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SET-UP AND DEMONSTRATION OF A LOW ENERGY ELECTRON MAGNETOMETER (LEEM)

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TABLE OF CONTENTS

LIST OF FIGURES

FINAL REPORT
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INTRODUCTION

The author, with the assistance of graduate student E. Darnell Moffett, designed, constructed and tested a magnetometer whose basis of operation was the deflection of of free, focused, monoenergetic electrons by the ambient magnetic field. The idea that a reliable magnetometer capable of very fast response was needed for a variety of tasks both on Earth and in space and that the deflection of free electrons was a possible means of achieving a fast, sensitive magnetometer was due to Dr. Jag J. Singh of the NASA Langley Research Center. The device was built and tested by Mr. Moffett and Dr. Grayson H. Rayborn under NASA Contract NAS1-16503. The magnetometer was christened LEEM, for Low Energy Electron Magnetometer, following the usage of Dr. Singh *et al* in previous publications that described the theoretical behavior of such a device.[1,2]

This first device, constructed principally of stainless steel and teflon, and featuring a homemade electron gun faithfully obeyed the principles of operation theoretically described in the previous publications[1,2] and in United States Letters Patent No. 4,414,509.[3] However, the beam currents in the device were weak in typical operation, making the LEEM difficult to use and the method of actually performing the magnetic field measurement was to restore the beam to the Faraday cup manually. This method of operation obviated the inherent speed of the instruments. Finally, a need for precision Helmholtz coils was recognized so that the capabilities of the instrument could be evaluated properly. For these reasons a second contract was undertaken, NASA Contract NAS1-17435, to set-up and test an improved version of the LEEM. The contract was later modified to require the construction of a device capable of producing precision magnetic fields and the installation of a position sensitive detector. This report describes the performance of these tasks.

CONSTRUCTION OF LEEM-2

The generally good performance of LEEM-1 indicated that no radical design alteration was necessary for LEEM-2, so LEEM-2 was also designed to be a two-stage, second-order focusing, thirty degree, parallel-plate device. This design commends itself for ease of construction, ease of operation, and its strong focusing properties. Although the basic thirty degree design of LEEM-1 was retained in LEEM-2, several major modifications were effected. First, a design flaw that placed the slits of the device at other than there optimal position was corrected. Second, the materials of the device were changed to permit the device to be baked and used in ultra-high vacuum, and to prevent small, stray magnetic fields from forming in the metal plates. Third, a commercial electron gun with an indirectly heated, oxide coated cathode and a non-inductively wound filament was purchased and installed in order to minimize the stray magnetic fields associated with the production of the electron beam itself. Fourth, shielding plates were introduced into both stages to shield the electron beam from stray fields due to the accumulation of charges on the insulators. Extensive numerical modelling was performed to simulate the electric field in the analyzer stages and Laplace's equation was solved numerically for the analyzer geometry to guarantee that the perturbation of the uniform electric field by the shield plates was acceptably small. Finally, performance testing of the device mandated two changes whose necessity was not forseen: deflection plates were installed between the electron gun and the first analyzer stage to permit the adjustment of the beam's lateral position and the electron detector was totally encapsulated to protect it from the general background of stray electrons which was found to exist whenever the LEEM-2 was operated.

This section discusses the construction of LEEM-2 with these changes, and its set-up and testing.

Design of LEEM-2

Each stage of LEEM-1 and LEEM-2 is a thirty degree, second-order focusing, parallel-plate electrostatic analyzer. Parallel-plate analyzers were first described by Yarnold and Bolton[4], and soon thereafter by Harrower who gave an extensive description of the forty-five degree analyzer.[5] The second-order focusing properties of the thirty degree, parallel-plate analyzer were revealed by Green and Proca.[6,7] A description suitable for design was given by Poul Dahl in his textbook on electron and ion optics.[8] Study of these sources revealed that a slight error had been made in positioning the slits in LEEM-1. To correct this error and to accomodate shield plates to protect the beam electrons from stray electric fields originating in charges collected on the insulators, LEEM-2 was re-designed. The new design is described in the remainder of this sub-section.

The size of the bell jar in which the LEEM-2 resides for testing limits the overall length of the device. When it is fully assembled with electron gun and full-length shielding, for the purpose of preliminary testing prior to actual operation, the length of the gun must not exceed thirty centimeters in length. This, in turn, limits the length of the analyzers and detector to approximately twenty-two centimeters. This length determines every other dimension of the analyzers except for their width, which was chosen to be approximately 4.7 centimeters to insure a uniform electric field in the center of the analyzers where the electron beam resides.

The analyzers were constructed with guard rings spaced 0.605 cm apart to insure that a uniform electric field would be present in the active part of the device. These guard rings were constructed by cutting the centers out of plates which were similar to the deflector plates which form the extremities of each analyzer. An eight millimeter wide rim was left on each side of each guard plate and a two centimeter wide rim was left on each end of each guard plate for the purpose of maintaining uniform electric fields. The cavities formed by these plates function in conjunction with the shield plates described in a later portion of this section of the report and are explained more fully there. They do, however, permit the hollow, central portion of each analyzer which contains the entrance and exit slits and in which the electrons travel, to maintain homogeneous electric fields.

Before entering the first analyzer, electrons from the electron gun must pass through a defining slit which is 0.62 cm in length and is adjustable in width and position. Since both this defining slit and the entrance slit to the first analyzer, which the electrons next encounter, are maintained at ground potential when the LEEM-2 is functioning, the region between these slits is free of electric fields and the electrons travel without acceleration for a distance of about 1.21 cm in this region before entering the analyzer. They enter the analyzer through the entrance slit whose length is also 0.62 cm like the defining slit, but whose width is fixed at 0.16 cm. When the defining slit is adjusted to its proper operating position, the electrons enter the first analyzer at angles ranging from 29 to 31 degrees. The electrons follow a parabolic path through the first analyzer and exit through a slit in the same plate as the entrance slit, identical to the entrance slit and 4.192 cm from it. These slits are cut into plates which are 0.127 cm thick in a fashion which allows for the side facing the analyzer to remain flat while the side away from the analyzer is thinned out in a cup-like manner to prevent interference with the path of the electrons. The analyzer side of the slits is left flat to minimize the disturbance of the uniform electric field in the analyzer.

After the electrons exit the first analyzer they enter another (electric) field-free region which is called the separation chamber since it serves to separate the two analyzers and to provide the field-free region which both analyzers require to realize their second-order focusing capability. In order to maintain the strong focusing characteristics of the device and preserve the feature of LEEM-1 by which the value of the deflection potential on either analyzer in volts was made nominally equal to the energy of the electrons in electron volts, the thickness of the separation chamber <u>d</u> must be one-fourth the distance <u>D</u> between the analyzer plates. The length of the device is determined by the requirement that the distance between entrance and exit slits be the square root of three times the plate separation. Thus, the plates are separated by a distance of D = 2.420 cm, and the height of the separation chamber is d = 1.210 cm. The inside length of the separation chamber is 5.20 cm and the inside width is 1.22 cm. Travelling on a thirty degree slant, the electrons traverse approximately 2.42 cm in the separation chamber before entering the second analyzer, which is identical to the first. The potential on the guard rings of each analyzer are maintained by a string of precision resistors which are accurately measured to be equal. Potentials to the cathode, focusing cup, analyzers, and lateral deflection plates are supplied by well-regulated power supplies and precision, ten-turn potentiometers. For preliminary testing purposes, a magnetic shield to cover the entire LEEM-2 was constructed of thin metal sheets of high magnetic permeability, NETIC and CONETIC, by trade name.

Materials for Construction

The materials employed in the construction of LEEM-2 were chosen to solve two problems discovered in LEEM-1: the presence of small magnetic fields in the plates of the device itself, and the inability of the device to be heated to high temperatures for the purpose of outgassing and eventual use in an ultra-high vacuum. Although all metal parts used in LEEM-1 were of "non-magnetic" stainless steel, and any residual magnetic fields in the metal itself was below the level of detectability using state-of-the-art gaussmeters, it was found during the operation of LEEM-1 that, after use, small magnetic fields were present near the slits. The alloy of stainless steel used, while not itself a ferromagnet, was nonetheless an alloy of ferromagnetic metals. It is necessary for the operation of the device for intense beams of electrons to be generated initially, although their intensity is subsequently decreased by energy selection. Since even a strong focusing lens will not direct every electron through an aperture, a considerable current of electrons is incident on the perimeter of some of the slits when the device is in operation. Since stainless steel is a poor conductor of heat, the electron beam presumably resulted in intense heating of the stainless steel in the vicinity of its impact. Conceivably, the intense heat may have resulted in melting and a different alloy may have formed around the point of impact. It is worth noting, in this regard, that intense electron beams are employed in a similar fashion in zone refining of metals. Whatever the reason, magnetic fields were detected near the first defining and entrance slits of LEEM-1 after it was operated. Although these fields were quite weak, their proximity to the actual electron trajectory made it possible, if not likely, that they were interfering with the optimal operation of the device.

This problem was corrected in LEEM-2 by constructing it from a pure, non-ferromagnet. All metal parts in the device, with the exception of the electron gun and a few brass screws, were constructed of oxygen-free copper. Since copper is an element, no ferromagnetic alloys could be formed by intense heating. Since copper is a very good conductor, the heat formed by the impact of the electron beam is quickly spread throughout the device and dissipated without generatingy the stresses which might cause parts of the device to warp. The copper was plated with gold using an electroplating technique with gold cyanide in solution. The gold surface has several well-known advantages for an electron device. It is an excellent conductor, so that impressed potentials are accurately transmitted throughout the device. Furthermore, it will not readily oxidize so that no insulating spots form on the surface. Finally, gold has a very low coefficient for secondary electron emission. Thus, the impact of electrons on the plates around the slits result in fewer stray electrons, thereby preventing deterioration of the signal-to-noise ratio of the LEEM. Despite all this care in construction of the LEEM-2, one additional precaution was taken. A colloidal suspension of graphite in water was painted around all slits in the magnetometer and permitted to dry. This same coating was used on the back plates of the analyzers. Coating with graphite has been found to result in better conducting surfaces when pump oil is present in a conventional vacuum system such as was used to test LEEM-2. Presumably, the molecules of oil are subsumed into the graphite structure and prevented from remaining on the surface where they become charged from the presence of electrons forming electrostatic potentials which may inadvertently deflect the beam. These coatings were renewed periodically as the device was operated.

LEEM-1 used teflon where insulators were required for mounting the metal plates. Although teflon is easily machinable and wears well, permitting repeated disassembling, its vapor pressure is too high to permit its use in ultra-high vacuua. Also, it tends to flex excessively under bending stress. The decision to employ shielding plates in the analyzer sections of LEEM-2 necessitated a longer and larger device, thereby placing greater stress on the structural components. For these two reasons teflon was replaced in LEEM-2 with MACOR, a machinable ceramic manufactured by Corning Glass Company. Data provided by the manufacturer indicate that MACOR is strong and has a very low vapor pressure.[9] Unfortunately, the ceramic is brittle and, although quite capable of being machined, does tend to chip and crumble under heavy use and frequent dis-assembling.

Shielding of Insulators

A rule of thumb of designers of apparatus using low energy ions and electrons is "not to let the electrons (or ions) <u>see</u> an insulator". By "seeing" an insulator is meant that a straight line path should not exist from the electron or ion at any point on its trajectory to an insulating surface. If other design considerations prevent this rule from being strictly realized, then the electrons should be permitted no more than a "peek" at the insulator. That is, the line-of-sight to the insulator should exist only briefly as the electron traverses its path. The reason for this rule is that insulators acquire charge by accumulating electrons or ions from the background. Since they are not capable of conducting these charges away, they remain and give rise to spurious electric fields that may disturb the electrons if the proper field is not re-established by potentials impressed on intervening electrodes. This rule, which is very difficult to follow in constructing a parallel-plate analyzer, was not observed in the construction of LEEM-1. To observe the rule in the design and construction of LEEM-2, it was decided to attach perpendicular plates to each end of each guard ring. After computer simulation, as described below, the overall height of these plates was chosen to be 0.55 cm which left a gap of only 0.045 cm between the guard rings and the next end plates. This small gap was just sufficient to prevent arcing between the plates during the operation of the magnetometer. Although the use of end plates prevented the occurence of stray potentials due to charge collected on insulators, they themselves carried the potential of the guard ring to which they were attached, thereby distorting the uniform electric field which is the basis of the operation of the parallel-plate analyzer.

To ensure that this non-uniform perturbation was sufficiently small as to have no appreciable effect on the flight of the electrons, a computer simulation of the perturbation was performed. Because the electrons travel on or near a plane of symmetry of the device, the potential in the three-dimensional analyzer could be validly simulated as a two dimensional problem. This was done and typical values of the operating potentials were taken for the end plates and guard rings of the analyzer. Numerical solution of Laplace's equation, using a relaxation technique, showed that the potential in the region of interest in the central one-third of the device would be disturbed less than one tenth of one percent if the height of the end plates was kept less than 0.60 cm while the length of the guard rings was at least 12.0 cm. The magnetometer was designed to conform to these requirements by making the inside length of the guard rings 12.7 cm and the height of the shielding end plates 0.55 cm. This resulted in a larger magnetometer, as was noted earlier in this report, and contributed to the decision to use a machinable glass ceramic in its construction. Since the portion of the electrons' trajectory that is exposed to the field is approximately 4.2 cm in length, the inside length of the analyzer is more than three times the trajectory length, ensuring good homogeneity in the field. The presence of a slight, known inhomogeneity is preferrable to the possible presence of a much larger inhomogeneity due to the obtrusion of insulators carrying accumulated stray charge.

Choice of Electron Gun

The electron gun in LEEM-1 was a simple, un-coated tungsten filament followed by a custom designed unipotential lens. Although custom design permitted a lens specifically planned to focus a beam of electrons on the defining slit, actual operation of LEEM-1 revealed that the unipotential lens was of slight efficacy. Furthermore, because the tungsten filament was not coated and thus had a large work function, an enormous filament current was required to heat the filament sufficiently hot to cause copious emission of electrons. Such a large current passing through a straight conductor (the filament) generates a considerable magnetic field of its own; a field which is difficult or impossible to shield since it is generated internally and which may well interfere with the operation of the device or distort the magnetic field measurements made with it.

To avoid these problems, the decision was made to purchase a commercial electron gun for use in LEEM-2. After careful analysis of the guns available, the electron gun used by Central Scientific Company in its laboratory device for student maeasurement of the charge-to-mass ratio of the electron was purchased, installed and tested. The gun was chosen because it was known to produce an intense electron beam, since this experiment requires that the path of the electrons be rendered visible by fluoresence and their impact point visible by phosphoresence, and because the gun cannot generate appreciable magnetic fields if the students are to determine the charge-to-mass ratio accurately. The gun has met these criteria well, operating with less than 0.7 amperes of filament current while generating intense electron beams. In addition, it appears that the cathode is indirectly heated by a filament which is non-inductively wound, further decreasing the magnetic field generated by the filament current. These characteristics are discussed further in the section on set-up and testing of LEEM-2. Unfortunately, the gun does not possess the capability of deflection in either of the transverse directions, and this appeared to be a larger defect as testing of LEEM-2 continued.

Installation of Lateral Deflection Plates

When LEEM-2 was originally designed, it was believed that the slits could be mechanically aligned by precise manufacture of the components and the electron gun aligned once and for all by optical means. Although it does appear that mechanical alignment of the slits in the analyzers has been achieved, precise alignment of the electron gun has been difficult and maintaining the alignment under thermal stress as the gun heated and cooled in repeated, discontinuous operation has been virtually impossible. That alignment is definitely a problem has been confirmed both by the operation of the magnetometer and by examination of burn marks on the graphite around the slits when the device has been disassembled after operation. These burn marks clearly show that after operation the LEEM-2 has generated a beam to one side of the slit. Sometimes a clear image of the slit shape can be seen on the exit slit of the first analyzer, coincident with it but displaced to one side. This lateral displacement has caused the deterioration of the performance of the magnetometer with resulting weak and erratic beams and has sometimes prevented the beam from even reaching the second analyzer.

In an attempt to solve this problem lateral deflection plates were installed between the electron gun and the entrance to the first analyzer as a post-construction retrofit modification. Unfortunately, the original design of LEEM-2 left very little room for the insertion of lateral deflection plates, and the plates that could be inserted had very little extent. Since the deflecting ability of such plates depends on the distance the electrons travel between them, the efficacy of the plates was minimal. Furthermore, since no provision was made for the plates originally, a firm sure mounting of them could not be achieved. They tended to move as stress was placed on their electrical leads, occasionally shorting out to the electron gun mounting plate which was held at ground potential. This, of course, totally prevented their use, causing them to have to be disconnected from their source of potential if the operation of the device was to continue in any form. Although these deflection plates were used with very little success, the need of plates capable of deflecting the beam in both transverse directions in future magnetometers is manifest.

Summary

In summary, then, LEEM-2 was designed to incorporate several features not found in LEEM-1. A small design flaw in the placement of the defining and entrance slits was corrected in LEEM-2. The material of construction was changed to prevent the occurrence of small magnetic fields around points at which the electron beam might impact the plates of the device. The use of oxygen-free copper with a gold plating also increased the electrical conductivity of the device, presumably resulting in the more accurate imposition of electrical fields. The teflon linsulators were replaced with a machinable glass ceramic to permit the LEEM-2 to be baked and used in ultra-high vacuua, and also to add mechanical stability to the device. The analyzers were re-designed and end plates added to shield the electron beam from any stray fields generated by charge on the insulators. A commercial electron gun was purchased, installed and tested to decrease the magnetic field generated by the filament current and to supply a more copious source of electrons. Finally, lateral deflector plates were added in attempt to increase the ease alignment of the beam and to permit the alignment to be restored after misalignment due to thermal strain. The LEEM-2 is shown, assembled, from two different perspectives in Figure 1. Figure 2(a) shows a close-up of the electron gun, while Figure 2(b) exhibits the device largely disassembled. Figure 3(a) compares the LEEM-1 (top) with LEEM-2 (bottom), and Figure 3(b) shows the device situated in the bell jar surrounded by one set of Helmholtz coils and ready for operation.

SET-UP AND TESTING OF LEEM-2

For testing purposes LEEM-2 was set up in a manner similar to that indicated in Figure 3(b). To test the ability of the electron gun to provide the large beam currents for which it was purchased and installed, arrangement was made to collect the beam current in the field-free region between the two analyzers. Initially a magnetic shield was installed to protect the entire device

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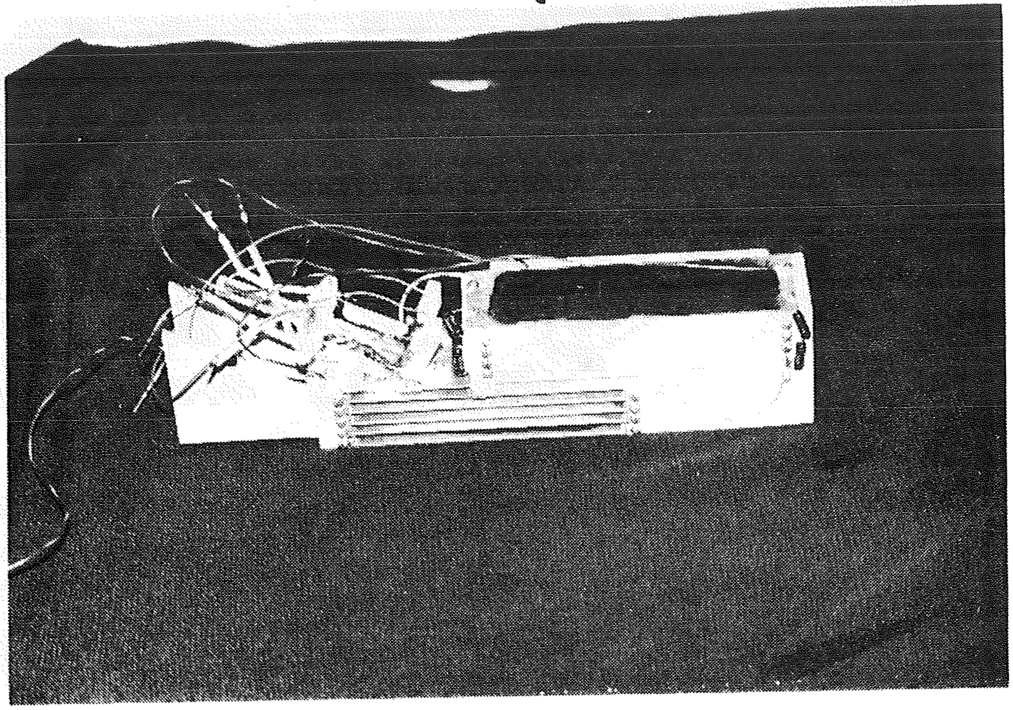

Figure 1(a). The LEEM-2.

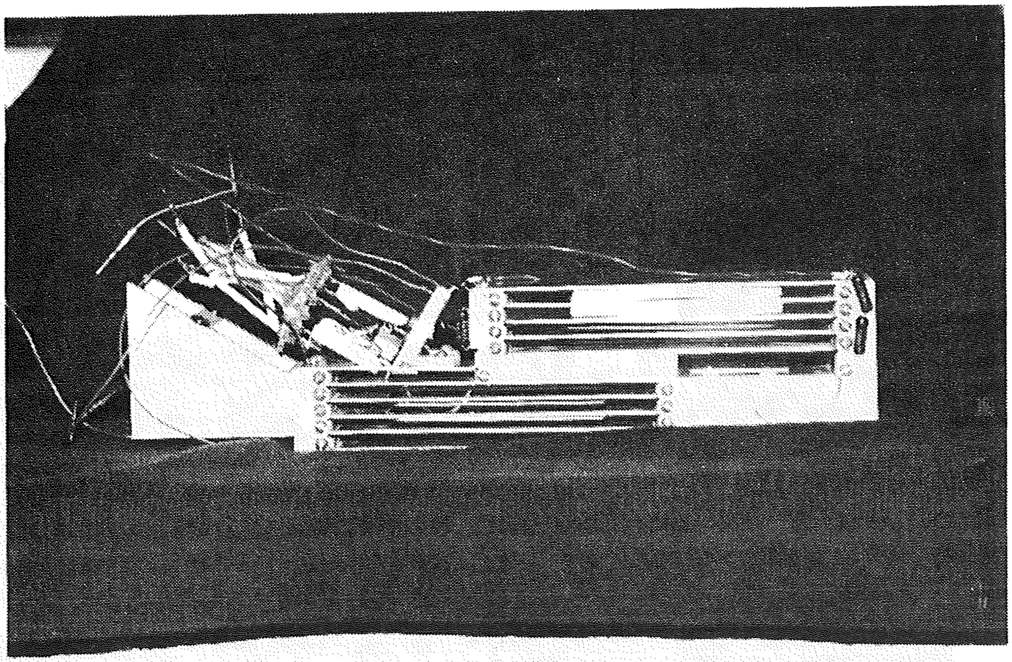

Figure 1(b). Another view of the LEEM-2.

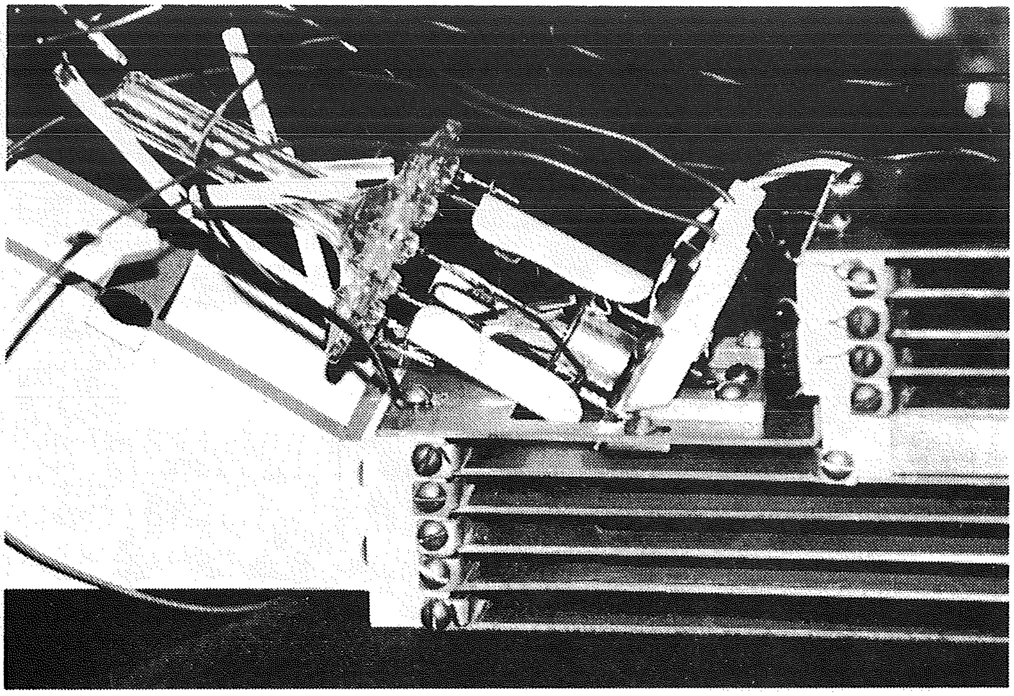

Figure 2(a). A close-up view of the electron gun.

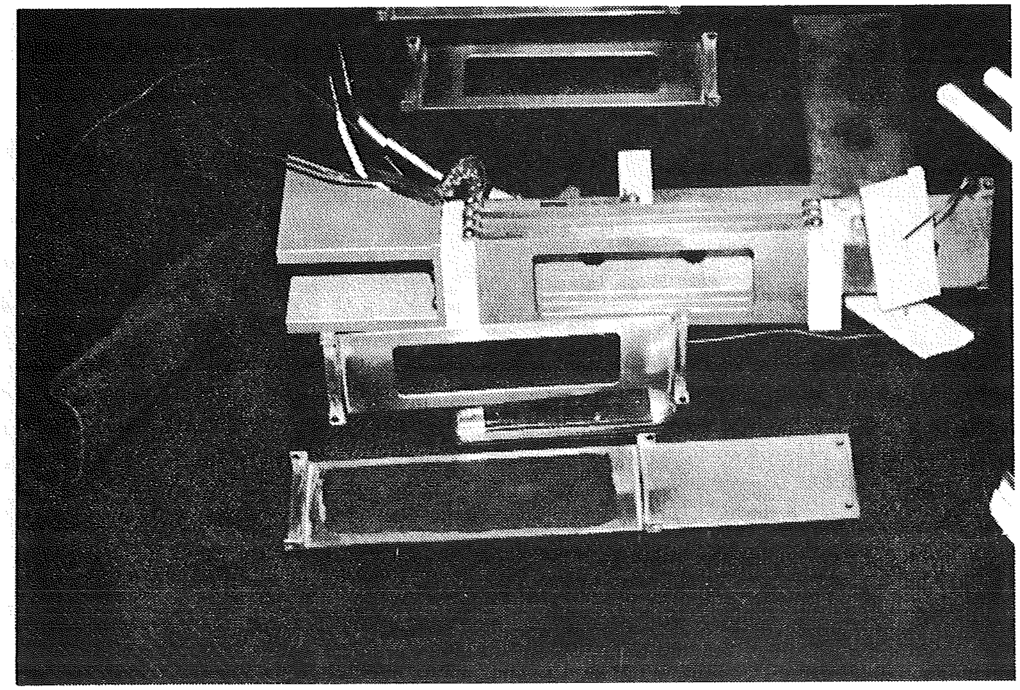

Figure 2(b). The LEEM-2 disassembled.

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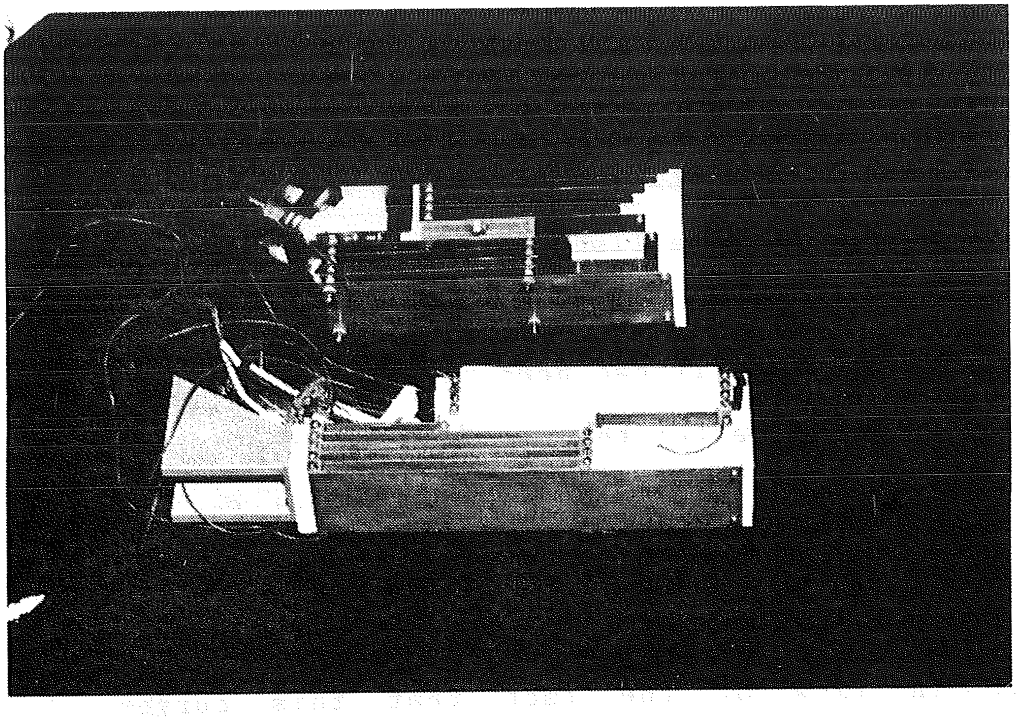


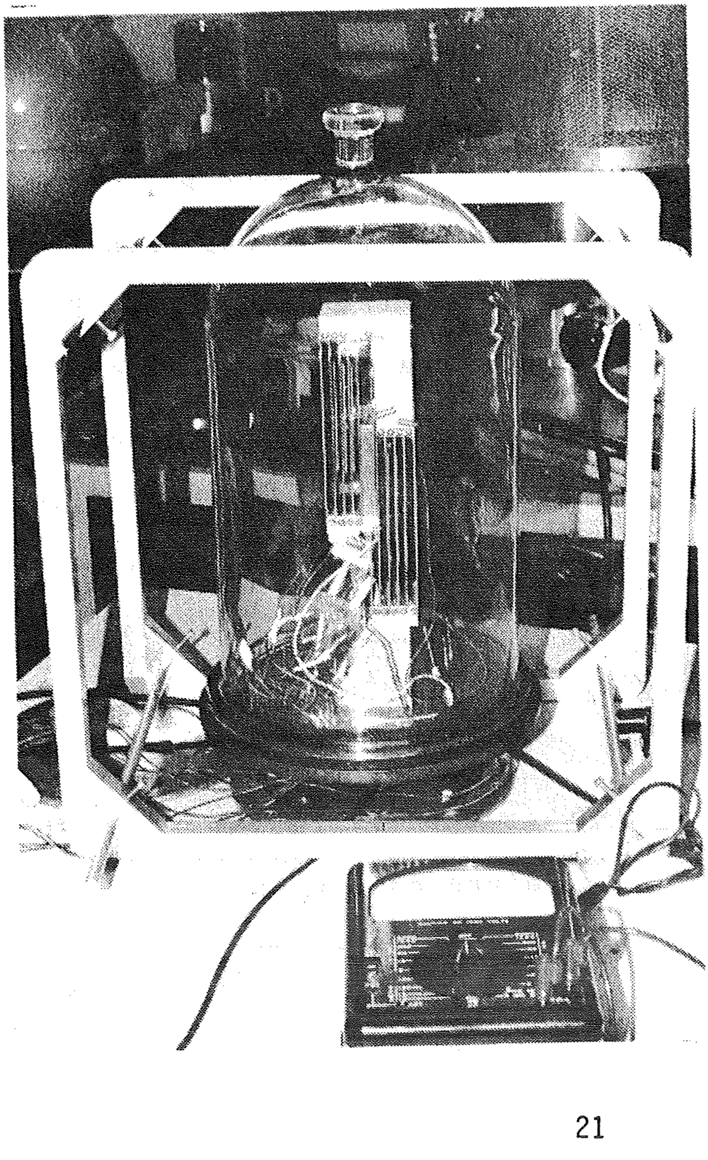
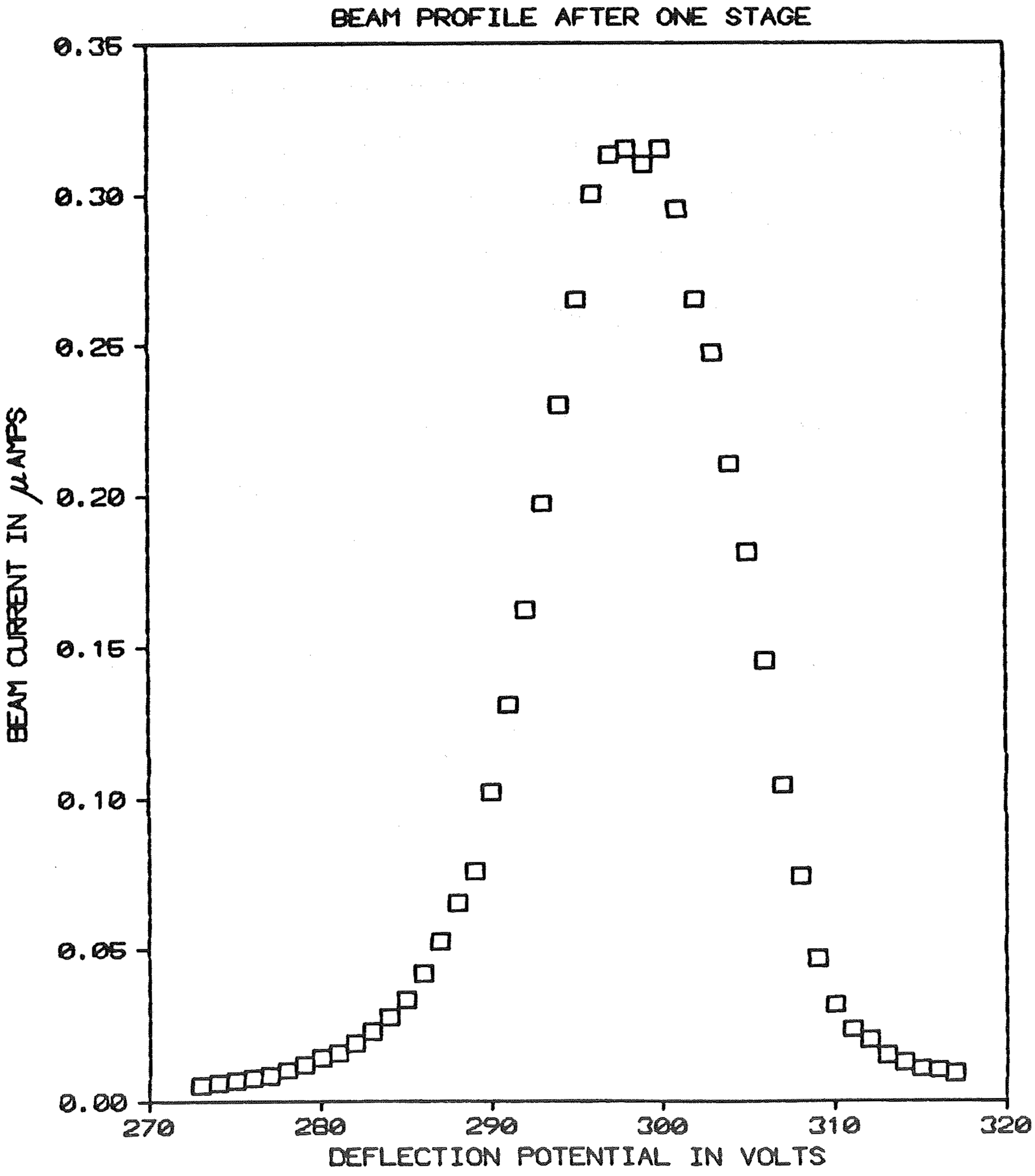


Figure 3(a), above. LEEM-1 and LEEM-2 seen together.

Figure 3(b), left. LEEM-2 in the bell jar ready for operation.

from the ambient magnetic field until its basic operating parameters could be established. This mode of operation established that LEEM-2 could indeed provide the enormous beam currents for which it had been designed. Figure 4 shows the current collected after the first stage as a function of the deflection potential on the first analyzer for a beam of nominal energy of 4.8×10^{-17}J, or 300 eV. The maximum beam current of greater than 0.3 microamperes is particularly impressive in view of the fact that this current has successfully undergone energy analysis in a dispersive energy analyzer. The smooth symmetry of the beam profile exhibited in Figure 4 also suggests that the first stage of LEEM-2 is faithfully performing according to its design principles. The slight flattening at the top of the peak suggests that the entire beam may be contained within the exit slit. Since the defining slit was deliberately set at maximum width for these tests, this would indicate that the focus cup on the electron gun was producing a focus wholly within the defining slit so that the beam diverging after this focus point did not wholly fill the entrance slit to the first analyzer stage. This in turn suggests that the focus adjustment on this commercial gun is effective in its present application. It should be noted, however, that the flattening on the top of the profile could also be explained as a widened image of the entrance slit of uniform electron density which wholly

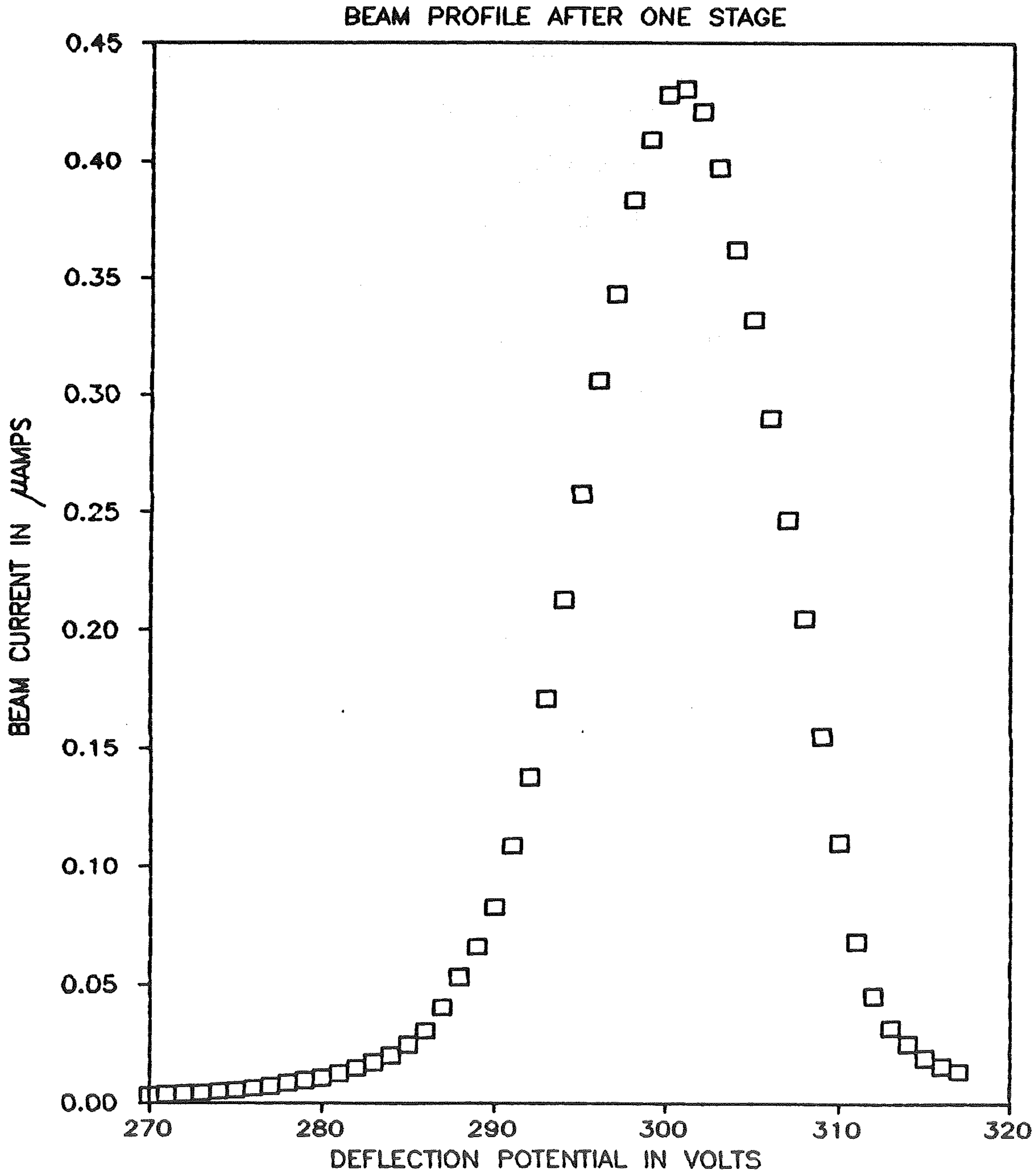
Figure 4. The beam profile through one stage with magnetic shielding.



encompasses the exit slit. In order to test LEEM-2 more strenuously, the magnetic shield was removed and the tests repeated with the entire device exposed to the ambient magnetic field. (Tests show that the horizontal component of the field is of the order of 3 x 10^{-5} T). One would, of course, expect deterioration of the performance of LEEM-2 when it was exposed to the ambient magnetic field. In fact, as Figure 5 clearly shows, the performance improved. The beam profile is smoother and even more symmetrical and the beam current has increased to an incredible 0.43 microamperes.

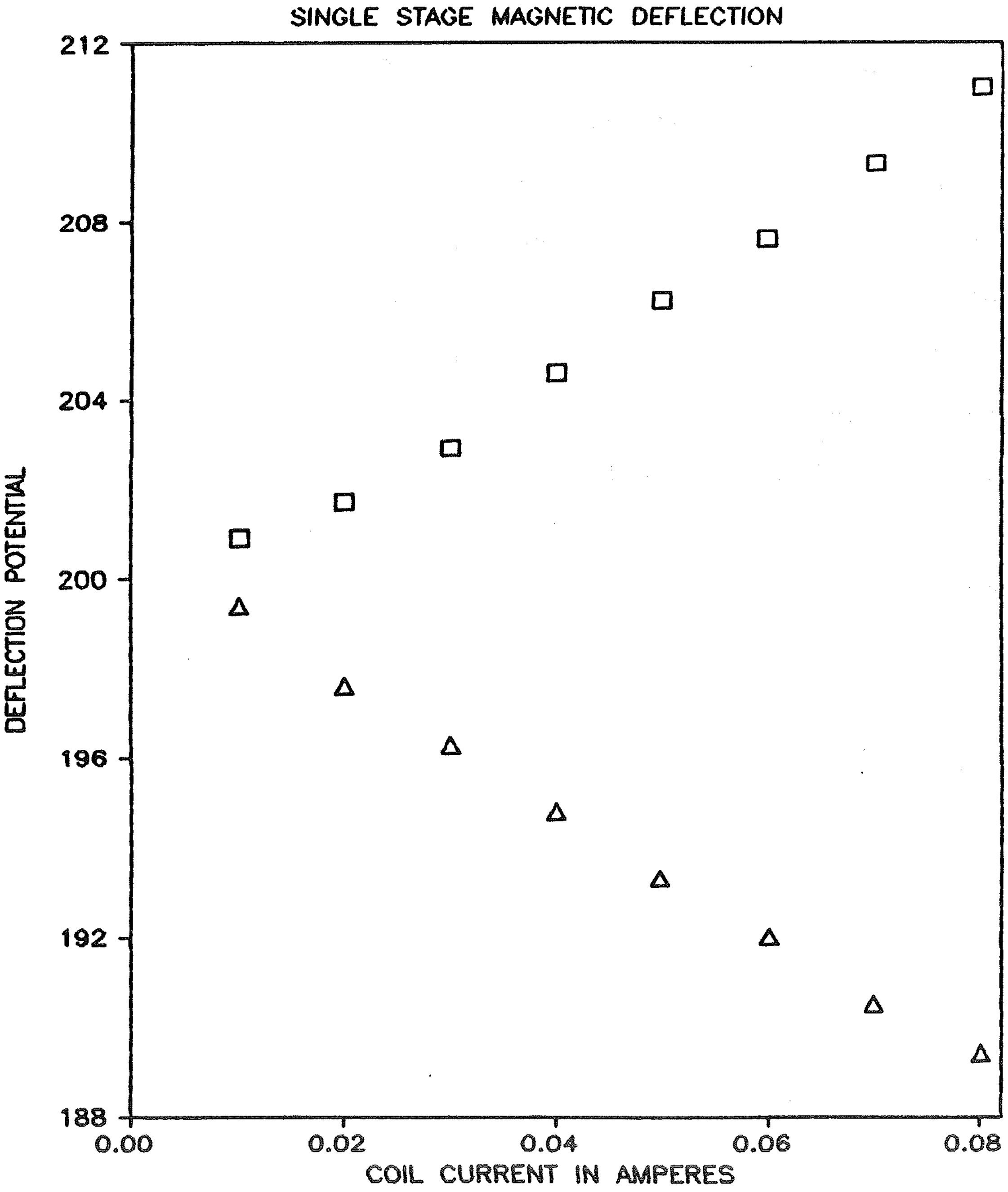
The strong beam produced through the first half of the LEEM-2 suggests that one stage alone might function as a magnetometer. Indeed, on reflection there is reason to believe that a single stage device may function better than a two stage instrument. Since great difficulty is encountered in transmitting the electrons through the second stage even with substantial decreases in beam current, a single stage device should be more sensitive since the magnitude of the current eventually determines the minimum detectable change in beam position. If more current than is needed is generated the spot size of the beam can be decreased by narrowing the defining slit. Since both characteristics contribute to instrument sensitivity, more flexibility in determining the optimum trade-off would be available.

Figure 5. The beam profile after one stage <u>without</u> magnetic shielding.



Furthermore, a single-stage instrument would be more reliable than a two stage device. For these reasons the ability of LEEM-2 to function as a single-stage magnetometer was investigated. Helmlholtz coils were installed around the device in such a manner as to produce a field perpendicular to the electrons' trajectories. The current to the Helmholtz coils was provided by a well-regulated power supply and monitored by a digital multimeter. As the current was increased the beam was partially, or completely, deflected out of the exit slit to the first stage. It was restored to the slit by adjustment of the deflection potential on the first analyzer. The measurements were made for a variety of Helmholtz coil currents with the currents flowing both ways through the coils at various beam energies ranging upward from 3.2×10^{-17}J, or 200 eV, to about 4.8×10^{-17}J, or 300 eV. Results from one of those runs which demonstrate the performance of LEEM-2 as a magnetometer is shown in Figure 6. Here the deflection potential for optimal transmission of the beam is plotted as a function of Helmholtz coil current for coil currents flowing in each of the two possible directions. The linearity of the plots suggests that the LEEM-2 magnetometer is a linear instrument. The upper data are fit with a straight line of slope 147.9 volts/ampere and an intercept of 198.9 volts. The lower data, taken with the

Figure 6. The performance of LEEM-2 as a magnetometer.



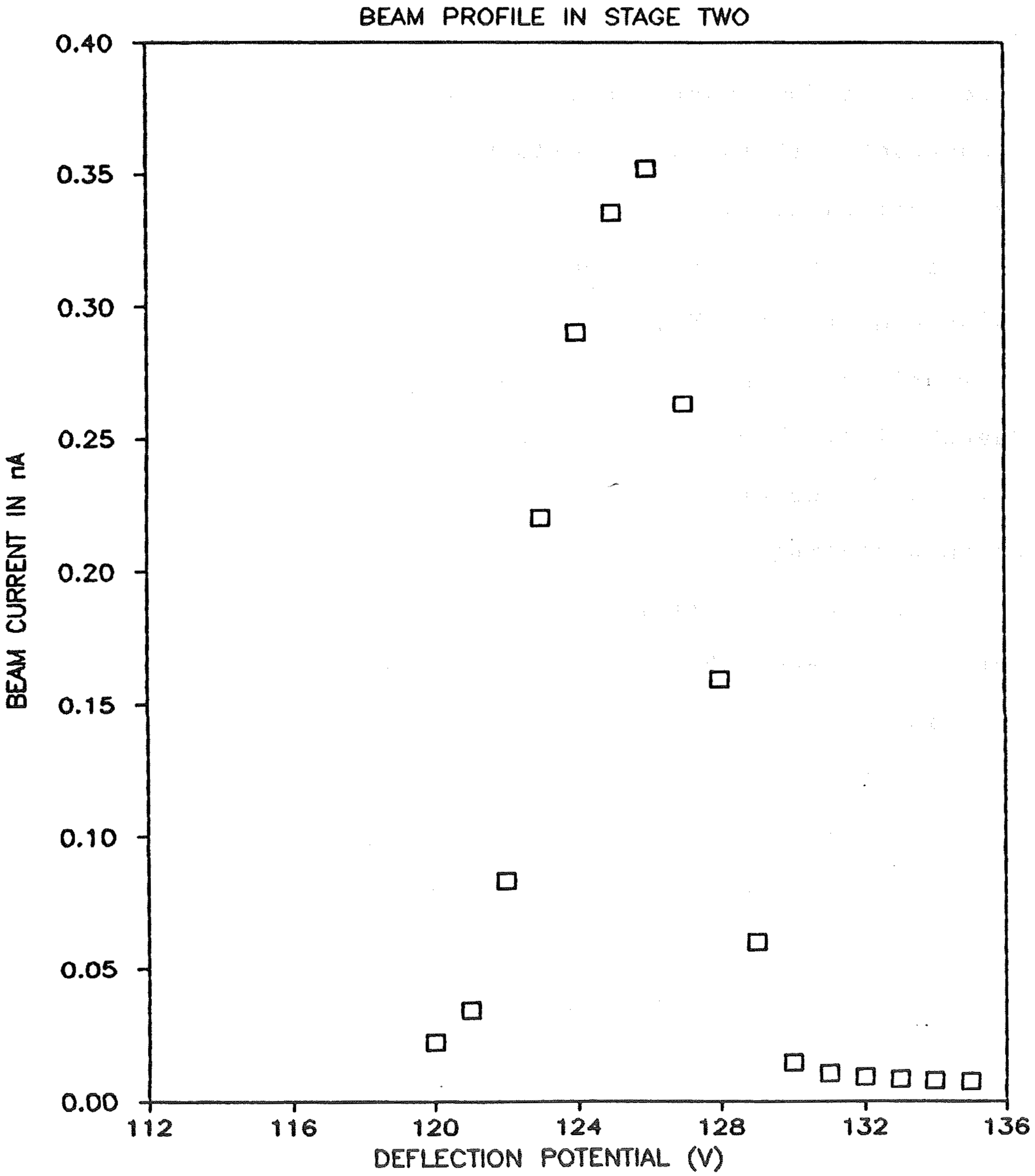
direction of the coil current reversed, are fit by a straight line with slope 142.0 volts/ampere and intercept 200.6 volts. That the LEEM is highly linear can be inferred from the correlation coefficients for the two sets of data. The correlation coefficient for the top data is r = 0.9968, while that for the bottom data is r = -0.9989. The negative sign for the second set of data simply indicates that the optimal deflection potential <u>decreases</u> with increasing coil current when the current flows in that direction, a fact that is already well understood.

The LEEM-2 performs better as a magnetometer using one stage rather than two. Part of the reason for this can be seen in Figure 7 which shows a beam profile in the second analyzer. Notice that three orders of magnitude have been lost in comparision to the beam profiles in Figures 4 and 5 which were made after the beam had left the first analyzer. The highly linear response of the device and the large currents available through stage one suggests good performance of the LEEM-2 in this mode.

CONSTRUCTION AND TESTING OF HELMHOLTZ COILS

In order to provide an ambient environment to test the performance of the LEEM-2, it was necessary to provide a means of accurately imposing a uniform magnetic field for the electrons to experience. This was accomplished by precision

Figure 7. Beam profile in the second analyzer.



construction of three pairs of square coils which were then operated in a modified Helmholtz arrangement. The two smaller coils were constructed for the purpose of controlling extraneous components of the ambient magnetic field during experiments with LEEM-2. The largest coils were constructed to produce the uniform magnetic field in compliance with the modified contract. It is these coils which were tested and which are described here.

The coils were constructed from three quarter inch channel aluminum by the Mr. Jim Bridges using precision milling techniques. They were then wrapped by hand with copper magnet wire. The width of the coils is 1.91 cm. The length of the side of a square is 47.78 cm inside diameter and 51.26 cm producing an average length of 49.52 cm. In order to test the coils a transverse probe and Bell Model 620 Gaussmeter were used. Both the coil current and the Hall probe potential were read with digital multimeters. The component of the Earth's field along the axis of the Helmholtz coils was carefully zeroed out before readings were taken. Figure 8 shows the coils situated for the measurements. Because varying the coil current and reading the Hall probe potential, that is the magnetic field, is a better method of avoiding systematic errors than simply reading one, or a few, values of the field at various locations, we have performed this linear regression analysis

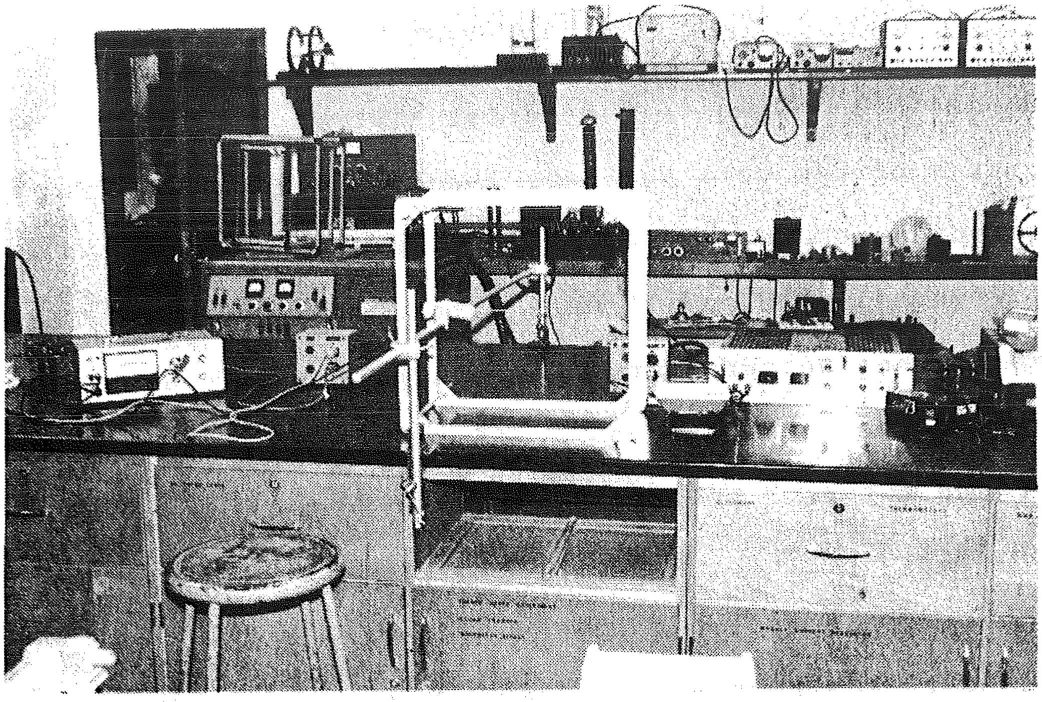


Figure 8(a). Arrangement for measuring the uniformity of the field in the Helmholtz coils.

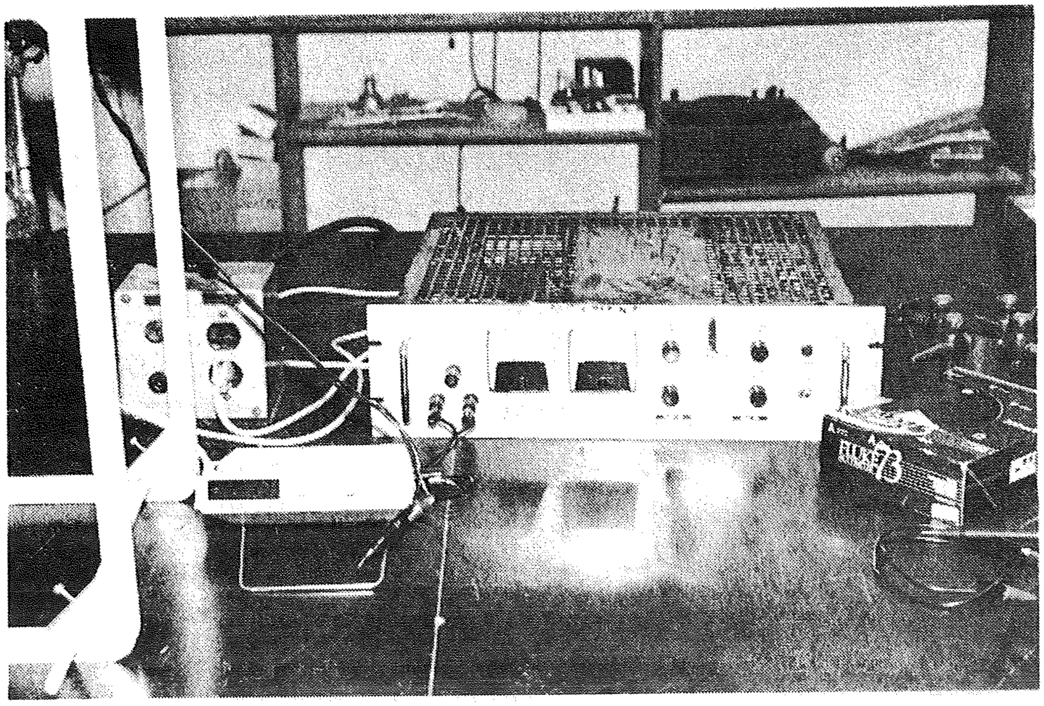


Figure 8(b). Close-up of the large coils.

at some nine locations in the coils. These locations were: the center of the coil and four locations along the axis and four locations transverse to the axis from the center of the coil. Figures 9, 10 and 11 show some of the results of these readings. The measurements were highly linear at all nine locations. The correlation coefficient between the coil current and the Hall potential was 0.99993 or greater for all nine locations. These highly linear relations are shown for the center of the coils in Figure 9, for a 2.0 cm axial displacement in Figure 10, and for a 2.0 cm lateral displacement in Figure 11. The following table shows the measured relation between Hall potential and coil currents and the calculated correlation coefficients for the nine locations.

Axial Displ (cm)	Lateral Displ (cm)	Slope (V/A)	Correlation coefficient
0.0	0.0	4.41	0.99994
0.5	0.0	4.40	0.99993
1.0	0.0	4.47	0.99997
1.5	0.0	4.44	0.99997
2.0	0.0	4.47	0.99997
0.0	0.0	4.46	0.99993
0.0	0.5	4.41	0.99997
0.0	1.0	4.40	0.99993
0.0	1.5	4.38	0.99997
0.0	2.0	4.44	0.99998

The data in this table are plotted in Figures 12 and 13. Figure 12 shows the variation of field strength with axial

Figure 9. Linearity of magnetic field with coil current in the center of the coils.

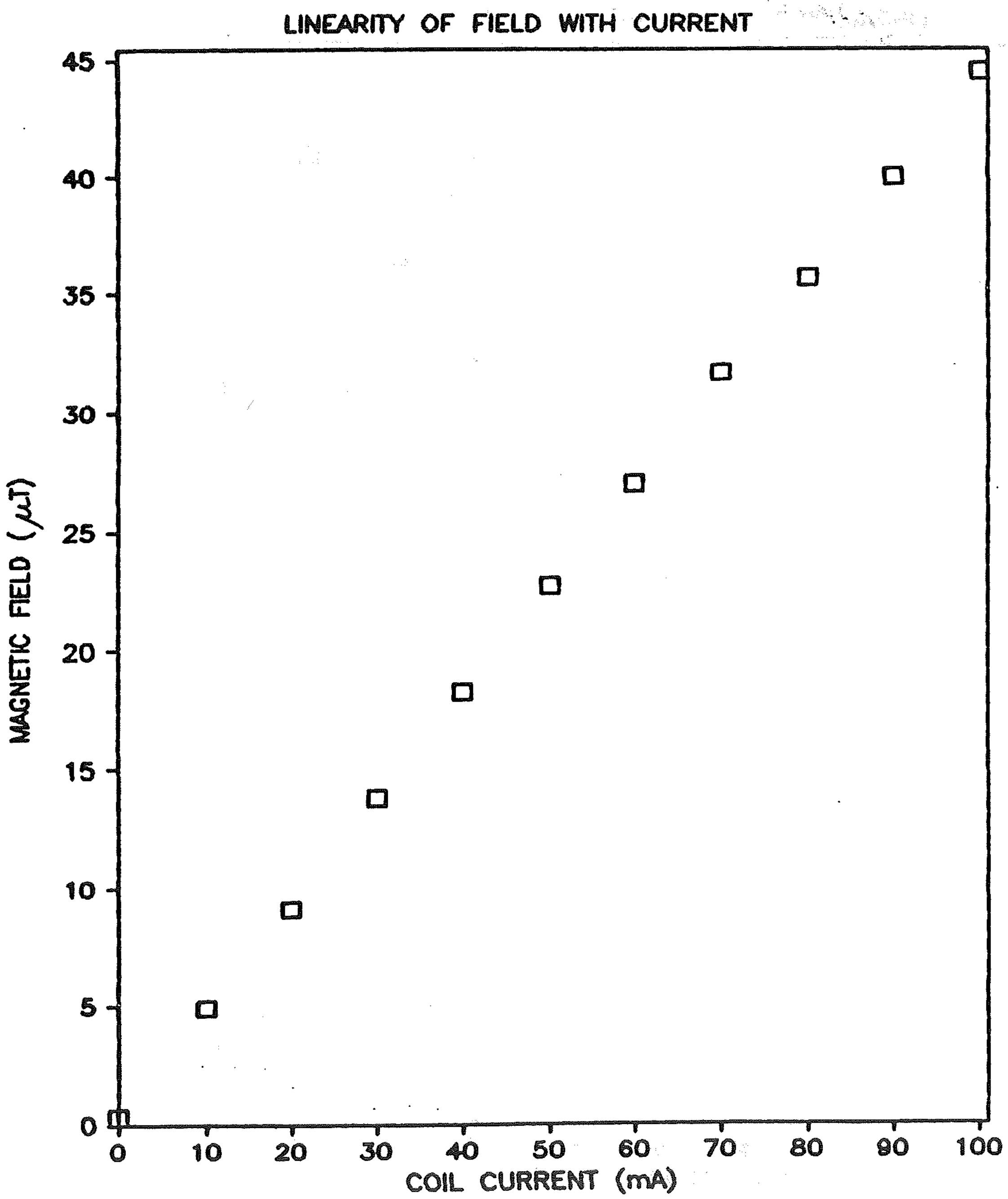


Figure 10. Linearity of magnetic field with coil current two centimeters axially displaced from the coil center.

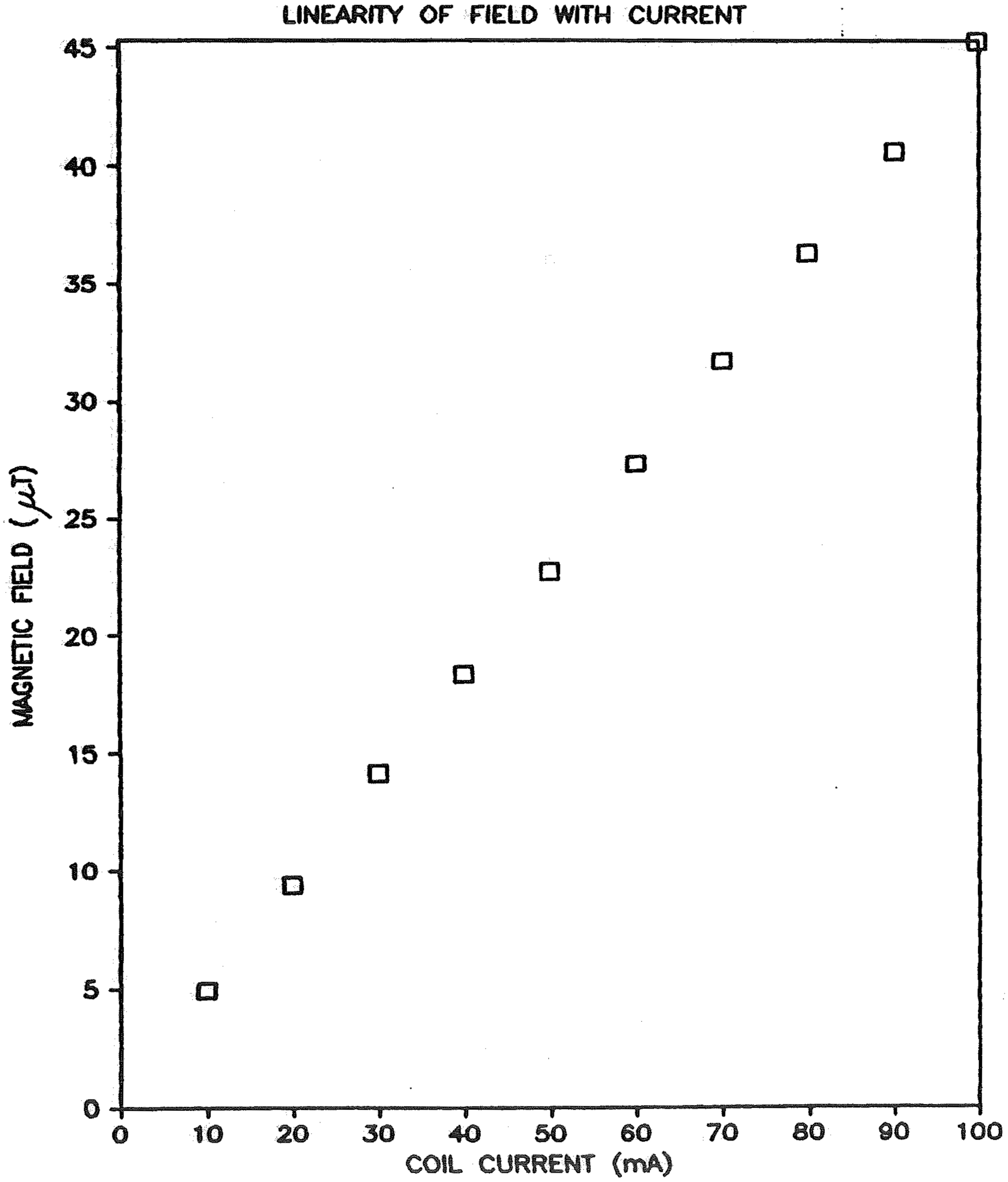


Figure 11. Linearity of magnetic field with coil current two centimeters laterally displaced from the coil center.

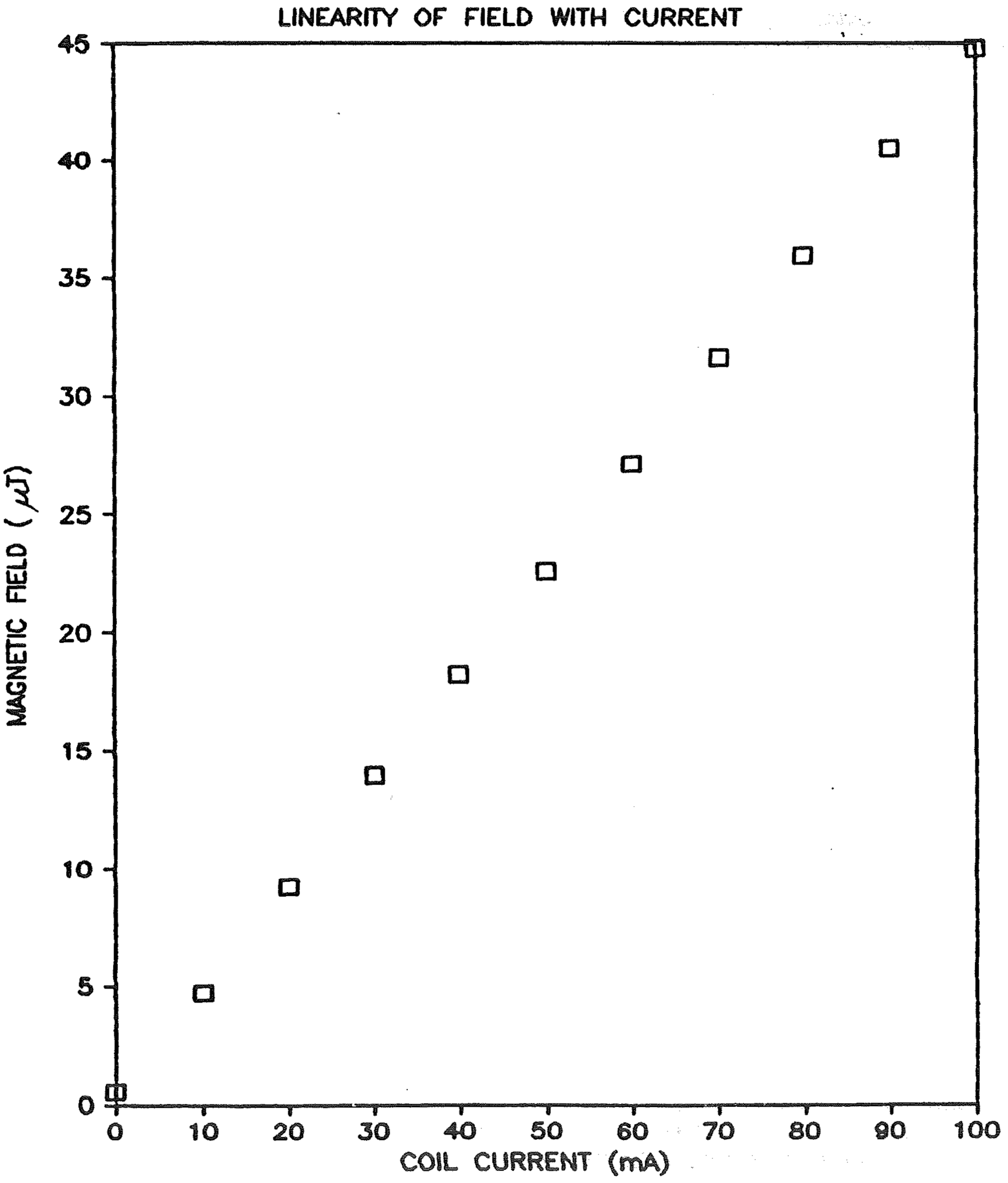


Figure 12. Uniformity of the magnetic field along the coil axis.

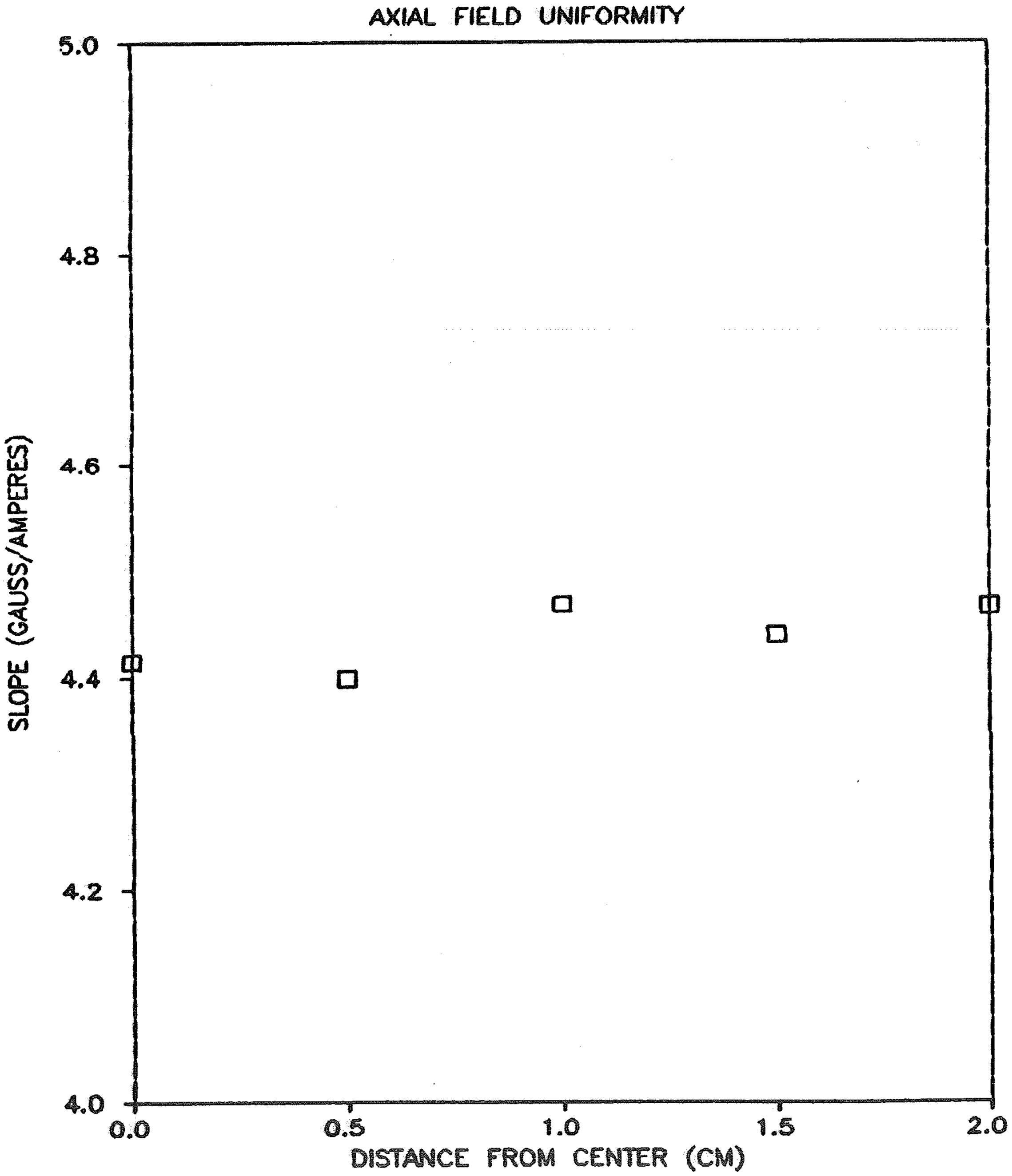
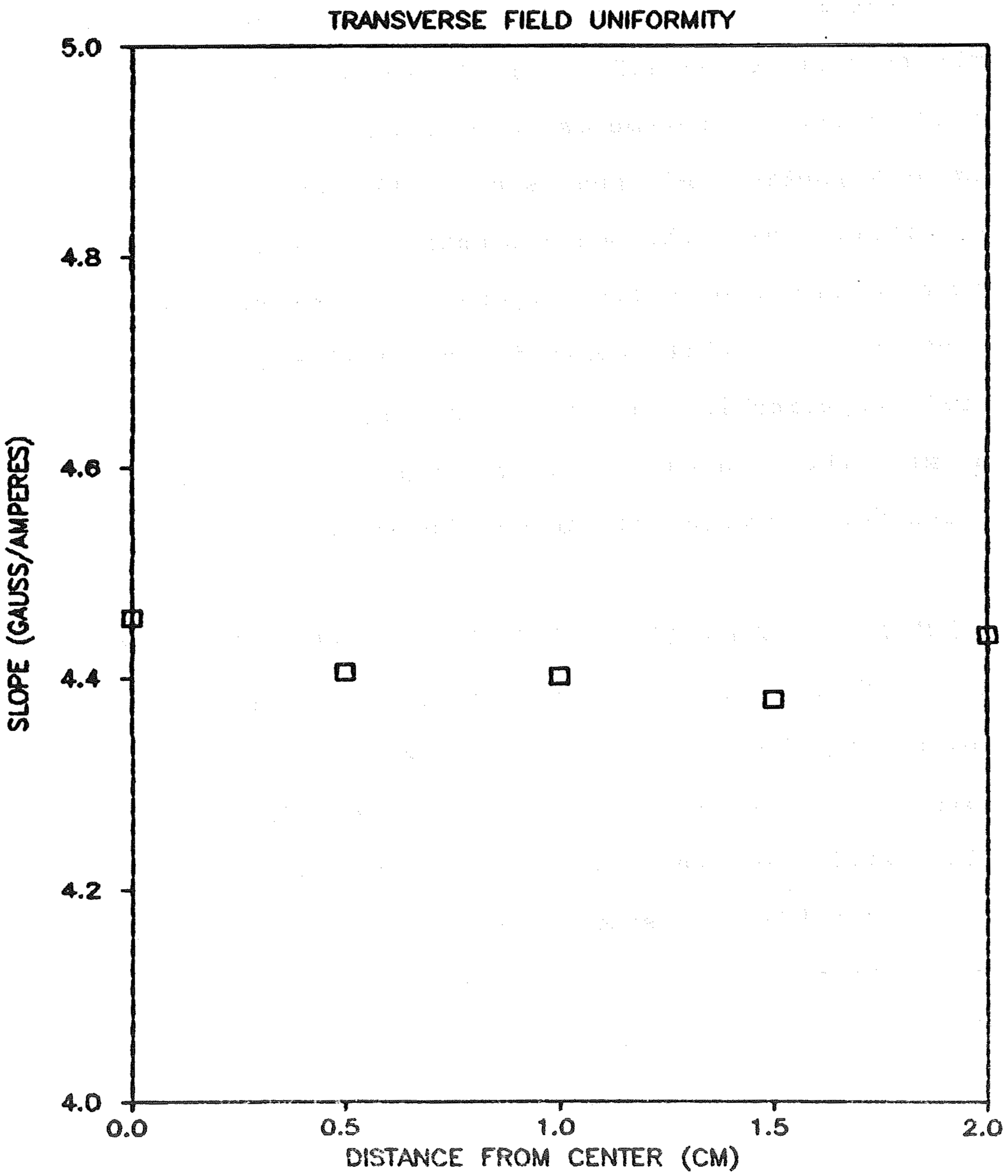


Figure 13. Uniformity of the magnetic field for lateral variations.



displacement, and Figure 13 shows the variation of lateral, or transverse, field strength with lateral displacement. Neither graph displays a systematic variation of field strength with distance from the center of the coils. Both plots show an almost constant magnetic field with small random fluctuation presumably due to random errors in the measurement. These measurements are deemed to establish uniformity of magnetic field consistent with the requirements of this contract. While the measurements were performed over two centimeters in the mutually perpendicular directions, the symmetry of the Helmholtz coils indicates that the results are actually applicable for four centimeters in each direction and the constancy of the measurements justifies extrapolation for the required ten centimeters.

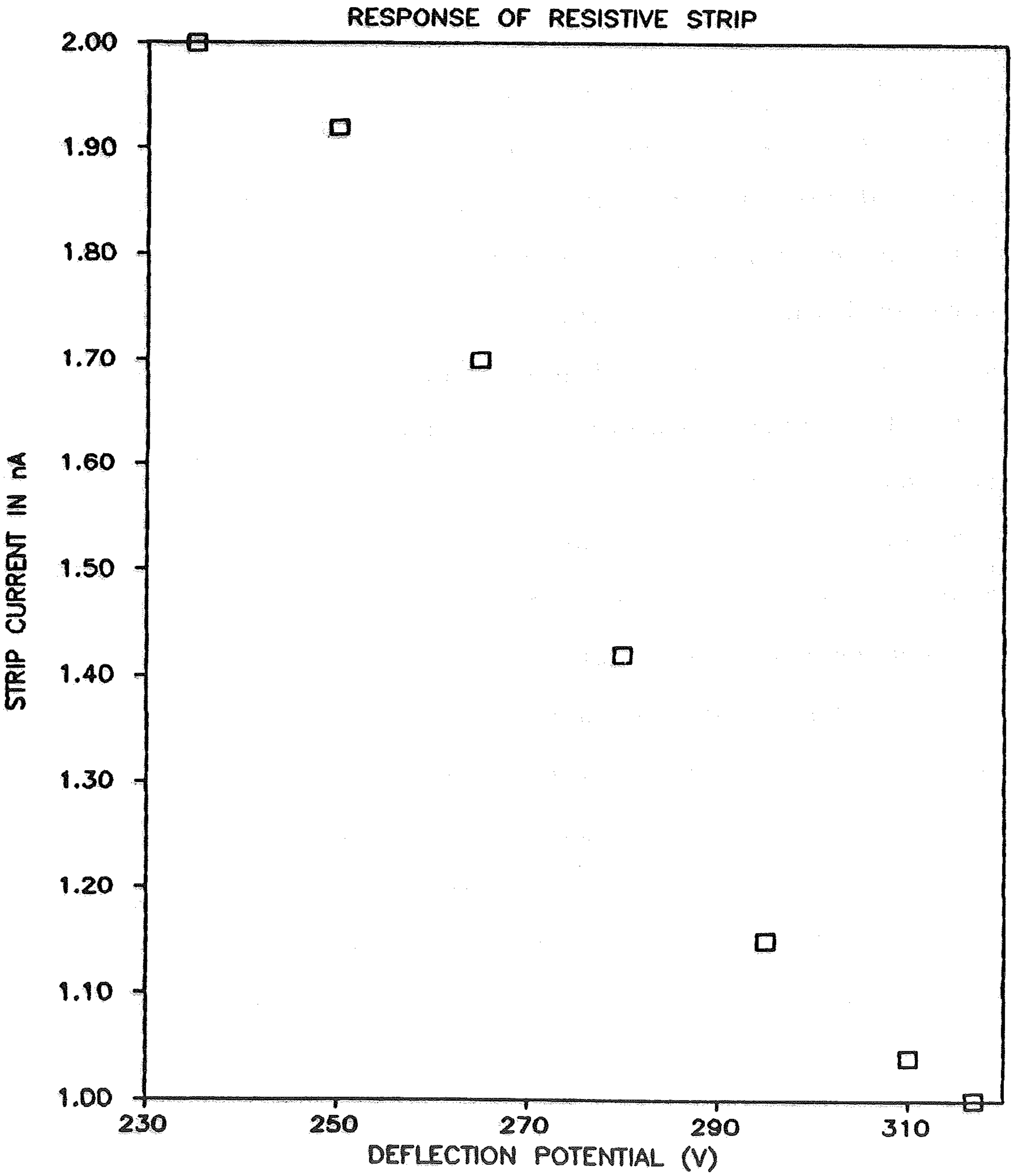
INSTALLATION AND TESTING OF THE POSITION SENSITIVE DETECTOR

Because LEEM-2 functioned well when only a single stage was employed and because this mode of operation tended to produce large beam currents, the decision was made to employ a resistive strip as the position sensitive device to be installed in the LEEM-2. Resistive strips were obtained from TRW and, after testing, one was installed in the first stage of the LEEM-2. The strip was run along the entrance plate of the first analyzer from just beyond the entrance slit to just past the exit slit, covering the exit slit in the process.

The strip was secured by mounting it in a teflon mount which experienced a compression fit between the entrance plate and the first guard ring in the first analyzer. To test the strip a beam was generated and a deflection potential imposed on the first plate. One end of the strip was grounded externally through two 6.3 megohm resistors in series, and the current was read from the other end using an electrometer. Occasionally, the roles of the grounding resistors and the electrometer were interchanged.

The measured variation of current leaving the resistive strip through the electrometer with the deflection potential impressed on the first analyzer is shown in Figure 14. Although the data seem to show a smooth decrease with impressed deflection potential consistent with the idea that the increasing electric field is moving the beam farther from the end attached to the electrometer, and despite the fact that the filament current was turned off to verify that the signal disappeared, the data seem unusually smooth and the slight S-shape seen in the curve is sometimes consistent with a leakage current rather than a true signal. Further tests are needed to confirm this response for the resistive strip. Should this behavior of the strip be confirmed, then it would indeed form a sensitive detector of the position of the electron beam since the current is easily detectable and varies substantially with the apparent position of the beam.

Figure 14. Current from one end of resistive strip as beam position varies.



FURTHER POTENTIAL IMPROVEMENTS FOR THE LEEM

The set-up and demonstration of LEEM-2 has, in fact, demonstrated some additional possible improvements. Should it be desired to perfect the device, the following changes are recommended.

1) The present electron gun should be replaced with a gun from a commercial cathode ray tube. Such a tube will have optimally designed deflection plates for each of the transverse directions. This feature will overcome the most serious defect of the LEEM by permitting easy adjustment of the beam through the device.
2) The LEEM should be reduced to a single stage. The stronger signal which would be thus produced would more than offset the spreading of the beam spot due to chromatic aberration. The device would probably be greatly simplified. Its operation might even be routine.
3) The larger beam currents would permit the firm adoption of the resistive strip for measuring the beam position, avoiding the use of complicated mircochannel plates.

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16. Abstract

This report describes the design, construction, and test results of a Low Energy Electron Magnetometer (LEEM). The electron source is a commercial electron gun capable of providing several microamperes of electron beam. These electrons, after acceleration through a selected potential difference of 100-300 volts, are sent through two 30 degree second-order focussing parallel plate electrostatic analyzers. The first analyzer acts as a monochromator located in the field-free space. It is capable of providing energy resolution of better than 10^{-3}. The second analyzer, located in the test field region, acts as the detector for electrons deflected by the test field. The entire magnetometer system is expected to have a resolution of 1 part in 10^3 or better.

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