Dynamic Aperture and Performance of the SSC Low Energy Booster Lattice

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Abstract

A systematic study of lattice designs proposed for the SSC Low Energy Booster has been performed, where the dynamic behavior of high transition gamma lattices is compared with that of a simpler FODO-like machine. After optimization of the transverse tunes, the dynamic aperture is determined by tracking the chromaticity corrected, "ideal" lattices, where the only sources of nonlinearity are the chromaticity sextupoles. The robustness of the lattices against misalignment, systematic and random errors is then evaluated and error compensation schemes worked out. The computational speed of the TEAPOT code has been greatly enhanced by porting and running its tracking core on the Intel iPSC/860 parallel computer.

I. INTRODUCTION

A coherent simulation program has been undertaken to support the design of the SSC Low Energy Booster. An overview of the characteristics and the present status of this accelerator, the first synchrotron in the SSC Injector Complex, can be found elsewhere[1] in these proceedings. The simulation activity described here addresses mainly the transverse stability of the machine. Space charge effects[2] and longitudinal dynamics[3] are the subject of other dedicated simulation efforts. After a description of the simulation goals and strategy, several design issues are discussed, where tracking has been instrumental in supporting design choices. Results are presented for the systematic comparison of lattice designs with low, high, and imaginary transition γ. The reasons for the choice of a high γ_T lattice for the LEB are discussed from the transverse beam dynamics point of view, as is the selection procedure of the optimal high γ_T lattice among the ones proposed. Some results about the ongoing, more detailed error analysis for the reference LEB lattice are finally presented.

II. SIMULATION : TASKS AND TOOLS

A. The 'procedure'

The main goal of this simulation activity is to explore the transverse stability of lattice designs as for example the extent of the dynamic and linear apertures, to help in lattice evaluations. The requirement of timely comparison of designs on the same basis points to the following tracking procedure. The lattices have been tracked at *injection energy* (600 MeV) and in the *"test-beam"* scenario, where the beam normalized emittance is $\varepsilon_x^N=\varepsilon_y^N=4\pi$ mm*mrad (in the *"collider injector"* mode $\varepsilon_x^N=\varepsilon_y^N=0.6\pi$ mm*mrad). Initial conditions have been taken for partcles at increasing amplitudes, at zero dispersion points ($x_o=n\sigma_x$, $y_o=n\sigma_y$, where $\sigma_{x,y}=(\beta_{x,y}*\varepsilon_{x,y}^N/\beta\gamma)^{1/2}$) and for a $\delta p/p < 3*10^{-3}$. The dynamic aperture is identified with the last amplitude (in σ's) surviving 1000 turns while a smear of less than 10% has been adopted as a rough criterion to assess the linearity of particle orbits. Tracking has been performed without synchrotron oscillations since the low synchrotron tune at injection ($Q_s \sim 0.005$) does not significantly alter the transverse behavior of the particles tracked when the rf cavities are placed in the dispersion free straight sections. With these boundary conditions and for each proposed design, the *ideal lattice* has been tracked, where the only nonlinearity arises from the sextupoles used to set the chromaticity to zero. After an optimization of the fractional tune where required, the same set of errors described in Table 1, is applied to each lattice.

Table 1. Standard set of errors.
Multipole errors are defined at a reference radius of 5 cm and the misaligment Δ's are 2σ values of a Gaussian distribution.

error type	element	error size
misalignment	bends quadrupoles sextupoles bpms	$\Delta x = 0.5$mm $\Delta y = 0.5$mm $\Delta\theta = 1$ mrad
mispowering	bends quadrupoles	$\sim 10^{-4}\ B_{ref}$ $\sim 10^{-3}\ K_{ref}$
multipoles	bends quadrupoles	$\sim 10^{-4}\ R_{ref}$=5cm $\sim 10^{-3}\ R_{ref}$=5cm

After the errors are added, the lattice undergoes a set of adjustments that simulate the operations on the real machine, like finding and correcting the *closed orbit*, readjusting the *tunes*, and refitting the *chromaticity* to zero. The stability of the *perturbed lattice* is finally checked by tracking around the corrected closed orbit. All the results described in the following, except where explicitly explained, assume the above described boundary conditions and procedure.

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B. The 'tools'

The tool used for this study is the TEAPOT code group, i.e the original thin-lens accelerator code[4], together with its graphic postprocessors[5]. For the simulation of a relatively small machine as the ~600m long LEB, it is necessary to split each quadrupole in 4 thin lenses in order to have the optics agree with "thick lens code" results. A typical run of the scalar version of the code on a Sun SparcStation2 is about 12 min. CPU time, for 15 particles and 1000 turns. For longer runs, with more than 10000 turns, the parallel version of the TEAPOT tracking core (Hypertrack[6]) has been used on the Intel iPSC/860 hypercube, giving a gain in tracking speed of at least a factor of 5.

III. SIMULATION: RESULTS

A. Comparison of lattices with different γ_T

One of the fundamental options in the LEB design is to decide whether the machine should cross or operate below transition in its momentum range (1.2 to 12 GeV/c). This decision impacts many aspects of the accelerator design; the question addressed here is whether the aperture of lattices with γ_T higher than the LEB extraction γ of 12.8 is adequate and which is the optimum γ_T range for the LEB. More detailed considerations about the design philosophy of high γ_T lattices can be found elsewhere[7] and they will not be discussed here, except where necessary for the sake of clarity. The solution proposed in the SCDR achieved a γ_T=14.5 with tunes Qx=16.85 and Qx=16.75, a rather high value for a 540m FODO machine.

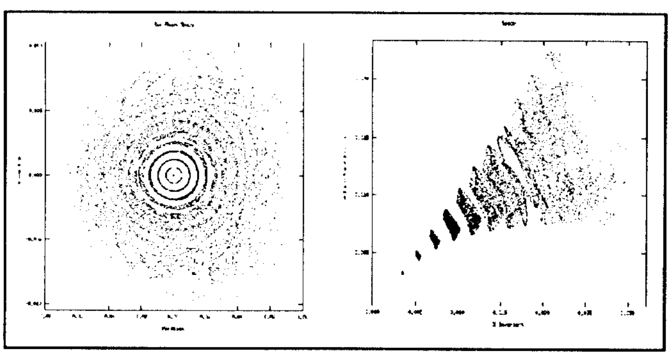

Figure 1. Phase space and smear plots for the lattice *leb_18nov*

Several lattices with γ_T>14.5 have been proposed during a phase of extensive design optimization. These have been tracked and the resulting dynamic aperture, together with some fundamental lattice parameters are presented in Table 2. The lattices have been tracked in this case *without imperfections*, in order to see directly the effect of the chromatic sextupoles on the aperture. The results are compared to a FODO lattice with similar characteristics but with a low γ_T. The lattices with high but *real* γ_T, give a larger aperture than the ones with *imaginary* γ_T . A lattice with γ_T~20 and integer tunes in the range 8-12 give an adequate aperture, while pushing the transition energy away from the extraction one. There is however a price to pay in terms of aperture with respect to a classical FODO machine of about a factor 2, since the higher natural chromaticity of high γ_T lattices requires stronger sextupoles for compensation.

Table 2: Comparison of high γ_T and FODO lattices

lattice	crf	γ_T	Q_x	Q_y	ξ_x	ξ_y	*dynamic aperture*
leb_2oct	480	15.6 i	13.58	13.77	-20.1	-20.9	3 σ
leb_17oct	540	21.5	13.61	13.77	-18.5	-19.1	8 σ
leb_18oct	540	6.2 i	9.84	9.84	-22.8	-13.6	6 σ
leb_6nov	540	19.3	14.12	14.14	-19.2	-20.4	9 σ
leb_18nov	540	21.3	8.43	8.42	-11.4	-10.0	14 σ
FODO	480	6.29	7.61	7.71	-9.9	-10.0	28 σ

B. Selection of the optimal high γ_T lattice

A successive phase of optimization consists of finding the optimal design given the already mentioned guidelines (tune in the range 8 to 12, γ_T~20, circumference~540m, η_{max}~4m), and practical constraints: adequate space for injection, extraction, RF cavities, etc. The need for long dispersion-free straight sections sets the superperiodicity to 3.

Two alternative lattices[7] that meet these requirements have been studied in more detail, one being the already mentioned *leb_18nov* (and its version at higher fractional tunes, *leb_28feb*), the other, *leb_feb91*, an optics design that, by having a virtual superperiodicity of 12 in the vertical plane, would allow for polarized beam in the LEB. The lattices are very similar in concept, differing in the choice of integer tunes, length of the straight sections, the number of dipole types and the design of the dispersion suppressor. These lattices have been tracked with and without errors and the results are listed in Table 3.

Table 3 :Comparison of alternative high γ_T lattices.

lattice	Qx	Qy	*dynamic aperture (σ)*	
			no errors	with errors
leb_18nov	8.43	8.42	14	7
leb_28feb	8.85	8.80	6	3
leb_feb91	11.65	11.60	16	9
leb_feb91	11.76	11.71	13	8
leb_feb91	11.85	11.80	8	7
leb_feb91	11.90	11.81	7	5

The lattice *leb_feb91* has been chosen as the LEB reference lattice on the basis of its larger tune range, more robustness versus negative tune shifts (space charge), hardware considerations (longer staight sections, 1 dipole type), and better dynamic aperture at high fractional tunes. Tunes far away from the half integer resonance (> 0.80) are more favourable in limiting the potential emittance growth arising from space charge effects.

C. Analysis of the LEB reference lattice

As already mentioned, the lattice *leb_feb91* has been taken as the baseline for the LEB and design optimization is now being actively pursued. The machine circumference has been increased and the design of the straight sections has been refined in order to optimize the extraction. Optimization of the location of the chromaticity sextupoles resulted in a decrease of their strength and hence in an increase of dynamic aperture for the 'ideal' lattice.

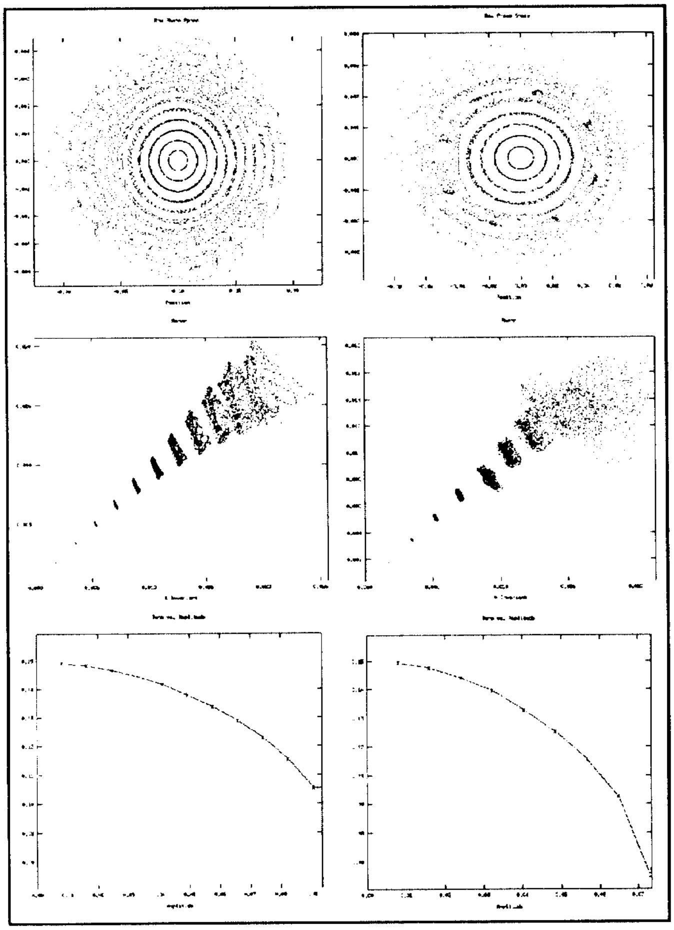

Figure 2. Phase space, smear, and Q_x vs.amplitude for the LEB reference lattice, without (left) and with errors(right)

As a complement of the analysis performed so far, a program of more detailed study of the stability has started, where errors and their effect on the lattice are singled out. The reference tunes have been fixed at Q_x=11.85 and Q_y=11.80 because of space charge considerations and the lattice tracked in presence of different error types. *Misalignment* and *mispowering* (the latter being defined as a random multipole term b_0 in the bends and random b_1 in the quadrupoles, at the level 10^{-3}) do not affect the dynamic aperture, once the closed orbit is corrected and tunes and chromaticity readjusted. Preliminary results on the effect of *multipoles* derived from field and mechanical errors of the magnets can be found in Table 3. Again, the entity of the single multipole error (*systematic* and *random* component) is meant to be 'order of magnitude' in spirit. The entries in the table are the relative error at a reference radius R_{ref}=5 cm.

Table 3: Effect of single errors terms on the dynamic aperture.The 'ideal' machine has 12 σ aperture.

multipoles in the bends			
b1(random)	b1(systematic)	b2(ran+sys)	dyn.ap.(σ)
10^{-3}	0	0	10
0	10^{-4}	0	9
0	$5*10^{-4}$	0	10
0	$7*10^{-4}$	0	10
0	10^{-3}	0	no cl.orb.
0	0	10^{-3}	10
multipoles in the quads			
b1(random)	b2(ran+sys)	b3(ran+sys)	dyn. ap. (σ)
10^{-3}	10^{-3}	0	11
10^{-3}	10^{-3}	10^{-4}	11
10^{-3}	10^{-3}	10^{-3}	8

The reduction in the dynamic aperture becomes more substantial when the errors are defined at a reference radius R_{ref}=2cm, as expected. The dynamic aperture in presence of the 'standard set' of errors, (10^{-4} in the bends and 10^{-3} in the quadrupoles) is, in this case, 3σ.

The effect of *superperiodicity* on the dynamic aperture has been explored by tracking a 16-fold symmetric machine obtained by repeating arc modules of the LEB reference lattice. The resulting machine, 588 m in length and tuned at Q_x=11.85 and Q_y=11.80, produced a dynamic aperture of 18σ for the perfect machine and 11σ for the machine with errors, to be compared with the 12σ and 8σ respectively of the reference design at this tune.

IV. CONCLUSIONS

The dynamic aperture of the high γ_T lattice chosen for the LEB is generally adequate as far as the transverse stabilty is concerned.

V. REFERENCES

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