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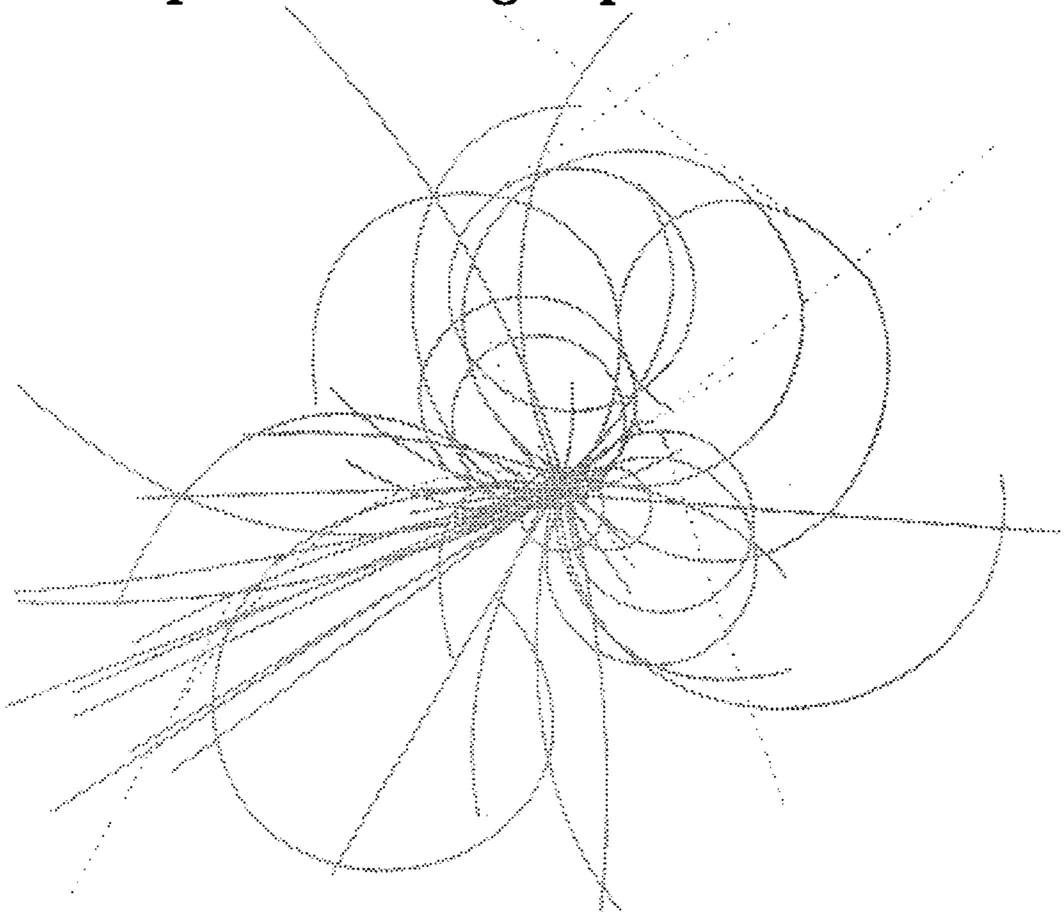

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THE SSC COLLIDER RING CORRECTION MAGNET SYSTEM

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Abstract

The correction system for the SSC Collider rings will have about 14,000 superconducting magnetic elements. Linear correctors (dipoles and quadrupoles) are located in spool pieces next to focusing (F) and defocusing (D) main quadrupoles. Systematic multipole correction utilizes nonlinear correctors (sextupoles, octupoles, and decapoles) located at positions (C) near half cell centers as well as in the F and D spools. The basic functions of correction magnets and the dynamics leading to the selected configuration are described. Strength requirements, the number and distribution of correction magnets, and initial prototype efforts at collaborating laboratories are outlined.

Introduction

The dominant features of the SSC Collider rings are roughly 8600 superconducting main dipoles for bending, nearly 2000 main quadrupoles for focusing, and about 1860 cryogenic spool pieces. Every cell of the SSC Collider arcs includes ten main bending dipoles, two main quadrupoles, and two cryogenic spool pieces. Much smaller in size and cost, but still essential to the machine are the superconducting corrector magnets. Table 1 outlines the major functions required of the corrector system.

The 1986 Conceptual Design Report[1] envisioned a correction system that utilized a standard dipole-quadrupole-sextupole primary corrector package located in each spool piece, plus powered bore tube trim coils (sextupole and decapole) for compensation of systematic errors in the main dipoles. (Octupole trim coils were added shortly thereafter.) Numerous secondary corrector packages were also located in spool pieces to compensate skew multipoles and augment the primary corrector packages.

The SSC Collider correction system has evolved significantly since the 1986 CDR. Requirements have changed due to a more complete knowledge of SSC main dipole and quadrupole design, deeper understanding of linear and dynamic aperture requirements,[2] and resulting changes in the lattice (linear dynamics) design. New correction methods

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Table 1: Corrector functions and corresponding magnets.

Function	Magnets
Steering and Closed Orbit Correction	Dipoles
Tune Correction and Control	Quadrupoles
Linear Chromaticity Control	Sextupoles
Compensate x-y Coupling	Skew Quadrupoles
Augment Main Quadrupoles	Quadrupoles
Compensate Main Dipole Error Fields	Various Multipoles
Compensate Persistent Current Error Fields at Injection	Sextupoles and Decapoles
Compensate Saturation induced Error Fields at 20 TeV	Sextupoles and Decapoles
Second Order Control	mainly Octupole
Compensate Error Fields in IR Quads	Various Multipoles
Control IR Beam Crossing Angle and Separation	Dipoles

involving the use of nonlinear correction elements at intra-cell (C) positions have been developed for the Collider.[3] These methods, suitable to large synchrotrons in general, have eliminated the need for bore tube trim coils.

Beam stability demands highly linear motion and, therefore, linear fields. The greatly increased energy and circumference of the SSC compared to earlier machines magnifies the effects of linear (e.g. alignment and tuning) and nonlinear (e.g. uncorrected multipole) errors, while forcing the design towards small aperture, more nonlinear magnets. The correction magnet system must compensate for such problems both during a thirty minute 2 TeV injection period, when beam profiles are largest and some multipoles (b_2, b_4) are time dependent, and also at 20 TeV where strength demands on the correctors are highest. The correction system described in the SSCL Site-Specific Conceptual Design Report (SCDR)[4] and outlined here should meet these requirements. It also contains allowances for optimization, future refinements, Collider upgrades, and uncertainties in correction magnet technology.

The correction system, shown in Figure 1, starts with linear correctors (dipoles, and normal quadrupoles) in spool pieces adjacent to each main focusing (F) and defocusing (D) quadrupole. Orbit correction and control employs horizontally bending dipoles at each F spool and vertically bending dipoles at each D spool. Since the main quadrupoles are on the same current bus as the main dipoles, quadrupole control is through the corrector quadrupoles. These devices are responsible for maintaining precise control of the central tune (ν) of the machine while compensating for imperfect tracking or "differential saturation" between the main dipoles and quadrupoles.

Nonlinear correction elements control tune spreads ($\Delta\nu$) due to the collider's natural chromaticity (ξ_{nat}) and low order error multipoles. Chromaticity control is provided by sextupoles in the F,D spools. These sextupoles also contribute to compensation of normal sextupole (b_2) errors in the main dipoles. For reasons discussed below, compensation of normal sextupole (b_2), octupole (b_3) and decapole (b_4) errors in the main bending dipoles uses the "Neuffer-Simpson" (NS)[3] quasi-local method with elements located at F, C, and D positions within each half cell. (The NS corrector pattern is also referred to as an "FCD" pattern.)

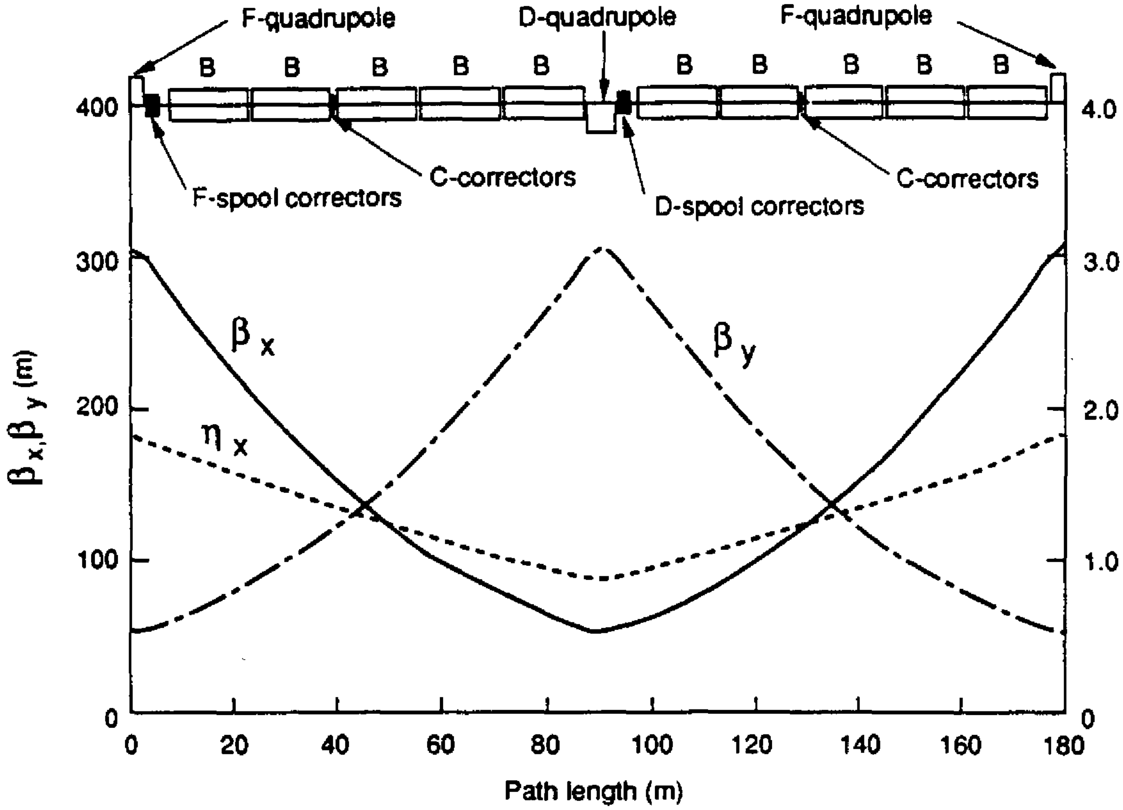

Figure 1. Normal cell of SSC Collider arc. Correction magnet packages at F,D, and C positions are indicated. Main dipoles, focusing and defocusing quadrupoles, as well as the amplitude (β_x, β_y) and dispersion (η) functions are also shown.

Thus each F and D spool contains a five element correction "package" consisting of dipole, quadrupole, sextupole, octupole, and decapole magnets. C-corrector packages contain sextupole, octupole, and decapole elements.

Physics of Multipole Correction and Control

The use of mid-cell (C) correctors for higher order nonlinearities is a significant change from previous correction systems. We outline here the physical basis for this change.

The magnetic fields in the dipoles may be represented by the complex expression

$$B_y + iB_x = B_0\{1 + \sum_{n=1}[b_n(s) + ia_n(s)](x+iy)^n\}$$

where B_0 is the bending field and $b_n(s)$ and $a_n(s)$ are the normal and skew multipole components. The transverse motion may be described by the Hamiltonian:

$$H = \frac{I_x}{\beta_x(s)} + \frac{I_y}{\beta_y(s)} + \Re\sum_n \frac{B_0}{B\rho}\frac{[b_n(s)+ia_n(s)](x+iy)^{n+1}}{n+1}$$

where I_x and I_y are the action coordinates, $\beta_x(s)$ and $\beta_y(s)$ are the Courant-Snyder[5] betatron functions of the linear motion. $\Re$ implies taking the real part of the summation. The coordinates x and y of particle motion are represented to first order by the action-angle variables: $x = \sqrt{2\beta_x I_x}cos(\phi_x) + \eta\delta$ and $y = \sqrt{2\beta_y I_y}cos(\phi_y)$. The terms ϕ_x and ϕ_y are the angle variables (betatron phases), and the off-momentum orbit displacement, $\eta\delta$, determined by the dispersion function $\eta(s)$ at $\delta = dp/p$ is included.

Table 2: Tolerances to Dipole Multipole Strengths.*

	Tolerance				Assumed Values			
Mult	No Corr	At Quads Only	NS at 1:2	NS Opt.	4 cm Spec	4 cm Persist	5 cm Spec	5 cm Persist
b_2	0.022	4.0	5.7	10.2	1.0	-3.0	0.63	-1.9
b_3	0.042	0.051	3.25	7.25	0.1		0.05	
b_4	0.093	0.097	2.8	18.0	0.2	0.2	0.09	0.09
b_5	0.18	0.18	2.5		0.04		0.02	
b_6	0.34	0.34	2.7		0.07	-0.05	0.02	-0.017
b_7	0.63	0.63	3.5		0.1		0.03	
b_8	1.28	1.28	4.75		0.2		0.05	

* Collider tolerances to normal dipole systematic errors (b_n) with various correction schemes are given in "Units" (10^{-4} of dipole strength at 1 cm). A 90-deg, 180-m lattice with 2 TeV injection is used. Assumed multipole values for 4 cm and 5 cm dipoles from Ref. 2 are also listed.

In the SSC, the dominant first-order nonlinear effects are the nonlinear tune-shifts. These can be calculated by integrating the phase advance around the ring:

$$\Delta\nu_{x,y} = \frac{1}{2\pi}\int \frac{d\phi_{x,y}}{ds} = \left\langle \frac{dH}{dI_{x,y}} \right\rangle$$

To first order in the coefficients b_n and a_n, only systematic multipoles ($\overline{b_n}$) contribute. The integrals have been calculated for the SSC lattice.[6] Requiring adequate linearity within the SSC design aperture ($\Delta\nu \leq 0.005$ for $x,y < 0.5$ cm and $dp/p \leq \pm 0.001$) sets limits on the allowable $\overline{b_n}$, which can then be compared with expected $\overline{b_n}$ for SSC magnets, Table 2 and Figure 2. Some correction of b_2, b_3, and b_4 is desirable regardless of the magnet choice (i.e. "4" or "5" cm dipoles).

Previously, correctors have been placed near F and D quadrupoles, and such correctors were sufficient for dipole, quadrupole, and first-order sextupole (linear chromaticity) control, but are ineffective for higher multipole effects. This failure is directly related to the increased apparent complexity of the Hamiltonian which includes coupled motion terms, as well as separable horizontal and vertical terms. However, a great improvement is obtained by adding correctors to the center (C) location of each half cell. For the correction of constant systematic multipoles, the optimum corrector strengths are close to the Simpson's Rule derived values $(S_F, S_C, S_D) = -(\frac{1}{3}, \frac{2}{3}, \frac{1}{3})B_0 b_n L$, where $B_0 b_n L$ is the n'th systematic multipole error integrated over a half cell. This reduces all nonlinear effects by about two orders of magnitude.

The accuracy of the correction can be understood by noting that any $\Delta\nu$ term can be expressed as an integral over the lattice. For example, a b_3 term may be written as

$$\Delta\nu_3 = \int b_3\beta_x^2 ds - S_{3,F}(\beta_x(0))^2 - S_{3,C}(\beta_x(L/2))^2 - S_{3,D}(\beta_x(L))^2.$$

where $S_{3,I}$ are octupole corrector strengths. All other nonlinearities, such as orbit distortions and higher-order $\Delta\nu$, can be expressed as similar integrals. The correction is equivalent to approximating a continuous integration by a sum over discrete points. Simpson's Rule is a generally valid solution. Its use corresponds to forming the FCD correctors into an optimal three-point quasi-local cancellation of the continuous mul-

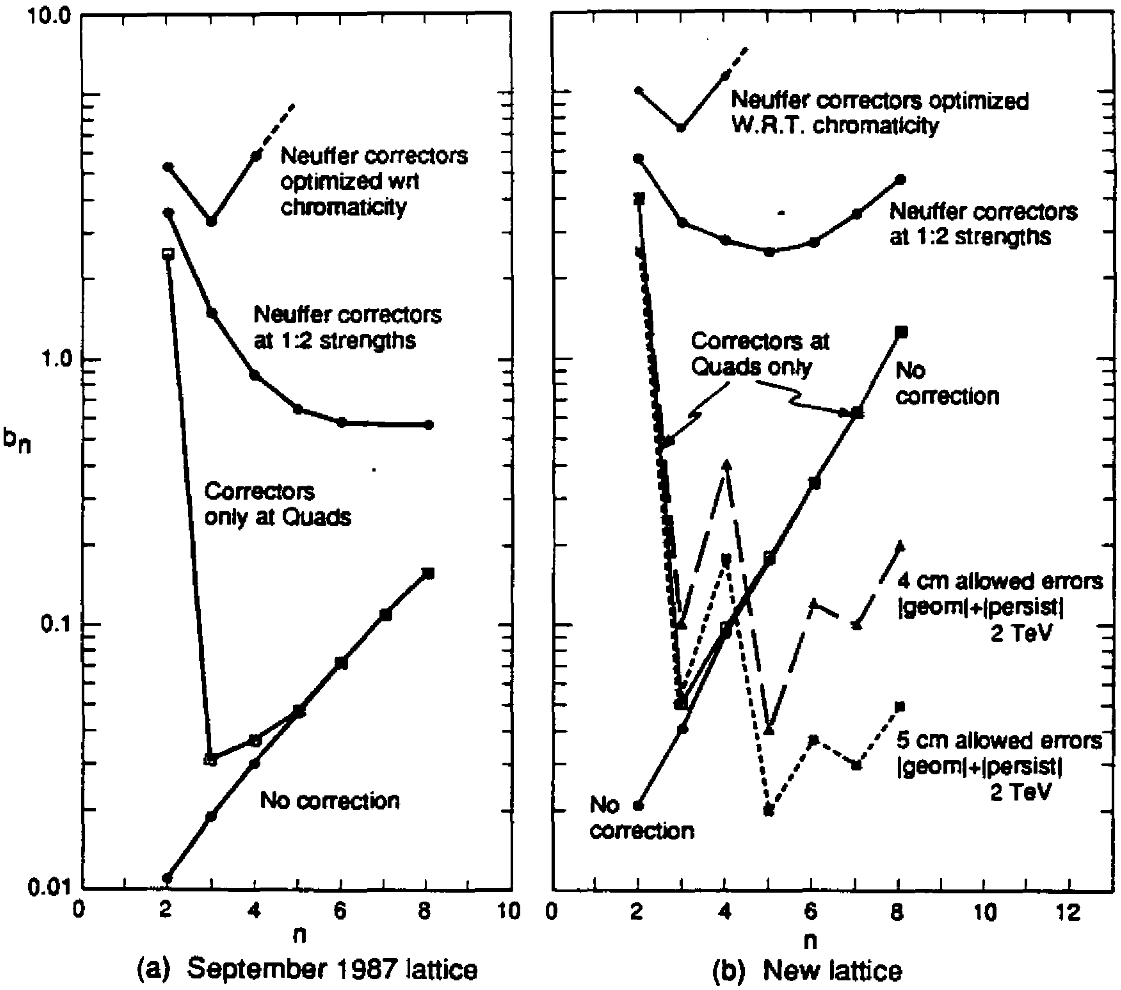

Figure 2. Systematic multipole tolerances from tune shift criteria. (a) For September 1987 lattice. (b) For current lattice. Also included are expected multipoles from Table 2.

tipole content of the dipoles. Optimization about that solution can reduce critical nonlinearities by another order of magnitude (Table 2).

For effects above first order sextupole, the Hamiltonian can be separated into horizontal, coupled, and vertical motion terms; for example x^4, $-6x^2y^2$, and y^4 terms in octupole order. The FCD correctors are at the optimal locations for control of these horizontal, coupled, and vertical motion parameters, and these are precisely the operational observables, as well as the separable terms in the Hamiltonian. This tunability can be used in improving correction from initial approximations. For instance, FCD octupoles are appropriate elements for control of all amplitude dependent and second order chromatic tune shifts. The FCD elements permit exact control of the motion through 10-pole order. The results of Table 2 and Figure 2 do not imply that one should allow dipoles with excessive multipoles: corrector magnet strengths and space for them are limited. However, they represent a compelling case for FCD correction, and illustrate the ability to optimize operation beyond simple multipole cancellation.

In the SSC cell with 5 dipoles per half-cell (Figure 1), the center corrector is slightly displaced from the optimal half-cell center. This shifts corrector values from the symmetric cell Simpson's Rule values of F:C = 1:2 to F:C = 22:50, yet correction capabilities are reduced only 10-20%.[6]

Primary Correctors

The correction magnet strengths were set assuming the Collider will use FCD correctors in each half cell of the regular lattice. A given family of primary correctors would be included in the system if linear aperture tune shift calculations and tracking studies demonstrated that it was necessary.[3,7] The 90 degree, 180 meter cell lattice with five dipoles per half cell (Fig. 1) is assumed. Injection energy is 2 TeV. The corrector strengths, however, are determined by requirements for 20 TeV magnetic fields. The present strength values were set assuming expected multipole errors for 4 cm dipoles as estimated in Table 2, and conservatively estimated dipole saturation and saturation sextupole moments at 20 TeV. Table 3 lists the strengths of primary correctors at F,C, and D locations within a cell.

Corrector dipole strengths are driven primarily by main quadrupole alignment uncertainties (0.5mm rms), with main dipole strength and roll errors contributing a few percent of the needed strength. The rms strength needed was found to be 0.60 T-m. To account for the statistical nature of the errors involved, the corrector dipole strength requirement is set at 2.50 T-m, a factor 4.2 above the rms need. This "safety factor" is consistent with Tevatron experience. Each corrector dipole is independently powered.

A corrector quadrupole is associated with each main quadrupole of the arcs and cluster region cells. Requirements for a central tune control range of $\Delta\nu = \pm 3$ while compensating up to 2% differential saturation between the main dipoles and quadrupoles dominate the integrated strength of GL = 53 Tesla (or BL = 0.53 T-m at r = 1 cm). The corrector quadrupoles are powered in two families, one family for focusing and one for defocusing.

Sextupole strengths were estimated by adding in absolute value the strengths needed to cancel a natural (from the linear lattice optics) chromaticity of $\xi_{nat} = -340$ with sextupoles at F and D locations, and the strengths to compensate a systematic sextupole (b_2) error of 2.6 "units" in the main dipoles. The b_2 compensation uses the NS arrangement with F:C strength ratio 22:50 appropriate to a 5 dipole half cell. The resulting integrated strengths are 0.13, 0.21, and 0.09 T-m at r = 1 cm for the F, D, and C corrector sextupoles. (Magnets made to the strength standards of the D location are likely to be used also at F positions instead of having two distinct types.) These are conservative choices reflecting significant uncertainties in 20 TeV dipole saturation b_2 and desires to allow luminosity upgrades through reducing interaction region β^* values. The sextupole strength is sufficient to consider binned, multi-cell applications of the Forest-Peterson[8] random error correction scheme using NS correctors. The F, D, and C sextupoles are powered as three separate families.

Although octupole field components do not occur in magnets with perfect dipole symmetry, extrapolation from Tevatron experience suggests a possible residual systematic an order of magnitude larger than desired. Effective octupole compensation requires NS correction (see Table 2 and Figure 2); spool-only octupoles have little effect. The FCD octupole corrector strengths of $BL_F = BL_D = 0.007$ T-m and $BL_C = 0.016$ T-m are able to compensate 0.46 units of systematic b_3. This allows the options of compensating random b_3 if necessary, of reducing the number of octupole correctors, and compensating skew (a_3) octupoles. Further, if the C corrector is separately powered, b_3 correctors can be useful for independent control of horizontal, vertical, and coupled amplitude dependent tune shifts, and for control of second order chromaticity. With the current strengths, second order tune shifts of ≈ 0.07 at 1 cm amplitudes and ≈ 0.04

Table 3: Primary Corrector Magnet Strengths*

Pole	F	C	D
Dipole	2.50	–	2.50
Quadrupole	0.53	–	0.53
Sextupole	0.13	0.09	0.21
Octupole	0.007	0.016	0.007
Decapole	0.004	0.009	0.004

* Values are full field (20 TeV) integrated strengths, BL, in Tesla-meters at a reference radius r = 1.00 cm.

at $(\Delta p/p)^2 = (0.002)^2$ can be controlled at 20 TeV.

Decapole field components are allowed by dipole magnet symmetry. While the random decapole is not considered a problem, compensation of systematic b_4 is required, especially at injection. As with octupoles, FCD correctors are required. The strengths to correct 0.24 units of b_4 are $BL_F = BL_D = 0.004$T-m and $BL_C = 0.009$T-m.

The strength requirements discussed above are for estimated 4 cm dipole error content. Use of larger aperture (5 cm) main dipoles, as currently planned, may reduce some multipole correction requirements. However, the requirements on corrector dipoles do not depend on main dipole aperture, and corrector quadrupole strength is dominated by tune adjustment ability and differential saturation. Also, the sextupole strength is dominated by the linear chromaticity of the lattice and saturation sextupole moments of the dipoles. These effects are not subject to simple aperture scaling. Only b_3 and b_4 may be dominated by scaling arguments. The actual multipole content of SSC dipoles is not precisely predictable, and will not be known until dipole production and measurement are underway. With that uncertainty, smaller effects have not yet been folded into the corrector strength estimations. Also, the degree of desirable tuning flexibility to be obtained with the correctors has not been fully evaluated. As these factors become more accurately known, corrector specifications will be appropriately revised.

Secondary Correctors

Much less reliance on secondary correctors is placed in the current system than in the 1986 CDR. However, with expectations of a possibly large a_1 skew multipole, correction of x-y coupling is essential. If global x-y coupling correction is sufficient, then skew quadrupoles might be placed only in cluster straight sections.[9] A more local correction would replace primary corrector packages with skew quadrupoles in pairs of adjacent C locations at a rate of one pair per half sector throughout the ring. This arrangement would make optimal use of the vertical and horizontal phase advances in a half cell.[10]

Cluster Region Correctors

The basic NS pattern of FCD primary correctors is repeated in each cell of the clusters where bending dipoles are present, with modifications for the changing optics. In empty cells, which include no main dipoles, the C correctors are deleted.

The interaction regions (IR's) will demand special attention. Correction dipoles will be used for closed orbit correction and control of beam separation and crossing angle. Their strength requirements will be dominated by the need to maintain (separated

Table 4: Collider Corrector Magnet Totals.

Region	$D_H + D_V$	$Q_F + Q_D$	$S_F + S_D$	S_C	$O_F + O_D$	O_C	$De_F + De_D$	De_C
North Arc	392	392	392	372	392	372	392	372
South Arc	392	392	392	372	392	372	392	372
Clus. W	12	12	12	12	12	12	12	12
Clus. E	12	12	12	12	12	12	12	12
Skew		40	40			40		
Clus. Type	124	124	80	50	56	50	56	50
Subtotal	932	972	928	818	864	858	864	818
I.R.	176	24						
Total	2040	1968	1856	1636	1728	1716	1728	1636

beam) injection optics during acceleration to 20 TeV. The problem is complicated by the need for local control at each IR. In one study,[11] a minimum of 8 horizontal/vertical dipole pairs per beam were required and rather strong (over 10 T-m) dipoles were needed. Space constraints imply that special dipoles will be needed.

Non-linear error fields in the IR quadrupoles can severely restrict the Collider linear aperture because of large amplitudes in the beam motion and high gradients in the long quadrupole triplet magnets. Local corrections of all a_n and b_n through $n = 5$ were found necessary in the 1986 CDR and bore tube correctors were proposed for compensating all these errors. Since then, it has been found that discrete correctors within the quadrupole triplets can also provide sufficient compensation, provided quadrupole units are arranged to allow corrector placement. The details of IR region design and correction are important remaining problems for the SSC Laboratory.

Magnet Totals

Each arc of each ring in the Collider contains 192 cells. When account is taken also of the cluster regions, there are roughly 3900 corrector packages in about 1800 F/D spools, 1700 C locations, and roughly 360 other assemblies. Including skew secondary correctors and about 250 IR region corrector dipoles, the corrector system will consist of about 14,000 magnetic elements, exclusive of IR quadrupole triplet correctors. This assumes that each bending half cell has a full corrector package of dipole through decapole, and FCD correction for the nonlinear elements. These elements are summarized by region in Table 4. In the table, we list the elements as if each were an independent magnet. Totals for each Arc, and two sets of standard "Arc type" cells within the clusters hold to a regular pattern. This is broken in the other cluster region cells ("Clus. Type") where both empty cells and dispersion suppressor cells are included. The "subtotal" line accounts for one of the two Collider rings excluding interaction regions. Both rings and the IR corrector dipoles are included in the final "total" line.

Magnet Development

The correction magnets needed to implement the corrector system are relatively small, but numerous. They need to be cost effective, but strong in comparison to previous superconducting correction magnets. The preliminary specification requires the magnets to reach full strength at or below 100 Amps, and to do so without training. The field quality is currently 1% field error at r = 1.0 cm. Mechanical tolerances must

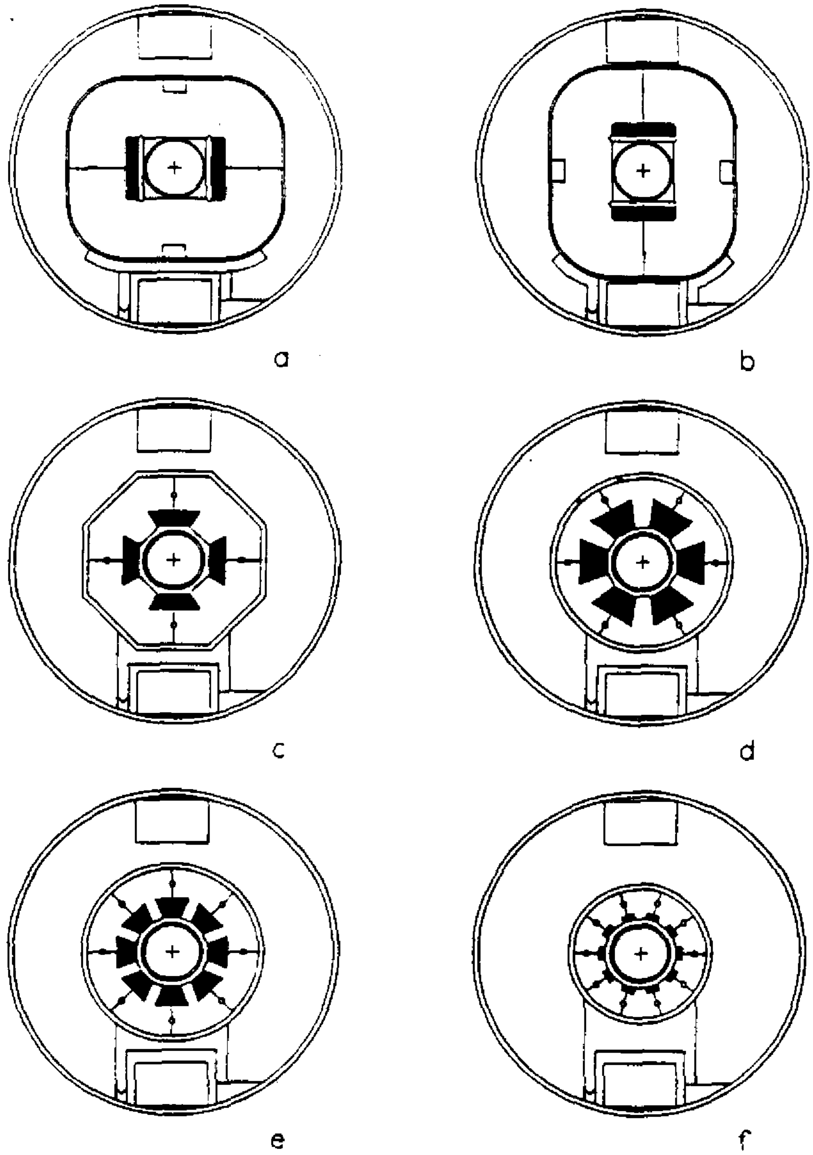

Figure 3. TAC Superferric Correction Magnets. The outer circles represent the cold mass pipe. Rectangles above and below magnets are main dipole current busses and signal busses. a) Dipole oriented for F spool, b) Dipole at D spool, c) Quadrupole, d) Sextupole, e) Octupole, and f) Decapole.

permit alignment of the F/D sextupoles and beam position monitors to within 0.1 mm.

The space in which the correctors must fit is limited. The current length allocation for the primary spool package of dipole through decapole is only 2.25 meters. The corrector cold mass diameter is about 18 cm (in the spools). Main dipole current busses and signal busses, both about 25 mm by 42 mm, also fit within the cold mass above and below the correction magnets. The length available for C region correctors is 0.50 meters. Present thinking is that at least the dipole corrector will be a separate magnet. While the others might be a radially nested package, a sequentially distributed package of magnets has received the most study.

In addition to developing specifications for correction magnet strengths and performance, SSCL needs to explore promising designs and methods of corrector fabrication.

Given the magnitude of the development and production tasks, close collaboration with existing labs and good working relations with industry are essential. We intend to have correction magnet development facilities at SSCL by the end of this year. Corrector design studies and prototyping are already in progress at Lawrence Berkeley Laboratory (LBL), the Texas Accelerator Center (TAC), and Brookhaven National Laboratory.

Development of "random wound" magnets at LBL has demonstrated successful operation of dipoles at over 2.5 T on first quench.[12] These magnets are based on the technique used for Tevatron correctors, although fields needed at the SSC are significantly higher. Careful control of the winding and potting process, as well as attention to the insulation have raised first quench fields from approximately 1.0 T to over 3.0 T.

TAC has designed a series of superferric magnets which meets the above criteria and integrated strengths of Table 3, assuming a beam tube diameter of 34 mm (as for the 4 cm dipole). The B fields for these magnets (evaluated at r = 1.00 cm) are Dipole: 2.50 T, Quadrupole: 1.44 T, Sextupole: 0.61 T, Octupole: 0.25 T, and Decapole: 0.072 T. Allowing 2 cm intermagnet spacing, and total lengths 4 cm longer than magnetic lengths, the D spool package requires 2.10 meters, leaving 0.15 m contingency. Figure 3 illustrates the cross sections of the TAC magnets.[4,13] TAC is currently working on prototype quadrupoles of the this design. They will also test application of Multiwire[14] methods for coil winding without splices.

Conclusion

The SSC Collider correction magnet system reflects the evolution of the machine and recent advances in correction theory. While future modifications and adjustments to the correction system can be expected, we feel we have the broad outline of the new system in hand. Initial test and prototype facilities at SSCL will begin operation this year. Prototype development is currently underway at LBL and TAC, and we hope that industry will join in the development process. Developing cost effective magnets to satisfy the strength, space, and reliability requirements will be a challenging task.

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13. Figure 3 courtesy R. Huson, Texas Accelerator Center.

14. "Multiwire" is a registered trademark of the Kollmorgen Corporation.