SIMULATION OF SPACE CHARGE EFFECTS IN JPARC

K. Ohmi, S. Igarashi, Y. Sato, KEK, Tsukuba, Japan

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 have been performed for JPARC-Rapid Cycle Synchrotron (RCS) and Main Ring (MR). Whole acceleration processes are 20 msec and 1 sec for RCS and MR, respectively. Long-term simulation is necessary for the processes. We show results of the long-term simulation using ordinary method with step by step potential calculation 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, in Summer 2010. 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} at the target. The repetition rate is 25 Hz and 0.45 Hz. The collimators are designed to be 4 kW and 450 W for RCS and MR, respectively. That of the beam transport line from RCS to MR is 2kW. Previous simulations [1,2,3] showed the loss limit is to tight, especially in MR. The collimators will be upgraded in the future to 2-4 kW in MR. Hurdle toward the target intensity seems to be very high even the update of the collimators. 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.) named SCTR [4]. 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)	0.4-3	3-30
Circumference (m)	349	1567
Bunch population, Np	4.17x10^{13}	4.17x10^{13}
Number of bunch (Harm.)	2 (2)	8 (9)
Repetition (Hz)	25	0.45
Beam power (MW)	1	0.72
Emittance (collimation)(m)	~324 x10^{-6}	<65x10^{-6}

SIMULATION CODE

The simulation code has been developed since 2007 [3]. 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 two-dimensional Poisson equation,

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

where ρ is the projected 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,

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

The transformations of the lattice elements, drift space, magnets and cavities are expressed by 6 dimensional symplectic map. The azimuthally step Δs should be shorter than the beta function. Since the beta function is in the range of 2.5-20 m and 4-30 m for RCS and MR, respectively, Δs is chosen ~1 m.

Two types of computers were used for the simulation. One is PC with dual multi-core CPU's; 2x8 and 2x6 cores. The other is Blue Gene L. Typically 1024 CPU's (Power PC 440) connected by a fast network. Two simulation methods are used depending on the two types of computers. One is ordinary method: i.e., the potential is calculated every azimuthally steps. PC is used for the simulation. In Blue Gene computer, the potential is calculated every 50 turns element by element and is frozen till next 50 turns.

BEAM LOSS SIMULATIONS FOR RCS

Proton LINAC delivers the beam with energy of 181 MeV to RCS in 2010. The target intensity of RCS and MR is realized after energy upgrade of LINAC to 400 MeV in 2012. In this paper we perform beam loss simulation for the beam injected at 400 MeV. Figure 1 shows the acceleration and cavity voltage in RCS [3]. The turn number 15,000 corresponds to the acceleration time 25ms. The cavity voltage of the first and second harmonics are expressed by

$$V(z) = V_1 \cos(2\pi Hz/C + \phi) + V_2 \cos(4\pi Hz/C) \qquad (4)$$

where z=s-vt.

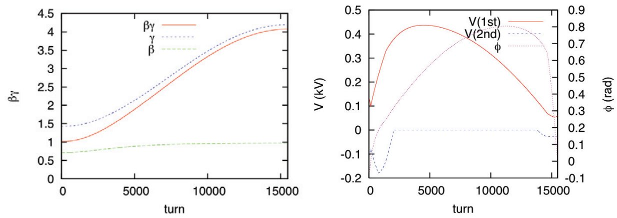

Figure 1: Evolution of the beam energy (left) and cavity voltage (right). Courtesy of H. Hotchi [5].

LINAC beam is injected using a painting orbit bump. It is known that beam particles experience linear transverse space charge force for KV distribution [6],

$$\psi(x,p_x,y,p_y)=\frac{N}{\pi^2\varepsilon_x\varepsilon_y}\delta\left(\frac{J_x}{\varepsilon_x}+\frac{J_y}{\varepsilon_y}-1\right) \quad (5)$$

where $J_{x,y}$ and $\varepsilon_{x,y}$ are Courant-Synder invariant (not half) and full emittance, respectively. To realize the KV distribution, injection amplitude is swept so that $J_x= \varepsilon\ t/t_{inj}$ and $J_y =\varepsilon(1-t/t_{inj})$: that is, $\Delta x= (\beta_x\varepsilon\ t/t_{inj})^{1/2}$ and $\Delta y =(\beta_y\ \varepsilon(1-t/t_{inj}))^{1/2}$ for example, where $\varepsilon= \varepsilon_x =\varepsilon_y$ and t_{inj} is injection time. Since LINAC beam has an emittance of $\Delta\varepsilon =0.28$ μm (4π μm for 99 %), the delta function in Eq.(5) is actually an Gaussian distribution with the emittance: J_x+J_y spreads due to the emittance of the injection beam as

$$\psi(x,p_x,y,p_y)\approx\exp\left[-\frac{1}{2}\left(\frac{J_x+J_y-\varepsilon}{\sqrt{2\varepsilon\Delta\varepsilon}}\right)^2\right]. \quad (6)$$

In this simulation pure KV distribution in Eq.(5) is used in the transverse to know a space charge limit of J-PARC. The spread is roughly 10 % of the whole emittance for 100 or 150 π μm. The longitudinal profile is assumed elliptic with ε_z=0.28π m. The KV distribution is not perfect one even in this simulation, because of the longitudinal distribution, dispersion, chromaticity and other parameters.

Macro-particles 200,000 are tracked with taking into account of the space charge force. Particles with larger amplitudes than the collimator aperture in Table 1 are lost. Figure 2 shows the proton loss for several beam intensity, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 times of the design bunch population, N_p=4.17x10^{13}. Beam loss rate is plotted for the emittance, ε=100π μm in the figure. The simulations for ε=150, 200π μm are performed.

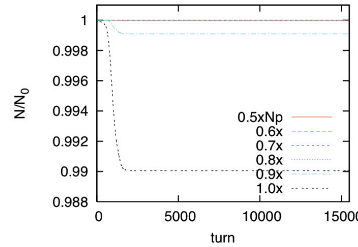

Figure 2: Beam loss rate for the intensities, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 times of the design bunch population, N_p =4.17x10^{13} in RCS, where $\varepsilon=\varepsilon_x+\varepsilon_y$=100π μm.

Figure 3 shows the beam power loss as a function of the intensity in each case of the emittance. The loss for the emittance of 200 π μm exceeded the limit 4kW, while it is safe for 100 and 150π μm.

Figures 4 and 5 show the particle distribution of the extracted beam from RCS. The distribution for J_x+J_y in Figure 4 should be the delta function, if the injected beam is accelerated with keeping KV distribution. The distributions for J_x and J_y in Figure 5 should be step function. KV distribution is broken as shown in the figures.

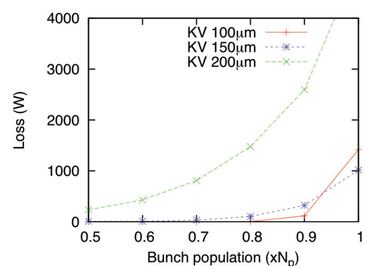

Figure 3: Beam power loss as a function of intensity in RCS. Limit is 4 kW.

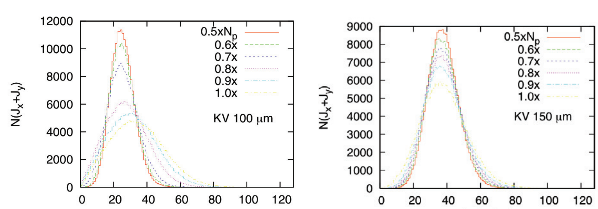

Figure 4: Particle distribution of extracted beam from RCS.

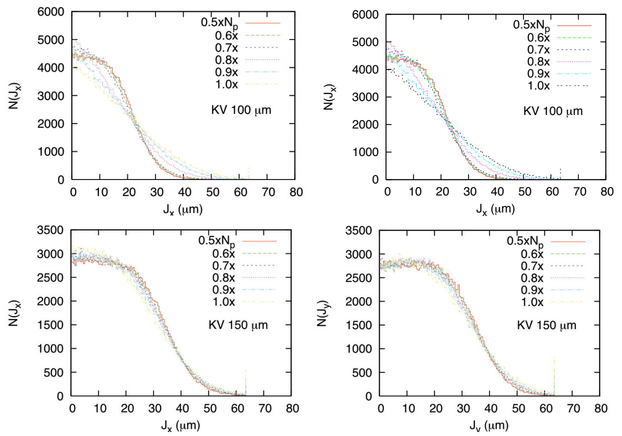

Figure 5: Particle distribution of extracted beam from RCS.

BEAM LOSS SIMULATIONS FOR MR

The beam extracted from RCS is injected to MR through 3-50 BT line. RCS extracts 2 bunches in every 40 ms. It takes 40x3=120 ms to fill 8 bunch in MR. The first injected bunch has to wait for other three pulses with keeping the injection energy during 120 ms. Simulation is performed for the first injected bunch as a pessimistic case: the acceleration starts after 23,000 turns. Figure 6 shows the acceleration of MR beam. At the injection, first and second harmonic cavities are excited to match to the RCS beam. The second harmonic voltage is reduced, and the first cavity voltage is increased and its phase is changed in next 100 msec. Accelerating voltage is 390 kV and the phase is 0.4 rad in this simulation. The whole acceleration time to 30 GeV is 1.1 sec in this condition.

Figure 7 shows the loss rate as function of time evolution for various beam intensity. Figure 8 shows the beam power loss as function of the intensity. The loss in Figure 8 includes that at BT. Limit of the total power loss is 3-4kW for BT and MR. The loss increases severely for higher intensity and is very high, 8kW, for the design bunch population, N_p. The maximum intensity is around $0.8xN_p$. The initial distribution is spread Gaussian distribution for J_x+J_y. A significant number of particles already exceed the aperture limit of BT and MR at the initial stage.

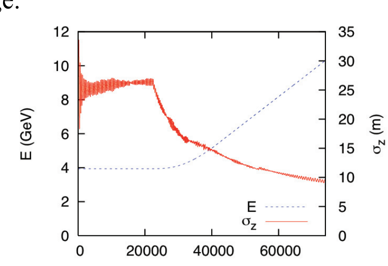

Figure 6: Early stage of acceleration in MR.

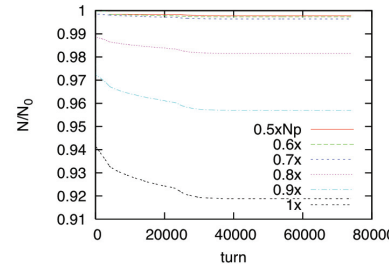

Figure 7: Beam loss rate for the intensities, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 times of the design bunch population, N_p $=4.17x10^{13}$ in MR, where $\varepsilon=\varepsilon_x+\varepsilon_y=100\pi$ μm in RCS injection.

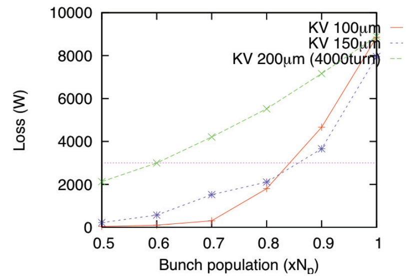

Figure 8: Beam power loss as a function of intensity in MR. The repetition is 0.45 Hz. The loss for $\varepsilon=200\pi$ μm is integrated only up to 4000 turns.

Figures 9 and 10 show particle distribution during the injection and acceleration period. The initial distribution is Gaussian for J_x+J_y at lower intensity and the distribution is kept during the acceleration. The central position and spread get small due to the adiabatic damping. The initial distribution for N_p with 100 π μm is not Gaussian for J_x+J_y. This means the characteristics of KV distribution is lost in the high intensity.

One of our strategies toward 0.75MW is high repetition of 1.3 Hz with lower bunch population $0.6xN_p$. We study whole acceleration process for $0.6xN_p$ case. Figure 11 shows particle distribution in the horizontal and vertical plane after acceleration to 30 GeV for the bunch population of $0.6xN_p$. The aperture of the extracted beam is designed 6π μm. The numbers of particles, which exceed the aperture limit, are 0.43% and 3.8% for 100 and 150π μm emittance at RCS injection, respectively. The limit of the power is ~100W at the extraction line. The aperture larger than 8π μm is necessary. It is safe, since the aperture is designed 6-10π μm.

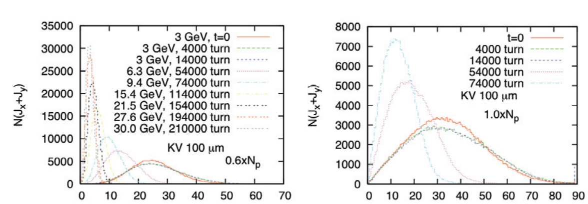

Figure 9: Beam particle distribution during MR injection and acceleration. The initial distribution is given by RCS simulation shown in Figures 4 and 5, where 100π μm in RCS injection.

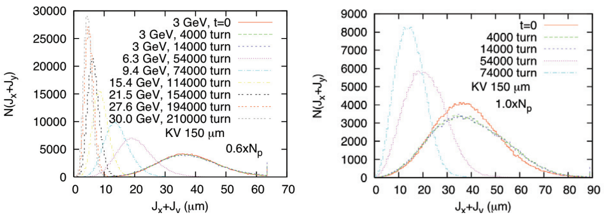

Figure 10: Beam particle distribution during MR injection and acceleration. The initial distribution is given by RCS simulation shown in Figures 4 and 5, where 150π μm in RCS injection.

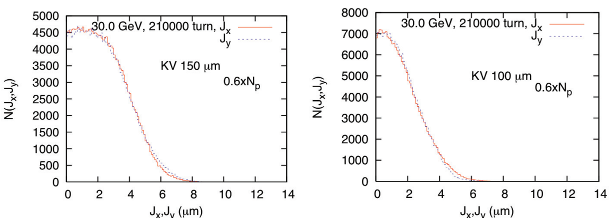

Figure 11: Particle distribution in the horizontal and vertical plane after acceleration to 30 GeV for the bunch population of 0.6xN_p.

The beam loss in MR depends on the distribution of the injection beam: i.e., the extracted beam from RCS. Suppression of the power loss at BT and the injection period 120 msec of MR is effective. The breaking of KV distribution occurs the early stage of RCS injection. There may be some rooms to avoid or to reduce the breaking. We now assume to inject KV distribution of the beam with the emittance of 25 or 37.5 π μm into MR. The emittances are 1/4 of those of RCS with considering βγ ratio. Figure 12 shows the change of KV distribution up to 20,000 turns (the starting time of acceleration) for the two initial emittance cases. The beam loss rates are 0.001% and 0.23% (172W) for 25 and 37.5π μm initialization, respectively. Numerical noise may affect the spreading of J_x+J_y, since a simulation with a frozen potential gives better results. Anyway the loss is very small. This result indicates that it remains a little possibility for 0.75MW in 0.45Hz repetition.

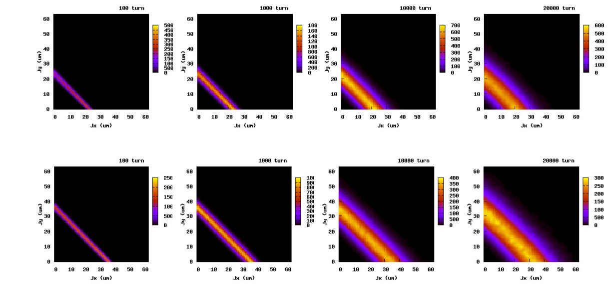

Figure 12: Particle distribution in J_x-J_y plane. Upper and lower lines of pictures are obtained for 25 and 37.5 π μm. Four pictures of each line are the distributions after 100,1000,10000 and 20000 turns.

SUMMARY

Space charge simulation has been performed for J-PARC MR and RCS. The beam loss limit is very serious for JPARC-MR. Close linking of the both ring, RCS and MR, will be necessary to achieve high intensity in operations and simulations. The whole acceleration process of RCS and MR are surveyed using KV initialized beam. The design parameter, 0.72MW at 0.45 Hz repetition, is hard for the large bunch population, 1xN_p=4.17x10^{13}. The population 0.6xN_p=2.5x10^{13} relaxes the beam loss. Faster repetition 0.7 Hz with the lower population of the beam is a choice toward 0.72MW operation. Improvement of magnet and RF system is required for the faster repetition.

The study will be extended to a realistic painting injection to study more detail. Fine-tuning at RCS injection is indispensable. Choice of the tune operating point and evaluation of error tolerance are also important.

ACKNOWLEDGEMENTS

The authors thank to Drs. K. Fan, H. Hotchi, T. Koseki, A. Molodozhentsev, Y. Shobuda and H. Kobayashi for fruitful discussions.

REFERENCES

[1] H. Hotchi et al., proceedings of IPAC10.
[2] A. Molodozhentsev et al., proceedings of IPAC10.
[3] K. Ohmi et al., proceedings of IPAC10.
[4] K. Ohmi et al., proceedings of PAC07, 3318 (2007).
[5] H. Hotchi, private communications (2010).
[6] I.M. Kapchinskij and V.V. Vladimirskij, Proc. 2nd Int.Conf. on High Energy Accel. and Instr., CERN, 1959, p. 274.