SPACE CHARGE EFFECTS IN THE SSC LOW ENERGY BOOSTER

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Abstract

By means of multi-particle tracking, we explore space charge effects in the Low Energy Booster (LEB) which has a strong requirement for small transverse emittance. Macro-particles are tracked in a self-consistent manner in six dimensional phase space with transverse space charge kicks so that the emittance evolution as well as the particle distribution are simulated as a function of time. Among recent improvements of the code, the longitudinal motion, i.e. synchrotron oscillations as well as acceleration, makes it possible to simulate the capture process of linac micro-bunches. The code was calibrated by comparing with the experimental results at the Fermilab Booster. Preliminary results of the LEB show slow emittance growth due to the space charge.

I. INTRODUCTION

The Low Energy Booster (LEB) is the first synchrotron in the SSC accelerator complex [1]. Although the beam intensity is rather low compared with existing and proposed low energy ($\leq$10GeV) synchrotrons like the Fermilab Booster or the TRIUMF Booster, the small transverse emittance results in high beam density in the transverse phase space. In terms of the Laslett tune shift, it becomes for the LEB about $\approx$ 0.5 right after injection at the 600 MeV injection energy. Consequently, space charge effects are the major issue among beam dynamics considerations, rather than any other collective effects which are usually scaled proportionally to the intensity.

Although space charge effects are a common bottle neck of low energy machines and are observed in existing facilities, the understanding is limited. So far, the best we can do is to calculate the Laslett tune shift, but the maximum allowable tune shift is not a well defined number. Experimental results of the Fermilab Booster and the AGS indicate that a tune shift of even more than 0.5 is acceptable. This implies a naive model that the emittance growth occurs by linear resonances unavoidable with a large tune spread, is not necessarily correct. Presumably, the machine parameters, such as the strength of resonances, the superperiodicity, the operating tune as well as the tune of synchrotron oscillations alter the effect.

The approach of simulating the effects by a multi-particle tracking code has recently been undertaken at several places and is providing reasonable results [2]. Although understanding of the simulation results are, at present, inadequate, they remain an extremely useful with which to explore the machine parameter space, and therefore to provide both valuable guidance in machine design and understanding of experimental results. The combination of these will, hopefully, lead to more complete understanding of the space charge phenomena.

II. RECENT CODE DEVELOPMENT

Based on the thin lens code TEAPOT, the space charge force is introduced as kicks. Multi-particles, usually about 2000 are tracked self-consistently with the space charge force so that the emittance evolution as well as the particle distribution are obtained as a function of time. Detail of the calculation of the space charge force is in another paper [3].

For the simulation of the LEB, the synchrotron oscillation and acceleration have recently been implemented to model the capture and bunching of the linac micro-bunches. The rf voltage curve and the excitation pattern of the bending field are read as a table so that realistic modeling of the longitudinal dynamics becomes possible. This is especially important in rapid cycling machines like the LEB, because the bunch shape, i.e. bunching factor, and the beam energy change quite rapidly, and therefore, also the space charge force. To check the longitudinal dynamics additions to the code, synchrotron tune as a function of the whole LEB cycle was calculated by FFT and agrees with the analytical result.

In the current version of the code, the longitudinal space charge force is not included. According to the simulation results from ESME [4], that force increases the bunching factor (defined by the average intensity over the peak intensity) by about 30% and the ratio is almost constant for the first few milliseconds. We have therefore, approximated the effect by reducing the intensity such that the peak line density becomes equivalent to that of the longer bunch produced in the case with the longitudinal space charge.

The typical cpu time is one minute for one turn on CRAY-2.

III. CALIBRATION OF THE CODE

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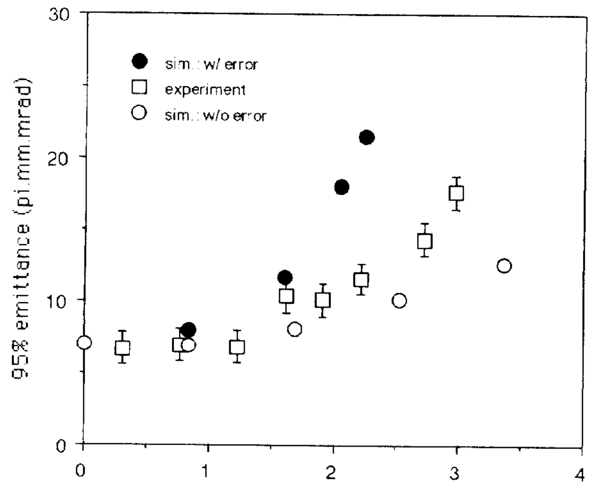

Figure 1: Experimental and simulation results of vertical emittance vs. total intensity in the Fermilab Booster.

The code was calibrated by comparing to experimental data, that is, the 95% emittance as a function of the intensity taken at the Fermilab Booster [5]. The bare tunes were chosen at $\nu_{x/y}$=6.70/6.80. Since we do not know the magnitude of multipole errors accurately, the two cases of a perfect lattice and a strongly perturbed lattice with the errors of quadrupole, sextupole, and octupole components in the main gradient magnets were examined separately. The "strengths" of multipoles are defined in the Appendix.

Figure 1 shows the 95% emittance which was taken for the simulation results as being six times the rms emittance. The square marks with error bars indicate the experimental data of the vertical emittance [5].

The emittance evolution and the transmission as a function of time are shown in Figs.2 and 3. Particle loss occurs when either the transverse amplitude becomes more than 5cm, (equivalently 50πmm.mrad acceptance) or the longitudinal position deviates from the synchronous phase by more than five rf wave lengths. In time scale explored, the asymptotic emittance was not obtained for the high intensity cases. When there are large multipole errors, rapid growth of the emittance after a bunch is shaped was noted; that is not the case without errors.

IV. Emittance Growth in the LEB

The goal is to achieve at an intensity of 10^{10} particles per bunch from the LEB an extracted emittance (rms) $\leq$ 0.60πmm.mrad. We assume the emittance from the linac is 0.40πmm.mrad, including effects of the injection mismatching and scattering at the charge exchange foil.

The LEB lattice design has slightly changed since this study began and some parameters differ from those in another paper [1]. Among them, the change of the circumference from 540m to 570m increases the importance of the space charge force in the same ratio. The following results

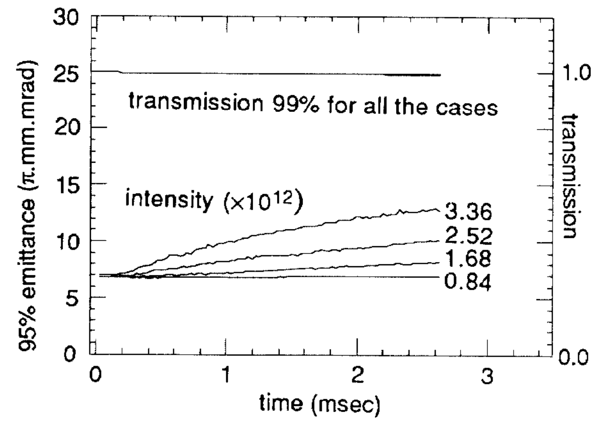

Figure 2: Emittance and transmission as a function of time without errors.

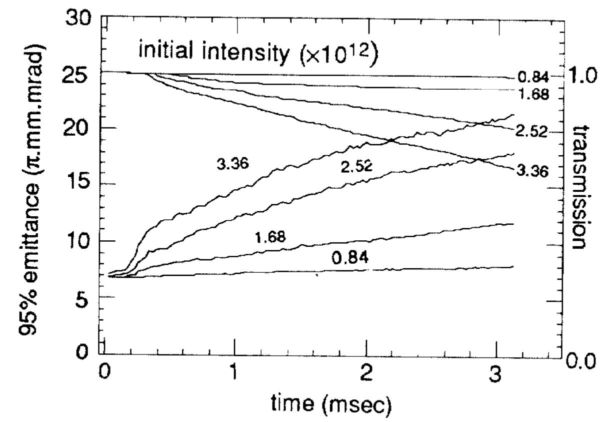

Figure 3: Emittance and transmission as a function of time with errors.

are based on the smaller circumference lattice with 600 MeV injection. We included multiple errors listed in the Appendix. The newest lattice with 570m circumference will be tracked in future.

Figure 4 shows reference results of the emittance as a function of time. Up to about 10 milliseconds, the rms emittance has not yet reached an asymptotic value and has nearly reached the emittance budget value of 0.60πmm.mrad. The transmission in the first 10 milliseconds is 99%. The 1% beam loss occurs due to particles not captured in longitudinal buckets in the adiabatic bunching process. Beam profiles in the both planes remain gaussian. That is also seen more quantitatively by measuring emittance in different ways: the emittance defined by the sigma of a gaussian fit to the beam profiles and by the beam size in which 99% of the particles reside. Both emittance evaluations yield similar results.

One of the reasons that it takes longer time in the LEB than in the Fermilab Booster to reach asymptotic emittance might be explained by the slower machine cycle, 10Hz for the LEB, 15Hz for the Fermilab Booster, and the higher injection energy, 600MeV vs. 200MeV, respectively. Hence the beam stays for longer time in the LEB under the condition of significant space charge.

Multipole error dependence of the emittance are plotted for the first few milliseconds in Fig.5. Quadrupole, sextupole, and octupole errors, both systematic and ran-

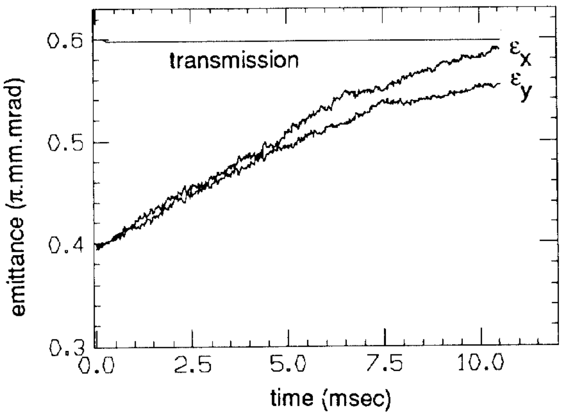

Figure 4: The rms emittance in the LEB as a function of time.

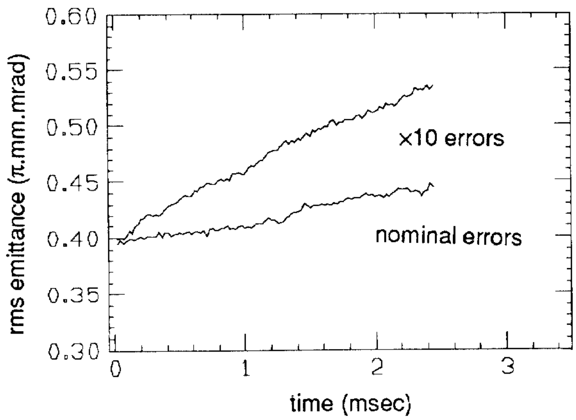

Figure 5: Emittance evolution for different strength of errors.

dom, in the quadrupole and dipole magnets are increased by factor 10. Although all cases do not reach the asymptotic value, a larger slope of the emittance with larger field errors is noticeable.

All the results on the LEB are preliminary and we will continue to refine the code and evaluate various parameter dependences.

V. Summary

Synchrotron oscillations and acceleration have been implemented in the space charge simulation code. This makes it possible to simulate space charge effects with the capturing and bunching process, which increase the line density, and with the time dependent kinematic factors; β, γ, which influence the space charge force. Synchrotron oscillation itself is expected to modify the resonance structure in tune space.

The code was checked against experimental data of the Fermilab Booster. The experimental data could be reproduced between the two extreme cases, the perfect lattice and the strongly perturbed lattice; the intensity thresholds above which significant emittance growth occurs are similar. In the perturbed lattice, large beam loss as well as emittance growth was observed, both increasing with intensity.

The preliminary results of the LEB show slow emittance growth up to 10 milliseconds. The growth rate becomes higher with the increase of multipole errors.

errors	Fermilab Booster	LEB
$\Delta e_x(1)$	1.6e-2	1.4e-3
$\Delta e_y(1)$	8.2e-3	1.2e-3
$\Delta e_x(2)$	5.5e-4	1.3e-4
$\Delta e_y(2)$	6.7e-4	1.1e-4
$\Delta e_x(3)$	5.8e-5	4.4e-6
$\Delta e_y(3)$	2.9e-5	9.2e-7

Table 1: Width of resonances defined by the equation above.

VI. Appendix

To estimate the magnitude of multipole errors, we calculate the following value.

$$\Delta e_{x,y}(n) = \frac{\epsilon_{x,y}^{(n-1)/2}}{2\pi 2^n n! B\rho} \left| \int B^{(n)} \beta_{x,y}^{(n+1)/2} \exp[i(n+1)\phi(s)] ds \right|,$$

where $\epsilon_{x,y}$ is four times the rms emittance, $\phi(s)_{x,y}$ is the phase of betatron oscillations, and n=1 for quadrupole, n=2 for sextupole, and n=3 for octupole. For the Fermilab Booster and the LEB simulation, we use the lattice in which the errors are listed in Table 1.

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VII. References

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