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DESIGN OF SEXTUPOLE MAGNET FOR 200 GeV LINE

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Summary

Sextupole magnets of 4 inch aperture, 2 kG/in^2 strength have been designed for use in the NAL Meson Area beam line. Pole shapes have been determined by conformal mapping to give continuous contours which are approximated by short straight line segments to facilitate machining. The resulting field quality is within .17 percent of a pure sextupole over a 3 inch "Good Field Width". The excitation is provided by a monolithic coil on each pole wound from .230 inch solid square copper. Four water-cooled flattened tubes provide heat sinks for conduction cooling with a maximum temperature rise of 20° C in the winding. Magnetic field measurements are presented.

Introduction

The Meson Area is one of the major research facilities which has recently been built for use in the 200-500 GeV proton synchrotron of the National Accelerator Laboratory. When the protons are used for experiments in the Meson Area, extracted proton beam is deflected to the left, and is bent up to the Meson Target Area. At the target, six secondary particle beams are produced. These beams are semi-fixed installations for repeated use by experimenters. The beams are defined in size by a system of collimators and are transported with use of beam-transport magnets 1400 ft to the Meson Detector Building which houses the experiments. The sextupole magnet described in this paper will be used in the M1 and M6 beam lines. Pairs of sextupoles are used in the above lines to correct for chromatic aberrations. Beam line M1 is produced at 3.5 mrad with respect to the incident proton beam and it is designed to have High Energy-High Intensity beam. Beam line M6, produced at 2.5 mrad, is a High Energy-High Momentum Resolution.[1]

A prototype sextupole magnet has been constructed at NAL. The six coils were wound and potted at the NAL Magnet Facility and the magnet core was fabricated at the Village Machine Shop. A total of six sextupoles are required.

Design

Sextupole magnets may be designed using continuously contoured profiles by a method previously outlined.[2] However, in order to reduce machining costs, the present magnet has been designed using only straight line machining cuts. The design of sextupoles with linearly segmented profiles may be accomplished through the use of complex variable transformations as in the case of continuously contoured profiles. The parameters in the transformation are determined by a computer code LSPSEXT from input value of aperture, good field width, and percentage deviation of the sextupole strength over the good field region. Since there is one extra unknown in the transformation sequence chosen, one is permitted to design to a pre-assigned coil slot width.

Table 1 lists the design parameters chosen. Actually, a tolerance of ±.5 percent in B''/B''_o was chosen. This resulted in the tolerance indicated for $\Delta B/B$.

Table 1. Sextupole Design Parameters

Sextupole Strength (B")	2.0 kG/in^2
Aperture	4.0 in
Width of Good Field Region	3.0 in
Field Tolerance ($\Delta B/B$ at Good Field Limit)	± .17 %
Coil Slot Width	1.0 in
Magnet Dimension	16 in diameter
Magnet Length	30 in
Conductor (solid square)	.230 in
Coil Turns Per Pole	54
Conductor Current	100 A
Current Density in Conductor	1898 A/in^2
Power	3.5 kW
Inner-Fin Cooling Tube Dimensions	.200 in x 1 7/64 .233 in x 1 15/32
Water Flow for 100 psi Pressure Drop	2 GPM
Maximum Temperature Rise of Coil	20° C

Figure 1 shows the resulting pole tip profile in relation to the excitation coils and the return yoke. Note that the profile which gives a constant slot width of 1 inch is interrupted some distance into the slot where, for the design strength indicated, it is possible to undercut the pole tip to provide more space for the coil without producing excessive fields in the iron.

Table 2. Pole Profile Corners Coordinates

X(in)	Y(in)	X(in)	Y(in)	X(in)	Y(in)
1.871	.760	1.594	1.240	.277	2.000
2.019	.760	1.669	1.368	.351	2.129
2.168	.503	1.519	1.626	.649	2.129

Cooling is provided by conduction with four water-cooled copper tubes inserted between the solid conductors. The flattened copper tubing is made from inner-fin tubes. These were made by flattening inner fin tubes until the fins touch each other. The inner fins are spiralled so when the tube is flatened, opposite fins cross each other to form good compression members. The location of the cooling tubes was calculated to give symmetrical temperature rise.

Fabrication

A prototype sextupole magnet has been constructed. A cross section of the magnet is shown in Figure 2. The magnet core is made up from a 16 inch diameter, 1.437 inch wall, low carbon steel pipe. To minimize close tolerances, a mandrel was made in the shape of a hexagon to hold the six poles in the true position during machining. The mandrel was machined within ±.001 of a true hexagon and keys were put in to simulate the keys in the pole tips. This same mandrel will be used to make up the remaining six sextupoles. The poles were made up of a low carbon steel, 1018. Each pole was faced and bolted onto the mandrel. Matching keys were put in on faces of the poles to align the pole tips. The back face was machined on the lathe. A slip fit clearance was left between the outside diameter of the poles' back faces and the machined inside diameter of the pipe. With the poles bolted on the mandrel, the whole assembly was then inserted inside the pipe for the drilling of the pin holes on the side of the pipe. This was done in a horizontal boring mill; .001 inch shims were placed between the pole pieces and the pipe to precisely center the mandrel assembly to the pipe. The pins accurately transferred the pole location from the mandrel to the permanent pipe yoke. The relative location of the pins did not matter because both the pipe and the corresponding pole were machined in one operation. Each pole was numbered to be replaced in the same location. Two one-half inch bolts were used to clamp each pole tip, with the pole to the yoke. The poles were located within ±.005" of their true position.

The coils were wound with #3 gauge square copper conductor. Non-certified, oxygen-free, high conductivity copper #102 was used in the dead soft condition. The conductor was specified to be coated with a fully cured "Heavy" film layer of polyimide film. With the insulation film, the overall nominal dimension was .230 inch square. The coil was wound on a vertical turn table. Spacers were used in the winding fixture to provide room for the flattened cooling tubes.

Figure 3 shows a cross section of the coil. Only half coil is shown because of its symmetry. After the coil was wound, the cooling tubes were inserted with .028 inches of G-10 insulation epoxyed on each side. The coil was then wrapped twice with .007 inch glass tape, half lapped, giving a total .028 inch ground insulation. Because of the cooling tubes at each coil end, the wrapping was only made in the straight section of the coil. The coil was then placed in the potting fixture and vacuum impregnated with epoxy. This was done in a vacuum tank. When the potting fixture showed to be full of epoxy, the tank was set to atmospheric pressure and heated up to 220° F for curing of the epoxy. The epoxy mix was made-up from:

22.0 %	Araldite 6005
19.7 %	Nadic Methyl Anhydride
55.0 %	Alumina Powder
3.3 %	DMP 30 (for accelerating the curing time)

After each step the coil was tested for turn-to-turn shorts and also for possible short with the grounded cooling tubes.

It takes an average of 10 hours for the epoxy to cure at the above temperature. Six coils were made for the prototype magnet.

Results

The effective length of the magnet and the excitation curve were measured using a Rawson-Lush rotating coil Gauss-meter. The integrated gradient was measured using a pair of long gradient coils. In addition to the results shown in Figure 7, the excitation curve indicated a residual sextupole strength of B" = .02kG/in^2 and an AMPFAC = 1.025 at 100 A. Assembly errors and absolute calibration errors could well account for the remaining 4 percent difference between the design strength of 2.0 kG/in^2 and the measured strength of 1.872 kG/in^2.

Acknowledgements

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References

[1] J. C. Orr, A. L. Read, "Meson Laboratory Preliminary Design Report" March, 1971, NAL, Batavia, Illinois

[2] S. C. Snowdon, Magnet Profile Design, IEEE Trans. on Nucl. Sci., NS-18, 848 (1971)

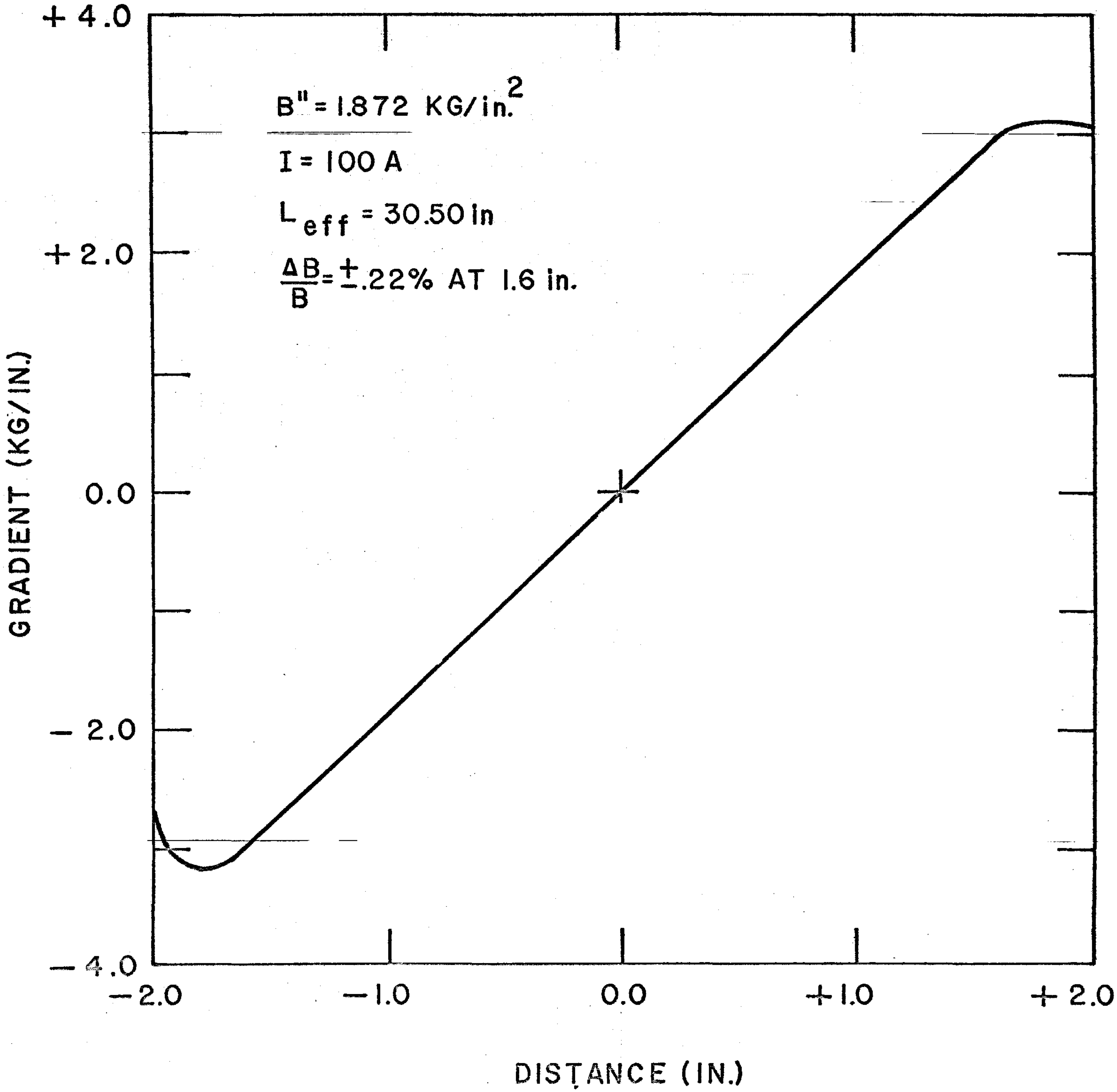

Figure 7. Measured Gradient

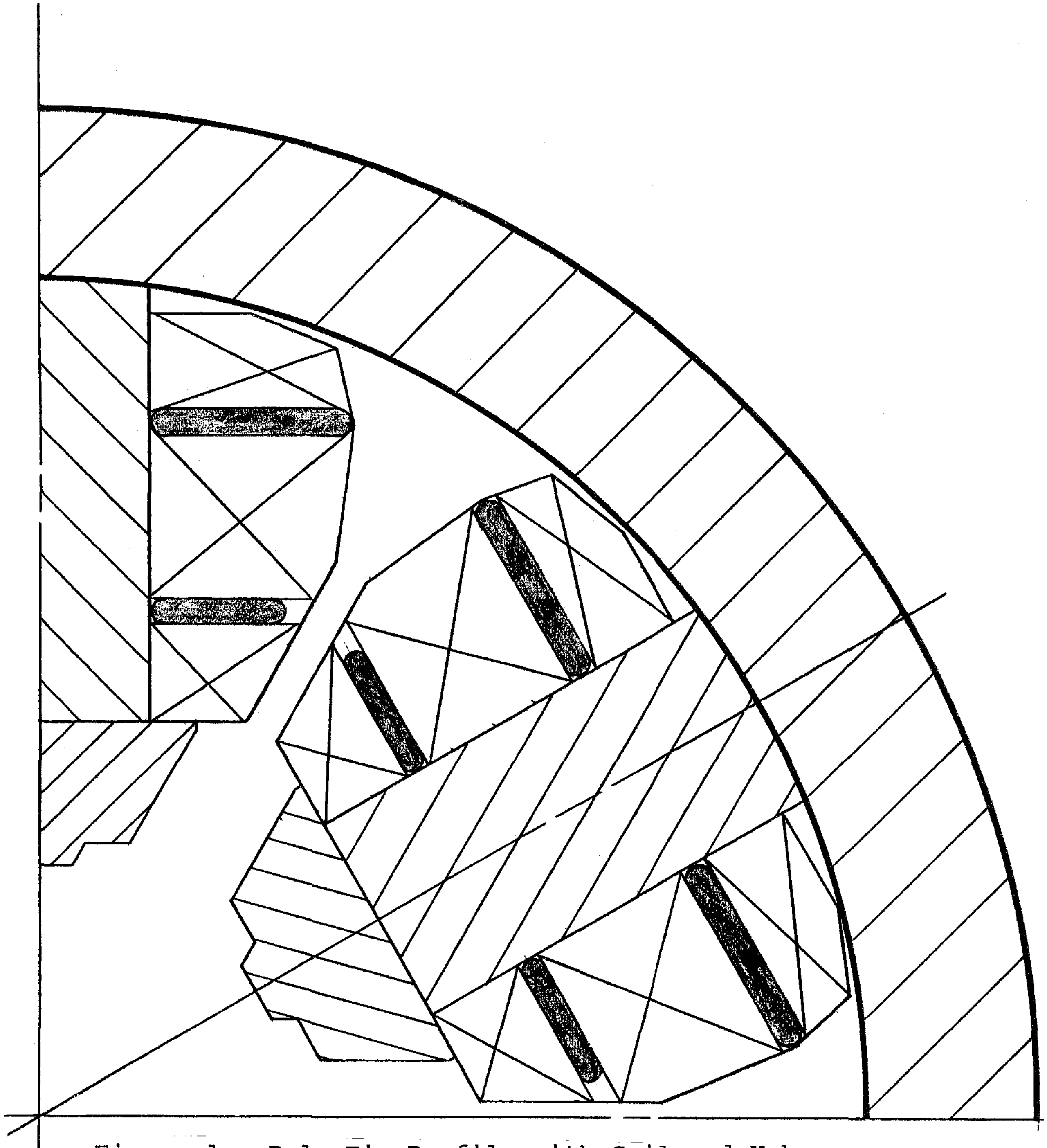

Figure 1. Pole Tip Profile with Coil and Yoke.

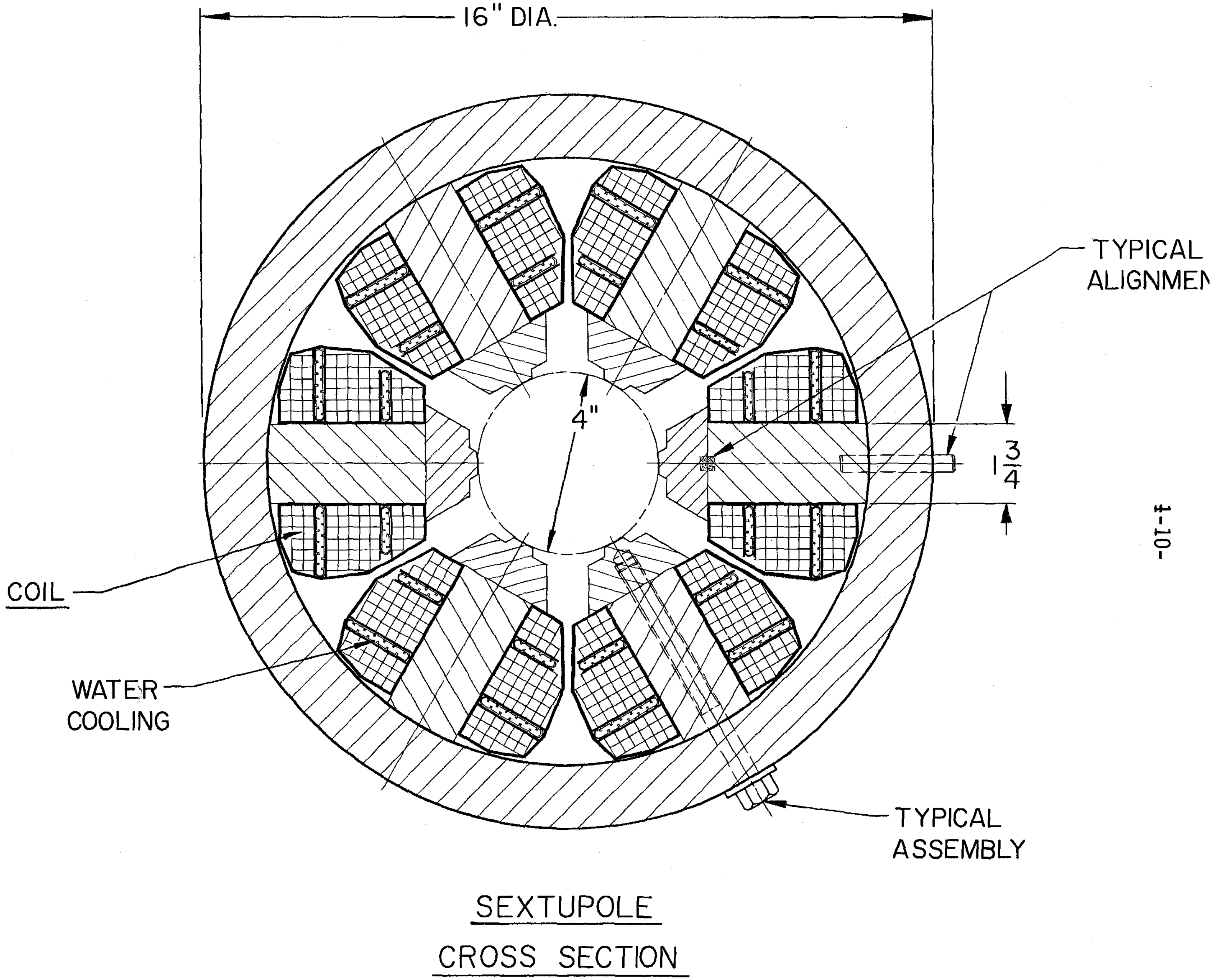

Figure 2. Sextupole Magnet Cross Section Showing Typical Alignment and Assembly

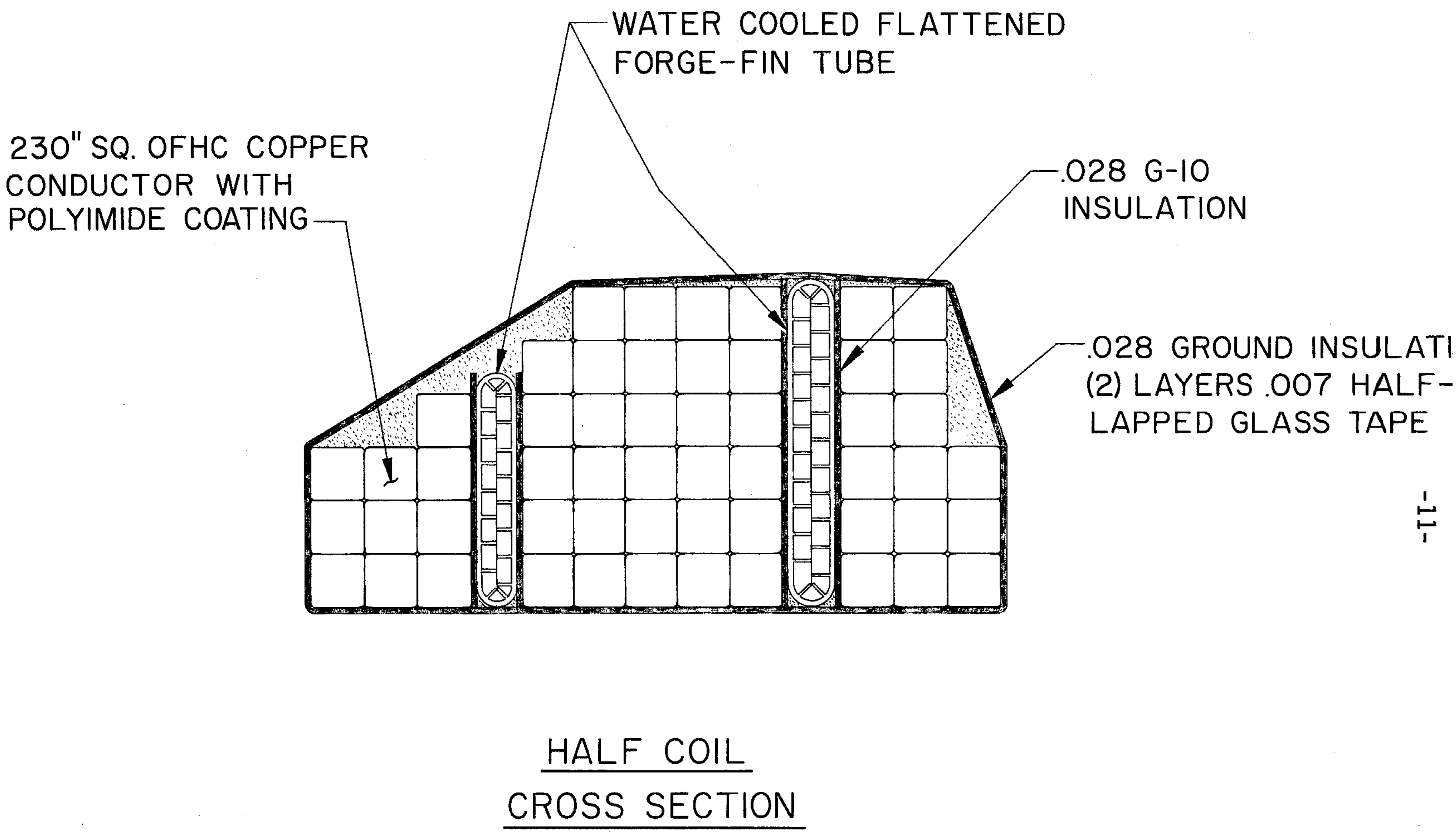

Figure 3. Half Coil Cross Section showing Conduction Cooling and Electrical Insulatio

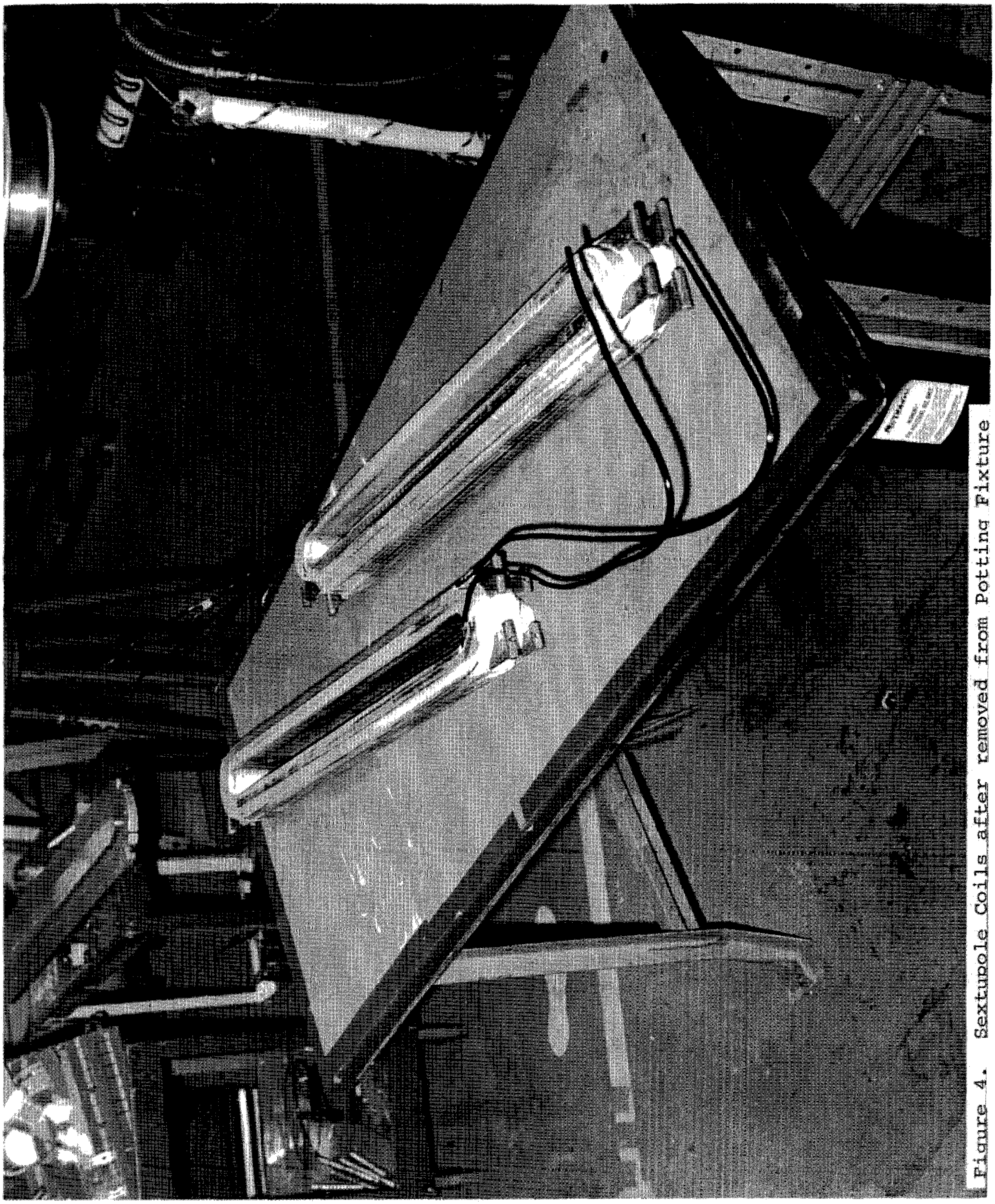

Figure 4. Sextupole Coils after removed from Potting Fixture

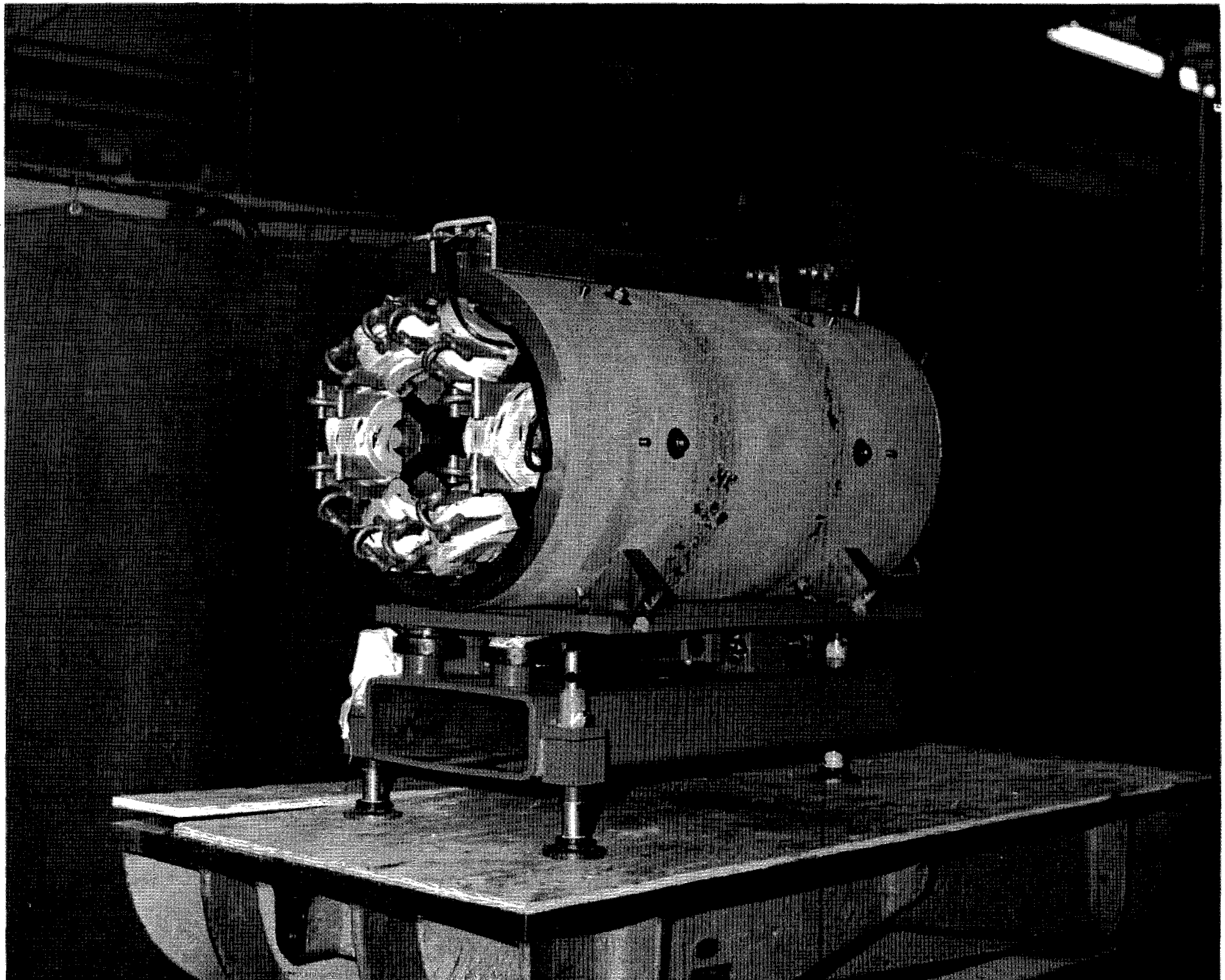

Figure 5. Sextupole Magnet on Alignment Stand

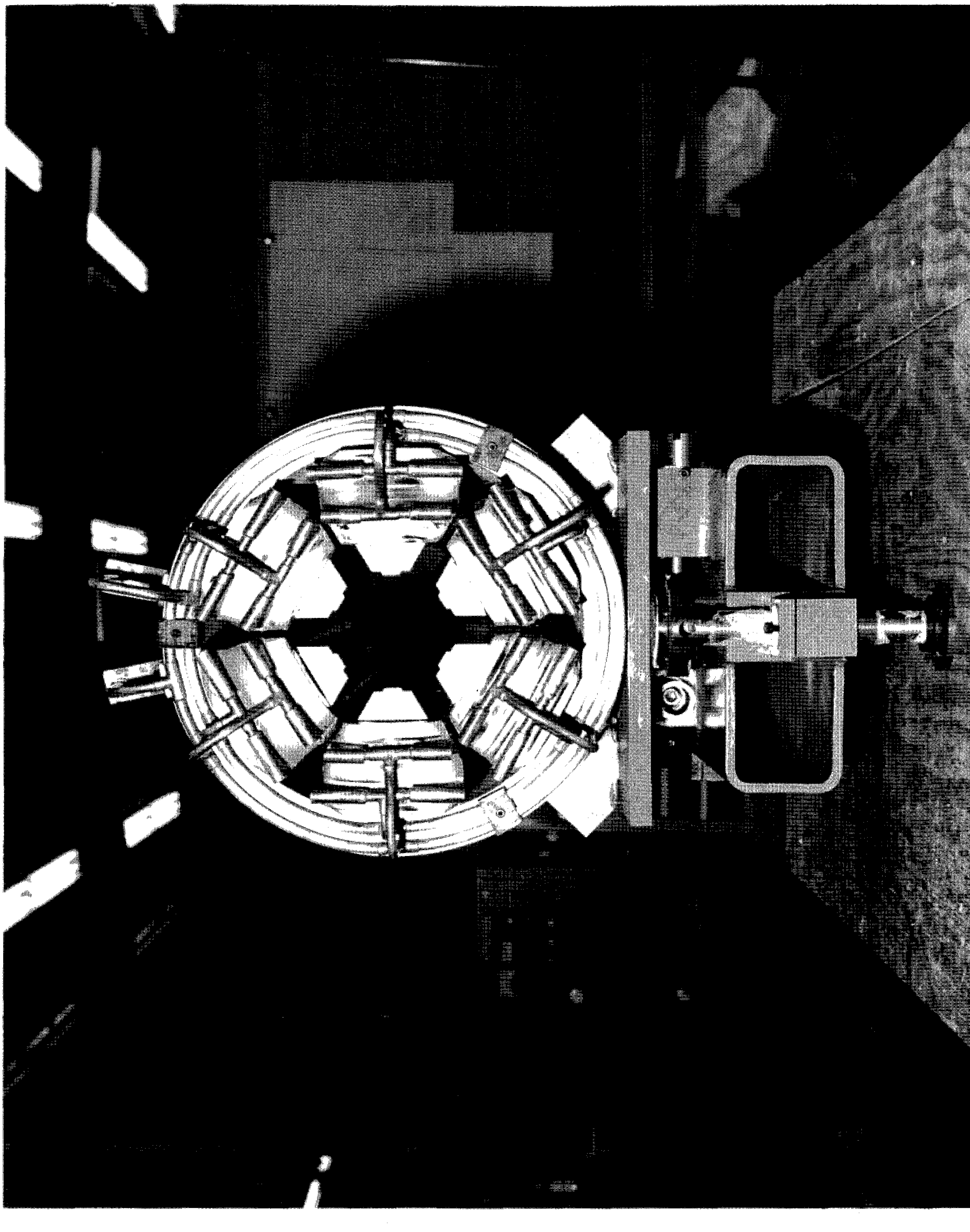

Figure 6. End View of Magnet showing Cooling Water Manifold