SIMULATION STUDIES OF TRANSVERSE BEAM INSTABILITIES AND MEASURES BEYOND 1 MW BEAM POWER IN THE 3-GeV RCS OF J-PARC

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Abstract

The beam instability caused by the transverse impedance of extraction kicker magnets (KM) is one of the main issue in the 3-GeV Rapid Cycling Synchrotron of Japan Proton Accelerator Research Complex. The designed 1 MW beam power has recently been accomplished by careful parameter optimization, such as betatron tunes and by reducing the degree of chromaticity (ξ) correction. Realistic parameters as determined by systematic simulation studies performed by using ORBIT 3D code were consistent with measurement results. The extracted beam from the RCS is simultaneously delivered to the MLF (Material and Life Science Experimental Facility) and the MR (Main Ring Synchrotron) at a repetition rate of 25 Hz. In order to cope with upgrades in the downstream facilities, a beam power of 1.5 MW has to be realized in the RCS. However, the simulation results show that the beam is unstable beyond 1 MW even for no ξ correction. A reduction of the KM impedance by at least a half is required in order to achieve 1.5 MW beam power. Furthermore, such a reduction of the KM impedance also enables to realize even 2 MW beam power in the RCS.

INTRODUCTION

Figure 1 shows a layout of the 3-GeV RCS (Rapid Cycling Synchrotron) of J-PARC (Japan Proton Accelerator Research Complex) [1]. The RCS is designed for 1 MW beam power (8.33×10^{13} protons/pulse) for the muon and neutron production targets at the MLF (Material and Life Science Facility) as well as for the MR (Main Ring Synchrotron). The beam energy at injection is 0.4 GeV, while it is accelerated up to 3-GeV and simultaneously delivered to the above two facilities at a repetition rate of 25 Hz. RCS beam power for the routine operation has been reached up to 0.5 MW, but an acceleration of 1 MW beam power has already been demonstrated as well as operation parameters at 1 MW beam power have also been determined [2].

The transverse beam instability cause by the transverse impedance from 8 pulse extraction kicker magnets is the most significant issue in the RCS [3, 4]. Systematic simulation studied were performed by using ORBIT 3D space charge code by introducing all realistic time dependent machine parameters including time dependent impedances as well. In the simulation, realistic strategy to accomplish the designed 1 MW beam power was determined by utilizing a proper betatron tune variation during acceleration process as well as by controlling the degree of chromaticity (ξ) correction as minimum as possible. The simulation results were well consistent with measurement results, while 1 MW beam power was accomplished by utilizing no ξ correction for the entire acceleration cycle.

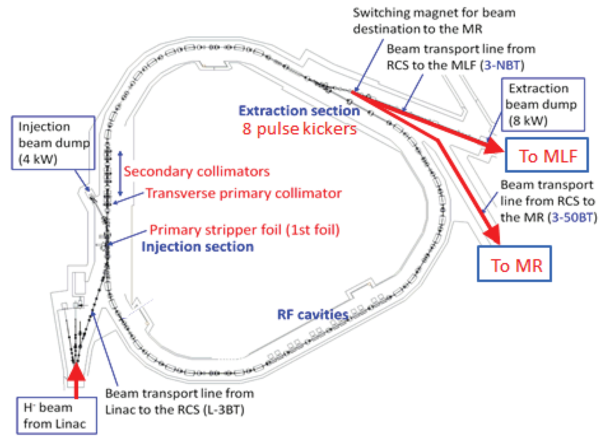

Figure 1: Layout of the 3-GeV RCS of J-PARC. The transverse impedance of the extraction KM is the main and a significant beam instability source in the RCS.

However, in order to cope with upgrades of the downstream facilities, a mid-term plan for the RCS beam power upgrade has been set to 1.5 MW. Obviously, present KM impedance is one of the serious concerns to realize such a beam power. A trial to reduce the KM impedance nearly to a half was experimentally demonstrated, but detail R&D studies are required for a realistic implementation [5]. At this stage, detail simulation studies are therefore very essential in order to determine realistic parameters to suppress the beam instability beyond 1 MW. Introducing an extra ξ in the middle of acceleration is found to be very effective at around 0.8 MW, particularly for the MR beam (smaller transverse injection painting area). It can be also be applied beyond 1 MW for the designed transverse injection painting. The detail studies are ongoing at present. On the other hand, it is also important to check whether the given reduced KM impedance is sufficient or not in order to stabilize 1.5 MW beam power. In the present study we have taken into account newly given reduced KM impedance and found that the beam can be successfully stabilized even up to 2 MW if such a scheme for the KM impedance reduction is implemented.

In this paper, we first present simulation and the corresponding measurement results of beam instability up to 1 MW beam power. Next, we explain the reason and strategy to upgrade the RCS beam power to 1.5 MW. The beam instability scenarios up to 2 MW beam power at the presence of the present KM impedance and by taking into account newly given reduced KM impedance are finally presented.

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BEAM INSTABILITY AT 1 MW BEAM POWER

Figure 2 shows comparison of beam instability results between simulation (left) and measured (right) at 1 MW beam power. In addition to a proper betatron tune manipulation, especially the horizontal one (ν_x), the degree of ξ correction was reduced to be as minimum as possible to suppress the beam instability at 1 MW. The beam instability scenarios and necessary measures as obtained in the simulation were well consistent in the corresponding measurements. Here, "SX DC $\times$1" means SX DC full strength for a full ξ correction only at the injection energy but the strength factor naturally becomes weaken due to beam energy ramping, resulting a 75% of the natural ξ remaining at the extraction energy. The plots in blue and sky blue colors correspond to further reduction of the degree of ξ correction to half and a quarter at injection, respectively by scaling down SX DC $\times$1 field. The operation parameter for 1 MW was determined as shown by the data in green color, where no ξ correction was applied by keeping the "SX OFF" throughout the acceleration cycle.

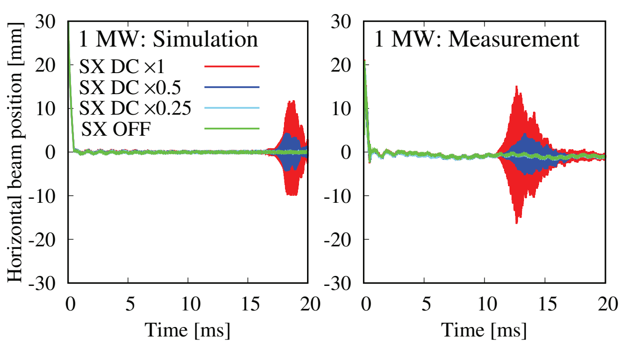

Figure 2: Comparison of simulation (left) and measurement (right) results of beam instability scenarios and measures at 1 MW beam power. The designed 1 MW beam power was accomplished by turning SX off (no ξ correction) for the entire cycle.

RCS BEAM POWER UPGRADE SCENARIO AND THE STRATEGY

Figure 3 shows RCS beam sharing scenarios between MLF and MR at the present (top) and upgraded (bottom) MR cycles of 2.48 s and 1 s, respectively for the FX (Fast extraction) operation. As RCS operates at 25 Hz, the beam sharing ratio at present between MLF and MR is 0.935 (93.5%) : 0.065 (6.5%), while it becomes 0.84 (84%): 0.16 (16%) for the upgraded MR cycle of about 1 s soon [6]. In order to ensure 1 MW beam power at the present MLF target, RCS has to provide nearly 20% higher protons/pulse from that of designed 8.33×10^{13}. That requires RCS to realize 1.2 MW equivalent beam power. In addition, construction of a 2nd target station at the MLF with a lower duty is also under planned. As a result, a mid-term plan for the RCS beam power upgrade is set at 1.5 MW. The corresponding protons in the RCS is calculated to be as high as 1.25×10^{14}/pulse. A

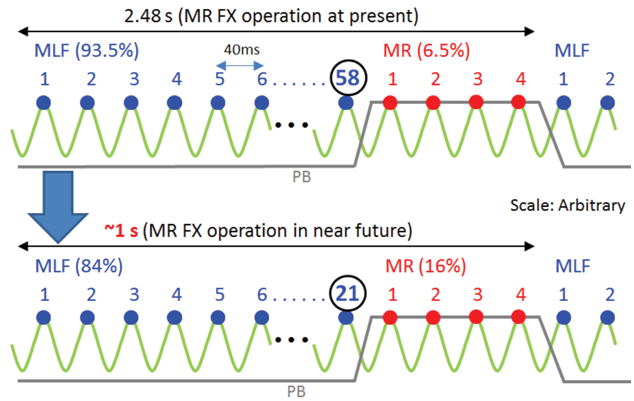

Figure 3: RCS beam sharing strategies to the MLF and MR at the present and future FX operation cycle of the MR. In order to ensure 1 MW beam power at the present MLF target, RCS has to realize at least 1.5 MW beam power due to such and upgrade of the MR cycle as well as when a 2nd target station is constructed at the MLF.

combination of LINAC peak current and the injection pulse length increasing by about 20% of each is an effective way to achieve 1.5 MW beam power in the RCS.

BEAM INSTABILITY SCENARIO BEYOND 1 MW BEAM POWER

In the presence of huge impedance of the present KM, the beam instability scenario beyond 1 MW beam power naturally becomes further critical as compared to that at 1 MW. Figure 4 shows the simulated beam growth for above 1 MW beam power, where beam instability occurs even for no ξ correction is done throughout the acceleration cycle. It is thus one of the big issues to exceed 1 MW beam power in the RCS. As a result, direct and efficient way is to reduced the KM impedance itself, which has already been demonstrated recently [5]. The present KM impedance was shown to be reduced by at least a half. We have taken into account newly given reduced impedance for the beam instability simulation beyond 1 MW beam power as presented in the next section.

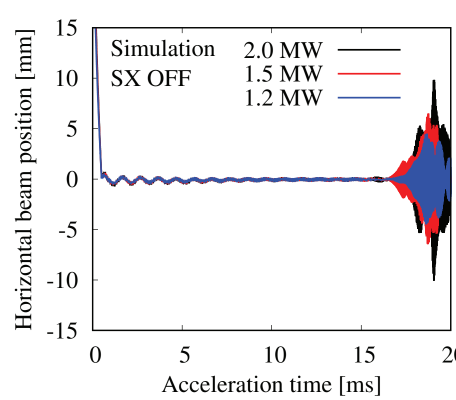

Figure 4: Simulation results of beam growth beyond 1 MW beam power in the RCS. The beam instabilities beyond 1 MW occurs even when no ξ is corrected for the entire cycle.

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SUPPRESSION OF BEAM INSTABILITY BEYOND 1 MW BEAM POWER

In order to suppress the beam instability beyond 1 MW, we have taken into account newly given reduced impedance of the KM. The principle of impedance reduction has already been demonstrated [5]. The idea is to inserting diodes and matched resistors between the pulse forming line of the KM power supplies and the coaxial cables in order to dump the beam induced voltages by the circulating beam when passing through the KM. Figure 5 shows real (top) and imaginary (bottom) parts of the KM impedances plotted for relativistic β of 0.7 (left) and 0.97 (right), correspond to nearly RCS injection and the extraction energies, respectively. The plots in red color represent the present KM impedance named as "terminal open", while those with green color are with diodes and resistors are named as "terminal close". The sharp peaks are the characteristic RCS kicker impedances due to cable resonances of the beam induced currents in the kicker magnets. It can be seen that the impedances in the lower frequency region can be significantly reduced and in average a more than a half reduction can be achieved.

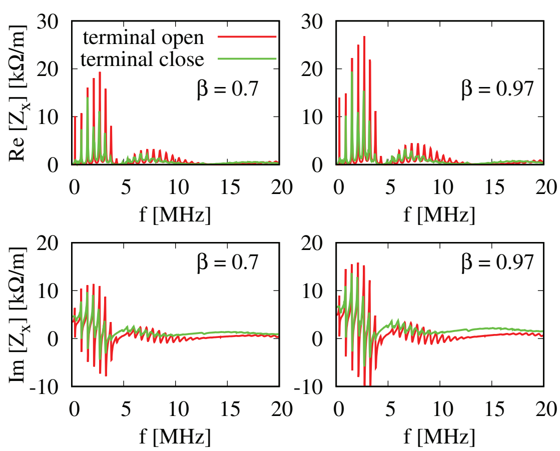

Figure 5: Real (top) and imaginary (bottom) parts of the KM impedances with (red) and without (green) measures for impedance reduction are shown for relativistic β of 0.7 (left) and 0.97 (right), correspond to nearly RCS injection and the extraction energies, respectively.

Figure 6 shows simulation results of the beam growth for 4 different beam power up to twice of the designed 1 MW beam power by taking into account the reduced KM impedance. There occur no beam instabilities at all for any beam power up 2 MW. It is worth mentioning that in contrast to the beam instability scenarios shown in Fig. 4 by using SX OFF, a DC SX field was applied here for a full correction of the ξ at the injection energy. Even though a significant beam instability occurs by applying such a ξ correction at 1 MW (see Fig. 2), a reduction of the KM impedances by about half is shown be very essential in order to stabilize the beam further beyond 1 MW beam power.

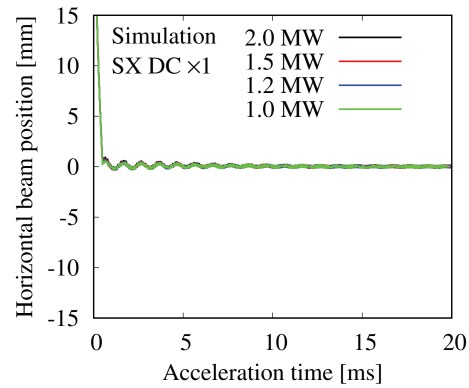

Figure 6: Simulation results of beam growth by taking into account of newly given nearly a half reduced KM impedance. The beam is stable even up to a beam power of 2 MW.

SUMMARY

The beam instability scenarios and useful measures beyond 1 MW beam power in the 3-GeV RCS of J-PARC were studied by using ORBIT 3D simulation code. The transverse impedance of the RCS extraction kicker magnets (KM) is the main and a very significant beam instability source in the RCS. The designed 1 MW beam power has been accomplished by using a proper betatron tune manipulation as a function a time including no ξ correction is applied for the entire acceleration cycle. In order to cope with upgrades in the downstream facilities, RCS has to realize at least 1.5 MW beam power in the near future. However, beam instability beyond 1 MW is further critical and occurs even if the ξ is not corrected at all. As a direct measures, we have taken into account nearly a half reduced KM impedance as the principle has been already demonstrated. The simulation results show that 1.5 MW beam power can easily be achieved, if such an impedance reduction scheme is implemented and it works for as usual beam extraction. Furthermore, such a reduction of the KM impedance also enables to realize even 2 MW beam power in the RCS. An implementation of the KM impedance reduction scheme is very essential.

ACKNOWLEDGMENT

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