Fermilab

UPC 136

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Forces and Distortions

in the Collared Coil

Section 5 - The Amateur Magnet Builder's Handbook

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*Sections without UPC Nos. are in UPC No. 86.

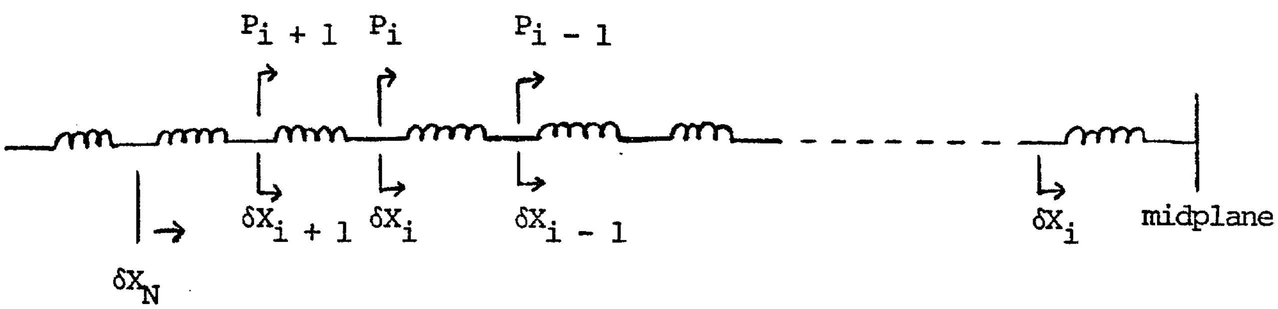
5.1 Azimuthal Coil Deflection

The magnetic forces on the individual strands of cable in the magnet winding are rather large. Forces and fields at various points in the winding of the magnet are shown in Fig. 5.1.1. These forces are taken from calculations that have been made by Stan Snowdon. They are shown resolved into radial components and azimuthal components and as a function of wire number. One can see in this figure that the radial forces on the outer coil are rather small. However, it should be remembered that the radial forces in the inner coil must be transmitted through the outer one to the collars in the central region of the magnet. What we are concerned with here is the azimuthal force. These forces tend to cause a compaction of the coil when the magnet is excited.

Consider for a moment a coil that is restrained in the radial direction but has no azimuthal constraint. Then as the magnet is excited, the topmost conductor on the inner coil experiences a force of almost 120 lbs. per inch of length toward the median plane of the magnet. This force causes a compaction of the coil and hence an azimuthal motion of the conductor. Suppose now that we compress the inner coil so that the mechanical forces on it are greater than the magnetic forces. Under these conditions there will be no motion of the wire next to the key and by symmetry, there will also be no motion of the midplane. Consequently, the only conductor that can move in an azimuthal direction will be conductors around 45°. As the coil is excited, pressure on the median plane is increased, and the pressure on the key is decreased. We will now construct a model of the coil that will allow us to get approximately the motions of the wire under these conditions.

We see from Fig. 5.1.1 that the azimuthal forces are almost linearly proportional to the conductor number. Furthermore, we have made extensive measurements on the coil package and know its elastic properties. Measurements made by Karl Koepke and John Saarivirta are shown in Fig. 5.1.2. Measurements are shown both with the coil at room temperature and cooled to liquid nitrogen temperature. As the coil cools, it shrinks and the Youngs modulus increases. We will come back to this point later.

A model of the coil is shown below:



The coil is a series of springs between conductors with a force applied at each spring junction. The strength of the springs, k, is taken from the measurements in Fig. 5.1.2, and the force on the individual conductors is taken from linearizing the forces shown in Fig. 5.1.1. The conductor number is designated by i and runs from 1 to N. The boundary conditions on the problem are that we want zero displacement at i = 0 and i = N + 1, the midplane and the key, respectively. Balancing forces, we can write the difference equation as shown:

$$
\begin{aligned}
&+ k(\delta X_{i+1} - \delta X_i) - k(\delta X_i - \delta X_{i-1}) = - P_i = - \alpha i \\
&\delta X_{i+1} - 2\delta X_i + \delta X_{i-1} = - \frac{\alpha}{k} i
\end{aligned}
\qquad (5.1.1)
$$

The proportionality constant between conductor number and force is designated by α. The solution of this difference equation is a simple cubic. In addition, there are two particular solutions that enable us to fit the boundary conditions. Combining these equations with the boundary condition, we get the solution for the problem:

$$\delta X_i = \frac{\alpha}{6k}\, i \left[(N + 1)^2 - i^2 \right] \tag{5.1.2}$$

This equation represents the motion of the individual conductors away from the equilibrium position as the magnet is excited. A plot of this equation is shown in Fig. 5.1.3 for the inner and outer coils. It is seen that the maximum wire motion occurs about half way through the coil and for the inner coil, is about 3 mils and for the outer coil, is about 0.6 mil.

The peak deflection occurs at conductor number given by the following equation:

$$i = \frac{N + 1}{\sqrt{3}}\; ; \; \delta X_m = \frac{\alpha}{6k} (N + 1)^3 \; \frac{2}{3\sqrt{3}} = \frac{\alpha (N + 1)^3}{9\sqrt{3k}}$$

For the inner, this gives conductor number 21 away from the median plane and for the outer coil, it gives conductor number 13.

If we insert the constants α and k, we can calculate the maximum deflection, and the forces at the two ends of the coil. In this model, since we have set the deflection at the key equal to zero, the equation will yield a tension. In order to deep the actual physical coil clamped, we must have a precompression on the coil that exceeds this tension. The tension at the key is given by:

$$F = k\, \delta X_N = k \frac{\alpha}{6k} N \left[(N + 1)^2 - N^2 \right] = \frac{\alpha}{6} N (2N + 1) \approx \frac{\alpha N^2}{3} \tag{5.1.4}$$

The Youngs modulus is about 7×10^5 lbs. per square inch (see Fig. 5.1.2). Since the wire has a width of .315 in. and the average spacing is .062 in., we can caluclate the spring constant $k \approx 3.5 \times 10^6$. From Fig. 5.1.1 we obtain a value of α equal to about 3.5 lbs. per inch per conductor for both the inner and outer coil. Inserting these numbers in Eq. 5.1.4, we calculate the necessary preload and maximum deflection of the inner and outer coil as given below:

$$\text{Preload} = \frac{\alpha}{6} N\ (2N + 1) \qquad \begin{array}{l} \text{Inner} = 1{,}450 \text{ lb./in.} \\ \text{Outer} = \quad 527 \text{ lb./in.} \end{array} \tag{5.1.5}$$

Note that the preload necessary is independent of the spring constant k and is only a function of the force on the conductor due to the magnetic field, as it should be.

The perturbation to the magnetic field caused by the conductor motion that we have calculated is shown in Table 1.5.5, and the perturbation has been normalized to a peak motion of the wire equal to 10 mils. The displacement, of course, would be proportional to B^2.

5.2 Clamping the Coil

We come now to the central difficulty of collaring a superconducting coil. We have calculated the forces that are necessary in order to restrict the motion at the end of the coil. However, an unpleasant fact now must be coped with and that is that the coil shrinks more than the collars when it is cooled. The coil, therefore, must be molded considerably bigger than the space in the collars, and the collars must be applied with a correspondingly large pressure. The situation is illustrated in Fig. 5.2.1. This measurement is called a split-collar measurement. A 1 in. section was cut out of a finished magnet. Then the collar was carefully measured and then split on one side at the midplane with a saw cut. The force necessary to close this gap back to the original collar size gives the preload. This technique has two advantages:

1. It directly measures the preload in the collared coil. (The mechanical stiffness at the collar is almost negligible, and so the displacement-force curve gives the total elastic constant at the coil package.
2. It gives a direct measurement of the relative size of the coil to the collar when measurements are made at reduced temperature and hence the preload necessary at room temperature to produce the required preload at low temperature. This is a very difficult measurement to make by any other means.

As a collared coil is cooled, the pressure in it decreases and yet must remain above the minimum force as dictated by the magnetic pressure as calculated above. This forces a design constraint upon the coil matrix. A solution does not have to exist. The necessary room temperature forces may take the coil out of its elastic range and crush the matrix. The cooldown path is shown as a line of arrows in Fig. 5.2.1. The room temperature force of 4,000 lbs./inch in this case would load to a total force of about 1,400 lbs./inch when cold. This is less than given by Eq. 5.1.5 for the total force necessary to clamp the coil. A force at room temperature of > 5,000 lbs./inch has been found to clamp the coil.

We now consider how this necessary preload is obtained. It is to be emphasized at this point that the accuracy of the final coil package is determined by the collars. The coil itself is molded oversize and compressed into the collars by means of large presses. However, we must consider the accuracy of the molding process for the coil and must be sure that even at the minimum fluctuations in its size that the pressures will be large enough so that the coil remains clamped. In the case of the Fermilab coils, each coil is measured by means of a special gauge that applies a high pressure locally to the coil and measures its circumferential size. Ten measurements are averaged for each side of each of the four coils. The size of the coil is controlled by means of shims at the time the coil is molded. The amount the coils are oversize has been determined so that when the coil is cold and collared, it will still have the necessary preload on it.

A monitor of this preload is furnished by observing the force applied to the coil during the collaring operation. The total force of the press is equal to the sum of the preload necessary on the inner and outer coil plus the safety factor. A typical collaring curve is shown in Fig. 5.2.2. The amount that the collars are open is determined by the gaps between scribe marks on some specially selected hardpacks. Before the coil is collared, these hardpacks are assembled, and a fine mark scribed across the interlaced fingers. When these hardpacks are placed around the coil, the gaps between the adjacent scribe marks show how far the collars are from being in the closed position. In general it takes about 10,000 lbs. per linear inch of coil to close the collars. This is equivalent to 5,000 lbs. per linear inch on each side of the magnet and should be compared with about a total of 1,977 lbs. per inch which is the sum of the necessary magnetic preload on the inner and outer coils per inch as given in Eq. 5.1.5.

Early in the program a great deal of difficulty was experienced in getting adequate preload applied to the coil conductor. In order to study the motion of the wires as the magnet was excited, an instrument called a sissometer was invented which measures the relative deflection between the 32nd conductor on the top coil and the 32nd conductor on the bottom coil. The problem was first observed in the 1 ft. magnet series and was not solved until E22-52. Figs. 5.2.3 and 5.2.4 show curves from this early series of magnets. The first curve is for Magnet E22-33. The sissometer measurements on this magnet are shown at the bottom of the curve. The vertical axis shows the compaction of the whole coil in mils and hence half this number would correspond to the motion of the conductor away from the key. Two effects are seen in this curve, the first is that there is a large motion in the conductor as the magnet is excited, and second that there is a considerable amount of hysteresis displayed. If the coil is changing its configuration with current, it follows that the multipole moments should also change. The top of the figure shows the change of b_2 and b_4 with field. (The hysteresis displayed in b_2 is partly due to the persistant currents.) The upward slope of the curve for b_2 corresponds to the inner coil becoming more compact. This is also verified by the shape of the curve for b_4. As the inner coil becomes more compact, b_4 becomes more negative. The motion of the coil does not correspond to a uniform compaction, however, it is possible to verify the signs for these two effects by looking at Table 1.5.6 which shows the variation of b_2 and b_4 with key angle.

Fig. 5.2.4 shows the typical sissometer curve for a later magnet. It is noticed that in this case the motion is completely elastic, and no hysteresis is present. The instrument used, the sissometer, responds also to other distortions in the collar as the magnet is excited. The amount of this correction is shown in the dotted curve and should be subtracted from the top curve. The fact that there is any motion at all is because the motion shown is not at the end of the winding but rather three conductors in from the key. In addition to this, the model is a little bit idealized in that in a real magnet there is over 30 mils of compressed Kapton at the key for electrical insulation. Thus the motion that is calculated is not exactly correct but is linearly superimposed upon a small motion at the end of the winding due to the weaker end spring.

We no longer make sissometer measurements on all of the magnets. These tests were run in the vertical dewar. However, there is no reason to believe that Magnet 256 is any different than the average clamped magnet that was studied in the vertical dewar tests. Fig. 5.2.5 shows the histogram of the motion observed in the 22 ft. magnets that were run through the standard vertical dewar test routine.

Fig. 5.2.6 shows the typical variation of sextupole and decapole moments with field that is observed in our present series of magnets. The vertical scale for these coefficients is the same as Fig. 5.2.3 and does not correspond to the standard units that we use in that they are expressed in the centimeter system.

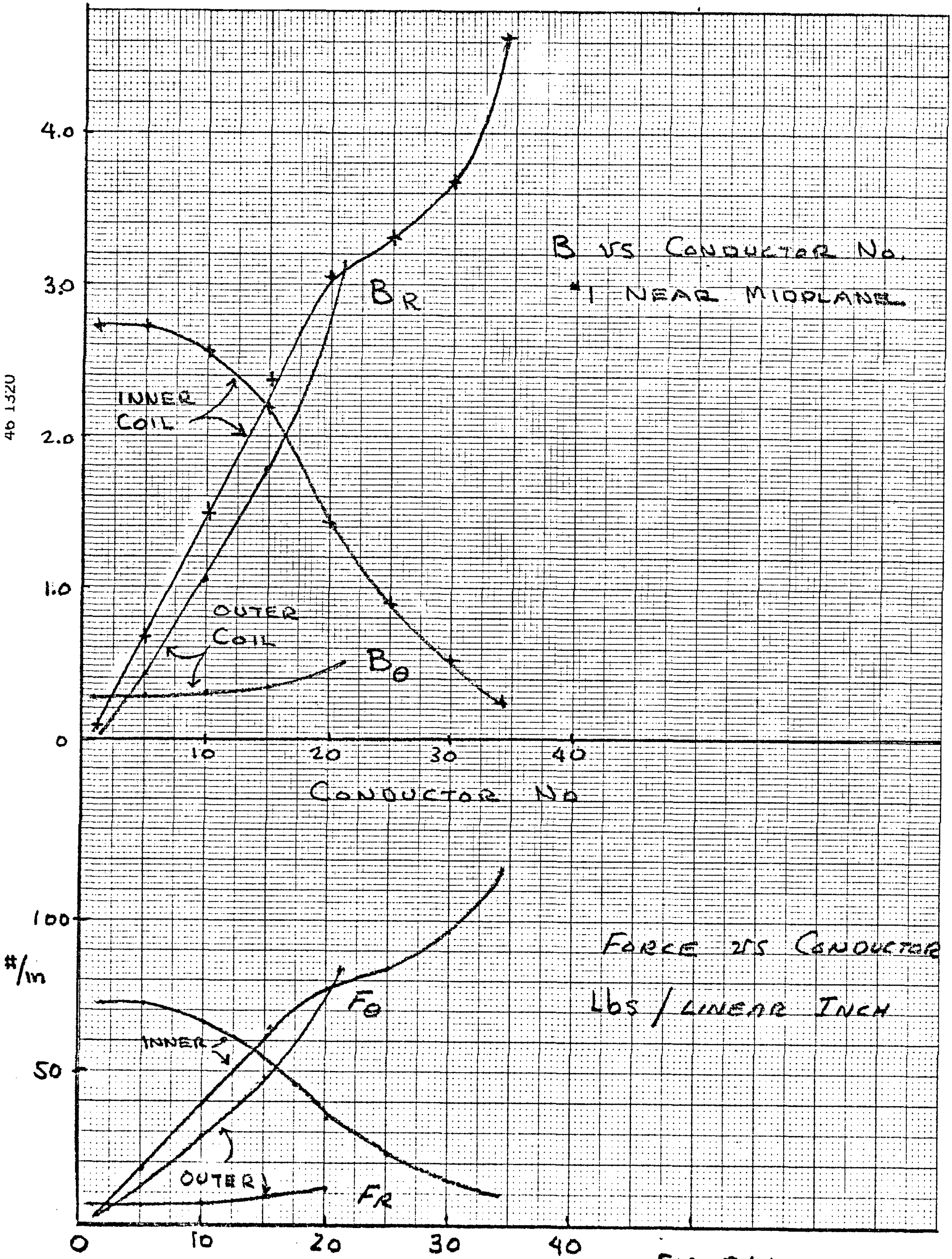
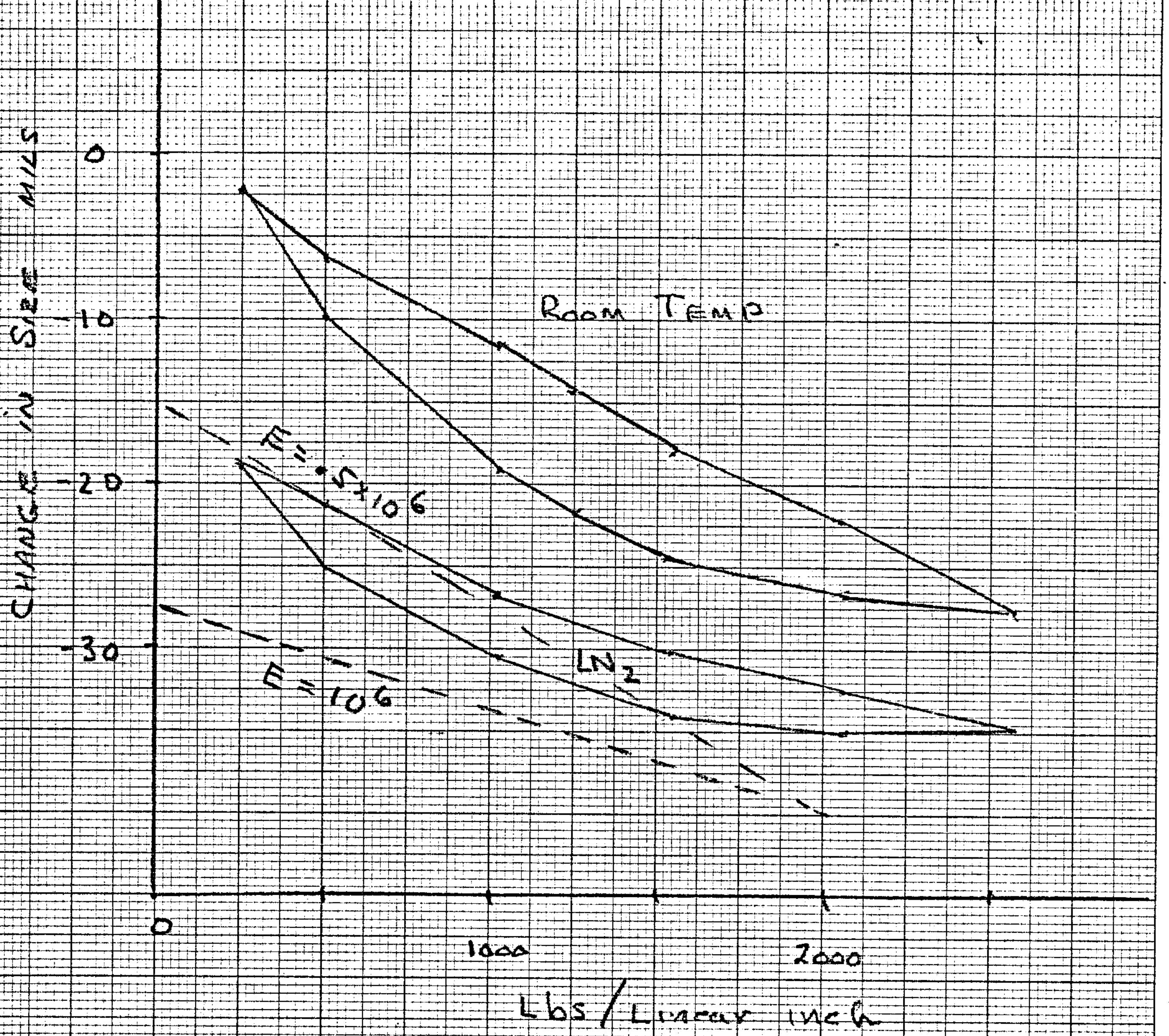

B VS CONDUCTOR NO.
#1 NEAR MIDPLANE
B_R
B_θ
INNER COIL
OUTER COIL
4.0
3.0
2.0
1.0
0
10
20
30
40
CONDUCTOR NO
FORCE VS CONDUCTOR
LBS / LINEAR INCH
#/in
100
50
F_θ
F_R
INNER
OUTER
0
10
20
30
40

FIG 5.1.1

SIZE VS FORCE FOR
31 CONDUCTORS

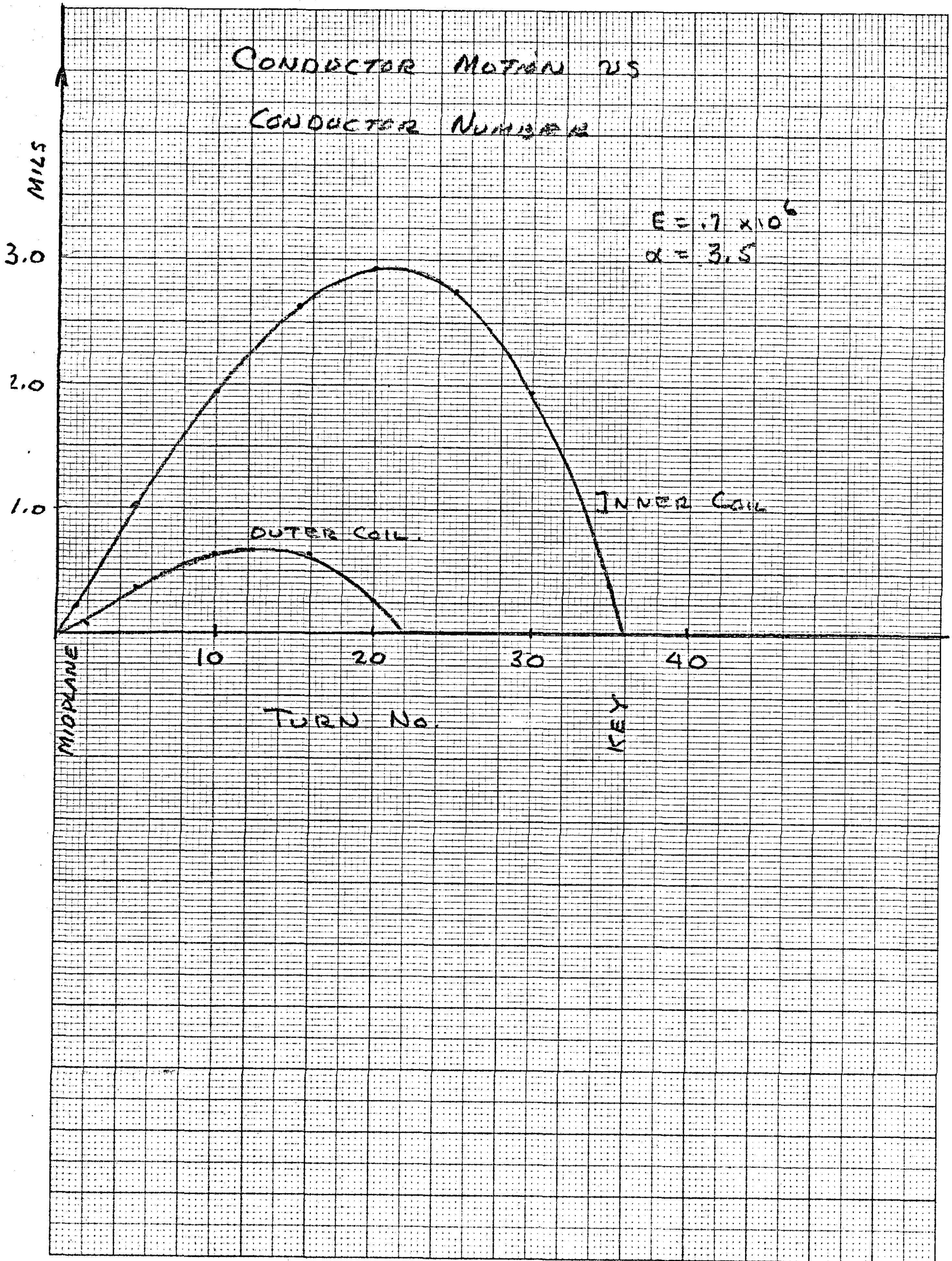


31 CONDUCTORS

MYLAR (.001", 7/12 LAP, .004" SHIM)

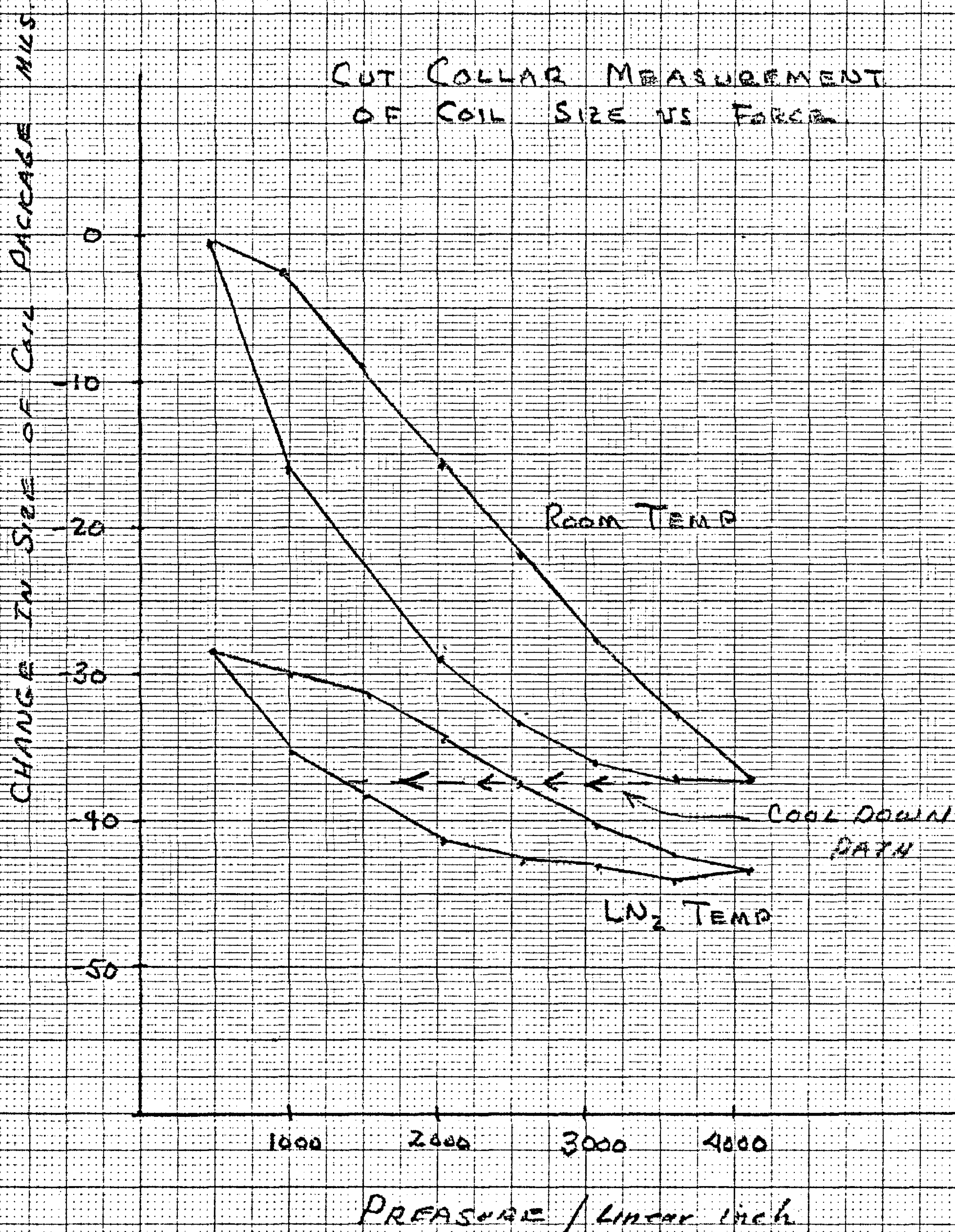
GLASS EPOXY
9/16/77
K KOEPKE / J SAARIVIRTA

FIG 5.1.2



CONDUCTOR MOTION VS
CONDUCTOR NUMBER
MILS
3.0
2.0
1.0
E = .7 × 10^6
α = 3.5
INNER COIL
OUTER COIL.
10
20
30
40
MIDPLANE
TURN No.
KEY

FIG 5.1.3.



CS #16 DATA
K. KOEPKE / J SAARIVIRTA

Fig 5.2.1

MAG. NO. TA0240 COLLARING DATE 8-31-79

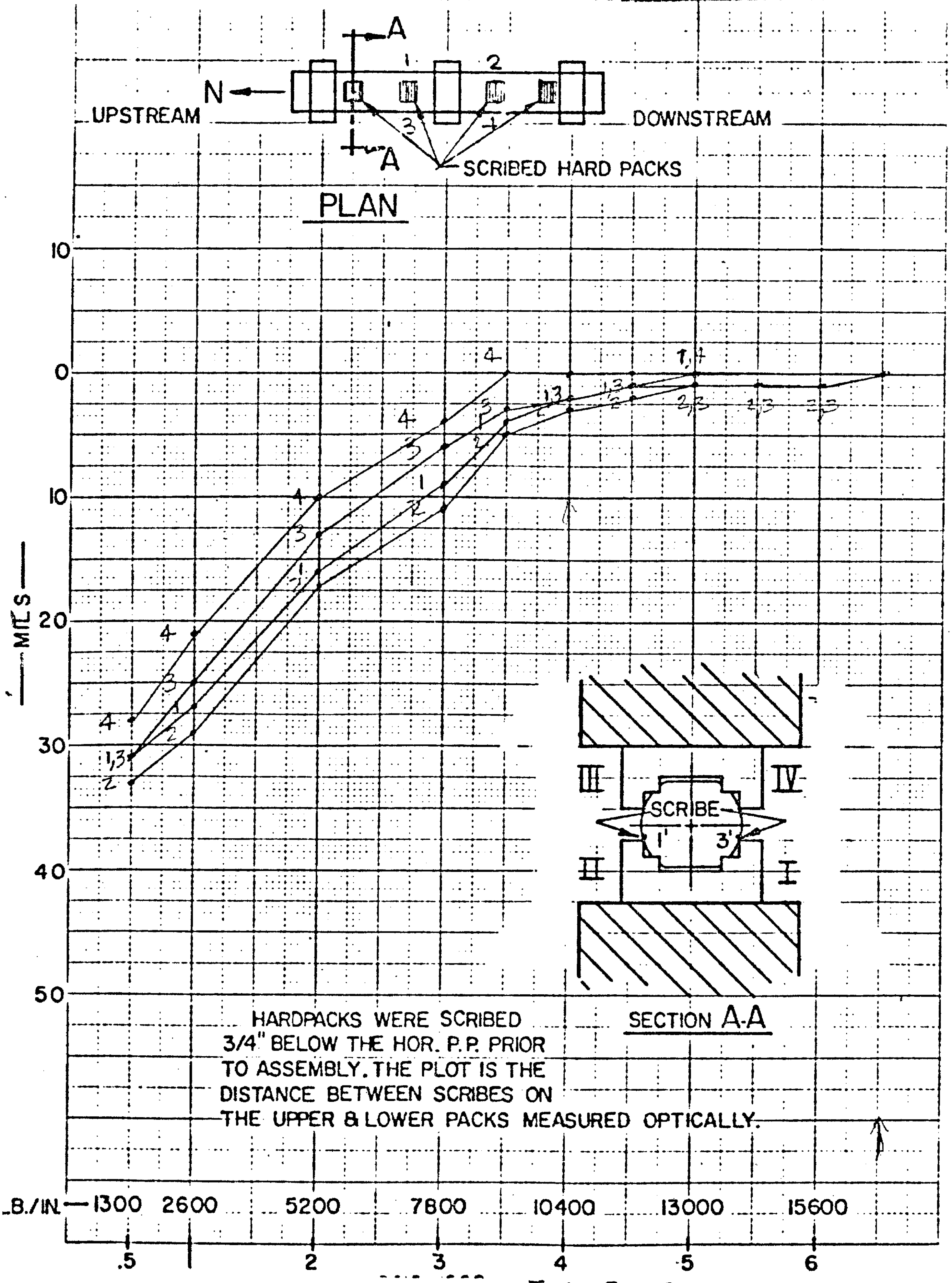


FIG 5.2.2

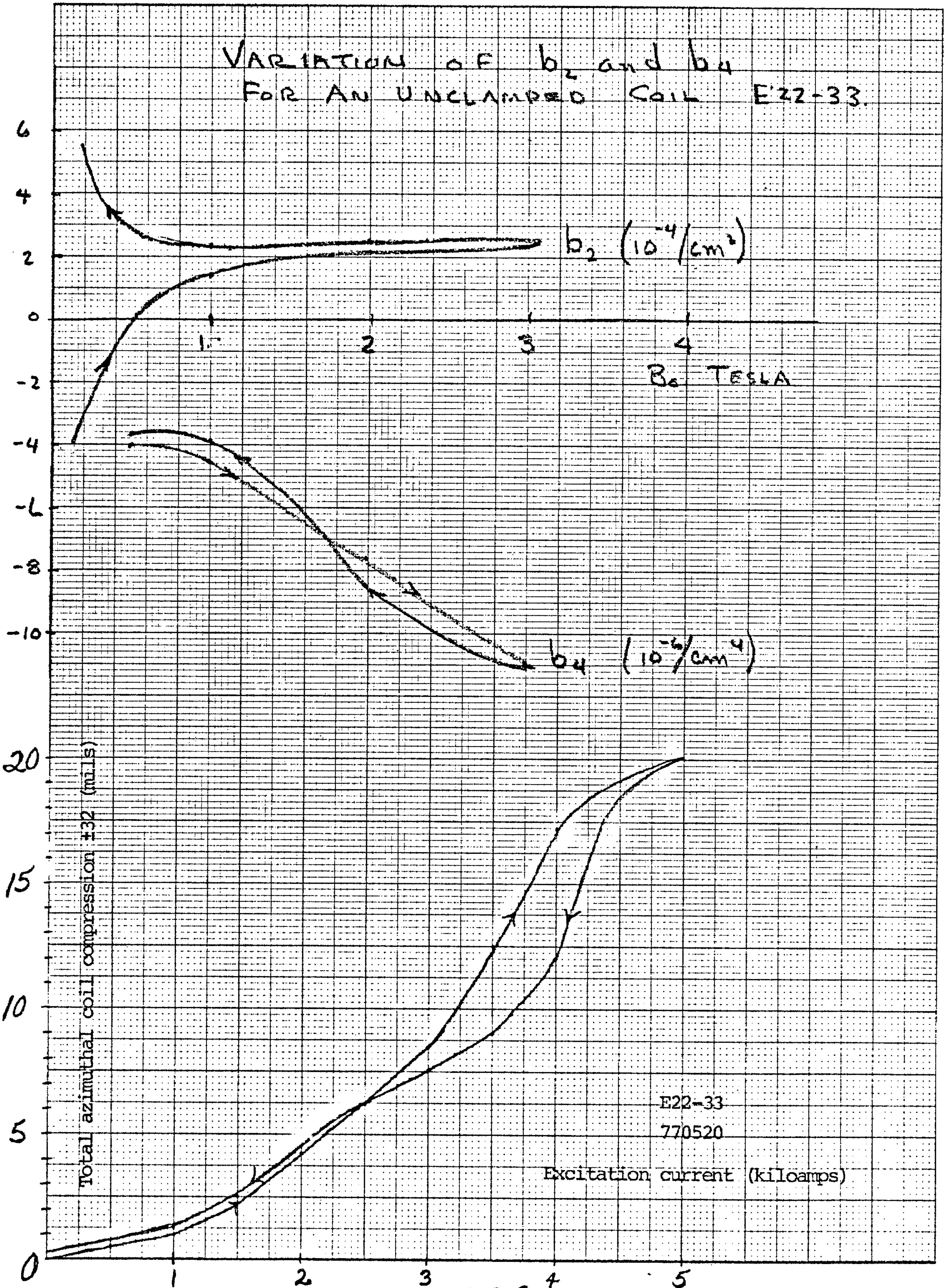

VARIATION OF b2 and b4
FOR AN UNCLAMPED COIL E22-33.
b2 (10^-4/cm^2)
B0 TESLA
b4 (10^-6/cm^4)
Total azimuthal coil compression ±32 (mils)
E22-33
770520
Excitation current (kiloamps)

FIG. 5.2.3

Magnet No. RBA-170

March 26, 1979

Vertical Dewar Test

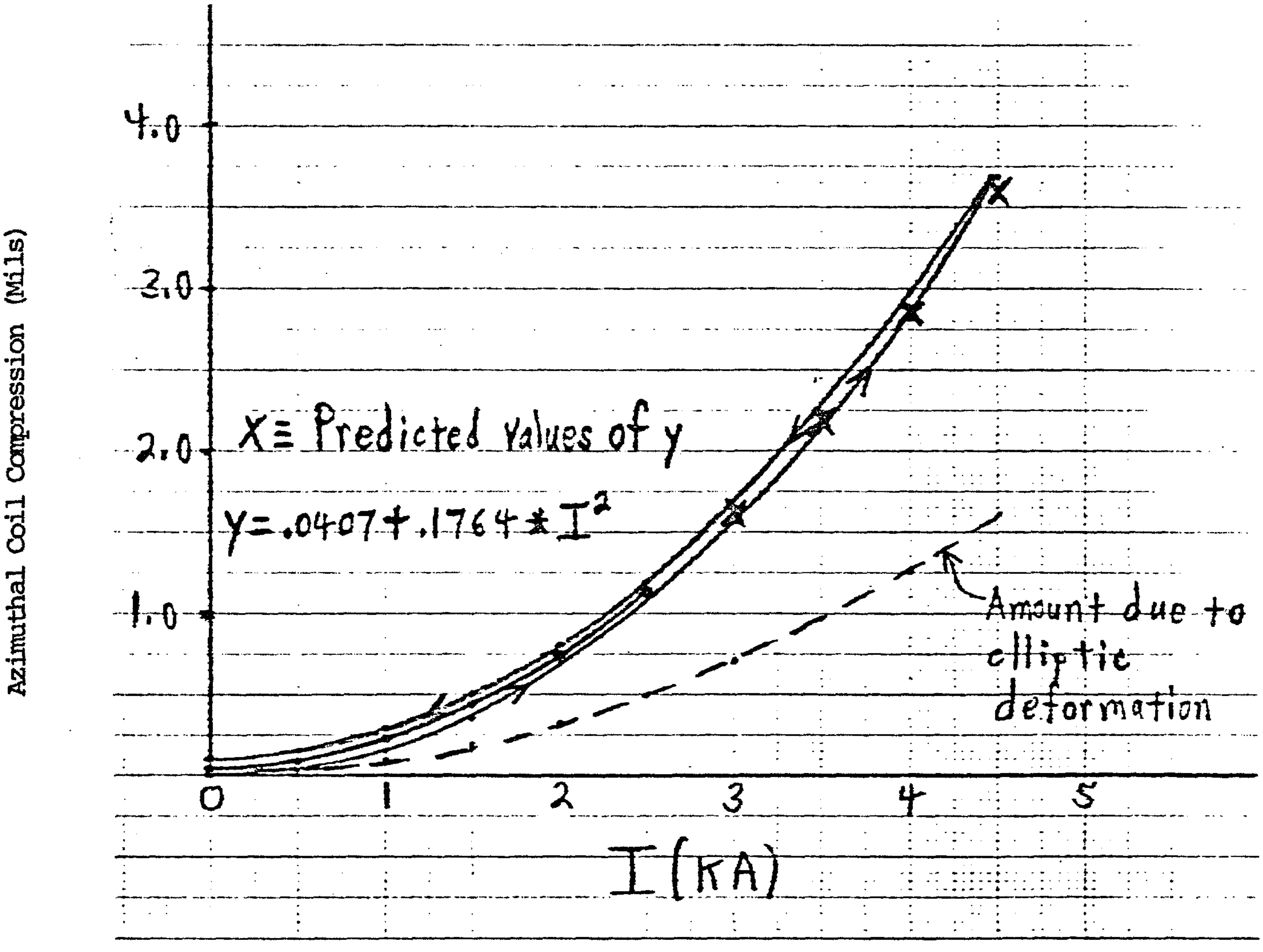


Fig. 5.2.4

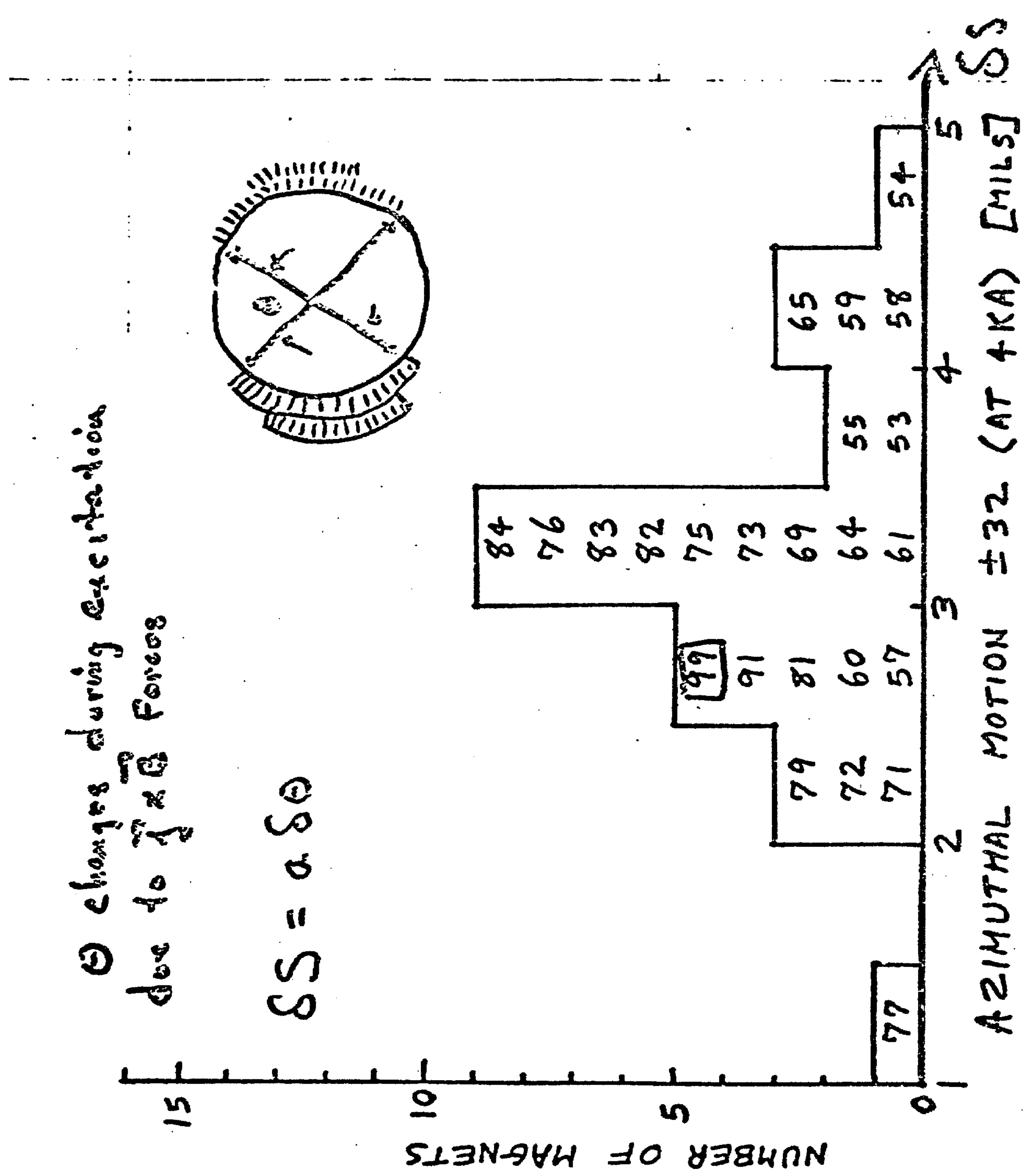
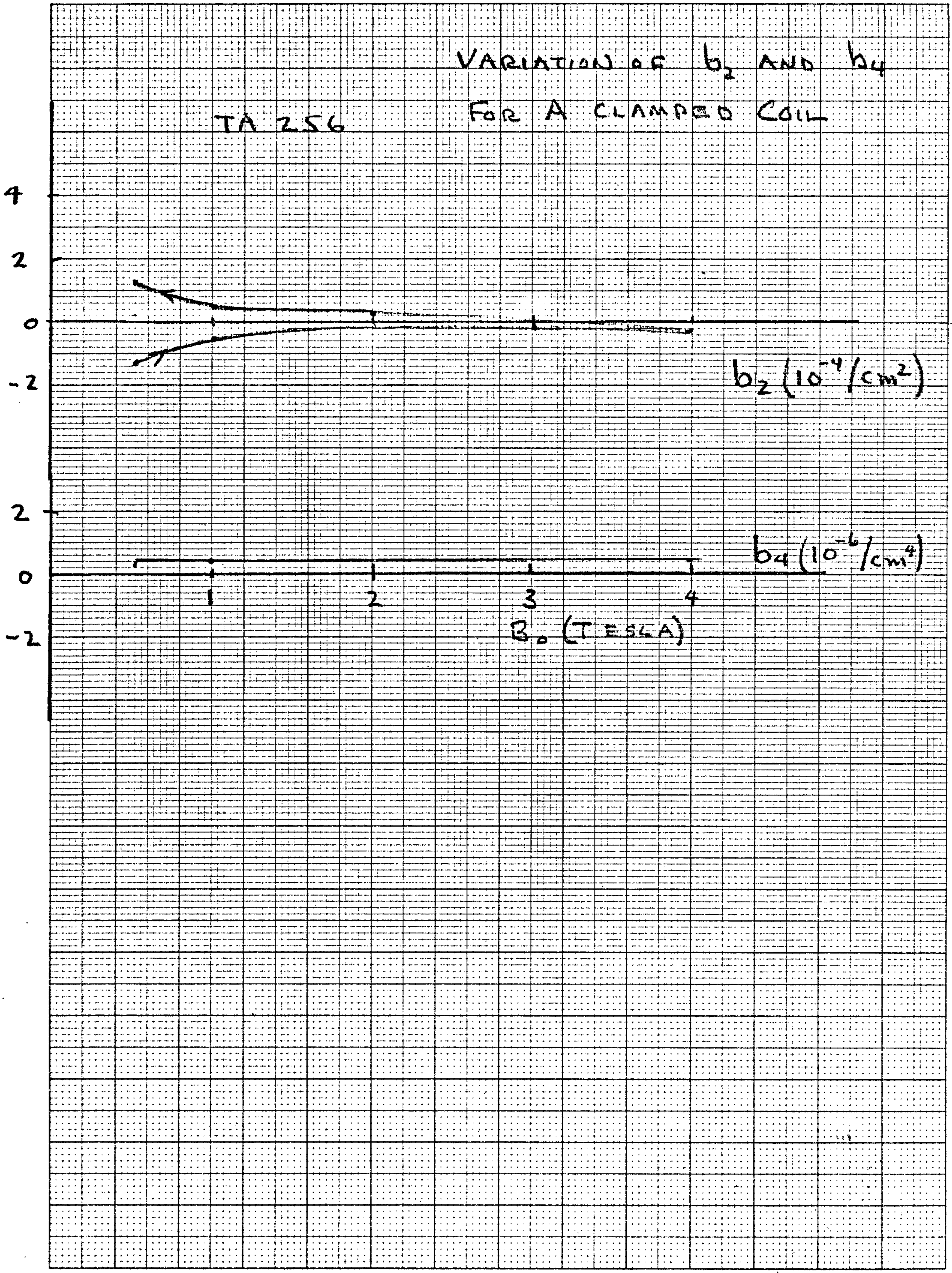

Θ changes during excitation
due to J×B Forces
δS = a δΘ
NUMBER OF MAGNETS
AZIMUTHAL MOTION ±32 (AT 4KA) [MILS]
δS

Fig. 5.2.5



VARIATION OF b_2 AND b_4
FOR A CLAMPED COIL
TA 256
4
2
0
-2
$b_2\ (10^{-4}/cm^2)$
2
0
-2
$b_4\ (10^{-6}/cm^4)$
1
2
3
4
B_o (TESLA)

FIG. 5.2.6