© 1985 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material

for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers

or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

LATTICES FOR THE SUPERFERRIC SUPER COLLIDER

# S. Heifets, University of Houston, Houston, TX 77004

D. Neuffer, Texas A&M University, College Station, TX 77843

Possible choices for SSC lattices are developed and their properties are discussed. The effects of cell length, and phase and superperiodicity on lattice parameters are discussed. Comments on beam separation, tune and tuning are presented and the effects of nonlinearities are introduced in a discussion of systematic sextupole effects. Sample lattices for SSC beam dynamics studies are presented.

#### Choice of basic cells

In the SSC, about 90% of the lattice is FODO cells and the properties of these cells dominate the beam dynamics. Past accelerator designs have determined that the optimum unit in a long lattice is a FODO cell (Fig. 1) with (nearly) equal horizontal and vertical focussing strengths given by the half cell length  $L_0$  and the betatron phase advance per cell  $\theta_0$  with  $60^\circ < \theta_0 < 90^\circ$ . This lens formulae are adequate for initial design; (see Table 1). Elementary practical considerations limit parameter choices for  $\theta_0$ ,  $L_0$ :

- 1. Long accelerators must have small apertures to conserve costs and beam sizes must be small to match. For the SSC, a 30 beam size at injection < 0.5 cm at injection and off momentum orbits at  $\Delta p/p = 10^{-3}$  also < 0.5 cm implies L<sub>0</sub> < 300 m.
- 2. Quadrupole and sextupole lengths  $l_0$  and  $l_s$  must remain small compared to the total cell length. With a gradient of 125 T/m and a requirement  $l_0/L_0 < 0.1$ ,  $L_0 > 80$  m is implied. With a maximum strength of 1T at 2 cm and sextupoles set to correct chromaticity, with  $L_s/L_0 < 0.01$ , then  $L_0 > 50$  m is implied.

The above constraints are valid for a 3T ring. A 6T ring obtains similar results but is more closely constrained in the momentum aperture requirement:  $L_0 \leq 150 \mbox{ m}$  is required.

The linear focusing constraints remain quite broad; however, nonlinear effects tend to favor greatly the stronger focussing limits at smaller  $L_{\rm o}$ . In this paper we have chosen to consider two cases.

- A: L,  $\tilde{=}$  150 m, which requires a relatively short quadrupole (L<sub>0</sub>  $\leq$  5 m).
- B: L. = 110 m, which requires L  $_Q$  = 7 m, relatively strong focussing.

For both of these we choose  $\theta_0$  in the  $60^{\circ}-90^{\circ}$  range;  $\theta_0 = 60^{\circ}$ ,  $80^{\circ}$ , and  $90^{\circ}$  are considered. These choices retain some flexibility in the choice of sextupole arrangement, permitting cancellation of some geometric effects.

## FODO CELL

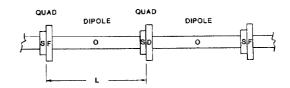


Fig. 1. A FODO cell of an accelerator arc, showing F and D quads, S sextupole/spool pieces, and O dipoles.

Table 1 Thin Lens Equations for FODO Cell Parameters

 $\beta_{max} = \frac{L}{\sin(\phi_0/2)} \cdot \left( \frac{1 + \sin(\phi_0/2)}{1 - \sin(\phi_0/2)} \right)^{1/2}$   $\beta_{min} = \frac{L}{\sin(\phi_0/2)} \cdot \left( \frac{1 - \sin(\phi_0/2)}{1 + \sin(\phi_0/2)} \right)^{1/2}$   $\sin \frac{\phi_0}{2} - \frac{pL}{2} \quad \text{with} \quad p = \frac{B_0^{1/2}}{B_0}$   $n_{max} \frac{L\theta}{2 \sin^2(\phi_0/2)} \cdot (2 + \sin(\phi_0/2))$   $n_{min} \frac{L\theta}{2 \sin^2(\phi_0/2)} \cdot (2 - \sin(\phi_0/2))$   $\theta = \frac{BL}{B_0}$ Focussing and defocussing sextupole strengths

$$S_{F} = \frac{p}{2 n_{max}}$$

$$S_{F,D} = \frac{B^{*t}s}{2B_{0}}$$

## Straight Section Insertion Region (IR) Design

The SSC requires strong focussing of colliding beams at the collision points to beam sizes on the order of 10µ, corresponding to a B-function of 1 m. This is obtained by triplets of high gradient, 200 T/m quadrupoles. Fig. 2 shows a low-beta insertion indicating magnet locations and lattice functions ( $\beta$ , n). Following the crossing point beams pass through a triplet followed by a long drift containing vertical separating magnets, then matching quadrupoles and a two cell dispersion suppressor (DS), then an SSC bending arc. Utility insertions for rf, tuning, and injection/abort may be included between matching quads and DS, or, in a racetrack lattice, between IR's as shown in Fig. 2.

The two magnet rings share common elements only near IR's. In the rest of the SSC they are stacked vertically within the same cryostat, with the beam centers separated by 14 cm. Beam separation is obtained by pairs of vertical dipoles following the IR triplet; 5 m 2T dipoles are adequate. These dipoles introduce a vertical dispersion n in the lattice, which in initial design is uncorrected.  $n_y = .01$  m at the IR crossing, which corresponds to a vertical displacement of  $.01\mu$  at  $\Delta p/p = 10^{-5}$ , a small value.

In the arcs  $\eta_{\rm r}$  reaches a maximum value of 0.20 m. These values appear acceptable, but the vertical  $\eta$  dispersion can be corrected if necessary.

#### Ring Layout/Periodicity

The SSC requires six collision regions (IR) with  $\beta^* = 1$  m. The simplest way to permit this is with a 6-fold (hexagon) lattice. This, however, has the disadvantage of requiring an excessive number of matching and utility insertions, and separates experimental groups by ~ 20 miles, diminishing their ability to share resources. A potentially more economic solution is to cluster IR's near each other, with utility insertions between IR's, and that produces the racetrack lattice option pursued in this note. The greater complexity of a superperiod (2) makes this somewhat more difficult and the close proximity of IR's may have important beam dynamics effects. In particular, local chromaticity correction between IR's is not practical.

Assuming major superperiod resonances are avoided, we do not expect great differences between 6-fold and 2-fold lattices in beam stability; the dominant nonlinearities are expected to have either periodicity 1000 (systematic multipoles) or periodicity 1 (random multipoles & misalignments). Only IR region effects may be influenced by the periodicity.

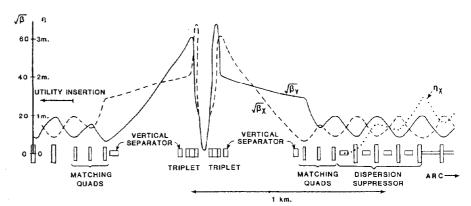
#### Comments on tune and tuning

The arcs and the IR's set approximate values for the integer part of the tune in SSC lattices (v = 100 for  $L_0 = 150$  m or v = 140 for  $L_0 = 110$  m) but precise values for the integer and fractional values of the tune may be adjusted to obtain optimum dynamics. It is advisable to avoid superperiod resonances, particularly integer and half integers. The tunes of the sample lattices are chosen to avoid these, and to permit operational variation of tune over  $\pm 0.5/turn$ .

Operational tuning may be obtained either through special insertions ("phase trombones") in straight sections or by global tuning, a distributed correction through the ares using trim quads or main quad power supplies (The Superferric Super Collider has separate quad and dipole supplies.). The very large scale of the arcs (100's of cells) permits significant changes in v with minor betatron function changes. For example, changes of tune over  $\pm$  0.3% developing maximum changes in  $\beta$ ,  $\alpha$ ,  $\eta$  of less than ~ 3%, even without rematching of the rest of the lattice.

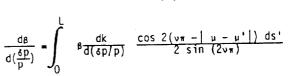
## Fig. 2

Layout and lattice functions near an IR region of a racetrack. The region from the utility insertion between IR's through an IR into the arc is shown.



Our lattice simulations have determined that global tuning is adequate for overall tune adjustment. However, local tuning ("phase trombones") may be desirable for adjustment of phases between IR's and space for this is included in the racetrack lattices.

Some beam dynamics parameters are sensitive to the fractional part of the superperiod tune. Nonlinear chromaticity  $\frac{d^2v}{d(\Delta p/p)^2}$ ,  $\frac{dg}{d(\Delta p/p)}$  has been found to be very sensitive to the fractional tune in 6-fold lattices. This dependance can be approximately understood by considering the perturbation expression for  $\frac{dg}{d(\Delta p/p)}$ 



where k is the focussing strength. The expression is dominated by the contribution of the IR quads, which can be shown to scale as  $\cot (2\pi\nu)$ , becoming small as the fractional part of  $\nu + .25$  or .75. Similar scaling applies to  $\nu''$ . Fig. 3 shows DIMAT results indicating the above scaling in 6-fold lattices. Results indicate tuning within  $\pm .05$ obtains adequately minimized  $\nu''$ .

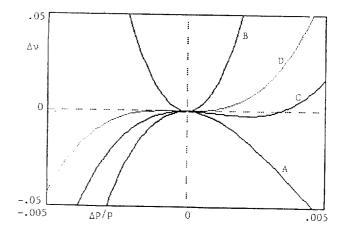


Fig. 3. Chromaticity (v as a function of  $\Delta p/p$ ) for 4 sample hexagon lattices, showing the dependence on the fractional part of the superperiod tune:  $A - v_6 = N.64$ ,  $B - v_6 =$ N.42,  $C - v_6 = N.20$ ,  $D - v_6 = N.754$ 

Similar dependences also occur in racetrack lattices but are less striking. The large uncorrected chromaticity accumulating over three successive IR's prevents coherent cancellation of the IR quad contribution over  $\Delta p/p \ge \pm .002$ .

## Lattices and nonlinear dynamics

Nonlinear dynamics is most likely to determine optimum lattices. We initially consider the effects of sextupoles. Any lattice must include sextupoles for chromaticity correction and dipoles may have a sextupole component  $(b_2)$  with  $B(x) = B_0(1 + b_2x^2)$ . We have explored the effects of sextupoles for several lattices spanning the range of focussing strengths using HARMON to calculate the resulting chromaticities. The results are summarized in Table 2. All lattices are acceptable for  $b_2 \leq 5 \, \times \, 10^{-4}$  cm<sup>-2</sup> with ( $\Delta\nu \leq .02$ ) for  $\Delta p/p < 10^{-3}, \, \langle x^2 \rangle < (\,10_0\,)^2$ . The weak focussing case (A) appears best as  $b_2 \rightarrow 0$ , but strong focussing (C) has a larger aperture for greater b2.

Particle tracking using MARYLIE confirms these general observations; beam distortion at  $b_2 = 0$  is about three times smaller at  $x_0 = 10\sigma$  for A than C. However, at  $b_2$  = 5  $\times$  10-\* the distortion is the same. Stronger focussing lattices tend to be more stable with respect to higher order nonlinearitites  $(b_{4}, b_{6}, \ldots)$ . This is discussed in a separate paper. Beam tracking, nonlinear motion analysis, magnet field analyses and cost studies will be needed to determine an optimum choice.

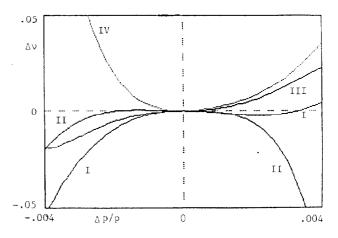
### Sample Lattices

Table 3 shows parameters of four sample lattices, demonstrating the range of possibilities. Two racetrack and two hexagon lattices are included, with the hexagons not yet augmented to include utility insertions. Figure 4 shows tune as a function of momentum offset  $\Delta p/p$  for the four lattices. All accept  $\Delta p/p \pm = .002$  with  $\Delta v \leq \pm .01$ .

Lattice II (weak focussing racetrack) is the current standard. stability studies will determine whether the others (stronger focussing or higher periodicity) are preferable.

|   |                                       | Table 3                                    |                                  |                                  |
|---|---------------------------------------|--|----------------------------------|----------------------------------|
| LATTICE<br>PARAMETER  | I<br>6-sided<br>Weak                  | II<br>2-sided<br>Weak                      | llI<br>6-sided<br>Strong         | IV<br>2-sided<br>Strong          |
| Circumference*  | 161,892km                             | 167.892                                    | 172.368                          | 174.128                          |
| Tune  | 121.20                                | 125.63                                     | 172.63                           | 174.24                           |
| 8*  | 1.0                                   | 1.0  | 1.0                              | 1.0                              |
| <sup>8</sup> max  | 4500 m                                | 4500 m                                     | 4200 m                           | 4200 m                           |
| Cell half length  | 150 m.                                | 150 m                                      | 110 m                            | 110 m                            |
| Ф »   | 80°                                   | 80°  | 804                              | 80°                              |
| # Dipoles   | 1002.                                 | 998.                                       | 1470.                            | 1427.                            |
| (Y,)  | 10 <b>9.</b>                          | 115.                                       | 155.                             | 162.                             |
| v <sub>1</sub> (uncorrected)<br>v <sub>2</sub> (corrected)<br>v <sub>3</sub> (corrected)<br>( <u>óp</u> in units of 1)<br>p | 111. * 10-*<br>0014<br>.00045<br>0-*) | 120. × 10- <sup>3</sup><br>.0025<br>000732 | 304.4 × 10-*<br>.00090<br>.00039 | 305.4 × 10-*<br>00080<br>.000059 |
| anax (arcs)   | 500 m                                 | 500 m                                      | 362 m                            | 362 m                            |
| max   | 2.91 m                                | 2.91 m                                     | 1.57 m                           | 1.57 1                           |

Six-sided lattices do not include utility insertions.



Chromatic properties of some hexagon lattices with a systematic sextupole component  $(\nu_{1})$ . Linear chromaticity  $(\nu_{1})$  is corrected to zero by two families of sextupoles.  $\nu_{y^{2}}, \nu_{y^{3}}$  are the coefficients of the chromaticity expansion:  $v_y = v_{y^2} + v_{y^1}\delta + v_{y^2}\delta^2 + v_{y^3}\delta^3$ , with  $\delta = \Delta p/p \times 10^3$ 

Table 2

The geometric chromaticities  $3\nu/3\epsilon_{\pm}$  , is used to find a maximum tune shift at  $\epsilon$  = 10-7 (10s at injection).

| Lattice                 | bı           | ٌy ۲                  | ∿γ ه                      | Δυ (geometric)      |
|-------------------------|--------------|-----------------------|---------------------------|---------------------|
| A: L = 145m             | 0            | 0014                  | .00059                    | 001                 |
| ¢∎ = 60°                | 5<br>10      | .023<br>.089          | .0036<br>.014             | .028<br>.11         |
| B: K = 145m<br>¢₀ = 90° | 0<br>5<br>10 | 0013<br>.0017<br>.012 | .00059<br>.00092<br>.0015 | 0021<br>.044<br>.14 |
| C: L = 110m<br>¢, = 90° | 0<br>5<br>10 | 022<br>022<br>022     | .00088<br>.0015<br>.0024  | 011<br>.022<br>.058 |

