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HARMONIC ANALYSIS OF TWO EXPERIMENTAL SUPERCONDUCTING ENERGY DOUBLER QUADRUPOLE MAGNETS

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October 19, 1977

INTRODUCTION

The transfer constant and harmonic content have been determined for two, three-shell superconducting quadrupoles; QA-2 and QA-3. The results presented here were obtained with a 1.194 in. radius "Morgan coil"[1] and integrator. Each 2n-pole component (n=1,2,3,4,5,6,9,10) was measured without an external iron yoke.

TRANSFER CONSTANT

The load line was determined by measuring the quadrupole gradient at 0.5kA intervals from 0.5kA to 5.0kA. The slope is the same for rising and falling currents to within 0.02% (statistical). The calculated transfer constants (with estimated absolute errors) of 5.13±.02kG/in./kA (QA-2) and 5.11±.02kG/in./kA (QA-3) are in good agreement with the design value[2] of 5.13kG/in./kA. The maximum gradient attained for a two minute cycle time was 26.4kG/in. at 4.2°K.

HARMONIC ANALYSIS

The two dimensional harmonic content of QA-2 and QA-3 is presented in Figs. 1 through 11. Each coefficient (C_n) represents the field due to the 2n-pole divided by the field due to the quadrupole, evaluated at a reference radius of one inch. An N(S)

denotes the normal (skew) component. The only harmonics "allowed" are n=2 (quadrupole), 6 (12-pole), 10 (20-pole), etc. The presence of any other terms is indicative of search coil misalignment or magnet construction errors.

I. Quadrupole-like Harmonics: n=6,10

These terms are expected to be present in the current three shell quadrupole design. The measured values of the normal 12- and 20-pole components do however differ from their design (two dimensional) values of $3.62\times10^{-4}/(\text{in.})^4$ and $-11.51\times10^{-4}/(\text{in.})^8$, respectively. The overall average shift in these values is the result of a missing parting plane shim which altered the angle subtended by the conductor bundle.

The 12-pole term illustrates a second effect of the missing shim. Without this shim, the azimuthal preload is insufficient to withstand the electromagnetic forces. The resultant azimuthal coil compression causes the 12-pole to vary with the excitation current. The calculated motion of -0.007 in. (over 16 conductors) in the inner shell is in reasonable agreement with the measured motion of -0.004 in. The balance of the difference between the actual and design strength can be accounted for by allowing the excitation coil arc lengths to vary by ±0.004 in.

The 20-pole harmonic, after the inclusion of the perturbations described above, is within $5\times10^{-5}/(\text{in.})^8$ of the design value.

In addition to the two dimensional harmonics, we have also measured the integrated 4-, 12- and 20-pole strengths. Even though these measurements are somewhat perturbed by a nonstandard buss configuration at the magnet end, a few conslusions can be

drawn: 1) the integrated quadrupole strength is within 0.4% of the desired value; 2) the 12- and 20-pole components of the magnet end have the correct magnitude and sign. A more detailed investigation of end effects will commence with QA-4.

II. Unwanted Harmonics: n=1,3,4,5,9

A. Dipole (n=1) and 18-pole (n=9).

The amplitude and phase of the dipole and 18-pole harmonics are consistent with a (calculated) search coil misalignment of -0.028 in. (+0.028 in.) horizontally and 0·008 in. (-0.017 in.) vertically in QA-2 (QA-3). These positional uncertainties arise from unknown differential motion when the search coil and its support structure are immersed in liquid helium.

B. Sextupole (n=3), Octupole (n=4), Decapole (n=5).

With the exception of the octupole, which is smaller than $2\times10^{-5}/(\text{in.})^2$ in QA-3, these harmonics are present in both magnets. It is these terms which are due to asymmetric construction/assembly errors in the individual coil octants. The number of possible perturbation terms prohibits an unambiguous determination of the origin of these harmonics. There is, however, a simple model which accounts for the observed amplitudes and phases.

Figure 12 is a simplified cross section of a typical conductor shell comprised of eight current blocks. When the quadrupole is assembled, the external stainless steel clamping collars, with their integral keys, effec-

tively limit the total angle subtended by the two coil halves which straddle a parting plane; e.g., $\theta_0+\theta_1$ is close to the design value. Even though this can still lead to n=3,4 and 5 harmonics, the data are grossly inconsistent with this form of asymmetry. The lack of a mechanical constraint at the parting plane does allow $\gamma_n \neq \gamma_{n+1}$, n=0,2,4,6. This is believed to be the case for QA-2 and QA-3. In order to estimate the errors, δ_i, in γ_i we have ignored the relatively small contribution of the outer shell and treated the two inner shells as though they were rigidly attached to one another at the parting plane. The eight unknown perturbations are then determined from the sextupole, octupole and decapole data, subject to the constraint that no quadrupole-like harmonics are introduced. The results of this calculation are given in Table I where a positive entry represents an increase in the magnitude of γ_n. The largest motion involved is less than 0.008 in., the average magnitude being 0.0025 in.

REFERENCES

1. G.H.Morgan, Stationary Coil for Measuring the Harmonics in Pulsed Transport Magnets, Proceedings of the Fourth International Conference on Magnet Technology, Brookhaven, p. 787 (1972).

2. S.C.Snowdon, private communication.

TABLE I

CALCULATED PERTURBATION ANGLES FOR N=3,4 AND 5

OCTANT NUMBER	δ (mrad) QA-2	QA -5
0	0.38	3.65
1	0.54	-0.99
2	2.13	-0.07
3	-0.30	-0.41
4	-2.25	-3.65
5	1.34	0.99
6	-0.26	0.07
7	-1.58	0.41

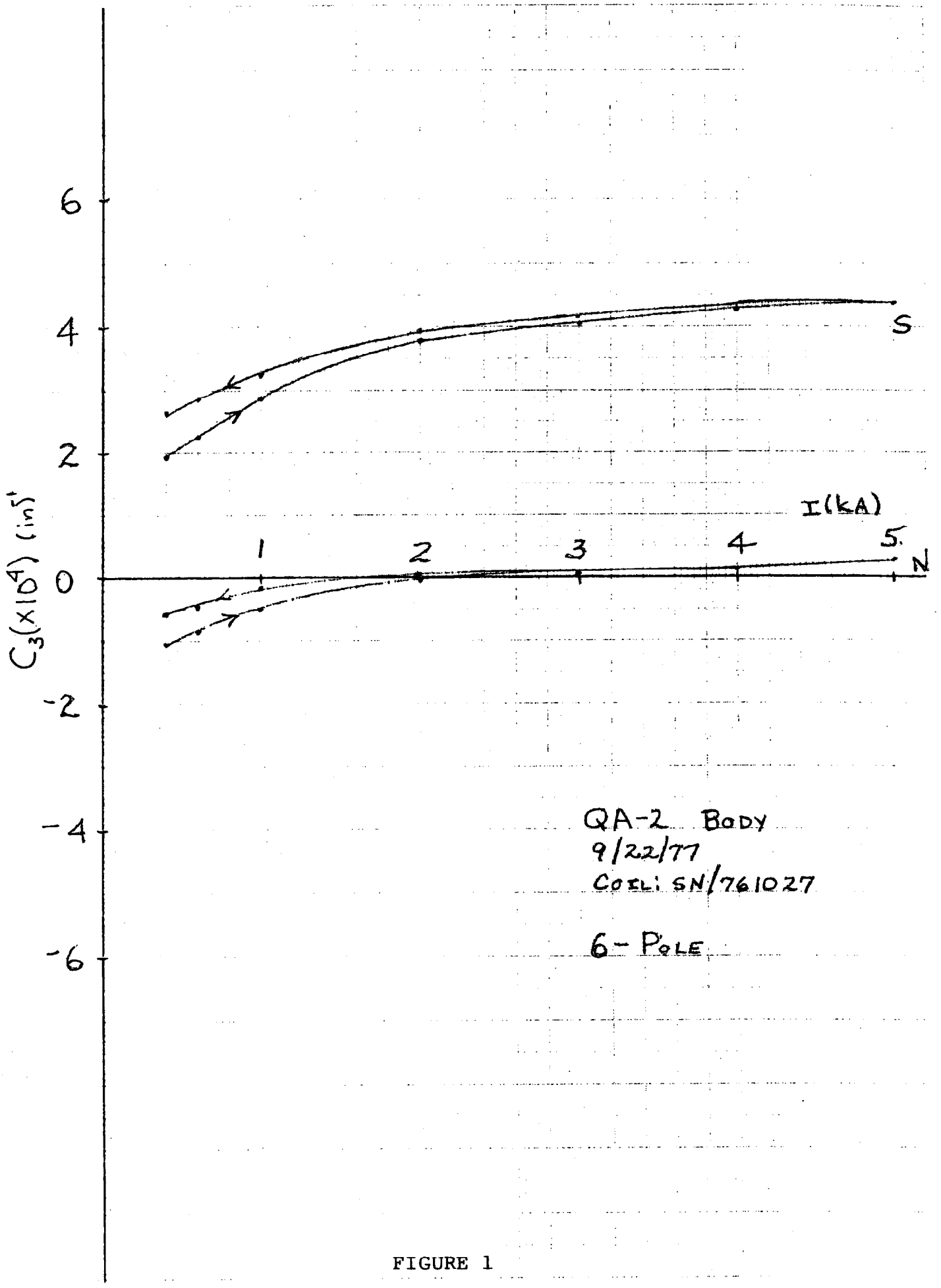
6
4
2
0
-2
-4
-6
$C_3(\times 10^4)$ (in^5)
I(kA)
1
2
3
4
5
S
N
QA-2 BODY
9/22/77
COIL: SN/761027
6-POLE

FIGURE 1

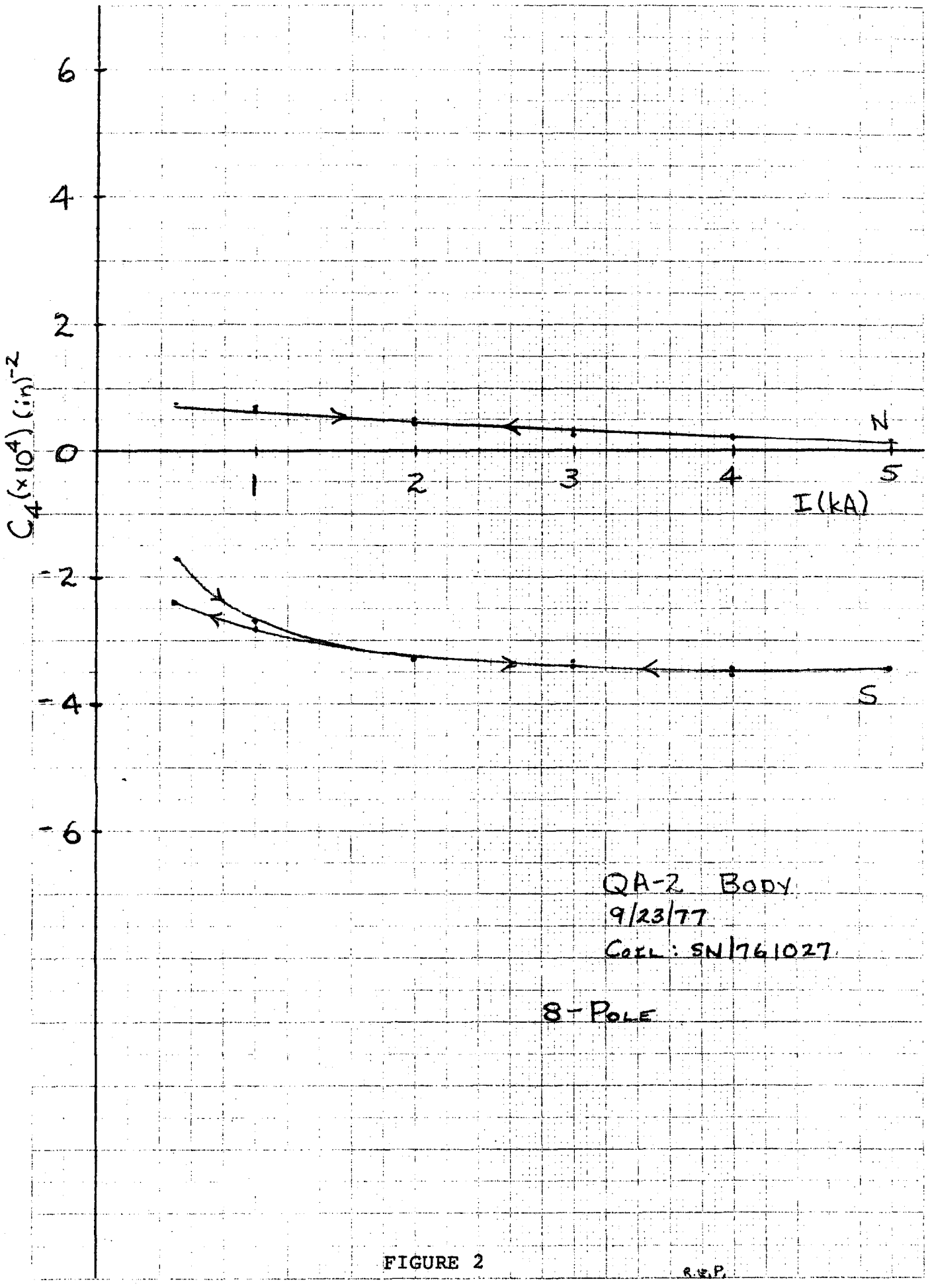
6
4
2
0
-2
-4
-6
$C_4 (\times 10^4)\ (in)^{-2}$
1
2
3
4
5
I(kA)
N
S
QA-2 BODY
9/23/77
COIL: SN/761027
8-POLE

FIGURE 2

R.E.P.

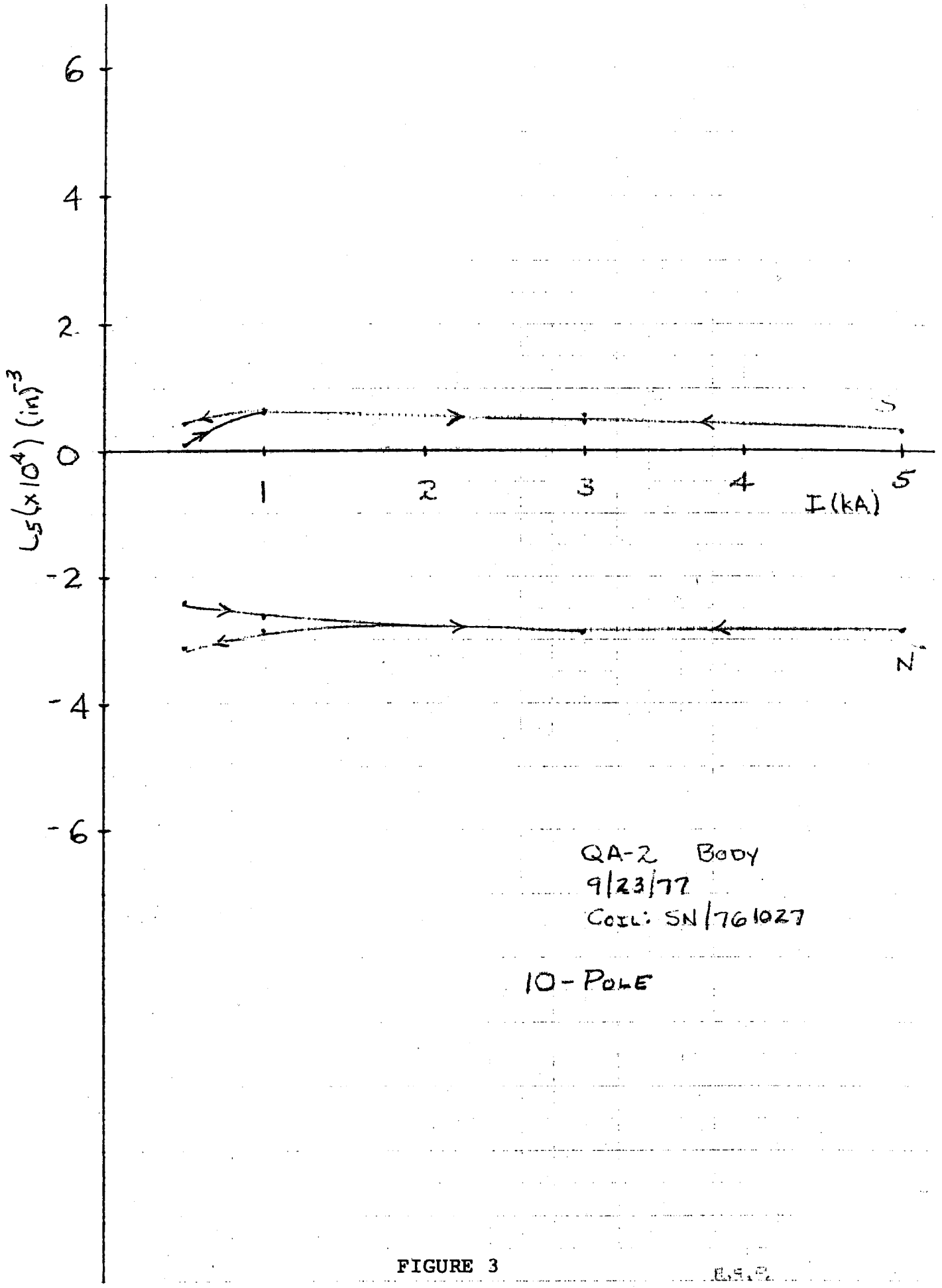
6
4
2
0
-2
-4
-6
$L_5 (\times 10^4)$ $(in)^{-3}$
1
2
3
4
5
I (kA)
S
N
QA-2 Body
9/23/77
Coil: SN/761027
10-Pole

FIGURE 3

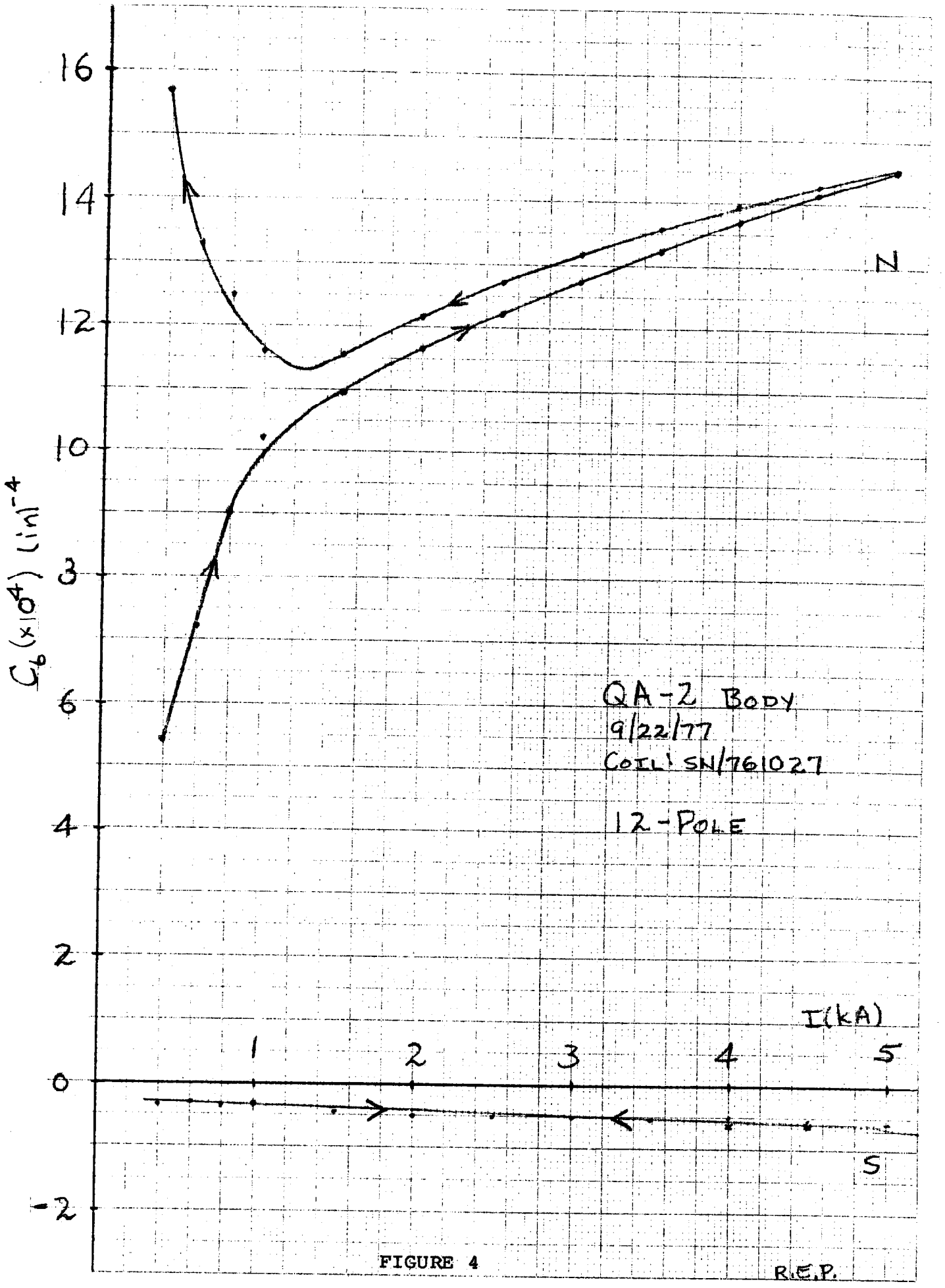
16
14
12
10
3
6
4
2
0
-2
C_6 ($\times 10^4$) $(in)^{-4}$
N
QA-2 BODY
9/22/77
COIL SN/761027
12-POLE
I(kA)
1
2
3
4
5
S

FIGURE 4

R.E.P.

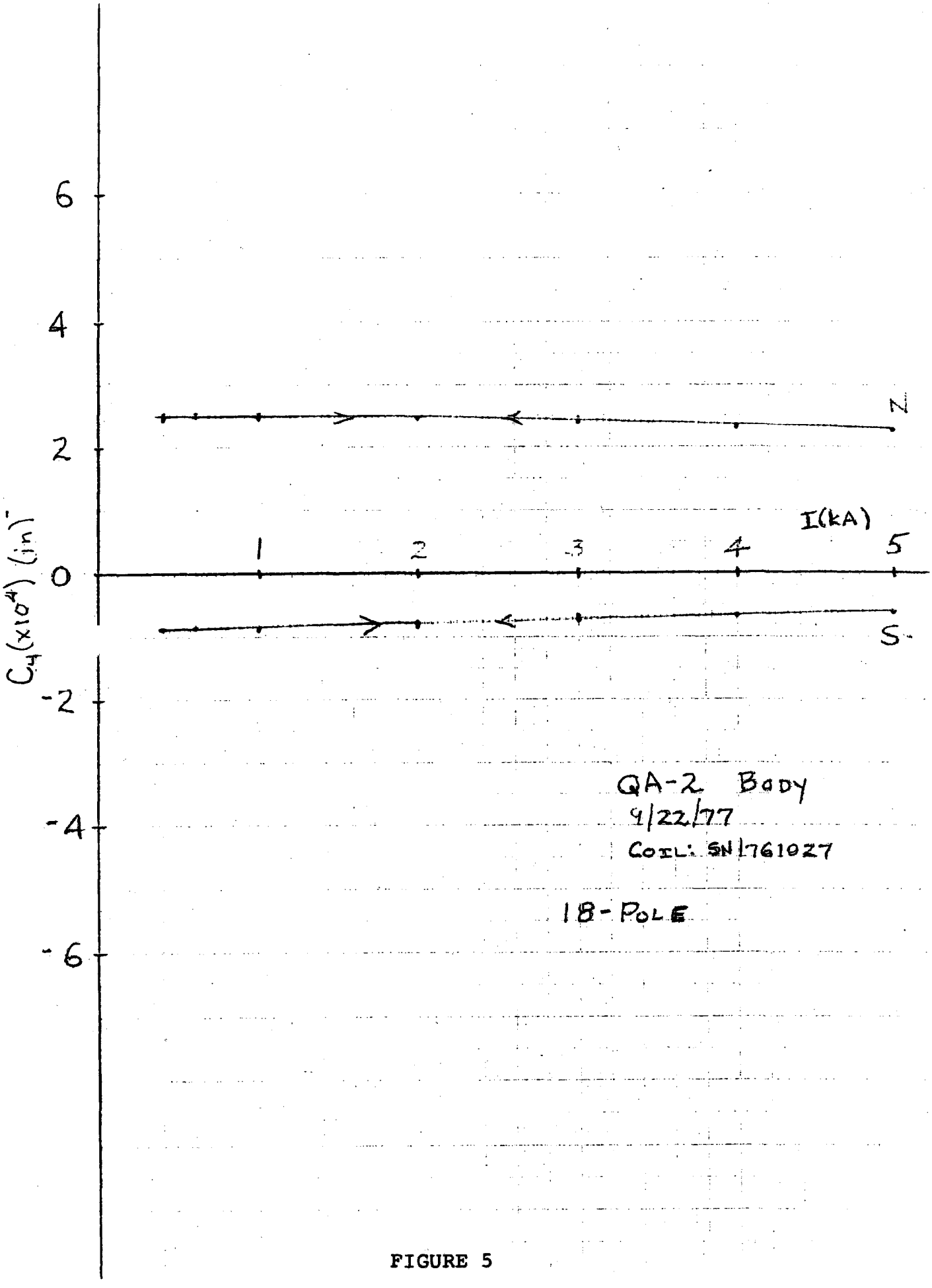
6
4
2
0
-2
-4
-6
$C_4 (\times 10^4)$ (in)$^{-1}$
N
S
I(kA)
1
2
3
4
5
QA-2 Body
4/22/77
Coil: SN 761027
18-Pole

FIGURE 5

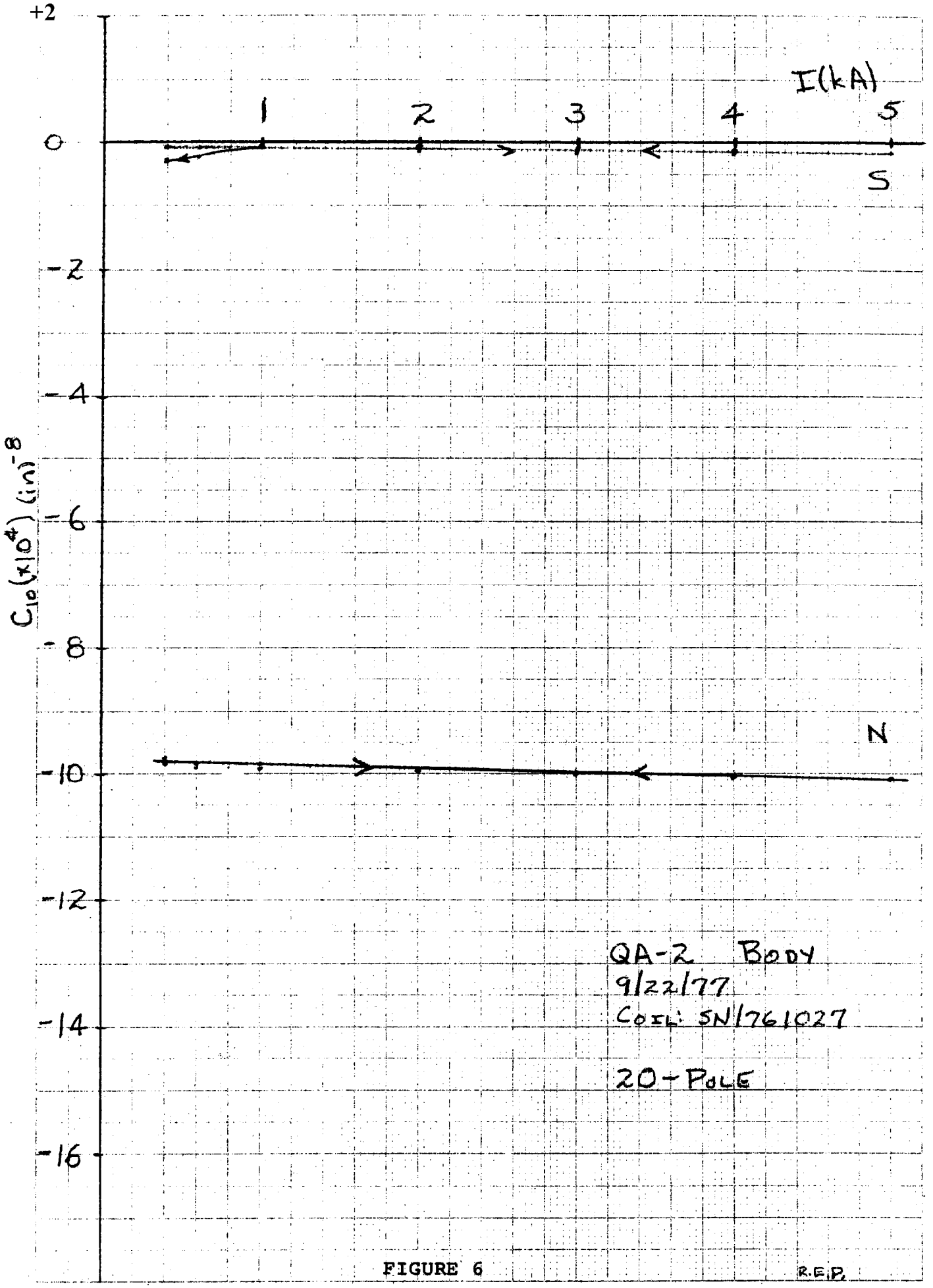
+2
0
-2
-4
-6
-8
-10
-12
-14
-16
$C_{10}(\times 10^4)\ (in)^{-8}$
I(kA)
1
2
3
4
5
S
N
QA-2 BODY
9/22/77
COIL: SN/761027
20-POLE

FIGURE 6

R.E.P.

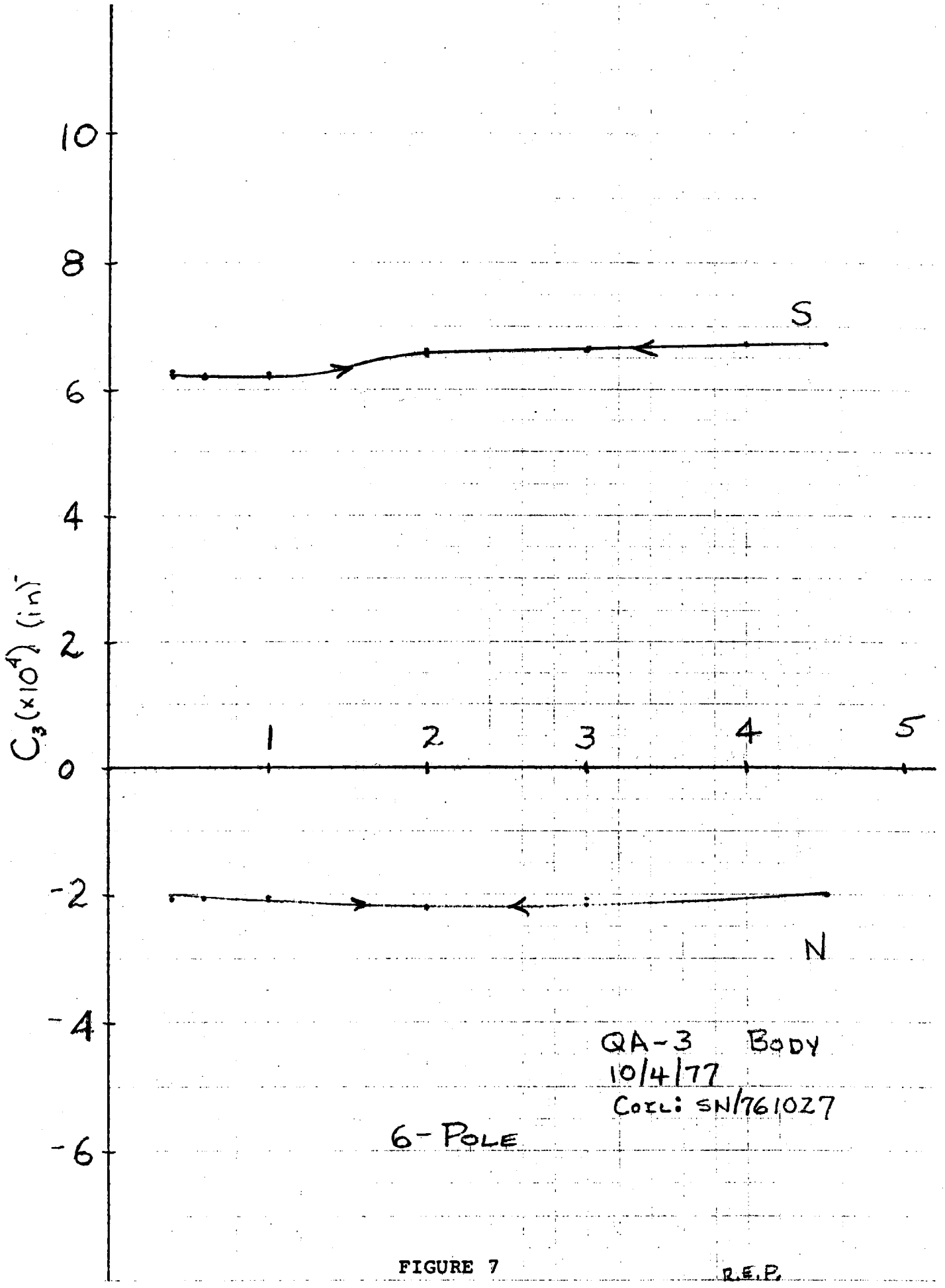
10
8
6
4
2
0
-2
-4
-6
$C_3 (\times 10^4)$ (in)$^{-1}$
1
2
3
4
5
S
N
QA-3 BODY
10/4/77
COIL: SN/761027
6-POLE

FIGURE 7

R.E.P.

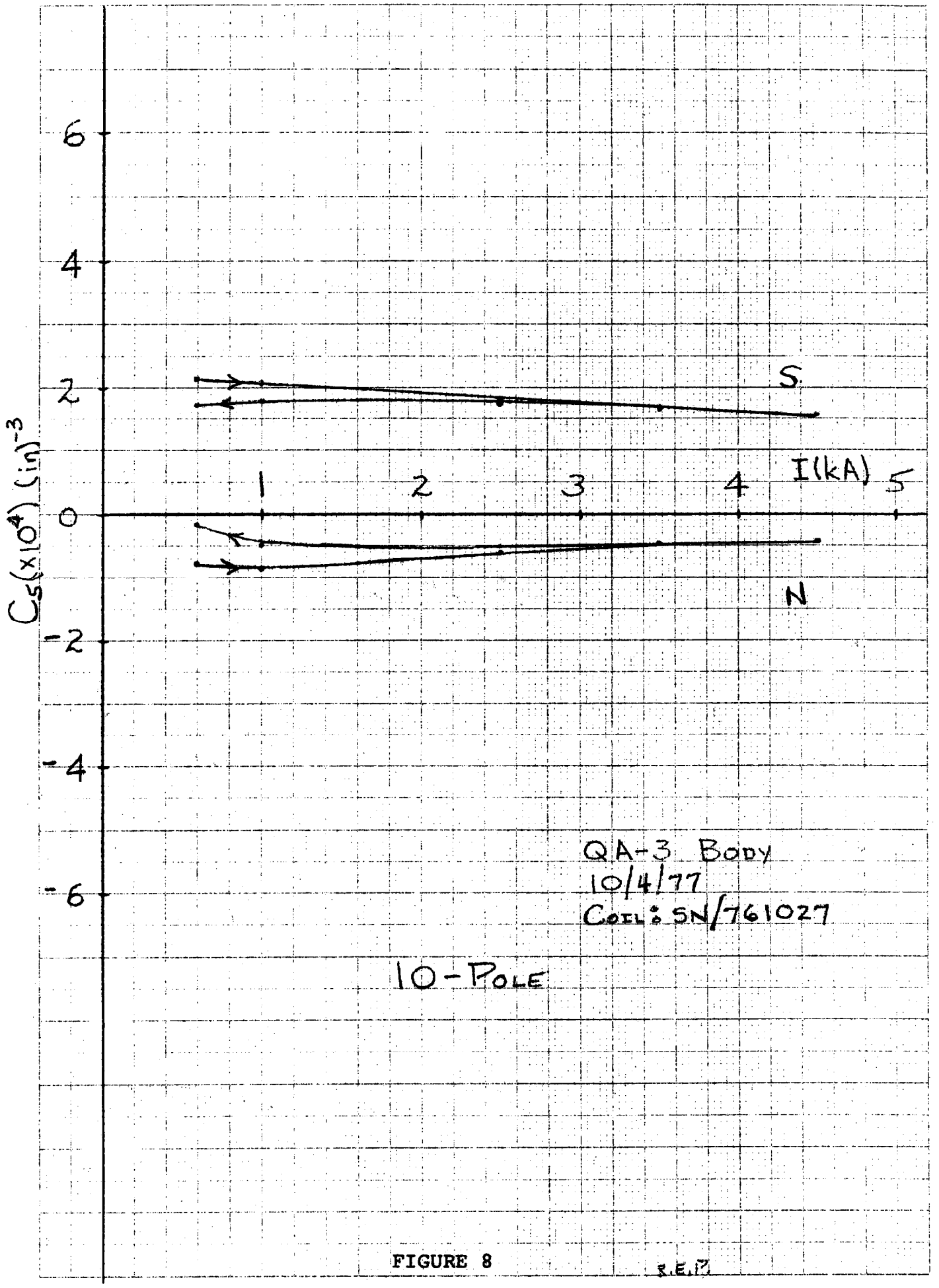
6
4
2
0
-2
-4
-6
$C_5(\times 10^4)\ (in)^{-3}$
1
2
3
4
5
I(kA)
S
N
QA-3 Body
10/4/77
Coil: SN/761027
10-Pole

FIGURE 8

R.E.P.

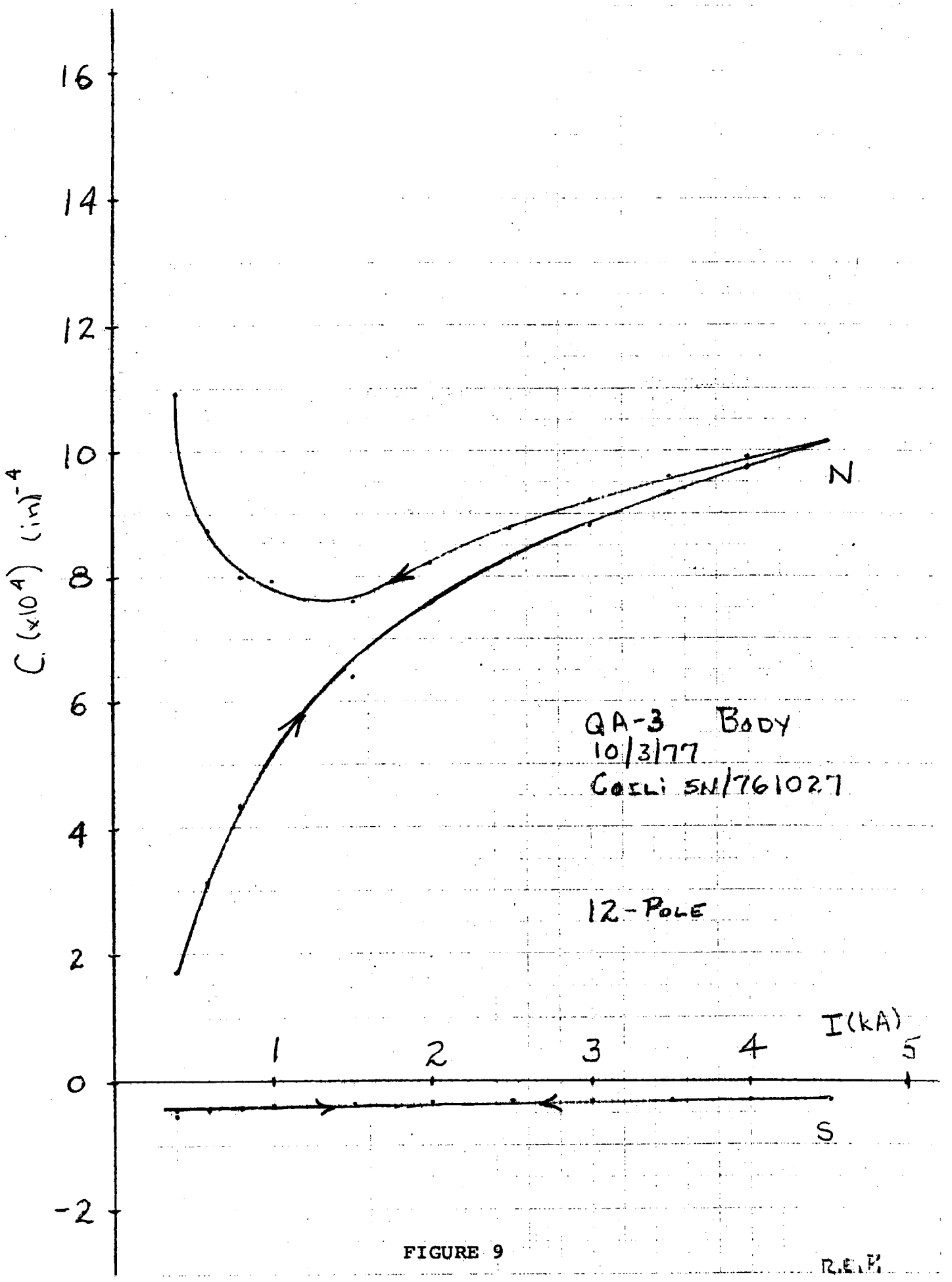
16
14
12
10
8
6
4
2
0
-2
C (×10^4) (in)^-4
N
S
QA-3 BODY
10/3/77
COILI SN/761027
12-POLE
I(kA)
1
2
3
4
5

FIGURE 9

R.E.K.

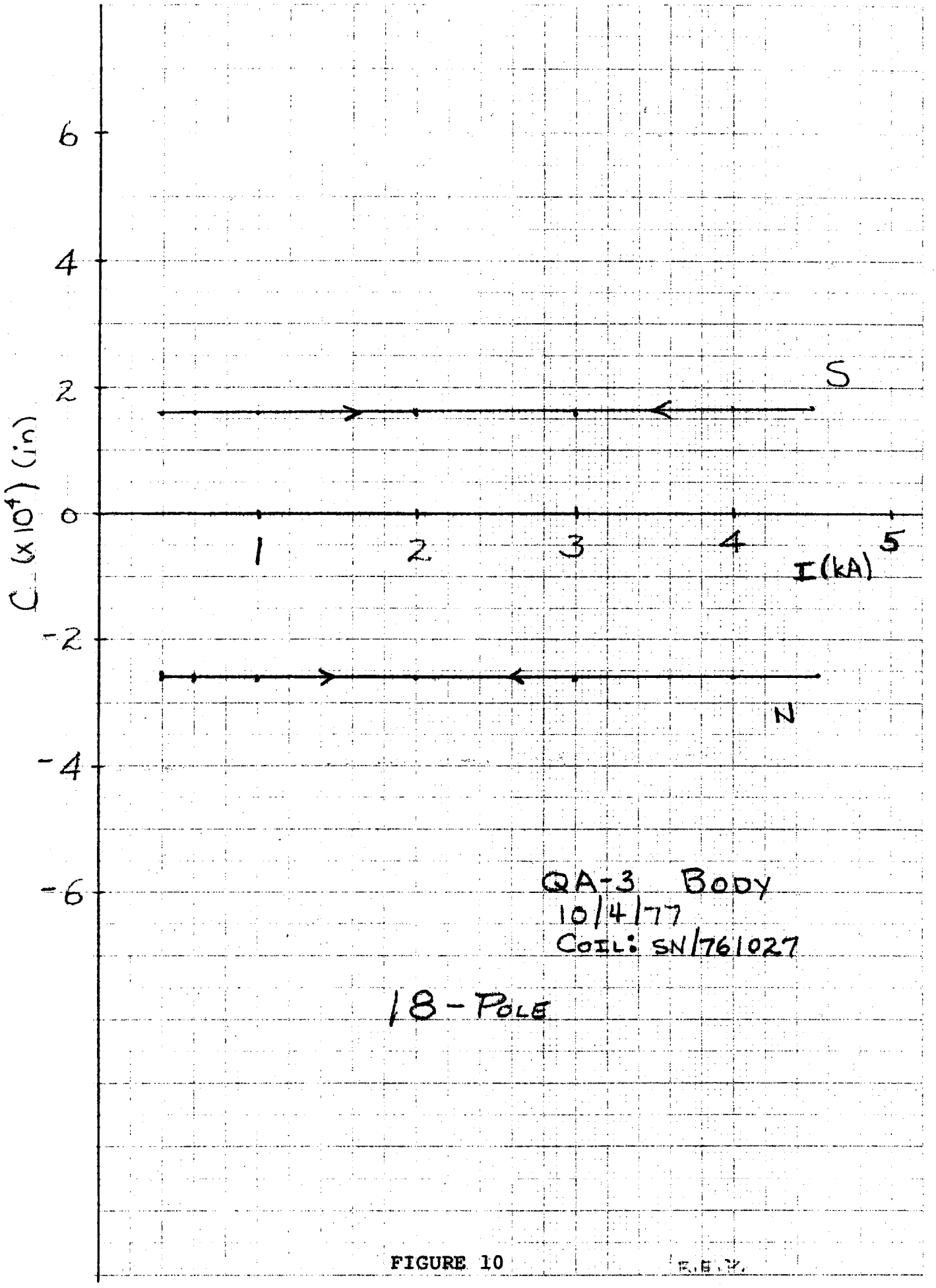
6
4
2
0
-2
-4
-6
C (x10⁴) (in)
1
2
3
4
5
I(kA)
S
N
QA-3 BODY
10/4/77
COIL: SN/761027
18-POLE

FIGURE 10

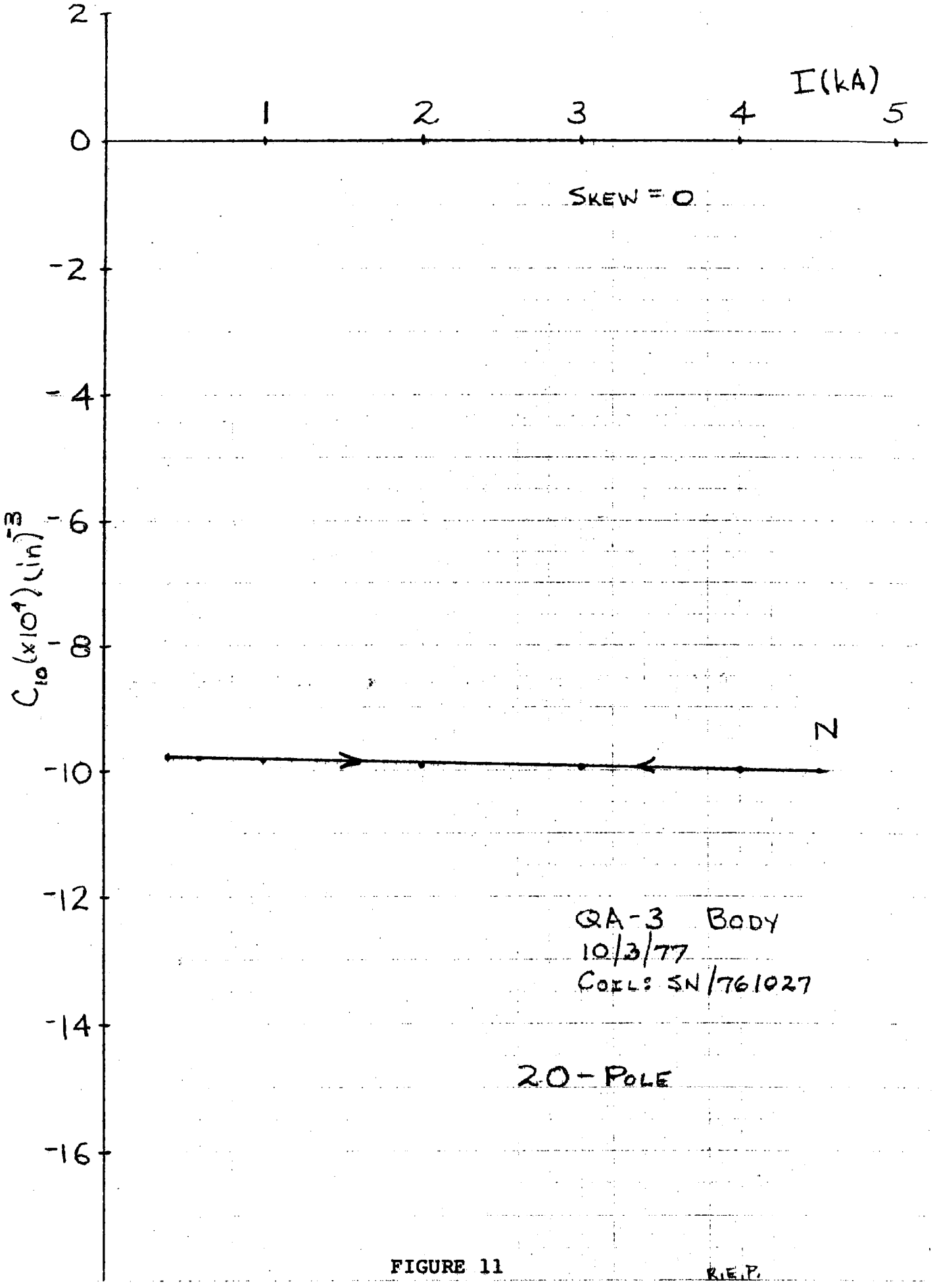

FIGURE 11

R.E.P.

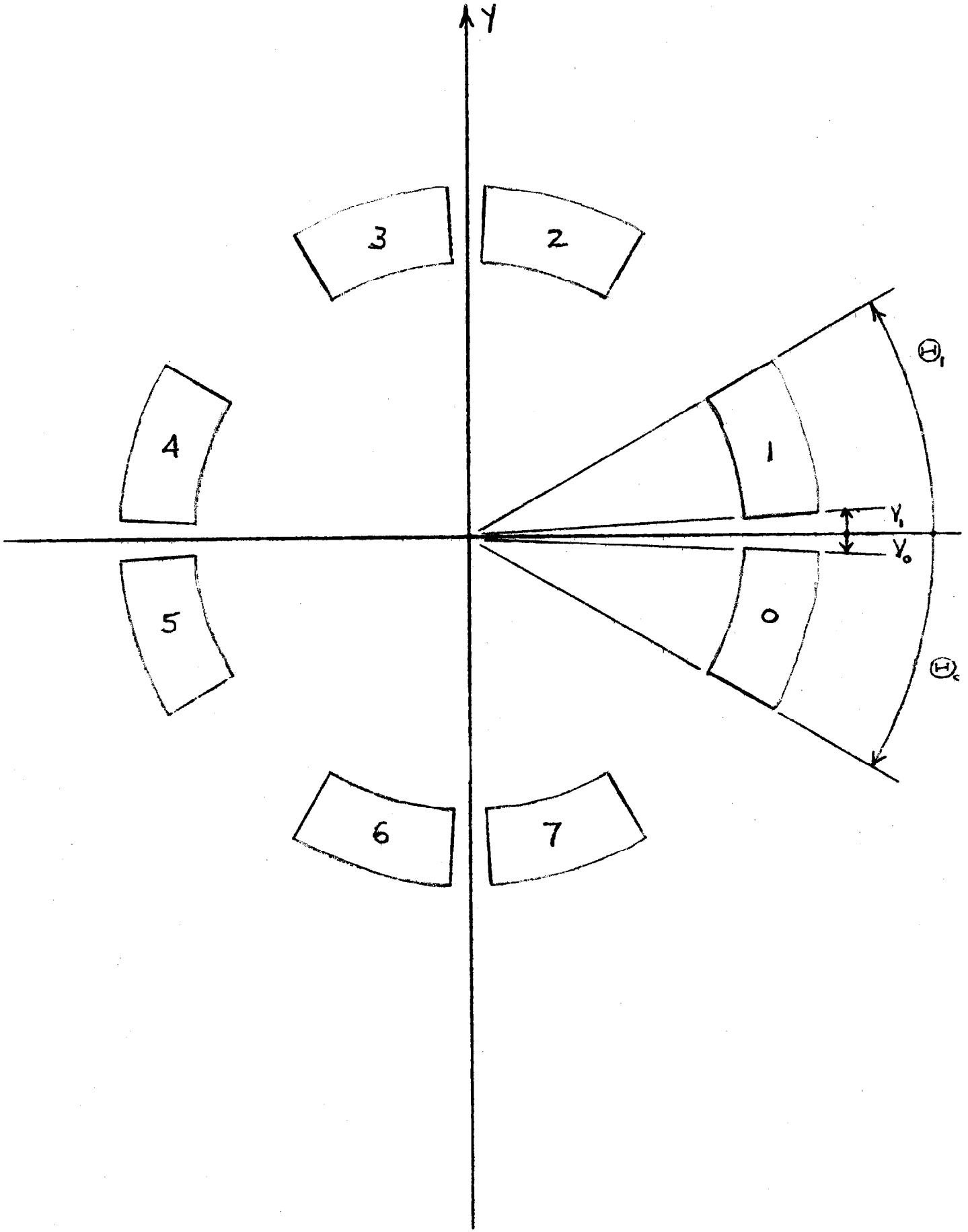

FIGURE 12