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Production Techniques for the Superconducting Super Collider Low Energy Booster Quadrupole Magnet

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DISCLAIMER

Production Techniques for the Superconducting Super Collider Low Energy Booster Quadrupole Magnet*

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Abstract—**The manufacturing techniques used for a prototype quadrupole magnet, developed at Lawrence Berkeley Laboratory (LBL) for the Superconducting Super Collider (SSC) Low Energy Booster (LEB), are described. The SSC LEB Ring employs 96 dipoles and 90 quadrupoles connected in series to form the magnetic lattice, requiring the use of a 21.9 mm × 23.0 mm hollow conductor for the quadrupoles. Due to the large conductor size and small bend radii required, development of special fixtures was necessary. A unique coil-forming method with close attention paid to tooling design and special assembly procedures was required to manufacture this prototype to stringent specifications.**

INTRODUCTION

The SSC is a complex of proton accelerators presently under development by the Department of Energy and the Superconducting Super Collider Laboratory (SSCL) in Ellis County, Texas. The cascade of accelerators includes a series of linear accelerators, a low energy booster, a medium energy booster, a high energy booster, and the collider ring. The LEB itself is 570 m in circumference and its lattice will consist of 96 dipoles and 90 quadrupoles. The SSC culminates in two counter-rotating pulsed beams of protons with energies up to 20 TeV. When completed, the SSC will be the largest scientific instrument ever constructed.

QUADRUPOLE PARAMETERS

Quadrupole design parameters include an aperture of 100 mm and a field strength of 14.9 T/m. Individual quadrupoles will vary in length between 0.57 and 0.71 meters. Both dipoles and quadrupoles are connected in series to a single power supply operating at 10 Hz, with a peak current of 3745 amperes. The magnets utilize laminated cores with water-cooled, hollow, copper-conductor coils. The four coils of each quadrupole are connected in series, both electrically and hydraulically, and the four quadrants are mechanically joined together to form the complete magnet, as shown in Fig. 1.

CONSTRUCTION APPROACH

Several requirements made the fabrication of these coils especially challenging: very short radii bends in a heavy conductor, little or no distance along the conductor between corner bends and layer-to-layer transition bends, and limited space between pole tips for the coils. For example, the inner turn of the 21.9 mm × 23.0 mm conductor required an inside turn radius of 23.0 mm. Each coil had three layers, with a total of only four turns. Initial tests with this conductor quickly demonstrated that there was no conventional coil-winding equipment that could form a bend this tight on this size conductor. These tests also showed that keystoning at the bends would exceed the height available for coil stackup; therefore keystoning was removed.

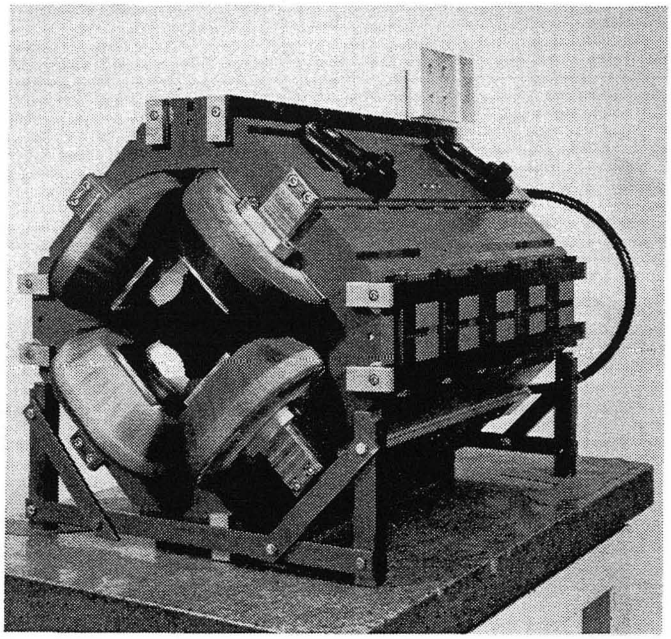

Fig. 1. Quadrupole magnet assembly.

Three unique bending tools were developed to perform inner turn bends, transitions, and outer turns of the coils (see Figs. 1-3). Powered by a hand-operated 5-ton hydraulic ram, each tool formed the desired bend by "wrapping" the conductor over a mandrel machined to the correct corner radius or transition shape. Hardened steel shoes placed between the conductor and the tool's jaw allowed sliding to occur and prevented deformation of the conductor.

COIL FABRICATION

Each of the four coils was wound from a single ten-meter length of straight conductor. Coil winding was divided into six steps: 1) winding the first three turns around an internal

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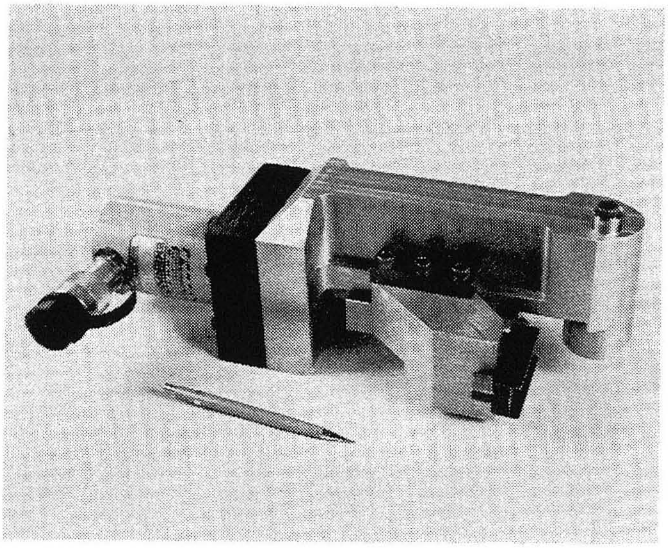

Fig. 2. Inner-turn bending tool.

form using the inner-turn bending tool and the transition bending tool; 2) insulating the three inner turns and the straight conductor left for the last outer turn; 3) winding the fourth outer turn over the top-layer inner turn using the outer-turn bending tool; 4) bus soldering; 5) ground wrapping; and 6) coil potting.

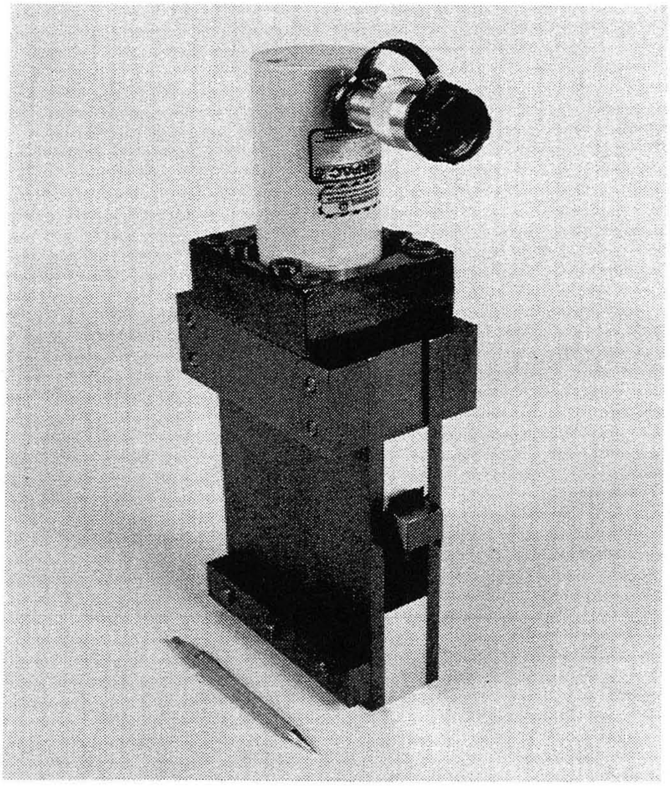

Fig. 3. Transition bending tool.

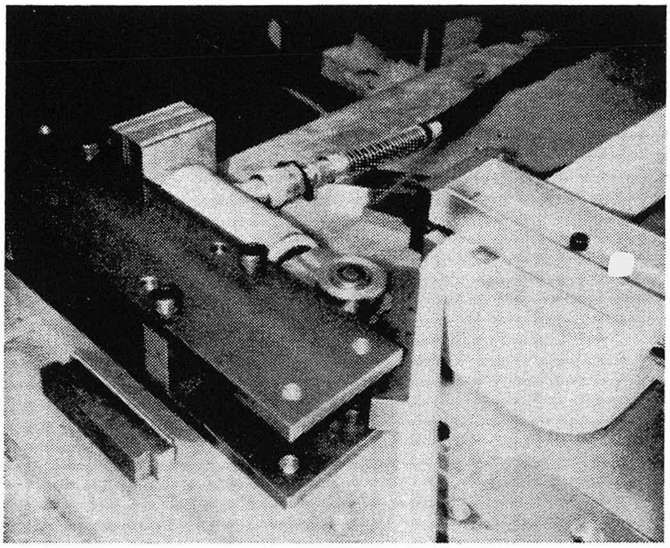

Fig. 4. Outer-turn bending tool.

WINDING — FIRST THREE TURNS

All corner bends were made by placing the inner-turn bending tool over the conductor at a predetermined reference point prior to bending (see Fig. 5). Actuating the hydraulic ram pulled the mandrel into the inside surface of the conductor. The shoes of the bending tool then distributed the reaction forces from the ram along the conductor, reducing distortion and "walking" the conductor and tool around the mandrel, thus forming the bend.

Transition bends were made between the second and third corner bend and between the sixth and seventh corner bend. The transition bending tool, shown in Fig. 6, was turned over for the second transition bend to allow proper nesting of the conductor layers.

In general, keystoning is lessened when the conductor is wound with an axial tension, as with conventional winding

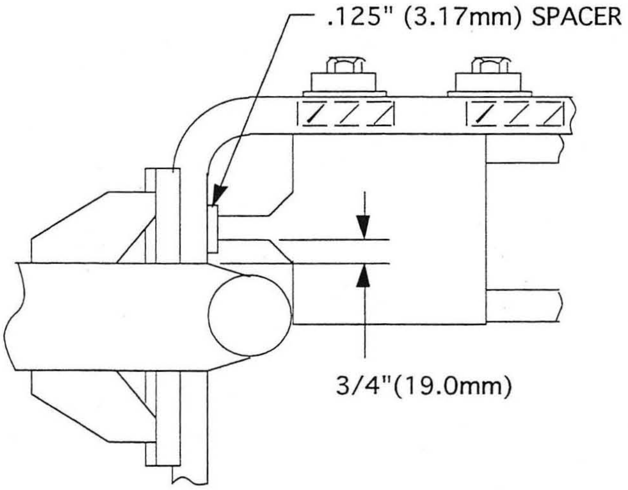

Fig. 5. Typical corner bending set up.

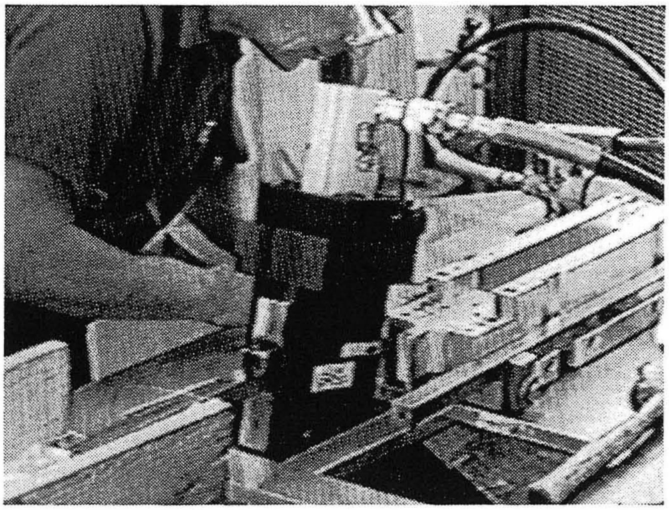

Fig. 6. First transition bend.

machines. In our method of making these bends, there is essentially no axial stress, and significant keystoning occurred. The actual maximum keystone height measured at the inner edge was 25.02 mm. It was necessary to remove all keystoning from the first three layers to meet dimensional requirements. This was done after the coil was removed from the winding fixture by spreading the turns and grinding off the excess material in the bends.

INSULATING

After inspection and removal of any burrs, the conductor was wrapped with 25.4 mm non-adhesive Mylar tape on long sides of the turns, and with 12.7 mm non-adhesive tape around the corners and short lengths. This reduced the bunching on the inside radius of the bends (see Fig. 7). The use of non-adhesive insulation made it possible to weave tape between conductors and allow for easier wrapping. The remaining straight length of conductor was wrapped with 19.1 mm adhesive-backed Mylar tape. A second layer of Dacron insulation was wrapped around the complete length of the conductor prior to making the coil's fourth and final turn.

WINDING — FOURTH TURN

The outer-turn bending tool was used to complete the last three bends. This tool employed a roller and guide plate placed perpendicular to the conductor, as shown in Fig. 8. As the roller moved forward, the bend was formed. The roller and the larger bend radius (46.8 mm) allowed the bend to be made after the conductor had been wrapped, without damaging the insulation. At this point, all dimensions were checked and any further bending or straightening was completed.

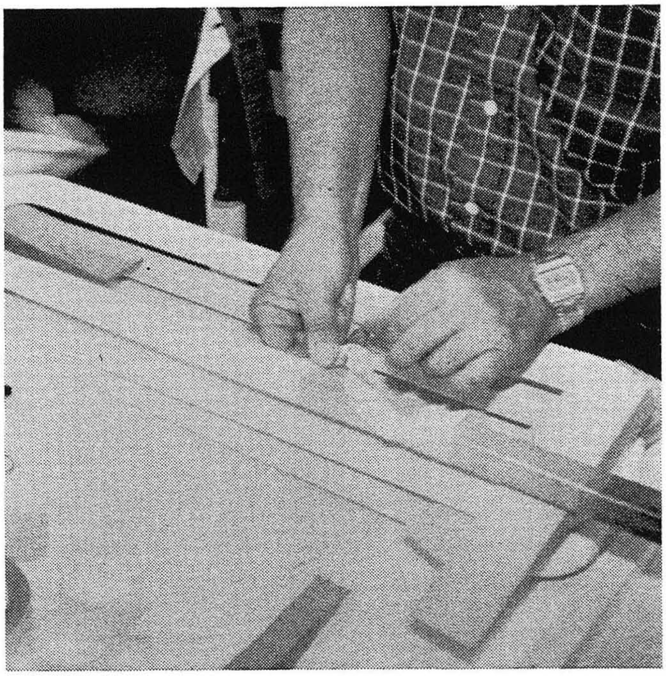

Fig. 7. Insulating coil.

BUS SOLDERING, GROUND WRAPPING AND COIL POTTING

After the coil winding and wrapping was completed, the insulation was wound back enough to allow bus terminals and water fittings to be hard soldered in place. Insulation was added between layers as needed to achieve proper coil height. All voids were filled with bunched fiberglass while wrapping the first layer of ground insulation. Both first and second ground-wrap layers were half lapped. A third, butt-wrapped layer was added to achieve the specified insulation thickness. Coils were placed and aligned in the potting mold (see Fig. 9). The mold assemblies were pre-heated and vacuum potted using conventional methods.

CORE FABRICATION

The four magnet-core quadrants were stacked, without adhesive, from pieces of laser-cut, 0.64-mm-thick AISI M-27

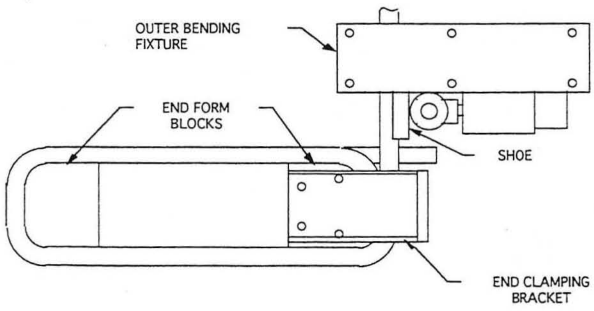

Fig. 8. Outer bending fixture.

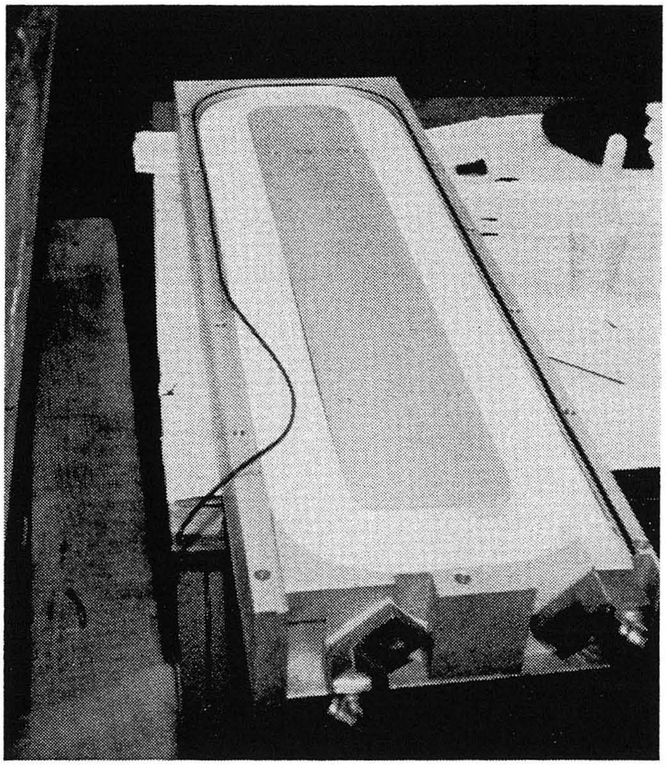

Fig. 9. Coil potting fixture.

steel. These pieces, supplied by SSCL with a C-5 coating, were all flat with no edge burr. The lamination stacking fixture (see Fig. 10) aligned the pieces and allowed the stack to be compressed to 7 kg/cm^2 while fusion welds were applied along two edges and a tie bar was welded to the laminations.

A special glued-core "end pack" design was developed for this prototype which allows removal of the core ends without disassembly of the magnet or removal of the coils. This simplified the modification of the pole tip end chamfers between the field measurements. Inner cores were assembled in three sections, consisting of a dry center section and two 23.8 mm glued end caps to stabilize the assembly (see Fig. 11). Laminations were secured by a skip-welded bar centered at the root of each core assembly plus fuse welds along two lamination edges. A 10 mm threaded rod through the pole tip secured the assembly. Coils were fastened to the core quadrants with clamps attached to the end of each core bar. The core quadrants were then clamped together with clamping bars to form the completed magnet.

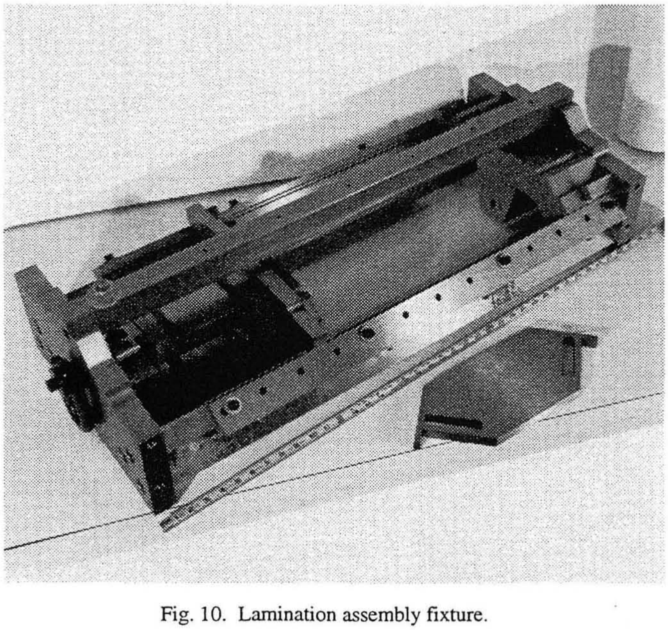

Fig. 10. Lamination assembly fixture.

SUMMARY

This project required a new approach to the process of forming hollow conductor coils for an electromagnet. The resulting techniques proved to be elegant, highly functional, and inexpensive in terms of capital expenditures. The possibility of using this approach to conductor forming in a wide variety of applications is very promising, particularly when large forces and difficult transitions are required.

Elements of such a system are quickly and inexpensively modified for use in future applications. Additionally, the degree of financial risk associated with attempting an experimental procedure is minimal since large, engineered coil winding machines are not required.

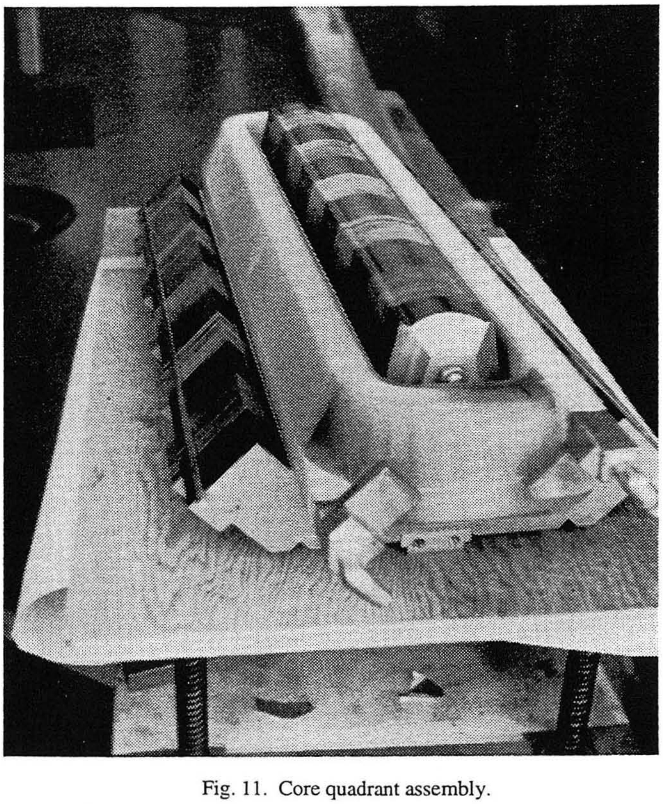

Fig. 11. Core quadrant assembly.