# Tracking Studies and Machine Performance Simulation of the SSC Low Energy Booster

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*Abstract*

The features of the SSC Low Energy Booster (LEB) lattice design include a high transition $\gamma_t$ to avoid transition crossing during acceleration, dispersionless straight sections and moderate peak dispersion in arc sections. It has a three-fold symmetry with separate arcs and long straight sections to provide adequate azimuthal space for the required hardware. We have done tracking studies and machine simulations to verify the optical stability and performance of the LEB lattice. The results of these studies including misalignment, closed orbit correction and simulation of magnetic field errors are presented in this paper. Linear coupling resonances and 3rd order structure resonances have been analyzed and correction schemes have been developed to minimize their effect.

## I. INTRODUCTION

The Low Energy Booster (LEB) of the SSC will accelerate protons from an injection momentum of 1.22 GeV/c to a final momentum of 12 GeV/c in 50 ms. It will operate in two different modes, the collider fill mode and the test beam mode with a normalized transverse beam emittance (rms) of 0.6 $\pi$ mm-mrad and 4.0 $\pi$ mm-mrad, respectively. The overview of the lattice and status of the LEB are included in these proceedings and elsewhere.[1,2] Figure 1 shows the lattice functions of a superperiod of the LEB at the nominal working tune point of (11.65, 11.60) calculated using the code DIMAD.[3]

The main goal of this study is to explore the optical stability and the machine performance of the LEB lattice. It consists of evaluating the effects of misalignment and field errors of the magnet elements and providing schemes for closed orbit and resonance corrections. The procedure begins by tracking and analyzing the performance of the "ideal" LEB lattice for which the only nonlinear magnet element is the chromaticity sextupole. Then the misalignment, closed orbit correction and the field errors of the magnet elements are included. Finally, the resonance corrections have been performed and similar tracking studies done to verify their effects. The lattices have been tracked for 1000 turns at the injection momentum of 1.22 GeV/c. No acceleration and space charge effects are included.

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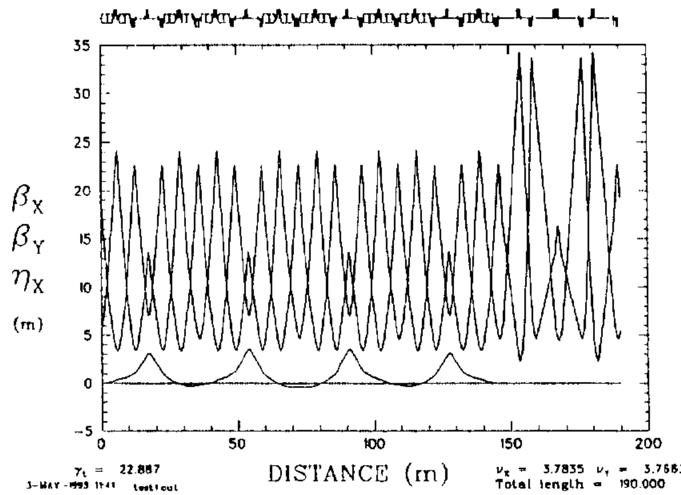


Figure 1. Lattice Functions of the LEB Superperiod

## II. TRACKING STUDIES AND SIMULATION

### A. The "Ideal" LEB Lattice

The linear LEB lattice has a natural chromaticity of about −15 in both horizontal and vertical planes. A total of 48 chromaticity sextupoles belonging to three families are positioned in 16 short straight sections inside the arcs. They are used to correct the chromatic aberrations. Protons with different initial amplitudes are tracked using the "*ideal*" LEB lattice where the only source of nonlinearity is the chromaticity sextupoles. Figure 2 shows the transverse phase space plot and the resonance spectrum of the tracking result of a proton at $\epsilon^* = 36\ \pi$ mm-mrad. The dynamic aperture of the "*ideal*" lattice, determined by those particles surviving 1000 turns of tracking, is larger than 800 $\pi$ mm-mrad. The horizontal and vertical smear (*rms*) for the proton beam are 2.01% and 3.67% in collider fill mode, 6.23% and 9.52% in the test beam mode, respectively. The dominant resonance causing smear is the 3rd order structure resonance $\nu_x - 2\nu_y = -12$, which arises due to the presence of second-order geometric aberrations in the arcs.

### B. Misalignment, Closed Orbit Correction and Magnetic Field Errors

The LEB lattice elements were misaligned assuming a Gaussian distribution with position errors of $\sigma_{x,y} = 0.4$ mm, $\sigma_z = 5$ mm and yaw errors of $\sigma_{z'} = 1$ mrad in our



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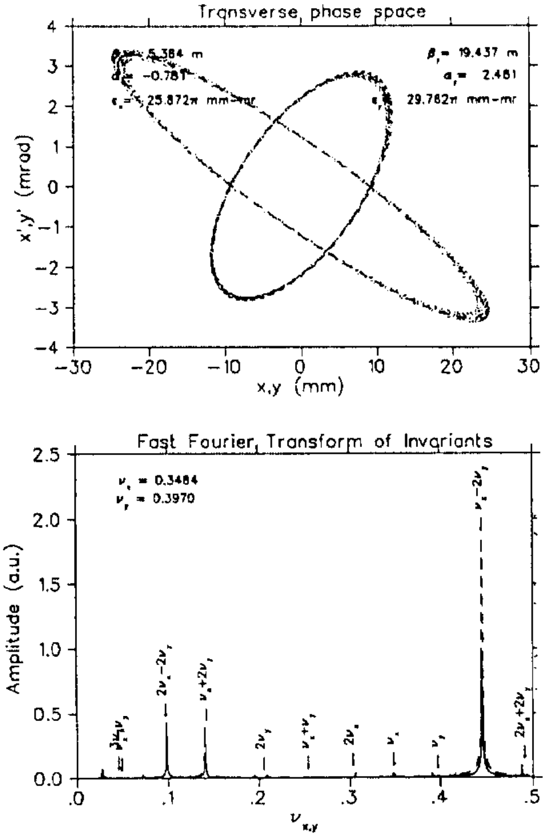


Figure 2. Transverse Phase Space and Resonance Spectrum of the "*ideal*" LEB lattice

simulation. Ninety beam position monitors adjacent to all main quadrupoles with an overall error of 1 mm were used to read the beam $x$ and $y$ positions. The dipole orbit correctors adjacent to quadrupoles focusing in the plane were then used to minimize the beam position monitor readings in that plane using a least square fit procedure. Table 1 shows the resultant uncorrected and corrected rms and peak closed orbit excursions.

Two prototype quadrupoles have been built at LBL and INP. The magnetic field multipoles were measured using a rotating coil device and used to provide the systematic and random magnetic field error multipoles for main quadrupoles in our simulation. Similar prototype dipoles are also being built at SLAC and INP. Meanwhile, field multipoles calculated using POISSON were used in our simulation for LEB bending dipoles and chromaticity sextupoles to determine their effects on the machine performance of the LEB lattice.

Figure 3 shows the transverse phase space plot and the resonance spectrum of the tracking result of a proton at $\epsilon^* = 36\ \pi$ mm-mrad using the LEB lattice with magnetic field errors, misalignment and closed orbit correction. In addition to the dominant 3rd order structure resonance, strong linear coupling resonances have been generated by the misalignment and magnet field error multipoles. Much larger smear has been generated for the protons with larger amplitudes, and the dynamic aperture of the LEB lattice

Table 1
Uncorrected *rms* and Peak Orbit Excursion

| Random Seed | $x(rms)$ (mm) | $y(rms)$ (mm) | $x(peak)$ (mm) | $y(peak)$ (mm) |
|---|---|---|---|---|
| *Uncorrected* | | | | |
| 1 | 3.91 | 3.82 | 12.75 | 11.34 |
| 2 | 4.30 | 4.98 | 15.75 | 11.56 |
| 3 | 5.10 | 4.92 | 17.76 | 12.58 |
| 4 | 3.17 | 3.15 | 14.54 | 9.30 |
| 5 | 4.12 | 3.43 | 14.58 | 10.88 |
| *Corrected* | | | | |
| 1 | 0.87 | 1.06 | 4.48 | 5.28 |
| 2 | 0.95 | 1.02 | 3.55 | 4.48 |
| 3 | 0.89 | 0.86 | 4.42 | 3.83 |
| 4 | 0.87 | 1.06 | 4.08 | 5.06 |
| 5 | 1.11 | 0.90 | 4.86 | 4.24 |

has been reduced to about 60 $\pi$ mm-mrad. Our tracking studies indicate very little dependence on the random seed. The dynamic aperture is, however, well beyond the LEB vacuum chamber admittance of 40 $\pi$ mm-mrad. Although resonance corrections are certainly required to minimize the resonances, and in turn, reduce the the smear and increase the dynamic aperture, the specifications for the LEB element alignment tolerances and magnetic field error multipoles appear to be quite adequate.

### C. *Resonance Corrections*

Third order structure resonances are generated mainly by the 48 relatively strong chromaticity sextupoles in the arc sections. The magnetic field error multipoles and misalignment also contribute to these resonances. Corrections can be made by adding new sextupoles or by adjusting the strength of existing sextupoles in the LEB lattice. Previous tracking studies indicate that the dominant 3rd order resonances have little influence on the dynamic aperture. However, they do cause significant smear for the protons with large amplitudes. We have developed a resonance correction procedure using the basic lattice code DIMAD to transfer a complete LEB lattice description with imperfections, including field and alignment errors, to the differential-algebra (DA) code COSY INFINITY[4] and obtain a high order Taylor series map of the LEB lattice. The DA tools available in COSY INFINITY are then used to analyze the Taylor series map, evaluate the high order resonances and then perform the resonance correction using the proposed correction scheme.

The current 3rd order structure resonance correction scheme is to adjust the strength of existing chromaticity sextupoles in 8 families in each arc section since each of the LEB sextupoles has its own independent power supply. The zero chromaticity requirement is satisfied by having a pair of sextupoles with the opposite polarities located at symmetric positions of the lattice. Any specific 3rd order

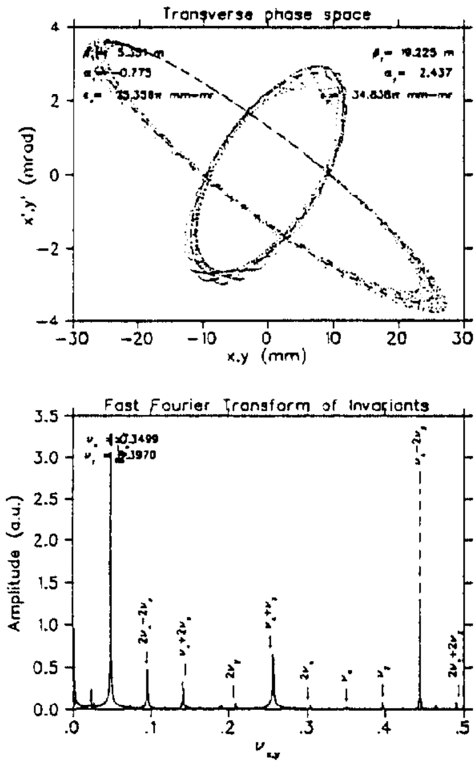


Figure 3. Transverse Phase Space and Resonance Spectrum of the LEB lattice with Magnetic errors, Misalignment and Closed Orbit Correction

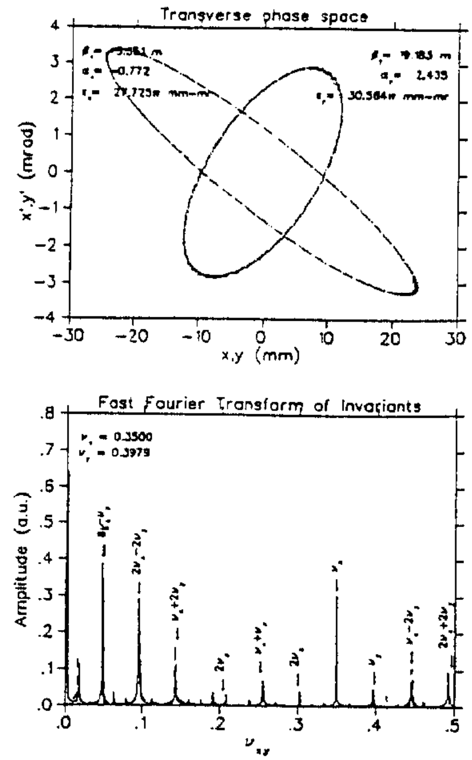


Figure 4. Transverse Phase Space and Resonance Spectrum of the LEB lattice after the Resonance Correction

resonance can be completely cancelled using the current scheme. However, the resultant sextupole settings will affect the amplitudes and phases of the other resonances. The goal is to reduce the dominant resonances and at the same time keep the others undisturbed as much as possible.

The coupling resonances $\nu_x+\nu_y = 23$ and $\nu_x-\nu_y = 0$ are mainly caused by the skew quadrupole terms of the field error multipoles and the misalignment. Four skew quadrupoles similar to the regular trim quadrupole in the lattice have been added in the injection straight section to correct these coupling resonances. The complex coefficients of the coupling resonances were calculated using a resonance analysis code[5] and four independent knobs were then defined which are the linear combinations of the four skew quadrupole strengths. Each can be used to correct the amplitude or phase of a certain coupling resonance with little influence on the others. The correction procedure consists of iterating back and forth between skew quadrupole strength adjustment and tracking with DIMAD in order to simulate the correction process in a real machine scenario. Different random seeds and LEB working points were used in the process, and another code SIMPSONS[6] was also used to compare the tracking results.

Figure 4 shows the transverse phase space plot and the resonance spectrum of the tracking result of a proton at $\epsilon^* = 36\ \pi$ mm-mrad using the LEB lattice after the resonance correction. One can clearly see the improvement of the LEB lattice linearity and the effects of the resonance correction. The horizontal and vertical smear ($rms$) for the proton beam after resonance correction are 2.93% and 2.54% in collider fill mode, 5.64% and 4.07% in the test beam mode, respectively.

## III. REFERENCES


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