# FABRICATION AND MAGNETIC FIELD MEASUREMENTS OF THE IUCF COOLER RING DIPOLE MAGNETS*

T. Sloan, O. Dermois and M. Yurko
Indiana University Cyclotron Facility Bloomington, Indiana 47405

## Abstract

The Cooler Ring Dipoles are curved, laminated C-section magnets. They are a little unusual in that the radius of curvature is only 2.39 M. The assembly jig design and actual stacking of the magnets was done by the Fermi National Accelerator Laboratory.

The fabrication techiques are discussed. The variations in the mechanical dimensions of individual laminations and the assembled cores are presented. The effect of these variations on the magnetic field, as mapped, are discussed.

## Cooler Dipole Magnet Construction

The principle parameters of the IUCF Cooler Dipole Magnets are given below.

| | | |
|---|---|---|
| Bend Angle | 30 | 27 |
| # Required | 8 | 4 |
| Bend Radius | 2.39 M | 2.39 M |
| Max Field | 1.53 T | 1.53 T |
| Effective Length | 1.246 M | 1.122 M |
| Gap | 5.19 cm | 5.19 cm |
| Max Beam Size | 3.7 x 8.8 cm | 3.7 x 8.8 cm |
| # Coil Turns | 80 | 80 |
| Max Current | 860 amps | 860 amps |
| Max dI/dT | 258 amps/sec | 258 amps/sec |
| Weight | 6477 kg | 5818 kg |

### 1. Laminations.

Figure 1 shows a drawing of a Cooler Dipole lamination. These laminations were punched from 16 gauge (1.52 mm ± .13 mm) 1008 cold rolled sheet steel which had been phosphate coated to improve epoxy adhesion. In order to minimize variations in the laminations caused by releasing stresses in the steel, the laminations were punched from a blank. The blanks were produced by an inexpensive punch and die with relaxed tolerances. The blanks were approximately 6 mm larger than the final lamination on all edges. Most sheet steel suffers from crown, meaning that the center of the sheet is thicker than the edges. To allieviate this problem, we slit a 1.52 m wide piece of sheet and stamped one lamination with its gap in what was the center of the sheet and one with its gap near the edge of the sheet. This process is indicated in Fig. 2. We could then remove any unwanted curvature in the magnet caused by the wedge in lamination thickness by selectively stacking these two types of laminations.

Fermilab recommended that the steel be lubricated for punching and rust protection with an air dry, non-chlorinated lubricant. When we initially failed to do this, we had to wash laminations twice in order to get adequate epoxy bond strength.

Sample laminations were dimensionally checked on a Cordax coordinate measuring machine. The laminations met the mechanical tolerances specified for the pole tip regions. These were: flat ±.025 mm, parallel ±.05 mm, and deviations between laminations of ±.013 mm.

### 2. Magnet Construction.

The laminations were coated with a thin layer of epoxy and stacked in the assembly jig. The curvature of the magnet core was determined by two rails on which the laminations were stacked with the gap facing down. A vertical plate projected into the gap and held the

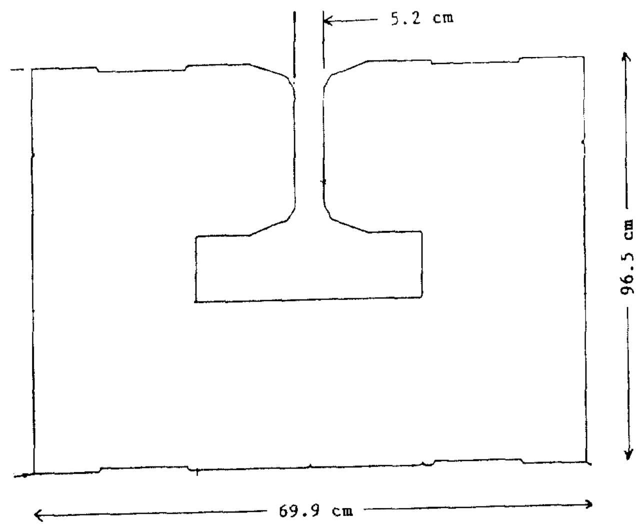


Figure 1.

laminations in position using part of the pole tip surface outside the Rose shims. The magnet was then compressed with a force of approximately 25 tons. The magnet was held under compression by tightening long thru bolts. The magnet was compressed to the proper length which was determined by mechanical stops in the assembly jig. The magnet core, still compressed in the assembly jig, was then placed in a large oven and baked

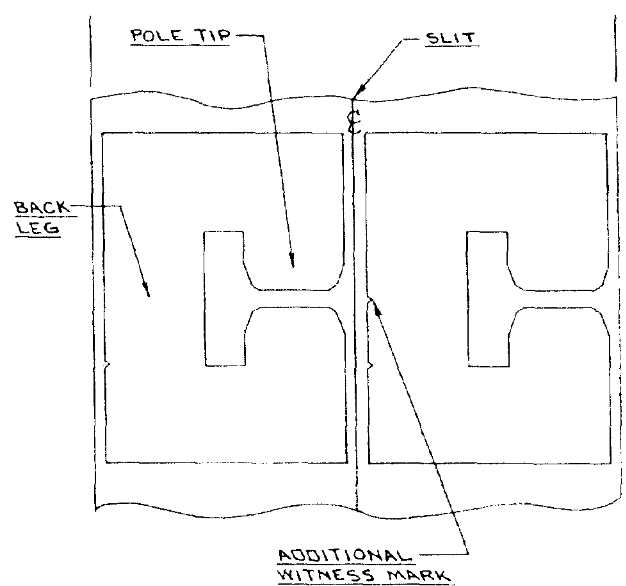


Figure 2.

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to insure an optimal epoxy cure. After sand blasting to remove excess epoxy, 2.2 cm steel plates were welded to the top and bottom of the cores and four 1.3 cm curved plates were welded into notches in the sides. These plates protect the lamination epoxy joints from shear loads. By gluing the entire magnet together we eliminated the difficulties in making the magnets rigid against forces trying to twist one end of the magnet relative to the other.

3. Pole Tip End Packs.

The magnet design called for the cores to be undercut at an angle of 22.5° in the pole tip region at each end of the magnet. In addition a cross section taken vertically thru the magnet perpendicular to the 22.5° undercut, should be the same approximation to a Rogowski contour used on each edge of the pole tip. Even if it is possible to machine such a shape after the magnet has been epoxied, the process would have been quite expensive. In addition to the normal machining difficulties there would have been the danger of delamination. This problem was solved using a techinque which Fermilab developed on their Antiproton Accumulator Ring quadrupoles. A stepwise approximation was made to the desired shape by individually modifying about 80 laminations at each end of the magnet. There are only three different end profiles among the 12 magnets. These laminations were modified using a numerically controlled Turret press. This machine can punch the straight edges and angles for the end packs with an accuracy of ±.13 mm. This process cost about $2.00 per lamination.

4. Lamination Thickness Variation.

As noted earlier the specification for normally available sheet steel allow thickness variation of ±8%. In our case we found 2% variations in a given coil and as much as 4% between coils. By measuring laminations punched from the beginning, middle, and end of each coil we obtained an average thickness of 1.45 mm. This average lamination thickness, the number of laminations used, and the measured length of a finished magnet, gives a packing factor greater than 99%. Unfortunately, the step size for the 22.5° end packs was calculated using a thickness of 1.52 mm. This error should result in end angles of 21.56°. Measurements on the magnet cores give end angles of 21.5° ± .5°.

## Fieldmapping Results

Each magnet was mapped using a grid having a data point spacing of 1.25 cm. The magnets were aligned in front of the mapping table with an accuracy in the X and Y direction of .75 mm. This corresponds to a maximum deviation of about 2 mrad between magnets. Maps were taken at 0.36, 1.05, 1.31, and 1.51 T. From these maps the field distribution along a defined central trajectory was calculated. This trajectory was a circular arc with a radius of 238.68 cm inside the pole tip boundaries and had connecting straight lines outside these boundaries. In addition the field along six offset trajectories was calculated. These offset trajectories where calculated at larger and smaller radii using 1.25 cm steps. From these field distributions the effective length along the central trajectory, the position of the effective field boundary, and the angle between the field boundary and the central trajectory was calculated. As a basis for the effective length the average field in the "good" field region was used. The average effective length along the central trajectory of the four 27° magnets is 115.34 cm at 0.36 T and 115.05 cm at 1.51 T. The geometrical length between the pole tip boundaries along the same path is 112.47 cm.

For seven of the 30° magnets the average effective length along the central trajectory is 127.74 cm at 0.36 T and 127.45 cm at 1.51 T. The geometrical length between the poletip boundaries along the same path is 124.97 cm. One 30° magnet has an effective length which is 0.25 cm longer for all field values. This is 1.5 times the lamination thickness. Counting the laminations showed that there were two extra laminations in this magnet. Except for this magnet the other magnets deviate less than 1mm in effective length from the average value at the measured fields. Since all these magnets will be connected in series, trim coils are provided to compensate for the variations in the effective length and field based on mapping data.

Figure 3 shows a typical field distribution along the central trajectory at 1.05 T. The fluctuations have an amplitude of about 1 mT around a best fit parabola which varies with excitation. If these fluctuations were due to saturation properties of the steel, one would expect to see their relative size increase at higher fields. If, on the other hand, they are due to remnant fields in the steel, one would expect their relative size to decrease with higher fields. In fact, their relative size remains approximately the same. This seems to indicate that they are due to variations in the gap width. We have not yet made measurements along a magnet pole tip in an attempt to correlate these fluctuations with variations in gap width.

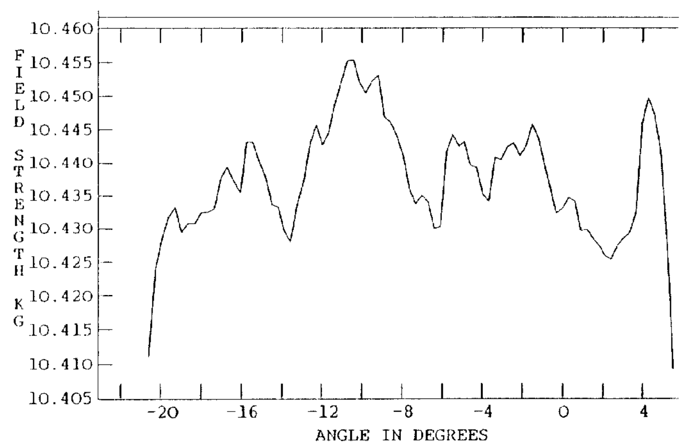


Figure 3. 30° field map along central trajectory.

Figure 4 shows a typical field distribution perpendicular to the central trajectory at angles of 0°, 6°, 12°, and 18°. The 0° point is defined by the position of the lamination which is perpendicular to the central trajectory. The derivative of the curves corresponds to a field index n = 0.035. The fact that the fluctuations in Fig. 4 are much smaller than those in Fig. 3 indicates that the "isofield lines" are mainly perpendicular to the central trajectory.

Figure 5 shows the field distribution as in Fig. 4 but for 1.51 T. here n = 0.032 and the sextupole term beta = -1.35 where $B = B_0(1 - nx + beta * x^2)$.

The most important difference between the design and reality is the longer effective length. This means that the actual effective field boundaries are about 1.5 cm outside the actual pole tips. This is corrected for during alignment of the magnets in the ring.

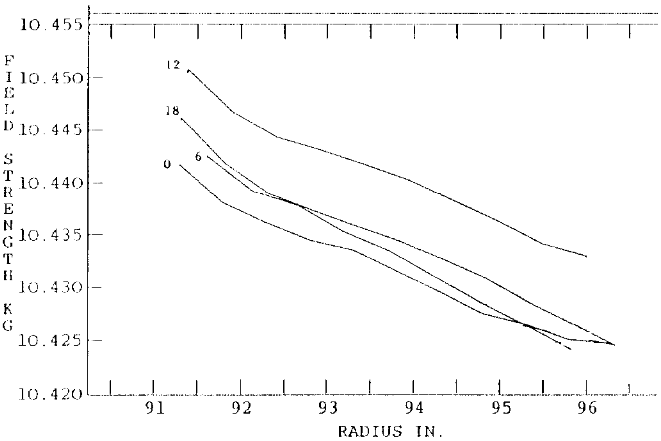


Figure 4. 30° field map perpendicular to central trajectory at four angles 1.04 T.

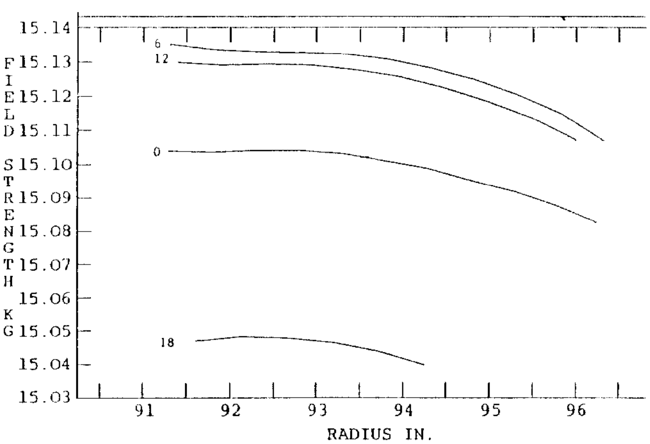


Figure 5. 30° field map perpendicular to central trajectory at four angles 1.51 T.

If one defines the effective field boundary as the position where the measured field was one half the average value in the "good" field region, then the angle between the normal of the field boundary and the central trajectory should be 15° at one end and 0° at the other. From the field map grids these angles were calulated to be 16° and 1° for the 27° magnets. Since these angles had the same rotation relative to the ideal angles the included angle is still 15°. For the 30° magnets the angles from the field maps are 13° and 1° resulting in an included angle of 12°. The field map angles change about .1° with a change of magnet field from .36 T to 1.51 T. The alignment accuracy was such that it cannot explain the 1° deviation at the 0° end. The seven points used in each case to define the field boundary lie on a straight line within .25 mm over a 9 cm width. We are unable to account for the difference between the measured angles on the magnet cores and the angles calculated from the field maps.