31
11/29/91 JS(2)

SSCL-556

SSCL-556

Superconducting Super Collider Laboratory

Proposal of a Beam Study in the AGS Booster

S. Machida and S. Chen

October 1991

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

SSCL--556

DE92 003600

Proposal of a Beam Study in the AGS Booster

S. Machida and S. Chen

Superconducting Super Collider Laboratory*
2550 Beckleymeade Avenue
Dallas, TX 75237

October 1991

* Operated by the Universities Research Association, Inc., for the U.S. Department of Energy under Contract No. DE-AC35-89ER40486.

MASTER
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED
EB

1.0 INTRODUCTION

In order to achieve the design luminosity, the Superconducting Super Collider (SSC) parameter choices emphasize the preservation of the transverse emittance requiring in the collider a normalized transverse emittance of $1 \pi \cdot \text{mm} \cdot \text{mrad}$. A stringent accelerator chain emittance budget must be maintained to achieve the final value. Budgeted emittance specifications for the Low Energy Booster (LEB) include $0.4 \pi \cdot \text{mm} \cdot \text{mrad}$ at injection and $\leq 0.6 \pi \cdot \text{mm} \cdot \text{mrad}$ at extraction. The space-charge tune shift is expected to be more than 0.5 when the rms normalized emittance is $0.4 \pi \cdot \text{mm} \cdot \text{mrad}$ at injection and the total number of particles is 1.1×10^{12} with 1×10^{10} particles per bunch. Therefore, it is necessary to cope with a large tune shift and avoid emittance deterioration.

We have been studying the beam emittance evolution in the LEB by a multi-particle simulation code with space-charge effects. As reported in the several papers¹ (and summarized later in this note), we have obtained from the simulation some new insights into the effects which seem to explain qualitatively a cause of the emittance growth. Even quantitatively, we believe that the simulation can predict the emittance growth as a function of time quite accurately because the code includes most details of the physics processes, such as the adiabatic bunching process and acceleration in the fully 6-D phase space treatment, transverse as well as longitudinal space-charge calculations in a self-consistent manner, and intensity decrease due to particle loss.

The simulation study has limitations. Whether the physics model is adequate can only be checked experimentally. In this context, we did a beam study in the Fermilab Booster a couple of years ago which gives supportive evidence for the results of the simulation study.² However, lack of complete experimental data for the Fermilab Booster prevents us from comparing data quantitatively. First, there was a lack of information on the detailed lattice parameters such as the higher multipole contents of each magnetic element. Therefore, we simulated two extreme cases: without multipole fields and with rather strong multipole fields to estimate the upper and lower limits of the emittance growth. Secondly, the errors of the experimental emittance measurements were large due to the limitations of the available diagnostics.

The Alternating Gradient Synchrotron (AGS) Booster will provide significantly better experimental data. Because it is a newly-constructed machine, we can access all the data we need to simulate the machine lattice. The ionization type profile monitor will provide improved data of the transverse emittance as a function of time. Although the brightness design value is not as high as the SSC LEB, we believe the brightness can be increased by injecting a larger number of particles. In conclusion, the AGS Booster provides a preferable

machine in which to study the emittance evolution under space-charge effects. Therefore, we propose a beam study in the AGS Booster.

The purpose of the study is to determine quantitatively the emittance deterioration due to space-charge effects, not to find the maximum current an accelerator could accommodate (so-called "space-charge limits" of a machine). Since the charge distribution itself may not remain the same, an accurate measurement of the beam profile is an essential factor of the beam study.

2.0 SUMMARY OF THE SSC LEB RESULTS

This section summarizes LEB simulation study results. The previous study had two phases. The initial study phase was done for coasting beams to examine the qualitative aspects of space-charge effects. There, a simplified physics model was used assuming a coasting beam, constant energy, no bunching process, and no longitudinal space-charge. A second study phase sought a more quantitative estimation of the emittance growth in the present LEB lattice with a more complete model.

2.1 Qualitative Findings

An extensive study of space-charge effects on coasting beams has been done for the LEB lattice with the race track shape proposed in 1988. We have investigated the effects in two different lattice conditions: a lattice rather strongly perturbed by half-integer resonances and a perfect lattice, meaning that there are only linear elements except chromaticity correction sextupoles. The findings of that study have been published,¹ and are summarized below.

In the lattice strongly perturbed by half-integer resonances, the phase space density limit appears when we move the bare tune close to the resonance or increase number of particles keeping the bare tune at a fixed value. As a result, an initial Gaussian charge distribution is totally distorted and becomes more or less uniform. Figure 1 shows the phase space density as a function of a particle amplitude before and after the emittance growth occurs. The Laslett tune shift seems to overestimate space-charge effects. When the vertical bare tune was varied (keeping the initial beam brightness constant), the bare tune could be brought within half the Laslett tune shift from the resonance. This implies that some of the particles can cross over the resonance without causing an emittance growth.

By comparing different types of initial distributions: Gaussian, water-bag, and pseudo-KV,³ we found that the allowable distance from the resonance is somewhat independent of the initial distribution if we take the same rms emittance for all of them. According to

a naive picture, it should differ for each distribution with the same rms emittance, since the Laslett tune shift depends on the peak phase space density which is dependent on the distribution. To explain this result, we introduced an “rms tune shift,” which only depends on the rms emittance, not the peak phase space density as,

$$\Delta\nu_{rms} = -\frac{r_p n_t B_f}{2\pi\beta\gamma^2(4\epsilon_{rms}^{nor.})}, \quad (1)$$

where r_p is the classical proton radius, n_t is the total number of particles in the ring, β and γ are the Lorentz factors, $\epsilon_{rms}^{nor.}$ is the normalized rms beam emittance, and B_f is the bunching factor, which is the ratio of peak beam intensity to average around the ring and becomes unity for coasting beams. The rms tune shift is defined by the rms linear part of the space-charge force in terms of the rms envelope equations.⁴ The beam with the same rms emittance has the same rms linear part of the space-charge, thus the same rms tune shift. The rms tune shift explains the allowable distance between the bare tune and the resonance much better than the Laslett tune shift.

Figure 1. Phase Space Density vs. an Amplitude Before and After the Emittance Growth Occurs.

In a lattice without half-integer resonances, there appeared to be no phase space density limit. As far as the core of the beam and the charge distribution is concerned, little change was observed when increasing the number of particles and/or moving the bare tune around the design value in a reasonable range. The rms emittance, however, becomes large when we choose the bare tune slightly above structure fourth-integer resonances⁵ and it seems that the emittance growth is caused mostly by the tail of the beam.

The fourth-integer resonance structure was clearly identified by launching a few test particles with macro particles in such a way that the test particles are subject to the space-charge force but do not disturb the macro particle distribution. Figure 2 shows the Poincaré map of the test particles when the bare tune is 11.60 and the Laslett tune shift is -0.33 . The resonance islands in the phase space only appear near structure resonances and not near non-structure resonances. To make sure that this was not because of the second order effects of chromaticity correction sextupoles, we increased their strength by a factor of 10 and found no difference in the rms emittance growth.

Figure 2. Poincaré Map of Test Particles.

Consequently, higher superperiodicity would reduce the number of resonances which should reduce the emittance growth due to space-charge effects. In the model lattice, we checked that the resonance can be eliminated by taking superperiodicity four, in that case the tune 11.50 is no longer fourth-integer structure resonance.

2.2 Estimation of Asymptotic Emittance

Obviously, the coasting beam assumption oversimplifies or even ignores some important factors such as the time dependence of the bunching factor, synchrotron oscillations and their coupling with transverse oscillations, the time dependence of Lorentz factors β and γ . To include these factors correctly, we improved the code such that particle tracking in the fully 6-D phase space with acceleration can be modeled.⁶ Quite recently, the longitudinal space-charge kicks have been added in addition to the transverse ones by means of the

particle-in-cell method (PIC). The details of the code are described in another paper.⁷ With these additional features of codes, we have estimated the asymptotic emittance growth in the present LEB lattice.

Figure 3 shows the emittance as a function of time in the LEB. Here, the lattice was assumed to be perfect, meaning there are no other nonlinear multipoles except chromaticity correction sextupoles. The input beam was characterized by normalized rms emittance of $0.40 \pi \cdot \text{mm} \cdot \text{mrad}$, number of particles per bunch of 10^{10} with an injection energy of 600 MeV. Initially, the beam has the linac rf structure of 428 MHz and is injected into the LEB in four turns. The result shows that it is possible to keep the emittance below the design constraint, $0.60 \pi \cdot \text{mm} \cdot \text{mrad}$, in this perfect lattice.

Figure 3. Emittance in the LEB.

The qualitative beam behavior such as fourth-integer resonance caused by the beam itself was also observed in bunched beams. The emittance after 100 turns is recorded as a function of the horizontal bare tune as shown in Figure 4. The vertical tune is fixed to 11.80. The beam is assumed to be initially matched to the longitudinal bucket which gives the synchrotron tune of 0.001. There is no longitudinal space-charge turned on. Since the present LEB lattice has superperiodicity three, the horizontal tune: 10.5, 11.25, and 12 are structure fourth-integer resonances and, at the same time, 10.5 and 12 are structure half-integer resonances. We can see the effects by those resonances in Figure 4. A similar simulation with a different synchrotron tune of 0.100 shows essentially the same behavior.

Figure 4. Bare Tune Dependence of the Emittance. Large solid circles are horizontal emittance and small empty ones are vertical. The vertical bare tune is fixed to 11.80.

3.0 PRELIMINARY RESULTS ON THE AGS BOOSTER

3.1 AGS Booster Modeled in the Code

The AGS Booster is a multi-purpose machine that delivers high intensity protons as well as heavy ions to the AGS and eventually to the Relativistic Heavy Ion Collider (RHIC). Space-charge effects are most significant in the proton acceleration mode and therefore we only consider the machine parameters for protons. Table 1 shows the basic parameters.

TABLE 1. AGS Booster Parameters.

Circumference	201.78 m
Superperiodicity	6
RF harmonics	3
Injection momentum	0.6444 GeV/c
Beam pipe aperture	0.10 m (?)

In the simulation, the all lattice elements are replaced by thin lenses. The layout and the lattice functions of one superperiod after making the thin lens approximation are shown in Figure 5. Beams are injected at the straight section C6 and two rf cavities are located at A6 and E6 as in the real machine. The path length of the lattice functions is measured from the injection point at the middle of C6. No multipole errors are included in

the lattice at present. The only nonlinear elements are chromaticity correction sextupoles. The synchronous momentum and rf voltage as a function of time used in the simulation are shown in Figure 6. These curves were reconstructed referring to Booster Design Manual.⁸

Figure 5. AGS Booster Layout and Lattice.

Figure 6. Synchronous Momentum and RF Voltage as an Input to the Code.

We assume that the rms transverse normalized emittance of injection beams is $12.5 \pi \text{ mm.mrad}$ and has Gaussian distribution in both position and gradient axes in the transverse phase space. Longitudinally, the particles are distributed uniformly along the spatial direction and have Gaussian distribution along the momentum axis with $\sigma_{\Delta p/p} = 0.548 \times 10^{-3}$. The Gaussian distribution was truncated at 3σ . The total number of macro particles, about 10000 representing a beam of 0.5×10^{13} per bunch, are injected in 84 turns in about $100 \mu\text{sec}$. During the multi-turn injection process, we suppress the

space-charge calculation since the number of macro particles is not enough and space-charge effects are relatively small. At the completion of the injection process, a bunch corresponding to the Booster rf structure is formed. We then start applying the transverse and longitudinal space-charge kicks. We do not take into account the chopper scheme used to remove particles near the ends of an rf bucket. Figure 7 shows the phase space distribution right after the multi-turn injection is over.

Figure 7. Phase Space Distributions Right After the Injection: (a) Longitudinal, (b) Horizontal, and (c) Vertical.

3.2 Laslett Tune Shift

To achieve an estimate of space-charge effects, the Laslett tune shift is calculated. The incoherent Laslett formula without image charge effects is:

$$\Delta\nu = -\frac{r_p n_t B_f}{4\pi\beta\gamma^2\epsilon_{rms}^{nor.}}, \quad (2)$$

where r_p is the classical proton radius, n_t is the total number of particles in the ring, β and γ are the Lorentz factors, $\epsilon_{rms}^{nor.}$ is the rms normalized beam emittance (we assume Gaussian distribution), and B_f is the bunching factor.

Just after the multi-turn injection process, 100 μ sec from the start of a cycle, the bunching factor becomes about 3 according to Figure 7(a). At that time, the synchronous momentum has already slightly increased to 0.6451 [GeV/c]. By putting the design value for the emittance and number of particles into the formula, we get

$$\Delta\nu = -0.527.$$

In the Booster Design Manual,⁸ it is estimated smaller; $\Delta\nu = -0.35$, because the bunching factor is assumed to be about 2.

3.3 Profile and Emittance

For three different particle intensities, 1.5×10^{13} , 3.0×10^{13} , and 5.0×10^{13} , Figure 8 shows the emittance evolution as a function of time. Note that the vertical scale is different for each figure. Figure 9 shows the transverse beam profile after 2000 turns for each intensity. The vertical scale is normalized by the peak intensity. The bunching factor for a beam intensity of 1.5×10^{13} particles is shown in Figure 10. The transmission efficiency for 1.5×10^{13} particles is 94.4% in the first 2000 turns. The efficiency is defined both by longitudinal loss—we consider a particle to have been lost when it is not captured in the center bucket or both neighboring buckets, and by transverse loss—a particle hits a wall.

4.0 PLAN OF THE EXPERIMENTS

As mentioned earlier, the primary purpose of the experiment is to observe the emittance evolution for different initial conditions: intensity and emittance, and with different lattice parameters: chromaticity, multipole errors, and betatron tune as well as synchrotron tune. Ideally, the experiment will reproduce the correspondence of Figure 8 and/or Figure 9 in each condition. At the moment, we think that the priority for each parameter to be examined should be in the following order.

Figure 8. Emittance Evolution: (a) 1.5×10^{13} , (b) 3.0×10^{13} , and (c) 5.0×10^{13} .

1. *Number of Particles.* With chromaticity corrected to zero and without correction elements for half-integer and nonlinear resonances (except orbit error correction), change the intensity either by increasing the injection turn number or linac current, keeping the emittance the same. Then, take beam profile data every $\simeq 100 \mu\text{sec}$ from the start of a cycle. The first 5 msec is probably enough to get the asymptotic value of the final emittance. In addition, the bunch shape measurement should be done at the same time. The intensity of every profile measurement should be

Figure 9. Horizontal and Vertical Profiles: (a) 1.5×10^{13} , (b) 3.0×10^{13} , and (c) 5.0×10^{13} . Dashed line is the initial profile and solid line is 2000 turns later.

Figure 10. Bunching Factor. Intensity is 1.5×10^{13} .

recorded also. We can define the so called “space-charge limits” as the upper limit of the number of particles, although that is not the main purpose of the experiment.

2. *Emittance.* With the same lattice conditions as for the experiment above, change the emittance instead of the intensity. In terms of the beam brightness, the two experiments create the same condition. The simulation for the LEB implied, however, that the two parameters defining the brightness are not necessarily equivalent. In other words, the Laslett tune shift may not be an adequate way to scale space-charge effects. We would like to see if that is the case. In practice, it may be difficult to get vary the emittance while maintaining the intensity.
3. *Third and/or Fourth-Integer Resonance Strength.* By exciting the sextupole and/or octupole correction elements at several different values, eliminate third and/or fourth-integer resonances or even intentionally drive them strongly and see the effects of these resonances. It would be interesting to see if there is a threshold strength below which we cannot observe the effects of these resonances.
4. *Chromaticity.* In the same context above, examine if the nonlinearity of the chromaticity correction sextupoles affects the emittance. Apart from nonlinearity, the chromaticity itself might affect the emittance through the synchro-beta coupling.
5. *Betatron Tune.* All the proposed experiments should be repeated at several betatron tunes. Surely, the effects of resonances differ at different tunes. The effects of the coupling resonance $2\nu_x - 2\nu_y = 0$ and fourth-integer structure resonances especially

should be examined. Practically, it is very important to find an optimum operating tune at which the least emittance growth occurs.

6. *Synchrotron Tune.* The simulation results of the LEB show that there is a strong correlation between synchrotron tune and the emittance growth, namely, the higher synchrotron tune, the greater the emittance growth. We may be able to infer the result of the synchro-beta resonance, but the detailed source of the correlation is not clear. On the other hand, it is difficult to separate the effect of the synchrotron tune because the other parameters easily change once we manipulate the rf voltage to get the different synchrotron tune. Even in the simulation, it is a difficult task.

5.0 SCHEDULE

More extensive simulation study should be done before taking experimental data to explore the initial condition dependence and lattice parameter space. This should be accomplished in the months before the next AGS Booster run in early 1992. A time schedule of the actual experiments depends on the availability of the Booster beam for a study and other factors. We would like to request two contiguous weeks with one shift (8 hours) every day for the preliminary experiments.

ACKNOWLEDGEMENTS

We would like to thank Drs. W.T. Weng and Y.Y. Lee for their courteous help to make the simulation of the AGS Booster possible. Drs. R.C. York and A.W. Chao also should be acknowledged for their continuous encouragement.

REFERENCES

1. S.Machida, "The Beam Tracking during the First Few Milliseconds of a Low Energy Booster," *Proceedings of the 1989 IEEE Particle Accelerator Conference*, pp. 1061–1063, Chicago, March 1989. S. Machida, "The Tracking Study of a Low Energy Proton Synchrotron," *Particle Accelerators*, Vol. **28**, pp. 131–136, 1990. S. Machida, "Space Charge Effects in Low Energy Synchrotrons," *2nd European Particle Accelerator Conference*, pp. 1655–1657, Nice, France, June 1990. S. Machida, G. Bourianoff, N.K. Mahale, N. Mehta, F. Pilat, R. Talman, and R.C. York, "Space Charge Effects in the SSC Low Energy Booster," *Proceedings of the 1991 IEEE Particle Accelerator Conference*, San Francisco, May 1991. S. Machida, "Space Charge Effects in Low Energy Proton Synchrotrons," to be published in *Nuclear Instruments and Methods in Physics Research A*.
2. S. Machida, et al., "Study of Space Charge Effects in the Fermilab Booster," EXP-170, Fermilab, April 1990.
3. Because the Kapchinskij-Vladimirskij distribution is a purely mathematical model; δ -function in the 4-D phase space surface, it is impossible to make it with a finite number of macro particles. In the sense that we put macro particles on the phase space surface *initially* and there is no assurance afterward that it remains KV, we call it a pseudo-KV distribution.
4. F.J. Sacherer, "RMS Envelope Equations with Space Charge," *IEEE Transactions on Nuclear Science*, Vol. **NS-18**, No.3, pp. 1105–1107, June 1971.
5. The similar results are obtained by the much simpler simulation by G. Parzen. G. Parzen, "Intrinsic Space Charge Resonances and the Space Charge Limits," *2nd European Particle Accelerator Conference*, pp. 1658–1660, Nice, France, June 1990.
6. S. Machida, "Modification of TEAPOT to Include Acceleration," ADOD-028G. SSC Laboratory, January 1991.
7. S. Machida, et al., "Modeling Low Energy Proton Synchrotron," to be published.
8. Booster Design Manual, Revision 1, October 1988.

END

**DATE
FILMED**

01/02/92