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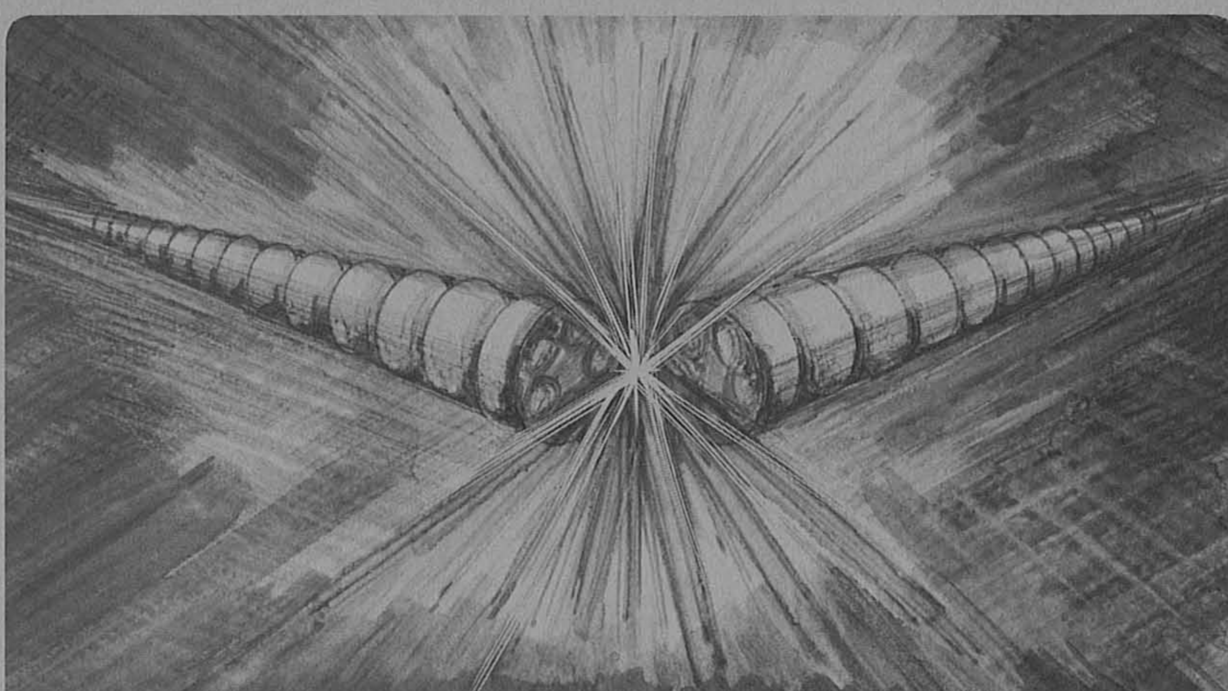

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DYNAMIC APERTURE OF THE ALS BOOSTER SYNCHROTRON*

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Abstract

Effects of the anticipated lattice imperfections on the dynamic aperture of the ALS booster synchrotron were studied using a particle tracking method. The dynamic aperture was found to be sufficiently large at the selected operating points and at the designed repetition rate.

1. Introduction

The booster synchrotron was designed to serve as a full energy electron injector for the Advanced Light Source (ALS).[1,2] It must provide sufficient number of electrons per booster cycle to fill the storage ring quickly; particle losses during acceleration must be closely watched. Particles are lost when they hit either the vacuum chamber or the dynamic aperture limit.

The booster vacuum chamber was designed to be large enough to accommodate the positron option, if necessary. Positrons normally have much higher emittance than electrons. The dynamic aperture is larger than the physical aperture defined by the vacuum chamber wall for an ideal lattice. Lattice imperfections are expected to reduce the dynamic aperture; the purpose of the present study is to investigate the extent of this reduction. Lattice imperfections included in the present study are: multipole errors of the magnets; magnet strength errors; and misalignment errors of magnets and beam position monitors. Results of the recent measurements [3] of the LBL engineering model magnets are incorporated in the present study.

The dynamic apertures were calculated by numerically tracking an electron 400 turns around the booster ring using the program Gemini[4].

2. The Lattice and Its Anticipated Imperfections

The ALS booster synchrotron [2] has a missing magnet FODO structure with 24 dipoles, 16 focusing and 16 defocusing quadrupoles, and 20 sextupoles for chromaticity correction. The bare lattice is defined as a lattice which does not have any imperfections, i.e., in which all the magnets are assumed to be ideal. The sextupole magnets are primarily responsible for defining the dynamic aperture of the bare lattice. Two operating points were investigated in the present study: the nominal tune as specified in the conceptual design report [1] and a "low tune". Parameters for the two operating points are summarized in Table I.

The following complex number notations are adopted in this report in describing multipole components of a magnet:

$$B_x - iB_y = [B\rho]\sum_n (a_n - -ib_n)(x+iy)^{(n-1)}$$

where x is the radially outward direction, y is the vertically upward direction, and a_n (b_n) represents a skew (normal) component of the magnetic field.

Engineering models for the dipole, the focusing quadrupole, and the corrector magnet were constructed and measured. Some of the measured multipole errors [3] available at the time of this study are listed in Table II. They all are allowed harmonics and treated as systematic errors in the present computation.

Field errors of the dipole magnets come from four different sources: remanent field; eddy currents in the vacuum chamber (largest at injection energy); geometry of magnet ends (independent of energy); and saturation of the core material (largest at extraction energy). The stainless steel vacuum chamber wall is 0.8 mm thick at dipole locations and 0.7 mm thick at quadrupole locations. Sextupole errors produced by eddy currents were measured at 2 Hz and scaled as (dB/dt)/B for other frequencies.

Multipole errors for the defocusing quadrupoles (QD) are obtained by scaling the QF measurements, with the assumption that the main contribution to the systematic errors comes from the geometry of the ends of QF; the end geometries of QF and QD magnets are identical.

Sextupole errors of the correction magnets are normal (skew) for horizontal (vertical) correction magnets. The strengths of the sextupole errors are proportional to the strengths of the indivisual correction magnets (denoted as b_1 and a_1 in Table II) and thus depend on the actual distribution of the misalignments. The strength of the multipole errors of the quadrupole magnets are also proportional to the quadrupole strengths which are denoted as b_2 in Table II.

For the purpose of tracking calculations, these multipole errors were assumed to be equally distributed over the length of the magnet.

Tolerance specifications for the random errors of the booster magnets and for their alignments are summarized in Table III. These consist of positioning errors (dx, dy), roll angle errors (dT), and strength errors (dK/K) of the dipole and quadrupole magnets and the positioning errors of the beam position monitors (BPMs).

Table I. The Two Operating Points

	Nominal Tune	Low Tune
Horizontal tune (ν_x)	6.264	5.764
Vertical tune (ν_y)	2.789	2.480
β_{min}	0.51	0.76
β_{max}	11.54	9.24
Natural Emittance (m rad)	1.5×10^{-7}	1.8×10^{-7}
Natural chromaticity (ξ_x)	-10.1	-7.5
Natural chromaticity (ξ_y)	-4.9	-4.8
Focusing quadrupole strength (b_2)	2.77	2.63
Defocusing quadrupole strength (b_2)	- 2.52	- 2.36
Focusing sextupole strength (b_3)	0.97	0.87
Defocusing sextupole strength (b_3)	- 1.18	- 0.98

Table II. Multipole Errors of the Booster Magnets

Magnet Type	a_3 or b_3 [m^{-3}]	b_6 [m^{-6}]	b_{10} [m^{-10}]
Dipole (50 MeV, 1 Hz) *	- 0.08	-	-
Dipole (50 MeV, 2 Hz)	0.71	-	-
Dipole (50 MeV, 10 Hz) *	3.46	-	-
Dipole (1.5 GeV, 2 Hz)	- 0.60	-	-
Focusing Quadrupole		$-2288\ b_2$	$-1.22\times10^9\ b_2$
Defocusing Quadrupole*		$-3432\ b_2$	$-1.83\times10^9\ b_2$
Horiz.Corr. Mag**	$-52.38\ b_1$	-	-
Vert.Corr. Mag***	$-52.38\ a_1$	-	-

* Extrapolated data. All the others are measured data

** Integrated strength along the magnet., $b_3 L$ [m^{-2}]

*** Integrated strength along the magnet., $a_3 L$ [m^{-2}]

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Table III. Alignment Tolerance Specifications (One Standard Deviation) for the ALS Booster

Magnet Type	dx[mm]	dy[mm]	dT[mrad]	dK/K
Dipole	0.15	0.15	0.5	0.001
Quadrupole	0.15	0.15	0.5	0.001
BPM	0.15	0.15	-	-

Random errors cause closed-orbit distortions which are corrected with the orbit correction system; the booster orbit correction system consists of 32 BPMs, 16 horizontal correctors and 16 vertical correctors. All the correction magnets are located adjacent to the quadrupole magnets with the exception of the vertical corrector magnet in the injection straight, which has been moved upstream from its usual location because of interference with the injection septum.

Effects of random errors can only be studied statistically at this time, assuming that a large number of similar machines (samples) were built with the same tolerance specifications. For each of the 25 typical machine samples used in the present statistical study, a series of random numbers was generated to simulate misalignments. Closed-orbit distortions were then computed, and corrected using a local bump method. The standard deviations for the closed-orbit distortions at BPM locations were 2.9 mm horizontal and 2.1 mm vertical before correction, and 0.12 mm horizontal and 0.10 mm vertical after correction. Standard deviations for the strengths of the correction magnets are 0.23 mrad horizontal and 0.13 mrad vertical. The correction magnets are designed for a maximum strength of 2 mrad at 1.5 GeV.

3. Dynamic Aperture

Now we compute the dynamic aperture of the booster ring including the effects of these lattice imperfections, according to the following Gemini procedures:

(1) the tunes are fitted to the selected values;
(2) systematic errors are introduced;
(3) chromaticities are corrected using the sextupole magnets;
(4) random errors are introduced;
(5) closed orbit distortions are computed and corrected;
(6) the tunes are fitted;
(7) sextupole errors of the correction magnets are introduced;
(8) tracking computations are performed;
(9) these procedures are repeated with a new set of systematic and/or random errors.

The computed booster dynamic aperture at the nominal tune and at extraction energy are shown in figure 1. All the errors we have discussed so far are included in this computation. Statistical fluctuations due to the different sets of random errors are shown with circles. The tracking point at which the dynamic aperture is computed is located in the middle of the defocusing quadrupole magnet, in the middle of the 90° arc where the emittance ellipse is upright in both transverse planes. The lines marked "physical aperture" in the figure represent the vacuum chamber wall projected to the tracking point.

Similar computations were performed for the low-tune case at extraction energy; the result, as shown in figure 2, represents a more relaxed operating condition, as expected.

4. Sensitivity Analysis

The absolute accuracy of the calculation of dynamic apertures is very hard to determine. Therefore, we decided to study the relative trends and sensitivities when some of the errors are varied.

Different operating conditions of the booster synchrotron, such as different repetition rates and different bending magnet strengths, are associated with different levels of sextupole errors in the booster dipole magnets, as shown in Table II. The sextupole magnets are adjusted in our tracking studies for these different operating conditions such that chromaticities are zero all the time. Geometry of magnet ends and core saturation at high fields produce defocusing sextupole errors which tend to improve the vertical

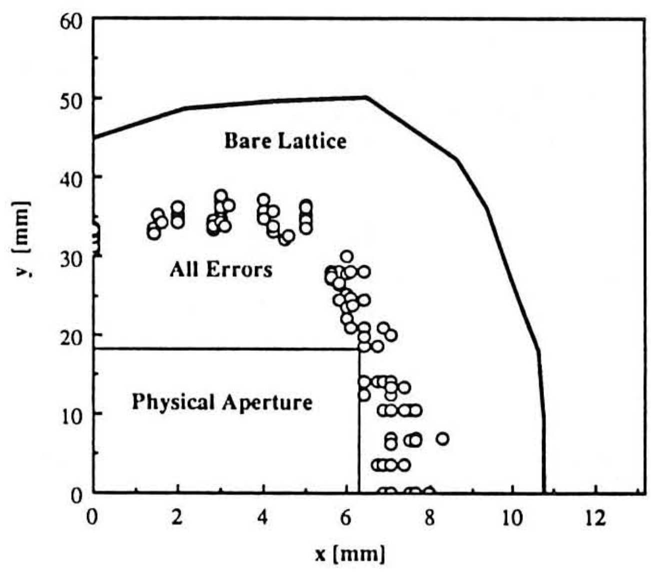

Figure 1. Booster dynamic aperture at the nominal tune.

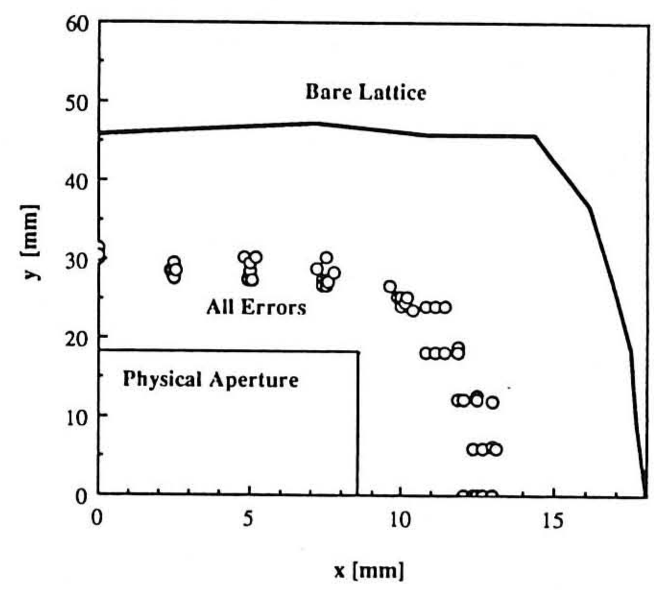

Figure 2. Booster dynamic aperture at the low tune.

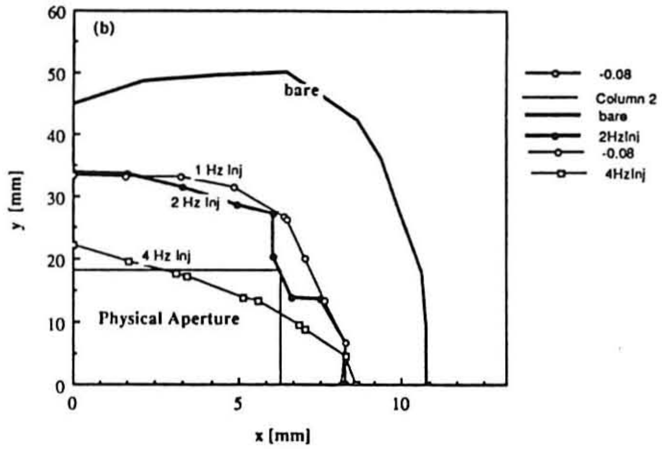

Figure 3. Eddy currents on the vacuum chamber wall produces focusing sextupole fields which limit the booster repetition rate. This figure shows dynamic apertures at injection energy for different repetition rates.

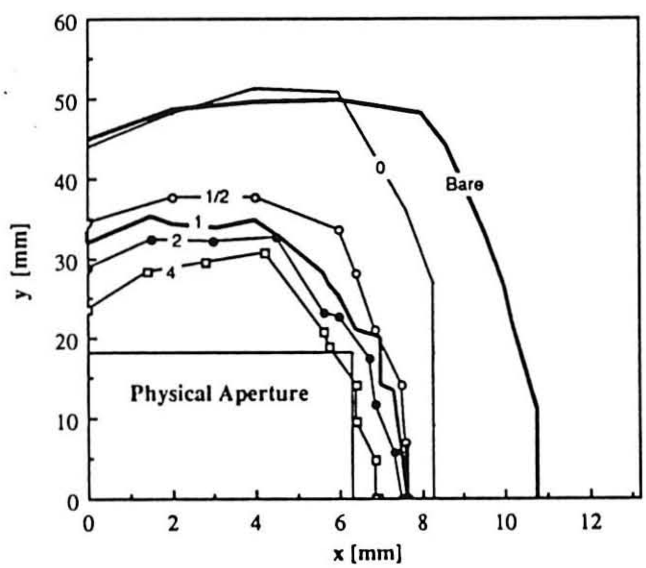

Figure 4. Variations of the magnitude of 12-pole and 20-pole errors of the quadrupole magnets. Numbers by the curves denote factors by which the measured multipole errors are multiplied.

dynamic aperture by taking away some of the burden that the defocusing sextupoles carry. However, they do degrade the horizontal dynamic aperture to some extent.

Focusing sextupole errors in the bending magnets are produced primarily by the eddy currents on the vacuum-chamber wall and degrade the vertical dynamic aperture at low beam energy and at high repetition rates. At 1 Hz, the effects of sextupole errors in the dipole magnets are very mild for all beam energies. At higher repetition rates however, the dynamic aperture at injection energy degrades very quickly, as shown in figure 3.

We also investigated the sensitivity of the dynamic aperture to the 12-pole and 20-pole errors of the quadrupole magnets. We varied the strengths of the 12-pole and 20-pole errors in the quadrupole magnets simultaneously by factors of 0, 0.5, 1, 2, and 4 while keeping all the other errors constant. Corresponding dynamic apertures are shown in figure 4. We note that the dynamic aperture is still outside of the physical aperture even if the errors become four times worse. On the other hand, the apparent improvement corresponding to 0 and 0.5 times smaller errors may not be real, because higher order components that are not considered in this study dominate beam dynamics at large radii. Based on all these results, we have concluded that the engineering model magnets are good enough for the ALS booster.

We also investigated the effects of the sextupole errors in the steering magnets in the same fashion as we did with the quadrupole magnets. Here again, a perfect correction does not improve the dynamic aperture very much and errors which are four times worse than the engineering model do not make the dynamic aperture any smaller.

5. Summary

Measurements of the LBL engineering model magnets confirm that the magnets meet the design specifications conservatively. Based on the tracking computations, we have concluded that the expected lattice imperfections of the ALS booster synchrotron are acceptable for the selected operating conditions. Repetition rates below 2 Hz are definitely acceptable, and perhaps, operations up to 4 Hz may be possible depending on the accuracy of the injection orbit. Thinner vacuum chamber is required if a higher repetition rate is desired. Power suppliers for the booster magnets are being designed for a repetition rate of 1 Hz.

All magnets are now qualified for production. Booster installation will begin in the fall of 1989 and expected to last about a year.

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