Beam dynamics study for JPARC Main Ring: Comprehensive study of the space charge and nonlinear field effects for JPARC Main Ring

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Summary report

1. <u>Motivation</u>

According to the design requirements the J-PARC Main Ring should provide users (Hadron and Neutrino Experiments) a proton beam with beam power up to 1MW at the energy 30GeV. Strict limitation of particle losses during the operation is required to avoid radiation damage. The particle losses are caused, first of all, by the combined effect of the machine imperfections and the low energy space charge. For design and operation the next generation of the high-beam-power proton rings, there is a need for comprehensive large-scale simulation program to study the injection, capture, acceleration, collimation and loss management in these rings, taking into consideration realistic machine imperfections.

The goals of this study are (1) <u>better understanding the emittance growth mechanism</u> at the injection energy for the J-PARC Main Ring to guarantee minimum particle losses around the machine and (2) optimization<u> the machine performance for different stages </u>of the machine operation to provide 'safe' machine operation.

The emittance growth during the injection and beginning of the acceleration processes is caused by the combined effects of the space charge of the low-energy high-beam intensity proton beam (internal nonlinearities) and the intrinsic field nonlinearities of the ring magnets (external nonlinearities). As the result, the optimum machine parameters should be determined, including the operational working point on the betatron tune diagram for different beam intensity, as well as the optimum beam parameters, produced by the injector (RCS). To reach the high-beam power operation regime with limited particle losses the correction of the machine resonances should be applied too. The determined optimum machine parameters have to guarantee the acceptable level of the particle losses in the ring, which has strict limitation by the radiation safety requirement (typical requirement for high-beam power accelerators).

2. Achievements:

2.1 Optimization of the JPARC Main Ring performance for the moderate beam power

The Main Ring computational model has been developed, representing the synchrotron with the realistic machine imperfections including measured field data and measured alignment error for each magnet. The measured properties of the MR focusing structure are in reasonable agreement with the simulated values, in particular the closed orbit distortion, the beta functions in the horizontal and vertical directions, linear chromaticity of the machine before and after the correction by using 72 sextupole magnets and so on.

Big efforts, connected to optimization the MR performance, have been made by the commissioning group providing the good agreement between the simulated and measured basic properties of the focusing structure of the machine: minimization the injection errors; closed-orbit correction and RF tuning; improvement the power supplies of the dipole and quadrupole magnets and other items.

Linear coupling [1,1,43] resonance correction

The resonance correction approach, which can be used to suppress the effect of the 'sum' linear coupling resonance, has been proposed and tested for J-PARC MR by using the computational model of the machine. It was demonstrated that the linear decoupling can be performed globally or locally at the MR collimation system.

The correction procedures for the both decoupling algorithms have been implemented to the 'PTC' code. The 'local decoupling' method is the method based on the matrix decoupling at the point of observation (at the position of the MR collimator). To perform the 'global' linear decoupling we minimized a 'Ripken' lattice function summed around the ring.

Using the results of the self-consistent multi-particle tracking, performed by using the PTC-ORBIT code, we defined the low and high-order moments of the 4D particle distributions as a function of time. The Fourier transformation of these time-dependent moments gives us the frequency spectrum of the moments, which can be used to check the coherent resonance response of the beam for different machine conditions. The performed spectrum analysis of the <xy> coherent mode for the 'bare' working point with the betatron tunes Q_x=22.27 and Q_y=20.82 indicates the coherent feature of this resonance. The spectrum analysis of the <xy> coherent mode of the 4D particle distribution before (A) and after (B) the 'sum' linear decoupling is shown in Fig. 1.

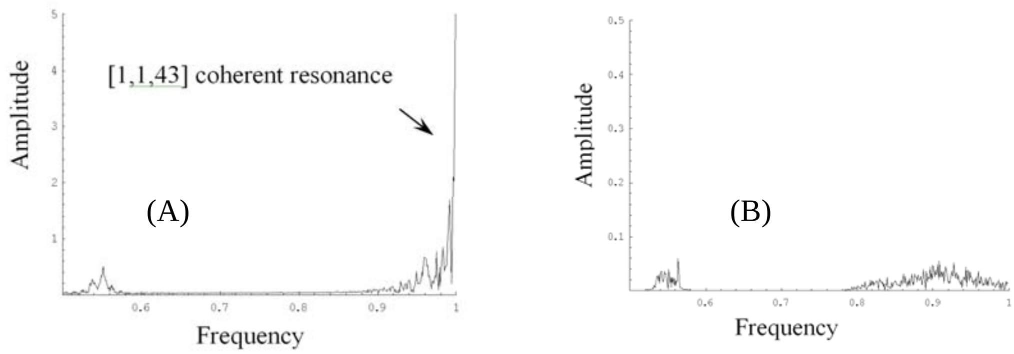

Figure 1: Coherent response of the beam with the space charge before (A) and after (B) the 'global' minimization of the 'sum' linear coupling at the injection energy for the MR operation with the working point Q_x=22.27 and Q_y=20.82 and the moderate beam power of 1.8kW/bunch (B_f ~ 0.16).

The DCCT output before and after the linear decoupling for the DC operation mode of J-PARC MR is presented in **Fig.2** (A) and (B) respectively.

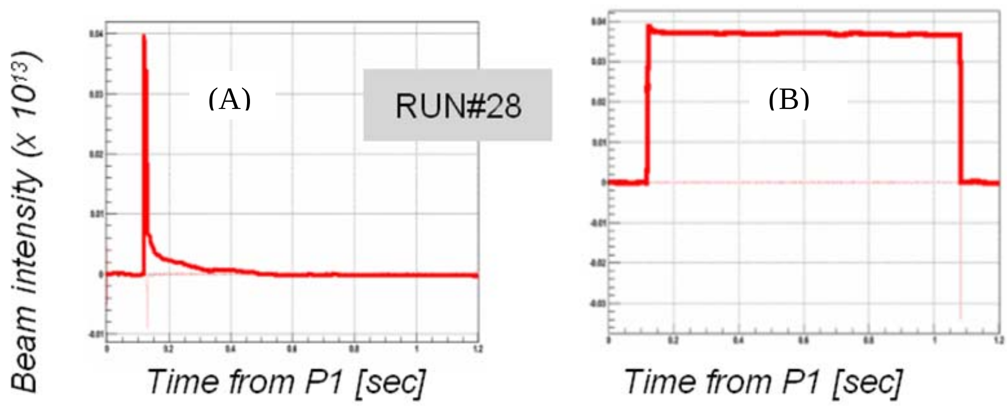

Figure 2: Beam intensity (DCCT output) during the capture process (T_{CAP} ~ 1sec) at the injection energy (no acceleration) before (A) and after (B) the [1,1,43] resonance correction by using the local vertical bump of the orbit at the position of two sextupole magnets (SDA019 and SDB028).

Horizontal 3rd order resonance correction [3,0,67]: Proof-of-Principal

The ‘Proof-of-Principal’ computational experiment has been performed to minimize the effect of the horizontal resonance $3Q_x=67$, observed in J-PARC MR during the ‘tune-scan’ study with the ‘zero’ beam intensity. To make some basic computational experiment, two sextupole magnets (SFA048 and SFA055) have been chosen to reduce the effect of the [3,0,67] resonance for the MR operation. It was shown that the strength of two sextupole magnets (SFA048 and SFA055) should be changed about 7% to suppress the 3rd order horizontal resonance at the injection energy.

This approach has been checked experimentally for the MR operation with small beam intensity (4×10^{11} proton per bunch) for the ‘bare’ working point with the betatron tunes $Q_x=22.32$, $Q_y=20.75$. It was demonstrated that after the [3,0,67] resonance correction the particle losses in MR, observed at the beginning of the injection process, have been reduced from 38% till 7%. The required changing the strength of the sextupole components of SFA048 and SFA055 magnets, obtained experimentally, was about 10% for SFA048 and 19% for SFA055. To improve the agreement between the prediction and the experimental observation it is necessary to continue this study.

‘Q_x=22.30’ tune scan

The tune-scan analysis for the fixed horizontal ‘bare’ tune of $Q_x=22.30$ has been performed for the case of the J-PARC MR operation with the moderate beam power at the injection energy. The ‘fast extraction’ scenario was simulated for this case by using the realistic computational model of the machine.

For this tune scanning with the MR moderate beam power at the injection energy a few machine resonances have been crossed. The horizontal tune ($Q_x=22.30$) is chosen near the 3rd order horizontal resonance, so that without the space charge detuning effect this resonance could lead to significant particle losses. The space charge will depress the incoherent and coherent betatron tunes, keeping the tunes away the resonance stop band. The ‘sum’ linear coupling resonance [1,1,43] can be corrected by using the correction approach, discussed above. The predicted and measured particle losses before and after the linear coupling resonance correction indicate that for the vertical ‘bare’ tunes above the [1,1,43] resonance line the particle losses after the correction reduce significantly. Increasing the particle losses for the vertical tunes above $Q_y=20.80$ is determined by the effects of the [2,-2,3] and [1,2,64] resonances.

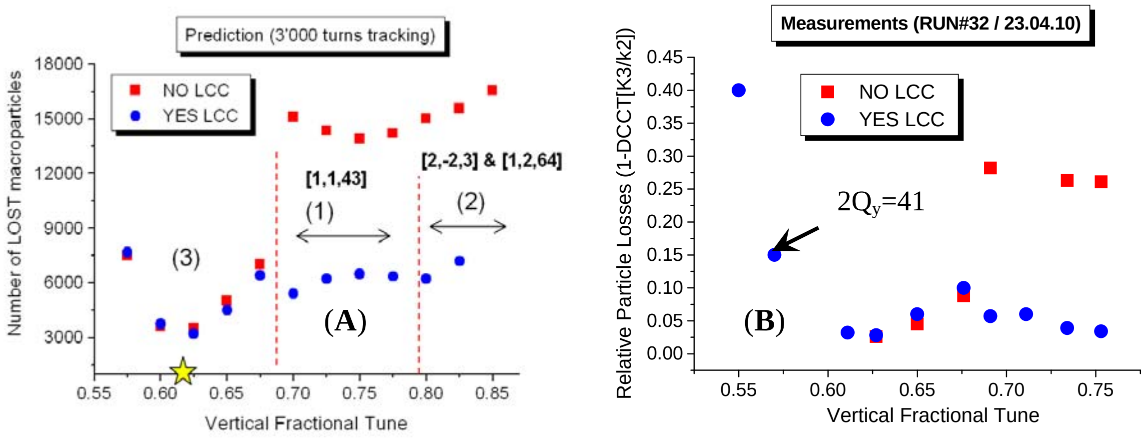

Figure 3: The predicted (A) and observed (B) particle losses at the MR collimator for the horizontal tune scan with the fixed horizontal 'bare' tune (Q_x=22.30).

The predicted and measured particle losses before and after the linear coupling resonance correction (Fig.3) indicate that for the vertical 'bare' tunes above the [1,1,43] resonance line the particle losses after the correction reduce significantly. Increasing the particle losses for the vertical tunes above Q_y=20.80 is determined by the effects of the [2,-2,3] and [1,2,64] resonances. Minimum particle losses for the vertical tune Q_y=20.625 has been observed for both predictions and measurements. For the vertical 'bare' tunes below Q_y=20.575 significant particle losses are determined by the half-integer resonance $2Q_y$=41, caused by the machine imperfections and the space charge of the low energy beam itself. The effect of this resonance on the particle losses in this area depends on the bunching factor of the beam.

'Q_x=22.20' scan

The vertical tune scanning has been performed also for the fixed horizontal tune Q_x=22.20 for the case of the moderate beam power for J-PARC MR, including the 'sum' linear coupling resonance. Minimum particle losses have been obtained just below the [1,1,43] resonance line (Q_y=20.77). The range of the 'bare' working points for this case is limited by the effects of the high-order coupling [2,-2,3] and normal sextupole [1,2,64] resonances. These results have been confirmed experimentally including the injection and acceleration processes.

2.2 High-beam power operation scenario for J-PARC Main Ring

Next ‘mile-stone’ of the beam power upgrade for the J-PARC Main Ring is the continuous operation with the beam power about 4.8kW/bunch. In this case the maximum energy of LINAC is 181MeV. The expected beam power from RCS at the 3GeV energy should be 600kW. The repetition time for the J-PARC MR should be reduced up to 2.47sec. The number of bunches, accelerated in MR, should be increased from 6 to 8. In this case the expected beam power from MR, delivered to the ‘Neutrino’ experiments, should be about 390kW at the extraction energy of 30GeV.

As was predicted by the obtained simulation results for the high-beam power operation of J-PARC Main Ring, to reach this goal during next two years it is necessary to increase the capacity of the 3-50 beam line collimator from 450W till 2kW and the capacity of the MR collimator from 450W till 2kW. The MR operation scenario should be based on usage the second harmonic RF system to modify the shape of the longitudinal separatrix.

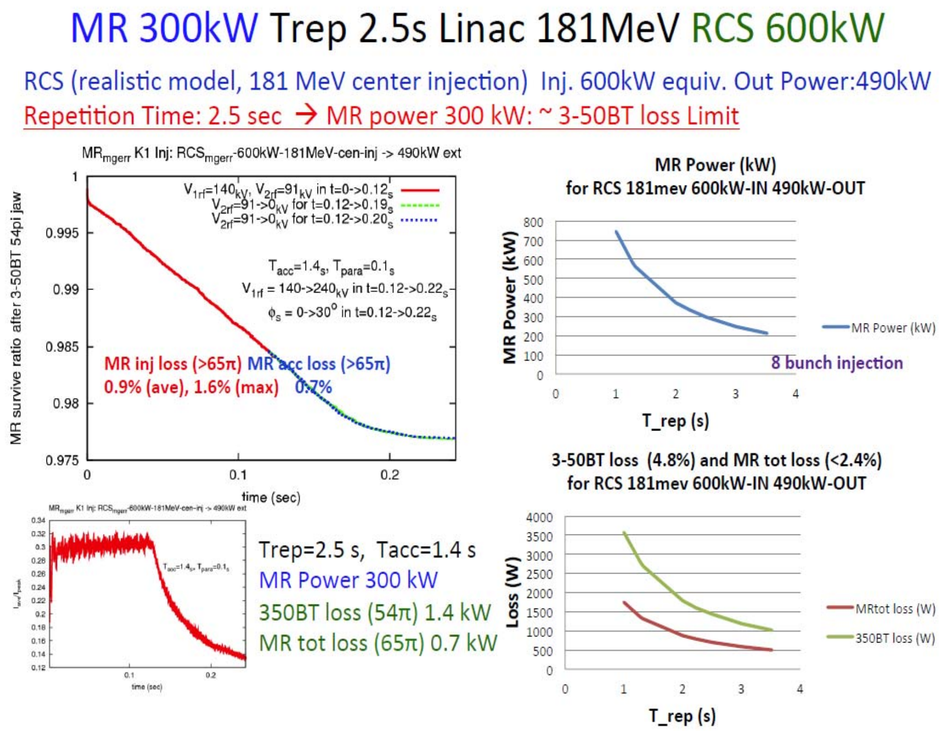

Figure 4: Operational scenario for J-PARC MR in the case of the 600kW beam power, delivered by J-PARC RCS (with LINAC of the 181MeV kinetic energy).

Extensive simulations now are in progress to establish the low losses operation scenario for both J-PARC synchrotrons, for RCS and MR.

2.3 Code development

'PTC-ORBIT' code

We continue our efforts to improve the 'PTC-ORBIT' code including the non-linear resonance correction approaches, developed for the J-PARC MR computational model. It was demonstrated that the effect of the 3rd order horizontal resonance $3Q_x=67$ can be minimized (if it's necessary depending on the 'bare' working point and the beam intensity) by using the sextupole trim coils. Developing the correction technique to minimize the 'octupole' resonances is in progress now in frame of the 'PTC' code. New elements have been introduced into the code to model the variation of the properties of different magnets as a function of time, which open new perspectives to analyze the dynamic variation of the synchrotron's focusing structure. In addition, new module of the code has been developed to simulate particle motion in synchrotrons with RF cavities with high harmonics.

'SAD-SCTR' code

The simulation code has been developed since 2007. The potential solver is based on FACR (Fourier Analysis and Cyclic Reduction) algorithm. The code could be used to simulate the acceleration process for J-PARC Main Ring as well. The code has been compiled successfully for both systems of the KEK super computer.

List of reports:

Published reports

1. A.Molodozhenstev, Operation of the J-PARC Main Ring with the Moderate Beam Power: Predictions and Observations, ICFA HB 2010 Workshop, Sept.27-Oct.1, 2010, Switzerland.
2. K.Ohmi et al, Simulation of Space Charge Effects in JPARC, ICFA HB 2010 Workshop, Sept.27-Oct.1, 2010, Switzerland.

Oral presentations

1. A.Molodozhentsev, ‘Operation J-PARC Main Ring with moderate beam power: predictions and observation’, ICFA HB10 workshop, Sep.27-Oct.1, 2010, Morschach, Switzerland: http://hb2010.web.psi.ch/talks/THO2B03_talk.pdf
2. K,Ohmi, ’Space charge simulation of RCS and MR’, ICFA HB10 workshop, Sep.27-Oct.1, 2010, Morschach, Switzerland: http://hb2010.web.psi.ch/talks/WEO1A04_talk.pdf
3. A.Molodozhentsev, ‘Beam dynamics study for J-PARC Main Ring with PTC-ORBIT’, Oct.6, 2010, ICE Meeting (AD), CERN, Switzerland.
4. Igarashi, A.Molodozhentsev et al, ‘MR plan for the 0.75MW fast extraction’, ATAC11 meeting, February 18, 2011, Tokai, Japan