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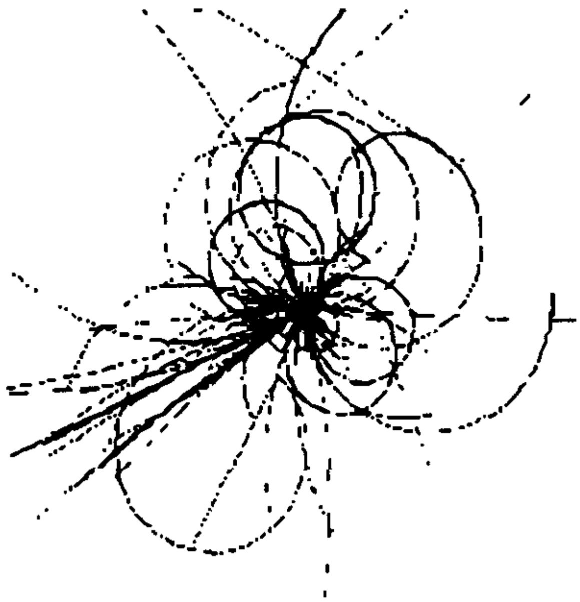

SSC - N - 226

NOTES

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SSC Technical Note No. 51
SSC-N-226

FIELD QUALITY FOR SSC INTERNAL TRIM COILS

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August 20, 1986

CONTENTS

I INTRODUCTION

This note presents calculations of the field errors induced in the proposed SSC internal trim coils by various construction and assembly errors. Tolerances have been derived from these errors. With tolerances of approximately 10 mils, which is achievable with the present technology, the worst case errors are about 5% of the fundamental harmonic. In may be possible to develop a technology which will produce 4 mil accuracies which correspond to worst case errors of 2 %.

II ERROR MATRICES

The program computes the perturbed positions of the wires of the coil under study. The field is sampled at 64 points around a 10 mm radius and a Complex Fast Fourier Transform is used to obtain the harmonic expansion. For calculation standard perturbations of 1 mm and 5 degrees have been used. These are larger than the tolerances which will be discussed latter. Six basic types of perturbation have been investigated:

1. Displacement, the coil as a whole is displaced in an arbitrary direction from the center of the main dipole coil. For simplicity, results are presented for a 1 mm displacement in the y direction. For small displacements the effects of multiple perturbations add linearly, and the effects of a displacement in x are similar to those in y except for the generation of normal rather than skew harmonics. The dominant effect is the generation of the (m-1)th normal/skew harmonic, with second order terms in (m-2).

2. Rotation, the coil as a whole is rotated about its center relative to the main dipole coil. Results are presented for a standard 5 degree rotation. The dominant effect is the generation of the m-th skew harmonic.

3. A gap in the Coil. If the diameter of the bore tube is larger than the coil, an asymmetric gap will be generated. The results for a 5 degree gap at 22 degrees are presented. 22 degrees is where the cut in the substrate will be made. This generates a very rich harmonic spectrum.

4. Ellipse. In assembly it is likely that the bore tube will b distorted. The simplest distortion is an ellipse. Results are given for a perturbation of 1 mm inward at the pole. This generates a significant normal (m-2)th harmonic. An ellipse with its short axis horizontal has the same harmonic but with the opposite signs.

5. Random Wire displacements. Calculations were done for the case where each wire is allowed to move up to 1 mm azimuthal from its nominal location. (In the physical coil these wire would often overlap for such a large variation). The disturbution used is flat from -1 mm to + 1 mm of displacement. The field perturbations generated in this manne are small, presumably due to the large number of wires (~200 involved.

6. Random Block displacements. Calculations were done where each block of wires was moved randomly over +-1 mm. For thi calculation, a block is the group of wires between each "midplane" and pole. Thus a sextupole coil consists of 12 blocks. The field distortions produced by these displacements are marginally significant. If the two blocks between adjacent poles were displaced as a whole, the field distortions would be approximately twice as large.

The results of these calculations are presented in tables 1-3; one table for b2,b3 and b4 coils. In these tables the perturbations are 1 mm for displacements and 5 degrees for rotations. These values were chosen for ease in comparing data and are larger than reasonable tolerances. A subsequent section of this note develops actual tolerances. The tables are arranged with 12 columns of harmonics subdivided into 6 groups of two. The first column in each group is the Bx or skew harmonic, the second is the normal harmonic. The rows are labeled with the power of R for the harmonic. The values quoted are percent (%) of the fundamental- evaluated at 10 mm radius. Thus the normal fundamental harmonic is usually close to 100%. For the two cases where random perturbations were applied, only the rms variation of the fundamental from 100% is given. This variation is of course unsigned.

Table 1: Field Perturbations for b2 Coil
(as percent of Fundamental)

COIL -- b 2 (C 3) 19 turns 6.70 G/Amp

m-1	displacement dy=1 mm		Rotation 5 deg		Gap 5 deg.		Ellipse dy=-1mm		Wire rms 1 mm		Block rms 1 mm	
0	0	-1.0	0	0	-2.5	1.3	0	-13.2	0.5	0.6	2.1	1.6
1	20.0	0	0	0	-3.1	4.4	0	0	0.7	0.6	1.7	2.4
2	0	100.0	25.9	96.6	-13.6	99.1	0	100.0	0.7	0	2.2	0
3	0	0	0	0	-1.0	-2.9	0	0	0.6	0.3	1.2	2.7
4	0	0	0	0	-0.7	-0.7	0	0	0.2	0.3	0.9	1.2
5	0	0	0	0	-0.4	-0.1	0	-2.2	0	0	0	0
6	0	0	0	0	-0.2	0	0	0	0	0	0	0
7	0	0	0	0	-0.1	0.1	0	0	0	0	0	0
8	0	0	0	0	0	0.1	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0

Table 2: Field Perturbations for b3 Coil
(as percent of Fundamental)

COIL -- b 3 (C 4) 14 turns 3.7 G/Amp

m-1	displacement dy=1 mm		Rotation 5 deg		Gap 5 deg.		Ellipse dy=-1mm		Wire rms 1 mm		Block rms 1 mm	
0	-0.1	0	0	0	-3.2	1.2	0	0	1.3	0.8	3.1	2.0
1	0	-3.0	0	0	-3.9	3.3	0	-26.1	0.9	1.0	7.0	2.7
2	30.0	0	0	0	-3.8	6.6	0	0	0.9	0.8	3.2	3.0
3	0	100.0	34.2	94.0	-17.4	98.5	0	100.0	1.2	0	3.2	0.1
4	0	0	0	0	-0.7	-3.9	0	0	0.9	0.5	2.2	2.0
5	0	0	0	0	-0.6	-1.1	0	-2.6	0	0	0	0
6	0	0	0	0	-0.4	-0.4	0	0	0	0	0	0
7	0	0	0	0	-0.2	-0.1	0	0	0	0	0	0
8	0	0	0	0	-0.1	0	0	0	0	0	0	0
9	0	0	0	0	-0.1	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0

Table 3: Field Perturbations for b4 Coil
(as percent of Fundamental)

COIL -- b 4 (C 5) 11 turns 2.0 G/Amp

m-1	displacement dy=1 mm		Rotation 5 deg		Gap 5 deg.		Ellipse dy=-1mm		Wire rms 1 mm		Block rms 1 mm	
0	0	0	0	0	-4.4	1.2	0	1.3	0.8	1.9	4.1	4.4
1	-0.4	0	0	0	-5.3	3.2	0	0	2.5	2.9	5.5	4.5
2	0	-6.0	0	0	-4.9	5.2	0	-39.0	1.7	1.3	7.1	6.0
3	40.0	0	0	0	-4.6	8.7	0	0	1.0	1.7	4.6	3.5
4	0	100.0	42.3	90.6	-21.2	97.7	0	100.0	1.3	0	1.8	0
5	0	0	0	0	-0.3	-5.0	0	0	0	0	0	0
6	0	0	0	0	-0.5	-1.5	0	-3.0	0	0	0	0
7	0	0	0	0	-0.4	-0.5	0	0	0	0	0	0
8	0	0	0	0	-0.2	-0.2	0	0	0	0	0	0
9	0	0	0	0	-0.1	-0.1	0	0	0	0	0	0
10	0	0	0	0	-0.1	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0

III TOLERANCES

It seems sensible to discuss two levels of manufacturing tolerances; the level which can be achieved with present technology and careful construction, and the level which could be reached with significantly improved technology. These are summarized below:

Technology Level	I	II
Tolerance		
Displacement of Coil	10 mil=0.25 mm	4 mil=0.10 mm
Rotation of Coil	10 mil=0.9 deg	4 mil=0.4 deg
Gap	10 mil=0.9 deg	4 mil=0.4 deg
Elliptical Deformation	10 mil=0.25 mm	4 mil=0.10 mm
Wire RMS	5 mil=0.12 mm	2 mil=0.05 mm
Block Rms	5 mil=0.12 mm	2 mil=0.05 mm
Coil Length	40 mil=1 mm	

The displacement of the coil comes from the tolerance build up in the locating keys and the uncertainty of the shape of the inner circumference of the main coil. To improve this significantly would require a more sophisticated locating system and a method of measuring the position of the bore tube accurately with respect to the main coil. The rotational uncertainties arise from the same sources. The gap in the circumference arises from uncertainties in the diameter of the bore tube. It may be possible to reach the 4 mil (1.3 mil on the diameter) tolerance by building up the bore tube with Kapton, this is a lengthy procedure.

The elliptical deformation comes from the assembly procedure for the main coils. Ironically, the deformation can be reduced at the expense of increasing the uncertainty in the placement of the coil as a whole. To achieve the 4 mil tolerance would require both a new assembly arrangement and a means of measuring the bore tube shape in situ.

The wire and block internal variations are the easiest to control and have the least effect upon the field quality. One could probably achieve 2 mil tolerances with the present techniques.

The tolerance on the overall length is a nominal one, and represents less than 0.03 % variation in effective length.

III.1 Results For Sextupole (b2) Coil

Refering to table 1, one can determine coefficients for the various harmonics, and multipling them by the tolerances above gives the following field errors:

Tolerance Level Perturbation	Coefficient	I Amplitude	II Amplitude
Displacement	b1/a1 = 20	5 %	2 %
Rotation	a 2 = 26	6 %	2 %
Gap	a2 = 14	2.5%	1 %
Elliptical	b0 = 13	3 %	1.5 %
Wire Rms	b's/a's ~ 0.6	0.1%	0.06 %
Block Rms	b's/a's ~ 2.7	0.7%	0.3 %

It is apparent from the above that the problems with trim coil fields are dominated by the positioning of the coil as a whole. In reading this table, it should be remembered that the harmonics are quoted as percent of the b2 field which is $<5 \times 10^{-4}$. Hence these fields are <6 ppm of the central dipole field. These field errors will also tend to be fairly random from magnet to magnet and perhaps even within a magnet. The exception is the dipole generated by elliptical squeezing of the coil. Any significant improvement below the 5% level will require an elaborate measurement technique to verif the placement.

III.2 Results For Octupole (b3)

The results for the octupole are of course similar, however because of the higher multipolarity, the coefficients are larger. Fortunately, this coil is only intended to supply 0.4 units of correction (a factor of 10 less).

Tolerance Level Perturbation	Coefficient	I Amplitude	II Amplitude
Displacement	b2/a2 = 30	8 %	3 %
Rotation	a3 = 34	8 %	3 %
Gap	a3 = 17	3 %	1 %
Elliptical	b1 = 26	6 %	3 %
Wire Rms	b's/a's ~ 1.5	0.4%	0.2 %
Block Rms	b's/a's ~ 5.0	1.2%	0.5 %

Although these errors seem large, one should recall that 8% x 0.4 x 10^{-4} is 3 ppm, and that the bulk of them will be random.

III.3 Results For Decapole (b4)

This coil is even more sensitive, but again is only intended for 0.4 units of excitation.

Tolerance Level Perturbation	Coefficient	I Amplitude	II Amplitude
Displacement	b3/a3 = 40	10 %	4 %
Rotation	a4 = 42	10 %	4 %
Gap	a4 = 21	5 %	2 %
Elliptical	b2 = 39	10 %	5 %
Wire Rms	b's/a's ~ 2.5	0.6%	0.3 %
Block Rms	b's/a's ~ 7.0	1.7%	0.7 %

If one takes the worst case of 10 %, at 0.4 units of excitation this becomes 4 ppm of the central field.

III.4 Forces

The Lorentz forces applied to these trim coils are comparatively low: 5 amps x 6.5 Tesla = 32.5 N/meter = 0.2 lbs/inch-wire. If the sextupole coil is unsupported, these forces will produce a maximum radial deflection at the midplane of 0.0009". The higher multipoles will produce even smaller deflections. There also can be collective forces between the trim coil and the main coil. For a pure dipole field, and the trim coils considered, the only force which is not identically zero occurs in the case of a gap in the coil (at 22 degrees). For a five degree gap a tangential force of 0.31 lbs/inch is generated in the sextupole. The equivalent numbers for the octupole and decapole are 0.24 and 0.19. If the bore tube were confined only at one end, this could produce rotations of 30 degrees. In the actual case where the coil is keyed every 24 inches, the accumulated rotation is <0.1 degree. The sideways force on the keys will be 7 lbs.

III.5 Magnetic Coupling

If there are any common harmonics between the trim and main coils, there will be electromagnetic coupling between them. The extreme case is where the trim coil has the same harmonic contentas the main coil. For the coils considered in this note, there are two sources of this coupling. 1) The main dipole has a small sextupole component which couples to the sextupole trim coils. This is dominated by 2) Dipole components in the b2 and b4 coils generated by elliptical deformations. The most serious effect of this coupling is that a quench in the main coil induces a voltage on the trim windings For the coils considered this coupling coefficient has been calculated to be 0.045 volts/meter/(Tesla/sec) for a 1 mm deflection of the b2 coil. (the equivalent coefficient for b4 is 0.002). For dB/dt = 50 Tesla/sec and a length of 8 meters this gives 18 volts/sextupole coil. If the level I tolerances (0.25 mm) are achieved this becomes 4 volts/coil.

IV MISCELLANEOUS FIELD ERRORS

IV.1 Ends

To eliminate coil-to-coil crossovers and for compatibility with the flat coil manufacturing technique, the coils are wound in pairs. This means (see Figure 1) that a sextupole has only 3 separate coils, rather than the 6 one might expect. The ends of such coils produce a small addition to the fundamental and a skew harmonic at twice the angular frequency. From the dimensions of the coils it is trivial to calculate upper limits on the sizes of these terms. For a Cm (bm-1) coil these limits are:

$C_m <$ theta*R/L and $C_{2m} <$ theta*R/L *(Ro/R)^m

where theta = 2*pi/(3*m), R is coil radius, L is coil length and Ro is the 10 mm reference radius.

The Results are:

Sextupole (b2) L=8 meters

$C_3 < 0.14$ %

$C_6 < 0.03$ %

Octupole (b3) L=3 meters

$C_4 < 0.30$ %

$C_8 < 0.04$ %

Decapole (b4) L=5 meters

$C_5 < 0.14$ %

$C_{10} < 0.01$ %

The addition to the fundamental is the same as a small increase in effective length and is unimportant. The skew terms are all <0.1% and can be ignored.

IV.2 Octupole Locator Pins

The pins which locate the trim coil within the main coil must be at 90 and 270 degrees to match the main coil poles. For the octupole trim coil, these pins lie on the midplane of the windings. To allow for this the windings must follow the cutouts around these pins. (This is shown in Figure 2). Because octupole symmetry is maintaine for these cutouts, the only harmonics generated are octupole (b3) an 24-pole (b11). The cutouts are spaced 18" apart, giving a reduction in octupole strength of 2.6 % and a b11 of 0.04% of b3 (at 10 mm).

IV.3 Magnetization

The trim coil conductor itself will exhibt magnetization effect from the interaction of the main dipole field with the superconducto in the trim coils. The volume of superconductor in the trim coils i approximately 0.5% of that in the main coils. The filament size is approximately 120 microns compared with 5 microns for the main coil. Thus the effective magnetization strength is 12 % of that of the mai coil. The dominant effect will be a dipole term which will be indistinguishable from the larger dipole magnetization term produced in the main coil. Smaller amounts of the higher dipole allowed harmonics will be produced. These are the same harmonics which are produced by magnetization in the main coil and are factors of four or more smaller, and their effect upon the beam is further reduced by th ratio of their lengths to that of the main coil. Although these fiel contributions could be reduced by using a multifilamentary wire for the trim coils, the added technical difficulties of using such a wire are not warranted by the negligible improvement in the magnet as a whole. The magnitudes of these perturbations are given in table 4 below.

Table 4: Trim Coil Magnetization
(Prime units at injection)

Trim Coil \ harmonic (m-1)=	0	2	4	6	8
Sextupole	-0.59	+0.08	-0.03	0.00	0
Octupole	-0.59	+0.06	-0.01	-0.00	-0.00
Decapole	-0.60	+0.07	-0.02	+0.00	-0.00

It is also possible for the trim coil to induce magnetization images in the main coil. This effect has a magnitude of 10% of the trim coil strength and can be reduced to a negligible level by careful cycling of the trim coil.

IV.4 Current Tolerances

To achieve 1% field accuracy the current supplied to the coils must be controlled to 1% . At low field the excitation current will be approximately 200 mA requiring a least count of 2 mA or less. Neither of these requirements is difficult to achieve.

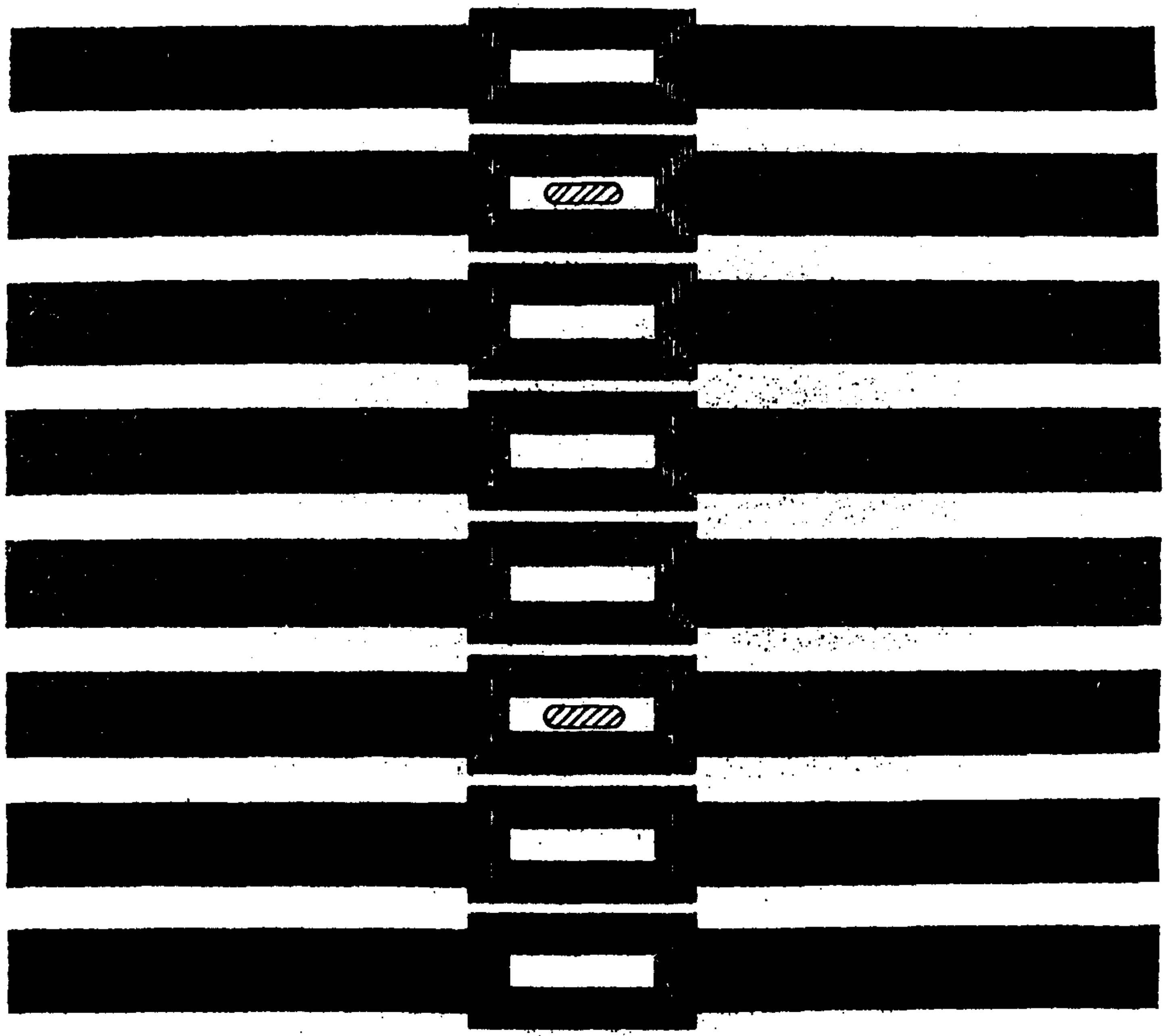
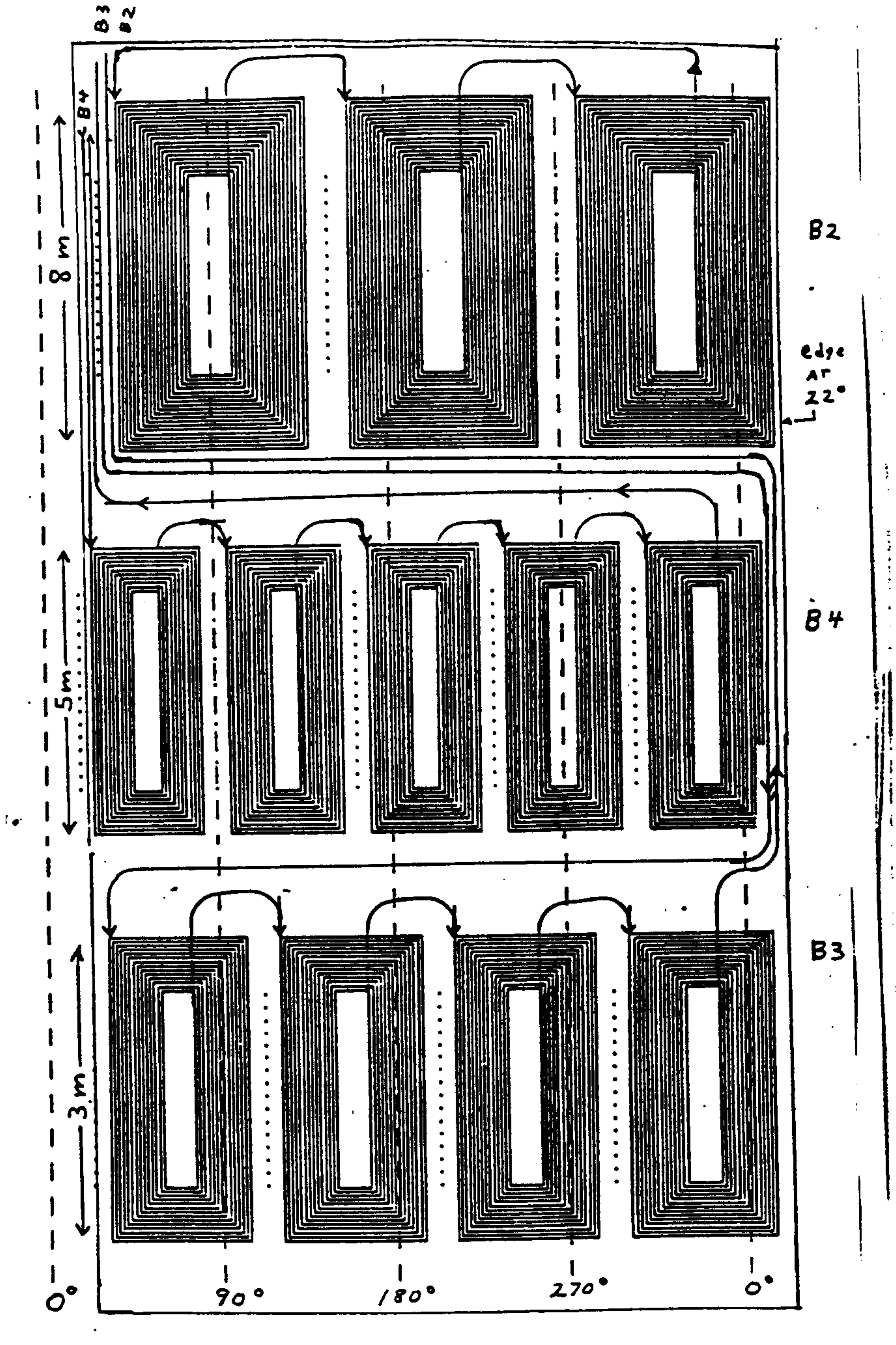


FIGURE 2: DETAIL OF OCTUPOLE CROSS SECTION SHOWING DETOURS AROUND 90/270 DEGREE POLE LOCATORS



B3
B2
B4
8 m
5m
3m
B2
edge at 22°
B4
B3
0°
90°
180°
270°
0°

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