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ACTIVE INTERNAL CORRECTOR COILS*

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INTRODUCTION

Trim or corrector coils to correct main magnet field errors and provide higher multipole fields for beam optics purposes are a standard feature of superconducting magnet accelerator systems. This paper describes some of the design and construction features of powered internal trim coils and a sampling of the test results obtained.

DESIGN CRITERIA

The coils under discussion are directly driven by an external power supply. Coils can also be constructed which are excited by the field of the main magnet.[1] The externally powered coils have the advantages of flexibility (the level of excitation can be changed as needed after construction and installation) and that only moderate accuracies (~1% in field quality) are needed in construction. They have the following disadvantages:

1. Unless one is willing to power each one separately, there is no way to compensate for magnet-to-magnet variations.

2. The connecting leads are lengthy (10's of km for SSC), and complex (thousands of connections) with the attendant problem of reliability.

3. The power supplies and controls are complex and expensive. In particular, it is difficult to confirm that the field being generated is accurately tracking the excitation of the main magnets.

The coils being discussed are contained within the bore of the main magnets. The advantages of this construction are:

1. Field perturbations are corrected locally. This is particularly important for non-linear effects.

2. The space between the bore tube and the inside of the main coil is to some extent "free." It is attractive to use this space rather than requiring additional straight sections in the lattice.

3. The length available is often 70+ % of the total length of a cell. Thus the coils need to generate only very small fields (usually a few gauss). It is attractive to contemplate coils of wire <1 mm in diameter carrying currents of a few amps. At first it would seem this ought to be orders of magnitude easier than the construction of the main coils.

One must pay for this "free" space with the following draw-backs:

1. Added Complexity -- the main magnet and the trim coil(s) are now one unit and if the "trivial" trim coil fails the whole unit is jeopardized. For positioning, the trim coil must fit tightly within the main coil. Unfortuntely, during assembly and prestressing, the main coil changes dimensions and shape.

2. Main Coil-Trim Coil Interactions -- at low fields, the trim coils can introduce magnetization effects in the main coil. This topic will be discussed at some length below. At high fields, the main field limits the current carrying capacity of the trim conductors; in addition, the Lorentz forces upon these conductors can cause deflections of the entire bore tube or shearing within the trim structure. Because of the very large torques generated it is generally impractical to place a skew multipole within a main coil of the same multipolarity. The trim coils often have approximately the same number of turns as the main coils. Thus the electromagnetic coupling to the very strong main field can produce significant voltages within the trim.

3. For the SSC, the bore tube may be heated by the synchrotron radiation. In this case the trim coils would operate at a temperature higher than the bath temperature.

In summary the design constraints are:

1. Very limited radial space <1-3 mm.

2. At low field, current limited by cryogenic load of leads (<100 A), and maximum current density in stabilizing copper (<1-2 kA/mm^2).

3. At high field current limited by main magnet field.

4. Field Quality -- usually the trim coils will be required to supply 10-100 times the rms tolerance of a particular multipole. With this level of excitation, an accuracy of ~1% of the trim field is usually acceptable.

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CBA Trims

High field strength internal trims were constructed for the CBA project.[2] After extensive experimentation, preproduction prototypes were manufactured. Because these coils were required to supply the sextupole for chromaticity correction in addition to compensating for a rather large saturation swing they were much more powerful than the coils currently being proposed. The coils consisted of one layer which generated both sextupole (3θ) and decapole (5θ) and a second layer generating octupole (4θ). The short sample limit of the wire used was 275 A in the 5.2 T main dipole field. The final prototypes reached this current without training. This current corresponds to 0.18 T at the trim coil; a figure of merit is the product of the main field and the trim coil field — for this case this product was 0.9 T^2. Figure 1 shows a cross section of this design. The following mechanical properties were found to be essential to the proper operation of this coil: a good bond between the trim substrate and the bore tube, the Kevlar layers to add rigidity to the structure, and support of the coil to minimize distortions.

The field of the trim coil penetrates the main coil windings and induces magnetization in the main coil. An example of this is shown in Figure 2. The fields generated are quoted in gauss at the trim coil radius (60 mm). (Notation used is C(n) for the coefficient of the nθ multipole.) The interaction between the trim coil harmonic (4θ) and the main coil winding produces significant induced fields of (2θ, 4θ, 6θ). The strength of these induced fields for 2θ and 6θ is plotted in gauss. If the trim strength is B_n for the n-th harmonic, one would expect the induced harmonic b_m to be given by:

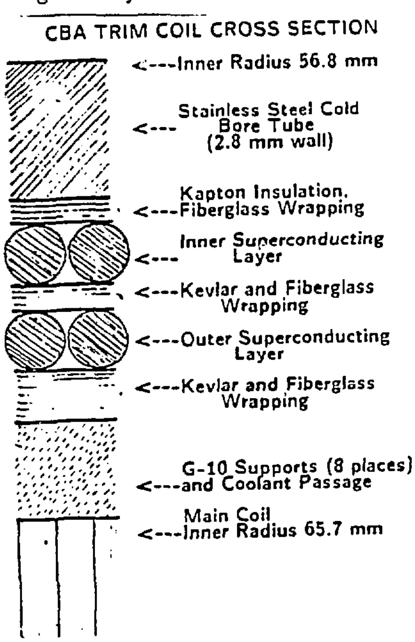

Figure 1. Cross section of CBA trim coil assembly.

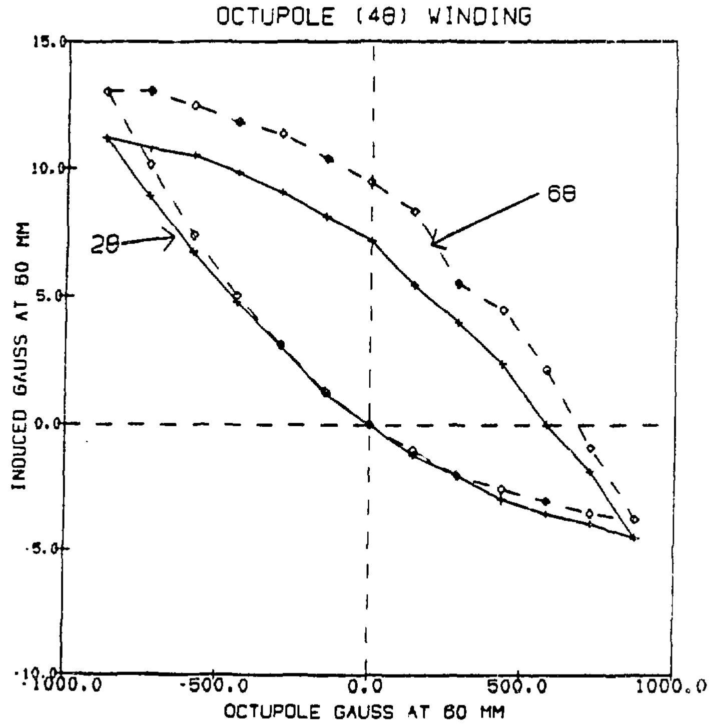

Figure 2. Magnetization produced in CBA main dipole coil by excitation of octupole trim coil. The units are gauss measured at the trim coil radius of 60 mm. The central dipole field was at the injection value of 0.4 T.

$b_m = K_{nm} \times B_n \times (r/R)^{(n+m)}$, where r = trim coil radius, R = main coil radius. The results for an octupole trim are presented in the table below.

Results for N = 4 @ B_o = 0.4 T

m	b_m/B_n	K_{nm}	$(r/R)^{n+m}$
2	1%	2%	0.40
3	1%	3%	0.34
4	3%	12%	0.29
5	0%	0%	0.25
6	1%	5%	0.21

As can be seen, careless operation of an internal trim coil can produce significant magnetization effects. These can be cleared by cycling the main coil to high field and back or reduced by cycling the trim coil.

SSC TRIM COILS

A research program is being carried out by BNL and LBL to develop internal trim coils for the SSC main magnets. The preliminary specifications were:

1. Harmonic(s) -- 3θ, (5θ,7θ).

2. Maximum strength at 10 mm -- 26 gauss = 75 gauss at coil,

$B(trim) \times B = 0.05\ T^2$

3. Very limited space <0.5 mm for wires.

4. Plan for large production, 8000+ 16 meter units.

The coils built and tested to date were designed to these specifications. (Recently the specifications have been revised, but the results obtained are still relevant.) The strength required is much less than that for the CBA, but because of the smaller dimensions, the absolute accuracies required in construction and assembly are higher.

CONSTRUCTION TECHNIQUES

The original technique was to wind the coil on a flat mandrel, cure the epoxy (which has a flexibilizer added) and bend the completed coil around the bore tube. With a coil radius of 17 mm instead of 60 mm this appeared to be impractical. A technique was developed at LBL for supporting the wires around the bore tube and carefully pushing them onto the tube. At BNL this was adapted for coils up to 4.5 meters in length. For production of 16 meter coils it seemed that this method was too labor intensive and the possible problems with 100 fine 16 meter long wires suspended on a jig were daunting. We were unable to find a feasible technique to use photo-etching for superconductor. During the investigation, it was found that Multiwire[3] had developed a technique for applying fine wires to a substrate. The method consists of a numerically controlled head which ultrasonically embeds wires in a special adhesive. The device can lay down wire at approximately 10 meters/min with an accuracy of 0.025 mm. Collaboration between this corporation and BNL verified that this would work for superconducting wire up to 0.2 mm in diameter and that the adhesive held at cryogenic temperatures. The substrate is prepared with accurately cut slots; the wire is applied relative to these slots and then the completed assembly is located over keys affixed to the bore tube. Figure 3 shows the construction of this coil. The inner layer of Kapton is bonded to the bore tube with a heat curing Teflon. The Kevlar wrap on the outside is secured with a conventional epoxy resin. The tables below give the results from the testing of seven 4.5 meter coils built to these specifications.

Results for SSC Sextupole Trim

	Handwound	Multiwire
Number Built	3	4
Wire	0.21"	0.008/6"
Turns	10	17
C3/I (G/A@10 mm)	3.56	5.57±0.08
---- @ B = 6.5 Tesla -----		
I quench	37 A	14 A
Iq wire	100 A	14 A
C3 quench	133 G	78 G
C3 required	26 G	

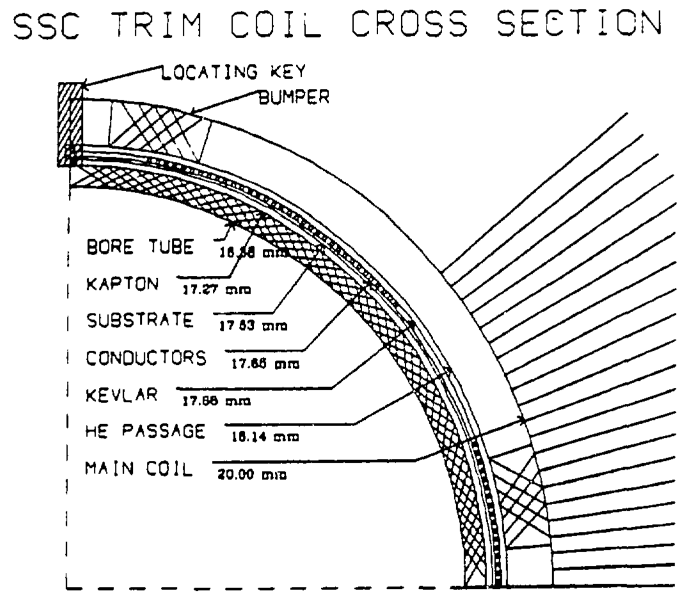

Figure 3. Cross section of SSC trim coil assembly.

As can be seen, the coils exceeded the required field strengths by at least a factor of 3. Because of the long history of poor performance of internal trim coils, a factor of 3 is a reasonable design margin. The next table shows the measured harmonics of these coils. For the machine wound coils there are two entries, the technique for mounting the completed coil on the bore tube was improved for the last coil tested. The results for this coil are listed in the second line. Using 1% as a guide for the field quality, we see that for the last coil built, all spurious harmonics except C4 are below this level. Further, the only ones which approach this level, C2, A3, and C4 are those induced by mis-positioning and misalignment of the trim coil with respect to the main dipole. This is generally true for internal trim coils. The field errors induced by displacement of the coil as a whole dominate those produced by the coil construction. The winding layout of this coil is just a single block of turns positioned so that $C9 \simeq 0$. The next allowed harmonic is C15, which falls off so rapidly with radius that it may be ignored.

HARMONICS FOR SSC WORST CASE

For the current SSC specifications, the biggest field erors produced by the sextupole trim occur at injection field. The table below summarizes this case using the coefficients measured for the last multiwire coil. These are all small compared to the rms tolerance of the main dipole.

SSC Sextupole Trim Coil Results
Harmonics (Gauss @ 10 mm)

		Handwound	Multiwire
Bo		0.25	---
	B_o/C3	7%	---
C2		0.04	0.2 0.03
	C2/C3	1.1%	3.5% 0.6%
C3		3.56	5.57
A3		0.24	0.61 0.34
	A3/C3	6.7%	10.9% 0.6%
C4		0	0.35
	C4/C3	0	6.3%
C9		0.008	0.005
	C9/C3	0.2%	0.1%
offset (mm)		0.13	0.45 0.08
rotation (mradian)		24	39 12

SSC Sextupole Trim

Worst Case = Injection, B_o = 0.33 T

b_2' = -5 (magnetization)

THEN:

C3 = 1.7G
I = 0.3 A

Harmonics

Gauss @ 10 mm			Cn/B_o @ 10 mm
C2	0.009 G	=	3×10^{-6}
C3	1.65 G	=	1.000 (sextupole)
A3	0.10 C	=	30×10^{-6}
C4	0.10 G	=	31×10^{-6}
C9	0.01 G	=	0.4×10^{-6}

CONCLUSIONS

The quench problems of internal trim coils can be solved with conservative electrical and mechanical design, and careful construction. For the SSC coil dimensions, positioning accuracies of 0.04 mm result in field errors of less than the rms tolerances. The Multiwire process is capable of mass producing coils which meet all of the current SSC specifications.

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