Title
HIGH-GRADIENT DRIFT-TUBE QUADRIPOLE MAGNETS

Permalink
https://escholarship.org/uc/item/0tn4d71f

Authors
Main, Robert M.
Haughian, James M.
Meuser, Robert B.

Publication Date
1966-09-28

UCRL-17156

University of California

Ernest O. Lawrence Radiation Laboratory

HIGH-GRADIENT DRIFT-TUBE QUADRUPOLE MAGNETS

Berkeley, California

Presented at the 1966 Linear Accelerator
Conference, Los Alamos, New Nexico,
October 3-7, 1966

UCRL-17156

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

HIGH-GRADIENT DRIFT-TUBE QUADRUPOLE MAGNETS

Robert M. Main, James M. Haughian, and Robert B. Meuser

September 28, 1966

HIGH-GRADIENT DRIFT-TUBE QUADRUPOLE MAGNETS*

Robert M. Main, James M. Haughian, and Robert B. Meuser

Lawrence Radiation Laboratory
University of California
Berkeley, California

Abstract

A new design for small high-gradient magnetic quadrupoles has been devised. This design utilizes a keyed-quadrant yoke-pole configuration which ensures fourfold symmetry of the pole. The coils are tape-wound, occupying the entire slot area and thus minimizing power consumption and cooling problems. The lenses are expected to achieve pole-tip fields in excess of 10 kG and gradients of more than 25 kG/in. for a 3/4-in. aperture. Methods of winding coils, insulation problems, steel configuration, and cooling schemes are discussed.

Introduction

Tungsten grids are used at the entrance bore of the drift tubes in the Hilac prestripper tank in an effort to reduce rf defocusing. With the present configuration, approximately 5/6 of the entering beam is lost in transit through the 36 randomly oriented drift-tube grids. To regain this beam, we plan to substitute alternating-gradient focusing in these drift tubes. A new design for the magnets is presented in this paper.

Magnetic-quadrupole lenses used for drift-tube focusing in low-velocity linear accelerators are subject to severe restrictions in size and extreme requirements in pole-tip magnetic field. The power required for a magnet is inversely proportional to the coil space factor. In present designs of drift-tube quadrupoles at Berkeley and Argonne, the coils are made of tubing and have only three turns per pole, resulting in a space factor of about 0.2, with correspondingly high power consumption. Furthermore, with such a design it is difficult to achieve perfect symmetry of the winding on the pole tips. The iron yokes are normally made of many pieces, and the achievement of the symmetry required to produce a high quality magnetic field necessitates extremely close-tolerance machining.

The magnetic-quadrupole lens described here has: (a) the pole-yoke steel sections fabricated as identical quadrants and (b) coils wound with a tape conductor such that all slots between pole tips are nearly filled with copper.

The tape-coil design has several advantages: (a) The space factor is high (approximately 0.90) resulting in low power consumption. (b) The position of the conductor is well-established, resulting in minimum distortion of the magnetic field. (c) The method is amenable to high-production-rate techniques and the associated economies (once a few minor difficulties are overcome!)

The core is assembled from only four identical pieces. Dimensional identity can be assured by machining the four quadrants simultaneously. This construction automatically achieves a fourfold symmetry which is obtained only with great difficulty with other types of construction.

Figure 1 shows a model of the first drift tube, which is suspended on two stems. Coolant and electrical leads enter via one stem and exit via the other. Figure 2 shows a model of the magnet assembly and the configuration of the iron yoke. Figure 3 shows a model of a completed coil.

The Coil

The coil is wound of tape, the thickness of which can be varied over a wide range to produce the desired electrical impedance. The coil-winding method is shown in Fig. 4. Two conducting tapes are superimposed and then joined at one end. The joined tapes are then wound together on a mandrel. Turn-to-turn insulation is provided by thin layers of glass cloth or other insulating material. As the coils are wound onto the mandrel, slots are cut into the edges of the tapes so that they appear at 90-deg intervals on opposite sides of the completed coil. The slots in one of the two joined tapes are offset 90 deg to those in the adjacent tape. Figure 5 shows the two tapes as they would appear if unwound after slotting.

After the coil is wound, it is vacuum-impregnated with epoxy, thus forming a solid body. The openings for the poles are then machined into the coil. Figure 6 shows the two tapes as they would appear if unwound after the machining operation. One can see that, with the two tapes superimposed, each turn of the double tape provides each of the four poles with one complete turn. The current flow shown is opposite in adjacent poles, as required to produce a magnetic quadrupole.

Prior to a typical winding operation, the conductive tapes are wound onto their respective feed spools with Kraft paper inserted continuously to prevent galling between turns. With both feed spools wound to the desired capacity, the two leading edges of the tapes are heliarc welded together, as shown in Fig. 5, and the resulting edge ground smooth. The joined ends are then attached to the winding mandrel, and the winding operation is started.

During winding, the conductor must be cleaned of grease and burrs that may have resulted from rolling and slitting operations. Copper conductors are sent through a nitric acid bath followed by a water rinse and a chromic acid bath followed by a water rinse; then they are dried. Aluminum conductors are scrubbed in a warm caustic solution, rinsed in water, and dried.

The 0.003-in.-thick glass-cloth insulation, previously wet with epoxy, is inserted between turns as shown in Fig. 4. The conductors are wound onto the mandrel in a reverse direction from that in which they were wound on the feed reels in order to minimize springback. The heights of the feed-reel spools are servo-controlled to minimize the tendency of the tape to wind helically onto the take-up spool.

As the conductors are wound onto the mandrel, pneumatically-operated cutters notch the tapes at the appropriate positions. A minimum braking tension is maintained on the feed reels in order that the tapes do not distort after being slit. The coils are typically wound at 1 rpm with a nominal stress of 16,000 psi in the unslit tape. When the last turns have been wound onto the coil they are clamped in place and removed from the feedspools. The holes for the bus bars are punched in place, and the tabs are bent outward as shown in Fig. 7.

The coil container is coated with mold-release compound and allowed to dry. With temporary electrical leads attached, the coil is placed into a container, kept off the bottom with Micarta spacers, and then completely covered with a long-pot-life epoxy. A Lucite cover is placed over the container, and the contents vacuum-pumped for approximately 8 h, or until all the bubbles have disappeared.

With the Lucite cover removed, the electrical leads are brought out of the can, which is thermally insulated from the surroundings. The coil is then resistively heated for approximately 24 h, and the epoxy cured. Then the coil is machined to the appropriate shape as shown in Fig. 7. A sharp cutter and fast speed chosen to minimize turn-to-turn shorts is used. The coil is etched all over to reduce the edges of the conductor below the level of the insulation, then rinsed. With the tabs pulled out in place for the leads, the coil is ready for assembly.

The Yoke

Figure 8 shows a yoke-pole quadrant. The four sections are fabricated as a single long piece of material, and quadrants are cut from this section after the contour is machined, thus guaranteeing identical quadrants and the precise fourfold symmetry required. This method of fabrication is particularly advantageous when a number of identical quadrupoles are to be produced, since only a single machining operation is required.

The contour shown in the sketch is not necessarily optimum. The design of the optimum configuration requires specification of the quadrupole aperture, the magnetic gradient required, and the magnetic properties of the steel to be used. With these parameters specified, however, optimization (minimum size, weight, and power consumption) can be carried out as follows:

(a) The coil-slot angle, ϕ, is adjusted to provide maximum slot area (coil cross section) consistent with the saturation properties of the pole base.

(b) For the chosen slot angle, the ratios d/R and r/R are adjusted to minimize the objectionable magnetic-field harmonics.

(c) The yoke throat section, t, is adjusted to carry the required magnetic flux without saturation.

The quadrupole is assembled by inserting the pole quadrants into the completed coil, and bolting the quadrants together at the corners as shown in Fig. 9.

Cooling

We plan to remove heat from the quadrupole assembly by circulating coolant directly against it. The coolant will be forced down one stem of the drift tube and exit via the other. (For less crowded applications; e.g., experimental setups, cooling plates can be bonded to the faces of the coil. These plates are capable of removing 20 to 30 W/in.^{2} with a 10 to 15 °C temperature drop across the bond.) Direct-contact cooling can remove more than 150 W/in.^{2}

If the coils are bonded to the poles, the entire contacting surface can be used to conduct heat from the coils to the poles. In this scheme, coolant can contact the poles directly or circulate through tubing welded to the pole.

Performance

It is expected that these lenses will produce pole-tip fields in excess of 10 kG with a resulting gradient greater than 25 kG/in. for a 3/4-in. aperture. The resulting power depends upon the pole-tip angle, ϕ, which is chosen. Typically, for a 0.35-in.-wide slot between pole-tips, the power required would be 1.2 kW, with a resulting flux density of less than 70 W/in.^{2} on each of two coil faces.

Other Applications

The same coil scheme can be applied to higher-order multipoles, and to bending magnets. Figure 10 shows how the scheme is applied to a picture-frame-type bending magnet.

Conclusion

We believe the tape coil and 4-piece yoke design presented in this paper have advantages over conventional designs for drift-tube quadrupoles, and possibly for other applications.

Footnotes

[*] Work sponsored by the U. S. Atomic Energy Commission.

Figure Legends

Fig. 1. Interior of the model drift tube.

Fig. 2. Model of the quadrupole magnet assembly.

Fig. 3. Model of the quadrupole coil.

Fig. 4. Coil-winding schematic.

Fig. 5. Coil unwound after slotting.

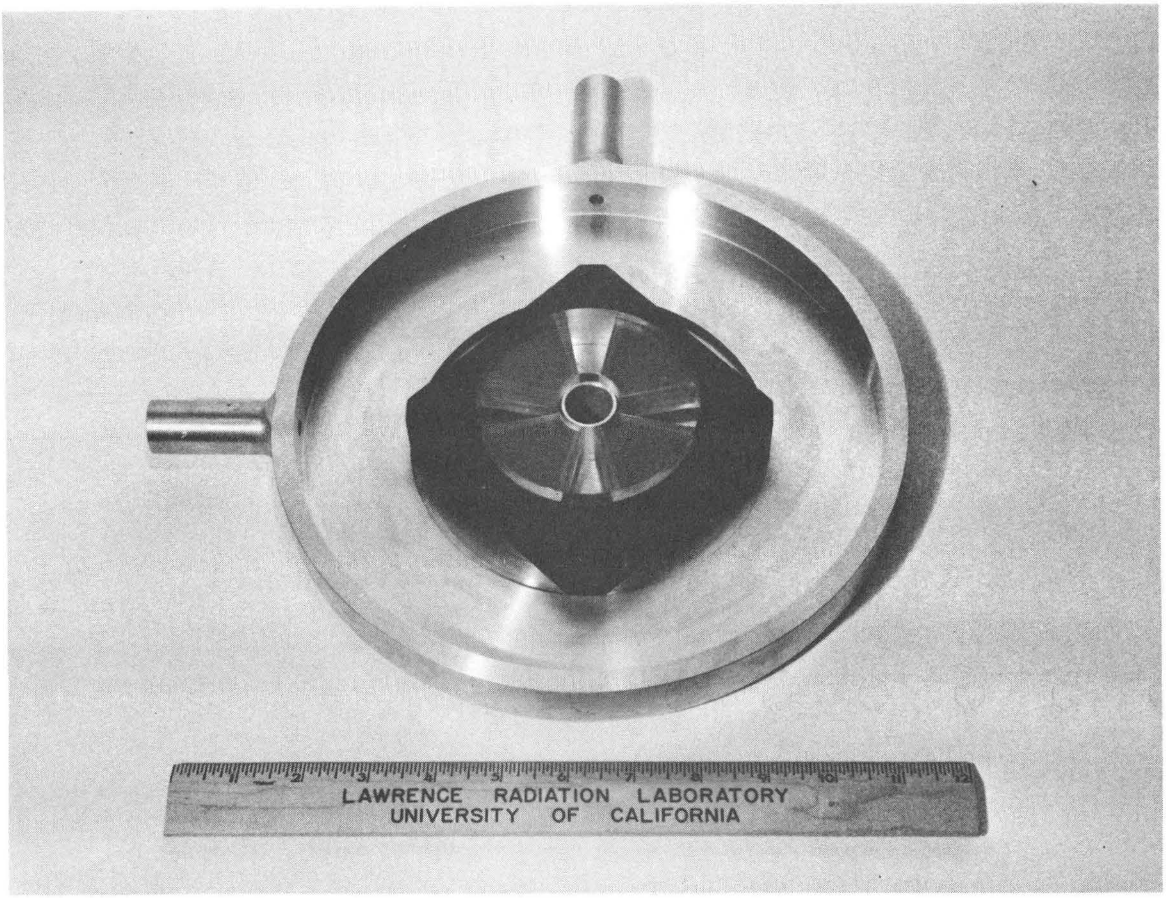
Fig. 6. Coil unwound after machining.

Fig. 7. Completed coil.

Fig. 8. Yoke-pole quadrant.

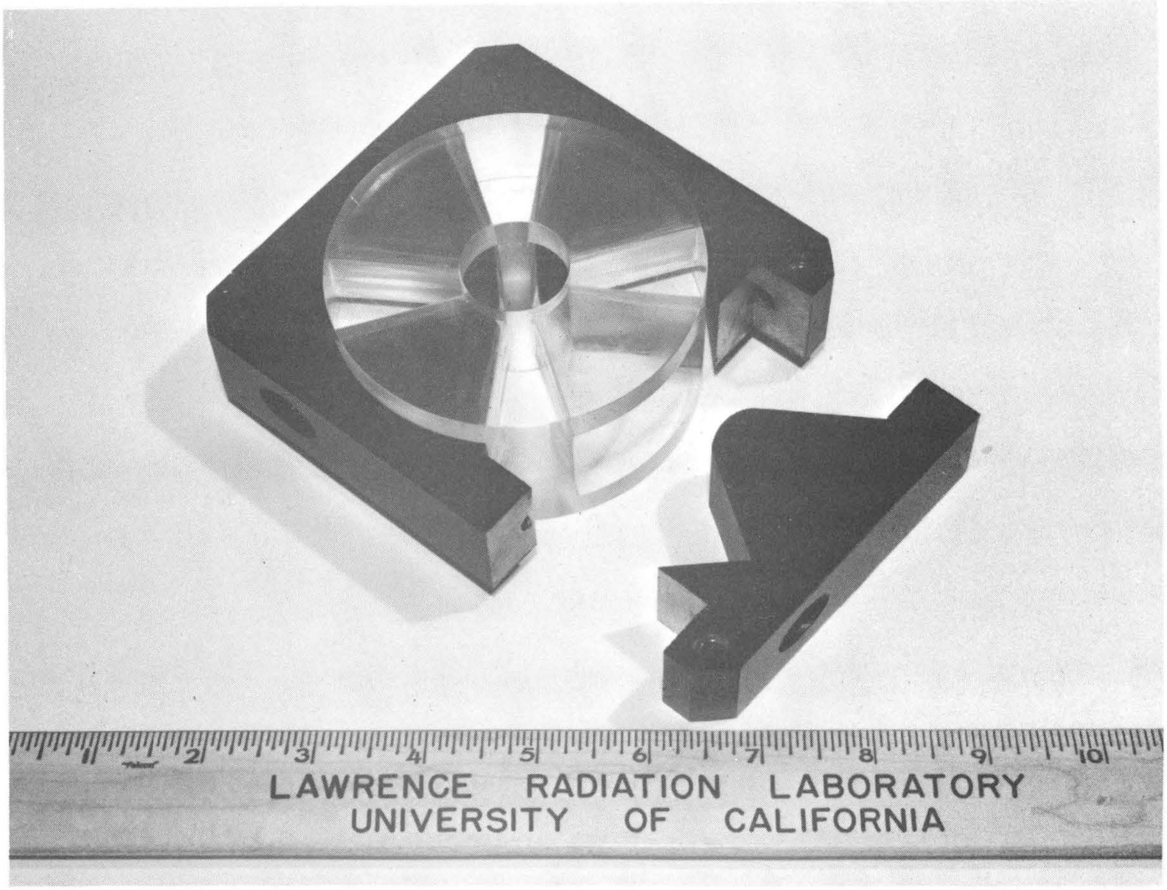
Fig. 9. Completed magnet prior to assembly.

Fig. 10. Picture-frame bending-magnet assembly.



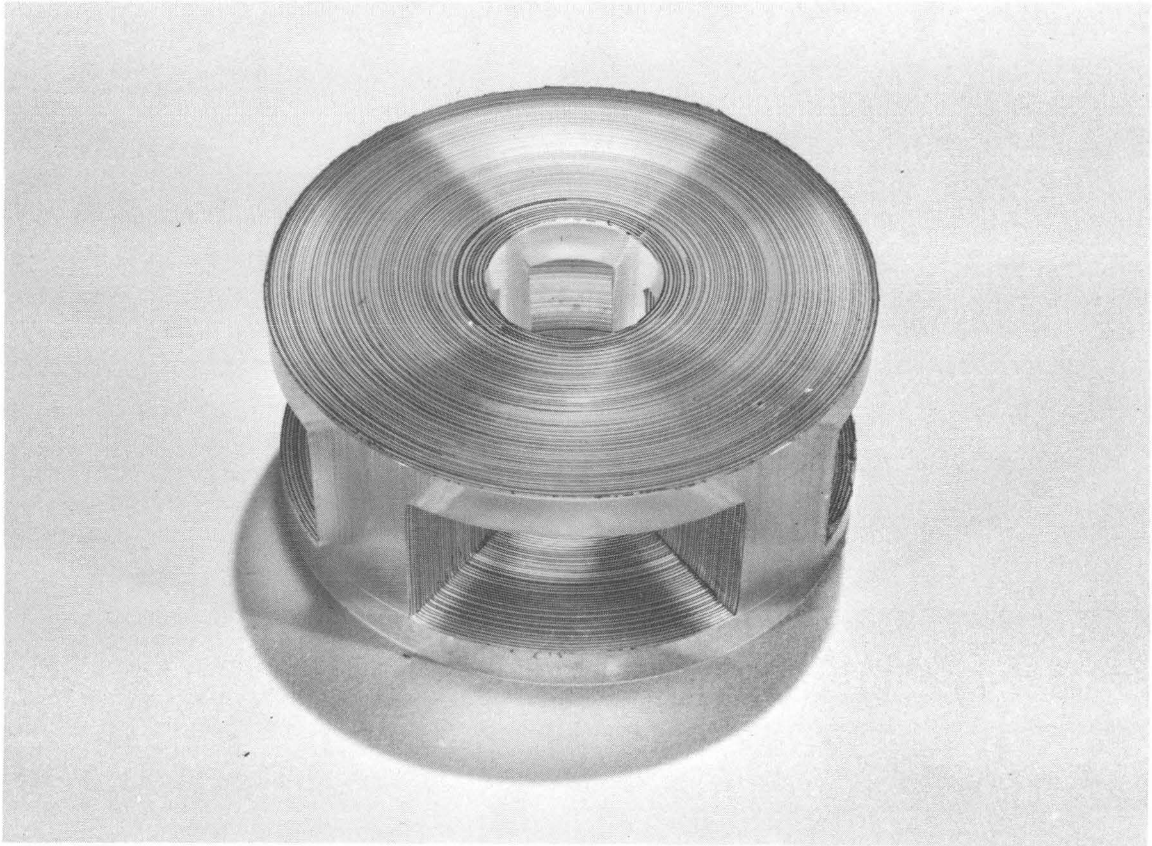
ZN-5903

Fig. 1


LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
1
2
3
4
5
6
7
8
9
10

ZN-5905

Fig. 2



ZN-5907

Fig. 3

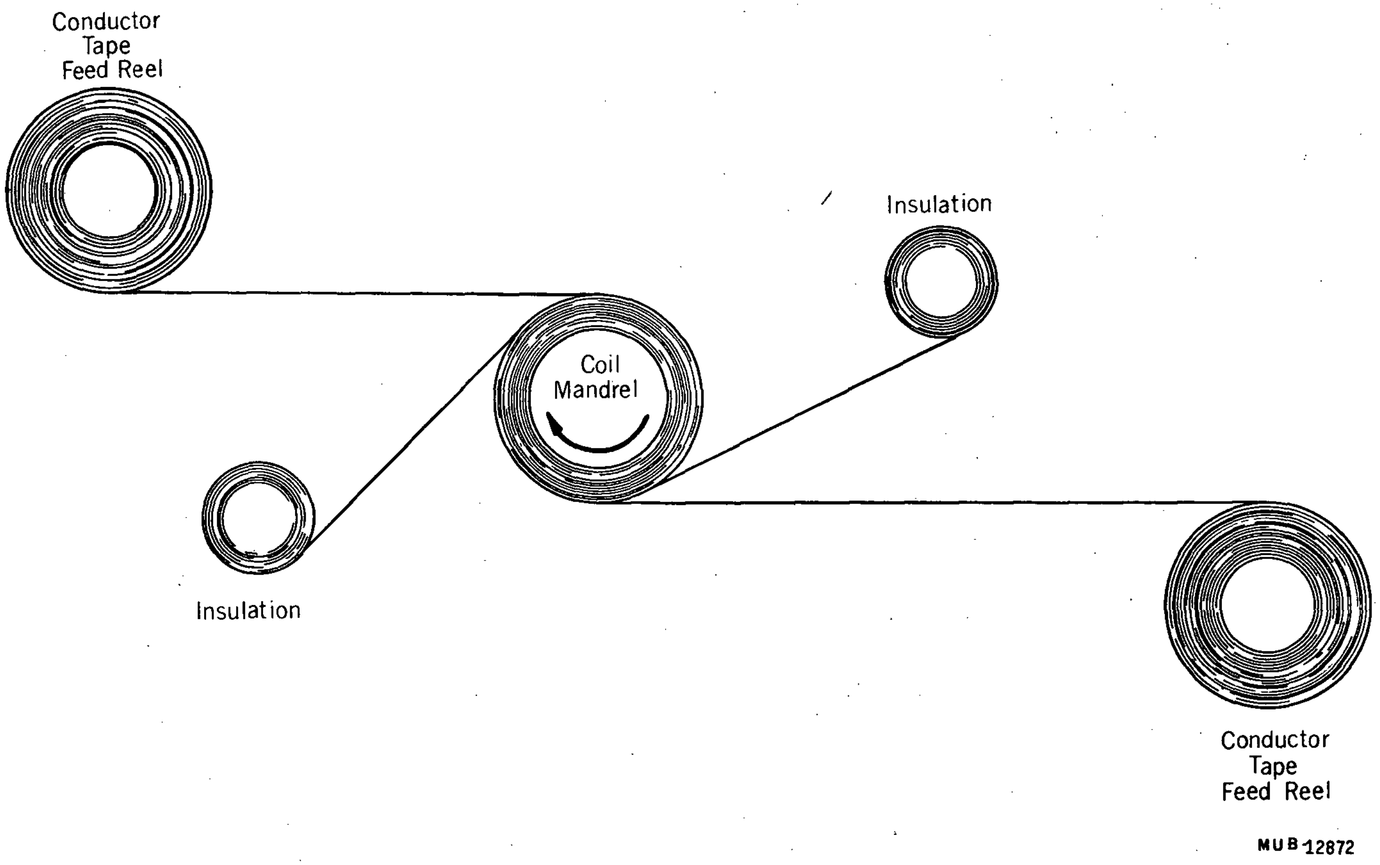

Conductor Tape Feed Reel
Insulation
Coil Mandrel
Insulation
Conductor Tape Feed Reel
MUB-12872

Fig. 4

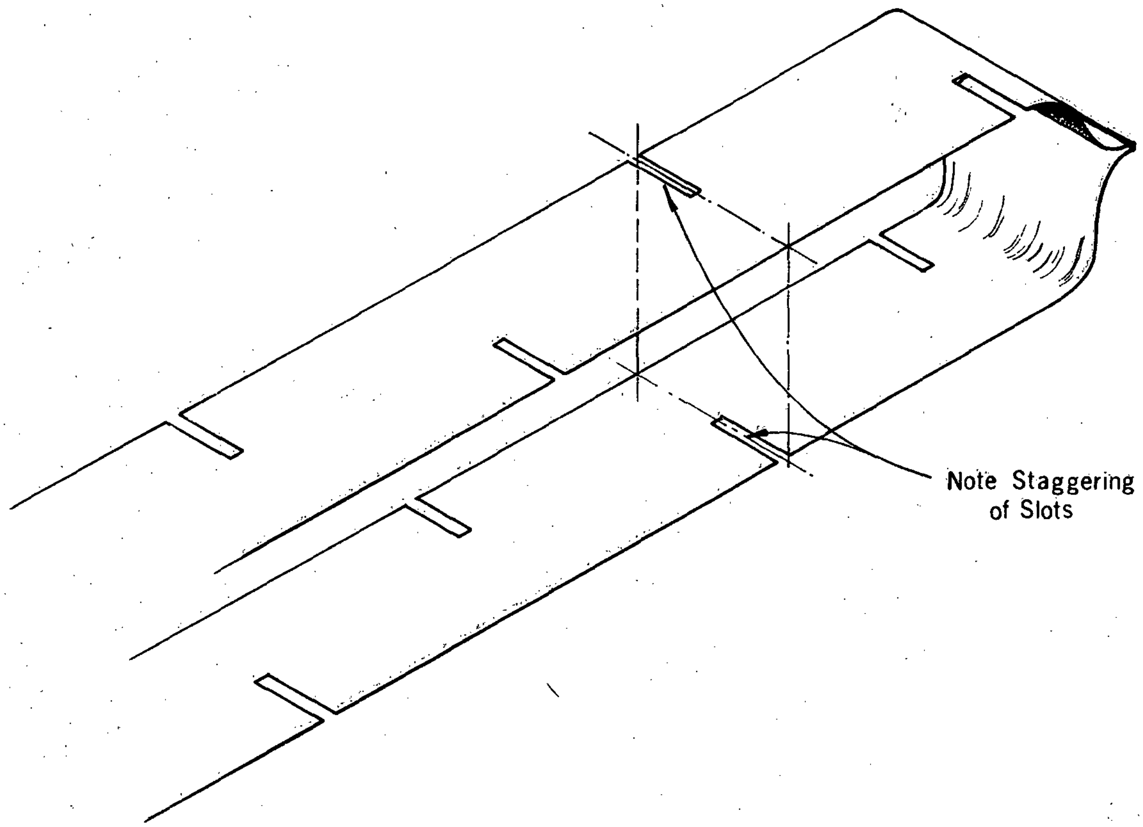
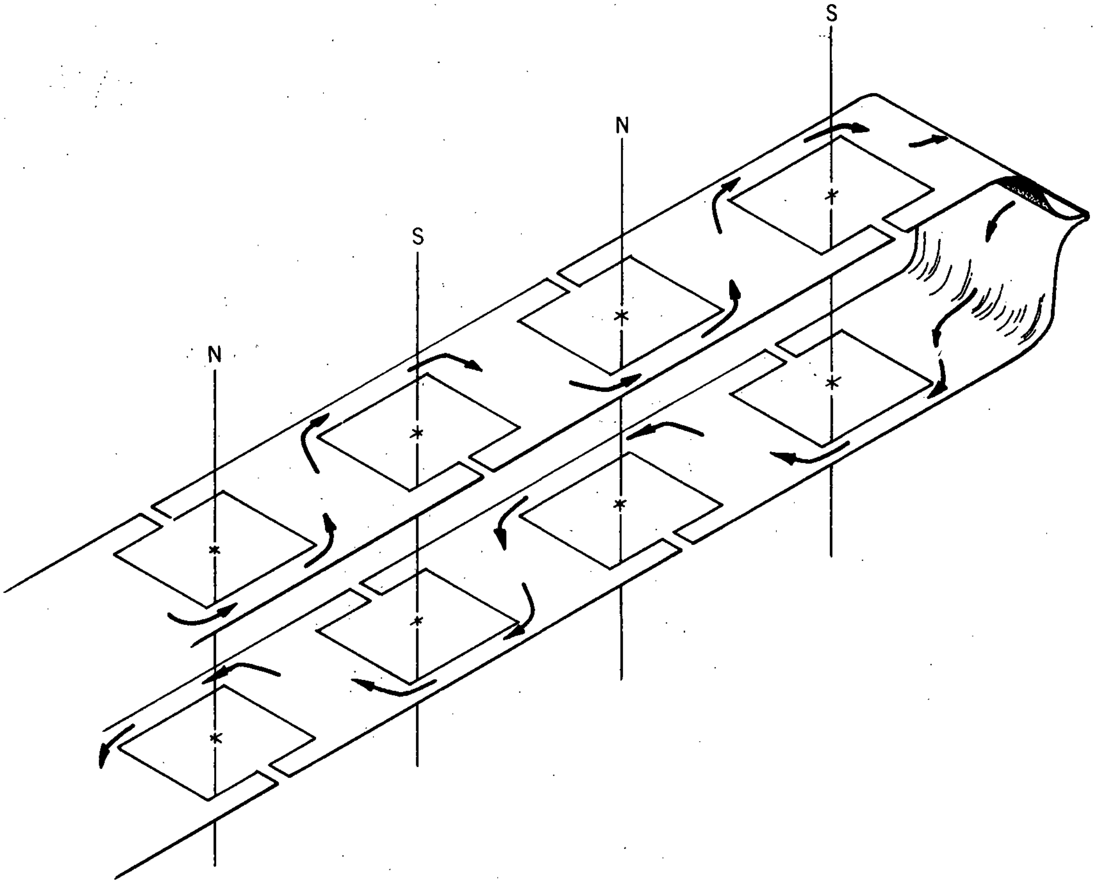
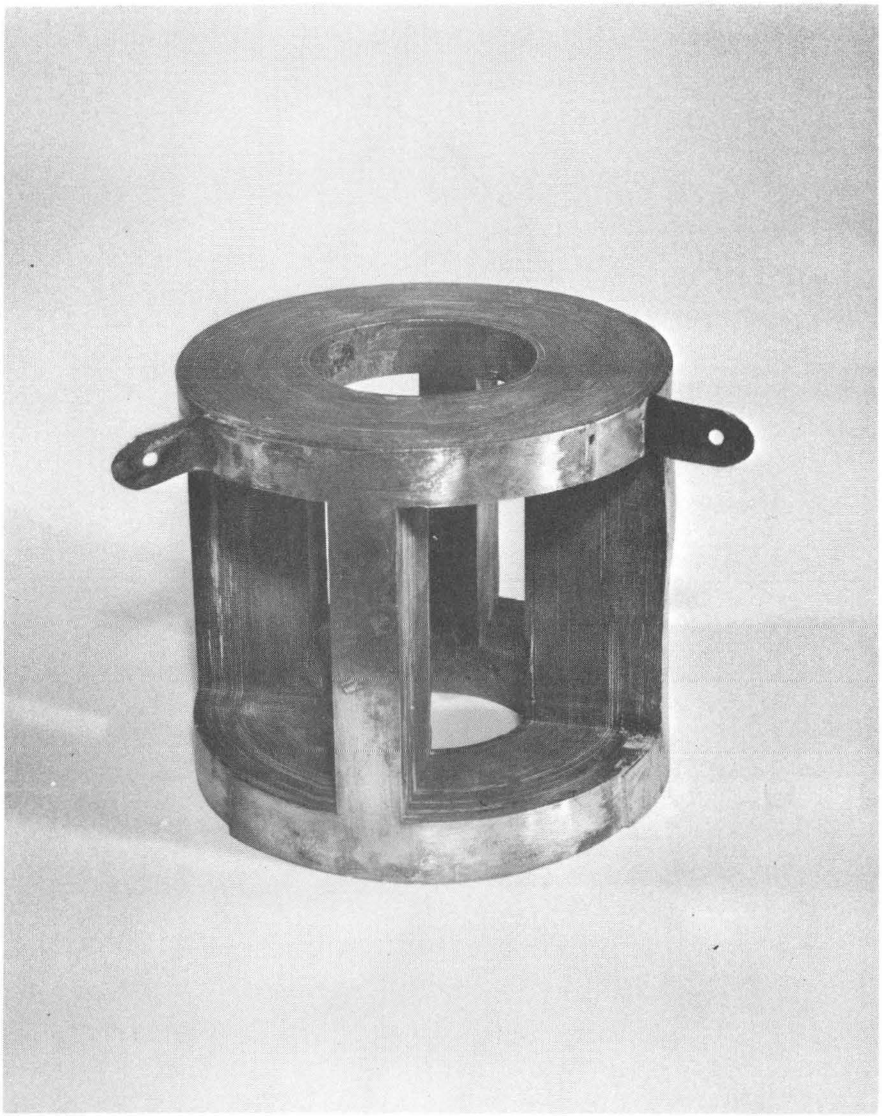


Fig. 5



MUB 12874

Fig. 6



ZN-5904

Fig. 7

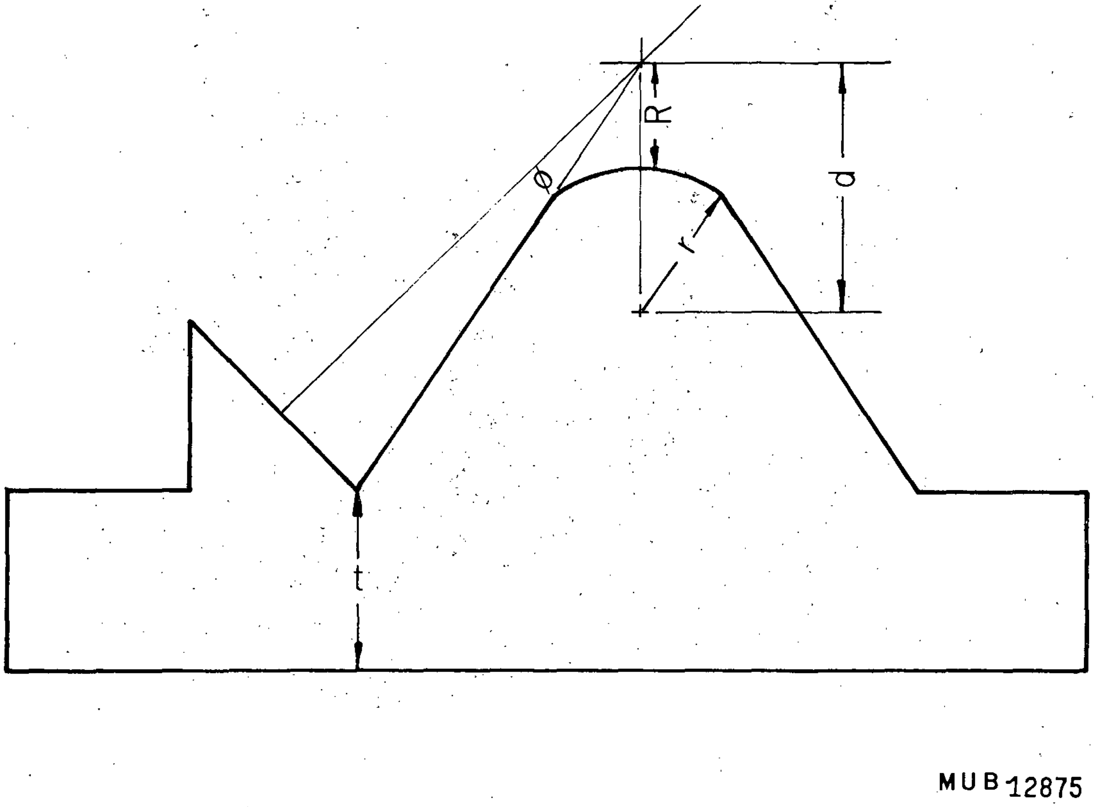
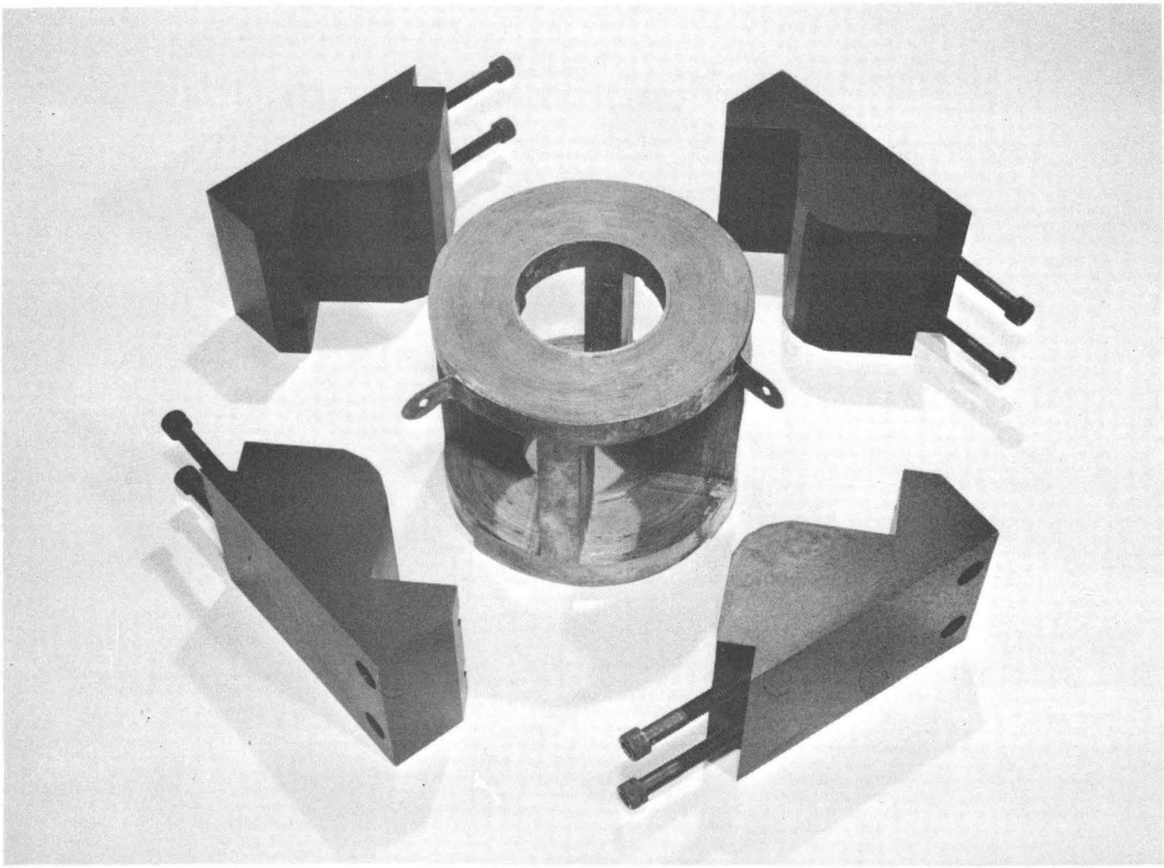
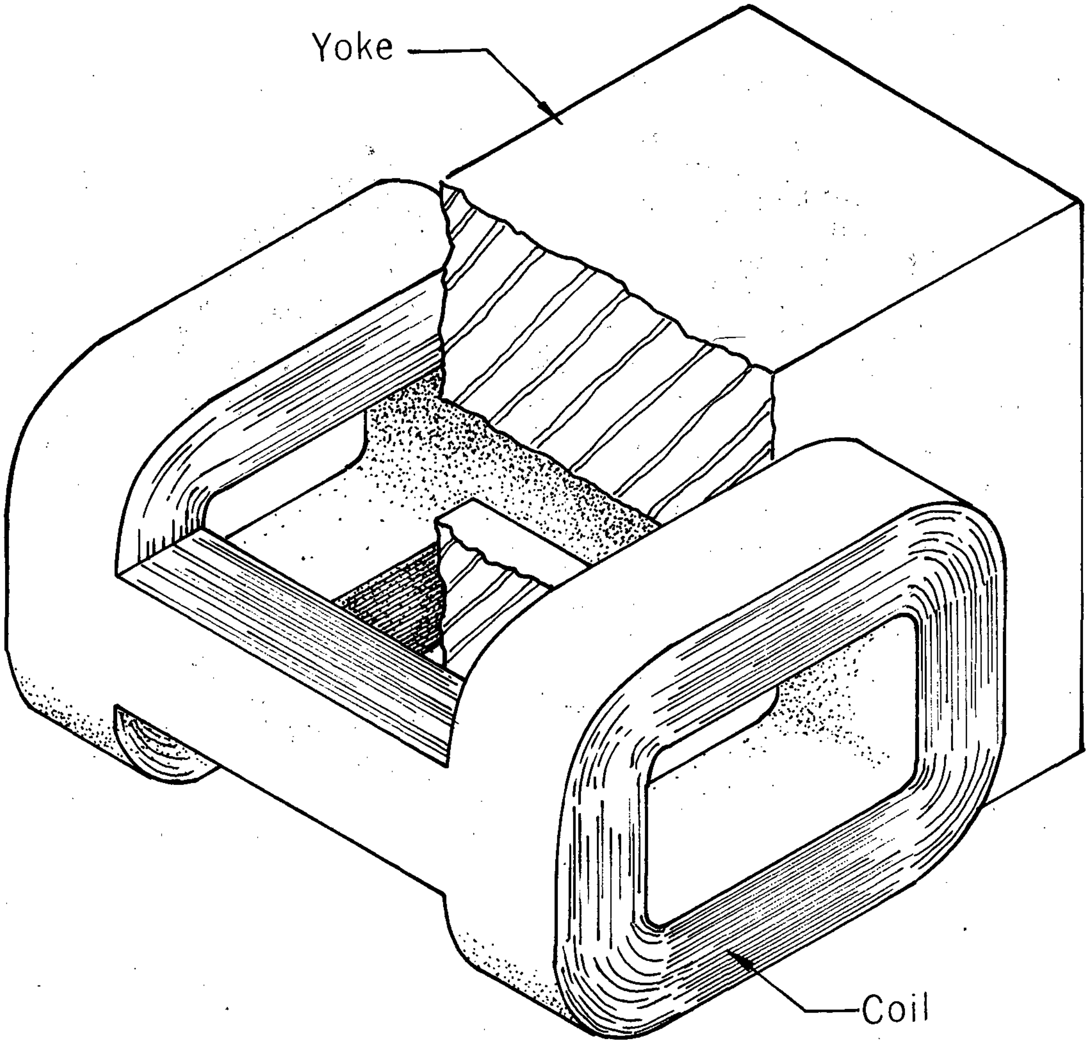


Fig. 8



ZN-5906

Fig. 9



MUB 12876

Fig. 10