SIMULATION OF SPACE CHARGE EFFECTS IN JPARC

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Abstract

Nonlinear space charge interaction in high intensity proton rings causes beam loss, which limits the performance. Simulations based on the particle in cell (PIC) method [1] has been performed for JPARC-Rapid Cycle Synchrotron (RCS) and Main Ring (MR). Beam loss estimation during acceleration and resonances analysis are discussed with various simulations using standard method and frozen model.

INTRODUCTION

Increasing the intensity of JPARC gradually, space charge effects are being crucial issue. The intensity is achieved 300kW and 100kW for RCS and MR, respectively.

The target intensity of JPARC is 1MW and 0.72 MW (30GeV) for RCS and MR, respectively. The bunch population is N_p=4.17x10^{13}/bunch at the target. Simulations have been done using SIMPSONS [1] and ORBIT for RCS [2,3] and MR [4] and have contributed the operation of JPARC. Hurdle toward the target intensity is very hard. Close linking of the both ring, RCS and MR, is necessary to achieve the high performance. In this paper, we report the space charge simulation of RCS and MR using a code developed by one of the authors (K.O.) [5]. The parameters of RCS and MR are summarized in Table 1.

Table 1: Parameter List of J-PARC RCS and MR.

	RCS	MR
Kinetic Energy (GeV)	0.118-3.9	3.9-30
Circumference (m)	349	1567
Bunch population	4.2x10^{13}	4.2x10^{13}
Number of bunch	2	8
Repetition (Hz)	25	0.3
Beam power (MW)	1	0.72
Emittance (collimation)(m)	~324 x10^{-6}	~65x10^{-6}

SIMULATION CODE

The simulation code has been developed since 2007 [5]. The potential solver is based on FACR (Fourier Analysis and Cyclic Reduction) algorithm. The boundary is square perfect conducting wall. The potential is normalized by

$$\Phi = \frac{N_p r_p}{\beta^2 \gamma^3} \lambda(z) \phi(x, y : s) \qquad (1)$$

where β and γ are relativistic factors. The potential is assumed to be proportional to the line density of the beam, λ(z), normalized by 1. The transverse potential ϕ is given by solving 2 dimensional Poisson equation,

$$\Delta_\perp \phi = \rho, \qquad (2)$$

where ρ is the integrated particle density in the transverse plane normalized by 1.

The space charge force is calculated by the gradient of the normalized potential and the dynamical variables are transferred by difference equations as follows,

$$\frac{\Delta p_x}{\Delta s} = -\frac{\partial \Phi}{\partial x}, \quad \frac{\Delta p_y}{\Delta s} = -\frac{\partial \Phi}{\partial y}, \quad \frac{\Delta p_z}{\Delta s} = -\frac{\partial \Phi}{\partial z} \qquad (3)$$

The transformations of the lattice elements, drift space, magnets and cavities are expressed by 6 dimensional symplectic map.

BEAM LOSS SIMULATIONS FOR JPARC-MR

The beam loss rate depending on the transverse tune is investigated by the simulation. The tune scan is performed in the area ν_x=0.1-0.45 and ν_y=0.6-0.9 for N_p=1.3x10^{13}/bunch. The initial beam is given by RCS simulation with SIMPSONS. The loss rate after 4000 turns in the tune space is shown in Figure 1. Clear coupling resonance line is seen. Lower area from the resonance line is better than upper area. Our nominal operating point is (ν_x, ν_y)=(0.15,0.65).

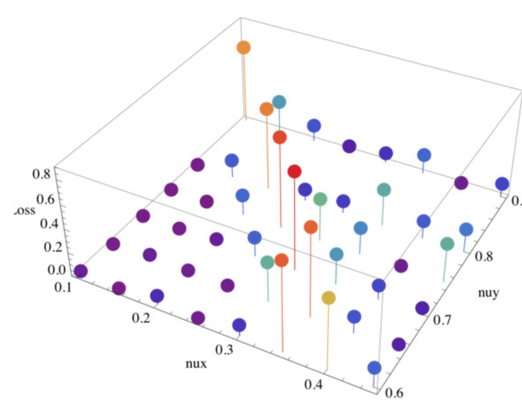

Figure 1: Beam loss rate for operating points in the transverse tune space. The intensity is 300kW, N_p =1.3x10^{13}/bunch.

Beam loss for 0.72 MW operation, N_p=4.17x10^{13}, at the nominal operating point is shown in Figure 2. The initial beam is given by RCS simulation and is collimated with an aperture of 65 π mm mrad. The collimator aperture of the ring is 65 π mm mrad. The beam loss of 1% arises at an early stage after the injection. The loss of 1% corresponds to 400W for 8 bunches and repetition of 0.3Hz. Three lines are depicted in the figure. One, marked original, is given by the standard simulation method using the injected beam. A strong beam loss occurs after around 300 turns. The bunch length shrank at the loss, because the longitudinal distribution is mismatched with MR ring. In the second, marked shuffled, the longitudinal distribution is enforced to match. Though the strong loss disappears, the slope is not improved. In the third, marked frozen, the beam potential, which is frozen at the first turn, is used for the successive revolutions. The slope of the loss is improved about a half. The injection is performed with 4 pulse of beam from RCS every 40ms. Each pulse contains two bunches. Since the total injection time is 120 ms, the beam is stored about 23,000 turns in maximum. This result shows the loss is 2-5kW at injection. The loss during the acceleration may be similar to that at the injection.

The loss of frozen model is better than that of standard. We consider that most part of the difference is due to a potential fluctuation numerical noise or mismatch. Including the early stage loss, careful simulation is necessary. The limit of MR is 450kW at the present. It is planned to improve the limit to 8kW.

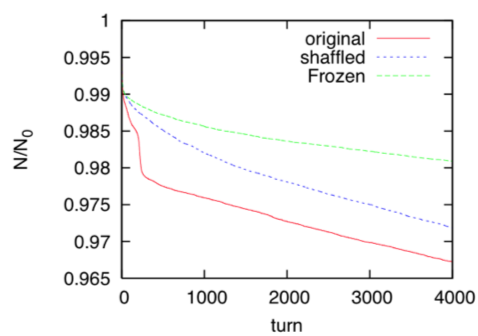

Figure 2: Beam loss for N_p=4.17x10^{13}/bunch operation.

It is known that beam particles experience linear transverse space charge force for KV distribution [6],

$$\psi(x,p_x,y,p_y) = \frac{N}{\pi^2\varepsilon_x\varepsilon_y}\delta\left(\frac{J_x}{\varepsilon_x}+\frac{J_y}{\varepsilon_y}-1\right) \qquad (4)$$

where $J_{x,y}$ and $\varepsilon_{x,y}$ are a half of Courant-Synder invariant and emittance, respectively. People make efforts to realize KV distribution using for example the painting injection. Simulations with KV distribution have been tried for JPARC MR. Figure 3 shows the beam loss for KV distribution with ε=54 (top) and 60 (bottom) π mm mrad, respectively. Pure KV distribution is uniform for longitudinal. First and second lines in legend are given for straightforward and frozen model, respectively, for the uniform longitudinal distribution; zero energy spread and no RF. Third and fourth are given for parabolic distribution in longitudinal. In either case of 54 and 60 π mm mrad emittance, the frozen model gives very good results, but standard method does not give. The big difference between frozen model and standard method is due to noises. Figure 4 shows the variation of beta function. Fluctuation of 0.5% is seen. Similar level of fluctuations are seen in the beam size $(\langle x^2\rangle)^{1/2}$ and emittance $(\langle x^2\rangle\langle p_x^2\rangle-\langle xp_x\rangle^2)^{1/2}$. Coherent motion may be doubtful but its growth is not seen. Figure 5 shows a breaking of the KV distribution. The beam loss is more serious than that with a realistic distribution. Figure 6 sketches the diffusion of beam distribution. KV distribution is weak for noises. Noises exist in real machines. Important point is how to evaluate the noise level of the real machine.

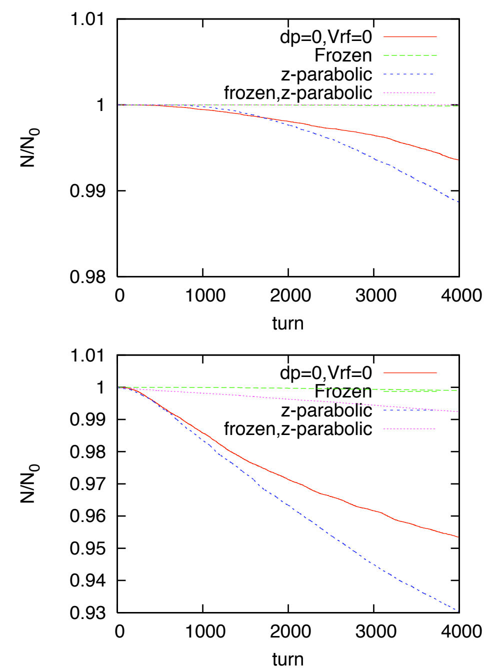

Figure 3: Beam loss for KV model for N_p=4.17x10^{13}/bunch. Top and bottom picture are for KV distributions with $\varepsilon_{x,y}$=54 and 60 π mm mrad, respectively.

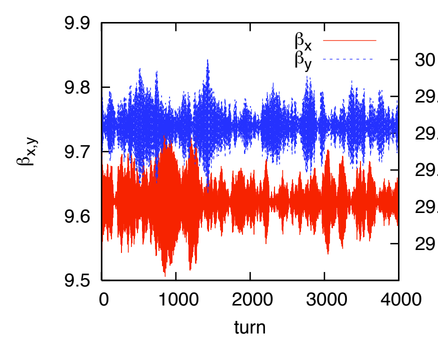

Figure 4: Variation of the beta function given by $\langle x^2\rangle/(\langle x^2\rangle\langle p_x^2\rangle-\langle xp_x\rangle^2)^{1/2}$.

In real machine, the injection beam has a finite emittance. The distribution described by delta function is not realistic. $J_{x,y}$ has a spread equal to the emittance of the injection beam. The simulation, which is performed with the 10% spread of $J_{x,y}$, results N/N_0=99.3% and 97% for frozen and standard, respectively. It seems there is room to improve the loss rate by inventing the distribution of injection beam.

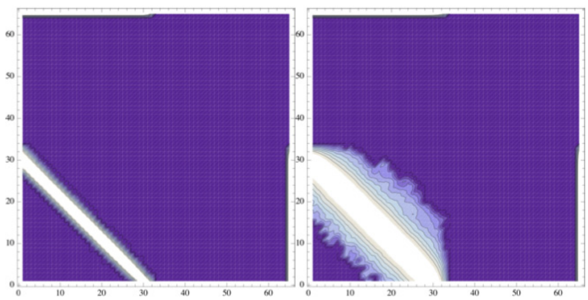

Figure 5: Contour plot of beam density distribution in J_x-J_y plane. Left and right plots are initial distribution and that after 4000 turns.

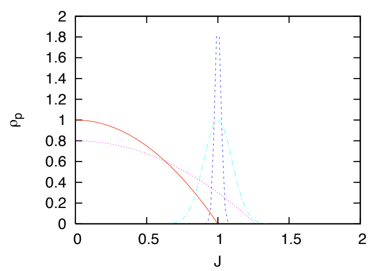

Figure 6: Sketch of diffusion of the beam distribution.

BEAM LOSS SIMULATIONS FOR JPARC-RCS

To control the injection beam of MR, studies for the extracted beam from RCS are not avoidable. Simulations for RCS are also important for RCS performance. Simulations for RCS using the same code have been begun these a few months. Beam injection for RCS is done by a linac with the energy 181 MeV. The beam is injected as 300-500 pulses into two buckets of RF cavity turn by turn, and then is accelerated 181 MeV to 3 GeV. The repetition frequency is 25 Hz, and the total designed beam power is 1MW for N_p=4.17x10^{13} after upgrade of linac energy 181MeV to 400MeV. RCS is operated with 300kW in 2009. The pulses, which have transverse emittance of 0.28 mm mrad, energy spread 0.016% and bunch length 80m, are painted in the transverse and longitudinal phase space. Remarkable beam loss was not seen in a painting injection and 7% loss in a centre injection. Simulations are started with benchmarking using the experimental results.

SUMMARY

Space charge simulation has been performed for J-PARC MR and RCS. The beam loss limit is very serious for JPARC-MR. Space charge simulations are started for J-PARC MR and RCS using the same code. Close linking of the both ring, RCS and MR, will be necessary to achieve high intensity in operations and simulations.

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