MECHANICAL DESIGN OF DRIFT TUBES AND QUADRUPOLE MAGNETS FOR THE ALVAREZ LINAC*

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Introduction

This paper describes our efforts at Los Alamos directed toward the mechanical design of drift tubes, drift tube stems, and quadrupole magnets for the 201.25-MHz Alvarez linac. The linac features necessitating this design effort are the high rf duty factor which may go as high as 12%, and the large time average current of one mA. Topics covered are limited to preliminary drift tube design with emphasis placed on the quadrupole magnets and their associated coils. Detailed effort on the final alignment mechanism and stem design has been temporarily suspended awaiting selection of the number and configuration of the drift tube stems. In the following sections our current drift tube designs, cooling schemes and fabrication techniques are discussed. Our approach to the quadrupole magnet design, fabrication, and analysis is outlined along with a description of the coated coil development program.

Design Criteria

The high duty factor necessitates an increase in the drift tube cooling capacity over that of existing designs.

The large time average beam current and the high duty factor give rise to increased radiation levels near the beam axis which may damage the common organic insulating materials. If the solution to the latter problem were to result in an insulation that could withstand brazing temperatures, it permits a brazed drift tube assembly, which might offer some improvements in ultimate vacuum, rf sparking characteristics, and assembly costs.

The geometrical dimensions of the accelerating structure and the strength of the quadrupole focusing system are generated by the PARMILA program.[1] This program draws its information on the accelerating fields and resonant frequencies from a series of MESSYMESH calculations.[2]

Drift Tubes

Figure 1 shows our Alvarez linac design parameters with typical drift tube geometries, and required quadrupole strengths. The drift tubes in Tank 1 have a diameter of 18 cm, 2 cm larger than those in the three remaining tanks, in order to accommodate the higher gradient quadrupole magnets. Where possible, identical component geometries were maintained in order to enhance fabrication. The rf power dissipated on the drift tubes is shown in Fig. 2. The low energy drift tubes are required to dissipate comparatively low power and the longer high energy drift tubes, with more heat transfer area, are required to dissipate the higher power.

With the significant difference in drift tube diameters between the first tank and the remaining tanks, it was decided to maintain similar styles on either side of this interface to permit more economical fabrication. Two drift tube body designs have been conceived. A schematic of the typical high energy drift tube, Fig. 3, indicates the water flow and assembly configuration. The low energy drift tube is similar to the high energy design, with exception of the two cylindrical sections of the body. Two end caps will form the entire body.

Three concentric tubes make up the stem assembly. Cooling water supplied between the outer and middle tube circulates through the drift tube body and returns between the middle and inner tube. The quadrupole magnet coil leads are contained within the inner tube.

Preliminary heat transfer calculations confirm the cooling capabilities of the design and permit ample space for cooling. A subroutine of PARMILA provides rf power dissipation on the various parts of each cell.

Prototypes of two half drift tubes and a high energy drift tube have been fabricated and will be driven to full power in a full size two cell power model presently being assembled. This model will be used to study temperature distribution, verify cooling capabilities, develop water pressure drop equations, in addition to evaluating fabrication techniques.

Alternate drift tubes in Tank 3 and Tank 4 will not have quadrupole magnets but will be fabricated with identical parts. However, the bore tubes will be omitted and the inner side of the drift tube body will operate in a high vacuum.

Quadrupole Magnets

Design

For specific linac parameters PARMILA provides the magnetic gradient required of each quadrupole magnet throughout the entire Alvarez linac. In our case the higher magnetic gradients are required in the shorter drift tube assemblies, Fig. 4. We define the quadrupole strength as the product of the gradient (gauss/cm) and the quadrupole length (cm). In other words, the longer the magnet, the lower are the required field gradients. From the quadrupole strength distribution, it can be seen that it is necessary to use the maximum quadrupole magnet length in Tank 1. The first part of Tank 2 also requires maximum lengths. However, in Tanks 3 and 4 the gradients are sufficiently relaxed to allow fabrication and production techniques to govern the design, with little or no increase in quadrupole excitation power.

Analysis

Here we found ourselves faced with the laborious task of studying the magnetic, electrical, and cooling properties of up to 175 different quadrupole magnets. True, a common quadrupole cross section was held for each tank but significant variations in current, power, and cooling parameters became apparent when groups of constant magnet length were investigated.

Subroutines of PARMILA were written which, given specific quadrupole magnet lengths for each cell, provided the coil conductor length, resistance, current, voltage, power, water temperature rise, velocity, and pressure drop. The section of the subroutine which deals with power is based on a generally accepted quadrupole magnet equation relating amp-turns, gradient, and pole radius. Preliminary gradient measurements on our prototype quadrupole magnets have confirmed the adequacy of our analysis. The section dealing with water pressure drop and flow information is based on equations using experimentally derived coefficients and verified by flow tests. This analysis proved to be of great value when analyzing the merits of various quadrupole magnet grouping schemes, in terms of operating temperatures, flow requirements, system pressure requirements, and power supply specifications.

The low energy quadrupole magnets are required to produce gradients as high as 5526 gauss/cm. To achieve this magnetic gradient our present four turn per pole design will operate at a current of 819A, with a water temperature rise of 30.2°F and a pressure drop of 57 psi.

Another code, QADFLX, was written which, given gradients, quadrupole magnet geometries, and adjacent magnet spacing determines the flux densities resulting at any radial station in the pole. This code is an adaptation of E. L. Hubbard's quadrupole magnet work[3] in which he was able to predict flux densities in the poles within 10%. It provides a design guide and through optimum use of the iron several subtle gains can be made such as: lighter iron structures, shorter coil conductors, and lower power requirements. This code was also written as a PARMILA subroutine and provides a printout of the flux density distribution in each quadrupole magnet of the Alvarez linac.

More extensive use of these codes is anticipated in the future, coupled with actual flux density measurements on typical quadrupole magnets.

Mechanical Design

Conducting paper plots were made of several quadrupole magnet designs to compare isofield lines with the desired hyperbolic fields. The plots were made at 16 times actual size for increased plotting precision. Resolution of the model was within ±1/16 inch corresponding to ±0.004 inch on the actual quadrupole magnet. Operator experience and improved techniques provide even better results. Plots showed the field of the hyperbolic cross section to be an improvement over that of a circular tip of the same geometry. While it is generally accepted that a circular approximation of the desired hyperbolic shape is adequate in strong focusing magnets, for this application it is also held that if costs are competitive the hyperbolic shapes are preferred.

In view of the rather recent advances in tape controlled machining it was decided to investigate the possibility of fabricating integral poles with hyperbolic tips. Short, low energy, magnets were machined, Fig. 5, directly on a No. 3 Cintimatic Numerically Controlled Milling Machine with a 200 series controller. One feature is the elimination of a possible gap where the pole tip joins the base in circular tip designs. With the one piece hyperbolic pole design the axial tip extensions used in typical circular cross sections cannot be incorporated.

A high energy hyperbolic quadrupole magnet was machined using a somewhat different technique. Hyperbolic cams (tape machined) were incorporated in a grinding fixture, Fig. 6. As the pole is rotated within the vertical guides the cams properly position the pole tip with respect to the grinding wheel, Fig. 7. The pole was held in the fixture by magnetism from the magnetic base of the grinder. The completed quadrupole magnet, Fig. 8, has poles essentially ground all over to ±0.001 inch tolerances with interchangeable poles. Poles for shorter quadrupole magnets could be cut from the longer ground pole stock. Costs appear to be nearly competitive using available material shapes. Forged pole stock could conceivably reduce the cost. With three quadrupole magnet cross sections in the entire linac, one fixture and three sets of cams will satisfy the tooling requirements and thereby permit fabrication of hyperbolic poles in any small job shop equipped with a lathe, milling machine, and surface grinder.

Quadrupole Coils

Continuous operation of the quadrupole coils requires cooled conductors and compels the use of large diameter hollow conductors to avoid excessive water pressure. This in turn limits the number of turns per pole and increases the current requirements. Our quadrupole magnets in Tank 1 will use four turns per pole, where the increased drift tube diameter permits, while those in the remainder of the linac will use three turns per pole.

To satisfy the brazing requirements and to reduce the susceptibility of the insulation to radiation damage three inorganic materials are being investigated: ceramic, porcelain, and cements. Porcelain and aluminum oxide are the two materials that have received major consideration to date. While aluminum oxide has melting temperature of 2050°C the bond to copper leaves much to be desired. Also the ceramic is very susceptible to thermal cracking due to different coefficients of expansion. Application of the Al_2O_3 was by flame spraying, and turn-to-turn bridging was impossible. We feel that turn-to-turn bonds are important to reduce chafing damage caused by coil deflections during current transients.

Porcelain coatings seem to offer several advantages. Well-chosen porcelain materials provide excellent bonds with copper and the expansion characteristics can be very nearly matched. Though stresses may cause crazing, a good bond can be maintained. Coatings have been applied by spraying (then firing) and by dipping with good results. Repeated dipping has provided adequate turn-to-turn bridging. The major disadvantage of porcelain suitable for copper is its relatively low melting point. In general porcelains with the higher melting temperatures have lower expansion characteristics. Several samples using various porcelains have been subjected to hydrogen furnace brazing atmospheres at 732°C for 10 minutes. Samples of ordinary copper tubing were found to contain sufficient oxygen to cause blistering. OFHC samples performed well with no apparent damage other than a slight discoloration of the porcelain caused by reduction of trace amounts of titanium oxide in the material. Figure 9 is one of our early style three-turn coils. Optimum coverage of the coil can be achieved using fewer turns per pole due to the increased conductor diameter and reduced number of interfaces. Another feature we incorporated that proved of value was the elimination of two conductor crossover points. This was achieved by using a two stage form. The two lower coils are wound flat followed by the 90° bend at the bottom. These are then transferred to a four-turn form and the remaining turns wound. The most promising coil porcelain material presently appears to be Chicago Vitreous No. 1501 frit fired at 755°C for 5 minutes. Porcelains typically have dielectric strengths of 400 to 500 volts/mil. We feel that it will be possible to cool the conductor during the braze by flowing hydrogen through the conductor.

As further protection the iron pole faces were porcelainized to obviate pole-to-conductor shorts, Fig. 10. Here again excellent bonds and rather high temperature capabilities can be achieved. The coating illustrated is Chicago Vitreous No. SL-13290B enamel, fired at 970°C for 8-1/2 minutes. This combination has been subjected to a hydrogen furnace braze atmosphere with no apparent effects.

Potting capabilities of several commercial cements are now being studied and some appear promising, but insufficient tests have been conducted at this time to fully evaluate their properties.

Magnet Measurements

Only preliminary quadrupole magnet measurements have been conducted using a Hall effect gaussmeter probe on a single low energy magnet. Gradients at various current levels and axial field surveys served to verify our analytical prediction of magnetic fields, power dissipation, and cooling water parameters.

Field surveys are currently being conducted on three adjacent low energy quadrupole magnets, Fig. 11, in order to measure the effect of the two adjacent magnets.

Acknowledgments

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References

1. B. Austin, T. W. Edwards, J. E. O'Meara, M. L. Palmer, D. A. Swenson, and D. E. Young, "The Design of Proton Linear Accelerators for Energies up to 200 MeV," MURA Report No. 713, Appendix B (July 1, 1965).

2. Appendix A of Reference 1.

3. E. L. Hubbard, "Design of Strong Focusing Magnets for Linear Accelerators," UCRL-8162 (November 15, 1953).

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DISCUSSION

E. D. BUSH, LASL

OHNUMA, Yale: I would like to make one comment. I think it would be very nice to have a capability of, let's say, 7 or 8 kG/cm, although your design value is about 5500 G at the low-energy end. This is particularly true for your machine because your design requires a rather tight bunch. Therefore, although the peak current, 20 mA, is rather low, the space charge effect is not so trivial. If you include the space charge effect, then a high field gradient is very much better than the 5500 you are now taking. Also, the increase of transverse phase space area due to the coupling is smaller at a high field gradient.

VAN STEENBERGEN, BNL: Could you just say a quick word about the thickness of the porcelain coating and the possibility of cracking at increased temperatures?

BUSH: Yes, we have tried several porcelains, all the way from some that were not designed for copper to some that were specifically designed for copper. The choice depends on what you want. Thicknesses of 0.005 in. for a one-dip process, or for a sprayed process, are typical. They do crack when subjected to mechanical stress, but two things work very much in our favor. An inherently excellent bond of porcelain to copper is obtained. Even though crazing occurs, you still have a good bond, so crazing is possible without necessarily causing a coil failure. The same holds for iron. Techniques for applying porcelain to copper have been practiced in art (jewelry) work for years and to iron in bathtubs for many more years. The techniques are now sufficiently developed that porcelain can almost withstand brazing temperatures. We feel that there should be no difficulty if we can cool the copper by flowing hydrogen through the coils during the braze.

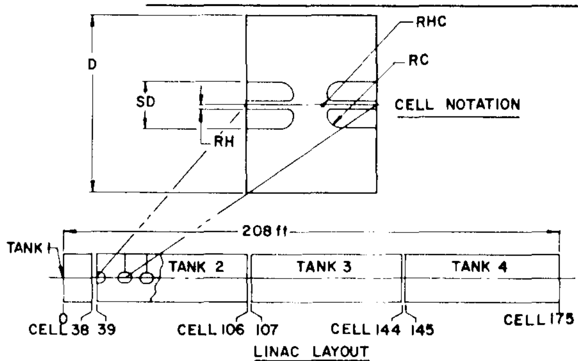
HUBBARD, Berkeley: Do you feel there will be any possibility of getting a good solid mechanical potting with the ceramic or porcelain insulators?

BUSH: We haven't potted (cast) with the porcelains, and they don't lend themselves to potting.

We have obtained solid coil assemblies with excellent turn-to-turn bonds by repeated dipping. Some porcelains yield thin coats while others permit thicker coating. If a porcelain of one type is coated with a different type, porcelain crazing frequently occurs.

There is another possible way to get a solid potted assembly. For instance, a porcelain-coated coil assembly might be potted in place on the poles using a cement. There are several commercial cements, similar to Sauereisen, that can be potted. We haven't subjected any of the cements to brazing atmospheres.

Ceramics can't be potted for this particular application because the firing temperature required would damage the coil.



LINAC PARAMETERS				
	TANK No.			
	1	2	3	4
ENERGY IN (MeV)	.75	5.03	41.2	72.3
ENERGY OUT (MeV)	5.03	41.2	72.3	100.3
TANK LENGTH (cm)	396.4	2000.5	1870.8	1851.0
D, TANK DIAMETER (cm)	94.0	90.0	88.0	88.0
SD, D.T. DIAMETER (cm)	18.0	16.0	16.0	16.0
RC, D.T. CORNER RADIUS (cm)	2.0	4.0	4.0	4.0
RH, BORE RADIUS (cm)	1.0	1.25	1.5	1.5
RHC, BORE CORNER RADIUS (cm)	1.0	1.0	1.0	1.0
QUADRUPOLE STRENGTH (G)	15141-12734	17138-12577	11365-12571	12571-12472
NUMBER OF CELLS	38	68	38	31
NUMBER OF QUADS	39	69	20	16

Fig. 1. Linac parameters.

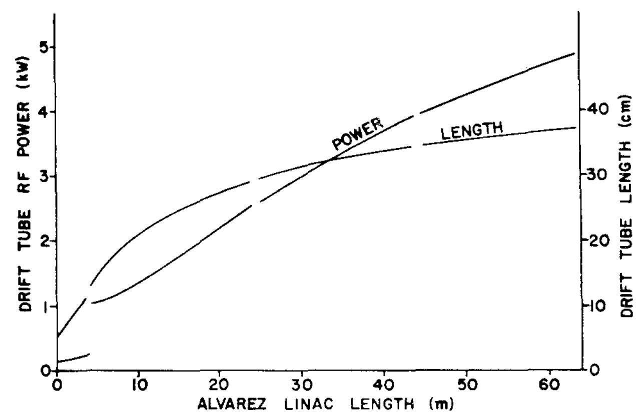


Fig. 2. Drift tube rf power distribution.

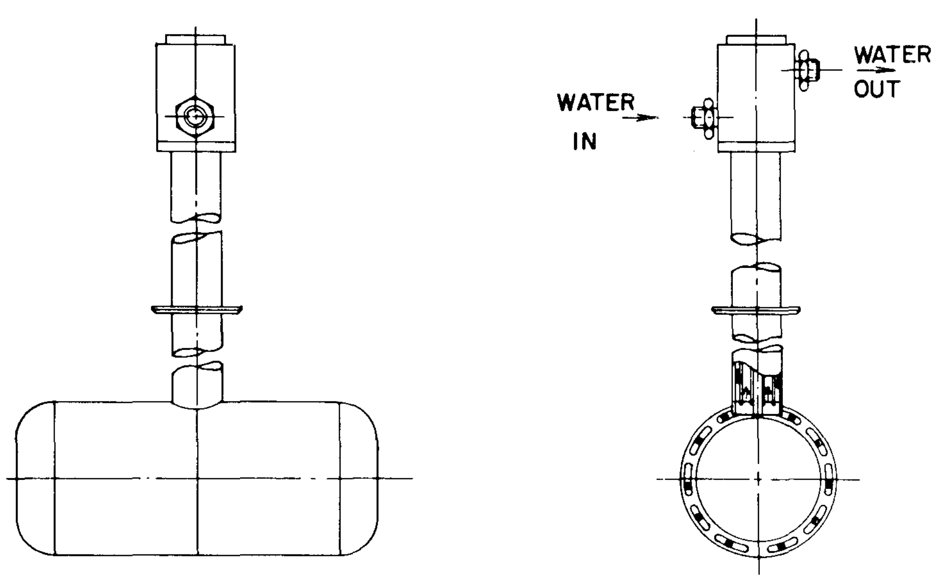


Fig. 3. Drift tube cooling configuration.

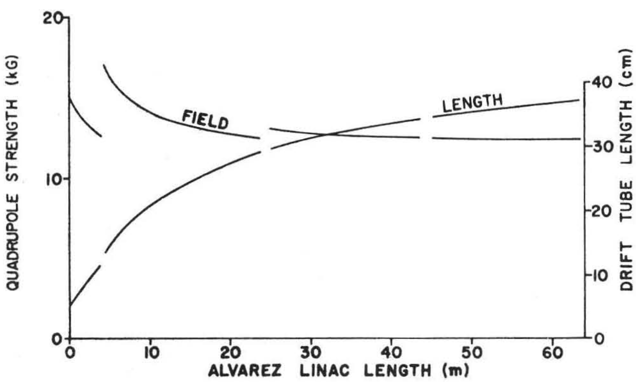


Fig. 4. Quadrupole magnetic field distribution.

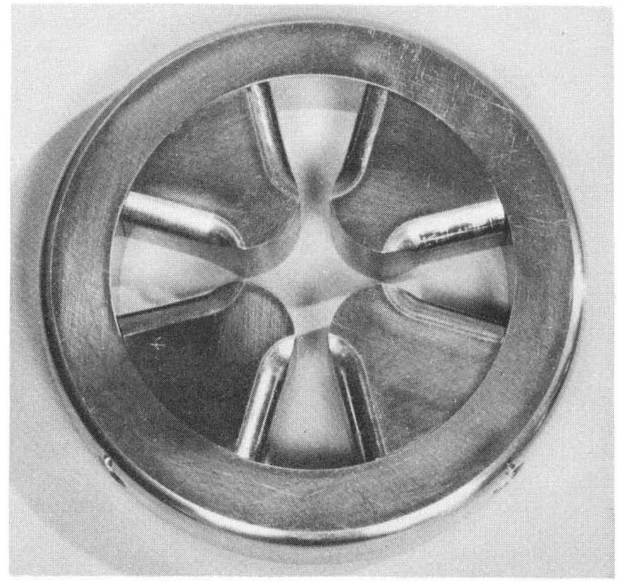


Fig. 5. Typical quadrupole cross section.

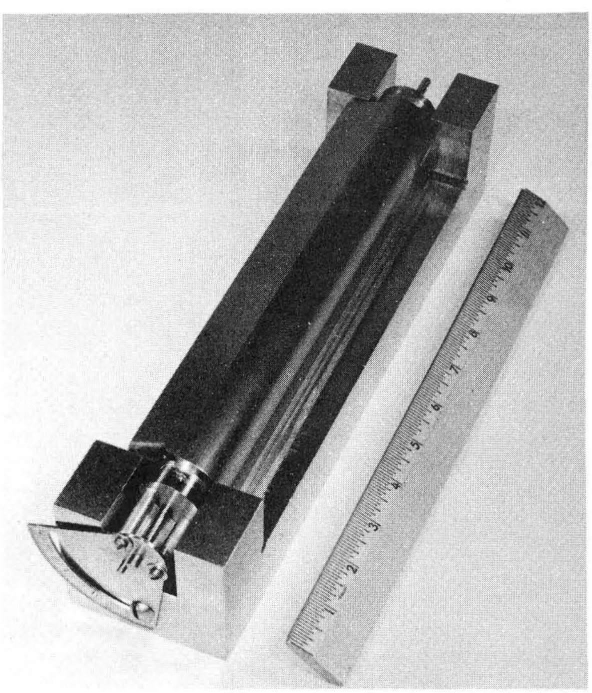


Fig. 6. Typical quadrupole cross section.

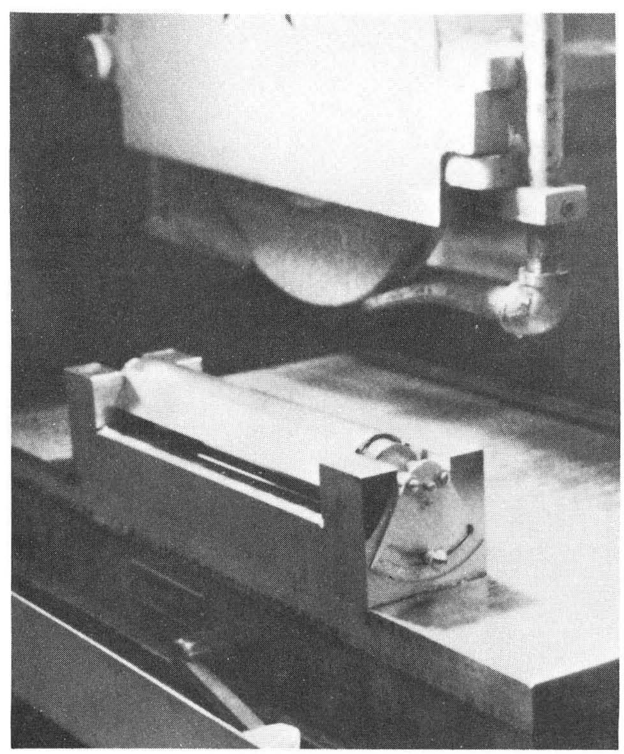


Fig. 7. Machining high energy quadrupole.

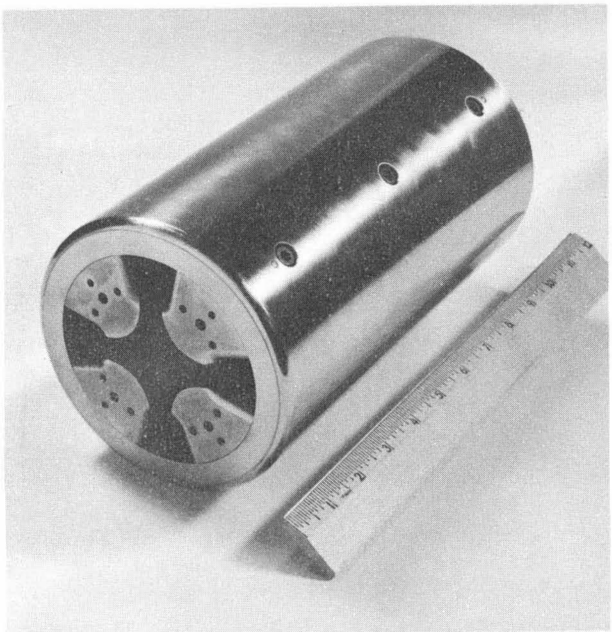


Fig. 8. High energy quadrupole.

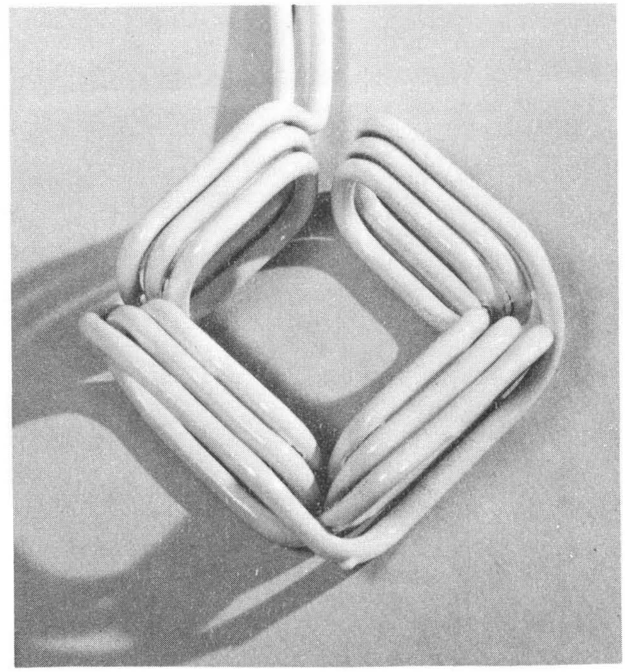


Fig. 9. Low energy coil.

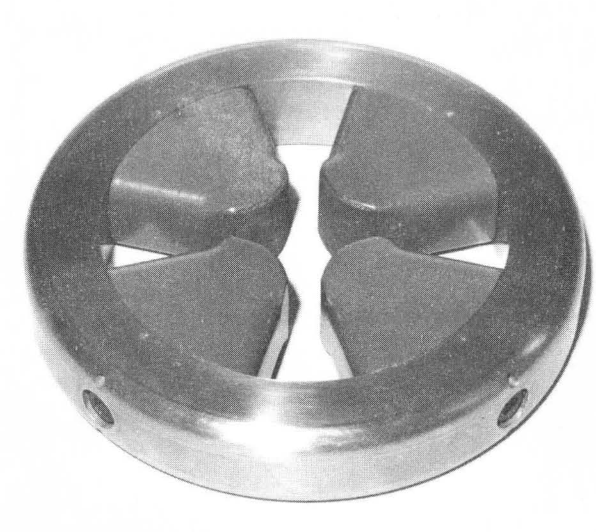


Fig. 10. Porcelain coated pole faces.

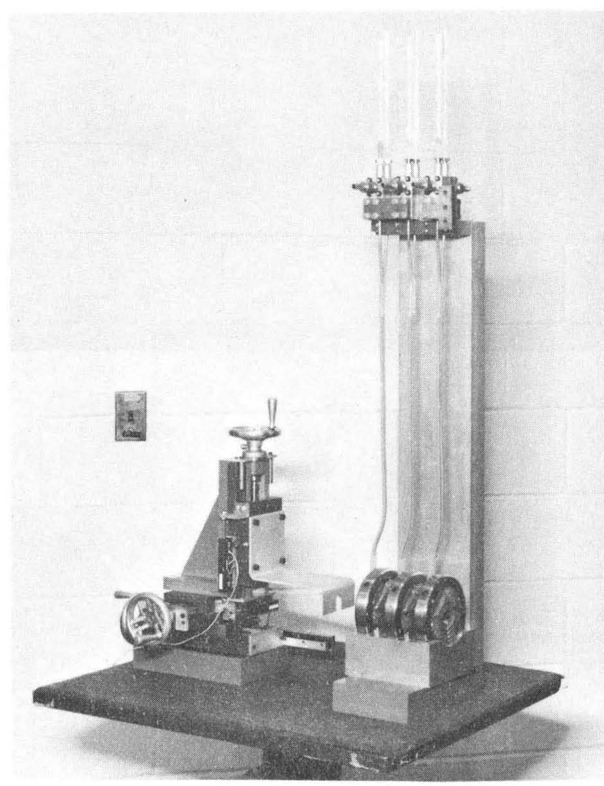


Fig. 11. Three quadrupole field survey setup.