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The Magnetic Field Measurement of Mark I Model Magnet

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This model magnet for the bending magnet of the main ring was made at PSL of University of Wisconsin, and its characteristics are described elswhere.[1] The shape of the yoke is of the window-frame type, and the coil is made of the spare copper bar for the ZGS of Argonne National Laboratory.

The field measurement of this magnet was done at Argonne using the high speed data acquisition system.[2] The excitation curve, the radial distribution of gradient k ($= \frac{1}{B}\frac{dB}{dx}$) at high field, the remanent field, and the field shape at the ends were measured. Usually three measurements were done to get an averaged value.

The power supply was the one for ZGS model magnet. Its output voltage is quite high ($\sim$ 600 V), so this model magnet was connected and excited in series with a ZGS model. The current capacity is limited to about 10,500 A, and we could go up to 18.2 kG at the central field. The current shape is 1 sec up and 1 sec down at about every 5 seconds without flattop.

Excitation Curve

A search coil was placed at the center of the magnet, and the field strength at several different excitation current was measured within a single excitation pulse. The excitation curve is shown in Fig. 1. It is straight up to 14.5 kG, then the saturation sets in. There should be about 1 % effect in the excitation due to the magnetic reluctance in the yoke. The magnetic field seems about 1 % less than the expected value at the straight part, which may be due to the error of the absolute calibration of the system.

At 18 kG corresponding to 400 GeV, the observed saturation effect is 4.3 %. ~~Meanwhile~~ The hysteresis curve of the iron of the magnet, which was measured at PSL, showed the onset of the saturation around 15 kG. The maximum flux density in the yoke is 17.1 kG from a simple calculation, when the field in the gap is 18 kG. The value of μ is about 310 at 17.1 kG, and the estimated saturation at 18 kG is 3.7 %, if we assume the flux density in the yoke is 17.1 kG everywhere. The detailed flux density distribution in the yoke was calculated by the computor program LINDA at LRL.

Remanent Field

The remanent field of the magnet was measured with the same device, but the search coil was flipped at every point and the its output voltage was integrated, after the magnet being pulsed to the maximum field of 18.4 kG for about one hour.

The observed remanent field shape shows a bump at the center as shown in Fig. 2. The central field is about 29 Gauss, which corresponds to the estimated field of 32 Gauss due to the observed coercive force of 3 Oersted. The observed bump is not symmetrical to the center line of the magnet due to the poor accuracy of setting of the coil.

The remanent field is proportional to the integral of the coercive force along the path in the yoke. Therefore this bump is due to the difference of the magnetic path lengths in yoke corresponding to the points on the surface of the pole piece. This bump may be reduced with the more favorable shape of yoke of the improved window frame, and can be definitely reduced by using better iron with a smaller value of coercive force.

Standby Field

The excitation pulse current starts from a standby current of 30 Amp due to the peculiarity of the power supply. The field values at the standby current are needed as the initial values for the measurement of high field. The standby field was measured with a single moving coil, which was electrically bucked against a stationary coil. The moving coil was translated from point to point across the gap, and the difference signal from the coils was recorded and converted to Gauss. The standby field is 80.5 Gauss at the center and proved to have the same bump as the remanent field.

High Field

The radial shape of high field was measured in two ways. In the first way, two almost identical search coils were used (two coils method). One of them was fixed at the center of the magnet and used as a standard. The other one was connected in series opposition ~~with it bucking each other~~ and moved radially. The small difference signals from these two coils were integrated and the small error due to their mismatching of the turn-area was corrected. The deviations from the central field values at different excitation levels were measured within one excitation pulse. Then the search coil was ~~is~~ moved one eighth inch radially and the measurement was repeated. The difference between these two adjacent deviations corresponding to the same excitation level was calculated. The radial distributions of k from 9 to 18 kG and at 500 G are plotted in Fig. 3, where the flags on ~~in~~ the curves show the typical value of the error of the measurement.

In the second method, two closely matched (to within 0.4 % in area) rectangular (1/8" × 1.5") coils were fixed 1/4" apart and the pair was connected electrically to buck each other (twin coils method).[3] The output of the pair was integrated to get the gradient. The pair was moved across the gap in 1/4" increments. After a series of ~~the~~ measurements, the pair was flipped over 180° and the same measurements were ~~was~~ done. These two measurements in different orientations were averaged to cancel out the error due to the mismatching of the pair. The results from 9 to 18 kG are shown in Fig.4.

The agreement of the two sets of results is quite good with the exception of those at the injection field, which is described later. The measurements show that the saturation effect sets in strongly above 17 kG. The dotted lines at $k = \pm 0.02$ show~~s~~ the allowable width of k. The observed asymmetry seems to be due to the irregularity of the magnet itself. It would have been desirable to make similar measurements at other places in the magnet and compare the results.

The comparison between the measured k-distributions and the ones calculated by the computer programm LINDA at LRL is shown in Fig.5. The comparisons are made at 9 and 18 kG. Also a curve calculated for the infinite value of permeability and curves corresponding to 20 and 21 kG are shown. The agreement between the measurements and calculations is fairly good.

The width of the gap is about 5 inches, and the usable region seems to be about 4 inch wide. Outside this region and up to the coil the field strength falls very sharply. This may be due to the small but finite air gap of about 100 mils between the top and bottom layers of coil. It may be interesting to measure the k-distribution not only in the median plane but also in the off-median planes to see the effect of the holes and gaps of the actual coil.

<u>Injection Field</u>

The distribution of gradient k at 500 Gauss corresponding to the injection field was measured in the two ways as in the high field. The results are shown in Fig.6. The result with two coils seems better than the other. In principle the other method of twin coils should give a better result, but the matching of the pair did not seem to be good enough at such low field. Therefore the curve due to the method of twin coils seems to have been shifted downward. The injection field was also estimated by superposing the remanent field of 29 Gauss and the homogenious field of 471 Gauss due to current. This process of superposition may be a good approximation with such a slow pulsed magnet, as is shown in the standby field. The estimated sextupole term of the injection field is $-2.9\ m^{-2}$ as shown in Fig.6. This is a quite big effect compared to the allowable width of $k = \pm 0.02$. But this effect may be reduced in the final magnets due to the shape of the improved window flame and to the better iron. Anyway it can be easily corrected with the sextupole magnets, which will be used for high field correction.

The measurement at injection field should be improved further in the future by using a better matched twin coils and by using other methods.

Field Shape at Ends

The ~~both~~ ends of the magnet have different shapes. One of them has a straight rectangular edge and the other one is linearly tapered to cut off 1" over the length of 2.5" to get rid of saturation effect somehow. The solid iron end plates on both ends occupy the most outside 1.5". The field shape at both ends ~~were~~ was measured with one search coil from point to point, and integrated numerically to get effective magnetic lengths, assuming the same type of end on both ends. The variation of the magnetic lengths on the center of the gap are shown in Fig. 7. The magnetic length changes only $\pm$ 0.1" from 0.5 to 18 kG with the tapered end, but it changes + 0.2" and $-$ 0.6" with the rectangular end mainly due to the saturation of the edge.

The variation of the magnetic length along the width of the gap is shown in Fig. 8. With the square end the distribution curve bulges out at the center at 9 kG and becomes almost straight at 18 kG. With the tapered end the distribution has always a concave curve, and the order of the difference of the magnetic lengths between the center and $\pm$ 2" is 0.05" at 9 and 18 kG and 0.1" at 500 G. The estimated equivalent sextupole term from this effect is $\frac{d^2B}{dx^2}/B_0 = 0.32\ m^{-2}$ for the change of 0.1" at $\pm$ 2", if we assume the length of the magnet is 6.27 m. It may be reduced by properly shaping the ends or it should be corrected with sextupole magnets. The effective magnetic length should be measured with long coils to improve the accuracy of the measurement in the future.

Homogeneity

The central field was measured with two coils method along the magnet and shown in Fig. 9. Roughly the same type of inhomogeneity is noted on both ends of the magnet. The amount of the variation is about $\pm$ 0.5 %. This corresponds to the variation of about 5 mils in the gap height of 2". The profile of the gap height was measured and ~~it looks like~~ shows that the inhomogeneity in the field may be attributed mainly to this source. This mechanical accuracy was achieved without too much attention and may be easily reduced by a factor of 2 or 3 in the future models.

At 18 kG the asymmetry of the field shape around the central part of the magnet is increased. This may be due to the possible difference in the local packing factor of the lamination.

<u>References</u>

1) W. Winter: To be written in another NAL report
2) E.C. Berrill and R.S. Odwazny: Preprint of The Second International Conference on Magnet Technology.
3) R. Yamada and S. Mori: Cornell 10 GeV Report CS-31, 1966

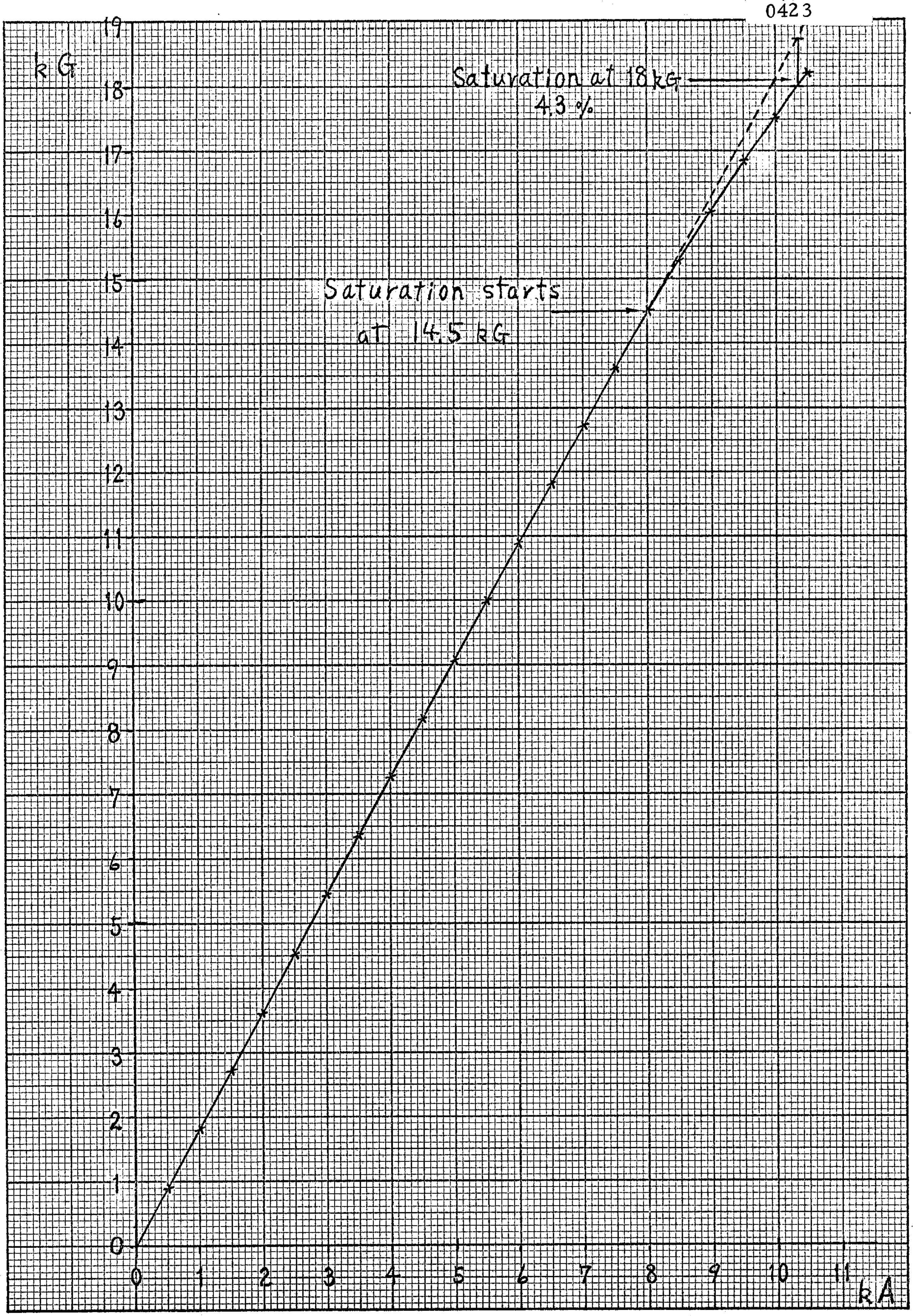

Fig. 1. Excitation Curve

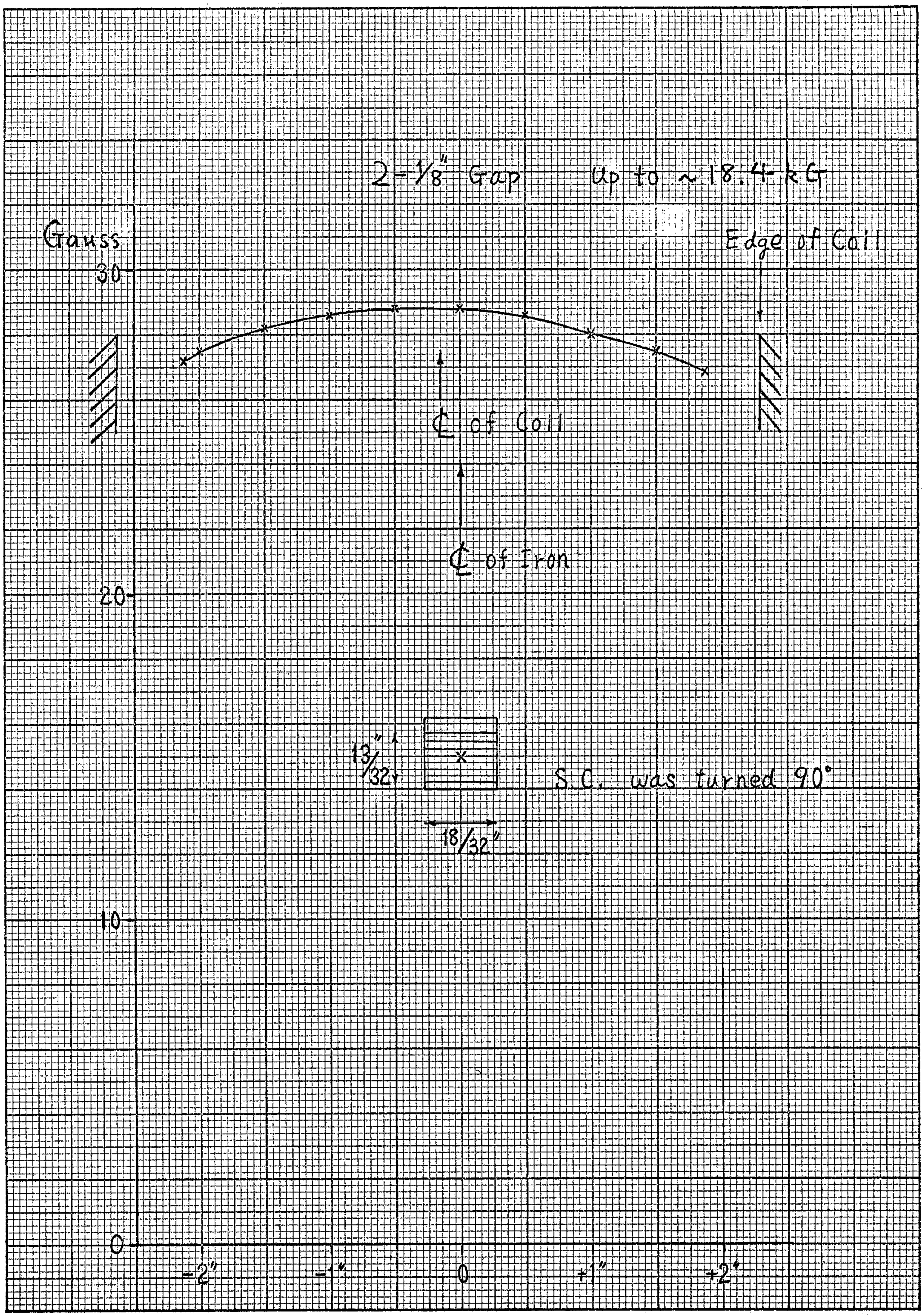

Fig. 2. Remanent Field

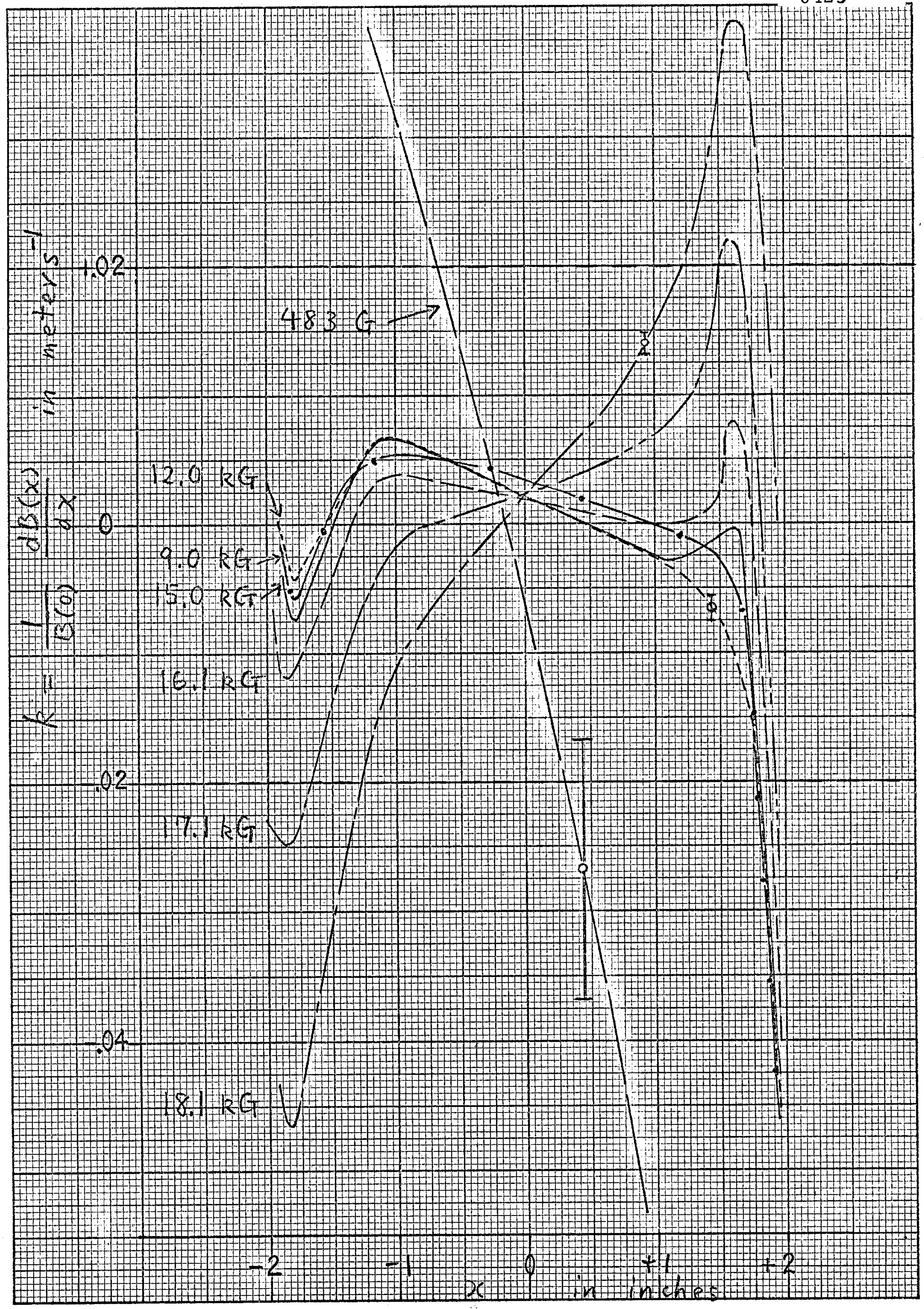

Fig. 3. Distribution of k measured by Two Coils Method

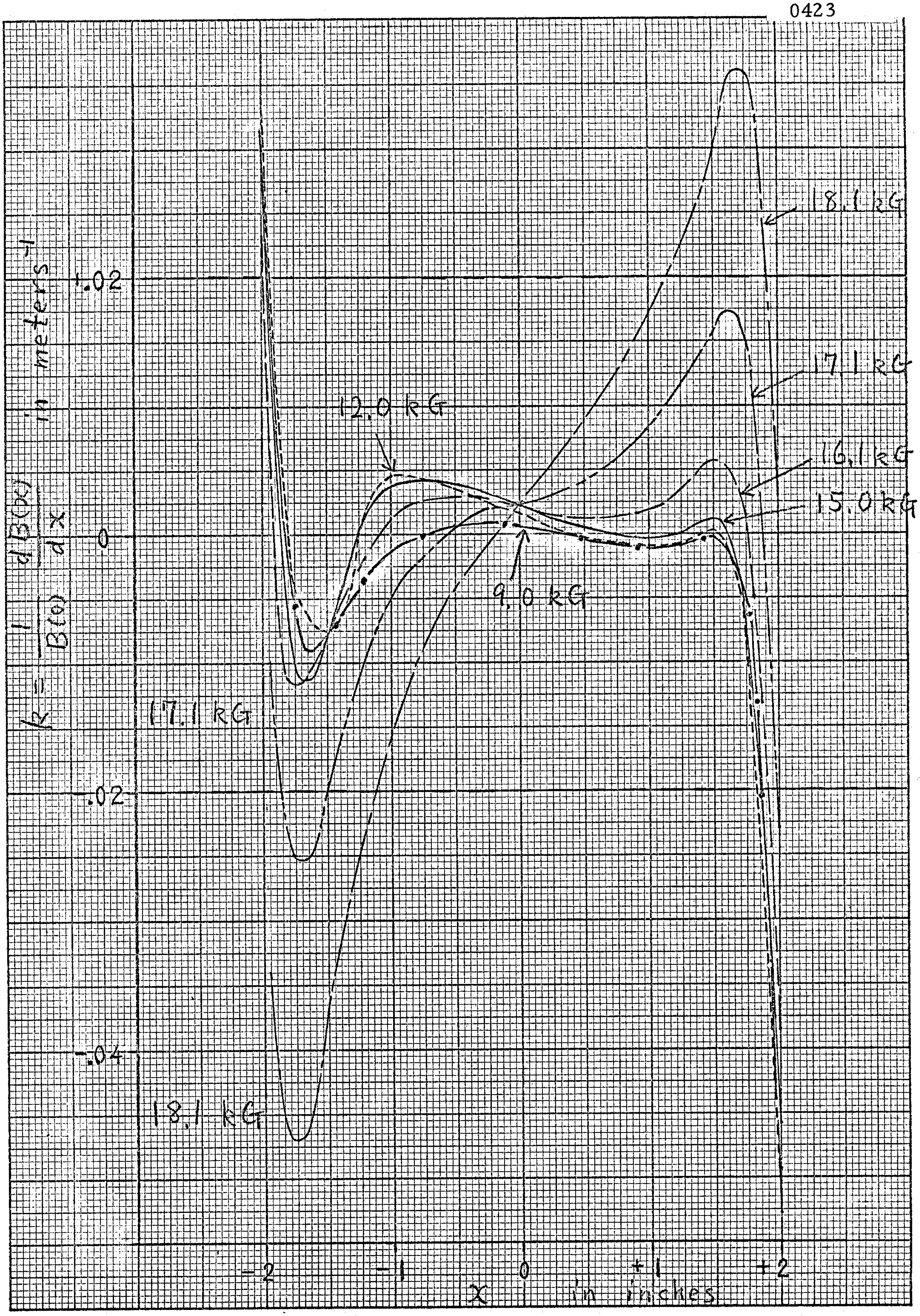

Fig. 4. Distribution of k measured by Twin Coils Method

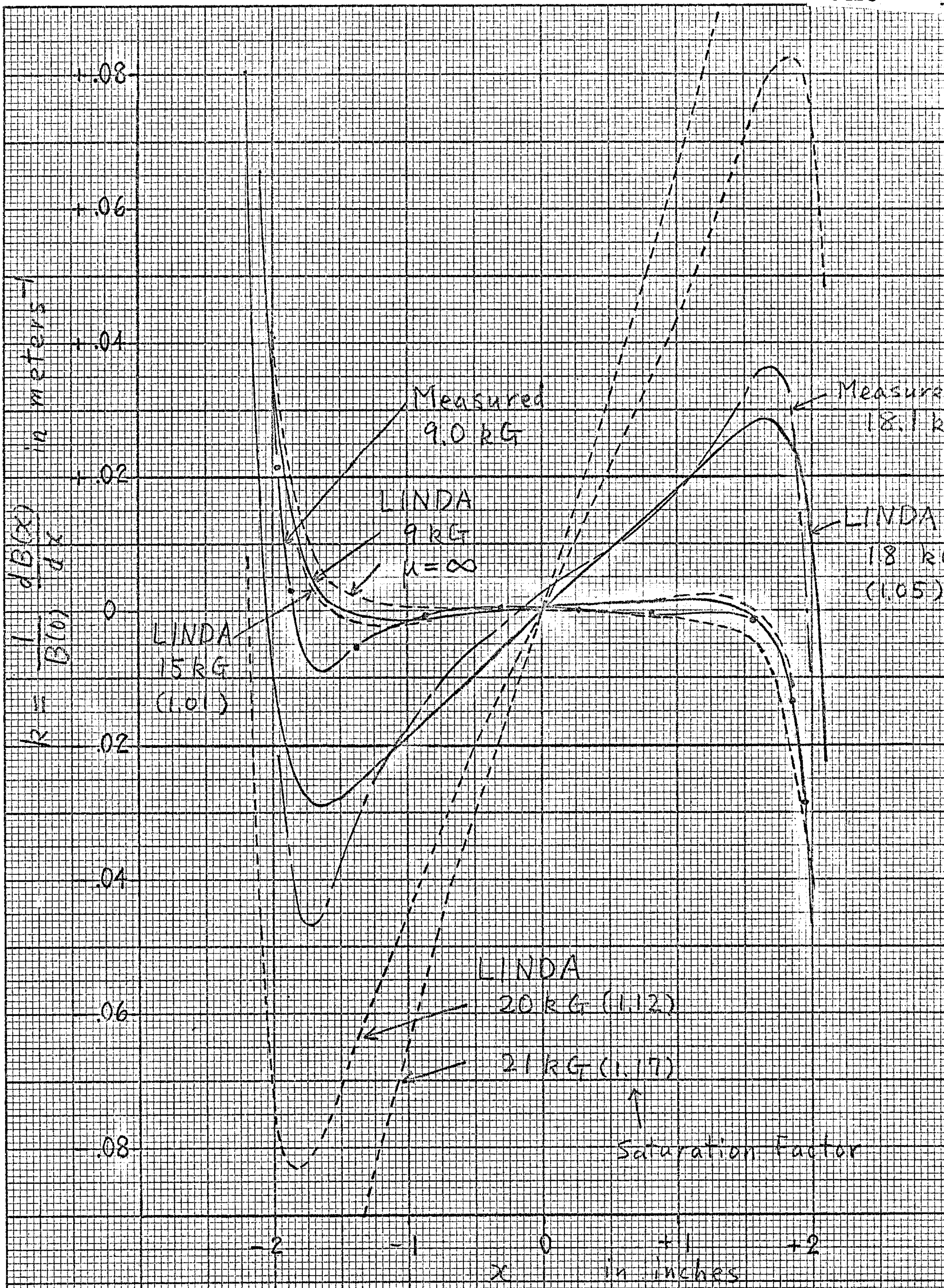

Fig. 5. Comparison of k Distributions between Measurement and Calculation by LINDA

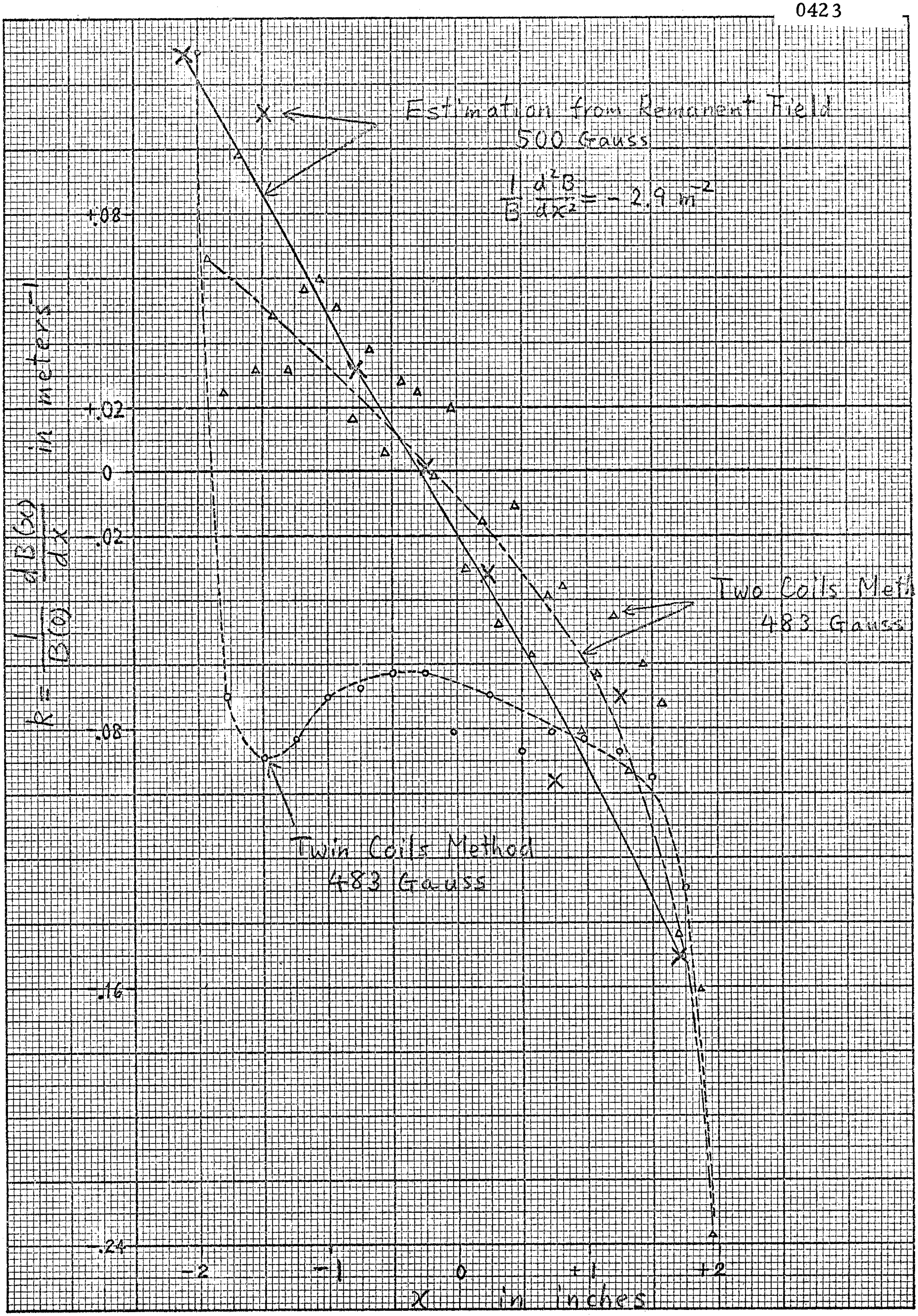

Fig. 6. k Distribution at Injection Field

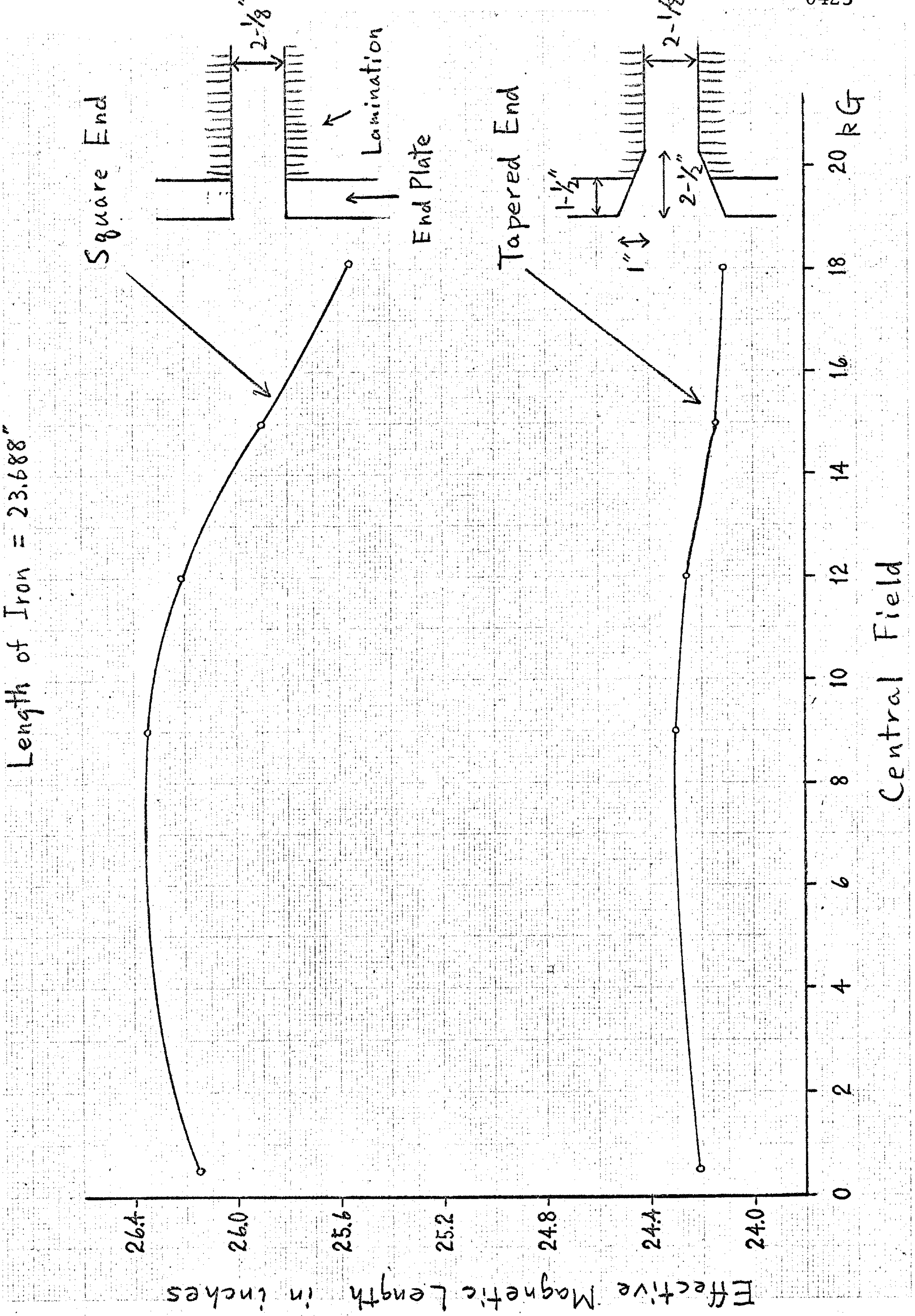

Fig. 7. Effective Magnetic Length and Excitation

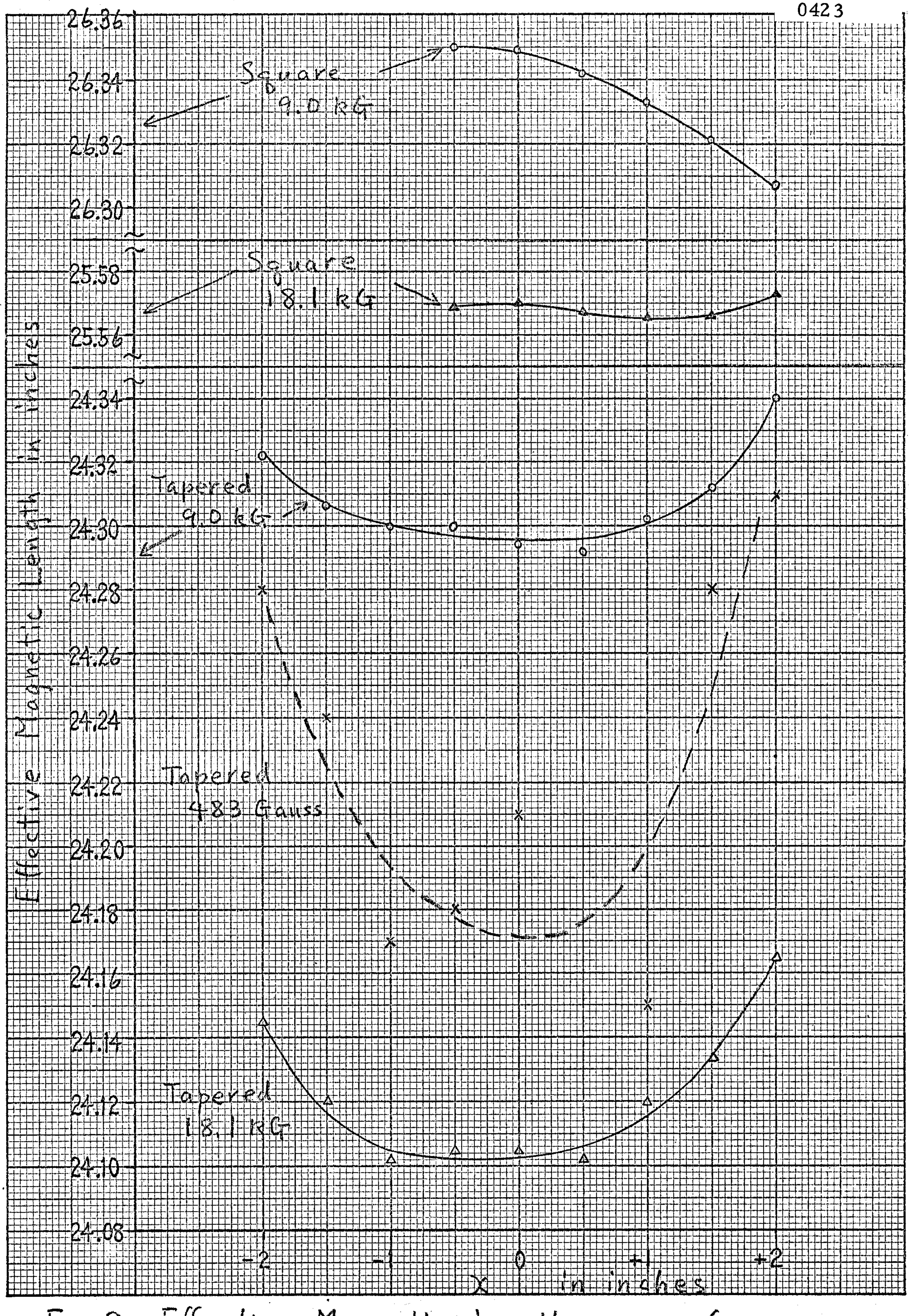

Fig. 8. Effective Magnetic Length across Gap