection energy but betatron tunes are fixed during acceleration process. However, the situation can be avoided by utilizing a proper tune manipulation so as to stabilize the beam. The measurements results and comparison between corresponding simulation results for equivalent beam power up to 500 kW including 1 MW simulation 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 are accelerated to 3 GeV at a repetition rate of 25 Hz and simultaneously delivered to the neutron and muon production targets in the Material and Life Science Experimental Facility as well as to the 50-GeV Main Ring synchrotron. 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 more than 500 kW with sufficiently low loss has already been demonstrated in recent beam studies [2]. It is thus believed that there remains almost no big issue for achieving the design goal, where beam studies for further higher intensities towards 1 MW will be started in the near future when ion source and the front end of the Linac will be upgraded to the final specifications [2].

For a MW-class beam, it is very essential to perform numerical simulation studies with all possible beam instability sources in the RCS, where transverse impedance of the extraction kicker magnets are identified as the most dominant source for beam instability [3]. There are a total of 8 extraction kicker magnets used for beam extraction from the RCS. The beam in the horizontal direction is gradually moved outside from the central trajectory by each kicker with a magnetic field of about 2.5 mT m and finally 3 DC septum magnets do the rest [4]. Experimentally detail beam instability studies were carried out with beam power up to 500 kW. The chromaticity fully corrected for the entire acceleration process (AC chromatic correction) causes beam instability for an equivalent beam power exceeding even around 250 kW but no instability occurs when chromaticity is fully corrected only at the injection energy (DC chromatic correction) even for a 500 kW beam. In order investigate such a beam instability through beam simulation so as to know a reliable scenario for designed 1 MW beam, recently we implemented a realistic time dependent impedances of the kicker magnets in the ORBIT code [5]. The ORBIT code itself has also been well updated for realistic beam simulation in synchrotrons.

IMPLEMENTATION OF KICKER IMPEDANCE IN ORBIT SIMULATION

A realistic beam simulation with any impedance source in synchrotrons obviously requires the ability to cope with time dependent change of many parameters, such as beam momentum, revolution frequency, impedance itself and similar parameters. Figure 1 shows the transverse horizontal impedances of one RCS kicker magnet given theoretically for relativistic ($\beta = 1.0$) and non-relativistic ($\beta = 0.5$) energies [3]. The left and right figures are for the real and imaginary parts of impedance, respectively. The RCS revolution frequencies at 181 and 400 MeV injection energies are 0.47 and 0.614, respectively, while it is 0.84 MHz at the extraction energy. One can see a strong Lorentz β dependence of the impedance, where the sharp peaks are the characteristic RCS kicker impedances due to the cable resonances of the beam-induced currents in the kicker magnets.

We introduced such a time dependent impedance in the ORBIT simulation code. The impedances tables for β 0.5 to 1.0 in 0.1 step are provided externally in the program. The program then generates an extrapolated impedance so as a transverse dipole kick essentially for every turn. However, the present ORBIT version can handle only with one impedance node instead of 8 for 8 kickers in the RCS. The 8 kickers are placed in about 8 m and a horizontally focusing quadrupole magnet is also exist in between 3rd and 4th kickers. As a result, we introduced the impedance node at a place where horizontal optical beta function (β_x) has an average value as shown in Fig. 2. The strength of the impedances shown in Fig. 1 are multiplied by 8 to take into

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account it for all kickers. As for the longitudinal impedance, the effect on beam is comparatively much smaller and in the real machine it is compensated by the rf beam loading. It is thus not included in the present simulation.

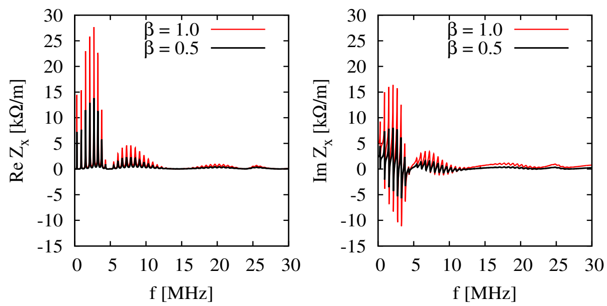

Figure 1: Real (left) and imaginary (right) parts of the measured transverse impedance of one kicker magnets for relativistic (β=1.0) and non-relativistic (β=0.5) energies.

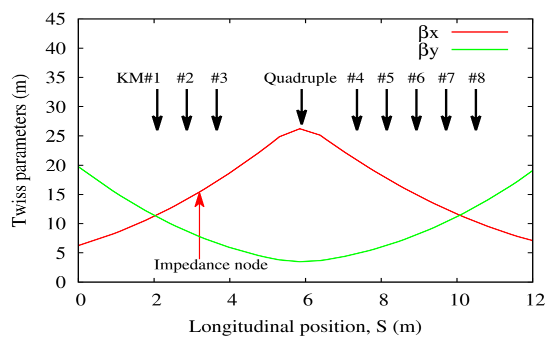

Figure 2: Twiss parameters (β_x and β_x) in the extraction kicker region. The impedance node in the simulation is placed at an average β_x as shown by the red arrow.

TRANSVERSE BEAM INSTABILITIES: COMPARISON BETWEEN MEASUREMENTS AND SIMULATIONS

Figure 3 shows the transverse beam instabilities measured for an equivalent beam power of 500 kW. The horizontal axis is the time, where vertical axis is the turn-by-turn horizontal beam position measured by a BPM (Beam Position Monitor). The injected beam energy was 181 MeV (left) and 400 MeV (right) but the extraction energy was same (3 GeV) for both cases. There occur no beam instabilities for DC chromatic correction but beam instabilities can be seen when AC chromatic correction is done as shown by black and red lines, respectively. The beam position offset near injection timing was due to the time dependent offset of the circulating orbit for painting injection as the BPM locates in the injection region, where 1 kHz oscillations clearly seen up to the mid acceleration period for 181 MeV injection was due to the ripples in the bending magnets power supplies but it was corrected by the orbit correctors for the 400 MeV injection. The growth rate for the present higher injection energy of 400 MeV was measured to be significantly stronger than that for the 181 MeV injection. Theoretically it has been discussed that the beam instability can be suppressed by the space charge effects, which was thus less significant for lower space charge effect at the higher injection energy at 400 MeV [6]. The impedance for the relativistic beams also becomes higher. As a result, 400 MeV injected beam tends to be more unstable than the 181 MeV one. The corresponding beam simulation results shown in Fig. 4 are also found to reproduce the experimental results fairly well.

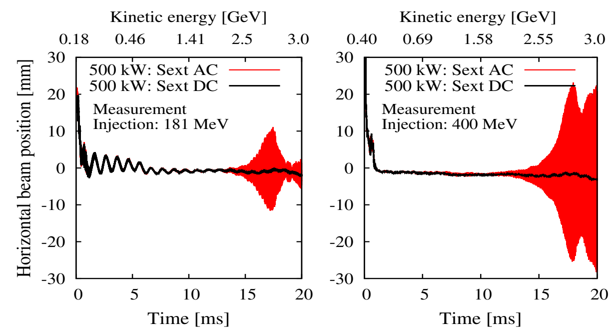

Figure 3: Measurement results of beam instability for 500 kW equivalent beam. The instability occurs only when AC chromatic correction is done. The 400 MeV injected beam (right) is more unstable than that the 181 MeV one (left).

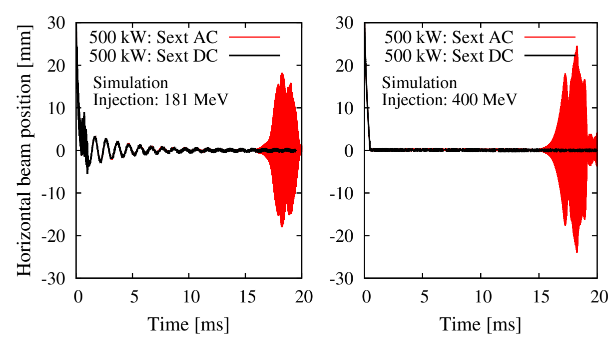

Figure 4: Simulation results for the corresponding measurements as shown in Fig. 3.

The intensity dependence of the measured and simulated growth rates for AC chromatic correction are shown in Figs. 5 and 6, respectively. The instability occurs for a beam power exceeding 250 kW and growth rate naturally increases with increasing beam power. The simulation results here also show quite similar behaviors as measurements. However, one can notice that simulation shows a comparatively stronger growth rate as well as the instability occurs in the later period as compared to those in measurements. We checked by giving impedance tables for β 0.05 step (instead of 0.1 step) but the results were almost unchanged. An increase of macro particles by a factor of 3 (2.8×10^6 for space charge mesh of $64\times 64\times 64$) also did not give any significant change. Further efforts are ongoing.

Usually sextupoles are used with DC patterns so as for full chromatic correction only at the injection energy and thus no beam instability occurs for the present operation

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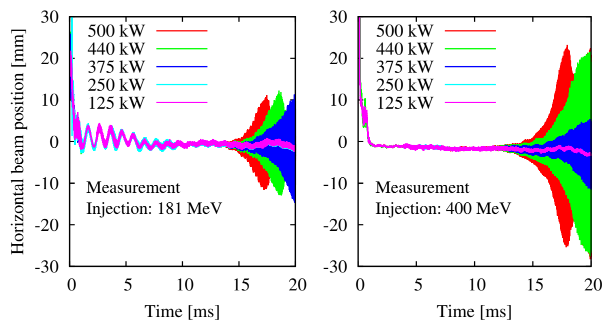

Figure 5: Measurement results of intensity dependence growth rates for AC chromatic correction.

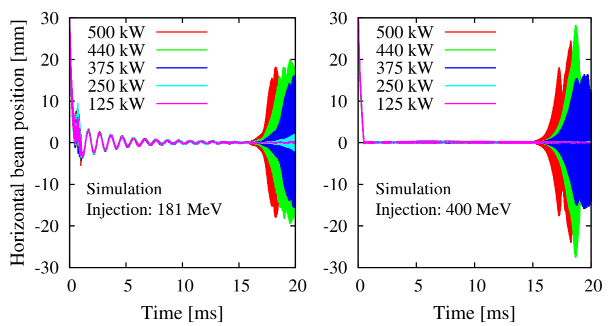

Figure 6: Simulation results for intensity dependence on growth rates show similar behaviors as measurements.

with 300 KW as well as up to around 500 kW. However, even with such a DC chromatic correction it is important to check the beam instability scenario for the design 1 MW beam as the beam power would be twice more than that achieved so far. Beam studies towards 1 MW goal is planed to start in the near future.

Simulation for 1 MW Beam

Figure 7 shows the simulation results for a particular beam instability scenario for 1 MW beam. A DC chromatic correction is applied and a case study was done for beam instability dependence on betatron tunes (ν_x and ν_y). The betatron tunes as a function of the acceleration time is shown in the left figure. The 1st case is with no tune manipulation (kept fixed) of either horizontal (ν_x) or vertical (ν_y) one, where the 2nd case is with a typical manipulation of both tunes during acceleration process as shown by the red and green lines, respectively. The beam instability for 1 MW occurs even for a DC chromatic correction for the 1st case when betatron tunes are kept fixed throughout the whole acceleration process and it is thus a big concern but fortunately in the same time it is also found that the instability can be suppressed enough and beam can be stabilized by using a proper tune manipulation. The present simulation result for 1 MW beam thus has a great influence in order to consider for reducing kicker impedances through necessary measures from the hardware point of view [7] even though a tune manipulation during acceleration process could be an alternate way to avoid such a beam instability.

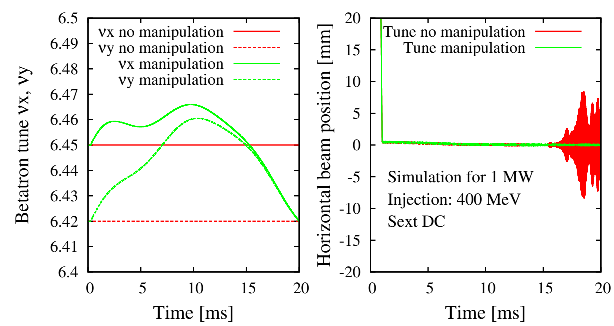

Figure 7: Simulation results for 1 MW beam. Beam instability occurs even for DC chromatic correction in case betatron tunes are kept fixed throughout the acceleration process.

SUMMARY

The realistic time dependent impedance of the J-PARC 3-GeV RCS extraction kickers are successfully implemented in the ORBIT beam simulation code. The simulation results show similar beam instability behaviors as compared to those measured ones. The beam instability occurs only when chromaticity is fully corrected throughout the acceleration process but no instability occurs for full chromatic correction only at the injection energy for an equivalent beam power up to 500 KW.

However, simulation result for 1 MW beam shows that the beam instability occurs even for a DC chromatic correction in case betatron tunes are kept fixed throughout the whole acceleration process and is thus one concern towards the design goal. A proper tune manipulation on the other hand shows that such a instability can be suppressed enough so as to stabilized the beam. It is thus very important to consider reducing kicker impedance itself through appropriate measures even though tune manipulation remains as an alternate option.

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