The Design and Manufacture of the Fermilab Main Injector Dipole Magnet

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Abstract

Fermilab's new Main Injector Ring (MIR) [1] will replace the currently operating Main Ring to provide 150 GeV Proton and Antiproton beams for Tevetron injection, and rapid cycling, high intensity, 120 GeV Proton beams for Antiproton production [2]. To produce and maintain the required high beam quality, high intensity, and high repetition rate, conventional dipole magnets with laminated iron core and water cooled copper conductor were chosen as the primary bending magnet. A new magnet design having low inductance, large copper cross section, and field uniformity sufficient for high intensity injection and efficient slow resonant extraction, is required to obtain the needed geometric aperture, dynamic aperture, and operational reliability. The current Main Injector Ring lattice design requires the use of 344 of these magnets. 216 of these magnets are to be 6 m long, and 128 are to be 4 m long .

1. INTRODUCTION

To insure that the needed MIR Dipole Magnets are designed and built to perform accurately and flawlessly over a period of many years, a complete and accurate set of magnet design standards, manufacturing specifications, and performance criteria is needed. To aid in the development of these standards and specifications, two prototype 6 m long magnets were manufactured at Fermilab's Conventional Magnet Facility. Problem areas encountered during the fabrication and testing of the first prototype magnet were corrected prior to the fabrication of the second prototype magnet. The first prototype used B-Stage fiberglass tape to insulate the coils and contained a single, "U" shaped copper bus, connecting the magnet's upper and lower coils together. In the second prototype magnet, the coils were insulated with treated fiberglass tape and then vacuum impregnated with epoxy following the planned fabrication method. The upper to lower coil connection was also modified to eliminate unwanted end field effects and to improve joint reliability and manufacturability.

Tests and measurements made during the manufacturing process, and extensive magnetic measurements made at the Magnet Test Facility, on both of the completed magnets, have shown that the prototype design and manufacturing processes [3][4] used were on target. Magnet performance results show extremely good correlation with design calculations. Also, very repeatable performance results were achieved between each of the two prototypes magnets built. The stage is now set to complete the design and manufacturing requirements for Fermilab's new Main Injector Dipole Magnets.

2. MAGNET DESIGN

For the lamination shape, tapered poles were required to reduce non-uniform saturation and thus reduce the magnitude of the multipoles produced. To improve the geometric aperture, a curved magnet was required. The magnet was to be constructed entirely of 16 gauge steel laminations. Modifications to the pole configuration were required at the ends of the magnet to help maintain proper field uniformity.

A field of 1.7 T and a ramp rate of 2.7 T/sec are required. The 8 turn, 2 coil design chosen, accomplishes this using a maximum of 9400 amps. The large cross section of copper used minimizes operating costs. To limit the amount of external buswork in the tunnel, each magnet was designed as a four leaded device containing a half turn length of copper that acts as a thru bus connection to an adjacent magnet.

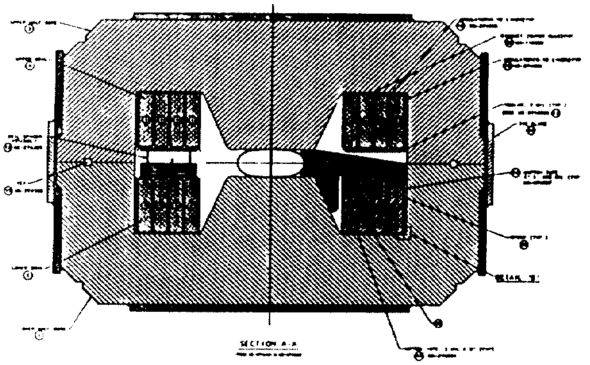

Fig. 1. Dipole Magnet Cross Section View

3. CORE CONSTRUCTION

The steel is manufactured in wide, 1.5 mm thick (nominal), low carbon steel sheets. Each are then slit into 5 coil widths and surface treated with a C-5 epoxy coating to reduce eddy currents. The material is specified to have an $H_c < 1.0$ Oe and a permeability of 180 ± 1 gauss/Oe at $H_m = 100$ Oe. Since the sheets of steel are normally crowned in the center due to the rolling process, thickness variations found in each of the coils of slit steel, due to sheet crowning, are noted. As boxes of stamped laminations are produced from these coils, they are tagged, noting the thickness

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variations to be expected based on the variations found in the individual coil from which the laminations came.

A rigid mass of steel is needed at both ends of the half cores of each magnet, to resist both internal spring forces of the pole area after assembly of each half core, and the magnetic forces created during operation. The pole face ends must be specially shaped to provide suitable end field properties [5]. To reduce manufacturing costs, instead of using solid steel "end plates", 100 laminations are epoxied together to obtain the required 150 mm thick rigid "end packs". Only laminations of the most uniform thickness are used in the manufacturing of these end packs. Approximately 30 laminations for each end pack are mechanically "nibbled", laser cut, or water jet cut, to create the proper end field pole face contour, prior to being epoxied together.

Each half core assembly is created by stacking laminations to the required length between two end packs located against a precision curved template rail, mounted on a surveyed flat assembly base. This base forms an integral part of a stacking table. Laminations are selected in 750 mm groups from marked boxes and "recipe" stacked in a fashion to produce cores having uniform density and consistent geometric shape. It may be necessary to further pre-select the laminations used in a given half core in order to account for differences in the magnetic properties of a given batch of laminations. Once selected and stacked, the laminations are held in compression by a screw press that forms a part of the stacking apparatus. Side and top plates are then clamped against the half core, using a hydraulic fixture, and welded in place to hold the half core together. A welding technique is chosen to minimize core distortion as a result of the welding process.

4. COIL CONSTRUCTION

Each of the two, 4 turn, racetrack copper coils are manufactured from 9 pieces of approximately 6 m long x 25.4 mm x 101.6 mm grade CD 102 copper bars. Using copper bars of this length, only 8 braze joints are required to completely fabricate the main body of each coil. Careful control in the copper bar extrusion process provides an accurate and consistent cross section and a precisely located 12.7 mm diameter coolant passage hole located in the center of the conductor.

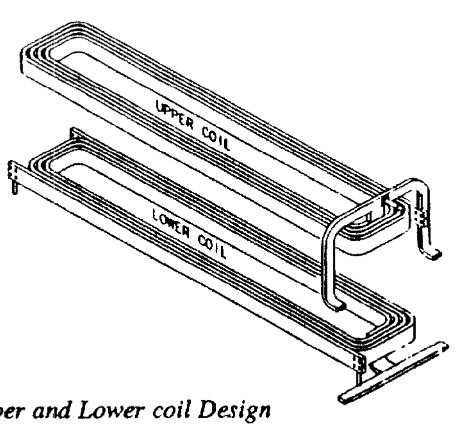

Fig. 2. Upper and Lower coil Design

All copper conductor joints are fitted with ferrules to help align the mating conductors, relieve stress, and help prevent leaks. To minimize the effect of generated coil stress on the braze joints, all joints are positioned a minimum of 300 mm away from bend radii and 600 mm away from adjacent joints.

Prior to being brazed, each length of copper bar generally receives two 90^{o} x 63.5 mm radius bends to form a "J" shaped configuration. The bar ends are then carefully cut to proper length and machined flat and perpendicular to the plane of the coil. The bending process has been refined to produce minimum cross section distortion or keystoning in sthe bent portion of copper.

Copper ferrules placed into the precisely located counter bored holes in the ends of each copper bar straddle the parting plane and help align the two bars to to one another. Rings of Silfos brazing material placed over each side of the ferrule and a Silfos washer placed between mating bar ends assures adequate brazing material to produce void free, leak free, high strength, joints. For the prototype coils, the brazed joints were made using a dual tipped brazing torch. Experimental joints have since been made using an induction clamshell coil placed about the joint. Results achieved thus far offer the promise of controlled repeatability, reducing the potential for operator error.

Once the coil segments are all brazed together, any joint mismatches are sanded smooth. The completed coil is then grit blasted to remove foreign material and prepare the conductor surface for better epoxy adhesion. It is finally checked for leaks and mechanical integrity. The coil is now ready to be insulated.

Coil insulation is provided by applying multiple wraps of 0.18 mm thick fiberglass tape, specially treated with an epoxy wetting agent, over the clean, bare copper. Both butt lap and half lap wrapping techniques are used to generate the required overall insulation thickness. To help eliminate pressure spots and also to help maintain required spacing, 0.38 mm thick G-10 strips are placed between adjacent conductors and along the copper surfaces that bear against the steel core when in place. To facilitate the manual "conductor" wrapping of insulating tape around each conductor, the coil is spread apart vertically. After conductor wrapping is completed, the coil is carefully collapsed into place and "ground" wrap insulated.

Once completely wrapped with the required thickness of fiberglass tape and G-10 strips, the coil is sealed in a mold designed to maintain a precise coil size and match the required core sagitta. The coil is epoxy vacuum impregnated at a temperature of about 50° C. It is then cured for an additional 16 hours at approximately 120° C. Once the epoxy material has cooled to about 40° C, the mold can be opened and the coil removed. This process helps limit the buildup of internal stresses and minimizes the potential of the epoxy to crack. Once cured and at room temperature, the impregnated coil insulation system will withstand up to 10,000 volts between coil and thru bus and 5,000 volts to ground without electrical breakdown.

5. COIL/CORE ASSEMBLY

The cured, vacuum impregnated coils are designed to fit into their respective half cores in such a manner that they are allowed to breathe longitudinally due to temperature variations, yet be restricted from transverse movement due to the Lorentz forces generated each time the magnet is ramped. To minimize these effects, only the center 1.0 m section of each coil is epoxies directly to the cores. This allows only symmetrical longitudinal movement about the center of the coil to take place. To further improve the ground insulation, a layer of Caption and G-10 is placed tightly against the coil, along the two sides of the coil that bear against the core. All remaining space between the vertical sides of the coil, along the G-10 slip plane interface, and the vertical core walls, is filled with epoxy to effectively prevent any outward movement due to Lorentz forces. The Kapton/G-10 interface provides a slip plane over which the coil can move in the core in response to changes in thermal characteristics.

The beam tube is now ready to be assembled. This 6.5 m long eliptically shaped seamed tube, with a 50 mm x 115 mm aperture, is made from 1.5 mm thick, type 316 Stainless Steel. It is wrapped with Kapton and set in place on the half core. Four specially made G-10 spacers placed along the length of the beam tube, between it and the core wall, retain the beam tube in a curved position to match the core sagitta.

During assembly of the upper half core/coil assembly to the lower half core/coil assembly to create the completed dipole magnet, the upper coil is supported by a combination of polyurethane and G-10 spacer blocks of sufficient height and durometer to elastically support the coil weight.

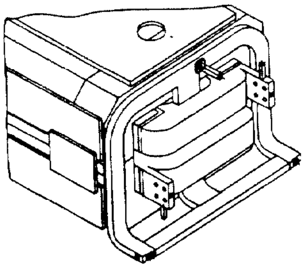

Fig. 3. Completed Magnet Connections

Additional G-10 blocks with epoxy sandwiched between them straddle the polyurethane. Once the half core assemblies are welded together, the cured epoxy/G-10 block sandwiches provide the final support and separation for the coils. Tie plates welded across the parting plane of the upper and lower cores, while they are clamped together, hold the dipole half cores together. Alignment keys keep the cores properly aligned during this stage of assembly.

6. FINAL ASSEMBLY

The series connection of the upper coil to the lower coil is made by connecting two parts of a symmetrical copper ring, that provide parallel conductive paths, each carrying half the current. The symmetrical configuration minimizes distortion to the desired end field characteristics. The final connections are made by two easily accessed braze joint operations. Magnet to magnet connections in the tunnel are to be accomplished by using flexible bolt on connections. The magnet will be supported at its quarter points by adjustable feet.

7. CONCLUSION

The experience and results achieved by building and evaluating the two prototype 6 m dipole magnets have provided the needed knowledge and technical details for the design team to confidently proceed to finalize the design and manufacturing requirements for this important component of the Main Injector. There is now a much better understanding of the magnet performance that can be expected, as well as the quality aspects of manufacturing process that are required to achieve the desired results.

8. REFERENCES

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