THE ARGONNE ZGS MAGNET

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Summary

The heart of the Argonne Zero Gradient Synchrotron is the large pulsed magnet approximately 180 ft in diameter. This magnet consists of eight curved sections or octants connected by long and short straight sections. It was designed to yield an external proton beam at magnetic fields up to 21.5 kilogauss. Major considerations in the design, fabrication, testing, and installation of the magnet and its coils are discussed.

Magnet Design

High field operation may be attributed to the "picture frame" cross section of the yoke, correcting holes in the steel, the relative positions of the magnets, and other design considerations.

Magnet Cross Section

The picture frame cross section of the magnet, shown on the lower right in Fig. 1, lends itself to high field operation. The highest average flux density is in the gap and not in the steel.

This design brings the coil near the gap. For this reason, the coil must not make error fields. The conductors near the gap are undersize. This can be seen in the center sketch of Fig. 1. These turns are put where they cancel the field error from the rest of the coil. On the other side of the coil, two pairs of conductors are wired so that either or both can carry the current. These can be used to correct the midplane if a coil should be skewed during construction.

Magnet Arrangement

The ZGS magnets are placed in a somewhat squared circle. This is shown in Fig. 2. Note that the smaller diameter high energy orbits enter the external beam deflecting magnets; yet these orbits spend most of the time near the center of the chamber where the field is more uniform. This improves beam extraction.

To use the whole chamber, the injected beam is bent so that it goes parallel to the main magnets. This bending, which also causes the injected beam to miss the external beam deflecting magnets, is done by four small constant field magnets. Extra coils in these magnets are used to trim field errors at injection.

Correcting Holes

The average field gradient along the orbits is corrected at high field by four holes drilled in the steel. These holes are seen above and below the coils in Fig. 1. Because the orbits are not lined up with the magnets, this simple method works up to a very high field.

The magnet design was based on a 1/7 scale model magnet program. The final model was a complete octant except that some of the center blocks were missing. The plate thickness was 6/7 scale so that the model could be pulsed. Computer programs were used to check the data, compute focusing along the orbits, and predict the required hole size.

Octant Ends

To eliminate field errors at the magnet ends due to the coils, the conductors are shaped like the magnetic equipotentials. This is shown on the left in Fig. 1. The increase in gap height near the end and a steel plate covering the end of the magnet make the required coil shape a reasonable one. A hole in the end plate or "guard" allows the proton beam to enter the magnet. The increase in gap height also controls the leakage flux to keep the shape of the field independent of the field as the steel saturates. This eliminates coil error at high field.

Magnet Iron Composition and Fabrication

Each octant is divided into ten center section block assemblies, and each of the flared ends into three end block assemblies.

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Figure 5 shows the typical construction details of a center block assembly. Each pole piece is laminated and consists of ninety-two uniformly tapered plates. Insulation and adhesive thickness is 12 mils. Thickness of plate plus insulation along the azimuthal centerline is 1/2 in. One tapered plate was added to or subtracted from the theoretical ninety-two plates of each pole piece to adjust for thickness variation of the plates and insulation. Also, in machining the pole pieces to size, plates of each pole piece were shaved to a minimum thickness of 1/4 in.

The magnetic field shimming holes were located and bored with respect to a 3 in. by 2 in. notch machined into the opposite edge of each plate along the azimuthal centerline. The plates of each pole piece were temperature bonded in sequence by means of special, hot platen horizontal presses. A machined curved key, fastened to the hot platen press, located each plate during bonding by engaging the 3 in. by 2 in. notch in each plate. In this manner the curvature of the magnet was generated in each pole piece.

After bonding each pole piece, the edge iron was welded in position. Four flange tips of the edge iron were then machined with respect to the mean plane of the pole face to provide convenient measuring surfaces for block assembly leveling and gap adjustment. These surfaces are shown in Fig. 5.

The inner and outer yoke pieces were constructed by bonding 1/2 in. plates in a similar manner to pole piece construction. Yoke plate insulation is 12 mils. The majority of the yoke plates are flat. (The magnet curvature was approximated by introducing tapered plates in pairs at regular intervals.) In order to assure uniform yoke piece thickness, top and bottom surfaces were machined after bonding.

Magnet Iron Alignment Considerations

Alignment of top and bottom pole pieces was controlled by optical measurements taken from hardened and ground gauge pins permanently installed into the azimuthal slot in each pole piece. Gap height uniformity was achieved by shimming between the pole and yoke mating surfaces and was checked by measuring between the machined flange tips of the edge iron. Permanent alignment of each block assembly was fixed by casting into position four 2-inch diameter hardened steel bushing and pin assemblies. Casting material was glass-filled epoxy resin. These pin and bushing assemblies were designed to maintain the alignment of both pole pieces and yoke pieces and to permit disassembly as required.

During assembly of the block assemblies into octants, shims were installed between the bolting flanges of the edge iron. Optical targets were fixed on the gauge pins of progressive blocks. Optical sightings on the targets served as a guide and final check of the assembly procedure.

Magnet Coil Composition

All ring magnet octants have identical coils, every other one being installed upside down and end-for-end. Each octant coil assembly consists of an outer side coil and an inner side coil, each of which has 32 copper conductors. These final side coil subassemblies were assembled to the end jumpers forming the completed coil (as shown in Fig. 3). The copper conductors were supplied in 60-foot continuous straight lengths with a 1/2-inch hole to carry the cooling water. They were drawn to have a 30,000 psi minimum tensile yield strength.

The mechanical accuracies called for tolerances like 0.004 in. for turn and layer spacing, 0.008 in. in overall coil height, and 0.030 in. in length and width co-ordinates. These tolerances were stringent enough to require the use of shim-like insulation for turn and layer stacking. Epoxy Fiberglas laminate of NEMA Grade G-10 sanded to 0.002 in. tolerance was used. The spaces between the turn and layer "T" joints and the adjacent round corners of the conductors were filled with continuous, solid strips of reinforced Fiberglas and epoxy resin. The laminates and fillets were coated with a single component epoxy adhesive. They were then assembled with preformed conductors in accurate, close-machined molds and cured under heat and pressure. Figure 4 shows a side coil assembly in the curing fixture molds. The stacking configuration can be seen in Fig. 1, lower middle.

Magnet Coil Operating Conditions

The coil is subjected to a pulsating magnetic force of 0 to 12 tons per linear foot and thermal forces of 42 tons at the ends. To handle these large forces and prevent fatiguing failures, the coils were installed in the ring magnet octants under tension (prestressed). This was accomplished by heating the coils to a temperature above the maximum operating of 100°F, shimming at the ends with filled epoxy between the magnets and coils, and then allowing the coils to shrink against the magnets. This resulted in a tensile prestress of approximately 8,000 psi. Subsequent measurements during operation show the movement at the ends of the coil to be less than 0.002 in.

The coils are also securely anchored to the magnet by spring-loaded anchor rods uniformly spaced approximately two rods every eight inches along the length and screwed into stainless steel plates. These plates are an integral part of the coil's monolithic structure. A strong shell material consisting of a combination of unidirectional and crossply Scotchply tape was used to bind the side coils and the anchor plates together and transmit these loads. Under normal operating conditions, the voltage between turns of the coil is about 50 volts dc; between layers, about 400 volts dc; and to ground, about 1500 volts dc.

Magnet Coil Alignment Considerations

The curing fixtures and other assembly tooling as well as the coil subassemblies and the final assembly all were accurately aligned and checked with specially designed precision optical tooling.

Augmenting this optical tooling, fiducial marks had to be accurately transferred starting with the current-carrying conductors all the way through fabrication to the final installation into the magnets. These hidden co-ordinate check and layout marks in the configuration were transferred within 0.002 in. from heavy punch marks on the buried conductors to the outside ground insulation by a "radioactive alignment" method developed by Mr. Norman Lapinski of Argonne's Metallurgy Division.

In this method, a small radioactive source was passed through the cooling channel of the conductor on which the reference marks were located, and a latent image was obtained on film located on the outside of the conductor.

Only a very small source would produce an acceptable sharp image of the reference mark. For this reason, radon implants were used which were 4 mm long by 0.75 mm in diameter. These sources were weak enough (5 millicurie) to be safely introduced by hand into the cooling channel. They were small enough so that even in their capsules they could be fed around the bends and down the length of the coolant channel on flexible tapes.

Lead (Pb) markers were placed close to the location of the reference mark, and then the source was pushed into place and the exposure made. The film was developed and a template made which, when placed over the lead markers on the conductor insulated surface, permitted accurate location of the reference marks.

Magnet Coil Scheduling Considerations

The fabrication procedures for nine magnet coils were planned into a Program Evaluation Review Technique (PERT program). The start and final dates for each detailed step in construction for a week at a time were supplied to the fabricator. It was absolutely necessary for ANL to lead, assist, and finally monitor both the engineering of the fabrication tooling and the fabrication itself.

Magnetic Measurements

Before the magnetic blocks were assembled in the ring building, the average characteristic of each block was measured. These measurements were performed in a test assembly, the design of which was based on the following considerations:

1. Each block had to be compared directly with a reference block to know the fluctuation of the magnetic field from block to block to better than one part in 10^3.

2. The magnitude, the shape of the field, and the magnetic median plane had to be measured for several values of the radial position and current.

The test assembly consisted of eight blocks - three long straight section end blocks, the block under test, the reference block, and three short straight section blocks. Figure 6 shows the test assembly; however, only one of the short straight section end blocks can be seen.

Fifty identical sets of measuring coils were placed in the block under test. The reference block had only 25. Three kinds of measurements were made. They were:

1. Azimuthal Measurements. In this case the absolute magnitude of the test block field was compared with that of the reference block.

2. Radial Measurements. These gave the average radial gradient in each test block.

3. Median Plane Measurements. The radial component of the magnet field was measured

for various values of the flux density to take errors in the coils and coil support alignment into account. It was assumed that the radial component of the magnetic field was zero at the geometric median plane for a flux density of 6000 gauss. This was justified because the permeability was very high at this flux density so that the pole faces could be considered as an equipotential.

The magnitude and shape of the remanent field was measured by flipping the center coil over 180° and shifting the other coils radially. During each pulse, only 1/4 of the block under test was measured. Only 13 coils were used on this test. A 14-channel analog-digital converter encoded the output voltages of the 13 electronic integrators and the current shunt onto a magnetic tape for futher data processing. During the static measurement of the remanent field, the ADC was sampled every 20 msec. For dynamic measurements, the sample interval was approximately 3 msec. This high speed data-acquiring method allowed us to make redundant measurements and apply the method of least squares for data adjustments. In less than 15 minutes, the magnitude and the gradient of the field and median were measured at 24 radial positions and 300 current values. The gradient measurement attained an accuracy of 0.03 gauss/in., and the location of the median plane was known to 1/4 in. The information on the variation of the average flux density from block to block was used to distribute the blocks in the eight octants. The major consideration in the location of the blocks was that the first and second harmonics of the field fluctuations be as small as possible, particularly at high field (21.5 k gauss).

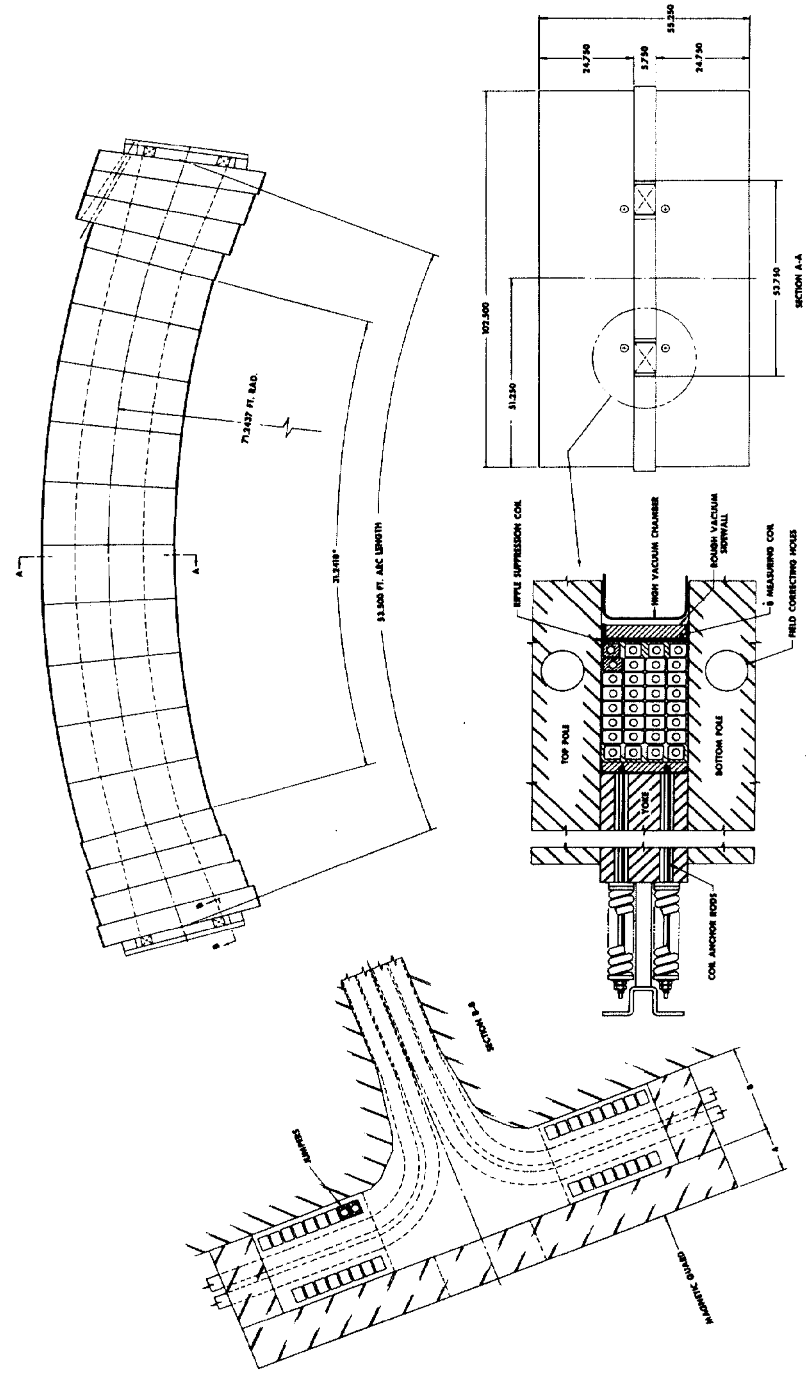

Fig. 1. Argonne ZGS Ring Magnet Plan View and X-Sections.

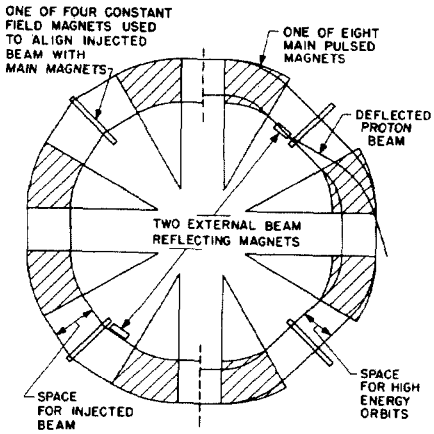

Fig. 2. Schematic of ZGS Magnet Plan.

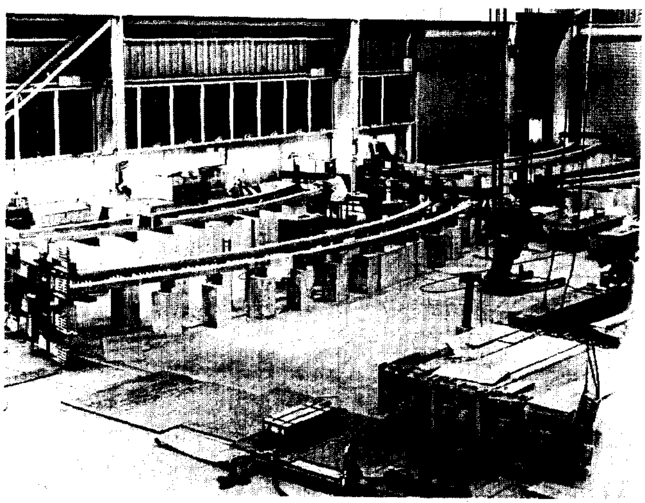

Fig. 3. Argonne ZGS Ring Magnet Coils.

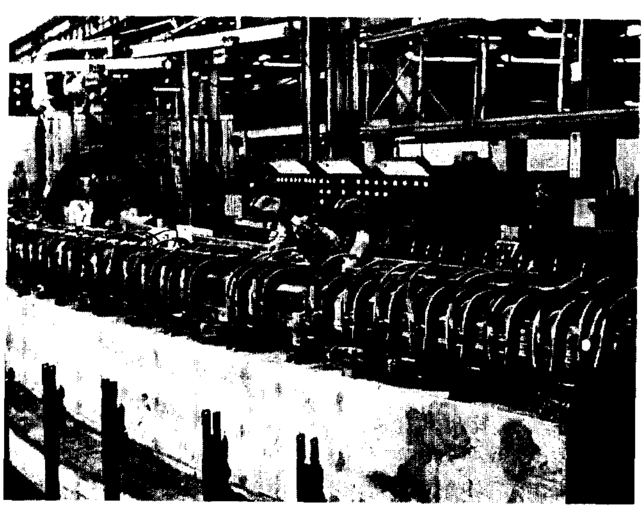

Fig. 4. Argonne ZGS Ring Magnet Coil Molding Fixture.

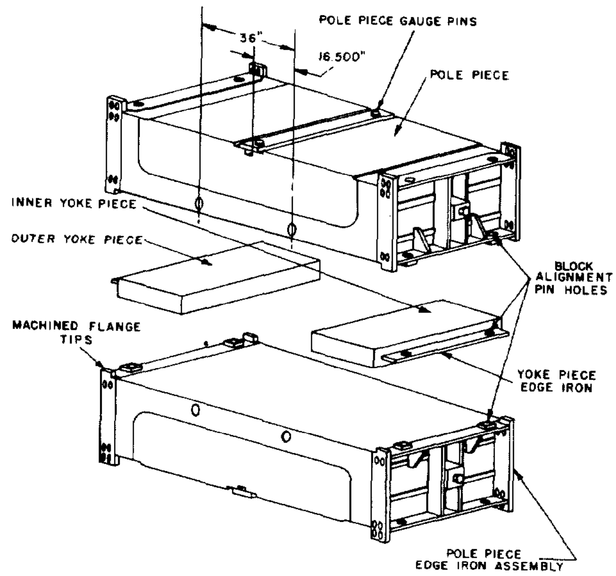

Fig. 5. Argonne ZGS Ring Magnet Center Block Assembly-Exploded View.

Fig. 6. Argonne ZGS Ring Magnet Test Fixture.