Dynamic Aperture & Extraction Studies for the SSC High Energy Booster

S. K. Dutt, A. W. Chao, D. E. Johnson, T. Sen, & Y. T. Yan
SSC Laboratory*
2550 Beckleymeade Avenue
Dallas, TX 75237

Abstract

We present the results of a study made to evaluate the coil-winding aperture needed for the final booster in the injector chain for the SSC. Lattice designs based on 5 cm and 7 cm dipole apertures are evaluated by looking at (a) the long-term dynamic aperture at injection and (b) the good-field aperture requirement for resonant extraction of high-energy test beams. The 5 cm dipole is found to be marginal, while the 7 cm dipole satisfies field quality criteria for both injection and extraction.

1 Introduction

The final booster in the injector chain for the Superconducting Super Collider is a machine approximately twice the size of the Tevatron, with superconducting dipoles and quadrupoles which are 1.5 times stronger. The original designs specified dipoles with a 7 cm coil-winding diameter and an inner horizontal beam-pipe aperture of 55 mm. This dipole design was chosen to provide an adequately large good-field aperture for beam injection, and for the slow-extraction of high-energy test beams. With the recent decision to increase the Collider dipole coil-winding diameter to 5 cm, an argument for dipole commonality between the HEB and Collider was developed, and a preliminary examination of a 5 cm HEB dipole was undertaken. We report the results of a detailed study of the injection dynamic aperture for magnet errors corresponding to 5 cm and 7 cm dipoles. Also reported are preliminary results of the resonant extraction process for the two magnet designs.

2 Lattice Description

The High Energy Booster lattice is designed to operate from 200 GeV to 2 TeV. The design was determined primarily by the maximum energy, the need to operate in a bipolar manner, the desire to eject beams for transfer into both Collider rings from one straight section, a geometry compatible with easy injection from the Medium Energy Booster, and the expected need to have a clean, resonant extraction system to produce slow-spill test beams. The use of superconducting elements in the HEB makes it imperative to keep extraction inefficiency under 2% to avoid quenching near the septum. Machines using conventional magnets do not face such exacting requirements.

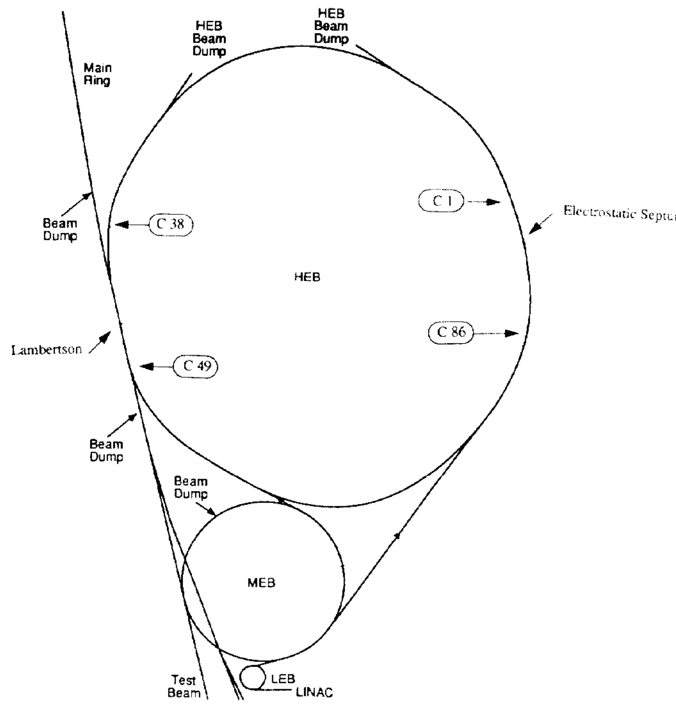

Figure 1: Schematic plan view of the injector complex. Also shown are the locations of special purpose quadrupoles and octupoles in cells 1, 38, 49, and 86 used for resonant extraction.

The HEB geometry is shown in Fig. 1. The west long-straight section contains the ejection channels for the transfers into the collider and the extraction channel for test beams. The east straight section contains the electrostatic septa needed for resonant-extraction. Extraction takes place in the horizontal plane. In order to minimize the excursions of the extracted beam in the arc magnets, the horizontal beta value in the two extraction straight sections is much larger than that of the rest of the machine. This large beta ratio allows the extracted beam to occupy

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Multipole Type	Systematic Errors						Random Errors	
	Geometric		Persistent Current					
			200 GeV		2 TeV			
Normal Multipoles								
Aperture	5 cm	7 cm	5 cm	7 cm	5 cm	7 cm	5 cm	7 cm
b_1	0.15	0.089					0.56	0.38
b_2	0.0	0.0	-1.89	-0.89	-0.189	-0.089	0.34	0.18
b_3	0.054	0.02					0.18	0.07
b_4	0.02	0.02	0.092	0.026	0.0092	0.0026	0.35	0.11
b_5	0.016	0.0035					0.043	0.011
b_6	0.0093	0.0016	-0.017	-0.0029	-0.0017	-0.00029	0.073	0.014
b_7	0.029	0.0039					0.063	0.0096
b_8	0.009	0.00094					0.027	0.0032
Skew Multipoles								
a_1	0.15	0.09					1.40	0.95
a_2	0.06	0.03					0.41	0.22
a_3	0.11	0.04					0.41	0.17
a_4	0.09	0.03					0.10	0.032
a_5							0.086	0.022
a_6							0.037	0.0072
a_7							0.063	0.0096
a_8							0.027	0.0032

Table 1: Multipole Coefficients for HEB Dipoles $[\times 10^{-4}\ \mathrm{cm}^{-n}]$

the same region of the dipole aperture as that required at low energy for the injected beam. Thus, the extraction process should not increase the required good-field aperture. In addition, the straight-section optics can be tuned to different high-beta values at the resonant-extraction devices. For the 7 cm dipole case, the extraction straight section was designed with $\beta_H = 305$ m. For the 5 cm dipole study, the beta value was increased to 500 m. This choice approximately scales the extracted-beam aperture in the arcs with the good-field region of the dipoles in consideration. The beta values in the straight sections and the dipole multipole error fields are the only differences in the lattices for the two studies. A detailed description of HEB design considerations is given in [1].

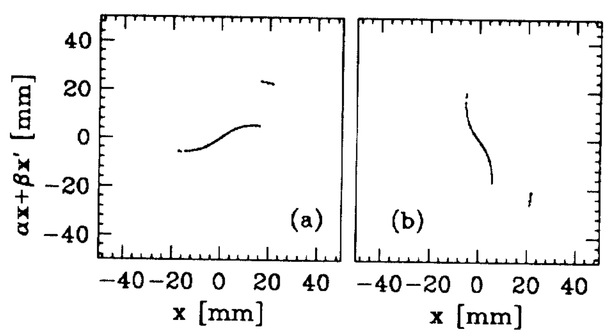

Figure 2: Phase space distribution of particles at (a) septum and (b) Lambertson after 50 turns for 7 cm aperture dipole.

3 Nonlinear Errors

The dipole error multipole coefficients used in simulating the dynamic aperture as well as the extraction process are given in Table 1 and were obtained by scaling the values for the 4 cm aperture Collider dipoles given in [2] according to the laws given in [3]. The values of random b_2 are 1/4 of the scaled values; also, simulations of the long term dynamic aperture, and of extraction have been performed with values of a_1 and b_1 set to zero. We assume that an appropriate correction scheme will be used. The considerations which went into obtaining these values are detailed in [4].

4 HEB Extraction

The extraction process used in the HEB is of half-integer type [5]. Special purpose octupoles are placed around the ring to excite the 69^{th} harmonic of the octupoles. The extraction octupoles are deployed in groups of 4. For a given octupole, we locate another of opposite strength at a phase advance of $\pi\nu$ around the ring. This enhances the 69^{th} harmonic of the octupoles, while cancelling the $zero^{th}$ and the 138^{th} harmonics. The two remaining octupoles in a group, also placed $\pi\nu$ apart with opposing signs, bring about a suitable phase for the fourier coefficient of the octupole perturbation. A total of six groups are used. The extraction quadrupoles are deployed in an identical manner at about the same locations as the octupoles. This cancels the zeroth harmonic of the quadrupole perturbation, so that the stopband halfwidth is determined purely by the quadrupole 69th harmonic. Figs. 2(a) and 2(b) show the phase space distribution of particles after 50 turns at the electrostatic septum and the Lambertson for HEB optics with 7 cm aperture dipoles. The simulations were carried out with 500 particles initially distributed with gaussian spreads in x, x', y, y', and in energy.The stable phase area is set to zero from the beginning of a run (no ramping).

For the 5 cm dipole aperture, the mean inefficiency (percentage loss at the septum) is $2.2 \pm 0.9\%$. No particles are lost in transit. The mean separation achieved at the Lambertson is 9.4 ± 1.7 mm. For the 7 cm dipole aperture, the mean inefficiency is $1.8 \pm 0.6\%$. No particles are lost in transit. The mean separation achieved at the Lambertson is 10.5 ± 2.5 mm.

5 Dynamic Aperture at Injection

The HEB injection process requires that particles survive more than 5×10^5 turns–loss of as little as 10^{-6} of the injected beam can cause the superconducting dipoles to quench. Long-term tracking studies were performed using a post-Teapot tracking program, Ztrack[6]. Hundreds of particles with well distributed initial displacements are tracked for ten thousand turns or more. A survival plot (turn at which a particle is lost *vs.* initial displacement) is then obtained for determining dynamic aperture. Random and systematic multipole errors are included along with errors due to misalignments: random steering errors, quadrupole rotations and displacements, and beam position monitor (bpm) displacements. The orbit is corrected to an rms orbit deviation of 1 mm in both the horizontal and vertical planes (with respect to the reference orbit). Chromaticities and working tunes are adjusted before initiating the run.

Long-term tracking was performed for two working tunes $(\nu_x, \nu_y) = (34.42, 33.38)$ and (34.425, 33.415), each with 5 random seeds for both the 5 cm and the 7 cm coil-diameter dipole cases. Chromaticities were fitted to either 0 or 5 units. All particles were initiated with the same energy, 200 GeV (HEB injection lattice), and with a $3\sigma_{rms}$ synchrotron oscillation amplitude, but with different transverse $(x/\sqrt{\beta_x} = y/\sqrt{\beta_y})$ amplitudes. The first set of tunes exhibited a chromaticity dependence of the dynamic aperture. This was eliminated by the choice of the second set of tunes.

500,000 turn tracking studies for 5 cm and 7 cm dipole apertures are shown in Fig. 3 for zero chromaticity.

6 Conclusion

The choice of the HEB dipole magnet aperture depends on the dynamic aperture at injection and on efficient slow extraction at 2 TeV. From the slow-extraction studies, we

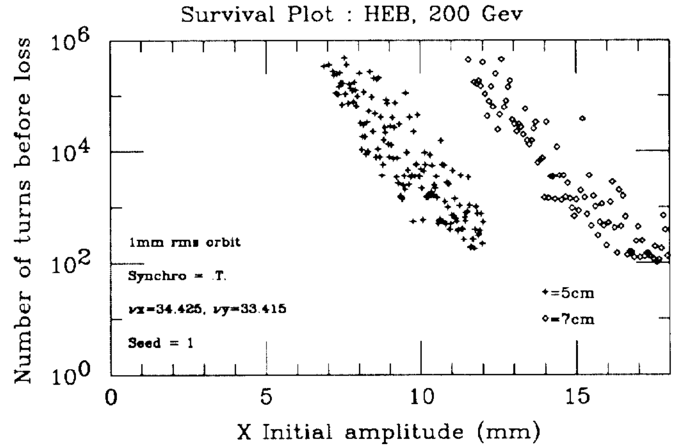

Figure 3: 500,000-turn survival plots for the tunes (34.425, 33.415) with zero chromaticity.

can see that the resonant extraction efficiency is somewhat worse for the smaller dipole aperture case, although both the 5 cm and the 7 cm dipoles possess acceptable apertures for the extraction process. Should we need to move the inner edge of the Lambertson channel out beyond approximately 5 mm, however, indications are that the 5 cm aperture extraction efficiency would be unacceptable, while the 7 cm case would remain adequate.

In the dynamic aperture studies, we suggest the requirement that the dynamic aperture be larger that ten times the nominal rms betatron beam size ($10\sigma_x = 10\sigma_y = 7$ mm), when the particle is executing a three-sigma synchrotron oscillation. The HEB was simulated with a 1 mm rms closed orbit error, but we have assumed a perfect correction of linear effects. Under these assumptions, we conclude that the 5 cm design *per se* is not adequate. To conclude otherwise would require, for example, a better working point, a simple and effective correction scheme, or a good reason to reduce the aperture goal mentioned above. Subsequent studies should concentrate on these areas. In the event that these concerns are not adequately resolved it may be necessary to increase the dipole aperture from the envisioned 5 cm.

References

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