A Beam Simulation of the Proton Storage Ring for the Neutron Science Project

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Abstract

We have started the design study of a 1.5GeV proton storage ring for the Neutron Science Project at JAERI[1]. This ring stores the 1.5GeV proton beam up to 2.5MW with charge exchange injection. It is important for us to control a beam loss in the ring to meet the requirement for hands on maintenance. For this reason, we have developed the simulation codes for estimation of injection and storage process. We have evaluated these processes using these new codes. In this paper, some preliminary simulations of transverse and longitudinal beam tracking for controlling the beam loss are reported.

1. Introduction

Many technical problems in injection and storage process have to be solved because storage beam power is very high up to 2.5MW in our ring. Table 1 and Table 2 show the parameters of injection beam and preliminary ring, respectively. The peak current of injection beam(H^-) is 30mA, and pulse length is 670nsec (filling factor is 60%). At first, the number of turns in the ring is nearly 2780 which corresponds to about 1.86msec in time. Injection turn number is very large, so it is very important to reduce a foil hitting probability of circulating beam(H^+). Secondly, the number of circulating particles is 2.08×10^{14} at the end of injection, so we have to prepare a large ring acceptance. In the present estimation, transverse emittance is about 200π-mm-mrad for reducing the foil hitting probability. On the other hand, the emittance of injection beam is very small (2π-mm-mrad, 100%-un normalized). We have to expand the emittance of injection beam up to 200π-mm-mrad using the painting method. Thirdly, we have to keep the bunched structure of stored beam in the ring during injection and storage process, because we must use the fast (single turn) extraction method for the experiments of neutron science. If we cannot keep the bunched structure, the beam loss at extraction process increases. Finally, the circulating beam current is very large. It is up to 50A at the end of injection. We have to make the bunching factor sufficiently large for reducing the effect of beam loading in the rf cavity which is used to keep the bunch structure.

For these reasons mentioned above, we have developed two simulation codes (transverse and longitudinal) for estimation of injection and storage process. In the following, we report the brief explanations of these codes and some preliminary simulation results.

2. Beam simulation

A. Transverse

The transverse simulation code is a multi particle tracking code using transfer matrix method. Basic input parameters of this code are the calculated results of the MAD which was developed at CERN. Bump orbits are produced by one set of bump magnets for each direction x, y. We set the phase advance between bump magnets to be π. In this preliminary simulation, we neglected the effect of space-charge and momentum spread.

We have simulated some injection processes using this code. The magnet lattice is temporarily selected to be normal 12 cell FBDO lattice[2]. FBDO lattice is chosen for its smooth betatron function around the ring. We assumed that

Table 1 Parameters of injection beam

Energy	1.5 GeV
β	0.923
γ	2.599
Pulse structure	On: 400nsec Off: 270nsec
ε x(100%,unnormalized)	2.0 πmm·mrad
ε y(100%,unnormalized)	2.0 πmm·mrad
momentum spread	±0.2%

Table 2 Parameters of preliminary ring

Type	12 cell FBDO
Super periodicity	12
Circumstance	185 m
Transition γ	2.599
circulating frequency	1.49MHz
Ring acceptance	200 πmm·mrad
Operating tune(nx,ny)	(3.85,3.75)
Operating cycle	50 Hz

the operating tune(vx,vy) is (3.85,3.75). In the following, we report two typical cases of painting process. The number of macroparticles of injection is 20 at a time and this beam is stored for 10 turns. For this reason, we cannot estimate the exact foil hitting probability due to the limited number of simulated particle, but we can compare the differences of the results among various painting patterns. Figure 1 and Figure 2 show the beam distributions at the end of the injection in the phase space and the x-y space respectively. In the figures, the solid curves show the density distribution of the beam. The bump orbits for x and y directions change as the following function respectively.

Case1:

$$x = x_0 + \Delta x\left(\frac{t}{T}\right)^2, \quad y = y_0 + \Delta y\sqrt{1-\frac{t}{T}}$$

Case2:

$$x = x_0 + \Delta x\sqrt{1-\frac{t}{T}}, \quad y = y_0 + \Delta y\sqrt{1-\frac{t}{T}}$$

Here $x_0(y_0)$ is the offset, $\Delta x(\Delta y)$ is the maximum distance of bump orbit, t is the time and T is the injection period. In case1, the shape of distribution in the x-y space is circle, and the density distribution for each direction is nearly Gaussian. In case2, the shape of distribution in the x-y space is square. In general, the circular beam is better than the square beam from the point of the view of stability. However, the foil hitting probability is low and the ring aperture is small in case2, because bump orbit can be reduced with painting process for both x and y direction. These effects are important to design our ring. From only these estimations, we cannot draw conclusions which is better, case1 or case2.

For the further calculation as the next step, we will have to consider the effect of space charge force and estimate the sensitivity of beam behavior for various lattice structures, for instance FBDO, triplet and so on.

B. Longitudinal

We have to extract the stored beam with fast extraction method for the neutron scattering experiment. Kicker magnets require about 150nsec for the field rise time, so we have to make a non beam area wider than about 150nsec. Injected pulse beams have a 400nsec-on and 270nsec-off structure. We have to maintain the bunch length growth with less than 120nsec. To estimate this effect, we developed the additional longitudinal simulation code. This simulation code is also a multi particle tracking code using the following difference equations in longitudinal phase space.

$$\Delta E_{i,n} = \Delta E_{i,n-1} + qek_t V_{s,n}(\sin \phi_{i,n} - U_{i,n} / V_{s,n})$$

$$\Delta \phi_{i,n} = \Delta \phi_{i,n-1} + \frac{2\pi}{\Omega_{s,n}}\left(\frac{h\eta_{i,n}}{P_{s,n}R_{s,n}}\Delta E_{i,n}\right)$$

Here E is the energy of beam, q is the charge state, e is 1, V is the radio frequency(rf) voltage, U is the space-charge voltage induced on the beam, ϕ is the phase for rf voltage, Ω is the angular frequency, P is the momentum of beam, R is the average radius of ring and η is the slippage factor, respectively. The subscripts i and n are particle number and turn number, respectively. The subscript s stands for the parameter of synchronous particle. The phase of synchronous particle is 0, because the beam is not accelerated in our ring. In this code, particle position is calculated each turn. The number of macroparticles is about 250 at a time and is stored. In the above equations, V consists of the space charge voltage U and the additional capture voltage V_{cap} which corresponds to the voltage due to the momentum spread. Firstly, we calculated the capture voltage using the following equation.

$$eV_{cap} = \frac{\kappa^2 |\eta| \beta^2 E \pi^3 B^2}{8\varepsilon}\left(\frac{\Delta p}{p}\right)^2 .$$

Here κ is the dilution factor, η is the slippage factor, β is the relativistic velocity, E is the energy of beam, B is the correction factor for bunched beam and ε is the charge to mass ratio.

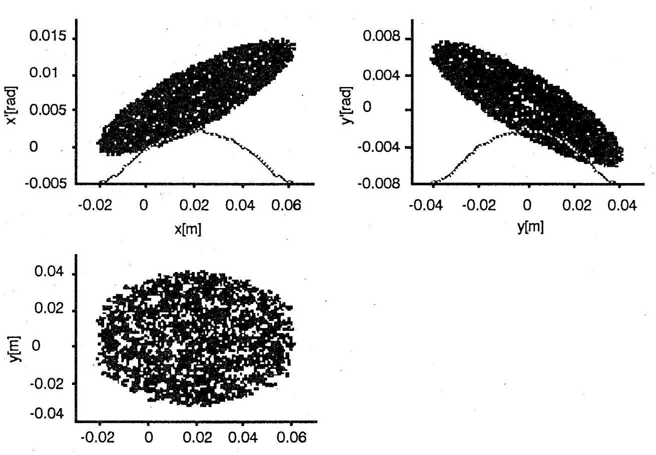

Fig.1 Beam distribution in phase and real space

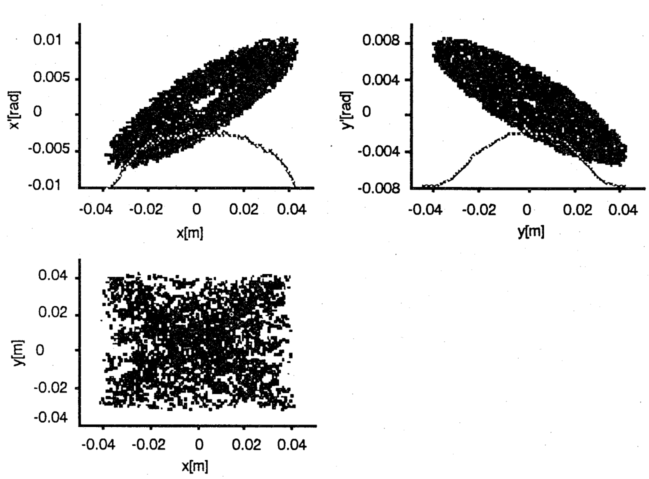

Fig.2 Beam distribution in phase and real space

In the present simulation, we took k=2, η=0.068 and B=0.6. We assumed that $\Delta p/p$ was $\pm 0.49\%$ to avoid the longitudinal beam instability, but we did not include longitudinal painting. Then V_{cap} becomes about 13.5kV. Secondly, we calculated the space-charge force using the following equation.

$$U = -\frac{e g_0 R}{2\varepsilon_0 \gamma^2} \cdot \frac{d\lambda}{ds}$$

Here g_0 is the geometrical factor, ε_0 is the permeability of free space, γ is the relativistic energy and $d\lambda/ds$ is the longitudinal gradient of electric charge in the beam. Here we neglected the effects of inductive wall current in beam duct. We assumed that the ratio of beam radius and beam duct radius was 1.5 and g_0 was 1.81, respectively. If the beam distribution has a parabolic distribution, the space-charge voltage induced on the beam is about 7.5kV. Total rf voltage becomes 21kV.

We simulated the storage process using this code. We assumed that the distribution of injection beam is uniform and this beam is stored for 100 turns. We calculated the stored beam distribution each turn. The rf voltage at start is 13.5kV and increases to 21kV during the injection. At first, we simulated the longitudinal motion with only first harmonic rf bucket (case1). Figure 3 shows the beam distribution at the end of injection in a longitudinal phase space. The horizontal axis shows phase for radio frequency. In this figure, the solid curve shows separatrix for the first harmonic rf voltage. The bunch length in time increased from 400nsec to 425nsec. But it was well contained within 120nsec. The bunching factor is to be about 0.33. We analitically estimated that bunching factor was 0.4 from filling factor and parabolic distribution, but result of simulation showed that bunching factor is smaller than the estimated value. Secondly, we simulated the longitudinal motion with the first and second harmonic rf buckets for reducing the space-charge force at the beam center and increasing the bunching factor (case2). We took the rf voltage of second harmonic to be 10.5kV which is half of the first harmonic voltage. Figure 4 shows the beam distribution at the end of injection in a longitudinal phase space. In this figure, the solid curve shows the separatrix for the sum of the first and second harmonic rf voltages. This result shows that the density distribution is close to uniform shape, and bunching factor is bigger than case 1. In this simulation, the bunching factor is about 0.45. The maximum momentum spread is smaller, and the beam size becomes smaller compared to the result of case 1.

As the next step, we will estimate the effect of beam loading, the effect of the barrier bucket and necessity of longitudinal painting.

3. Summary

We started the study of the 1.5GeV Proton Storage Ring for Neutron Science Project at JAERI. We have developed the beam tracking codes for transverse and longitudinal orbit. We estimated the effects for the beam injection and the storage process in our ring which has 12cell FBDO lattice. We can summarize these results of the estimations as follows: First, the foil hitting probability becomes small using painting method. Secondly, the bunching factor becomes big and momentum spread becomes small using the second harmonic bucket. Finally, the bunch structure of the stored beam is well kept. We will have to estimate a detailed study of injection and storage process to obtain more precise results. For instance, we have to consider the effects of space charge and the effect of momentum spread for transverse tracking code, and the effects of the beam loading for longitudinal tracking code. In the future, we will couple the transverse tracking with longitudinal one in order to study these effects in detail.

4. References

[1] M.Mizumoto et al, A High Intensity Proton Linac Development for Neutron Science Research Program XVIII International Linac Conference, LINAC96, Geneva, Switzerland 26-30 August 1996, p662-664

[2]M. Kinsho et al, : A Preliminary Study of the Proton Storage Ring for the Neutron Science Project at JAERI, in these proceeding

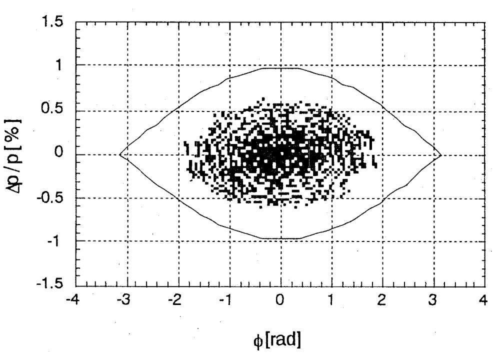

Fig.3 Longitudinal phase space distribution

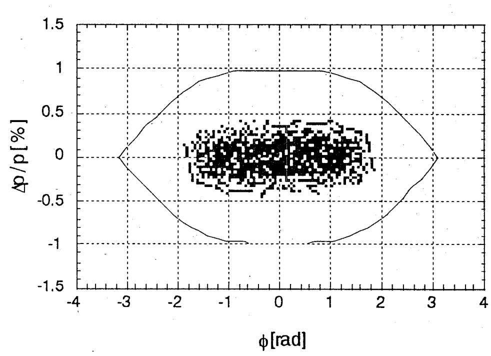

Fig.4 Longitudinal phase space distribution