DESIGN OF NAL EXTERNAL BEAM LINE QUADRUPOLES

F. Ascolese, R. Billinge†, H. Edwards, W. Hanson,
R. Juhala, A. Maschke,‡ J. Michelassi, P. Reardon, S. Snowdon

National Accelerator Laboratory*
Batavia, Illinois 60510

Abstract

The 3-inch aperture quadrupole magnets used in the extracted proton beam lines and in some secondary beam lines at the National Accelerator Laboratory produce a gradient of 5 kG per inch with 100 ampere excitation and a voltage of 225 V. The 10-foot long laminated core consists of four separate quadrants punched from main ring magnet steel welded together and completely vacuum impregnated with coils and vacuum chamber in place. The four coils each contain 118 turns of #3 U.S. gauge solid square copper insulated with a polyimide coating. Conduction cooling is provided by water-cooled fins located between conductor layers. The designed gradient is uniform to 1% over the 3 inch aperture.

I. Introduction

These three inch quadrupole magnets are the focussing elements of the beam transport system for proton beam from the accelerator and also for some secondary beam transport lines in the three external experimental areas. Because of the extended beam lines, it is desirable to have a magnet which can be powered with a low-current, high-voltage supply to minimize the cost of power transmission. The decision to use this type of magnet was made after comparing the 10 year operating cost for magnets of several designs, including their power consumption and cooling requirements, to the initial capital investment for the magnets and power supplies. The coils in this magnet are designed with 118 turns to provide ~12000 AT required for a field gradient of 5000 G/in. with a voltage of 225 V across the four coils. The design value for field gradient variation is one part in 10^3 over 2/3 of the aperture area. The magnet core, the coils, and the vacuum chamber are simultaneously vacuum impregnated into a monolithic unit.

The length of the magnet, plus the fact that it is not only laminated but consists of essentially six component parts making up the iron path, posed some difficulties in meeting the fairly tight tolerances on the aperture. In spite of the length, however, the magnet, when vacuum impregnated, forms an extremely rigid structure which shows essentially no deflection regardless of how it is supported. The tight packing of the turns of the coil led to some electrical insulation difficulties which were solved by additional insulation in critical areas of the coils. The magnets were built at three facilities: NAL, Westinghouse of Emeryville, California, and Magnetic Corporation of America (formerly Airco-Temescal) at Berkeley, California. Prior to, and during initial production, by the mentioned vendors, NAL built several magnets for two reasons; i.e., (a) to develop tooling and procedures to achieve the desired quality of magnet, and (b) to establish manufacturing tolerances consistent with the magnetic specifications. The vendors were then supplied punched laminations, specially contoured end packs, pre-insulated wire, and the expertise developed at NAL. This NAL experience was then supplemented by the experience of each vendor and resulted in the preparation of tooling and procedures that would yield acceptable magnets. A total of 170 magnets have been built with the Magnetic Corporation of America providing over 100. The magnets cost approximately $12,000 each and the power supplies (provided by ACME and Ling) approximately $4,500 each.

II. Construction

Stacking of the Core

The magnet consists of four quadrants which are held together by weldments on four keys. The laminations are punched from the same type of steel used for the main ring magnets, namely 1/16 in. thick Armco super soft, specially modified to develop large grain size, and control impurities which adversely affect magnetic characteristics. It is insulated with a light phosphate coating commonly known as core-plate.

After a quality control check, the laminations are vapor degreased and then stacked together in special stacking

---

† Present address CERN, Geneva, Switzerland

‡ Present address BNL, Upton, New York

* Operated by Universities Research Association, Inc. under contract with the U.S. Atomic Energy Commission

fixtures. There were two different approaches taken in the stacking of the core. MCA chose to stack a single quadrant at a time using the straight outside surfaces of the lamination as the guiding edge. The inner surfaces of a right angle were used to support the laminations with the pole facing upward. After compressing the quadrant, a coil was affixed to the core by glueing and clamping. These semi-rigid quadrants were then assembled into halves with the wide key and the halves tack welded together with the narrow key.

The other method of stacking employed both at NAL and Westinghouse consisted of stacking a half magnet with the coils loosely in place and then joining the two quadrants with the wide key. In this case, the guiding surfaces were two points on the pole face and the mating surface of the back leg.

The stacking fixture shown in Figure 2, the one used at NAL, consists of two outer 2 in. diameter steel cylinders which were case hardened and a V-block holding a 1.5 in. diameter steel cylinder in the center. The fixture was optically leveled and aligned to a tolerance of ± .001 in. By pressing on the outer corner in such a manner as to force the laminations against the guiding surfaces, the quadrants were held in place for joining together with the wide key. It was found that under this compressing force, the laminations tended to skew such that they would no longer be at right angles with the guiding rails. This was corrected by prestacking 9 in. hard packs on a very precise fixture. The laminations in the hard pack were TIG welded together. Usually four of these hard packs were used in each quadrant, spaced at equal intervals with loose laminations stacked between them. Before welding the wide key into place, it was found necessary to first TIG weld the laminations in the three locations shown in Figure 1. If the weld to the wide key is made first, the laminations pull, causing a wavy surface due to uneven shrinking of the welded joints. The wide key was stress relieved to reduce warping during welding, and machined to a width of 7.750 ± .0005 in. The quadrants are terminated at the ends with 2 in. wide hard end packs that have been contoured to allow a smooth transition to the zero field outside.

The magnet was then assembled from the completed half cores using a granite surface table. The halves were compressed together by clamping to the surface table. A round key is used to align the back legs of the laminations so they are not shifted with respect to each other. Obviously, the halves must be of the exact same width or the magnet will not fit together properly. Originally, the design called for a .250 in. dowel to be used. However, it was found necessary to use a somewhat smaller dowel (.247 in.) to allow for small irregularities in the stack. A 10 ft long, 4½ in. wide adjustable parallel was placed between the halves in the aperture to maintain the proper distance between the vertical tips. At this point the vertical tip to tip spacing was set .005 in. smaller than the assembled spacing. It was in this manner than an allowance was made for weld shrinkage occurring at the back leg. The most critical point of the assembly procedure (aside from careful stacking) is in joining the two halves together. They are best joined by TIG welding the back leg gap together, as necessary, to pull the mating surfaces flat to each other. Excess weld here would cause the vertical tip to tip dimension to open up. The actual amount of weld used here was usually a 1/2 in. bead every four to six in. With this weld complete the magnet could be moved about and would remain intact. The next step was to weld the small key in place. On the first magnets produced, a full weld on both sides of the key was used. The stresses produced as this weld shrunk increased the spacing between the vertical tips by as much as 1/32 in. Therefore, tack welds were used to hold this key in place spaced 9 in. apart and staggered so that no two welds were directly opposite each other (see Figure 1).

Coil

The coils are wound from #3 square OFHC solid copper with 118 turns per coil. There are approximately 2500 ft of wire in each coil (no splices were allowed). The insulation is a .0015 in. polyimide film coating which provides good resistance to radiation damage and mechanical abrasion. Cooling is provided by two edge cooled aluminum fins which are inserted between the coil layers. Because of the thinness of the insulation and the close packing of the turns, special precautions were necessary to avoid trapping foreign material in the coil, which could lead to failure. In fact, during the early production of magnets, a considerable loss in coils was experienced, some of which was apparently due to poor coating of the wire, some to foreign matter getting in between the turns of the coil, some to the use of metal tools which scratched the insulation and some due to abrasion of the coating during winding.

In addition, the handling of the copper and the final sizing process at the manufacturer were such as to produce nicks and slivers periodically in the bare copper.

To guard against this, special handling was required and additional inspections performed. It was found necessary to do the coil winding in a clean area shut off from other activities. It was also noted that attempts to clean the copper with acetone or similar cleaners tended to soften the insulation which apparently was not fully cured at the time it left the manufacturer. Thus, only a dry wipe was used and a procedure of post-curing at 375° F for 15 minutes was employed after winding but before compressing into the core. Also, in the end areas and in the cross-over areas, the conductors were wrapped with a few layers of either glass or 5 mil Kapton tape. The eight turn layers of the coils were separated by staggered strips of 5 mil Kapton tape to prevent abrasion during winding and handling of the coils. Mica insulation was used in the ground wall.

Two slightly different procedures were used by the suppliers to wind the coils and hold the turns in place. Westinghouse wound half coils and brush coated them with epoxy after winding, pressed them to size, pre-cured the half coil unit, and then assembled the rigid half coils with cooling fins and ground wrap. MCA preferred to wind the whole coil, insert the cooling fins, and ground wrap with B-stage mica-glass tape, then pre-cure the coil without attempting to bring it to final size. In this case the turns were loose, being held together by the outer ground wrap only.

Both procedures had advantages and disadvantages. The brush coating of the half coils provided an incomplete impregnation which could contain trapped voids that would not be filled during the final vacuum impregnation process, and in any case would hinder the epoxy flow. The cured B-stage, on the other hand, tended to form a closed outer shell which also hindered penetration by the epoxy during final impregnation. (This was later solved by perforating this outer shell.) Also, the loose turns rubbed against each other during handling, thus creating an opportunity for slivers and chips to dig through the insulation. (As mentioned above, this was later solved by separating the layers.)

Although the original subcontract required only a final test of coil integrity, it was desirable to subject them to induced voltage testing after each separate phase of construction. They were subjected to a maximum of ten volts per turn. In cases where a failure occurred, usually the coil could not be repaired. The additional inspections at the copper manufacturer, the imposition of tight standards of cleanliness at the vendor, the improved insulation system, and the improved handling techniques resulted in such a dramatic decrease in coil and magnet losses that no failure of either coils or magnets occurred during the production of the last hundred magnets.

Assembly and Impregnation

After welding the quadrants of the magnet together, it remained, of course, a very flexible unit. At this stage very careful handling was required so as to avoid overstressing any point. Because of this flexibility it was necessary to design a rigid carrier for constraining the magnet during impregnation. Such a unit was constructed from two I-beams welded together and stress relieved. Here again, cylindrical rails, optically levelled, were used to support the magnet as shown in Figure 3.

Since the magnets were laminated, they had to be wrapped tightly around the outside with a covering, which was essentially vacuum tight, to prevent the epoxy from leaking through the surface. There were three different techniques used. Westinghouse chose to build a rectangular box out of 1 in. thick steel to enclose the magnet. This, unfortunately, did not allow for the possibility of straightening the magnet, once inside, to the required tolerances. MCA used thin steel sheeting that was sealed with end caps and O-ring material. This eventually worked out quite well after some redesign of the supporting base. The technique employed at NAL was to use a 0.010 in. mylar wrap glued at the overlap and sealed at the ends with steel covers contoured to fit closely around the coil ends. To keep the rails from cutting into the mylar, 1/4 in. x 1 in. aluminum straps were placed on top of the rails before setting the magnet on the girder. Side plates and a bottom plate were then banded around the magnet to minimize the bulging of the mylar wrap during impregnation.

After the magnet was placed on the girder and before insertion of the vacuum chamber (a 2.950 in. diameter x 1/16 in. wall stainless steel tube), the spacing between tips and the pole to pole distance were measured at 6 in. intervals over the entire length of the magnet. The tip to tip dimensions are to be equal within a tolerance of ± 0.005 in. The averages of the two bore dimensions on a given magnet are to be equal to within 0.003 in. By constraining the magnet along the appropriate diagonal, it was possible to stay well within the 0.003 in. tolerance on the bore dimension. The method of clamping used to adjust these dimensions is shown in Figure 3.

The epoxy system[1] used in the magnet along with the curing cycle, has been used in several other magnets at NAL. One addition was made to this formulation; namely, tabular alumina filler. This mixture contains equal parts by weight of alumina and resin. The filled epoxy has better resistance to radiation, shrinkage, and has better mechanical properties with regard to rigidity, and most important for this magnet, it has a thermal heat conductivity five to ten times greater than the unfilled epoxy. Since the proper cooling of this magnet hinges on a very thorough impregnation with no voids, special precautions were taken to degas the resin and eliminate trapped air pockets by elevating one end of the magnet during curing.

Figure 4 shows a photograph of a magnet complete with electrical connections and water manifold. It is supported on a stand used in the secondary beam lines of the Meson Facility.

III. Testing and Performance

The magnets are subjected to the following measurements and tests: bore diameter and tip to tip measurements before potting, straightness and flatness both before and after potting, induced voltage test, inductance and resistance measurements. In addition, a few magnets were selected for a thermal cycling test, others for power tests to determine the effectiveness of water cooling and finally, of course, magnetic measurements. The data presented in the table below (with the exception of the power test data) represent the averages of measurements made on several magnets.

The quantities labelled Twist, Flatness, and Straightness, were determined by optical measurements at 13 sections along the length of the magnet[2]. The points on the surfaces at which the measurements were taken are indicated in Figure 1 by a circled X. The data presented here are taken from 11 magnets chosen at random and in each case the point on the magnet at which the maximum deviation occurred is the one chosen for use in determining the average. The "Twist" then is the maximum angle between any two sections of the magnet. The tolerance on the "Twist" is 1 mrad. The "Flatness" refers to the deviation of points measured on the wide face of the magnet from a plane passing through the measured points 24" in from the ends. The tolerance for the "Flatness" is 0.030 in. The "Straightness" refers to deviations of points from a line in the narrow face of the magnet which passes through the two points 24 in. in from the ends. The tolerance of the "Straightness" is 0.030 in.

The diameter of the bore and the tip to tip spacing were measured at 6 in. intervals. These measurements were made with the magnet under constraint just before impregnation. At this point adjustments could be made in these dimensions by altering the constraints. Thus, for each magnet the averages consist of 42 points for the bore diameter and 84 points for the tip to tip spacing. The average of these data for eleven magnets are presented in the table with their corresponding average deviations. The "Bore Diameter" is 2.997 ± .0015 in. The tip to tip spacing is 1.033 ± 005 in. Finally, the average dc resistance and equivalent series inductances for the eleven magnets are given.

TABLE I. Averages of Mechanical and Electrical Measurements on the 3 in. EPB Quadrupoles

Twist	0.6 ± 0.3	mrad
Flatness	0.0072 ± 0.0016	inch
Straightness	0.0052 ± 0.0011	inch
Bore Diameter	2.9985 ± 0.0014	inch
Tip to Tip Spacing	1.0323 ± 0.0006	inch
D.C. Resistance	1.620 ± 0.022	Ω
Inductance (at 1 kHz)	1.34 ± 0.034	mHy

Power tests were performed under conditions likely to occur in actual use of the magnets. In certain areas, for example it is intended to use air-cooled heat exchangers to cool the LCW water used in the magnet cooling system. In this case the water could be expected to enter the magnet at around 113° F during the hottest summer days. A magnet was powered at 100A using water at a supply pressure and temperature of 115 psi and 105° F, respectively. At steady state the voltage drop across the magnet was 225 V. The temperature of the water leaving the magnet was 150° F. Temperatures at points on the iron and coil surfaces ranged from 205° F to 212° F. Since the flow was 2.5 gpm, the amount of power absorbed by the water was 16500 W with 6000 W going into the exterior surroundings. In another test, this time with no water cooling, the magnet when powered at 40 A with 85.2 V reached a temperature of 212° F inside the coil and approximately 200° F on the surface.

At higher temperatures and corresponding increased stress on the coil, one might expect the insulation to fail at areas where slight flaws existed. To test this possibility, "life tests" were conducted with a few of the first magnets produced. These tests consisted of powering the magnet for four hours at 100 A with water cooling and then turning off the power and allowing the magnet to cool for four hours. These tests were carried on for 8-10 weeks. Of the magnets so tested, none were found to fail; failure would have been indicated by shorts to ground or turn to turn shorts.

The pole contour was determined by the method of conformal transformation of a complex variable from which a profile is generated based on the desired field characteristics.[3] The requirement on the field gradient is that it shall be uniform to within 1% out to a radius of 1.5 in. along the horizontal and vertical axes. The profile based on the above criteria would theoretically produce a gradient uniform to within 0.1% at a radius of .925 in. A plot of the ideal relative gradient is shown in Figure 5.

Based on the results of the method described above, the die for punching the laminations was constructed. As a check on the design, profile measurements were made on the first few laminations. These profile measurements were used as input to a magnet design-aiding program (LINDA) which calculated the corresponding field. The relative gradient $\Delta G_x/G_x$ determined from these calculations is also shown in Figure 5. The term relative gradient as used here means:

$$\frac{\Delta G_x}{G_x} = \frac{dBy/dx}{dBy/dx|_{x=o}} -1 \text{ and } \frac{\Delta Gy}{Gy} = \frac{dBx/dy}{dBx/dy|_{y=o}} -1.$$

Magnetic measurements have been made on several quadrupoles. Measurements of the relative gradient along the horizontal and vertical axes have been made at NAL. A measurement to determine the contribution of higher multipoles to the gradient has been completed at the Stanford Linear Accelerator by the Magnetic Measurements Facility[4]. Also, an excitation curve of gradient versus current has been measured.

The relative gradients were measured using a bucked pair of 2 in. long rectangular gradient coils. Because of the coil width, measurements could only be made out to x = ± 0.8 in. The average deviation in the measured values of $\Delta G/G$ is ± 0.0001. These data are averaged from measurements made at 3 points inside the magnet spaced 6 in. apart starting at 12 in. from the end. The magnet used is one manufactured by MCA (#87) which based on the mechanical measurements, is representative of the type of magnet produced after the production techniques were well established. The results in Figure 5 show that the measured gradients along both axes and the theoretical gradient provide a wider good field region than that which was determined from the measured profile.

For the harmonic analysis a magnet produced at MCA was sent to SLAC. Measurements were made at 40 A and 100 A. The 40A data were taken without water cooling; therefore, approximately the same coil and core temperatures existed during the two measurements. The measuring technique[5] employed a uniformly rotating 1 in. long coil which sensed the field out to a radius of 1.355 in. The instantaneous voltage waveform produced by the coil is frequency analyzed to determine the harmonic coefficients. Approximately 15 points were measured at each end. The maximum distance into the magnet that could be reached by the probe was 29 in. from the ends. Based on these measurements, the average relative gradients at both levels of excitation were calculated. The results are shown in Figure 6. Based on successive measurements, the average deviations are approximately ± ($\Delta G/G$) x (0.15). This magnet (MCA #5) has a somewhat narrower good field width over the region measured than that measured for MCA #87 shown in Figure 5. This could be due in part to the fact that it is among the first produced.

The gradient has been measured as a function of current. For this measurement a rectangular coil 2 in. by 3/8 in. wide was moved from x = -.5 to x = +.5 in. across the aperture at several points well inside the magnet. The search coil and integrator are calibrated using an NMR field sensor and a uniform field dipole magnet. The largest uncertainty is in the shunt calibration which is ± 0.25%. All other uncertainties are less than ± 0.05%. A straight line is a very good approximation to the curve up to 80 A. The magnet (MCA #87) was cycled several times to 110 A before the data were taken.

IV. Conclusions

As the result of the experience gained during the construction of these magnets, it might be appropriate to point out some of the areas where a slight modification of the lamination would have perhaps facilitated the construction somewhat. To do this we refer back to Figure 1, which shows the lamination. As it turned out, the small key really did not serve any essential part in the construction of the magnet; therefore, by eliminating the notch for this key, one gains by having a wider back leg which, although not necessary from the standpoint of flux density, would help in stabilizing the tip to tip dimension between halves. Then the two halves could have been joined simply by TIG welding as necessary to achieve a minimum back leg gap. Another point of difficulty turned out to be the large radius on the portion of the lamination which is welded to the wide key. The large amount of heat and rod required to fill this gap caused stresses which tended to distort the magnet half. It would have been better to have a very small radius here so that a TIG weld requiring no additional material and much less heat would have sufficed.

From the results of the power tests it can be observed that powering the magnets at full excitation (5000 G/in. at 100 A) does lead to some undesirable heating. One method of combating this would be to cool the iron since the coil contacts the iron over most of its perimeter. One possible way of doing this is to add a one-inch diameter hole in the upper corner of the lamination into which a thin wall stainless steel tube could be inserted. The tube could then be expanded under hydraulic pressure to provide positive contact with every lamination. In fact, four one-inch diameter tubes were added to one magnet in the space bounded by the coils, pole tips, and vacuum chamber. This resulted in coil and surface temperature reductions of 30° F when powered at 100 A.

The magnetic measurement data, though not extensive at this point, do indicate that substantial differences can exist in the good field widths of these magnets. The excitation curve indicates that 105 A are needed to achieve a gradient of 5 kG/in. With the limited water-cooling capability now present in the magnets, maintaining this level of excitation is probably not practical for long periods of time.

There are approximately 100 of these quadrupoles now installed in the various extracted proton beam lines throughout the Laboratory. In addition, several of the experimental areas will be supplied with these quadrupoles as components in the spectrometer lines.

Acknowledgments

Thanks are due to the Meson Laboratory technical support for their extra efforts during the building of prototype magnets. Appreciation is expressed to P. Foster for his thorough inspection of the magnets before shipment.

The fine work of M. Pastor and W. Heilbraun with MCA on the contract to build these magnets is acknowledged. The association with them has been very enjoyable.

References

1. R. Juhala, "Procedure for Vacuum Impregnation," NAL TM-316 (July 9, 1971)

2. R. Juhala, "Optical Survey of EPB Magnets," NAL TM-315 (July 9, 1971)

3. S. Snowdon, IEEE Transactions on Nuclear Science, Vol. NS-18, No. 3, pp 848, (1971)

4. J. Cobb, Private Communication

5. J. Cobb and R. Cole, SLAC-PUB-133, September, 1965

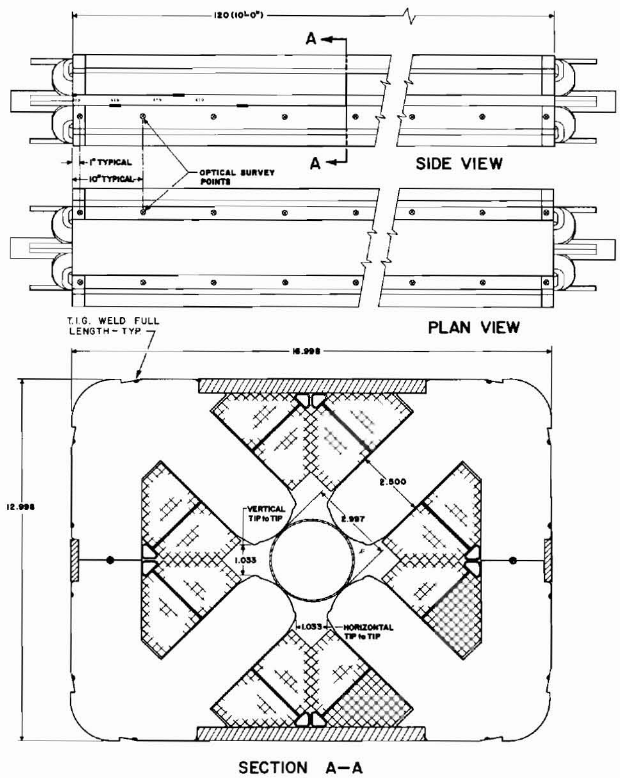

Fig. 1. 3-in. EPB Quadrupole with Cross Section.

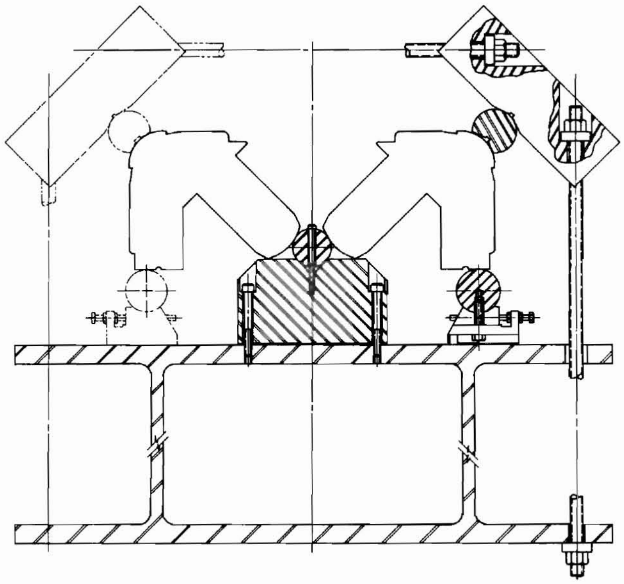

Fig. 2. Stacking Fixture for 3-in. EPB Quadrupole.

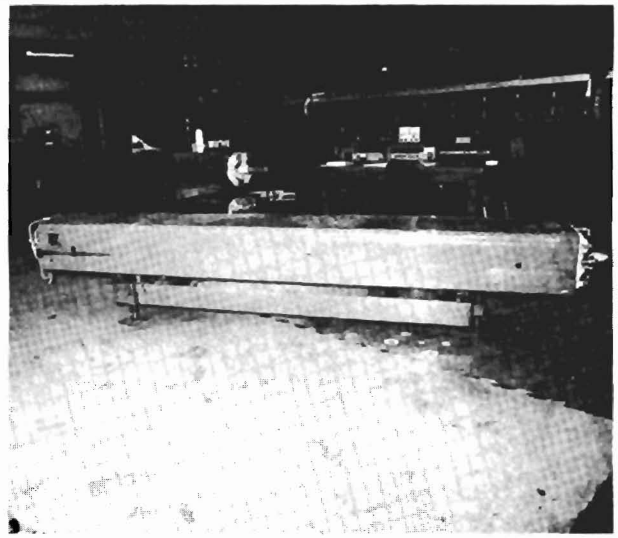

Fig. 4. EPB Quadrupole.

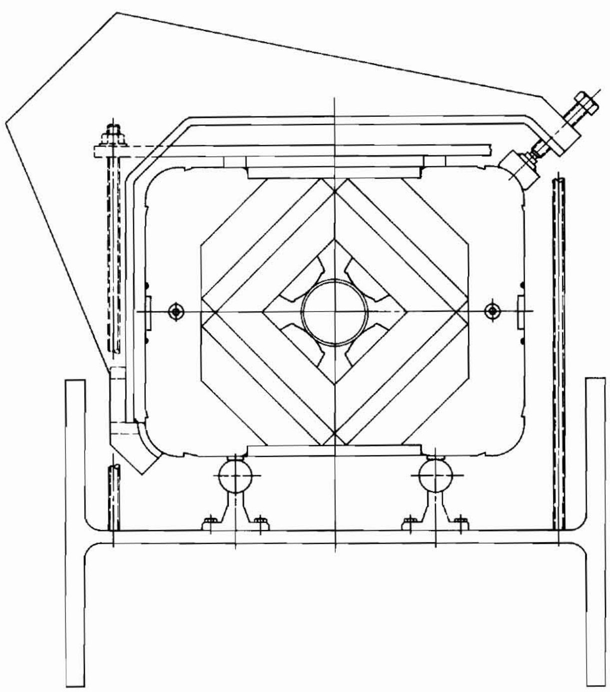

Fig. 3. Potting Fixture, 3-in. EPB Quadrupole.

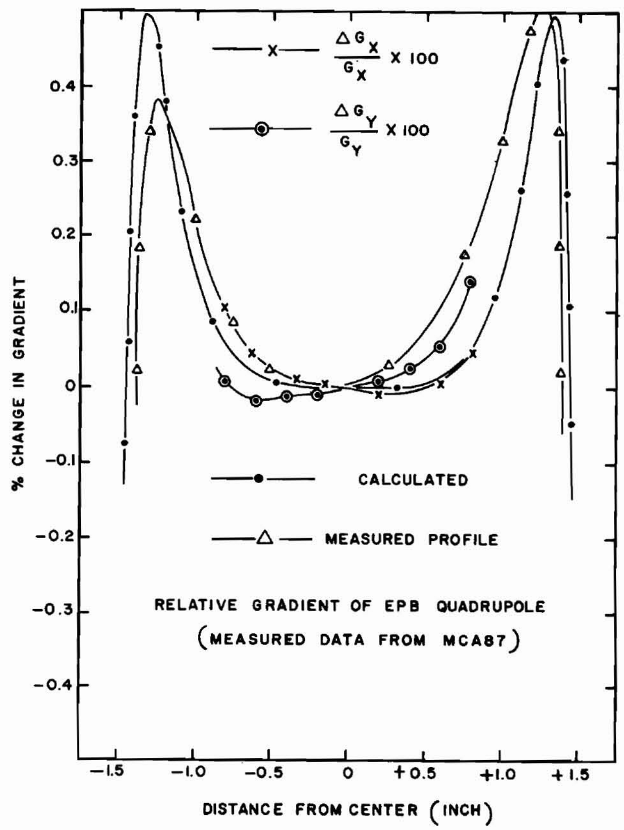

Figure 5.

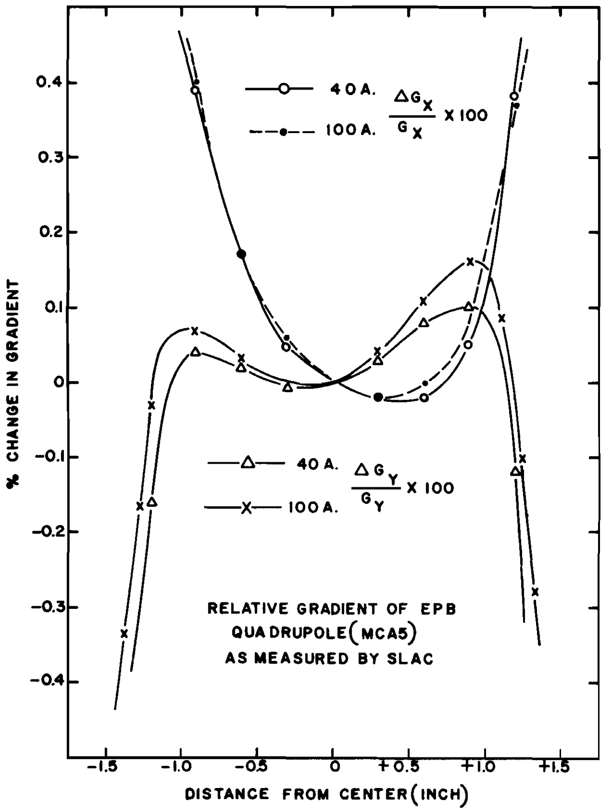

Figure 6.

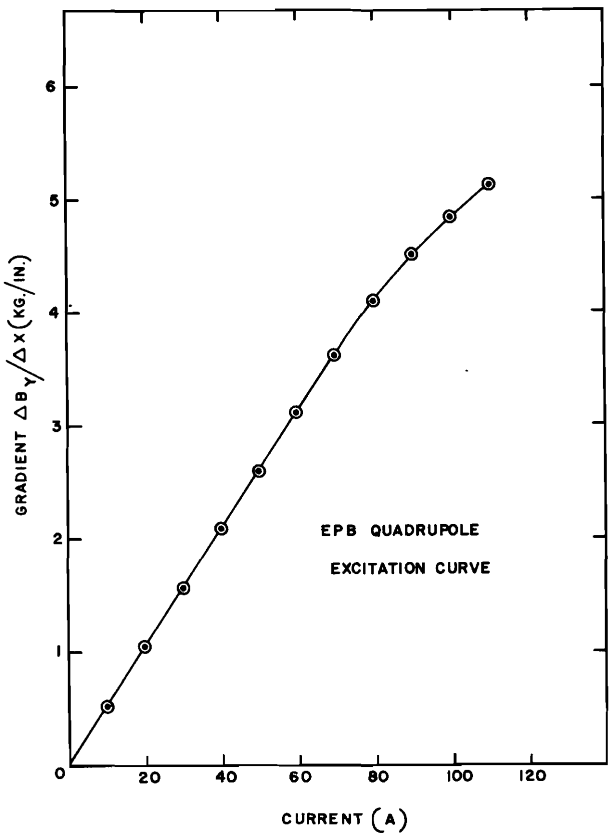

Figure 7.