DESIGN OF THE SPEAR 3 MAGNET LATTICE

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Abstract

The *SPEAR 3 Upgrade Project* seeks to replace the present 160 nm-rad FODO lattice with an 18 nm-rad double bend achromat (DBA) lattice. The new lattice must conform to the layout of the SPEAR racetrack tunnel and service the existing photon beamlines. Working within these constraints, we designed a lattice with 18 achromatic cells and 3 GeV beam energy. This paper reports on design of the main DBA cells, design of the matching cells leading into the 6.5 m racetrack straights, and simulation of the dynamic aperture. The new lattice has gradient dipoles, conventional quadrupoles, and provides horizontal dynamic aperture to ±20 mm with conservative magnetic multipole errors.

1 INTRODUCTION

The SPEAR storage ring at SLAC was constructed in 1972 to collide e^+e^- beams with center of mass energy 4-7 GeV [1]. From the beginning, synchrotron radiation experiments were also conducted at SPEAR, and since 1989 the storage ring has operated as a 3 GeV dedicated light source. Following the suggestion of Wiedemann and Safranek [2,3], a new proposal, the *SPEAR 3 Upgrade Project*, calls for replacement of the original FODO lattice with an 18 nm-rad double bend achromat (DBA) lattice.

The overall scope of the Upgrade Project includes replacement of the main ring magnets, vacuum chamber, septum and kickers for on-energy injection (3 GeV), and upgrades to the infrastructure where needed [4-7]. The 358.53 MHz RF system will be retained, but new power supplies and beam position monitors will be installed to improve beam stability.

The benefits to the user community are reduced horizontal beam size ($\sigma_x^{DBA} \approx \sigma_x^{FODO}/5$), higher beam current (200 mA initially) and improved photon beam stability. The critical energy from dipole magnets will increase from 4.8 keV to 7.6 keV, and the focused flux density from dipoles will increase by more than two orders of magnitude in the 20 keV range [6-8]. Insertion device beamlines receive an order of magnitude increase in focused flux density [6-8].

In this paper, we review the SPEAR 3 lattice design and simulations of the dynamic aperture. Tracking studies yield a ±20 mm horizontal dynamic aperture with conservative multipole errors that is stable for momentum deviations up to 3%. The dynamic aperture leaves ample room for injection, provides long beam lifetime, and is stable against tune variations.

2 LINEAR OPTICS DESIGN

This section reviews the storage geometry, design of the unit cell, and design of the matching cells. The resulting

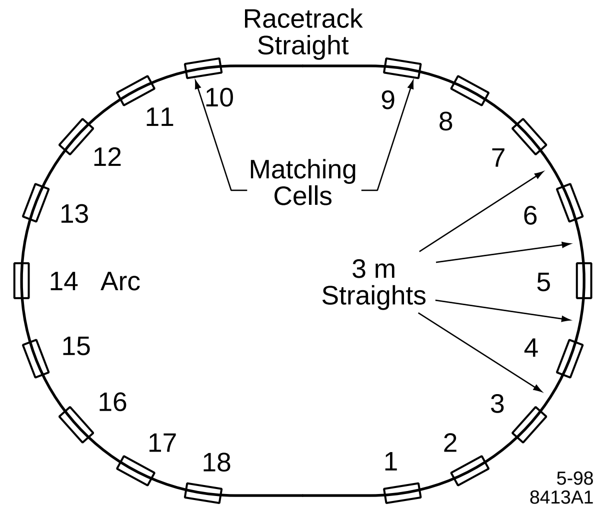

Figure 1: Layout of the SPEAR magnet girders.

18 cell lattice provides twelve 3 m straights, four 4.5 m straights and two 6.5 m straights. The straight sections have zero dispersion by design, but the dispersion can be tuned slightly positive to reduce the horizontal emittance below 18 nm-rad.

2.1 Lattice Geometry

Figure 1 illustrates the magnet girder layout in the SPEAR storage ring. For SPEAR 2 (the present lattice), the two matching cells on either side of the racetrack straights have an irregular dipole layout with girders {2,8,11,17} containing 1/2-length dipoles. In the past, this configuration provided dispersion control in the racetrack straights. For SPEAR 3, the new lattice must fit on the present SPEAR girders in order to maintain the present beamline alignment. To achieve this geometry, we replaced the FODO cells in the racetrack arcs and the FODO cells on girders {2,8,11,17} with standard DBA cells. This extended the periodic lattice structure further around the arcs. We then used two 3/4-bend dipoles in each of the SPEAR 3 matching cells to make up for the 1/2-bend dipoles in SPEAR 2.

2.2 Main DBA Cells

As shown in Figure 2, the main DBA cells feature a gradient dipole structure with β_x=10.1 m and β_y=4.8 m in the 3 m insertion device straights. The use of gradient dipoles yields a compact lattice with low beta functions throughout the cell. The low beta functions help to reduce sensitivity to magnetic field errors and limit demand on the vacuum system. The gradient dipoles also shift the peak vertical betatron function toward the center of the cell. The shift produces FODO-like optics with better separation of beta functions in the sextupoles.

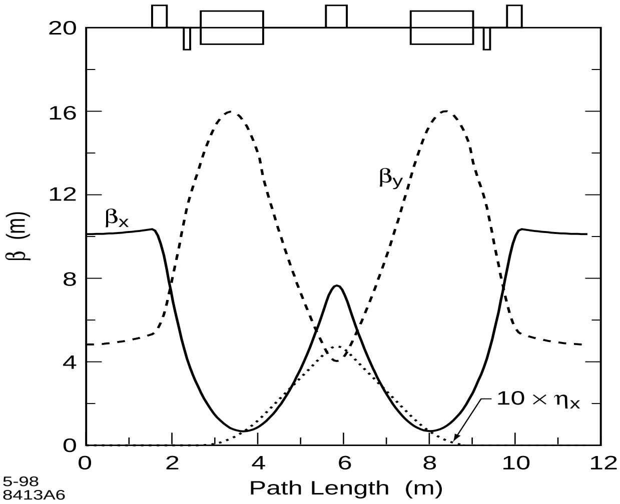

Figure 2: SPEAR 3 Main Cell Optics.

The DBA cell phase advances were constrained to ($\phi_x=3\pi/2$, $\phi_y=\pi/2$) to provide cancellation of chromatic quadrupole aberrations and geometric sextupole aberrations between cells. The final cell phase advance ($\phi_x=2\pi*0.79$, $\phi_y=2\pi*0.25$) was based on global tune considerations and tracking studies. Two sextupole families {SD, SF} in the cells control global chromaticity.

The lengths of the quadrupoles were adjusted to equalize the field gradients, and the coils were equipped with 10% trim windings. The magnet lengths and strengths for the main DBA cells are listed in Table 1.

Magnet	Length	K-value
Dipole	1.45 m	- 0.33 m^{-2}
QF	0.34 m	+1.82 m^{-2}
QD	0.15 m	- 1.57 m^{-2}
QFC	0.50 m	+1.79 m^{-2}
SF	0.25 m	+29.6 m^{-3}
SD	0.21 m	- 35.6 m^{-3}

Table 1: Standard Cell Magnet Parameters

2.3 Matching Cells

Since the electron beam path length through the main cells is less than through the original FODO cells, the path length difference must be made up in the matching cells. The girder layout also fixes the horizontal distance from the racetrack straights to the main arc cells. Working within these constraints (constant path length and fixed girder geometry) the 3/4-length dipole magnets were aligned in cells {1,9,10,18} so as to increase four of the original 2.6 m drift spaces to 4.5 m, and to produce two 6.5 m drifts across the racetrack straights (Figure 3). In total, the SPEAR 3 lattice provides 6 straight sections that are longer than the present 3 m wiggler straights.

The matching cell optics shown in Figure 3 includes a quadrupole triplet to improve optics control in the 6.5 m straights. The design of the matching cell optics was based on an optimization study that minimized peak beta function values and maximized the drift spaces on either side of the cell. The phase advance was varied across the cells to optimize dynamic aperture.

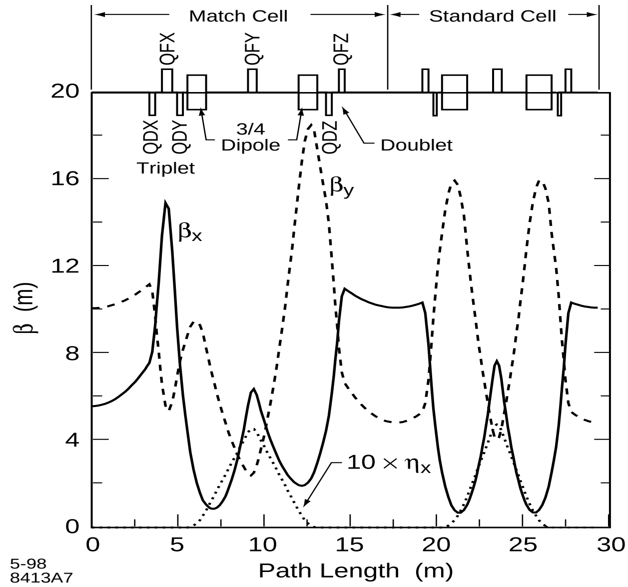

Figure 3: SPEAR 3 Matching Cell Optics.

For local chromaticity correction, we installed two additional families of sextupoles in the matching cells. The strength of these sextupoles was adjusted to maximize off-momentum dynamic aperture and to reduce off-momentum beta beats.

2.4 Storage Ring Parameters

The storage ring tunes, $Q_x=14.19$, $Q_y=5.23$, were chosen to avoid strong resonances in the working diagram, to provide an efficient horizontal tune for injection, and to obtain constant dynamic aperture in the vicinity of the working point. The horizontal integer tune (Q_x~14) produces a natural emittance of 18.2 nm-rad: with insertion devices active the emittance decreases to less than 16 nm-rad.

Table 2 below contains key parameters for the bare lattice (no insertions active). Note the gradient dipole magnets increase the horizontal partition number and so reduce the horizontal damping time.

3 TRACKING STUDIES

Dynamic aperture studies were performed with an element-by-element tracking code, LEGO [9]. The reference point was positioned between two main cells to observe dynamic aperture at the septum and in the insertion devices. To simulate lattice imperfections, we seeded the magnet lattice with four classes of errors, namely (1) alignment errors, (2) main field errors, (3) systematic multipole errors, and (4) random multipole errors.

For each class of magnet errors, we used conservative (large) values to obtain conservative (small) values for dynamic aperture. All of the error tolerances used for the tracking studies can be easily met with conventional magnet manufacturing and installation practice. For the tracking studies, many sets of random seeds were used to produce statistically stable results. For each seed, LEGO numerically corrected the electron beam orbit, betatron

Parameter	Symbol	Value
Nominal Energy	E (GeV)	3.0
Current	I (A)	0.2 ⇒ 0.5
Circumference	C (m)	234.126
Number of Cells	N_C	18
3 m Straights	$N_{L=3}$	12
4.5 m Straights	$N_{L=4.5}$	4
6.5 m Straights	$N_{L=6.5}$	2
Emittance	ε_x(nm-rad)	18.2
Energy Spread	σ_E/E(%)	0.097
Horizontal Tune	Q_x	14.19
Vertical Tune	Q_y	5.23
Synchrotron Tune	Q_s	0.0072
β_x at Insertions	β_x (m)	10.1
β_y at Insertions	β_y (m)	4.8
σ_x at Insertions	σ_x (micron)	430
σ_y at Insertions	($\varepsilon_y/\varepsilon_x$=1 %)	30
x-Chromaticity	$\xi_x=\Delta\nu_x/\delta$	-21.9
y-Chromaticity	$\xi_y=\Delta\nu_y/\delta$	-14.4
RF Frequency	ν_{rf} (MHz)	358.53
RF Voltage	V_{rf} (MV)	3.2
RF Bucket Size	$(\sigma_E/E)_{rf}$ (%)	3.6
Dipole Field	B (T)	1.27
Critical Energy	E_c (keV)	7.62
Energy Loss/Turn	U (keV)	913
Compaction	α	0.0011
Bunch Length	σ_s (ps)	19
x-Damping Time	τ_x (ms)	4.24
y-Damping Time	τ_y (ms)	5.14
s-Damping Time	τ_s (ms)	2.87

Table 2: SPEAR 3 Lattice Parameters

tunes, chromaticity and coupling. Since the skew quadrupole windings reside on sextupoles, skew octupole components were added in proportion to the skew quadrupole strengths. Matched insertion devices were also included in the tracking.

To maximize dynamic aperture, we chose the working point (Q_x=14.19, Q_y=5.23) away from strong resonances in the lower 1/4 of the working diagram, and then optimized the phase advance across the matching cells. The matching cell sextupole strengths were then adjusted to maximize off-momentum dynamic aperture. Based on these studies, a ±20 mm dynamic aperture was produced that remains large for many random error seeds and for a range of tunes around the working point. The result of tracking with different seeds is illustrated as a band of values in Fig. 4. The ±20 mm aperture at the septum (40 mm-mrad) allows efficient capture of the booster beam injected with 13 mm displacement (17 mm-mrad).

As shown in Figure 4, with 3% energy oscillations the reduction in dynamic aperture is <10%. The large off-momentum aperture yields long Touschek (185 hr) and bremsstrahlung (120 hr) beam lifetimes.

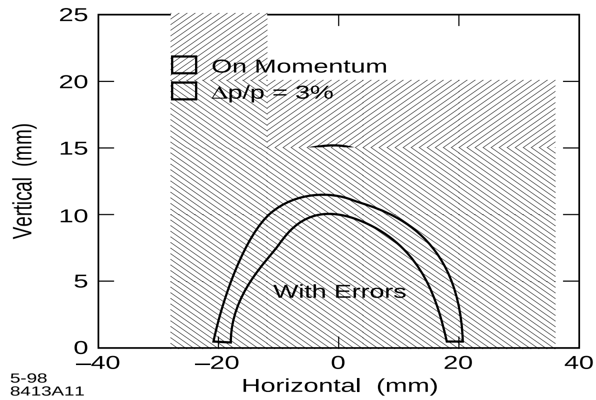

Figure 4: Dynamic Aperture with Errors

4 SUMMARY AND CONCLUSIONS

This paper was based on the SPEAR 3 Conceptual Design Report, submitted to the U.S. Department of Energy in 1998 [7]. The study found that conversion of SPEAR to a DBA lattice is straightforward and does not entail new developments in magnet or vacuum technology. The lattice design is conservative and delivers at least one order of magnitude increase in focused flux density to the photon beamline users. Tracking studies show that even in the presence of conservative magnetic multipole errors the dynamic aperture is adequate for injection and beam lifetime considerations, and constant as a function of lattice tune.

5 ACKNOWLEDGEMENTS

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