The SSC Collider Correction System

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Abstract

The magnetic correction system for the Collider Rings at the Superconducting Super Collider (SSC) is described. System evolution and recent developments are noted.

I. Introduction

The SSC Collider correction system is a collection of small magnets residing within the cold mass of spool pieces and mid half cell positions throughout the machine.

We outline below the functions covered in the point design correction scheme for the Collider Arc regions. The system is scaled back somewhat from that described in the SSC Site-Specific Conceptual Design Report (SCDR) [1]. At this stage, the design needs to be flexible, so that if need is demonstrated, modifications can be implemented with little or no impact on other systems. However retrofitting is not an option, and project delays can be costly. Working designs must be available to fulfill final requirements. A development program is underway to establish the most robust and cost effective correction magnets appropriate to the Collider.

II. System Description

The Collider Arcs contain roughly 7000 correction elements. These are physically separate magnets, not nested coils, assembled into packages prior to insertion into the cryogenic spool pieces. The basic "package" is one steering dipole, one tune adjustment quadrupole, and one chromaticity sextupole.

A standard Arc cell contains ten main collider dipole magnets (CDMs), two main collider quadrupole magnets (CQMs), two spool pieces (SP), and two mid half cell (C) positions. Measured with respect to CQM centers, the spool corrector package is about 4 m into the half cell. The C position, which is inside a CDM cold mass extension, is about 5.8 m from the half cell center.

Horizontally bending correction dipoles are in spools next to horizontally focusing (F) CQMs. Vertically bending dipoles are in spools next to defocusing (D) CQMs. Higher order correctors, octupoles and decapoles, will be appended to some spool packages, and will also be installed at mid half cell (C) position. Each higher order type will be present at a rate of one cell in five. Some C positions will contain skew quadrupoles. The beam position monitor (BPM) needs precise relative alignment to either the sextupole or the CQM. The BPM will be part of the spool, aligned to the sextupole to $\approx$ 0.1 mm (rms). Starting at the end closest to the CQM, the present spool corrector sequence is BPM, sextupole, quadrupole, higher order elements (if any), and finally dipole.

Table 1: Collider Arc Corrector Functions and Magnet Strengths (BL at r = 1.00 cm). Listed multipole values are CDM High Field systematic errors.

Magnet	Function	Range at 20 TeV	BL(1.0cm) T-m
Dipole	Steering	$\pm 37.5\mu$rad	2.50
Quadrupole	$\Delta\nu$	± 3	
	Diff. Sat.	2%	0.53
Skew Quad	Decouple	$\lvert a_1\rvert = 0.04$	0.5
Sextupole	b_2	$\lvert b_2\rvert = 0.8$	
	ξ_{nat}	$\Delta\xi = 340$	0.21
Octupole, F/D	b_3	$\lvert b_3\rvert = 0.026$	0.0020
Octupole, C	b_3	$\lvert b_3\rvert = 0.026$	0.0045
Decapole, F/D	b_4	$\lvert b_4\rvert = 0.08$	$\leq$ .006
Decapole, C	b_4	$\lvert b_4\rvert = 0.08$	$\leq$ .014

Corrector magnet strength needs are greatest at 20 TeV. The machine requirements are for integral field, BL, evaluated at a radius of 1.0 cm from the magnet axis. Table 1 summarizes the primary functions and strengths for Arc correction magnets in the SSC Collider point design.

Arc steering dipoles account primarily for alignment errors in the CQMs as well as CDM strength variations and roll errors. Their strength estimate is statistical, with a 20 TeV rms of 0.6 T-m. 2.5 T-m (4.2σ) is expected to provide adequate maximum steering strength.

The corrector quadrupoles are specified for BL(1.0 cm) = 0.53 T-m, or 5% of the CQM integral strength. This provides a tune range of $\Delta\nu_x = \Delta\nu_y = \pm 3$ and the ability to compensate a differential saturation between the CDM and CQM of up to 2% at 20 TeV.

"Local" linear x-y decoupling has been adopted for the Collider. In the SCDR, each ring has 20 pairs of individually powered skew quadrupoles at neighboring mid half cell positions. Sixteen pairs are distributed around the Arcs. The paired C positions take advantage of x-y phase ad-

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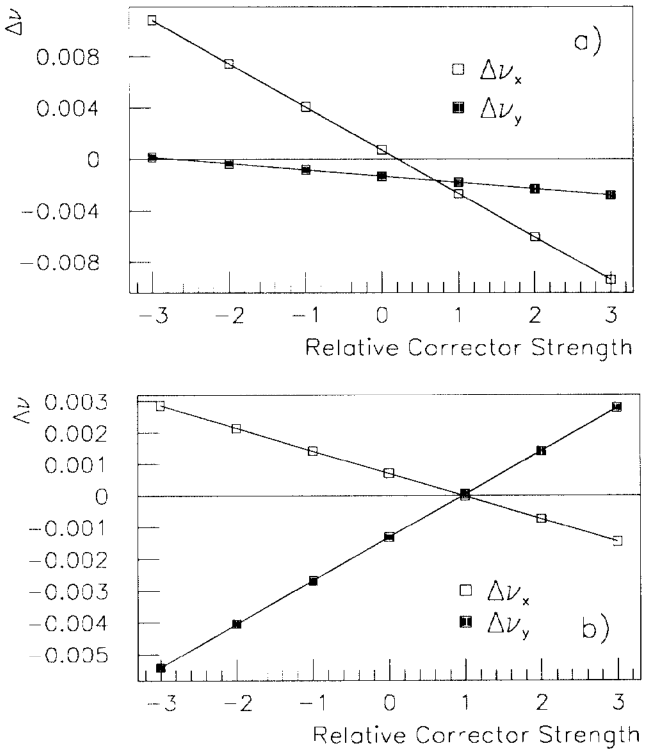

Figure 1: b_3 *Compensation with (a) Spool Only and (b) NS octupole correctors with* $b_3 = 0.026 \times 10^{-4} cm^{-3}$, $A_x = A_y = 5.0mm$, *and* $\delta p/p = 0.001$.

vance differences at the mid half cell point. TEAPOT studies at the SSC Laboratory (SSCL) using Arc skew quads only, found this pattern adequate for decoupling the collider with a small CDM systematic skew quadrupole (a_1) error. Eigenangles (orientation of the coupled motion eigenplane with respect to the machine plane) below 10 degrees were eventually achieved with integer split tunes [2]. However, with unsplit tunes decoupling efforts failed. Although the skew corrector quadrupole BL(1.0 cm) is limited because of the C slot length, the problem appears to be one of corrector density and not strength.

Recent estimates of the CDM quadrupole errors [3] indicate a potential for large systematic a_1, of order 0.2 units, possibly even 0.5 units at high field. If this is confirmed, much more extensive skew quadrupole compensation and x-y decoupling correctors will be called for.

Arc sextupoles must counter the full natural chromaticity (ξ_{nat}) of the machine as well as provide compensation for CDM systematic sextupole (b_2) errors. The specification of BL(1.0 cm) = 0.21 T-m is adequate for $\xi_{nat} = -340$ and systematic b_2 in the range ±0.8 at 20 TeV. The mid half cell sextupoles of the SCDR have not been found essential for compensating the systematic b_2 specified for 50 mm CDMs. There are no C position sextupoles in the point design correction scheme.

Although the b_3 error specifications for the CDM are fairly low, it seemed prudent to retain octupole correction as a contingency. Without mid half cell sextupoles, octupoles will be our principal tool for nonlinear tune adjustment. The point design retains octupoles in a sparse (one cell in five) Neuffer-Simpson (NS) [4] pattern. The four octupoles in a cell with compensation are sized to correct the integrated b_3 error for five cells. F and D spool octupoles need BL(1.0 cm) = 0.0020 T-m, while those at C positions need a strength of BL(1.0 cm) = 0.0045 T-m.

While not required for expected sextupole error levels, the mid half cell position is an essential element of octupole compensation. Spool only octupoles are little better than no octupoles [1,5]. An illustration is given in Figure 1 for an idealized Collider lattice with centered C position. First order tune shifts, $\Delta\nu_x$ and $\Delta\nu_y$, are plotted as a function of octupole strength for spool only (Fig. 1a) and fixed ratio (C=2F) Neuffer Simpson rule (Fig. 1b) compensation. In both plots, strength zero is no correction, and a strength of 1.0 is the nominal setting for cancelling b_3. The poor performance of the spool only correction is evident (note also change of scales), and good compensation in both views is obtained only with the NS pattern.

Decapole compensation primarily at injection energies has been retained as a contingency. As with the octupoles, a sparse (one cell in five) NS magnet pattern is used. The full compensation energy has not been set. Table 1 lists a 20 TeV full compensation strength.

In response to the lower multipole error specifications for the 50 mm CDM, the Collider Arc corrector system has been revised from over 14,000 elements to about 7,000 elements. Further evolution and optimization of the correction system can be expected, both in the Arcs - the subject of this paper - and in the Interaction Regions.

III. Corrector Development

The SSC needs an aggressive corrector development program, including in-house efforts, collaborations with other laboratories, and technology transfers to industrial vendors. The magnets must have high gradients, operate at currents less than 100 A, and have a useful life of 20 years in the collider radiation and temperature environment. They will be required to reach maximum expected operational fields without training. Corrector magnetic designs will set the maximum operational fields at $I/I_c = 0.60$.

Two major styles are under consideration: superferric, in which highly saturated pole tips enhance and shape the field, and air core, in which the iron yoke is used mainly for field return and only a modest field boost. The principal advantage of superferric correctors is efficiency in superconductor, reduction in sensitivity to wire positions, and ease of alignment. Potential disadvantages are hysteresis loop sensitivity to iron properties and higher peak fields in coils. Air core correction magnets have advantages of easier coil/yoke assembly and better linearity. Disadvantages are sensitivity of field quality and centering to conductor position errors, and need for a separate coil support structure.

Both styles can be used with a variety of winding and coil assembly techniques. After review, three winding technologies have been selected for Collider development: random/ordered winding, "jelly roll" coils, and "direct wiring". Potted random wind coils are an established method. Ordered winding is the high packing density limit of random winding. Jelly roll winding is an extension of the "Multiwire" techniques developed at Brookhaven National Laboratory for beam tube trim coils. Kapton insulated wire is ultrasonically bonded to a substrate. Precision digital control and a special wire feed head are required. A flat winding, spanning all coils of the magnet, is possible without splices. This is then rolled up on a mandrel to establish the coil geometry. The direct wire method also uses digital control and the multiwire ultrasonic head, but winding will be three-dimensional in the final coil shape. The many layers of substrate are eliminated, and maximum packing fractions will be approached.

The SSCL correctors laboratory is beginning operation this spring. Interim work at Lawrence Berkeley Laboratory (LBL) and at the Texas Accelerator Center (TAC) has been in progress since 1989. An SSC/LBL effort led by D. Bintinger has studied materials and techniques for random and ordered winding with air core dipole and quadrupole magnets. Under R. Huson, TAC has been developing superferric quadrupoles using two wire layer per substrate jelly roll coils. SSCL has tooling on order to begin building direct wire prototypes.

Wire diameter and J_c are important parameters for the corrector magnets through their impact on performance limits and lead pot heat losses. Driven by availability, LBL has used 0.020 in. diameter bare / 0.024 in. insulated wire and TAC has used 0.013 in. bare / 0.017 in. insulated wire. Neither is optimal. Based on the LBL and TAC experience to date, SSCL has selected 0.015 in. diameter, Cu:SC=2.2, $J_c \geq 3000$ A/mm^2 for further developmental work. The insulation for this wire is two layers of half mil Kapton. For use in Jelly Roll and Direct wire magnets, Bondal is used as the ultrasonic bonding agent until a more radiation resistant agent is developed.

The initial focus of the LBL study was optimum insulation type for random wind potted coils. Over 28 dipole magnets with 42 mm aperture and 6.6 mm thick potted coils have been tested [6]. Random wind packing fractions of 45% were routinely obtained. The LBL dipole design goal was first quench at 2.5 T and 80% short sample. The insulation study found wrapped Kapton insulation essential for achieving this goal. Other insulations, polyester and Teflon heat seal Kapton, were not acceptable. A first quench dependence on the wire J_c was observed. Table 2 summarizes the LBL first quench results for dipoles against three wire types. These magnets were found relatively easy to wind and pot. They tended to train slowly to their short sample limit, and did not remember training upon thermal cycling.

Since the wire packing fraction is an important parameter, LBL developed techniques extending random wind methods to high packing density and nearly ordered coils. Unfortunately, potting these has been difficult, and to date random wound dipoles have performed better.

Table 2: LBL Dipole First Quench J_c dependence with 0.020 in. diameter wire

Jc (A/mm^2)	Cu:SC	B_0(T)	%S.S.
2430	2.0	2.5	75
2795	2.2	2.9	85
3170	1.5	3.3	85

LBL has also built six random wind 42 mm quadrupole magnets. Their design goal was a gradient of 1.0 T/cm on first quench. Four of the six exceeded that goal, with two magnets (Cu:SC=1.5) having first quench at 1.5T/cm. These first quenches were at about 95% of a quickly reached plateau.

TAC has built and tested 8 jelly roll quadrupoles with 0.013 in. diameter, Cu:SC=2.0 wire and Kapton insulation. Their results are reported at this conference [7]. Since the preferred substrate (Kapton with XP-17 adhesive coat) was not available, the first four models used an older substrate material, RC205. Performance of these magnets was poor, although considerable insight was obtained through rebuilding them.

When Kapton/XP-17 substrates became available, a dramatic change in performance was observed. Three of the four such magnets built to date showed first quench over 80% short sample, and only one or two training quenches to reach a stable short sample plateau. Initial results also suggest Jelly Roll magnets may be able to remember their training. Data over more than 10 thermal cycles on two magnets are promising but not conclusive. Of interest for these magnets is that the substrate's Kapton backing was peeled off prior to magnet assembly, leaving only an XP-17 adhesive substrate.

Both programs have brought useful insights to correction magnet dymamics. While more work needs to be done with these winding techniques, results so far are promising.

IV. References

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