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COPPER-TAPE-WOUND, EDGE-COOLED SOLENOID*

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Abstract

Construction details and tests of a 10-cm-ID and 26.35-cm-long copper-tape-wound solenoid are described. Magnet measurements at 35 kW indicate an axial-field line integral of 193 kG-cm and a transverse-field line integral, measured on the geometric axis, of less than 0.1% of the axial-field integral.

Introduction

A tape-wound magnet has been designed and constructed to replace one of the existing magnets of conventional design on the Bevatron preinjector in order to increase the acceptance of the beam-transport system. Since space is at a premium at the magnet's location, its external dimensions had to remain the same as those of the conventional magnet. The bore diameter of the magnet had to be increased by 1 in., the axial-field integral had to be increased by 30%, and the magnet had to be powered by a supply whose maximum capacity was 70V at 700A. The greater packing factor of the tape-wound, edge-cooled solenoid design satisfied the above requirements and, in addition, offered a convenient means of accurately controlling conductor placement, thus allowing better field uniformity.

Design

A reliable estimate of the axial field of the iron-bound solenoid using the foregoing mechanical and power-supply restraints was obtained by assuming that all of the MMF appears between planes located through the center of the end flanges. The computed and measured values of field agreed to within 2.5%.

The assembled solenoid is shown schematically in Fig. 1. An exploded view is shown in Fig. 2. The magnet consists of a stack of six 46-turn coil elements separated by glass-epoxy water-flow guides. The water-flow guides have spiral grooves designed to increase the water velocity across the coil surfaces. The steel shell surrounding the coil assembly serves as the flux path and water jacket. An epoxy sleeve is bonded to the inside surface of the water jacket to minimize electrolysis problems. In addition the inside surfaces of the spool and end flange are coated with several applications of baked-on high-temperature varnish (Bisonite). The power leads pass to the beryllium-copper terminals on the end coils through insulated, water-tight epoxy sleeves in the water jacket. Water is supplied through a spiral guide at each end of the solenoid and leaves through five spiral guides at the center.

Coil Fabrication

The coil elements were wound as a sandwich of .81-mm-thick by 15.2-cm-wide copper strip and .08-mm-thick woven glass cloth. A schematic of the coil winding process is shown in Fig. 3. The copper was prepared during winding by going through a nitric acid bath, a water rinse, a chromic acid bath, a final water rinse, and a drying operation. Any burrs on the copper caused by tightening of the feed spool were removed by hand prior to the cleaning treatment. A 1600 lb-load (stress = 8500 psi) was applied to the copper while winding.

Hysol C-35, a long-pot-life, low-viscosity, high-cure-temperature epoxy resin was used to vacuum-pot the coils. The very low viscosity was required because the epoxy had to penetrate the small capillaries provided by the voids in the .08-mm-thick woven glass cloth tightly compressed between copper sheets. After curing the 15.2-cm-long coil for 16 h at 135°C, it was then sawed into 3.8-cm-thick sections, and the sections were finish-machined on a lathe to 3.225 cm. Each coil was then dipped in a nitric acid bath for approximately 2 min., which was usually sufficient to etch the copper surface to a depth of .025 mm below the glass insulation.

Coil Assembly

The mating surfaces of the machined coils and inner conductors were pretinned with a low-temperature 63-37 tin-lead solder prior to attempting to solder the joint. The coil elements were then paired together with a water-flow guide sandwiched between, and soldered together on the inside with 63-37 solder. In order to avoid possible epoxy damage, preheating of the entire coil was bypassed in favor of locally heating the pretinned joint very rapidly until the solder wet the joint.

The magnetic center of each coil pair (Fig. 4) was determined by energizing the coils to 100 A and then rotating a small search coil around the axis of the coil pair. The inside diameters of the coil pairs were bored for magnetic and geometric center coincidence. Following the boring operation, the three coil pairs were spaced with water-flow guides on a mandrel, and the outer diameter connections were soldered in the manner previously described. During assembly, care was taken to position the rotation of each coil so as to minimize the transverse-field integral component. After epoxy glass struts were bonded to the outside diameter of the coil assembly (Fig. 5), the unit was machined to permit accurate placement of the coil assembly within the water jacket.

Performance Tests

Figure 6 shows an axial-field profile of the solenoid. A power input of 35 kW is required to produce an axial-field integral of 193 kG cm. The transverse-field integral, measured on the geometric axis with a 76 cm line integral coil, was less than 193 G-cm. A pressure drop of 40 psi is required to drive 11 gpm of filtered, low-conductivity water through the magnet. With a 35-kW input to the magnet, and with supply-and-return water temperatures of 20°C and 34°C, respectively, the coil temperature reaches 42°C.

The completed solenoid assembly was bench-tested using the foregoing conditions. Visual inspection of the magnet after 350 h of continuous operation at 35 kW showed evidence of minute copper deposits and scaling on the coil surfaces and deposits in areas where the Bisonite coating appeared to have slight imperfections, such as pin holes. The largest concentration of deposits was located at the edges of the coils on the inner and outer diameters. Further examination revealed a small amount of loosening of the inner-coil lamination due to epoxy degradation during soldering.

It is apparent that if water is to be used as a coolant, the surfaces of the coils must be coated with a very thin coat of high-thermal-conductivity insulator. After several attempts, a method was developed to coat the edge of the coils with a thin coat of Isochem resin 1251, having a thermal conductivity of 19 times 10^{-4} cal-cm/cm^2-°C-sec, in order to eliminate the surface turn-to-turn .025 shorting effect. A uniform ~~0.25~~-mm layer of resin was applied to the coil surfaces by preheating the etched coils to about 50°C, brushing on the resin, and then using a rubber squeegee to remove any excess resin. The coated coils were then placed in an oven to cure for 1 h at 110°C, and after cooling to 50°C, the reverse side of the coils was treated in a similar manner. It is important to keep the film thickness to a minimum figure that does not increase the coil temperature excessively. A coated coil element is shown in Fig. 7. At 35-kW .025 input to the magnet and with a ~~0.25~~-mm layer of Isochem 1251, the present heat flux of 13 W/cm^2 increases the coil temperature 4.5°C over that of an uncoated coil. This is an acceptable figure at present; however, if input power is increased, as it is sometimes, then a water chiller in the supply line is the logical solution.

Improvements in the magnet would include redesign of the glass-epoxy water-flow guides to permit greater insulation between adjacent coils. A silver-loaded epoxy with a volume resistivity of less that 1 times 10^{-3} ohm-cm and a shear strength of 3600 psi is being considered as a possible answer to the problem of epoxy degradation due to soldering.

*This work was done under the auspices of the U. S. Atomic Energy Commission.

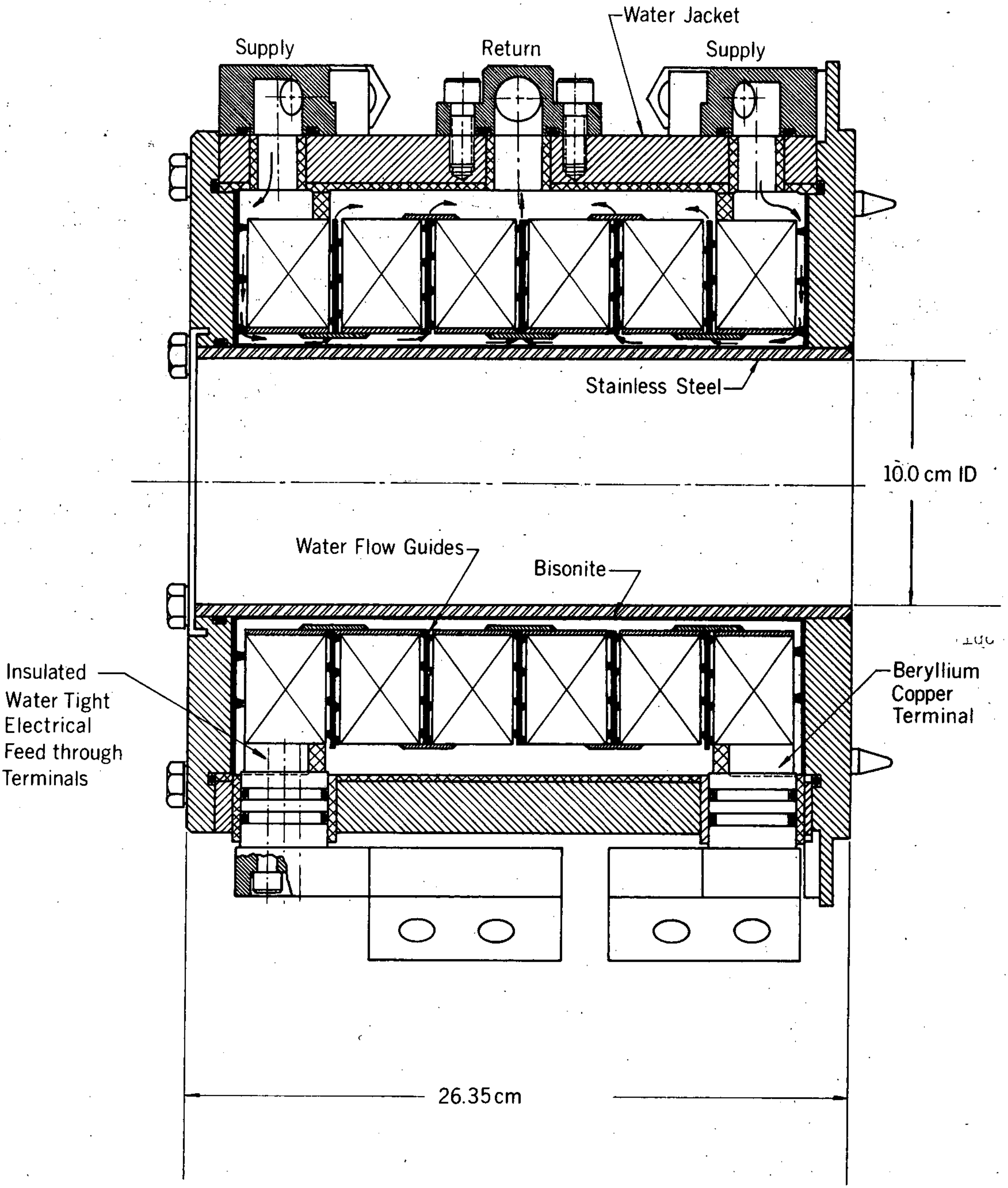

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Fig. 1. Schematic of assembled solenoid.

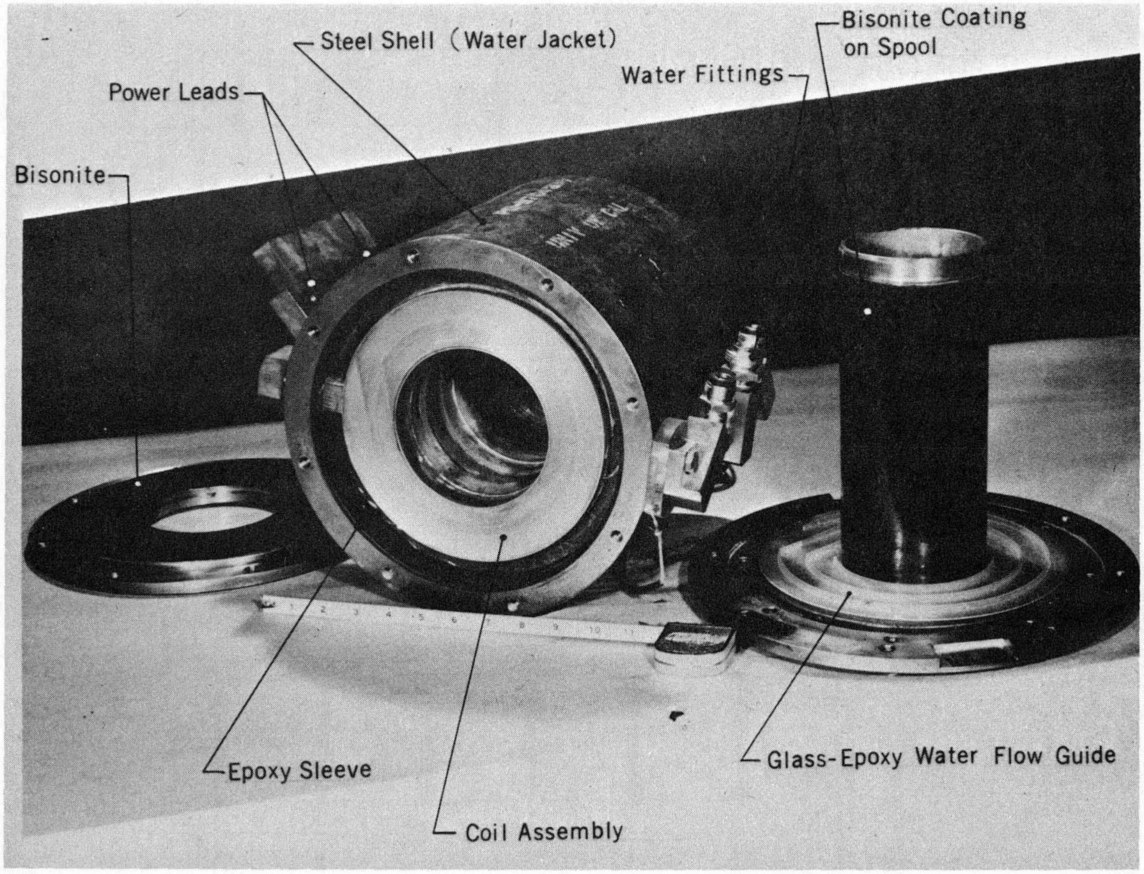

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Fig. 2. Exploded view of solenoid.

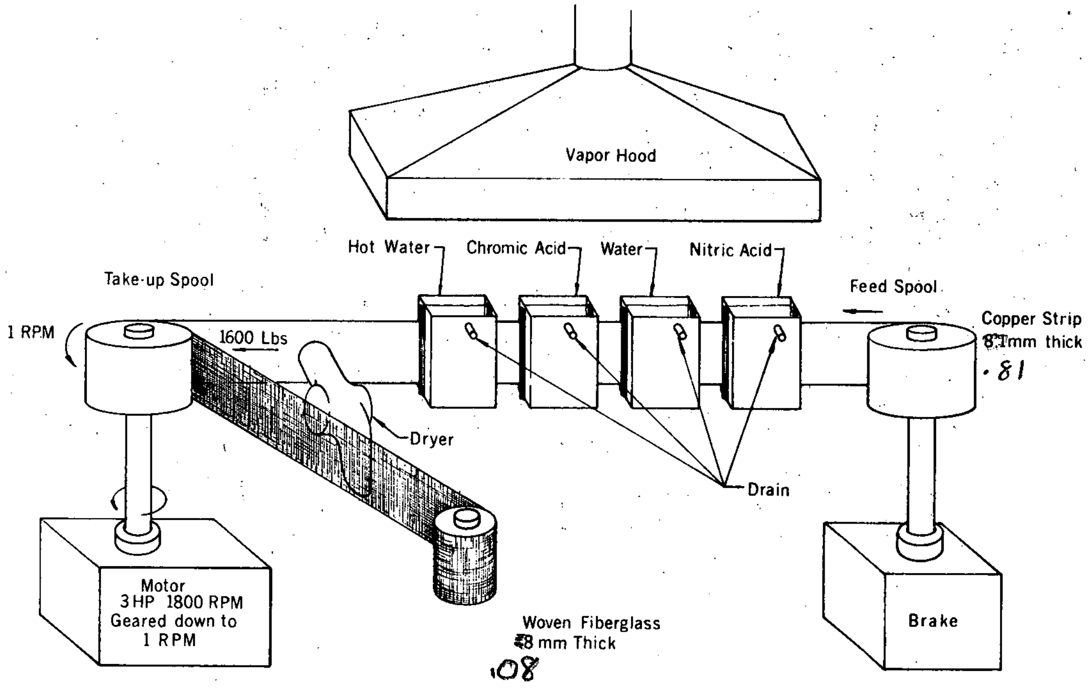

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Fig. 3. Schematic of the coil winding process.

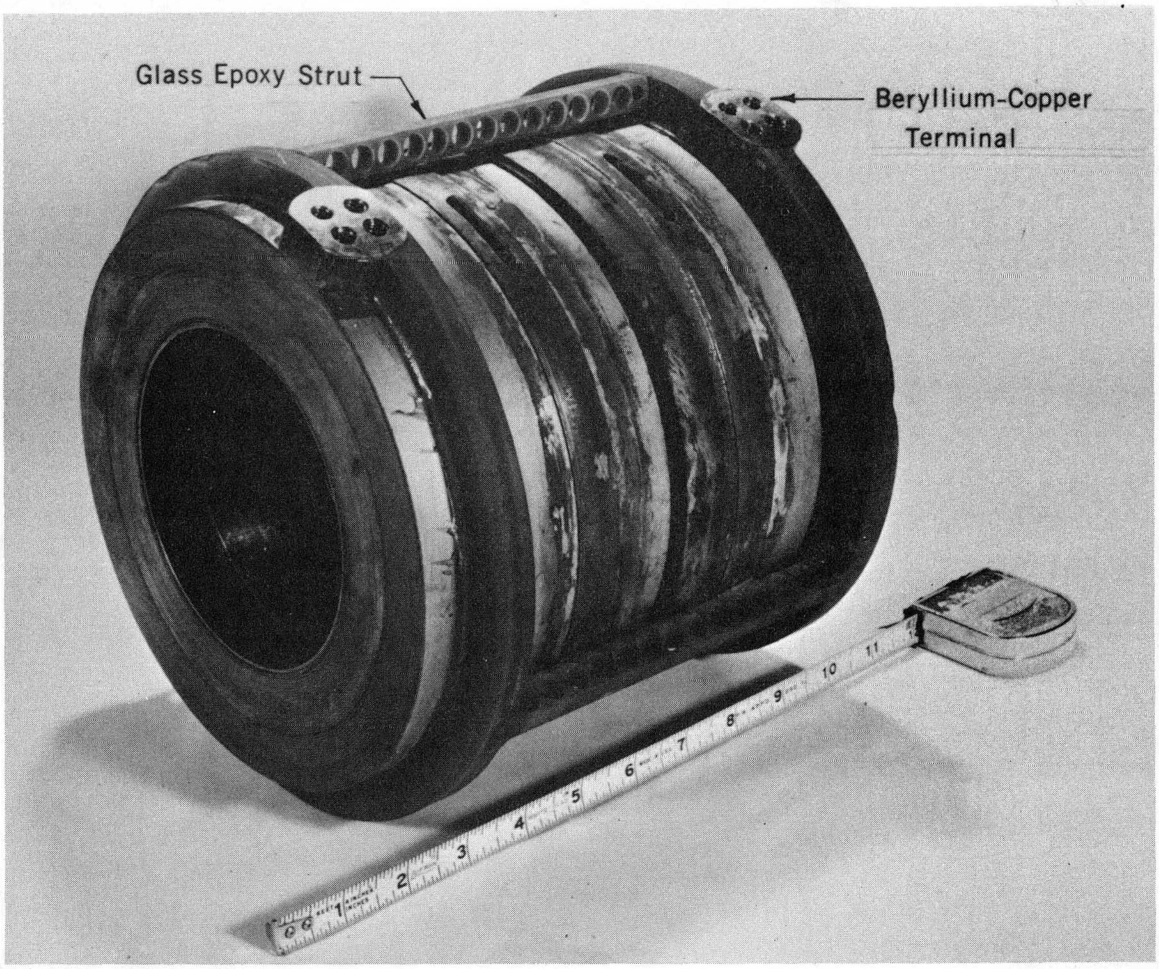

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Fig. 4. Coil pair components.

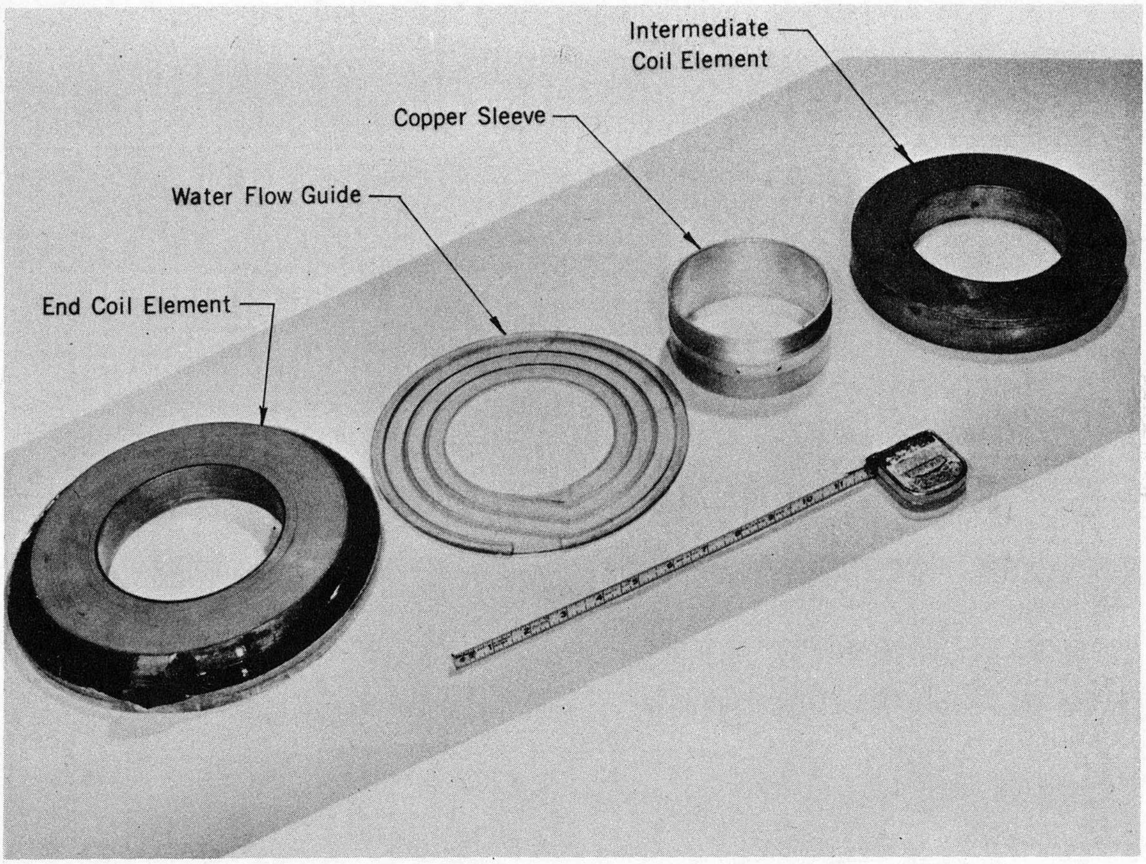

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Fig. 5. Completed coil assembly.

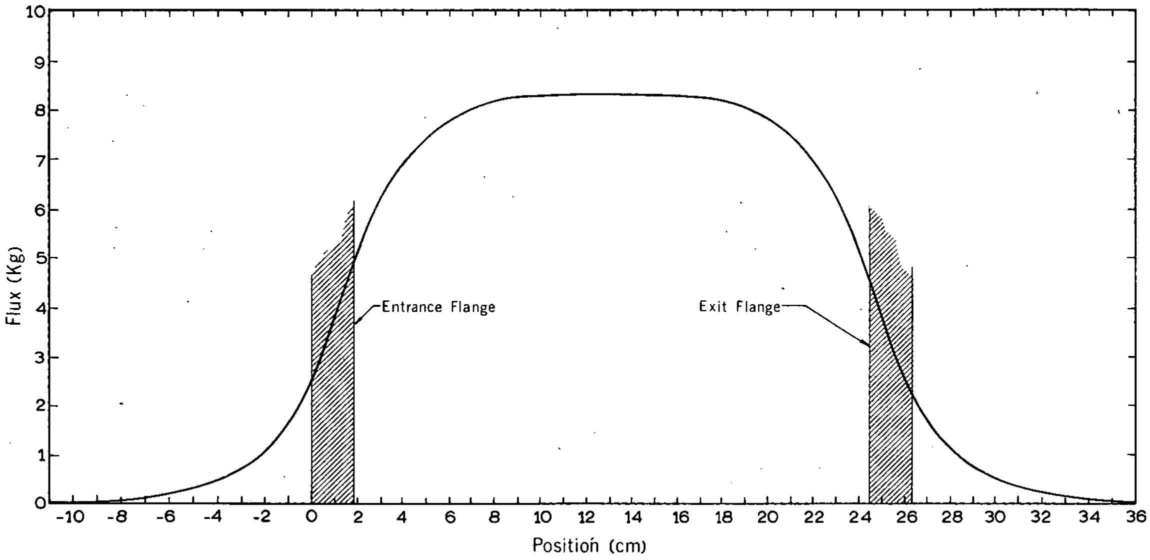

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Fig. 6. Axial field profile.

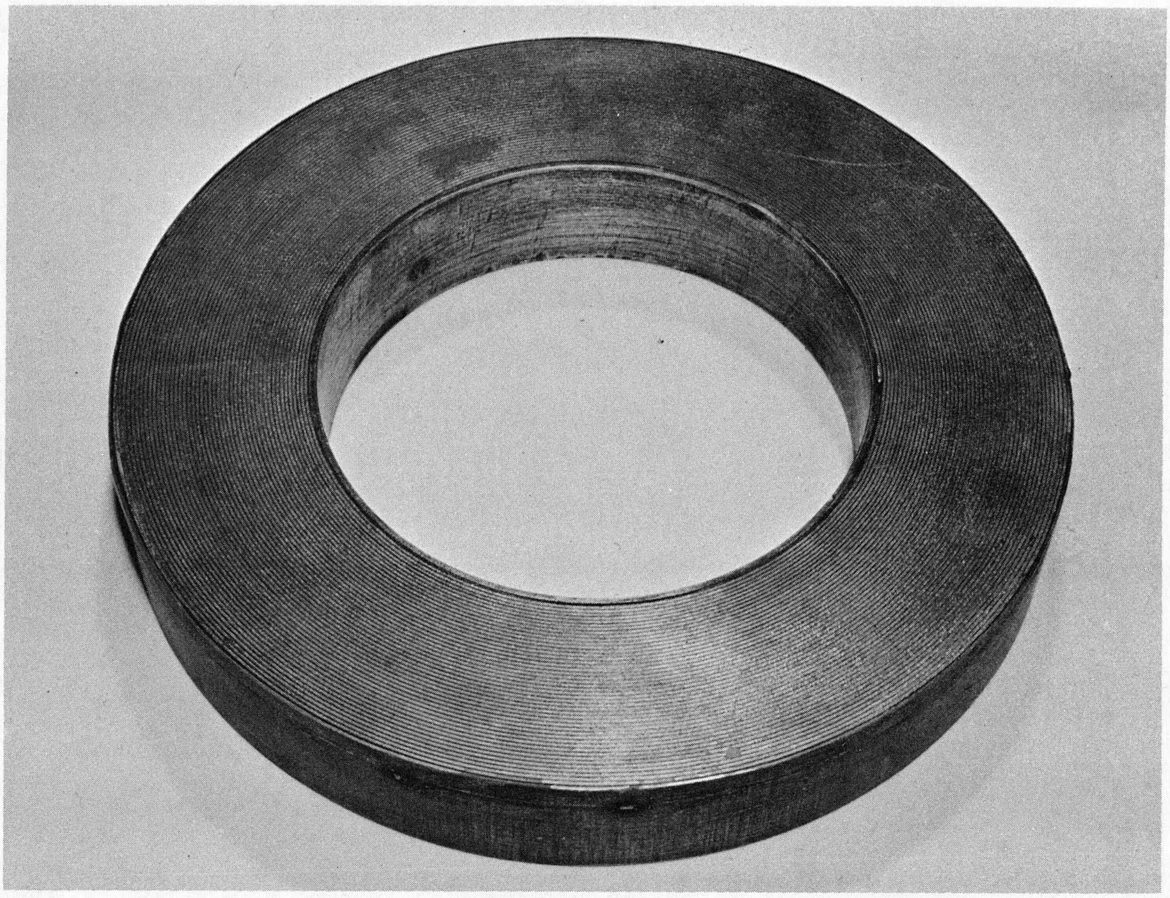

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Fig. 7. Coated coil element.