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MAGNETIC FIELD MEASUREMENT II

Introduction

The procedure for the production test of the magnetic field characteristics of magnets for Cornell 10 GeV synchrotron is described and some results are discussed. The production test consists of measurements of the isomagnetic line, the averaged value of Xo, the gap in the back legs, the phase lag measured with a peaking strip, and the remanent field of each magnet.

The high field characteristics of the high gradient magnets are also described.

The magnetic field and field gradient were measured at the injection field of 50 gauss. The measurements were made with biased peaking strips and the results are described.

Production Test

There are 192 magnets for the synchrotron as well as some spare magnets. Each magnet was tested and compared with a standard magnet.

We measured the magnetic characteristics of each magnet, as soon as it is manufactured and baked for obtaining good vacuum. After that it was assembled on the I-beam and installed in the tunnel sequentially. Therefore, we do not have the best possible arrangement of the magnets in the tunnel as far as magnetic field data are concerned.

1). Setup

Every test magnet is compared with the standard magnet (No.1010). They are connected in series and form a resonant circuit with two chokes and two banks of capacitors, tuned to 60 Hz (AC power line frequency). The connection is shown in Fig. 1. As there are two kinds of magnet with different inductance values, we have a switch, which adds trimmer condensers to the two main capacitor banks in case of the narrow gap magnets of a lower inductance value.

A pair of precision-made survey monuments are fixed on every magnet near to both ends. Each monument has a set of four precision pins with a concentric hole in it. The two pins on a magnet, which are near to the ends of the magnet and at the outside of the magnet, are used as the standard points of the magnet when the center line of the magnet is measured. The top surface of the pins are used for leveling the magnet with a precision level.

The standard and the test magnet are set on movable I-beam tables separately, on which the magnets are leveled. These tables have two mill tables on both sides beyond the ends of the magnets. The tables are movable rectangularly to the axis of the magnet, and one of them is movable along the axis as well. A 16 mil diameter phosphorous copper wire is stretched from one of the mill tables to the other through the gap of the magnet and then back to the first one. Thus the wire makes a one-turn coil in the magnet covering the central field as well as the fringing field. The wire is stretched uniformly tight at both ends of the wire on a same mill table with two pulling devices made of wheels and gears. The other mill table, which is movable parallel to the axis of the magnet, is used to stretch the wire much tighter. The spacing of the wire is made constant on both sides of the two magnets by using quartz spacers of the same thickness (around 1" with precision of 0.2 mil.) The four quartz spacers (about 1" x 1" x 1") were cut from a single parallel plate, and are always used at the same orientation. Thus we have one standard one-turn coil in the standard magnet and another one with equal turn-area in the test magnet.

The position of the geometrical center line of the magnet is determined with a long centering jig and with respect to the position of the standard pins on the survey monuments. The long centering jig is made of a 12' aluminum channel with two aluminum plates under each end of the channel. The flat plates sit on the pins of the survey monuments. A dove pin embeded under one plate fits into the inner hole of one of the standard pins. And a slot under the other plate with its axis parallel to the axis of the magnet, is used to house the other standard pin. At the outside end of a plate, a perpendicular 1" square bar is sticking down. Its both side faces are made parallel to the axis of the magnet, and symmetrical to the center line of the magnet, using a transit, gauge blocks and the special jigs placed on the magnet to determine the center line of the magnet.

A thin parallel plate is placed against the side surface of the perpendicular bar, and the plane can be extended down to the median plane of the magnet. The wire of the one-turn coil is moved toward the surface of the parallel plate until it touches, then the electric loop composed of the wire, the perpendicular bar, a dry battery and a lamp, closes and the lamp goes on. With this method we can determine the position of the wire with an accuracy of a fraction of a mil. With every dimension known, we can determine the position of the wire with respect to the position of the standard pins and then to the center of the magnet.

Error of Setting

The position of the geometrical center of a magnet can be determined with an accuracy of ±10 mils. The various causes and their contributions are as follows:

The pins on the survey monument apparently have a radial accuracy of ±5 mils, due to the mechanical accuracy of the monument itself, and to the procedure of setting the monument on the magnet.

The setting of the wire itself can be done with an over-all accuracy of ±5 mils. They include the possible errors due to the setting of the telescope and the special centering jigs, to the mechanical accuracy of the long centering jig, and to the procedure of reading the position of the wire.

2). Isomagnetic Line Measurement

The isomagnetic line was set at 69 and 131 mils outside the geometrical center of the magnet for the wide gap and the narrow gap magnets respectively, when the profile of the pole piece was calculated and determined assuming 1 mil gap in the back legs.

For the production test the standard isomagnetic line is set at 131 mils outside the geometrical center of the standard magnet (narrow gap). The standard magnet No. 1010 was found to have an average gap of 1.3 mils in the back legs, which is smaller than the average value of other magnets. The isomagnetic line is measured with the above mentioned 1" wide one-turn coils. The center of the coil of the standard magnet is set at the standard isomagnetic line. The center of the other coil of the same width in the test magnet is placed at its geometrical center line with the same device and method. Then the reading of the mill tables is set at zero.

The two magnets are excited in series to 10 GeV in biased operation. The two coils are connected in series to buck each other and their signal is integrated and measured on an oscilloscope, which is triggered by a peaking strip at zero field, as in the measurement of the absolute value of Xo at the center[1]. In this case the setting of the two dividers are set at the same values i.e. 9,000. We move the coil in the test magnet back and forth radially, until the integrated signal becomes zero at the time when the field is at the peak value. From the reading of the mill table, we are able to know where the isomagnetic line of the test magnet is. It is necessary to reduce any temperature change in cooling water for the standard and test magnet.

Shift of the Isomagnetic Line

The typical values of the observed isomagnetic line are 77 and 181 mils outside the geometrical center line for the wide gap and the narrow gap magnet respectively. Therefore the observed values are shifted further outside by 8 and 50 mils than the designed values for the wide gap and the narrow gap magnet respectively. The extimated amounts of shift are -5 and 29 mils for the wide gap and the narrow gap magnet respectively. Their contributions are listed in Table I and are explained in the following.

The back leg gap is not 1 mil as designed, but the typical value of the back leg gap of the production magnets is 2.4 mils for both types of magnets. The standard narrow gap magnet has 1.3 mil back leg gap. This extra gap δ_o=0.3 mil causes the shifting of the isomagnetic line of the wide gap magnet by $(1 + k)Xo\ \delta_o/G=8$ mils, and it is 69 + 8 = 77 mils outside the geometrical center for a wide gap magnet with 1 mil back leg gap. The extra back leg gap widens the main gap and shift the isomagnetic line to the narrow side of the main gap by Δx, which is given by [1)]

$$\Delta x = -(1 + k)Xo\,\frac{\Delta g}{G}$$

Therefore the typical value of the shifting of the isomagnetic line due to the typical extra 1.4 mil gap is 25 mils inside for the wide gap magnet, and that of the typical 1.1 mil gap is 29 mils outside for the narrow gap magnet.

The typical magnetic length of the narrow gap magnet turned out to be longer by 0.12" than that of the wide gap magnet. The magnetic length is about 127" for both types of magnet. Therefore this deviation causes a 9 mil inside shift of the isomagnetic line for the wide gap magnet.

There was some small systematic deviation in the punching of the laminations. The gap of the lamination for the wide gap magnet is 1 mil less than the design value, and that for the narrow gap magnet is not so bad. This means a 7 mil outward shift for the wide gap magnet.

The calculation of the isomagnetic line was done assuming an infinite value of magnetic permeability. Actually it is $\gtrsim$7,000 at 3.3 kG for ARMCO-6. This finite value of μ reduces the field at the center of the wide gap magnet by 0.2% compared to a value with an infinite μ. The ratio of the air gap length to the magnetic length in iron is different for two types of the magnets. This causes the center field in a narrow gap magnet to be lower by 0.1% than that in a wide gap magnet. Therefore, the isomagnetic line for a wide gap magnet is shifted outside by 11 mils.

The positions of the isomagnetic lines of the production magnets are distributed around the typical values by ±20 and ±30 mils for the wide gap and the narrow gap magnet respectively. The estimation of the variation is also listed in Table I. The principal cause is due to the variation of the back leg gap, which is ±0.6 mils for both types of magnet. Their estimated values are 11 mils and 16 mils for the wide gap and the narrow gap magnet respectively.

The error due to the setting is ±10 mils as described before for the test magnet. But it is much reduced for the standard magnet and may be ±3 mils. The spacing of the parallel wires may have an error of ±0.2 mil and it may cause a variation of ±2 mils. Some magnets are twisted as much as ±15 mils per inch radially at their ends, but the plane of the wire was made parallel to the median plane of the magnet within ±5 mil/inch. Therefore this causes a negligible error. The hard packs are found to have an error in the dimensions of tapering section, which is equivalent to ±40 mils (± 0.03%) in the magnetic length. This varies the isomagnetic line by ±3 mils. The agreement between the estimated values and the observed ones are fairly good as is shown in Table I.

Table I Shift of Isomagnetic Line and its Variation

	Wide Gap Magnet		Narrow Gap Magnet	
	Shift (mils)	Variation (mils)	Shift (mils)	Variation (mils)
	(calculated)			
0.3 mil of Std. Mag.	+ 8		0	
Extra Back Leg Gap	-25	±11	29	±16
Magnetic Length	- 9	± 3	0	± 3
Punching Error	+ 7		0	
Finite	+11		0	
Setting Error of Test Mag				
Pins		± 5		± 5
Coil		± 5		± 5
Setting Error of Std. Mag.		± 3		± 3
Width of Wire		± 2		± 2
Total Estimation	- 8	±29	+29	±34
Observed Values	+ 8	±20	+50	±30

3). <u>Averaged Value of Xo</u>

The values of Xo at the geometrical centers of the magnets were designed to be 9.223" and 9.010" for the wide gap and the narrow gap magnet respectively. These values refer to the values well inside the magnet. For the comparison with the values of the production test, we have to take into account also the fringing fields at both ends. Thus the averaged Xo values were calculated to be 9.297" and 9.115" for the wide gap and the narrow gap magnet respectively with 1 mil back leg gap, with the values of the measured magnetic and gradient length[1)]. The calcualtion of the averaged Xo value is done in Appendix I.

For the production test we use the same 1" wide one-turn coils, which cover the fringing field at both ends. We set the centers of two 1" wide coils at the geometrical centers of the standard magnet and the test magnet, and excite the magnet at 10 GeV as in the measurement of the isomagnetic line. The divider for the test magnet is set at a fixed value of 9,000, and that of the standard magnet is adjusted until we get zero signal on the scope. Then the coil is moved radially by +0.500" and -0.500" with the aid of block gauges and dial gauges. At these two points the divider for the standard magnet is adjusted for a zero signal on the scope again. From these three readings of the divider, we can calculate the averaged value of $\overline{X}o=Bo/(\Delta B/\Delta x)$ over the whole magnet. The typical values are 9.324" and 9.145" for the wide gap and the narrow gap magnet respectively.

The possible causes for the variation of Xo are as follows, and listed in Table II. The setting of the survey monument is done with an accuracy of $\pm$5 mils, which is 0.05% of Xo. The variation due to the extra back leg gap is given by $\Delta\overline{X}o=6.1\ (\delta - 18\varepsilon)$ mils for the wide gap magnet and $8.8\ (\delta - 18\varepsilon)$ mils for the narrow gap magnet, where δ is an extra gap in the back leg and ε is the inclination between the top half and the bottom half of the magnet[1]. The typical extra gap of 1.4 mils causes an outside shift of 9 and 12 mils for the wide gap and narrow gap magnet respectively. The observed distributed values of δ and ε are $\pm$0.6 mil and $\pm$0.03 mil/ inch respectively, and they cause $\pm$7 mils and $\pm$ 10 mils in $\overline{X}o$ for the wide gap and the narrow gap magnet respectively. The observed small variation in the shape of the hard packs causes $\pm$0.1" variation in the value of L_G, which is $\pm$ 0.08% ($\pm$ 7 mils) in $\overline{X}o$. Thus the total estimation including the possible errors is about $\pm$30 mils compared to the observed value of $\pm$20 mils.

The main error in the measurement is due to the setting of the coil at the center of the test magnet with respect to the survey pins to measure Bo, which is $\pm$5 mils, and this is $\pm$0.06% of $\overline{X}o$. The error in Δx is $\pm$0.5 mil for 1,000" displacement, and it is

$\pm$0.05% of $\overline{X}$o. We have to take a difference between two five digit numbers to get a value for ΔB, and this cause $\pm$0.02% of $\overline{X}$o. Thus the total possible error is $\pm$0.13%, and corresponds to $\pm$12 mils in $\overline{X}$o.

Table II Shift of Averaged Value of Xo and its Variation

	Wide Gap Magnet		Narrow Gap Magnet	
	Shift (mils)	Variation (mils)	Shift (mils)	Variation (mils)
Extra Back Leg Gap (=1.4 mils)	+ 9		+12	
Variation of Extra Gap		± 7		±10
Setting Error of Pins		± 5		± 5
Setting Error of Coil		± 5		± 5
Error in x		± 5		± 5
Error in B		± 2		± 2
Shape of hard Pack		± 7		± 7
Total Estimation	+ 9	±31	+12	±34
Observed Values	+27	±17	+30	±23

4). Zero Field Measurement with Peaking Strip

The long coils are placed at the geometrical centers of the magnets. A carriage is placed on the two parallel wires of the coil and is moved through the gap of the magnet by an attached fish line. A peaking strip and a Hall probe element are mounted on that carriage. Another peaking strip is placed at a fixed position inside the gap of the standard magnet, which is used to trigger the scope at the zero field.

A test magnet and the standard magnet are excited in series to the excitation level of 7.5 GeV with A. C. current only, because it is a more severe test at low field than such a test made at the injection field with D. C. bias. First the time of zero magnetic field (which is not exactly zero field time due to the coercive force of the peaking strip and some delay in the cables) is determined on the scope, by placing the peaking strip at the standard position of 1' inside of the standard magnet. Then the peaking strip is transferred into the gap of the test magnet. The signal is continuously monitored through the magnet to see any particular bump, and data are taken at 1' intervals.

The average values of the delay time are -1.5 ± 0.3 μs and 0.8 ± 0.3 μs for the wide gap and the narrow gap magnet respectively. The difference is 2.3 μs. (The value of dB/dt at zero field is 0.8 Gauss/ us.) This difference is mainly caused by the difference between the typical values of the remanent field of two types of the magnets, which is about 1.6 Gauss. The typical fluctuation inside a magnet is about ± 0.3 μs, which corresponds to the magnetic field variation of ± 0.24 Gauss. In some magnets it goes up to +0.6 μs locally. This fluctuation may be caused by the variation of the remanent field and/or eddy currents. We found some correlation between the variation of the measured dc remanent field and that of the zero crossing time.

5). Remanent Field Measurement

After the foregoing measurements, the magnet is excited up and down several times to the excitation level of 10 GeV with DC current of 400 Amp. The Hall probe element, which is connected to the Bell Gauss-meter with a long cable, is moved through the gap of the magnet on the carriage as the peaking strip. The remanent field on the geometrical center line is monitored continuously and the data is taken at the interval of one foot.

The average remanent field is 2.7 ± 0.4 Gauss and 4.3 ± 0.5 Gauss for the wide gap and the narrow gap magnet. The difference between them is 1.6 Gauss. The magnitude of the remanent field Br is given by $Br = H_c \times (L/G)$, where Hc is the coercive force of the magnet and may be about 2.2 oersted at 10 GeV excitation level, L is the magnetic length in iron, and G is the gap height of the magnet. Then the expected value of the remanent field is 2.8

Gauss and 4.3 Gauss for the wide gap and the narrow gap magnet and gives good ratio between them. The typical variation inside a magnet is $\pm$0.3 Gauss, but goes up +0.5 Gauss locally in some magnets. There is no remanent field bump at the ends of the magnets, as was seen in CEA magnets. The accuracy of the measurement is $\pm$0.2 Gauss.

The difference of the remanent fields between the two types of the magnet can be corrected, if necessary, by the aid of the two turn coil of the narrow gap magnet or by the correction coils in the straight section.

6). Gap in Back Legs

The gap in the back legs is measured by the method reported in the previous report[1]. The reading of Bell Gauss-meter with its element at 3/4" from the gap with a DC current of 154 Amp, gives the direct reading of the gap in mils. The gaps on both sides are measured continuously, data are taken at intervals of 1 foot, and their averaged value is calculated. The averaged gap heights are 2.4 $\pm$0.6 mils, and the accuracy of the measurement is $\pm$0.1 mil. The variation of the gap in a magnet is typically $\pm$ 0.5 mil, but it goes up to +1.5 mils locally in some magnets. This variation corresponds to the arrangement of the clamps, which were used for the assembly of the magnets, but it is not clearly correlated with the variations of the remanent field and the field delay.

In order to eliminate any systematic error, which might occur during the production test period of all magnets, several precautionary procedures were taken periodically. The centering jigs and the whole back leg gap of the standard magnet were checked periodically. The measuring equipments were calibrated and checked every time with the standard devices and the standard points of the standard magnet.

Modified magnets

There are two kinds of modified magnets, which are placed next to the 20' straight sections. About 17" length of the modified magnet is stacked with the normal lamination and the remaining

110" length is stacked with the modified lamination of the opposite stronger gradient. There is a transition hard pack between them of about 3/4" length.

The absolute values of Xo at the center, the radial distribution of Xo(x), and the magnetic and gradient lengths of the modified wide and narrow gap lamination, were measured as in the case of the normal lamination as described in the previous report[1].

The absolute values of Xo at the geometrical center of the modified wide and narrow gap lamination were measured at 7.5 GeV and are shown in Table III. The measured values were corrected for 1 mil back leg gaps, and found to be same as the designed values almost within the experimental error. These values were the same at the excitation level of 15 GeV.

Table III. Absolute Values of Xo at the Geometric Center at 7.5 GeV and 15 GeV

Magnet	Gap Height	Designed Value	Measured Value	Measured Minus Designed
Modified Wide Gap	1,482"	4.854	4.839" ±0.010"	-0.015"
Modified Narrow Gap	1.035"	4.588"	4.592" ±0.010	+0.004"

The radial distributions of Xo(x) of the modified wide and narrow gap magnet were measured at 7.5 GeV and shown in Fig. 2 and Fig. 3 respectively. The agreement of the observed distributions with the designed ones is fairly good.

The hard packs of the modified laminations, which are used at one end of the modified magnets, were made with the same die as in the case of those for normal laminations[1]. The effective magnetic length L'_B and the effective gradient length L'_G of the modified wide and narrow gap magnet are shown in Fig. 4 and Fig. 5 respectively. They are well constant within the usable regions at the hard packs. Their values with respect to the end of the lamination $\Delta L'_B$ and $\Delta L'_G$ at 7.5 and 15 GeV are listed in Table IV. $\Delta L'_B$ shrinks more with the narrow gap magnet than the wide one.

Table IV. $\Delta L'_B$ and $\Delta L'_G$ of Modified Lamination

Magnet	7.5 GeV		15 GeV	
	$\Delta L'_B$	$\Delta L'_G$	$\Delta L'_B$	$\Delta L'_G$
Modified Wide Gap	+0.376"	-0.253"	+0.357"	-0.247"
Modified Narrow Gap	+0.372"	-0.162"	+0.338"	-0.180"
Estimated Error	±0.010"	±0.020"	±0.010"	±0.020"

The shape of the transition hard pack between the normal and the modified lamination was made to have a smooth magnetic field variation between them. The field at the transition hard pack was measured and is shown in Fig.6 and Fig. 7 for the modified wide gap and the modified narrow gap magnet respectively. The respective gradient lengths on both sides of the transition hard packs were calculated and shown in Fig. 8.

The isomagnetic lines for these modified laminations were calculated with the aid of Fig. 6 and 7. The observed positions of the isomagnetic lines of the modified wide and narrow gap lamination are shown in Table V.

Table V. Isomagnetic Line of Modified Lamination

	Designed Value	Observed Value
Modified Wide Gap	+0.104"	+0.099"±0.010"
Modified Narrow Gap	+0.157"	+0.153"±0.010"

The isomagnetic lines and the averaged gradient values Xo of the modified wide and narrow gap magnet were calculated from the available data and compared with the measured values. They are listed in Table VI.

Table VI. Isomagnetic Line and Xo of Modified Magnets

Magnet	Isomagnetic Line (mil)		$\overline{X}o$	
	Calculated	Observed	Calculated	Observed
Modified Wide Gap (No. 1046)	120	115 ±10	6.159"	6.188" ±0.015"
Modified Narrow Gap (No. 1045)	183	198 ±10	5.867"	5.895" ±0.015"

Low Field Measurement

The magnetic field at injection is 50 Gauss at the center for the injection energy of 150 MeV. The absolute value of Xo at the center and the radial distribution of Xo(x) at 50 Gauss was measured with biased peaking strips[2,3]. A biased peaking strip was placed at a fixed position to trigger a scope, and its bias current was kept constant to give a time signal throughout the measurements.

A probe with two peaking strips as shown in Fig. 9 was made. These two peaking strips have bias coils around them and the radial distance between them is 250 mils. Another pair of bias coils is also used at the same radial positions of the corresponding peaking strips, and connected to buck their bias coils. In order to reduce the mutual coupling between these coils, they are displaced azimuthally from each other. The four coils are connected as shown in Fig. 10, and the signal from the peaking strips are observed on the scope.

The peaking strips are made of 2 mil 74 Mo-Permalloy and their length is 0.6". They are contained in quartz tubes and were annealed in hydrogen gas for 2 hours at 1100°C and cooled down at the rate of 50°C/min. A pick up coil of 260 turns was wound at the center of the tubes. Two well matched peaking strips with quartz tubes were selected out of ten peaking strips, placed in the ceramic tubes of 100 mil diameter and of 0.75" length, and glued with Epoxy. The bias coils were wound with #32 copper wire (9.5 mil dia.) with a turn number of 68 over 670 mils. The circuit for the precise measurement of the current through the bias coils is shown in Fig. 10. The current was measured with the aid of a potentiometer, which was later substituted by a digital voltometer of seven digits.

The absolute value of Xo at the geometric center was measured with one peaking strip with the full biased operation of 10 GeV. It was placed at the center of the magnet and the signal of the scope was set at one fixed position on the scope. Then it was displaced exactly by ±0.500" radially, and the bias current was adjusted to set the signals at the fixed position. Three readings of the bias current were used to get the absolute value of Xo at the center. The variation of the coercive force of the peaking strip to the change of dB/dt was measured and shown in Fig. 11. This effect and the effect of the pole piece were taken into the calculation of Xo and their corrections are given in Appendix II. The final values of Xo at the center are shown in Table VII. The observed values of Xo at 3.8 kG(10 GeV) on the same magnets are also listed in the table. All the values are not corrected for the back leg gaps.

Table VII Xo(0) at Low Field and High Field

	Wide Gap	Narrow Gap	Modified Wide Gap	Modified Narrow Gap
Xo at 25 G	9.066" ±.036"	8.985" ±.036"	4.803" ±.024"	4.508" ±.024"
Xo at 50 G	9.195" ±.036"	9.042" ±.036"	4.869" ±.024"	4.570" ±.024"
Xo at 3.8 kG	9.207" ±.014"	9.059" ±.014"	4.857" ±.010"	4.604" ±.010"
Deviation of Xo at 50 G	-0.1%	-0.2%	+0.2%	-0.7%

The values of Xo at 25 Gauss are lower than those at high field by one or two percent, but those at the injection field of 50 Gauss are the same with those at high field within a few tenth percents. The error of the measurement is ± 0.4~0.5%, including the positioning error of the peaking strips (± 0.1~0.2%), the error in Δx (± 0.05%), the reproducibility of the measurement (± 0.1%), and the error in the correction of the coercive force (± 0.1%). Therefore, the operation point at the injection seems to be well within the operation diamond without any correction.

The radial distribution of Xo(x) was measured with two peaking strips. Most of the mismatching between two bias coils was corrected by adjusting the fixed variable resistor in Fig. 10 with the reversal of the probe and its connection. The pulses of two peaking strips were add in the opposite polarity from each other. They were set at the same fixed position on the scope by adjusting the main current with 1 kΩ Helipot, and by adjusting the current through the bias coil for the peaking strip at the lower field with a variable resistor. Then the current in two bias coils were measured successively. To cancel out any mismatching between two bias coils, the measurement was done with two orientations of the probe and the averaged values were used to calculate the radial distribution of Xo(x).

The observed variations of Xo(x) at 50 Gauss are shown in Fig. 12 and Fig. 13 for the wide gap and narrow gap magnet respectively. These curves are normalized at the center using the observed absolute value. There is not so much difference between them and those at high field in the general tendency[1].

There are not any field bumps at the end of the magnets at 50 Gauss, as was observed on the CEA magnets.

The magnetic length at 50 Gauss was measured using a peaking strip and shown in Fig. 14 and Fig. 15 for the wide gap and narrow gap magnet respectively. The gradient length is also shown in these figures. They do not differ much from those at high field[1].

Appendix I. Calculation of Averaged Xo Value

Let the magnetic field at $r = 0$ and $\pm a$ well inside the magnet be $Bo(0)$ and $Bo(\pm a)$, and take the r-coordinate so that the magnetic field increases with r.

Then,

$$Xo = \frac{Bo(0)}{\left(\frac{\Delta B}{\Delta x}\right)_o} \doteq \frac{2aBo(0)}{Bo(+a)-Bo(-a)}.$$

$$\left(\text{or, } Bo(+a) \doteq Bo(0)\left(1 + \frac{a}{Xo}\right)\right)$$

With the long one-turn coil, we are measuring the magnetic field times the magnetic length BoL_B. Then the averaged value Xo over the whole magnet is given by,

$$Xo = \frac{2aBo(0)L_B(0)}{Bo(+a)L_B(+a) - Bo(-a)L_B(-a)};$$

where $2\,L_B'(x) \equiv L_B(a) = \int_{-\infty}^{+\infty} B(a,z)dz/Bo(a)$ and "a" is the radial displacement from the magnet center line.

$L_B(\pm a)$ can be expressed as follows:

$$L_B(+a) = L_B(0)\ \{1 + f\ (+a)\},$$

$$L_B(-a) = L_B(0)\ \{1 + f\ (-a)\}.$$

In our case L_B is shorter on the higher field, and $f(\pm a)$ is positive. Therefore,

$$Xo \doteq Xo\ [1 - \{f(+a)-f(-a)\}\frac{Xo}{2a} - \frac{1}{2}\{f(+a)+f(-a)\}].$$

If $f(+a) = -f(-a)$,

$$\overline{Xo} \doteq Xo\ [1 - f(a)\frac{Xo}{a}].$$

In another way,

$$L_G(0) = \frac{\int \frac{\partial B}{\partial x}ds}{\left(\frac{\partial B}{\partial x}\right)_o} \doteq \frac{Bo(+a)\ L_B(+a) - Bo(-a)L_B(-a)}{2a\left(\frac{\Delta B}{\Delta x}\right)_o}$$

Then,

$$\overline{X}o \doteq Xo \frac{L_B(0)}{L_G(0)} .$$

Appendix II. Corrections of Peaking Strip Measurement

(A) Effect of Coercive Force of Peaking Strip

The value of the coercive force of the peaking strip is not constant to the change of the rate of the field rise, as is shown in Fig. 11. First the rates of the field rise dB/dt at r = 0" and $\pm$0.5" are calculated by observing the phase angle of the measuring point (e.g. 50 Gauss) on the scope. The corresponding values of the coercive force Hc of the peaking strip are shown on Fig. 11. The delay times Δt of the signal of the peaking strip are calculated from these two values by $\Delta t = H_c/(dB/dt)$. Usually Δt is bigger at lower field side. Therefore, the field value given by the current, which is adjusted to set the signal on the scope at a fixed time, corresponds to an earlier lower field at a place with a smaller value of dB/dt. Therefore, the uncorrected measured value of Xo is smaller than the true value. The differences in Δt between the one at r = 0" and those at r = $\pm$0.5 are calculated, and the corresponding correction Δ(ΔB) in the field difference ΔB between the field values at r = $\pm$0.5" is determined. Then the corrected Xo value is given by,

$$Xo = \frac{Bo}{\Delta B - \Delta(\Delta B)} \doteq \frac{Bo}{\Delta B} \quad 1 + \frac{\Delta(\Delta B)}{\Delta B} ,$$

where (Bo/ΔB) is the measured uncorrected value. The correction in our case was about +2.3% at 50 Gauss and +4.6% at 25 Gauss. The amount of the correction might have been reduced by a factor of two or three with the development of a peaking strip with a smaller value of coercive force.

(B) Effect of Pole Piece to Bias Coil

The length of the bias coil of the peaking strip is finite and comparable to the gap height. The field value at the center of the bias coil is lower by a factor F(<1) than that with an infinite length. This factor can be calculated if the bias coil is in free space. Let the diameter and the length of a coil be 2a and 2b in cm, and its Ampere-turn be an Amp-turn/cm. Then the magnetic field at the center of coil H_{11}, which is parallel to the axis, is given by,

$$H_{11} = \frac{\pi a^2 n}{5} \int_{-b}^{b} \frac{dx}{(x^2+a^2)^{\frac{3}{2}}} = \frac{2\pi n}{5} \frac{b}{\sqrt{b^2+a^2}} .$$

The field H_{11}^{∞} inside an infinite coil with a same Ampere-turn is given by $2\pi\ n/5$.

Therefore,

$$F = \frac{b}{\sqrt{b^2+a^2}} \doteq 1 - \frac{1}{2}\left(\frac{a}{b}\right)^2 .$$

This factor is 0.986 for our bias coil.

The factor F increases when the coil is placed near to pole pieces due to its mirror images. Therefore, it is bigger at the higher field and lower at the lower field. And the value of the field measured by the current is lower at the higher field and higher at the lower field. Then the uncorrected measured value of Xo is bigger than a true value.

Assume the pole pieces are flat, and calculate the effect of the first mirror images on both sides. This may be a fairly good approximation, although the pole pieces are curved. Let the gap height be $2x_o$, then

$$H_{11} = \frac{\pi a^2 n}{5} \left\{ \int_{-b}^{b} \frac{dx}{(x^2+a^2)^{\frac{3}{2}}} + 2 \int_{2x_o-b}^{2x_o+b} \frac{dx}{(x^2+a^2)^{\frac{3}{2}}} + \dots\dots\dots \right\}$$

$$\doteq \frac{2\pi n}{5} \left\{ \frac{b}{\sqrt{b^2+a^2}} + \frac{4x_o a^2 b}{(4x_o^2-b^2)^2} \right\} .$$

The second correction term depends on x_0, and is about 0.2% for $x_0 = 0.5''$. With this equation, the variation ΔF of the factor F is calculated at $r = \pm 0.5''$ with respect to the value at $r = 0''$.

Then the true field values are given by

$B_1 (1 + \Delta F_1)$, $\Delta F_1 > 0$ at high field.

$B_2 (1 - \Delta F_2)$, $\Delta F_2 > 0$ at low field,

where B_1 and B_2 are the values given directly from the value of bias current. Then the corrected value of Xo is given with the measured uncorrected value $X_0^U = (Bo/\Delta B)$,

$$Xo \doteq X_0^U [1 - X_0^U \{(1 + \frac{\Delta r}{X_0^U})\Delta F_1 + (1 - \frac{\Delta r}{X_0^U}) \Delta F_2\}].$$

The correction of this effect in our case was about 0.8% for the regular and modified narrow gap magnets and about 0.2% for the regular and modified wide gap magnets.

Acknowledgement

Dr. F.C. Kellers designed and tested the constant current source for the peaking strips, which was indispensable for the field measurement at low field. Director R.R. Wilson, Professor B.D. McDaniel, and Professor R.M. Littauer gave constructive critical advice throughout this work. The cooperation of the personnel for the magnet construction and the machine shop were much appreciated. Dr. R.A. Beth at Brookhaven National Laboratory was kind enough to supply Permalloy wire for the peaking strips.

References

1. R. Yamada and S. Mori, CS-1, April 27, 1966.
2. H. Nysater, Nucl.Inst. and Meth. 4(1959) 44.
3. S. Yamaguchi et al., INS-TH-18 (Tokyo, Japan), Sep. 10, 1957.
   H. Sasaki and T. Yamakawa, INS-TH-44(Tokyo, Japan), July 31, 1962.
   H. Sasaki, Nucl. Instr. and Meth. 14(1961) 252.

Notes Added in Proof:

After the magnets were measured, some were baked out by passing a dc current through the coils for several days. After installation in the tunnel, remanent fields of up to 4 Gauss were observed. It was then discovered that it was not sufficient to excite the magnets with a large ac current to bring all the magnets to similar magnetic states.

If a dc current corresponding to 10 GeV excitation were passed through a magnet, and if this were followed by an ac current corresponding to 20 GeV excitation, then the remanent field could be reduced to only about half that found if only dc were applied. Therefore, a "training" process was used to bring all the magnets to a similar magnetic state. The magnets were excited with successive decreasing dc currents of alternating sign (starting with roughly the current used during the testing and bakeout). Thus, a damped ac excitation of very low frequency was simulated. The dc remanent fields of the magnets were reduced to a few tenths of a Gauss with a scatter of the same order. An additional demagnetization with ac excitation appeared to have some beneficial effect.

Systematic measurements of the instantaneous magnetic field at injection were not made before and after this training process. However, the evidence is compelling; the training process made the early operation of the machine possible.

Some measurements have been made of the variation of the time of zero-crossing of the field immediately prior to injection with a biased excitation corresponding to a few GeV. The narrow gap magnets have zero-crossing times delayed with respect to those of the wide gap magnets. At 4 GeV and an injection slope of 1 MeV/turn the delay is about 4 microseconds and the extreme fluctuations (of magnets of one type) are of the same order. In other terms, the instantaneous remanent-field <u>variations</u> may be of the order of 1% of the injection field of 50 Gauss.

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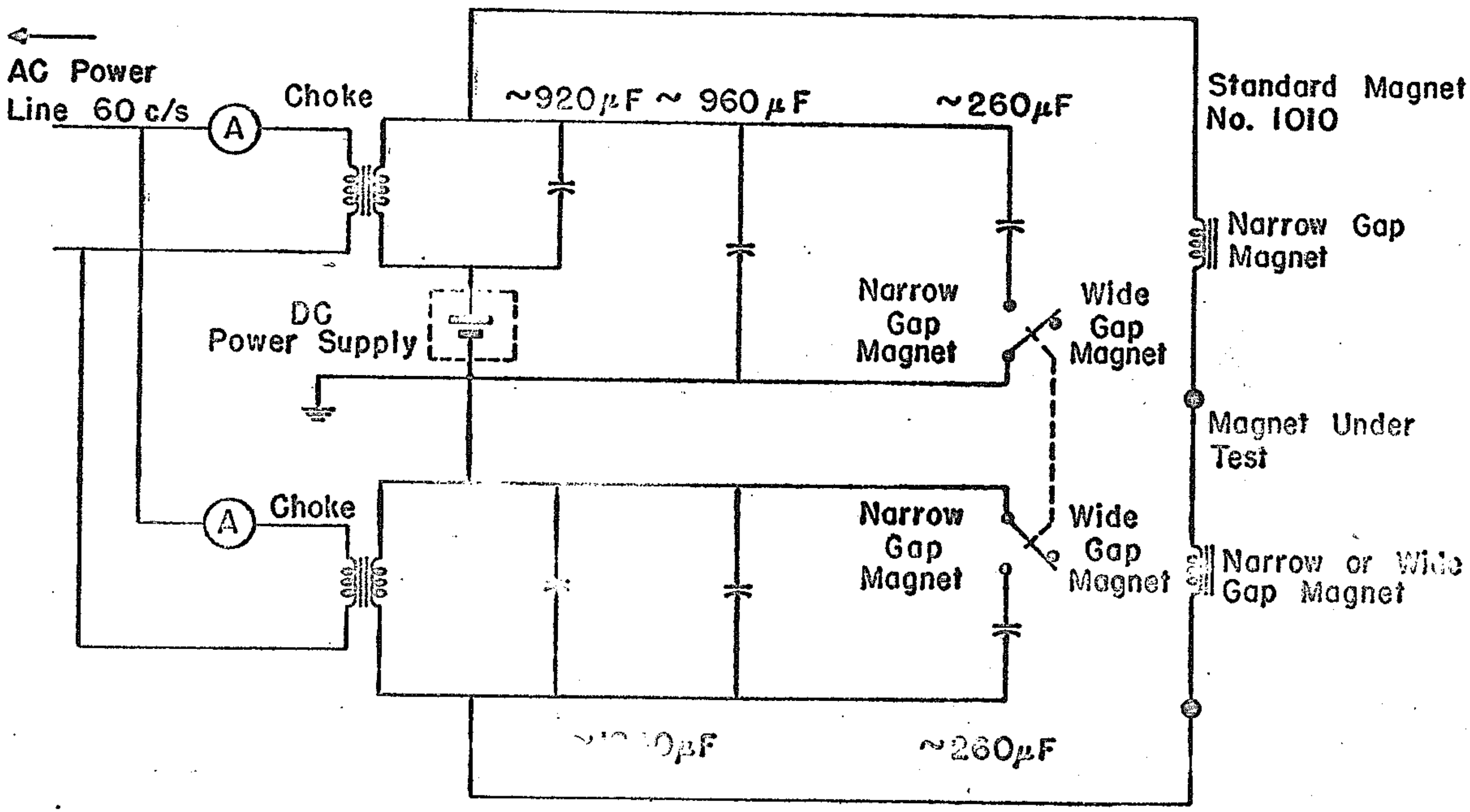

Fig. 1 Connection for Production Test

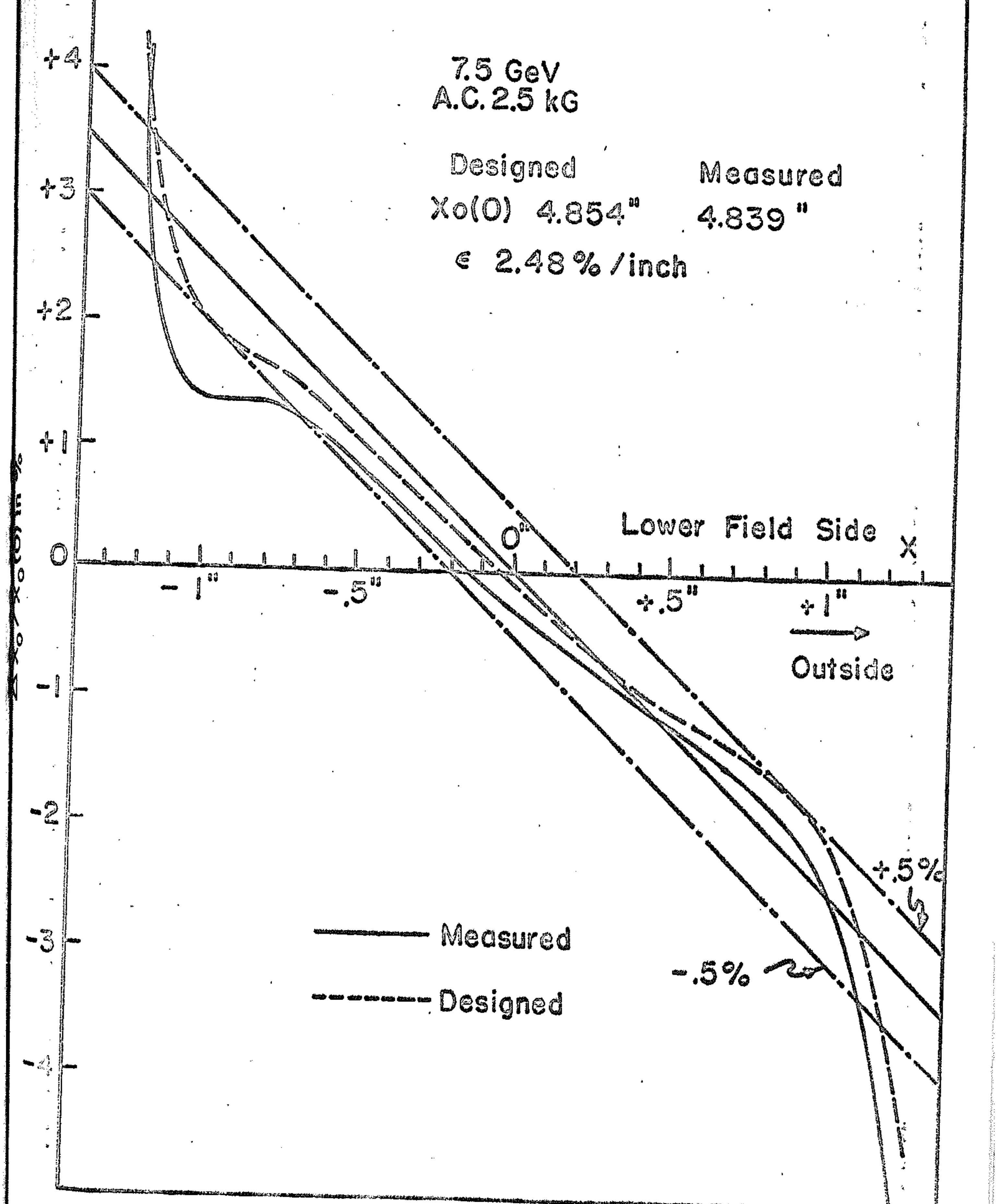

Fig. 2 $X_o(x)$ Distribution of Modified Wide Gap Magnet

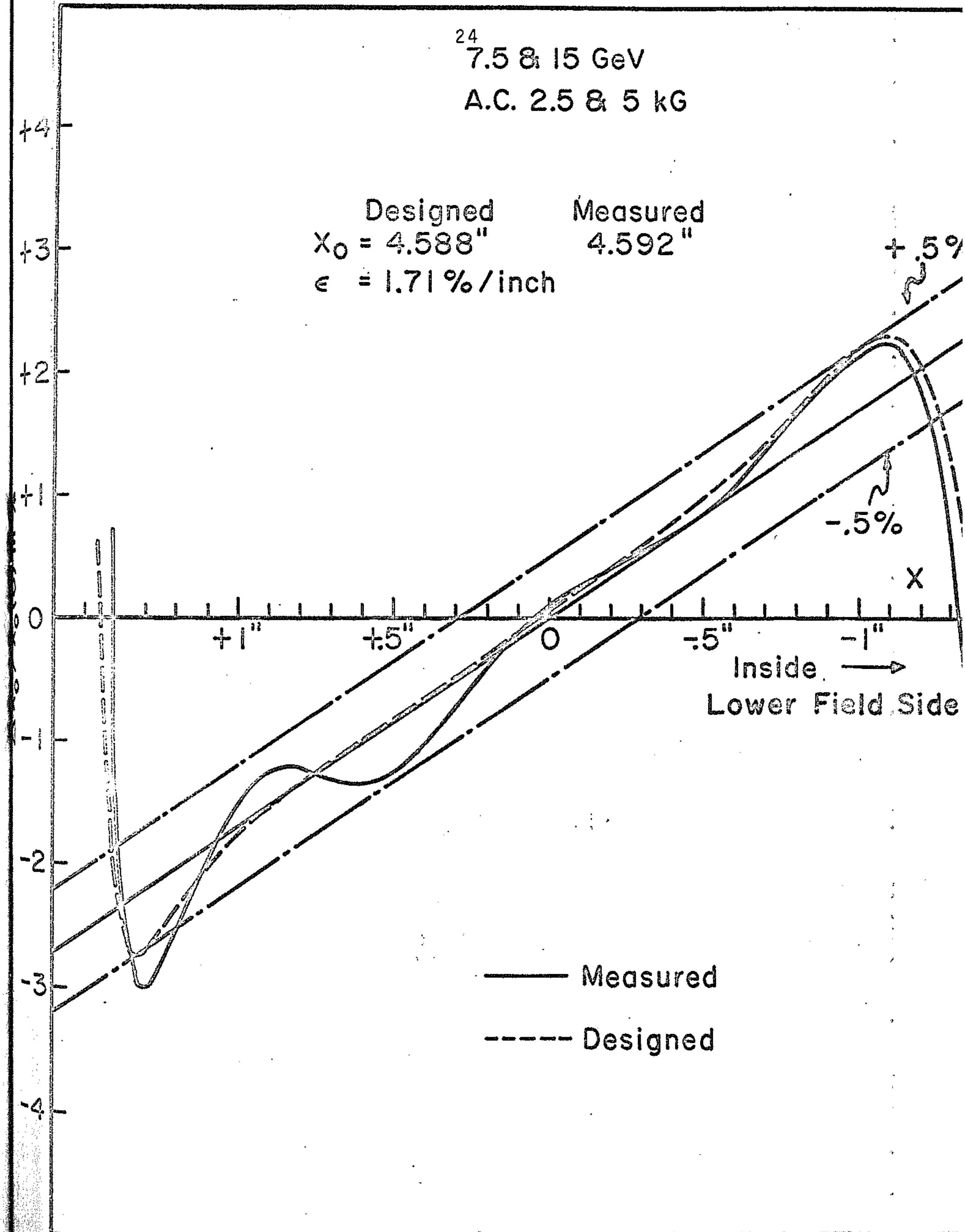

Fig. 3 $X_o(x)$ Distribution of Modified Narrow Gap

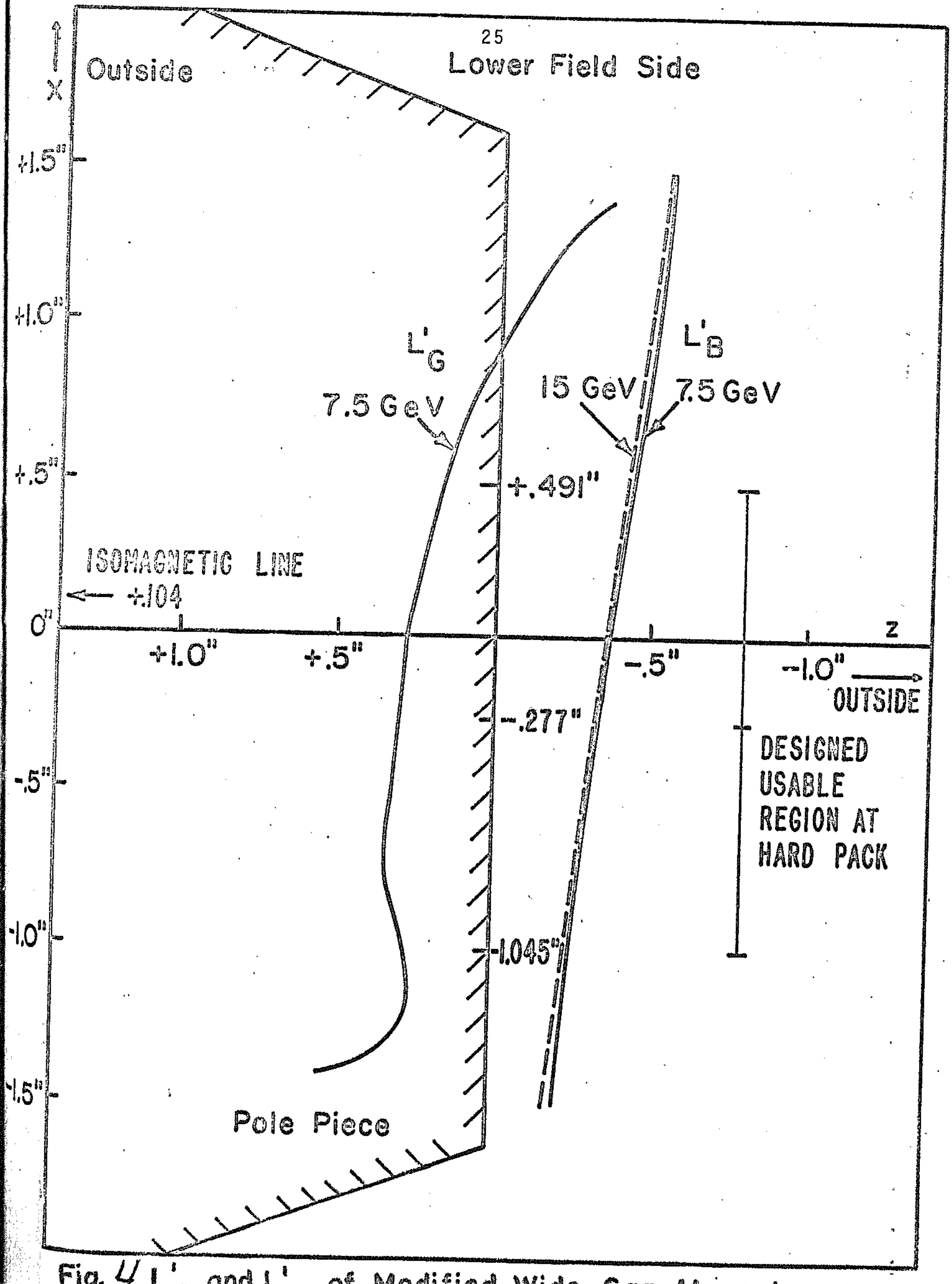

Fig. 4 L'_B and L'_G of Modified Wide Gap Magnet

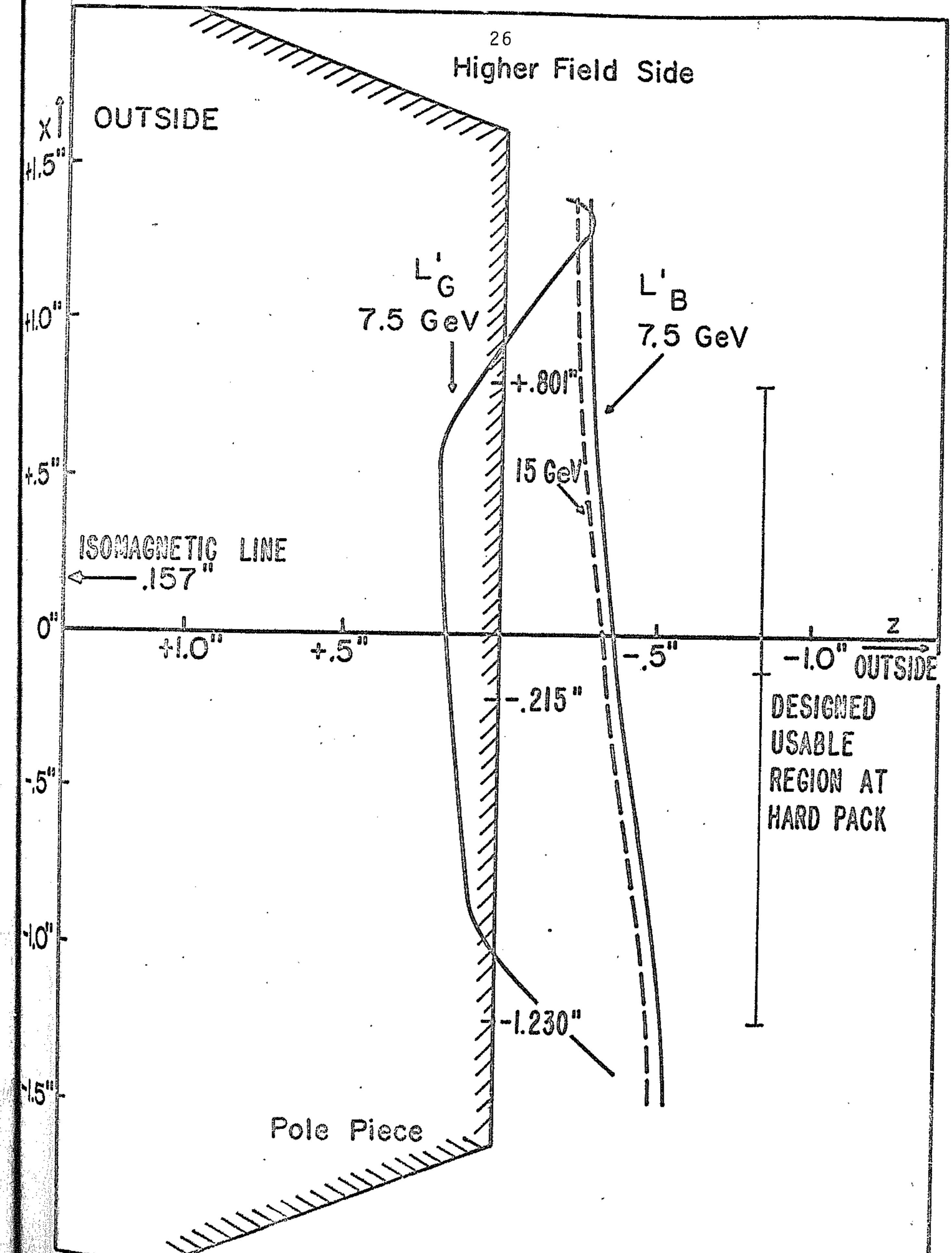

Fig. 5 L'_B and L'_G of Modified Narrow Gap Magnet

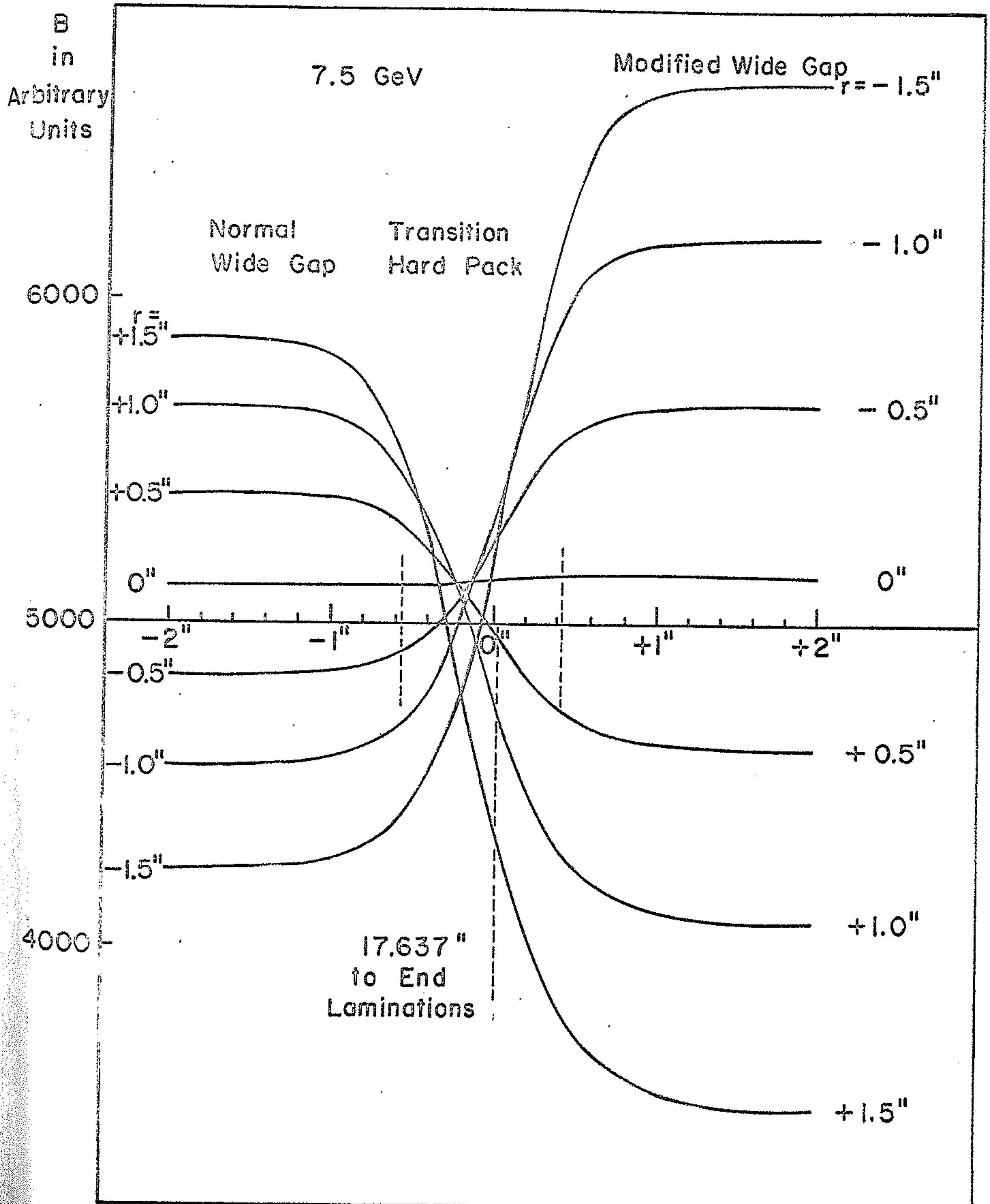

Fig. 6 Magnetic Field at Transition Hard Pack of Modified Wide Gap Magnet

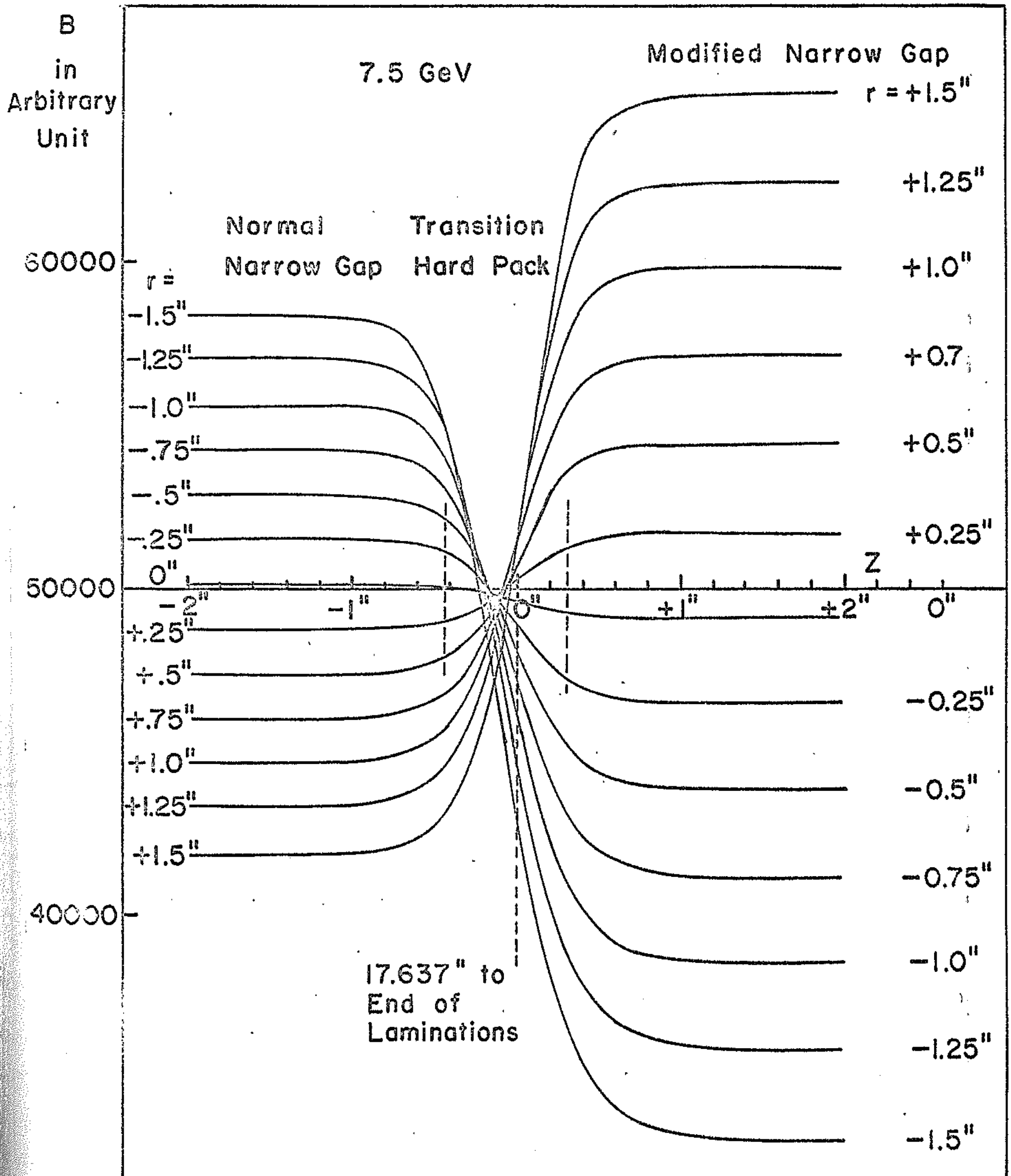

Fig. 7 Magnetic Field at Transition Hard Pack of Modified Narrow Gap Magnet

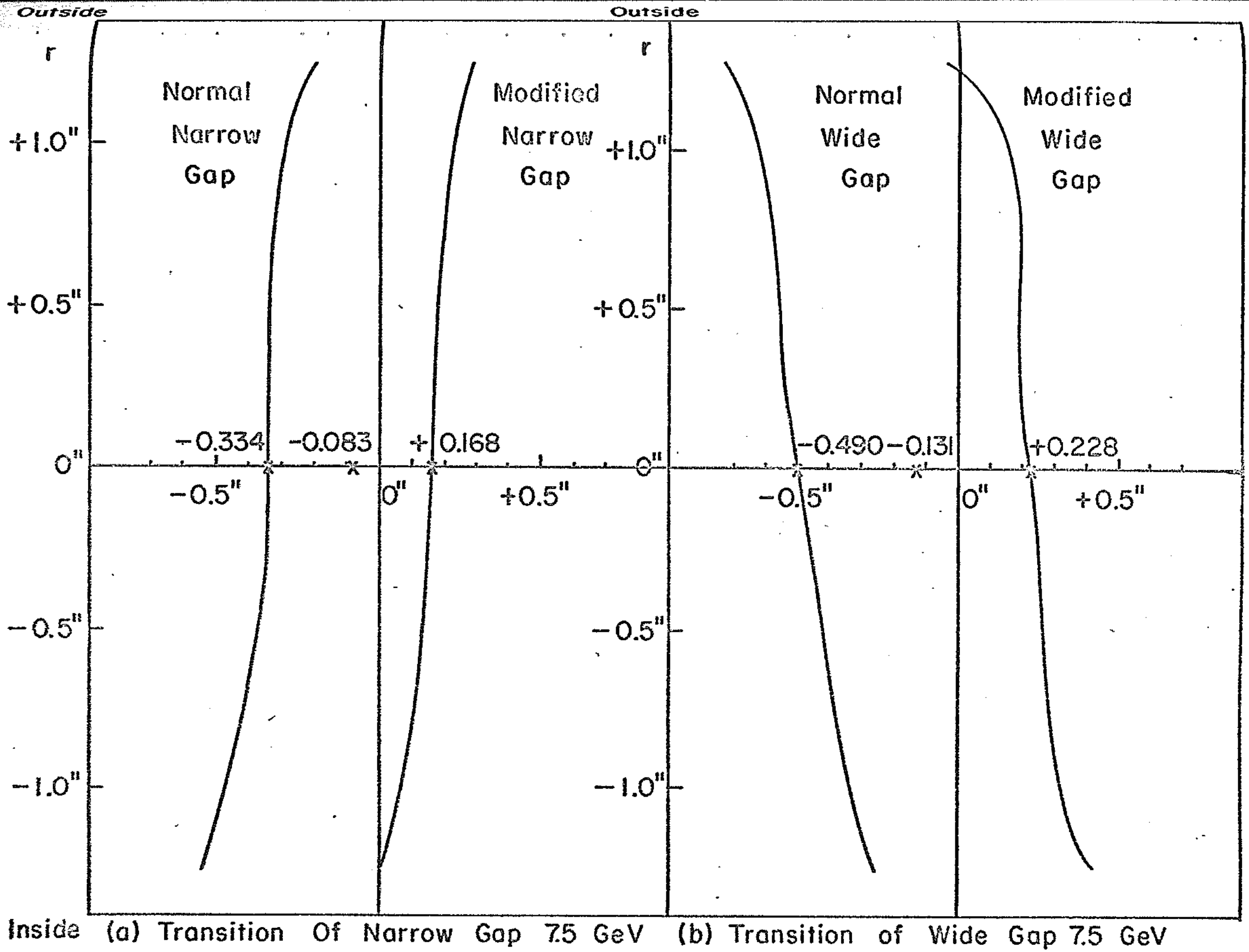

Fig. 8 Gradient Length on Both Sides of Transition Hard Packs.

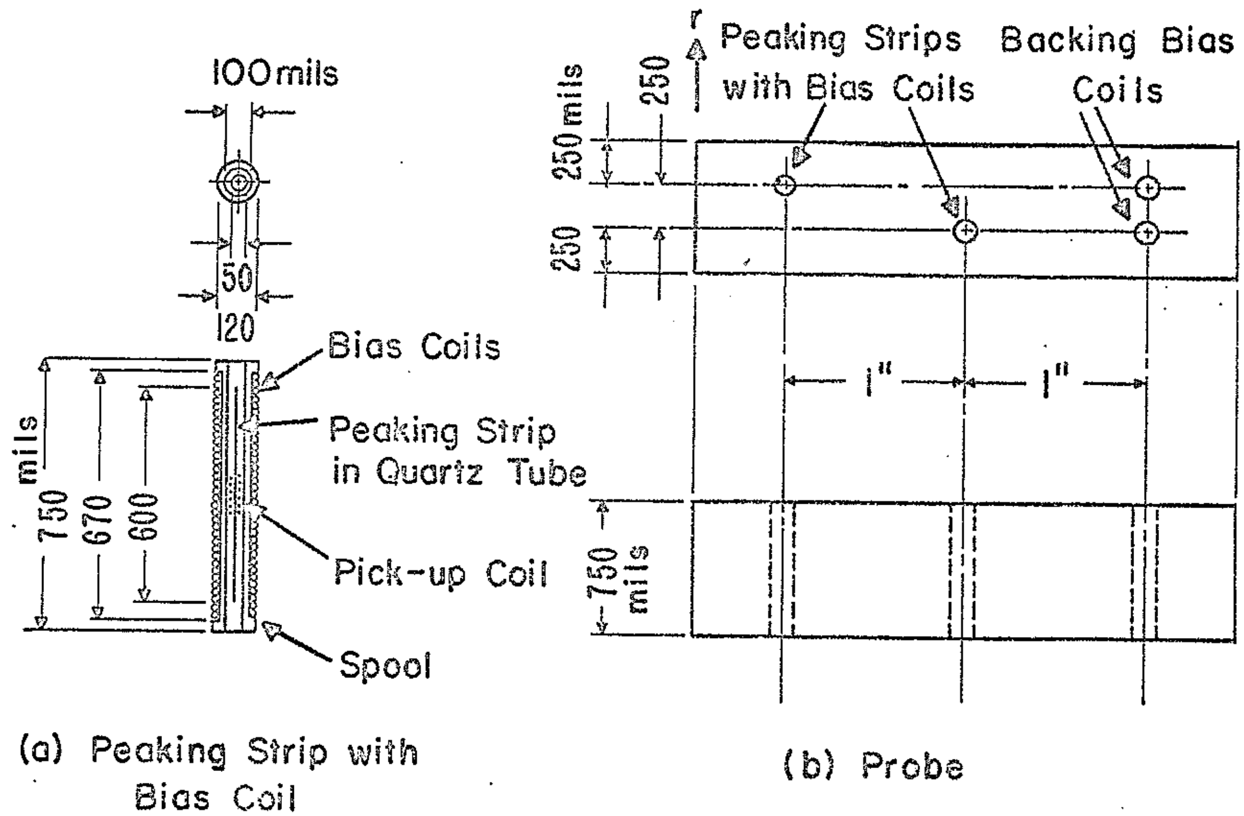

Fig. 9 Peaking Strip and Probe

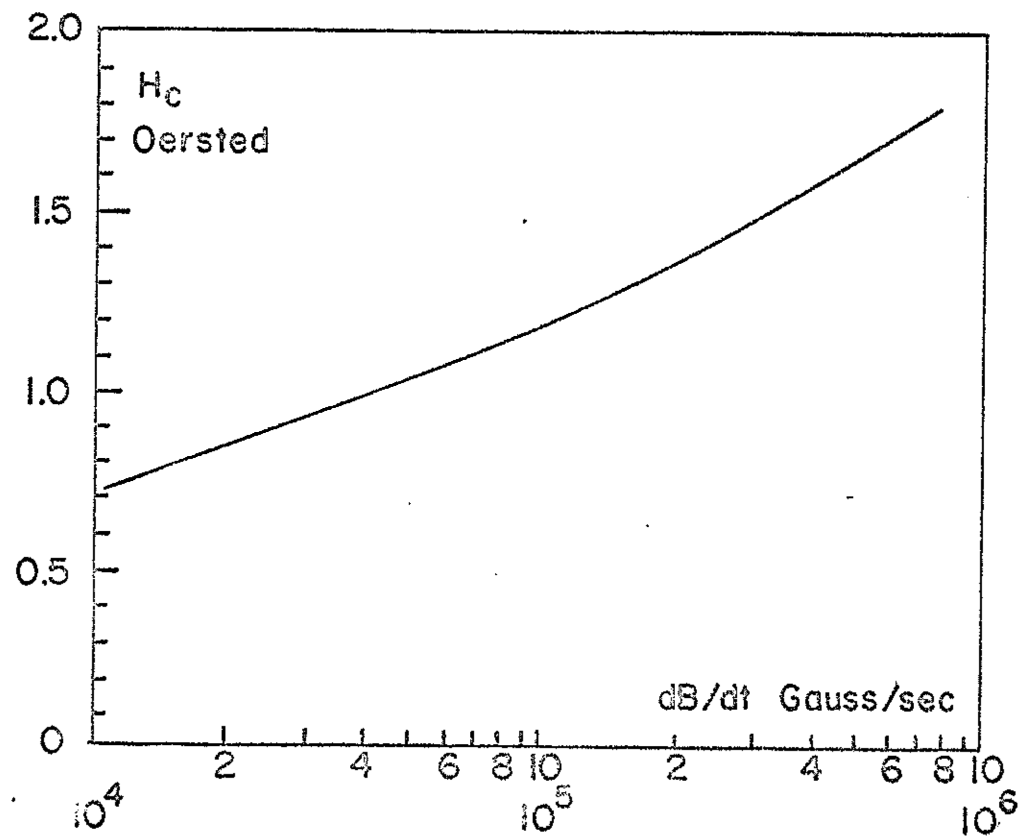

Fig. 11 Coercive Force of Peaking Strip and dB/dt

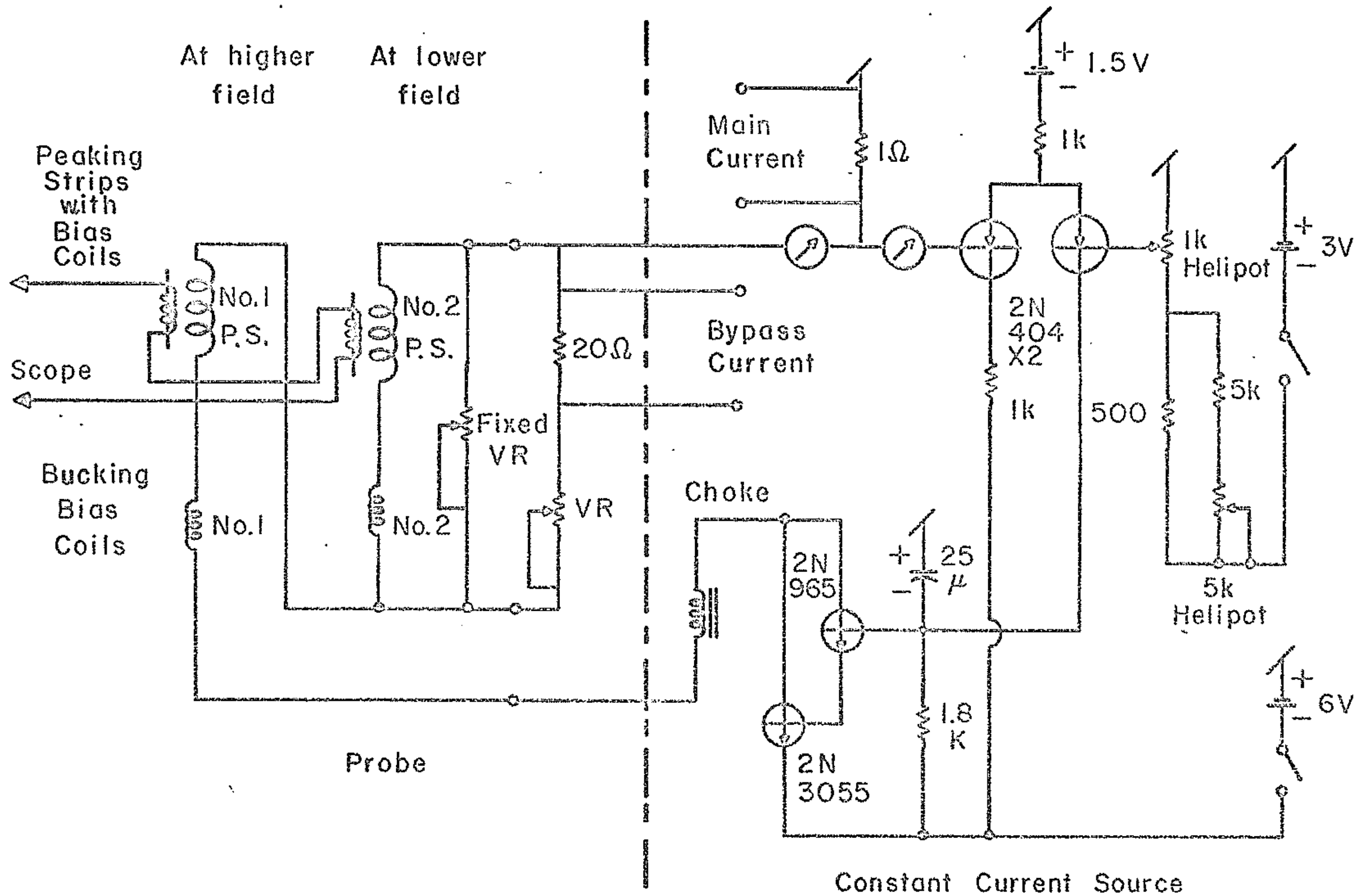

Fig. 10 Circuit for Peaking Strips

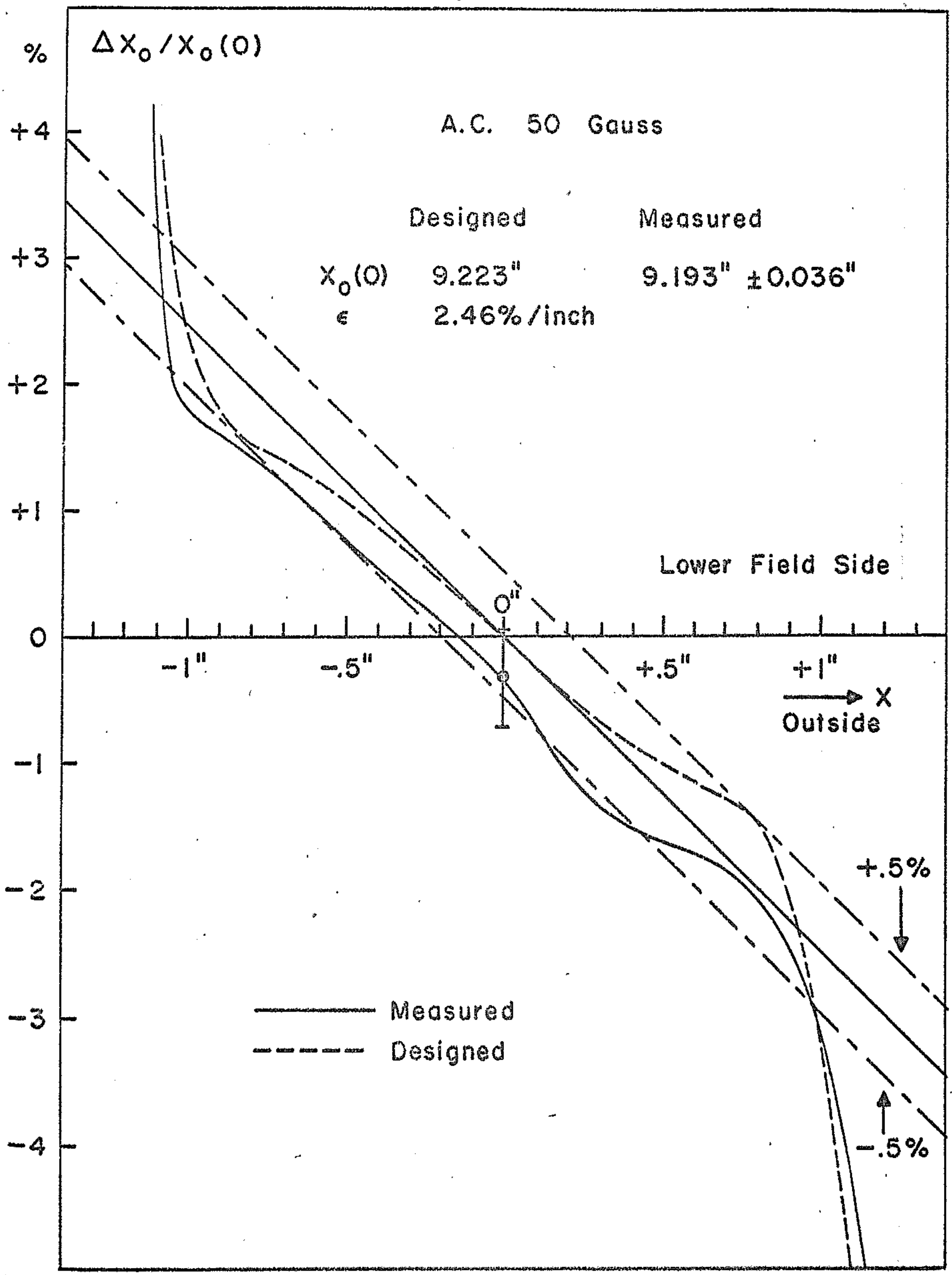

Fig. 12 $X_0(x)$ Distribution of Wide Gap Magnet at 50 Gauss

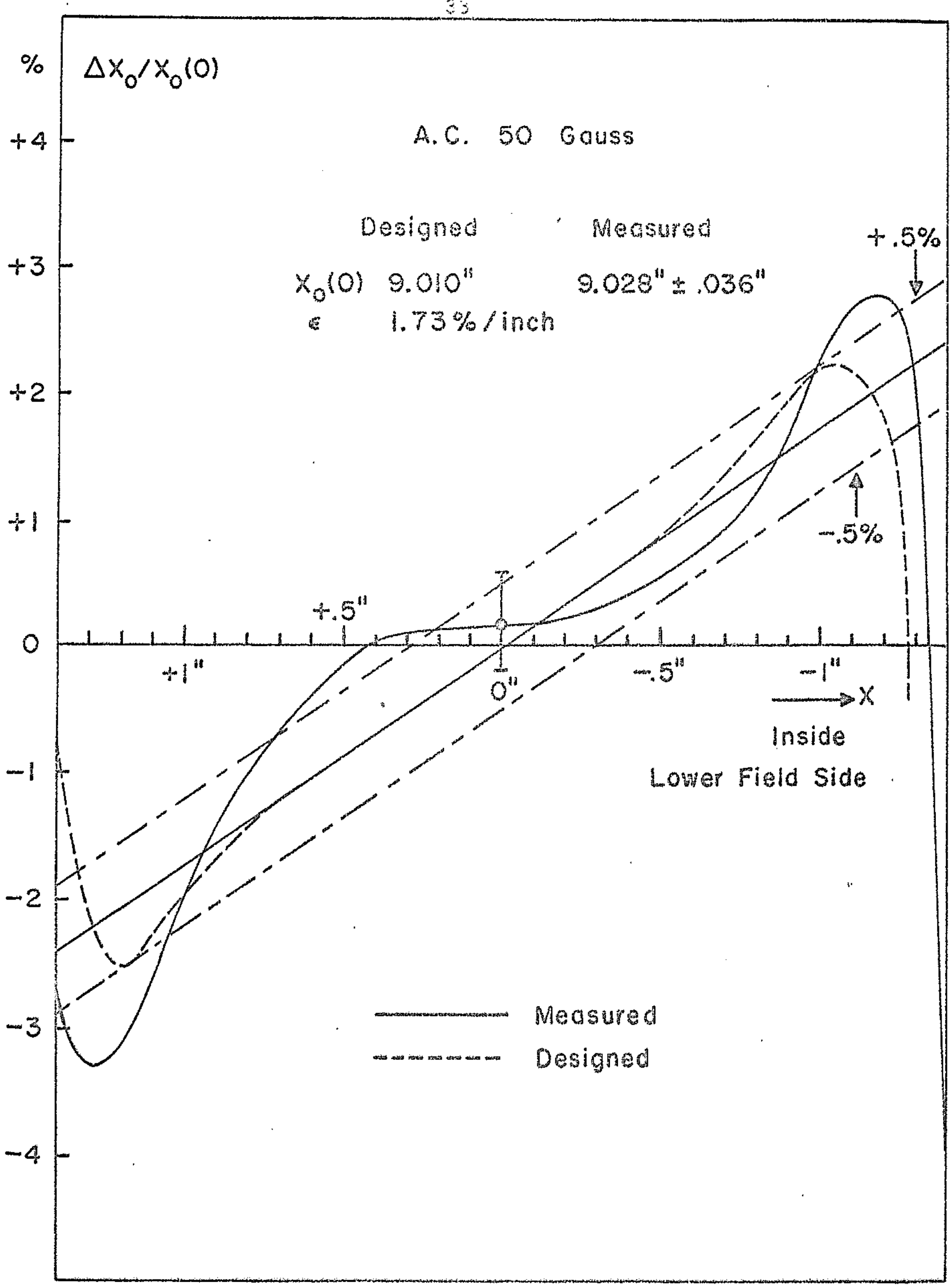

Fig. 13 $X_0(x)$ Distribution in Narrow Gap Magnet at 50 Gauss

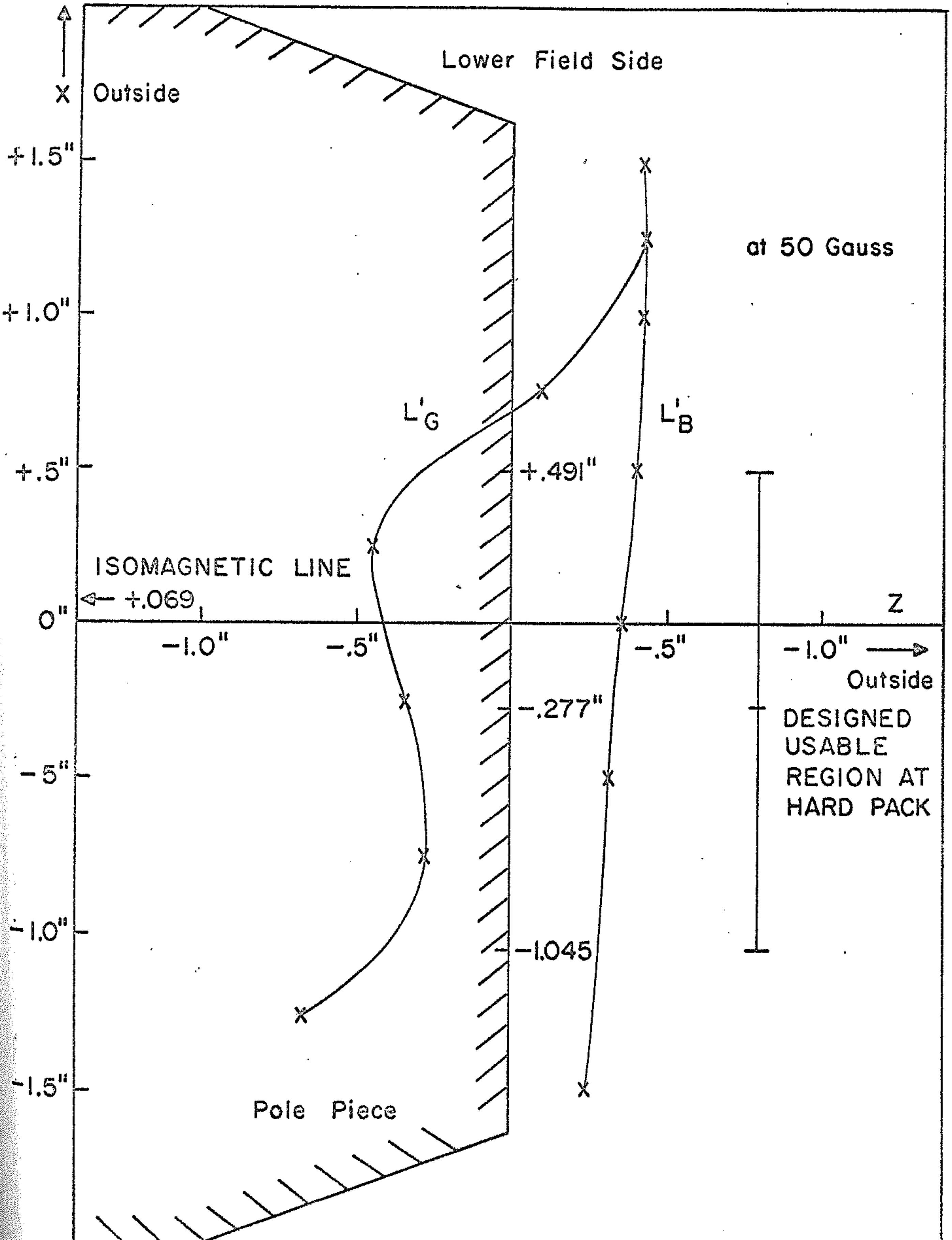

Fig. 14 L_B' and L_G' of Wide Gap Magnet at 50 Gauss

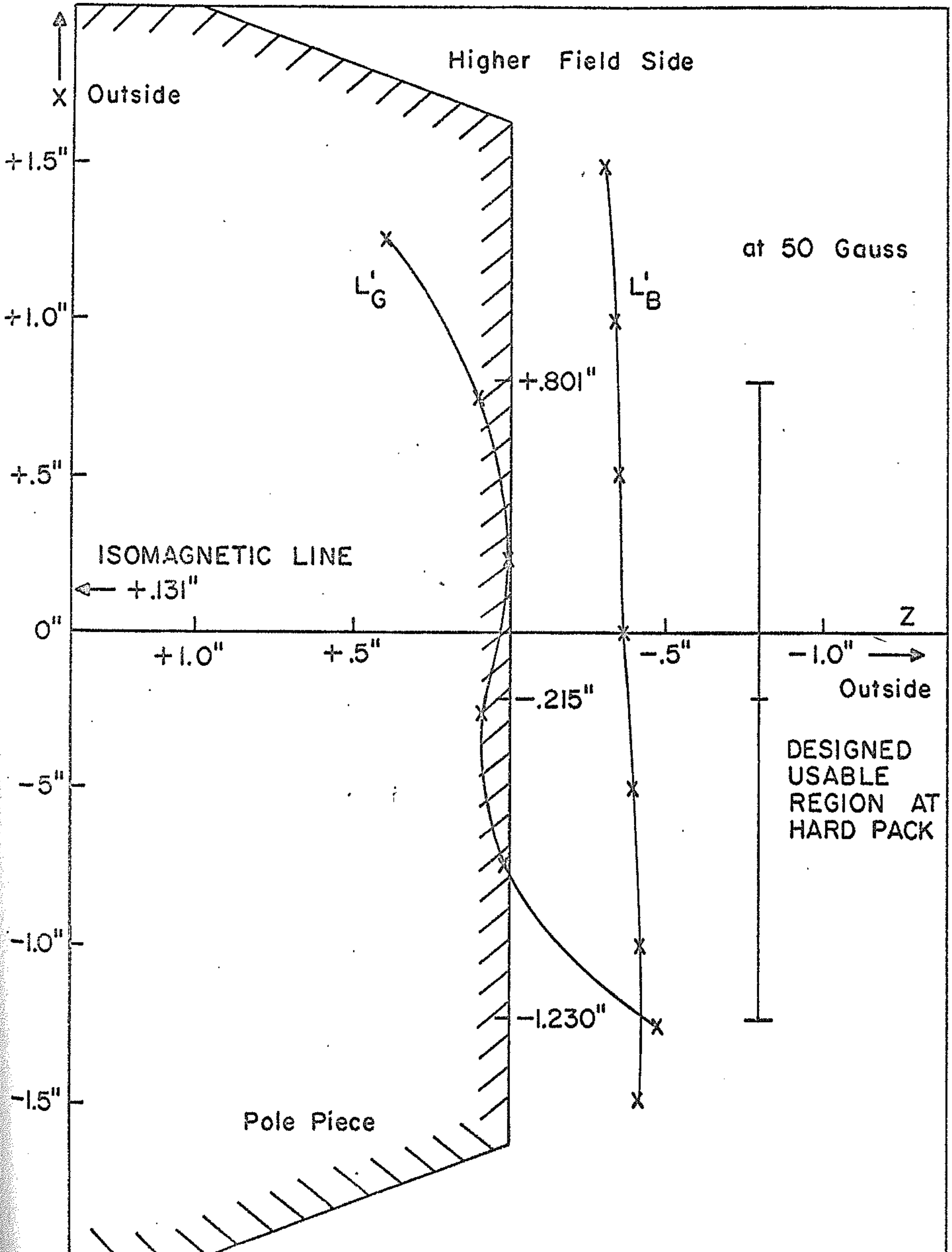

Fig. 15 L_B' and L_G' of Narrow Gap Magnet at 50 Gauss