Space Charge Effects in the JHF Proton Synchrotrons

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Abstract

In the JHF proton synchrotrons, the beam intensity is one order higher than that of the presently operated machines. Space charge effects in the booster and the main ring are studied. The beam emittance as well as beam loss are estimated using a tracking code.

1 Space Charge Tune Shift

In order to estimate the strength of space charge effects in the booster, the tune shift is calculated as

$$\Delta\nu = -\frac{r_p n_t F}{2\pi\beta^2\gamma^3\varepsilon B_f}$$

where r_p is the classical proton radius; 1.53 x 10^{-18}, n_t is the total number of particles; 5 x 10^{13}, ε is the unnormalized emittance, B_f is the bunching factor, and β and γ are the Lorentz factors at the injection energy of 200 MeV; 0.566 and 1.213, respectively. The emittance and bunching factor are determined by the injection process of the booster. For sake of argument, we assume that the emittance is 220 π mm-mrad and its distribution is "waterbag" in the four dimensional transverse phase space, which means the phase space density inside the four dimensional sphere is constant. The bunching factor is assumed to be 0.27 when the longitudinal emittance is 0.6 eVs and the distribution is parabolic. The number we quoted above should be in the ball park. The tune shift, as a result, becomes -0.36. Although there is no explicit criterion for the magnitude of the tune shift, -0.36 seems to be quite large and careful study on the effects is needed, especially in the machine which cannot tolerate more than a percent beam loss such as the booster.

In the main ring, n_t is 2 x 10^{14}, and β and γ at an injection energy of 3 GeV are 0.971 and 4.197, respectively. We assume that the emittance is 54 π mm-mrad and that its distribution is a "waterbag" in four dimensional transverse phase space, the same as the booster. The bunching factor is 0.27 when the longitudinal emittance is 3 eV s and the distribution is parabolic. The tune shift, therefore, becomes -0.08.

Table 1: Space charge tune shift in the main ring

Incoherent (horizontal/vertical)	
at Injection	-0.03 / -0.08
at Extraction	-0.00/ -0.004
Coherent	
at Injection	0.005 / -0.04
at Extraction	0.001 / -0.002

In fact, the longitudinal emittance immediately after injection is much smaller than that mentioned above, such as 0.6 eV s and the bunching factor is 0.12. Therefore, the tune shift becomes -0.22.

2 Simulation Methods

Space charge effects are investigated using a tracking code Simpsons [1]. Let us briefly explain how Simpsons track particles with space charge effects. In Simpsons, all the elements including bending magnets and quadrupole magnets are represented as thin lens. The conversion from a thick lens description of the lattice to a thin lens equivalence is performed by TEAPOT [2], which is another particle tracking code for more general purposes. In the thin lens lattice, three dimensional coordinates (*x, y, s*) are updated every time step of the order of 10 ns. The independent variable is time, not the longitudinal position. That is particularly useful for calculation of the space charge force because a snapshot of a beam in configuration space is obtained directly. If there is a lattice element within a time step, three dimensional momenta (*px, py, ps*) are changed.

Whenever the coordinates are updated every time step, space charge potentials are calculated in a moving frame in the following way. First, cylindrical meshes in (r, θ, z) coordinates is made just enough for enclosing a beam. Typically the number of meshes are 20 in r direction and 50 in z direction. Fractions of every macro particle are assigned to the nearest eight grid points by the area weighting method. The assigned charges at the grid points are Fourier transformed in θ direction to be decomposed into azimuthal modes, Then, the Maxwell equations are solved in (r, z) space for each azimuthal mode. Boundary conditions are included in such a way that a beam is surrounded with a beam pipe of constant radius which is made of a perfectly conducting material. Usually, the mode zero to four (octupole) is sufficient to reproduce the θ dependence of the beam distribution. Once electric fields are numerically calculated at the grid points, the space charge force at the position of each macro particle are estimated in the same weighting method as that for the charge assignment. Finally, the space charge forces are applied as a three dimensional kick. Typically, 4~5 space charge kicks are applied within a half FODO cell.

<u>Comparison of 2D and 3D Calculations</u>

Although Simpsons can handle tracking in six dimensional phase space and three dimensional space charge force, most of the tracking results in the booster are obtained by simplified version of the code; Simpsons2D, meaning that the 4D tracking with 2D space charge, because the 3D calculation requires a quite heavy CPU load. In the 2D approximation, we assume an infinitely long bunch in the longitudinal direction with the same line density as that at the center of the real bunch. Therefore, longitudinal space charge force is zero. Neither synchrotron oscillations or energy ramping is not included.

The 3D calculation is compared with the 2D one to ensure that they give reasonably similar results. The rms emittance and beam survival as a function of time for the first few milliseconds is calculated in 3D as shown in Fig. 1. Where the rms emittance is normalized and started from 26 π mm-mrad, which corresponds to the unnormalized 100 % emittance of 220 π mm-mrad when the distribution is waterbag. A particle is regarded as being lost when its amplitude becomes more than 120 mm, which is the nominal radius of the beam pipe. The circulating current is 4 A, which is equivalent to 5 x 10^{13} ppp when the kinetic energy is 200 MeV. A booster lattice without any nonlinear elements is modelled. The transverse bare tune is chosen at (6.35, 6.35). The number of macro particles is 100,000, that is barely enough for 3D calculation. The energy ramping as well as synchrotron oscillations are

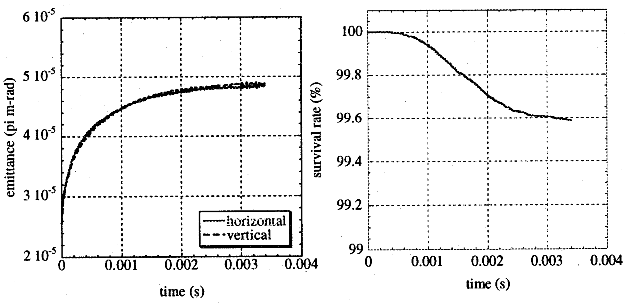

Figure 1:RMS emittance (left) and beam survival (right) for the first few milliseconds. The tracking has been carried out in 6D phase space with energy ramping and 3D space charge force. That is the most involved model of Simpsons.

included with the realistic rf voltage profile optimized by RAMA [3].

Then, 2D calculation is performed as shown in Fig. 2. The bunching factor is fixed and only the transverse space charge force is included. The number of macro particles are now 10,000. A quite noticeable difference between 3D and 2D is the growth time. Within much less than 1 ms, the asymptotic emittance is reached, whereas it takes a few milliseconds in 3D calculation. That is reasonable because the only part of a bunch, where the space charge force is always maximum, is simulated in the 2D model. The survival rate is almost 100 % (6 out of 10,000 particles are lost) up to the time we simulated.

We conclude that the 3D calculation is replaceable with

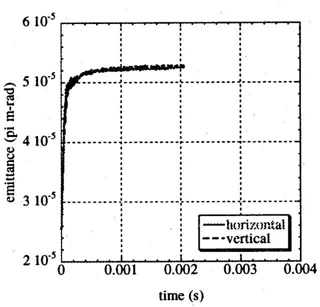

Figure 2: RMS emittance for the first few milli-seconds. The tracking has been carried out in 4D phase space with 2D space charge force. Almost no beam loss occurs in that time scale.

the 2D one as far as the rms emittance is concerned. As for the beam loss, its magnitude in the 3D case slightly bigger than the 2D one. The magnitude is, however, small in both. Keeping that discrepancy of the magnitude in our mind, we will show the beam survival rate in the following section.

3 Parameter Dependence of the Booster

Beam Intensity

We have looked at parameter dependence of the beam core size (rms emittance) and the beam loss in a quick manner using 2D space charge tracking. First, the beam intensity is varied around the design intensity of 4A and see the asymptotic emittance and beam survival. As we have already seen in the previous discussion, the emittance growth of the beam cores occurs at the design intensity. As shown in Fig. 3, asymptotic emittance is almost proportional to the beam intensity except below 3A, where the no emittance growth occurs and asymptotic emittance is simply determined by the initial emittance. On the other hand, above 5 A, where the asymptotic emittance is determined by the beam pipe aperture. The beam survival rate is also plotted. It shows that the beam loss begins to occur around the design intensity. A large beam loss at the higher intensity explained that the asymptotic emittance is determined by the aperture.

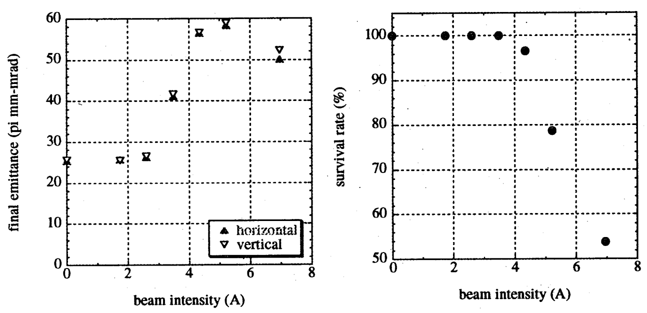

Figure 3: Asymptotic emittance (left) and beam survival rate (right) as a function of beam intensity. The design intensity is 4 A and we assume that the initial emittance is 26 π mm-mrad with waterbag distribution. That is the 100 % unnormalized emittance of 220 π mm-mrad.

Initial Emittance

Secondly, we looked at the asymptotic emittance as a function of initial emittance because the above results show that the initial emittance may be too small for the design intensity. When the initial emittance is more than 35 π mm-mrad, there is almost no emittance growth. Below that, even overshoot phenomenon is observed, meaning that the smaller initial emittance results in the larger final emittance. As long

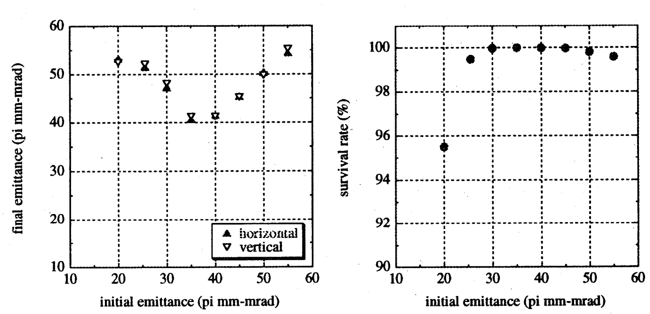

Fig. 4: Asymptotic final emittance and beam survival rate as a function of initial emittance. According to the current design, the initial normalized rms emittance is 26 π mm-mrad. Beam pipe radius of 120 mm is assumed.

as the beam pipe of 120 mm ϕ is assumed, there is almost no beam loss unless the initial emittance is too small to keep the space charge force moderate or too larger to accommodate beams inside the beam pine as shown in Fig. 4. The asymptotic beam profile when the initial emittance is 20 π mm-mrad is plotted in Fig. 5.

4 Space Charge Effects in the Main Ring

Space charge effects in the main ring are also investigated using a tracking code Simpsons [1]. We assume that the initial 100 % emittance from the booster is 220 π mm-mrad (unnormalized). This corresponds to a normalized rms emittance of 37 π mm-mrad if the charge distribution is a waterbag. Taking that as the initial condition, the transverse emittance evolution is simulated.

The tracking is done in the 6D phase space, and the 3D space charge force is calculated every 10 ns. The beam current is 6.8 A, which is equivalent to 2 x 10^{14} ppp.

The modelled lattice itself does not have any nonlinearity, except for the sextupole magnets for chromaticity correction. The chromaticity is corrected to zero. The transverse bare tune is (21.85, 15.40). With an rf voltage of 280 kV, the synchrotron period is about 1.5 ms. The beam pipe radius is assumed to be 7 cm, which determines the boundary condition necessary for the space charge potential calculation, and also for the beam loss criterion.

With a longitudinal emittance of 3 eV s, the emittance evolution is flat, except for a jump at the beginning, which is due to a transverse mismatch, which is inevitable in macro particle tracking, as shown in Fig. 6. If longitudinal blow up is not carried out and the lower emittance (0.6 eV s) is maintained throughout injection of the main ring, emittance growth occurs. Although there appears to be very little growth, it can be large after 120 ms, which is the nominal accumulation time for the first batch to complete injection from the booster. In either case, no beam loss is observed.

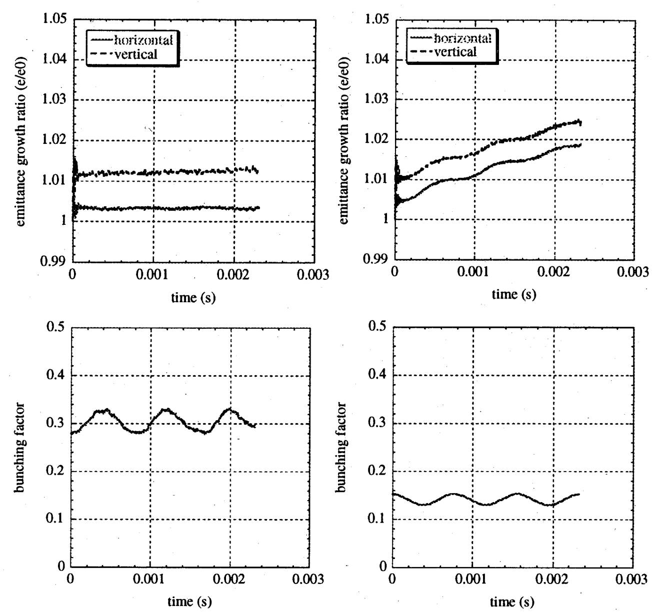

Figure 6: Normalized rms emittance and bunching factor as a function of time. The initial longitudinal emittance is 3 eV s (left) and 0.6 eV s (right). The ripples on the bunching factor come from any longitudinal mismatch. The ripples on the emittance growth of a 0.6 eV s bunch is synchronized with the bunching factor.

5 Summary

Space charge effects in the JHF synchrotrons are investigated using a tracking code Simpsons. In the booster simulations, most of the tracking has been performed by the 2D calculation, yet they give similar results as the 3D one made as a reference. The simulation study shows that the rms normalized beam emittance becomes about 50 π mm-mrad (it is more than 430 π mm-mrad in the unnormalized 100 % emittance with waterbag distribution) when the beam intensity is 4 A. There is the optimized initial emittance, around 35 to 40 π mm-mrad (it is 300 to 350 π mm-mrad in the unnormalized 100 % emittance). If we start from that, no emittance growth is observed and beam loss is prevented. One of the remaining study is to see if there is any bare tune dependence of the emittance and beam loss. That will be done when more details on the lattice and magnet design are fixed. The injection painting scheme should be optimized including those results.

In the main ring, space charge effects are less than those in the booster. Still, there is emittance growth when the longitudinal emittance is not blown up at injection. Although it seems a little in a time range we have investigated, that can be large in a few 100 ms, which is the time period required for accumulation of beams from the booster. A long term simulation is a must even though the tracking is quite time consuming.

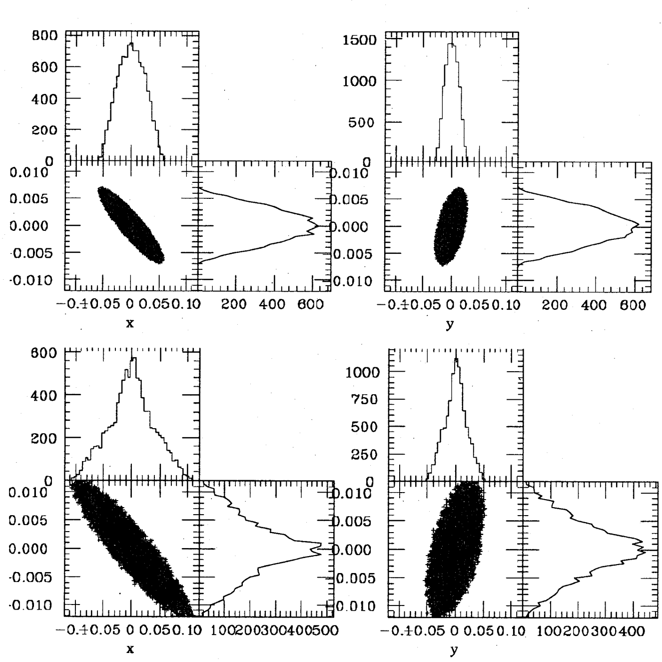

Figure 5: Initial beam profile (above) and asymptotic one (below) when the initial emittance 20 π mm-mrad. The growth of the tail explains the "overshoot" of the rms emittance.

References

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[3] R. Baartman and H. Schoenauer, TRI-DN-86-15, TRIUMF (1986).