SNO-STR-91-61

REPORT ON MAGNETIC FIELD COMPENSATION COILS CALCULATIONS.

H. Lee, R. Komar, S. Piechocinski and H.B. Mak.

September 17, 1991.

ABSTRACT:

The objectives of these calculations are to study the influence of an external magnetic field on the photon detection efficiency of the Hamamatsu R1408 PMT and to design current coils to cancel earth's magnetic field in the Heavy Water Cerenkov Detector cavity such that the capital cost of installing the coils can be recovered by reducing the loss in photon detection efficiency. This can be achieved by using 14 horizontal coils listed in the following table.

SPECIFICATIONS OF MAGNETIC FIELD COMPENSATION COILS

Coil #	Elevation (m)	Radius (m)	Amp-Turns
1A	11.9	9.3	320
1B	12.1	9.3	320
2	9.6	9.8	422
3	7.2	10.3	402
4	4.8	10.9	354
5	2.4	11.0	354
6	0.0	11.0	354
7	-2.4	11.0	375
8A	-4.7	10.9	275
8B	-4.9	10.9	275
9A	-9.5	9.8	365
9B	-9.7	9.8	365
10	-11.1	7.0	300
11	-11.1	6.0	293

In normal operation, the amp-turns in each coil will be 2/3 of the value listed in the above table. The maximum residual field in the PMT region is 19μT, and the average photon detection efficiency is more than 97.5% of zero field efficiency for 195mm projected photocathode diameter.

The amp-turns specified for each coil is a factor of 1.5 higher than its normal operating value. This spare current capacity is needed to satisfy the requirement that if any single coil should fail, the current in other coils can be adjust to maintain the high photon detection efficiency.

The elevations of the of the centroid of each coil can vary by ±10cm. If installation cost can be reduced substantially by relaxing this tolerance, this specification can be relaxed. Coils #1, #8 and #9 contain two closely spaced coils (coil A and coil B) each. Coil A and coil B should be physically separated so that it is extremely unlikely to destroy both coils in an accident.

The Hamamatsu R1408 PMT has a large dynode acceptance aperture and the photocathode to first dynode potential difference is typically at 800V; hence the photon detection efficiency of this PMT is not expected to be strongly affected by an external magnetic field. However, the efficiency does decrease slightly with external magnetic field strength. Monte Carlo simulations of the photoelectron trajectories performed at Hamamatsu Photonics and Queen's University show that magnetic fields along the PMT axis (B_z) has a negligible effect on the PMT performance while a 50μT magnetic field perpendicular to the PMT axis (B_x, the magnetic field along the directions of the vanes in the first dynode, and B_y, the magnetic field perpendicular to the direction of the vanes in the first dynode) may decrease the efficiency by about 14%. The influence of B_x and B_y have been measured on a number of PMTs. The PMTs have different sensitivities to magnetic field strengths and directions. The different behaviour is probably caused by misalignments of the dynode structure. The average relative efficiencies of two PMTs are listed in table 1. The effects of B_x and B_y are assumed to be equal and at each field strength, the 4 efficiencies measured at $\pm B_x$ and $\pm B_y$ for each PMT were averaged. The results of Monte Carlo simulations are also listed in table 1.

TABLE 1. EFFECTS OF MAGNETIC FIELD ON PMT

B_z (μT)	B_x (μT)	Relative Efficiency (%) Hamamatsu	Queen's	Experiment
0	0	100	100	100
10	0	100	100	/
40	0	100	100	/
0	10	96	98.5	98.6±0.5
0	20	/	96.5	97.0±0.5
0	30	/	93.4	94.7±0.5
0	40	92	90.0	90.8±0.5
0	50	/	86.3	85.7±0.5

It should be noted that the Hamamatsu and Queen's calculations have very different PMT parameters and initial photoelectron momenta. Hamamatsu used a 26mm diameter circular dynode acceptance aperture and full photocathode illumination. Queen's used a 26mm square aperture with round off corners (dimensions measured from dynodes of broken PMT) and the photocathode is collimated by a 190mm diameter aperture, the size of the collimator used in our measurements. The agreement between Queen's calculated results and data can be deceiving. A small misalignment of the dynode structure will increase the magnetic field sensitivity of the PMT, and the efficiencies may be higher or lower than those expected from a PMT with a perfectly aligned dynode structure (which the calculation assumed) depending on the magnetic field directions. The averaging may or may not smooth out such variations. It is very difficult to calculate the influence of magnetic field on the efficiency of a PMT with a tilted dynode structure. Most electron trajectory calculations assume a cylindrically symmetric electric field inside the PMT.

The earth's magnetic field in the Sudbury region is about 57μT, a combination of 55μT vertical field and 15μT horizontal field. However, there are substantial variations and a 60μT field is assumed in calculating the average reduction in the photon detection efficiency in the SNO detector. The PMTs are assumed to be evenly distributed on the surface of a sphere. The weighted average efficiency is 87.2% of the zero field efficiency if 195mm diameter projected photocathode is used. The weighted average efficiency is 88.0% of the zero field efficiency if 198mm diameter projected photocathode area is used. Calculations show that electrons emitted in the region corresponding to a projected diameter of 170mm have a higher probability of missing the dynode acceptance aperture than electrons emitted from regions closer to the edge of the photocathode. This is confirmed by photocathode scan measurements. Hence it is quite reasonable that the efficiency at 195mm diameter projected photocathode is less than the efficiency at 198mm diameter projected photocathode.

The 12% to 13% loss in photon detection efficiency is too high. The capital cost of the PMT system is about C$10.3M and a 12% reduction in photon detection efficiency is equivalent to a loss of C$1.2M which is much more than the capital cost of installing magnetic field cancellation coils. In the design criteria document, we recommended that current coils be used to cancel the earth's magnetic field in the cavity to reduce the loss to an acceptable value. The average efficiencies at 10μT to 30μT external magnetic fields for 195mm projected photocathodes diameter are shown in table 2. The efficiencies for 198mm projected diameter at corresponding external fields are expected to be slightly higher.

TABLE 2. AVERAGED RELATIVE PMT EFF. (100% AT B=0μT)

B (μT)	Averaged efficiency (%) 195mm
0	100.0 (normalized)
10	99.1
15	98.3
20	97.4
25	96.3
30	94.9

The calculations show that if the residual magnetic field within the PMT region can be kept to less than 20μT, the loss in the average photon detection efficiency will be less than 2.5%, a value deemed to be acceptable.

The horizontal component of the earth's magnetic field is approximately 15μT. Because of the shape of the cavity, it is difficult and expensive to construct vertical coils to cancel this component. At 15µT external field, the calculated photon detection efficiency is about 98%, 1% more than that at an external field of 20µT. The capital cost for installing the vertical coils will be substantially more than C$100k. Hence in the in the design criteria document, we recommended that vertical coils should not be used, and the configuration of the horizontal coils should be designed to cancel the vertical component of earth's magnetic field so that the total external magnetic field is less than 20µT. Calculations using 6 and 12 horizontal coils indicate that roughly the same number of total amp-turns is needed in order to reduce the total magnetic field to an acceptable level; hence there is no saving in material cost in using fewer coils. There may be a small saving in installation cost. However, with only 6 coils, if one coil should fail, it is not possible to adjust the current in the other coils to keep the residual magnetic field within acceptable value. Hence we recommended a 12 horizontal coils design. The characteristics of the coils are listed in 3. To allow for the possibility that 1 coil may be destroyed, it was recommended that the amp-turns capacity of each coil should be a factor of 2 larger than the values listed in the table. It was pointed out by Mr. R.K. Willmott (Monenco consultant) that the factor of 2 might not be sufficient in some cases.

TABLE 3. NORMAL OPERATING AMP-TURNS IN CURRENT COILS.

Coil #	Elevation (m)	Radius (m)	Amp-Turns
1	12.0	9.3	478
2	9.6	9.8	281
3	7.2	10.3	268
4	4.8	10.9	236
5	2.4	11.0	236
6	0.0	11.0	236
7	-2.4	11.0	236
8	-4.8	10.9	236
9	-7.2	10.3	272
10	-9.6	9.8	389
11	-11.1	7.0	165
12	-11.1	6.0	165

Mr. R.K. Willmot also pointed out that the lower ramp opening extends from elevation -8.73m to -4.77m. This will force coil #9 to bend around the ramp opening, producing a large horizontal field. Thus coil #9 is removed and new calculations were carried out using 11 coils. The amp-turns for each coil was calculated by a least-squares-fit program (Datanal by Dr. J.L. Ouellette) that centred the vertical component of the magnetic field generated by the current coils at -55µT. There are some constraints to keep the capital cost down and these are discussed later. The 11 coils configuration and the amp-turns are listed in table 4.

TABLE 4. GEOMETRY AND AMP-TURNS OF THE 11 COILS CONFIGURATION

Coil #	Elevation (m)	Radius (m)	Amp-Turns
1	12.0	9.3	427
2	9.6	9.8	281
3	7.2	10.3	268
4	4.8	10.9	236
5	2.4	11.0	236
6	0.0	11.0	236
7	-2.4	11.0	250
8	-4.8	10.9	366
9	-9.6	9.8	487
10	-11.1	7.0	200
11	-11.1	6.0	195

The amp-turns in coils #1, #8 and #9 are more than 350 amp-turns. If any of these coils should fail, the current in neighbouring coils will have to be increased by large factors in order to compensate for the failed coil; thus increase the capital cost because of the spare capacities required. It is more cost effective to replace each of these coils by two separate coils, each carries half the designed amp-turns. The two coils should not be in close contact so that the chance of damaging both coils in an accident is minimal. The recommended design has 14 coils and the normal amp-turns are listed in table 5.

TABLE 5. GEOMETRY AND AMP-TURNS OF THE 14 COILS CONFIGURATION

Coil #	Elevation (m)	Radius (m)	Amp-Turns
1A	11.9	9.3	213
1B	12.1	9.3	213
2	9.6	9.8	281
3	7.2	10.3	268
4	4.8	10.9	236
5	2.4	11.0	236
6	0.0	11.0	236
7	-2.4	11.0	250
8A	-4.7	10.9	183
8B	-4.9	10.9	183
9A	-9.5	9.8	243
9B	-9.7	9.8	243
10	-11.1	7.0	200
11	-11.1	6.0	195

The separations between coil A and coil B should be as small as possible; the specified separation between such pairs of coils are not critical, the only requirement being that the elevation of coil #1 should be close to 12m, coil #8 close to -4.8m and coil #9 close to -9.6m.

With the amp-turns listed in table 5, the magnetic fields in the region of the photocathode surface are shown in figures 1a and 1b. In figure 1, the x-axis are points on the semi-circle where the PMTs are located. The semi-circle is divided into 126 points, with point 0 being at the top (polar angle 0°) and point 126 being at the bottom (polar angle 180°). The large fields near the top and bottom are not real. They are artificial effects produced by the calculations. Cylindrical symmetry is assumed in the calculation. The residual field is the vector sum of the field from the current coils and earth's magnetic field (vertical component is 55µT and horizontal component is 15µT). The angle between the horizontal components of the magnetic field from the current coils and earth's magnetic field is the azimuthal angle of the PMT location. The maximum residual field is about 19µT which is mainly a horizontal field at polar angles around 135°. This may seem large. However, such large field exists only over a small region; azimuthal angle from 330° to 30° and polar angle from 125° to 160°. The PMT axes in this region are at approximately 45° to the horizontal; hence the maximum magnetic field perpendicular to the PMT axis is only about 14µT (the vertical fields have been taken into account in this estimate). With the current in the coils listed in table 5, The average photon detection efficiency should be approximately 98.2% of the zero magnetic field efficiency for a 195mm projected photocathode diameter and slightly higher for a 188mm projected photocathode diameter.

There is a remote possibility that one of the coils may fail, and the current in the other coils will have to be adjusted to partially compensate for this loss. An arbitrary condition that the amp-turns of any coil must be kept to be less than 150% of the values listed in table 5 is imposed in the optimization process. To study the effects of losing one coil, the current in one of the 14 coils was set to zero and the amp-turns in other coils were calculated by a least-squares-fit procedure. If the calculated amp-turns of some coils were more than 150% of the values listed in table 5, the amp-turns of these coils were fixed at 150% of the values listed in table 5 and the fitting was repeated. The results of this investigation show that, with the design specifications that are a factor of 1.5 higher than the amp-turns listed in table 5, it is possible to compensate for the loss of any single coil by suitable adjustments in the current in the other coils so that the average photon detection efficiency is not less than 97% of the zero field value. The calculations show that the most critical coil is coil #7. If this coil fails, the maximum horizontal magnetic field from the current coils is about 9µT. Fortunately, such large field exists around the polar angles of 90° where the horizontal field from the coils are along the PMT axes. Thus even the maximum residual field is about 25µT, most of the field will be along the PMT axes and has little effect on the PMT. The maximum residual field perpendicular to the PMT axis is about 16µT and is within our acceptable limit. The magnetic fields for one failed coils are shown in figures 2 to 11, where figures labelled by a are vertical fields and figures labelled b are horizontal fields. The large horizontal fields at polar angles 0° and 180° are artifacts produced by computer round off errors.

CONCLUSION

Photoelectron trajectory calculations show that at an external magnetic field of 15μT, the photon detection efficiency is about 98% of the zero field efficiency; and is about 1% more than the efficiency at an external magnetic field of 20μT. The horizontal component of earth's field in the Sudbury region is about 15μT. To construct vertical coils to cancel this horizontal field would be much more than 1% of the PMT system capital cost (about C$10.2M). Hence it was recommended that vertical coils should not be used. The horizontal coils should be designed to cancel the vertical component of earth's field so that the total external field is less than 20μT anywhere over the region where the PMTs are located.

With 14 current coils at 11 elevations, it is possible to cancel earth's magnetic field such that, over the region of interest, the residual magnetic field is less than 20μT. With this coil design, only a small fraction of the PMTs will be situated in the region where the residual field is as high as 19μT. Thus the average photon detection efficiency should be more than 97.5% of the zero magnetic field efficiency for a 195mm projected photocathode diameter and slightly higher for a 198mm projected photocathode diameter.

By splitting the high amp-turns coils into two physically separated coils, it is possible to allow for the destruction of any single coil with a spare current capacity of 50% for each coil, substantially less than the 100% recommended in the design criteria document submitted earlier. The recommended coil specifications are

SPECIFICATIONS OF MAGNETIC FIELD COMPENSATION COILS

Coil #	Elevation (m)	Radius (m)	Amp-Turns
1A	11.9	9.3	320
1B	12.1	9.3	320
2	9.6	9.8	422
3	7.2	10.3	402
4	4.8	10.9	354
5	2.4	11.0	354
6	0.0	11.0	354
7	-2.4	11.0	375
8A	-4.7	10.9	275
8B	-4.9	10.9	275
9A	-9.5	9.8	365
9B	-9.7	9.8	365
10	-11.1	7.0	300
11	-11.1	6.0	293

The elevations of the coils should be within ±0.1m of the values specified, a tolerance that can readily be achieved in standard construction. If this causes substantial cost escalation, it can be modified to an acceptable level. The diameters of the coils should be within ±0.5m of the values specified if this can be achieved easily. To avoid excessive back filling, the coil diameters can be increased. Deviations from true circle should be within ±0.1m. Again if this causes large cost escalation, this specification can be relaxed.

The amp-turns specified for each coil is a factor of 1.5 higher than its normal operating values. This spare current capacity is needed because the current in neighbouring coils will have to be increased to compensate for the destruction of any single coil. The separations of coils A and B are not critical, the only requirement being that the averaged elevation of coil #1 is 12m, of coil #8 is -4.8m and of coil #9 is -9.6m. Coil A and coil B should be physically separated so that it is extremely unlikely that both coil A and coil B can be destroyed by the an accident.

It should be pointed out that the amp-turns specified for the coils are estimates only. The earth's magnetic field in the detector cavity may differ from the field used in these calculations. When the cavity is excavated, the magnetic field in the cavity should be surveyed. Also, the dimensions and locations of the installed coils will likely to be different from those listed in the table of specifications; in fact, the coils may not be circular. As soon as the magnetic field and coil geometries are known, calculations should be repeated to optimize the current in each coil. The factor of 1.5 reserve in the current capacity will likely to be sufficient to cover unforeseen problems. Eventually, the current in each coil may have to be adjusted in-situ to produce the smallest residual field.

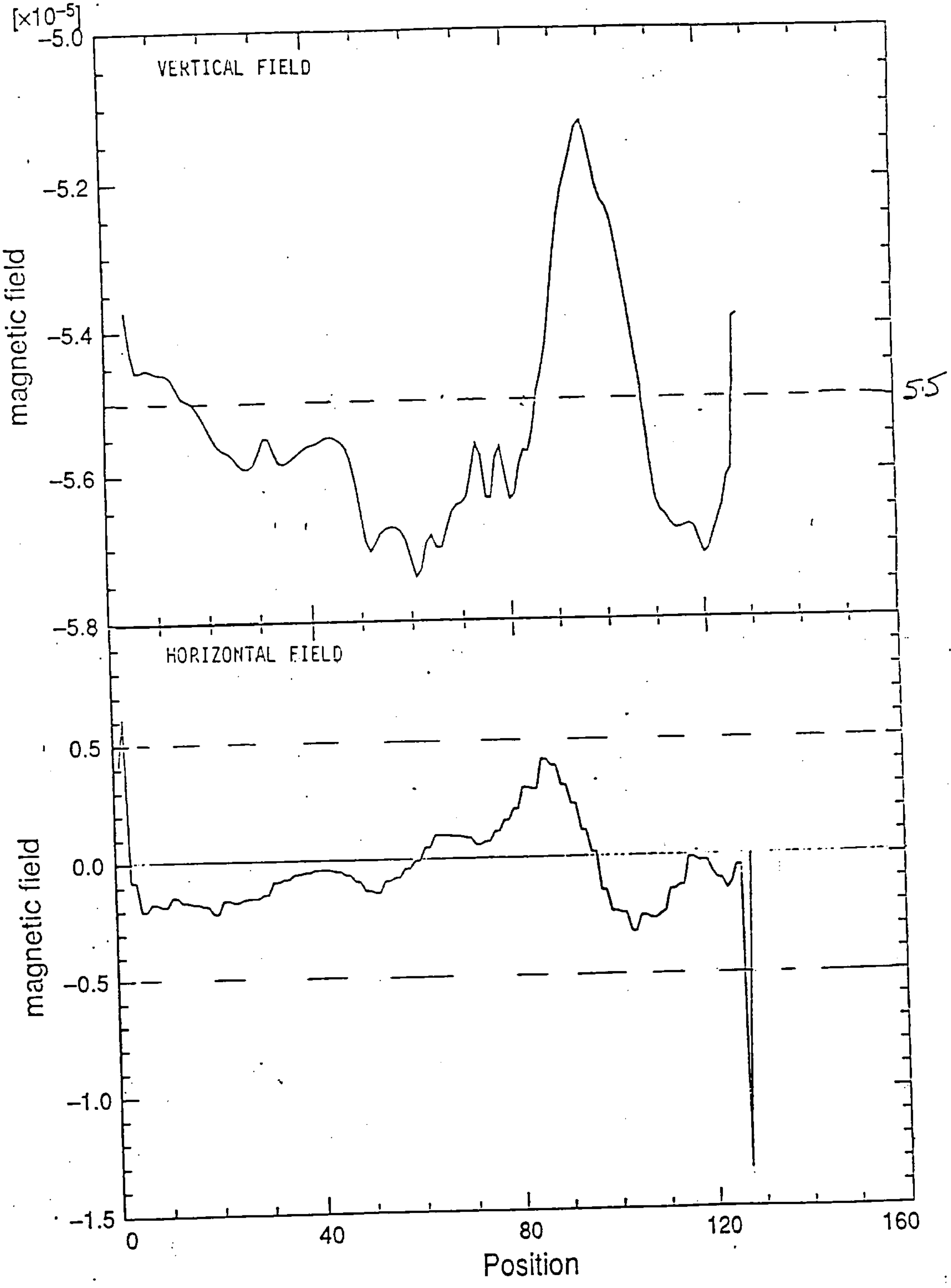


FIGURE 1 ALL 13 COILS

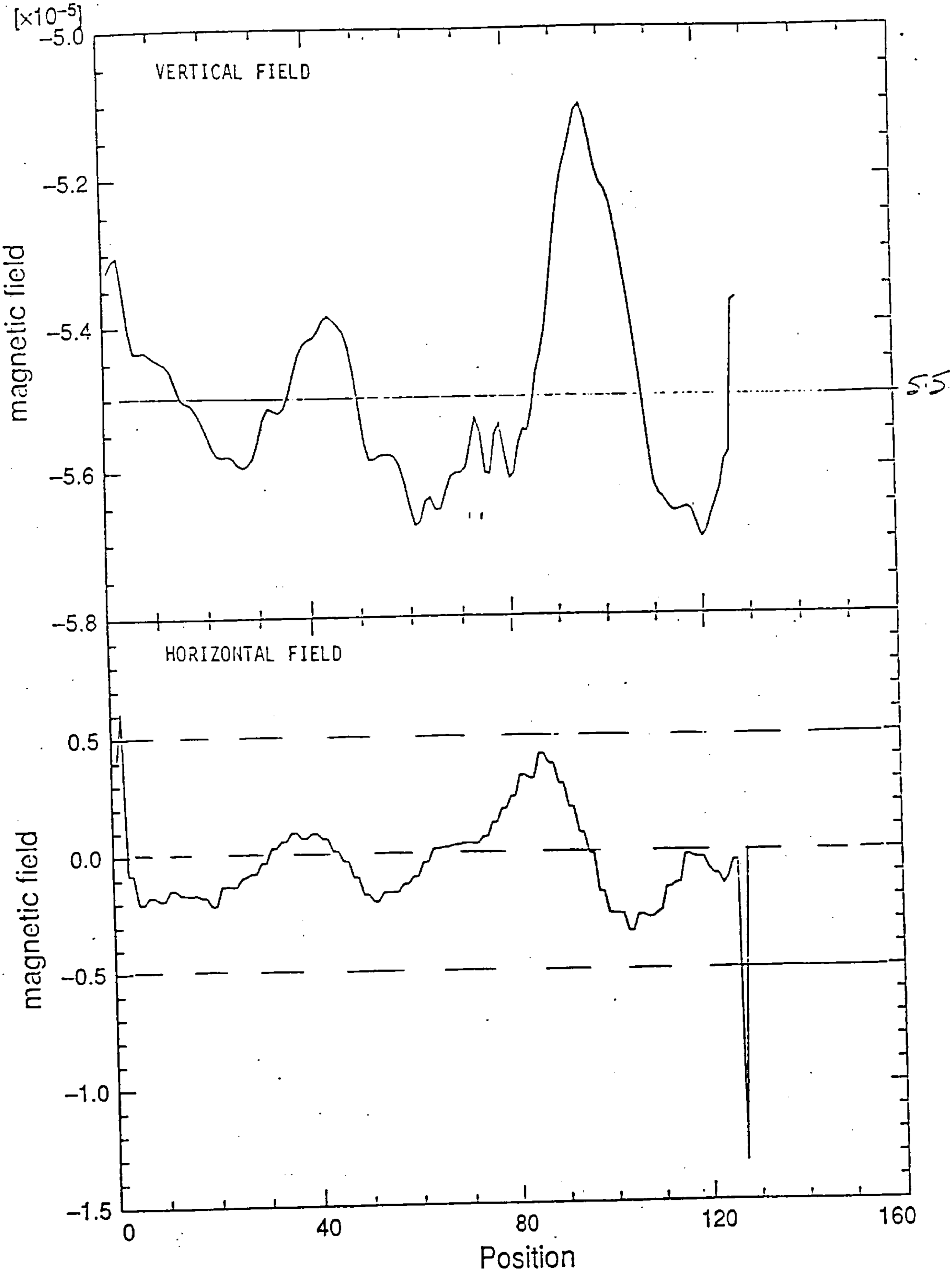


FIGURE 2 CURRENT IN COIL 1A OR 1B IS ZERO

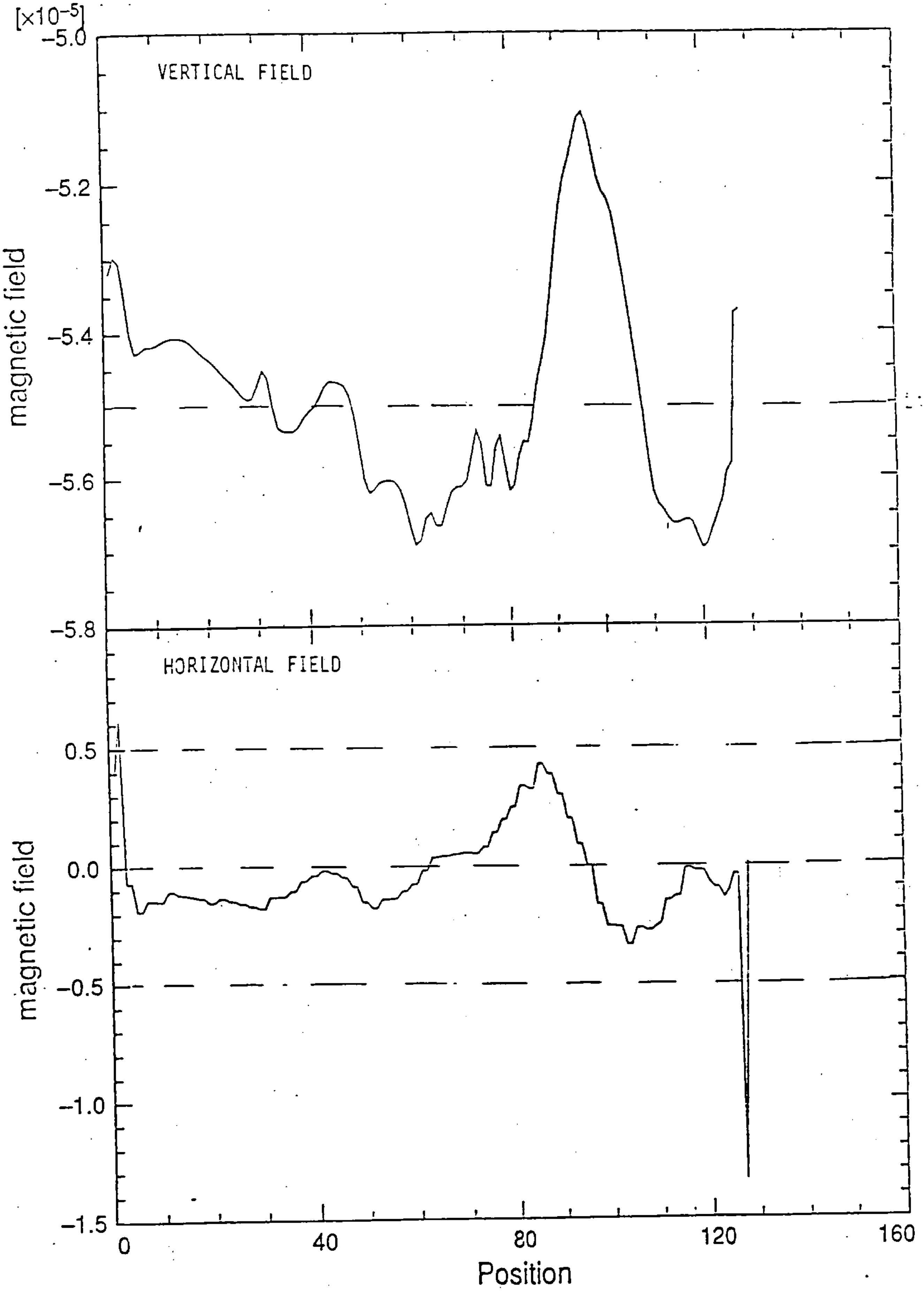


FIGURE 3 CURRENT IN COIL 2 IS ZERO

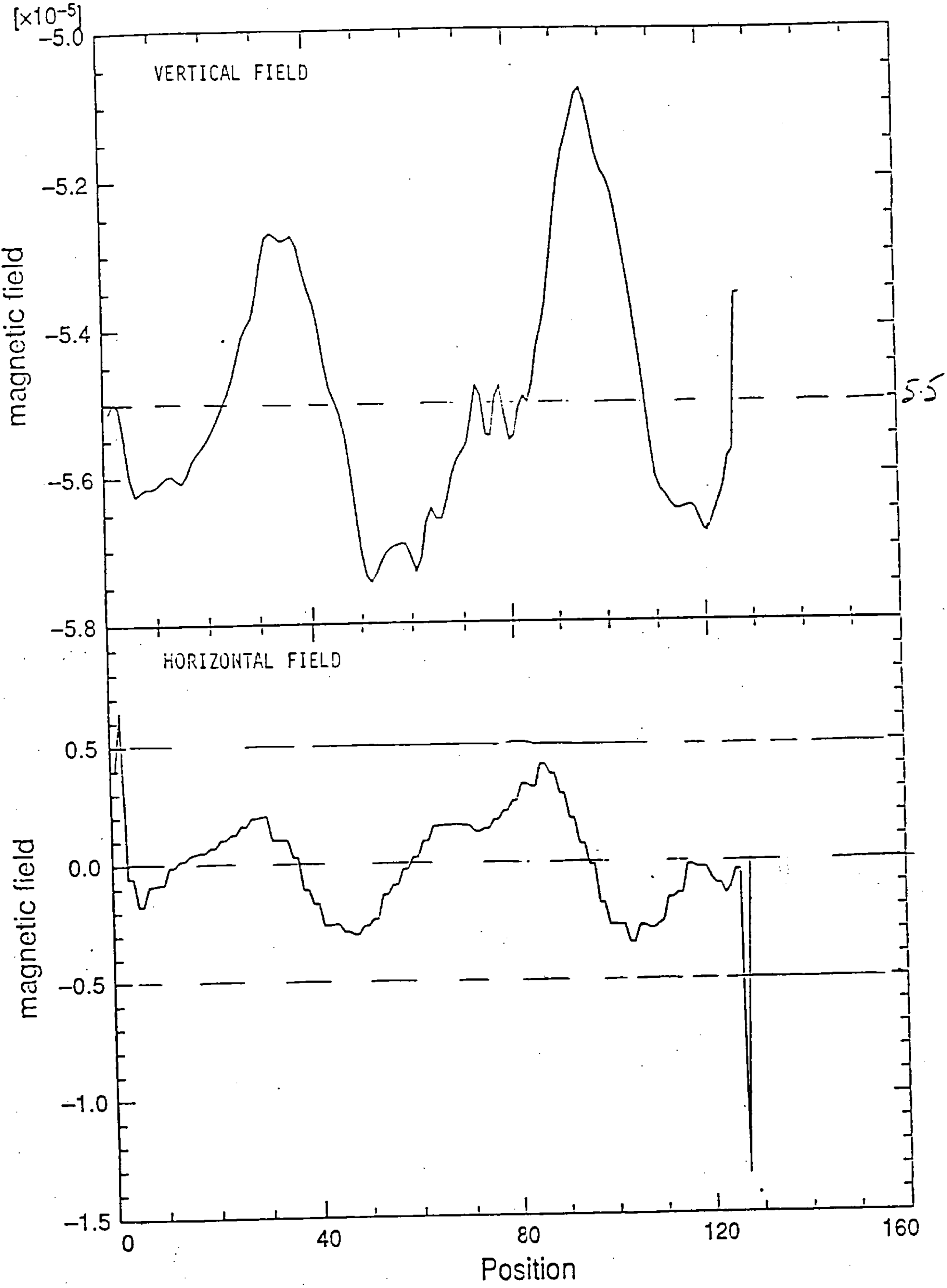


FIGURE 4 CURRENT IN COIL 3 IS ZERO

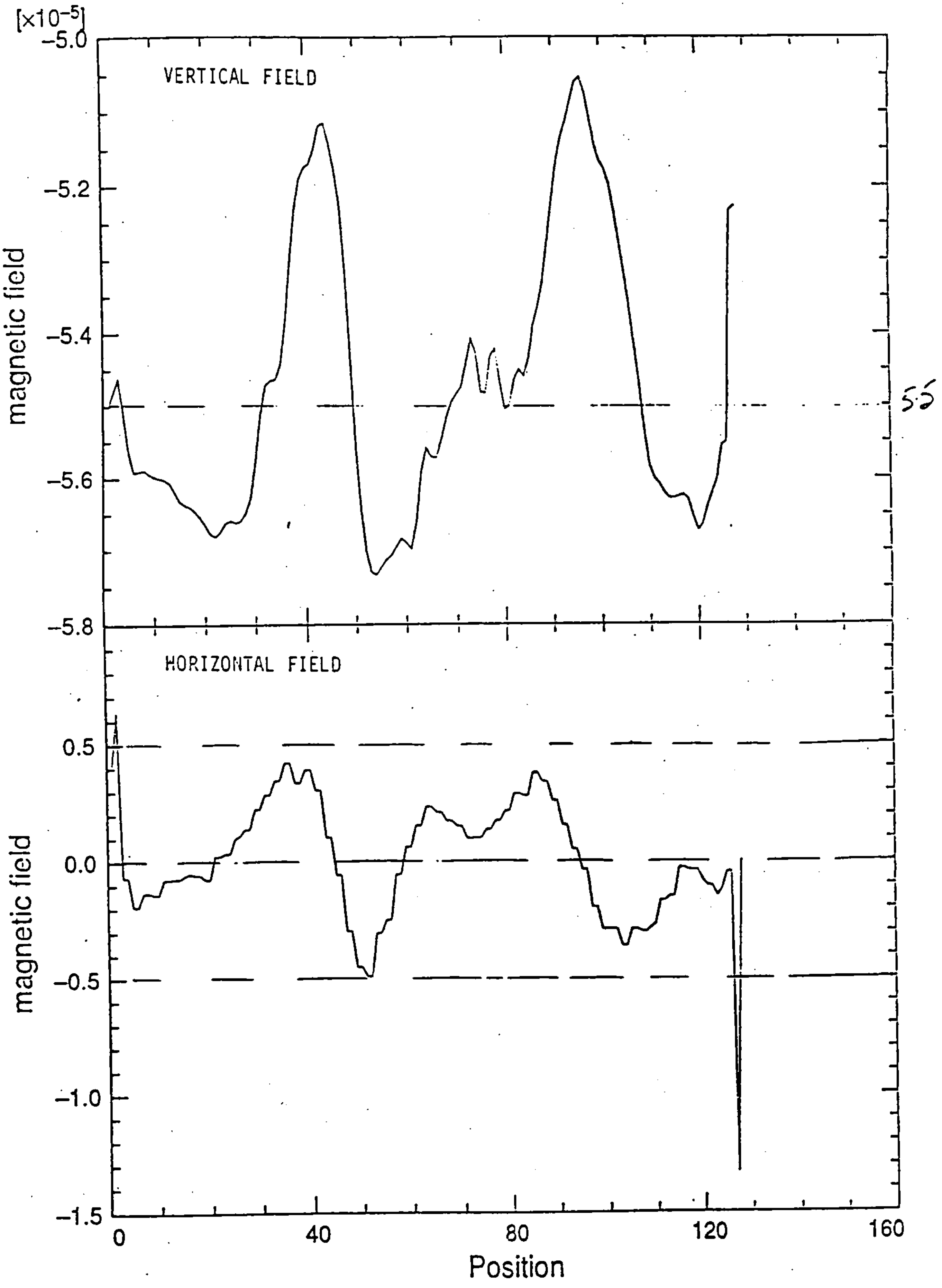
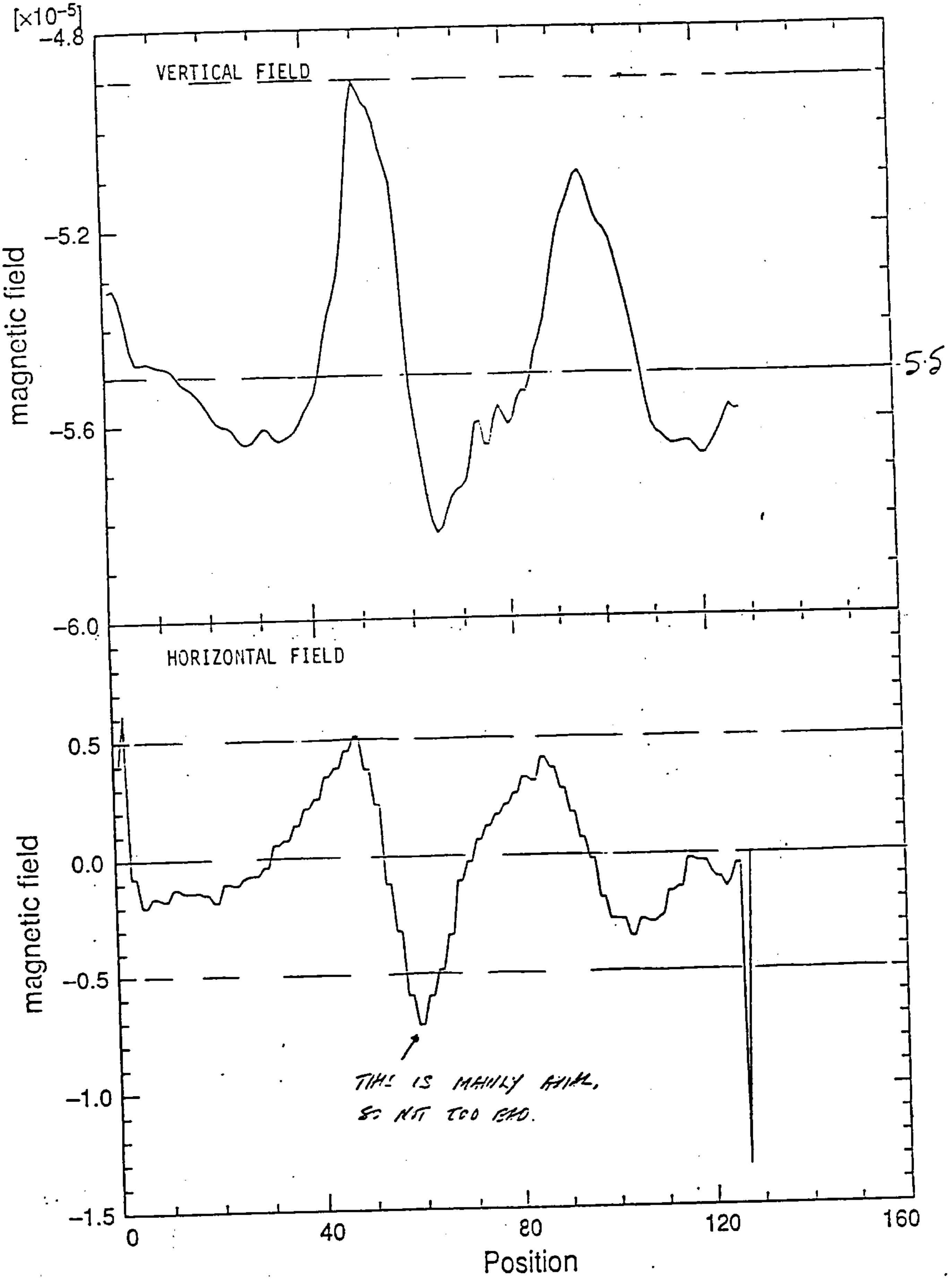
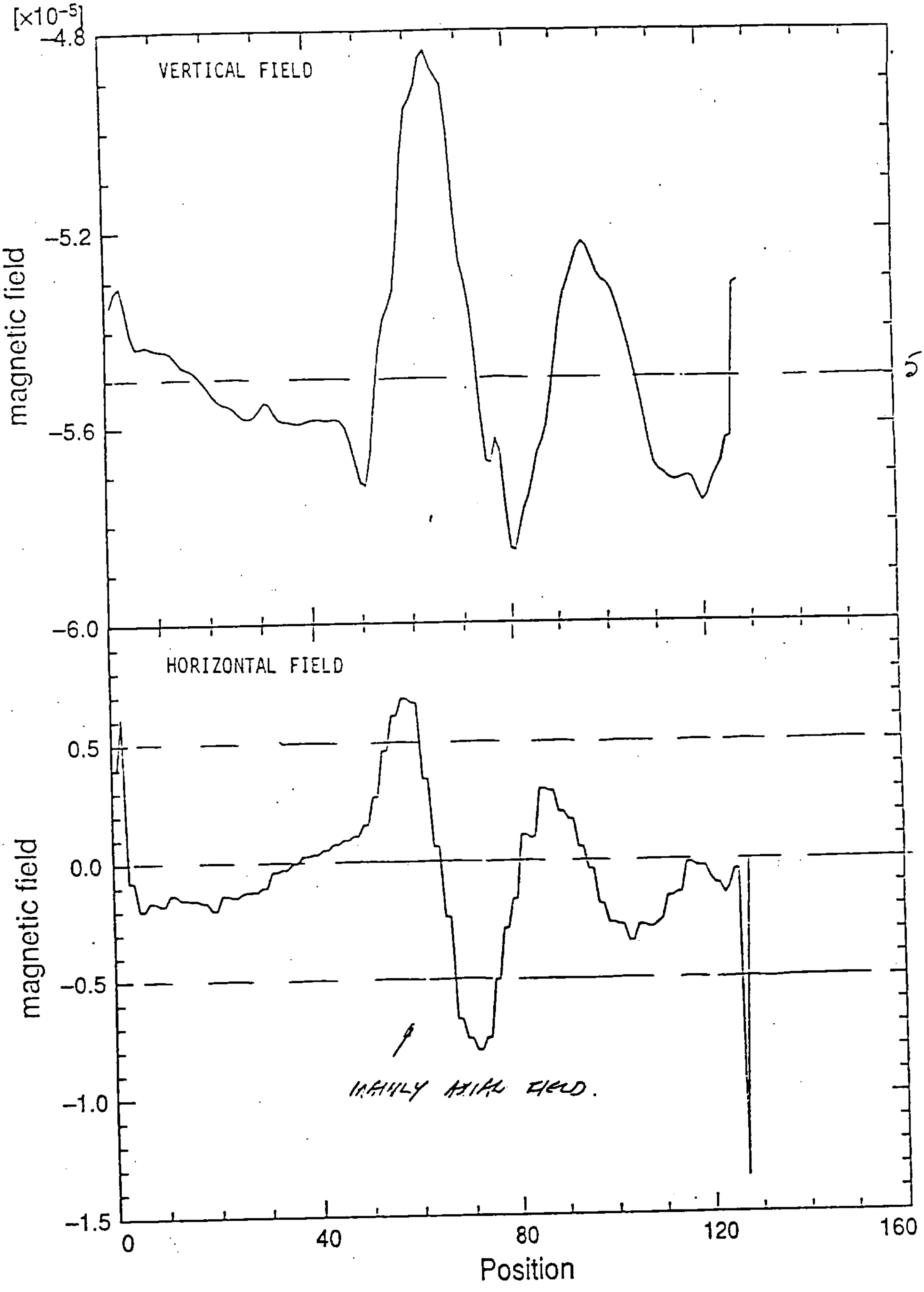


FIGURE 5 CURRENT IN COIL 4 IS ZERO



THIS IS MAINLY AXIAL, SO NOT TOO BAD.

FIGURE 6 CURRENT IN COIL 5 IS ZERO



5.5

MAINLY AXIAL FIELD.

FIGURE 7 CURRENT IN COIL 6 IS ZERO

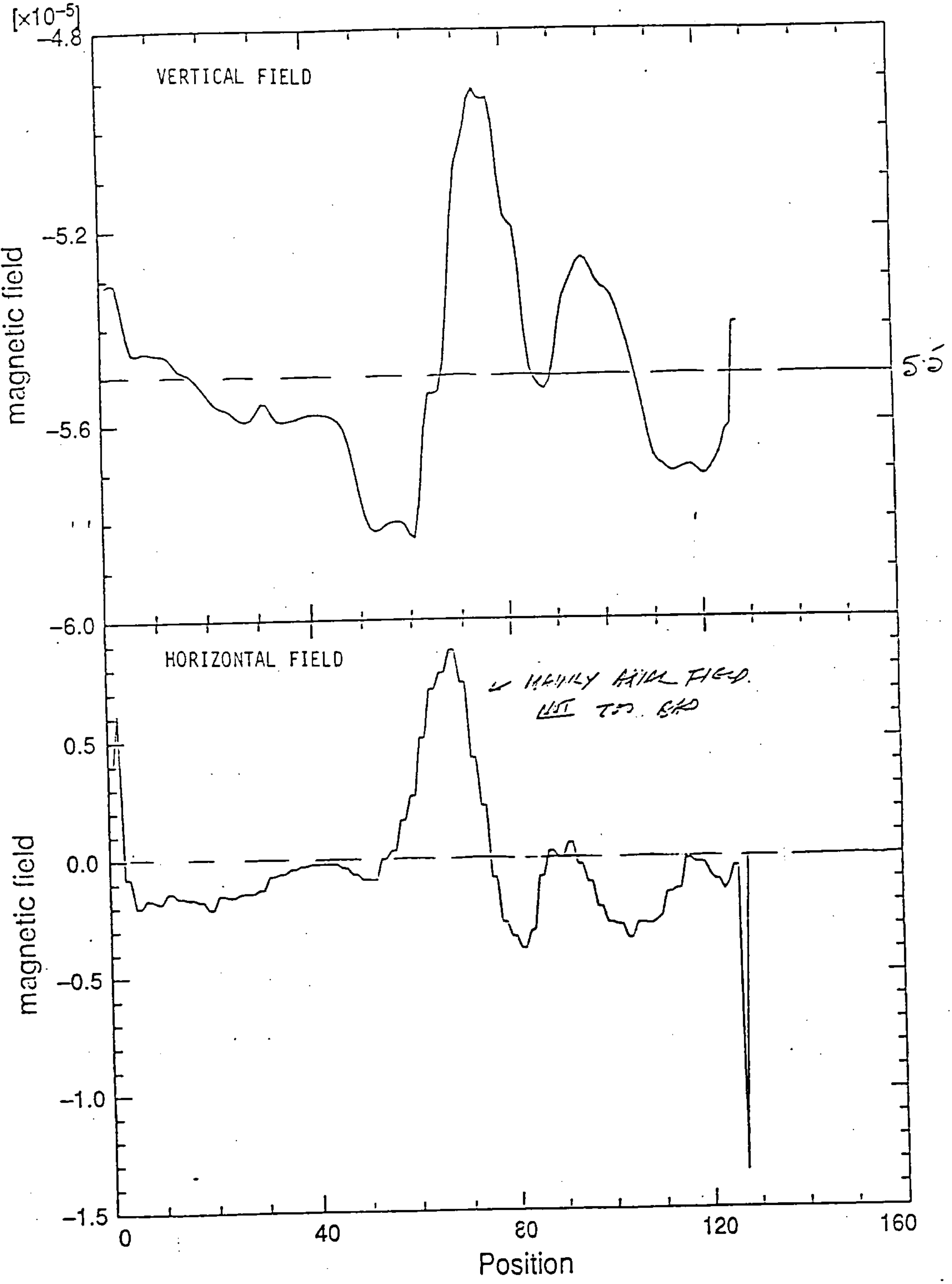


FIGURE 8 CURRENT IN COIL 7 IS ZERO

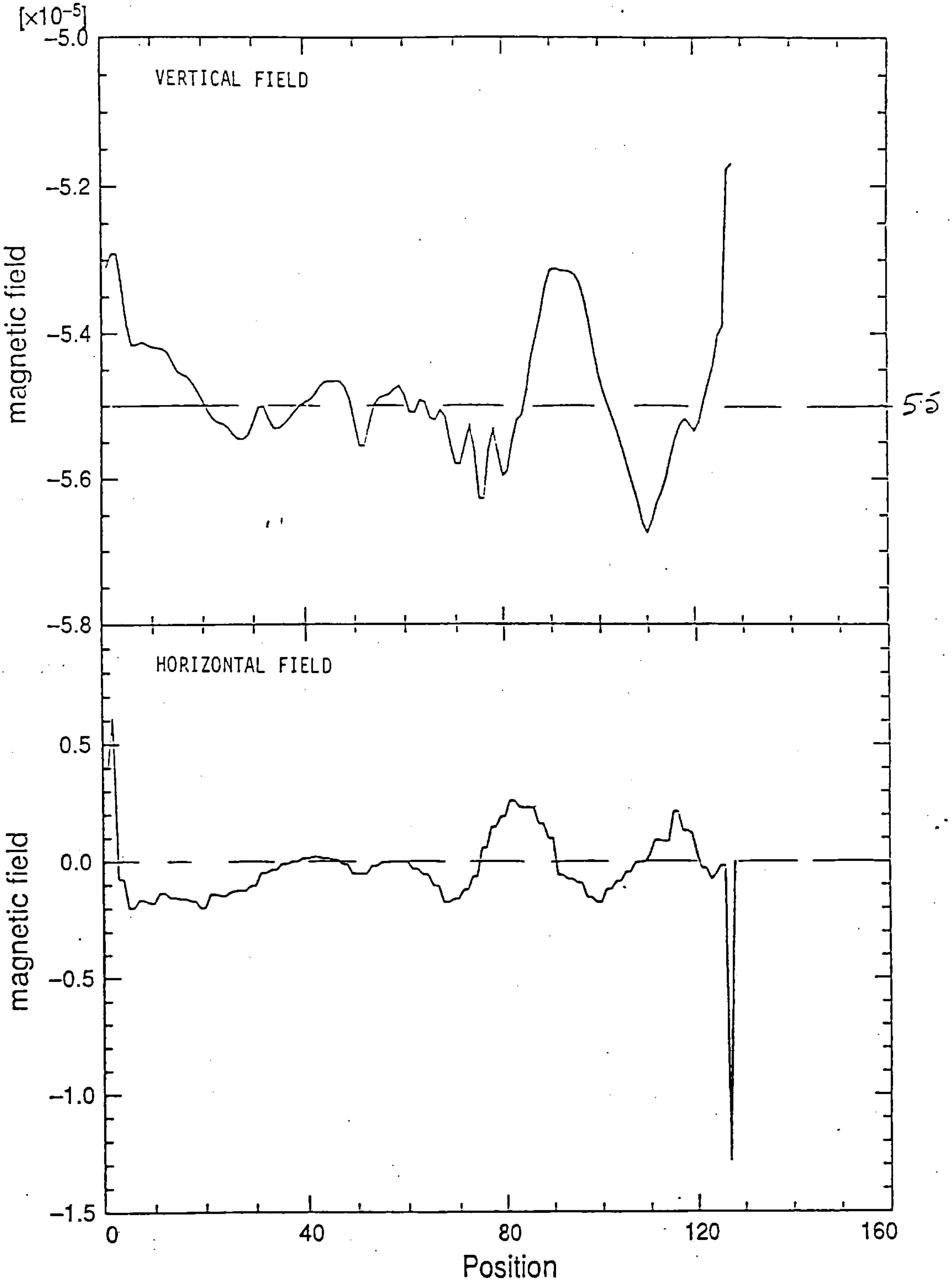


FIGURE 9 CURRENT IN COIL 8A OR COIL 8B IS ZERO

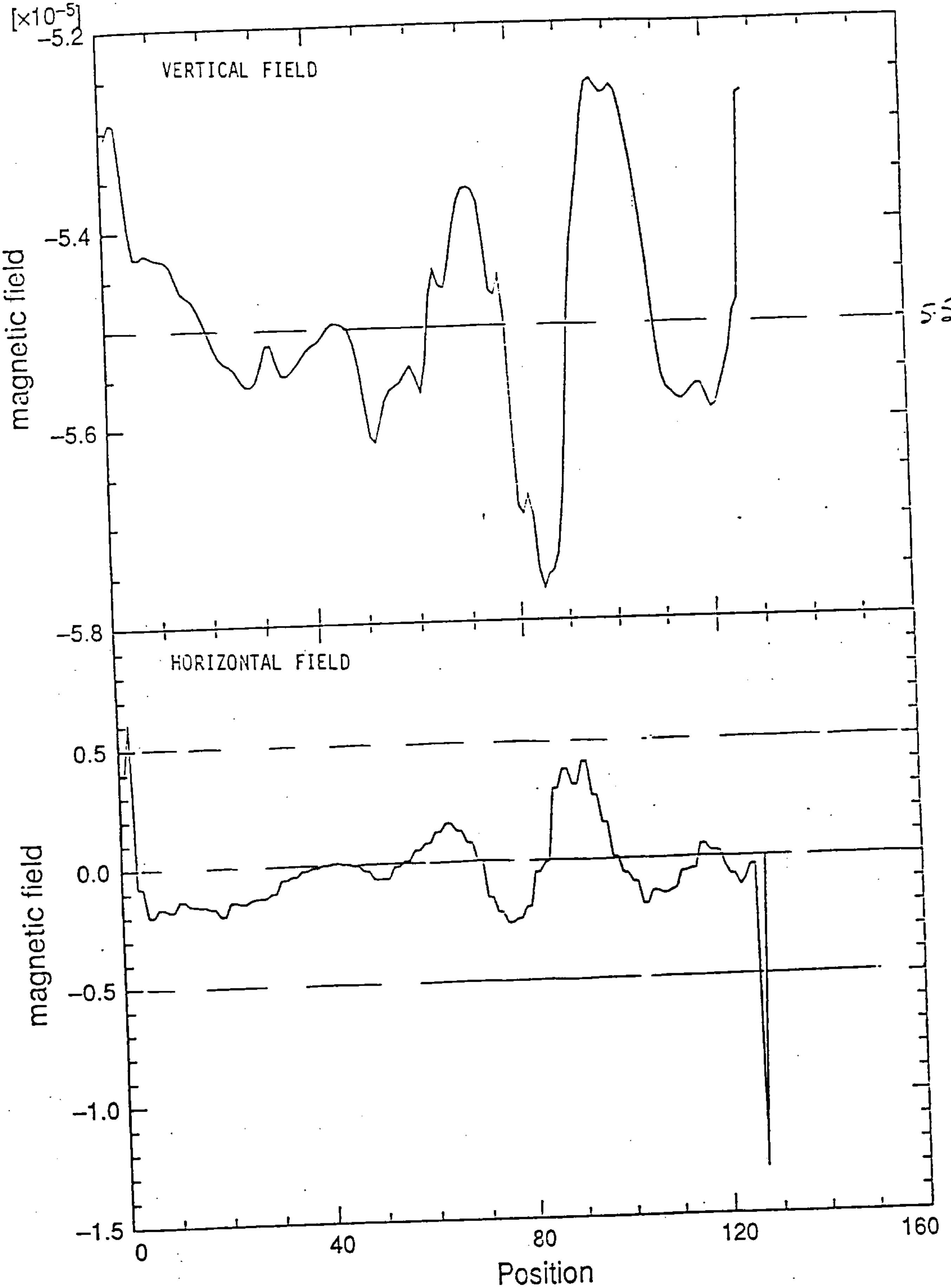


FIGURE 10 CURRENT IN COIL 9A OR COIL 9B IS ZERO

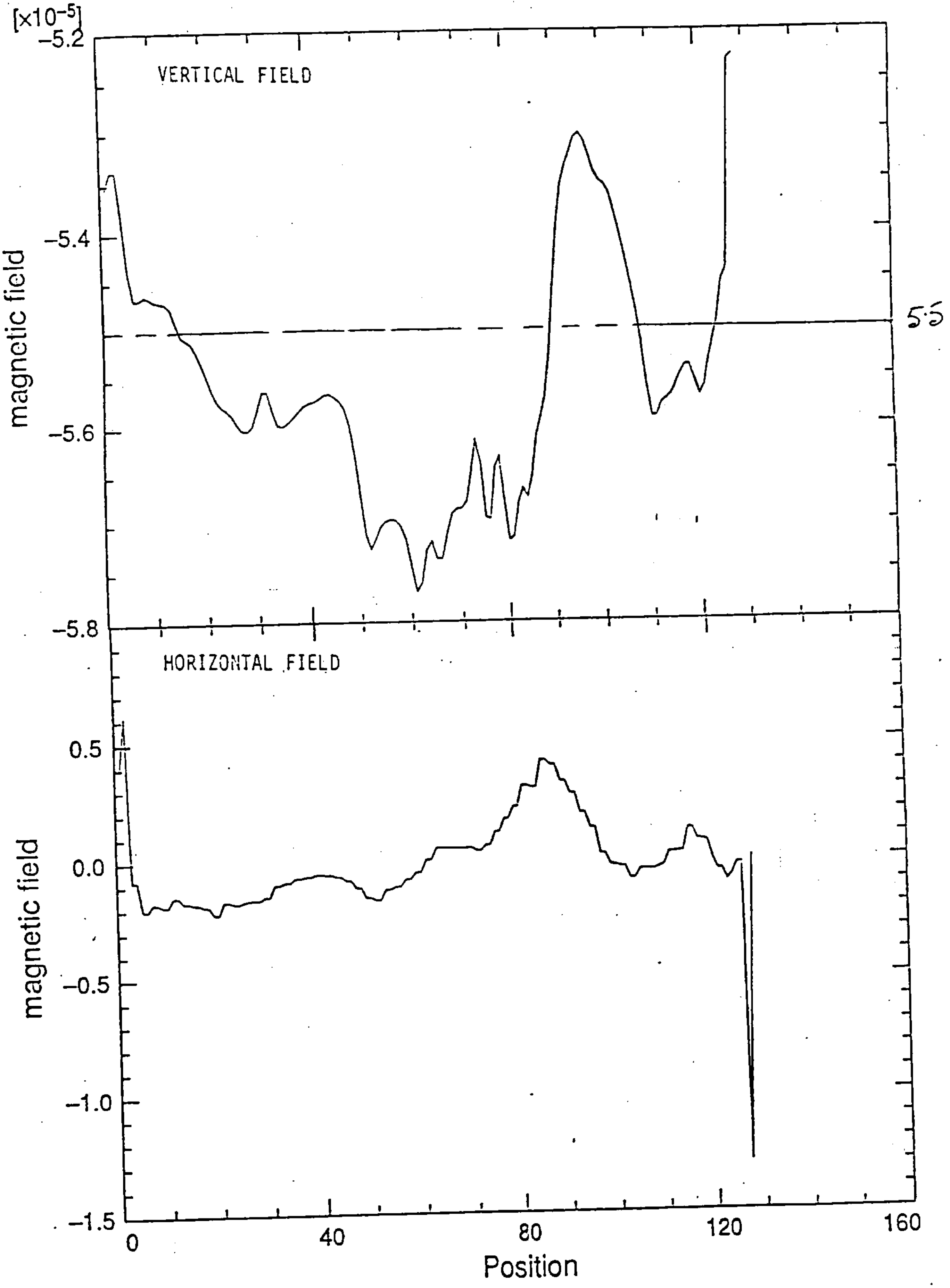


FIGURE 11 COIL 10 IS ZERO

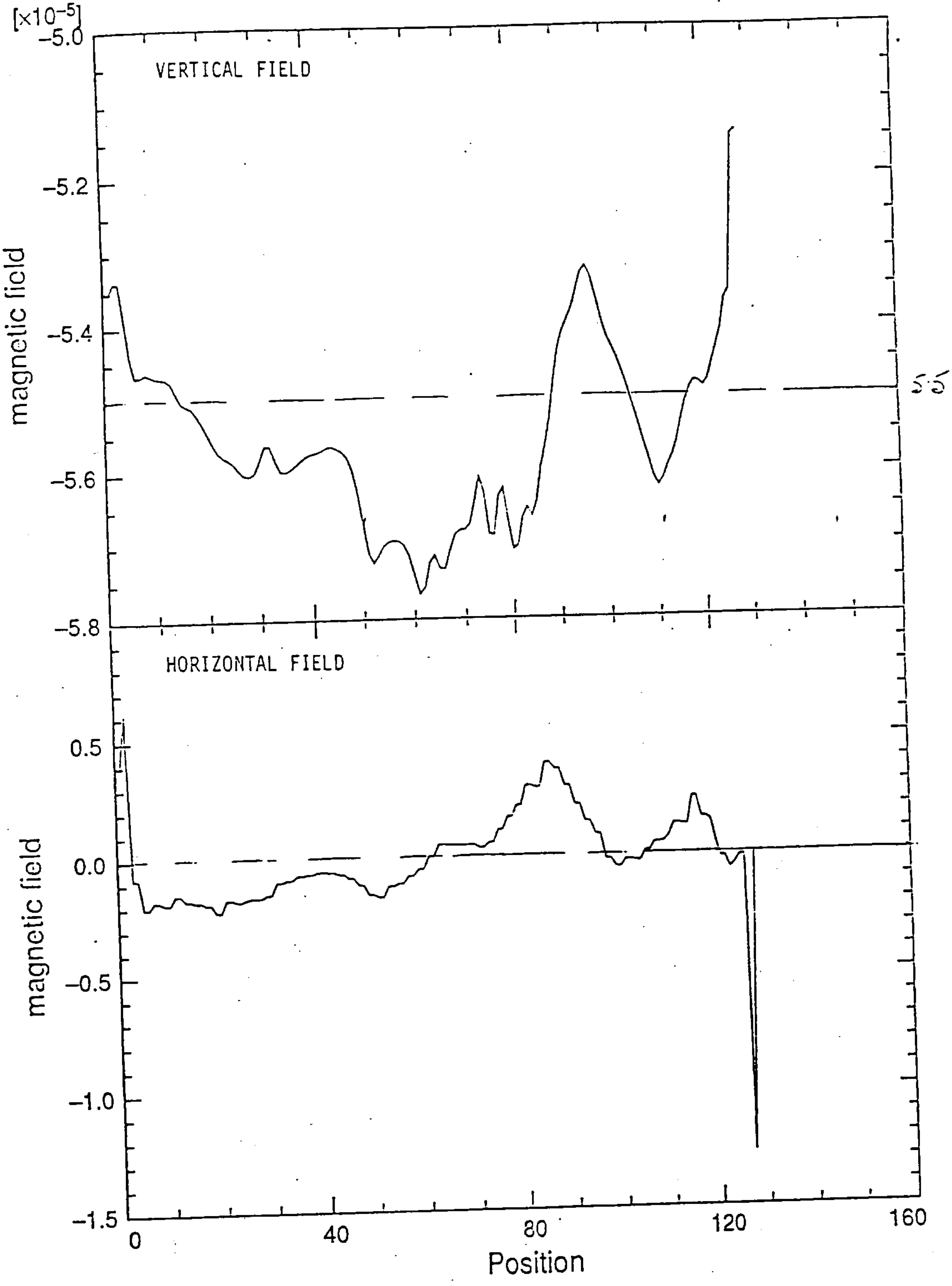


FIGURE 12 CURRENT IN COIL 11 IS ZERO