AD/SSC/Tech. No. 68

Accelerator Development Department

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SSC Technical Note No. 68

SSC-N-483

"Trim Coil Magnetization"

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February 26, 1988

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26-Feb-1988

I INTRODUCTION

As pointed out by Green and Peterson[1](GP),the magnetization currents in the proposed SSC bore tube windings produce significant field perturbations. This note presents a simplified, analytic calculation of these fields. The results are consist with the work mentioned above. Detailed calculations are presented for the most recent design[3]. The effects are surprisingly large even for 27 um filaments; it may be desireable to further reduce the filament size.

II CALCULATION

The magnetic field produced by a thin wire is given by[2]

$$B_\nu = I \frac{\mu_o}{2\pi} R^{-\nu} \cos(\nu\phi) \quad \langle 1\rangle$$

Where: B_ν is the $\cos(\nu\phi)$ moment of the field,
R is the distance of the wire from the origin,
ϕ is the angle, $\mu_o = 4\pi \times 10^{-7}$

In order to calculate the field produced by magnetization currents, the following assumptions are made:

1. The external field fully penetrates the filaments.

2. The transport current is negligible.

Under these assumptions, the filament is completely filled (up to Jc(Bext) with magnetization current, half flowing in the +Z direction, and half in the -Z direction. The dividing line is the diameter parallel to the external field. The field produced may then be calculated by integrating equation 1 over the two semicircles. For the case of an external dipole, the dividing diameter is vertical, and it is straightforward to integrate equation 1. Keeping only terms of order r/R gives:

$$B_\nu = \frac{\mu_0 I_f}{2\pi} \frac{4r\nu}{3\pi R} R^{-\nu} [\sin\nu\phi \sin\phi - \cos\nu\phi \cos\phi]$$

where: r= radius of filament, I_f = critical current of a filament.

To get the contribution from an entire wire(with diameter small compared to R), one replaces I_f with $N*I_f=I$. It is also convenient to replace the radius r with the filament diameter d. This gives:

$$B_\nu = \frac{\mu_o}{2\pi} \frac{I 2 d\nu}{3\pi R} R^{-\nu} [\sin\nu\phi \sin\phi - \cos\nu\phi \cos\phi] \quad \langle 2 \rangle$$

From this equation, it is apparent that the only way non-zero harmonics are produced is due to the non-uniformity of the winding. (ie. if the winding consisted of a constant number of turns per unit angle for the entire circumference, the net magnetization effect would be zero.) In principle, one could add dummy turns to the pole regions of actual coils to cancel the magnetization effects. This approximation is only valid when the transport current is << Ic. This note does not deal with the practicality of such a scheme.

For generalized coil configurations, equation 2 can be summed over the wires. For a simple multipole trim coil, one can replace the summation with an analytic integration. Evaluation of the resulting integrals is tedious and only one case will be presented below, that of a sextupole trim coil in an external dipole field. The first non-zero term produced by this coil is the 5ϕ one. The coil is of the "first order" type- it consists of a single uniform winding from 0 degrees to 20 degrees. The summation of equation 2 over wires can thus be replaced by the following sum of integrals.

$$B_\nu = \underbrace{\frac{\mu_0}{2\pi}\, I\, \frac{2d\nu}{3\pi R} R^{-\nu}}_{\alpha_\nu} \sum_{j=1}^{4M} \int_{\phi_j}^{\phi_j+\frac{\pi}{3M}} \left[\sin\nu\phi\,\sin\phi - \cos\nu\phi\,\cos\phi\right] \frac{\Delta\phi}{N}$$

$$= -\alpha_\nu \frac{4}{\nu+1} \frac{\Delta\phi}{N} \sum_{j=1}^{M} \sin(\nu+1)\phi \Big|_{\phi_j}^{\phi_j+\pi/3M}$$

For Sextupole: $M=3,\ \nu=5$

$$B_{\nu=5} = -\alpha_5 \frac{4}{6}\left(\frac{\sqrt{3}}{2}\ 3\right)\frac{\Delta\phi}{N}$$

with the information that:

$\frac{\Delta\phi}{N} = \frac{\pi}{3MN} = 0.035$ Radians/Turn

Ic=330 A(@ 0.33T)

d = 27 um

R =17.7 mm

N = 10 turns/pole

For Bo= 0.33 T this gives b4' = 0.92×10^{-4}

(in exact agreement with the numerical sum over the wires)

III NUMERICAL RESULTS

Because of the effort associated with evaluating the integrals associated with an analytic version of equation 2, particularly for somewhat arbitrary trim coil geometries, the sum has been performed explicitly to get the expected magnetization fields for the SSC trim coils.

It is useful to scale GP to the present case.

$$b'mag = K \{Bmag/Jc(Bo)\} \times \{Jc(Bo)/Jc(5T4.2K)\} \times Jc(5T,4.2K) \times d^3 \, N \, n/Bo$$

where: Bmag = b'mag*Bo, d is filament diameter
N number of wires/pole
n number of filaments/wire
Bo - external field
Jc - critical current density
K a constant

Parameter	GP value	Current Value
Bo	0.7 T	0.33 T
Penetration	almost 100%	100%
Bmag/Jc	0.109	0.139
Jc	6.3@0.7 T	9.3@0.33 T
Scale Factor	1.0	1.88
Jc(@ 5T,4K)	2.2	1.85 kA/mm^2
Scale Factor	1.0	1.19
Normalizing Field	0.7 T	0.33 T
Scale Factor	1.0	2.12
Filament Size	120 um	27 um
Number of Filaments	1	54
Number of Turns(b2)	20	10
Scale Factor =d^3*n*N	1.0	0.307
Overall Scale Factor	1.0	1.5

NOTES:

1. With the 120 um filaments, the filaments were not fully penetrated until the external field was >0.7 T. With the 27 um filaments, full penetration occurs well below injection field. Thus the magnetization field is larger compared to Jc. The values of Bmag/Jc are taken from Figure 1 of GP.

2. The lower Bo increases Jc significantly, and hence the magnetization field.

3. In GP, a Jc of 1.85 kA/mm^2 was assumed, 2.2 is the current specification.

4. The lower Bo also appears in the denominator when converting to normalized units. Note that the normalized units are b4 rather than B5 (ie power of R rather than multiple of the angle)

The rather surprising result is that the magnetization fields will be 40% LARGER for the new configuration. In the old configuration, the magnetization fields were artificially suppressed at injection because the filament size was so large that full penetration did not occur until 0.7 Tesla. Because of its sensitivity to Jc, this is not a practical way to suppress magnetization currents. Although the smaller filament windings give larger fields, these fields are much less dependent upon Jc and hence more uniform from magnet-to-magnet ;also they are less dependent upon magnet history.

Table 1 below gives the results of the calculation with this model for the "current" SSC trim coil designs and a comparison with the calculations of GP scaled as above. The agreement is excellent (the data presented in GP is unsigned). The b'_{10} moment is also allowed for the sextupole coil and has a value of 0.03 units. The other allowed moments are <0.01 units.

The values are comparable to those of the main dipole. It may thus be desireable to reduce them by a factor of two by reducing the filament size to ~12 um. This is practical.

Table 1: Magnetization Fields For SSC Trim Coils

Coil =	b2(sextupole)		b3(octupole)		b4(decapole)	
length	8 m		3 m		5 m	
turns/pole	10		7		6	
	b4'	-0.92	b6'	-0.38	b8'	-0.16
		1.0		0.4		0.18
		-0.5		-0.07		-0.08
	b10'	+0.003				

Units are x 10^{-4} of Bo.
The first value is the result from the calculations discussed in this note.
The second is the value from GP scaled for the revised trim coil configuration.
The third is line 1 corrected for the ratio of trim coil length to dipole length.

III.1 References

1. M.A.Green and J.M.Peterson, Magnetization in Bore-Tube Correction Windings, SSC-N-279,(1986)

2. H.Hahn,Ideal Multilayer Dipole Coil Configurations, BNL,ISABELLE Tech. Note 305,(1981)

3. P.A.Thompson, Magnetic Design-Report of the SSC Workshop on Distributed Correction Coils- Task Force Report - R.Sah, Editor,SSC-SR-1032(1988)