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Fabrication of a Prototype Dipole for the SSC Low Energy Booster

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***Abstract*—The Low Energy Booster of the Superconducting Super Collider (SSC) will be a synchrotron containing 96 dipoles operating between 0.13 T and 1.35 T at 10 Hz. Each dipole's 1.865 m-long core is made from ~2900 steel laminations (lams), each 52×66 cm and 0.635 mm thick. A need to minimize power supply costs and stringent field specifications led to a straight core with very tight mechanical tolerances of the order of 0.05 mm. To satisfy these tolerances, we decided to stack the core in a vertical position; i.e., with the laminations laid horizontally. We designed and built an unusual vertical stacking fixture that pivots into a horizontal position after all the laminations have been stacked and compressed and four support angles welded onto the laminations. The stacking fixture, our experience using it, and conclusions as to the merits of stacking such a long core vertically will be described. The methods of insulating and potting the pancake coils and their installation into the unsplittable core is also described.**

I. INTRODUCTION

The Superconducting Super Collider (SSC) Low Energy Booster (LEB) is a synchrotron that can accelerate bunches of protons from 1.2 GeV/c at injection to 12.0 GeV/c at extraction. The LEB will contain 96 main bending dipoles operating between 0.13 T and 1.35 T in a sinusoidal 10 Hz cycle. All the dipoles and the main quads will run off the same power supply drawing the same current. Both the dipoles and quads were designed by an SSC Lab–Lawrence Berkeley Lab team such that the ratio of the quad-field gradient to the dipole-bending field will remain constant during the acceleration cycle [1]. The dipole was engineered and drawn by Mechanical Engineering (ME) at the SSC. The Stanford Linear Accelerator Center (SLAC) ME and Mechanical Fabrications Departments contracted to design all the necessary tooling fixtures and fabricate a prototype dipole so the design could be thoroughly tested. SLAC personnel started work in April 1992 to design four tooling fixtures: a coil winding form, a coil potting mould, a core stacking fixture, and an end-pack stacking fixture. Magnet fabrication began in December 1992, and the completed magnet was shipped to the SSC in May 1993.

II. MAIN CONSTRUCTION CONSIDERATIONS

The operating mode of an LEB dipole and the beam requirements influenced its engineering and construction techniques. The dipoles run with a continually changing current, ranging from 390 to 3920 amps, so the core must be laminated to minimize eddy currents. All dipoles run off the same power supply (P.S.) and must produce the same integrated strength without any trim coils, so the core length is tightly specified at 1865±0.5 mm (73.43±.020 in).

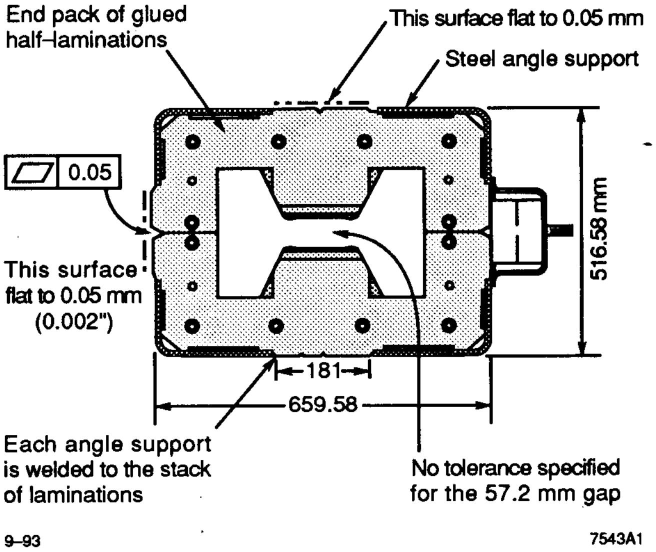

Fig. 1. Drawing of one end of the laminated dipole core.

The field uniformity is prescribed as $(\Delta B)/B < 10^{-4}$ over ±25 mm to keep the multipoles within certain limits, so as to minimize beam emittance growth during acceleration. Therefore, the poletip shape has been carefully crafted to maximize the good-field region [1]. The fabrication process must avoid increasing multipoles through mechanical asymmetries, so it was decided to use one-piece laminations to avoid having a top core half and a bottom core half that could be misaligned. The height of the gap is 57.2 mm to accomodate a particular beampipe. The overall size of the dipole needs to be as compact as possible to reduce the stored energy and P.S. costs; on the other hand, the pole width needs to be 146.32 mm to generate the desired good-field region. Beamline space is restricted, so the coil length and overhang must be minimized.

Fig. 1 is a drawing of the core end showing the mechanical tolerances deemed necessary to prevent fabrication errors from degrading the field uniformity. In the prototype only the end 38.1 mm of the core uses half-lams, whereas the main body of the core uses one-piece lams. Extra prototype half end-packs were made so that different poletip chamfers (used to help shape the fringe field) could be tried. These removable half-packs will be replaced by solid one-piece end-packs in the production magnets. Considering the difficulty of monitoring and measuring the gap as one-piece lams are stacked, especially in the centre of the long core, it was decided to specify some mechanical tolerances on the outside surfaces of the core stack. It is assumed that the lams are manufactured with even tighter tolerances, so that if the outside tolerances are met, then the poletips will be sufficiently flat.

For this prototype magnet, the lams were laser cut; their quality is not as good as die-punched lams [2]. Fully-processed type M-27 electrical steel, 24 gauge (0.635-mm

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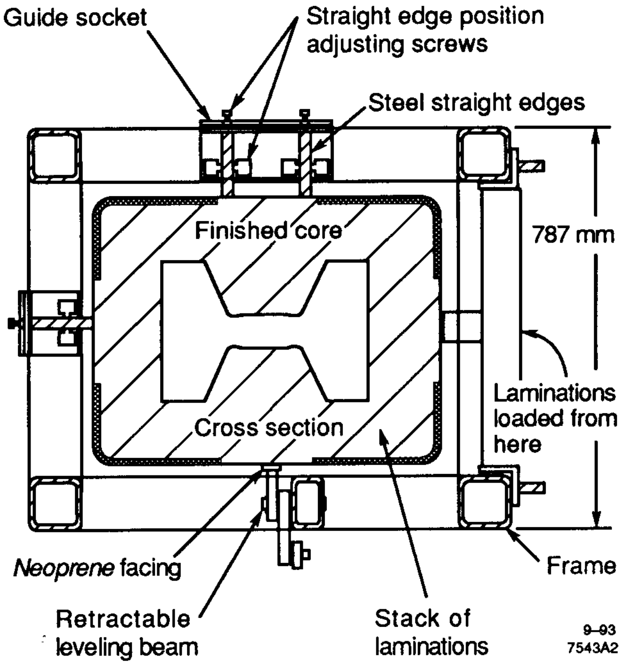

Fig. 2. Cross-section view through the vertical core stacking fixture.

thick), was used to make the lams; each one has a *Carlite*-surface insulation meeting C-5 requirements. They have no burr, which makes them easier to handle and to stack. Production magnets will use die-punched laminations with a maximum burr of 0.05 mm (0.002 in).

III. VERTICAL STACKING FIXTURE

Taking into account the tight flatness tolerances, and for the other reasons/assumptions listed below, it was decided that a vertical stacking fixture should be used to stack the lams:

1. It would be easier to meet the flatness tolerances, the fixture could be less massive than a horizontal one.
2. It would be easy to stack the lams.
3. It would be much easier to weld the angle supports to the stack of lams.
4. The flatness achieved when core was vertical would be maintained when it was horizontal.
5. The height of the stack (=core length) would be the same when vertical or horizontal.
6. It would be easy to measure the height as stacking progressed and calculate the packing factor; by changing the compression pressure one could change the height.
7. The packing factor value, calculated from weight and height, would be consistent thoroughout the stack.
8. The specs on the perpendicularity of the core ends could be met.
9. The tall fixture could be made to withstand a 3 g static horizontal force such as an earthquake might create.

Fig. 2 is a cross-section view through the lower end of the vertical stacking fixture that was designed. Three fixed vertical straight edges determine the location of each lamination and keep it horizontally fixed in place. To achieve flatness tolerances of 0.05 mm (0.002 in), the faces of the cold-rolled steel straight edges that touched the laminations were ground to 0.0127 mm (0.0005 in) flatness along their 1803.4 mm length. The adjusting screws allow the positions of the edges to be moved; they are aligned so their ground faces are coplanar to within 0.025 mm. Mounted on the front of the fixture is a retractable "leveling" beam with a *Neoprene* synthetic rubber facing which is lowered to squeeze against the third side of the laminations when needed.

Fig. 3. Empty vertical core stacking fixture

Fig. 3 shows the author standing next to the 3810 mm (12.5 ft)-tall vertical core stacking fixture, before any laminations have been placed in it. The single straight edge can be seen on the left side of the fixture; the pair of straight edges are mounted on the far side (only one is visible). The laminations will be stacked, laying horizontally, on the bottom platten, which has been ground flat to ±0.025 mm (±0.001 in). The bottom platten has been aligned by a standard transit method to be perpendicular to the straight edges to within 0.025 mm.

IV. CORE STACKING

Each lamination was individually placed in the fixture and was squared up against the three straight edges. Fig. 4 shows 1468 lams under compression of 8.41×10^5 Pa (122 psi) created thus: A 25-ton hydraulic jack is pumped up by a hydraulic hand pump (the apparatus at the very top of the fixture), the plunger of the jack forces down on the black cylindrical-ram extension that pushes on a 19.1 mm-thick steel pressure plate, which has the same profile as a lam. This plate is reinforced, and connects to the ram extension in a way that maintains it levelness. The pressure plate can be lifted or lowered by a motorized system of winch straps and drums. The levelling beam is held tightly against the lams during a compression; this prevents a tendency of the compressed stack to lean away from the straight edges, which we believe was caused by the pressure plate not being completely level. The stack was compressed four times, at 900-, 1468-, 2100-, and 2753-lams high. The flatness of the toleranced surfaces

Fig. 4. The stacking fixture partially filled with laminations under compression.

was measured by pushing feeler gauges between the stack and the straight edges. Lams that stuck out of the stack were pounded back into place with a sledgehammer.

Stacking of the lams in this fixture was convenient, and went quickly—it took about 24 hours to stack 2695 lams. Each time the stack was compressed, its height was measured with a 2133.6 mm (7 ft) vernier in six places and the packing factor was calculated. We were aiming to get at least 97%. When the final desired height and weight were reached, the four A36-steel angle supports were added and held tightly in place by special jigs. The ends of the angles were TIG (tungsten arc in inert atmosphere) welded to the laminations with 75 mm-long welds every 225 mm. The welder skipped about the stack to avoid distorting it; as the access was so easy, the welding took only 6 hours total. We estimate the stacking and welding times on subsequent cores would be about half those of this first prototype. The fully-stacked core and angle supports can be seen in Fig. 5.

The stacking fixture was designed to pivot about the ends of two of its legs, while suspended from a crane that can handle its loaded weight of 4330 kg (9546 lb). The four steel-tubing pillars of the fixture frame have cross-holes near their lower ends, through which 38.1 mm-diameter steel pivot pins pass. The pins also pass through two trunnions bolted into the steel-plated floor. Two of the pins are removed while the crane starts to take the load; then, by means of the arcane skills possessed only by the experts of the rigging profession, and as captured in Fig. 5, the crane is manipulated to simultaneously lift and translate the loaded fixture by rotation about the other two pins until the core rests on the specially designed core lay-down bench, on the right of Fig. 5. This rotation went very smoothly and took about 3 minutes.

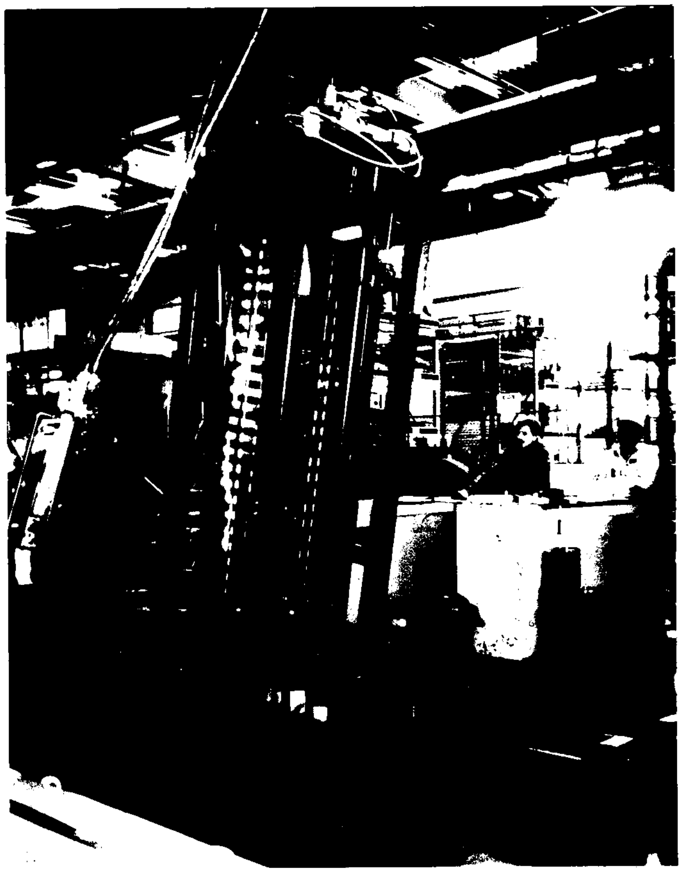

Fig. 5. Fixture and welded core being pivoted into horizontal position.

V. COIL FABRICATION

In order for the LEB dipole strength to track with the LEB quads, eight turns are needed per coil; but, to allow a pancake to pass through the gap in the unsplittable core, 16 turns with a smaller cross-section were chosen—this also facilitates the coil winding. Oxygen-free high-conductivity copper per CDA 102000, bright annealed to a deadsoft temper, was specified. Its cross section was 21 mm×18 mm with a 9 mm-diameter hole. There were to be no joints in a two-layer pancake, so 42 m continuous lengths had to be procured. The half-lap layers of 0.056 mm-thick *Mylar* tape and 0.18 mm-thick *Volan*-treated fibreglass tape were machine wrapped onto the copper *before* it was wound, under tension, around the winding form. Then the groundwrap (two half-lap layers of fibreglass tape) was tightly handwrapped, and the coil was placed in the potting mould and vacuum-impregnated with a four component epoxy.

The magnet core was designed to be as compact as possible; thus the coil pocket dimensions were very close

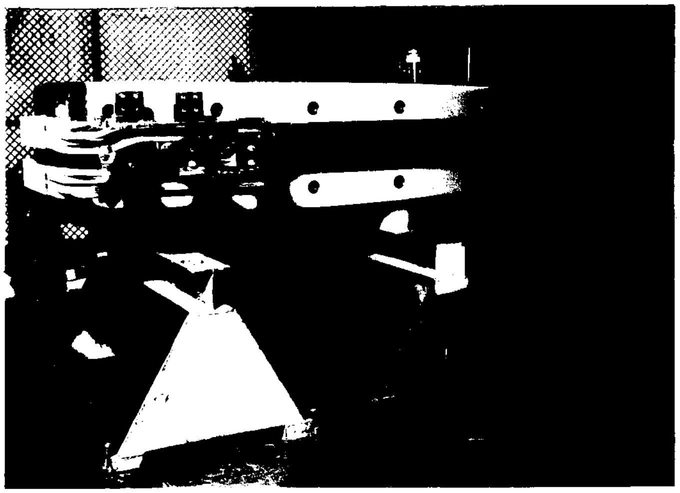

Fig. 6. Completed prototype LEB dipole.

to the potted coil dimensions—only a 1.78 mm gap was left on either side of the coil. This required that the coil mould be precisely machined to ensure the vacuum-impregnated coil would fit through the core gap for installation and would sit in the coil pocket.

The coils were subjected to the standard set of tests before they were installed in the core. The DC high-voltage tests used much higher test voltages (7750 V) than coils at SLAC are usually tested to (1000 V). The reason for this is to protect the coils against the 5000 V dump that is possible from the capacitor banks associated with the single magnet P.S. Consequently, both the turn-to-turn insulation and the coil-to-core insulation had to be exceedingly good—the aim was to have a void-free and crack-free casting. The epoxy resin mix that was identified as being capable of producing such a casting could not be used because it contains a particularly toxic chemical called *Tonox*, the use of which demands special rooms and equipment. Another transparent epoxy was substituted, which suffered some cracks corresponding to the tight spots in the potting mould. The cracks were patched with a paste epoxy, and all the high voltage tests were easily passed.

VI. MAGNET ASSEMBLY

The 38.1 mm (1.5 in)-thick end-packs were made by stacking 59 lams, individually-epoxied (with *E. V. Roberts RF5000*) and compressed for 16 hours with 5.41×10^5 Pa (78.4 psi), then welding the pack in 8 places. Each pack was machined to produce 1 half-pack, and 3 chamfers were machined on the poletip, without any peeling back of the lams. The end-packs are bolted and dowelled to the rest of the core; there is no air gap in their backlegs.

To install a pancake coil into the core, a thick sheet of polypropylene was placed over the pole at one end of the core, and one end of the coil rested on that, while most of its 107 kg-weight was taken up by a crane. The coil was then pushed into the gap, sliding with the polypropylene along the pole until it was lined up with the coil pocket. It was then either lowered down into the bottom coil pocket or squeezed up into the top coil pocket. Both pockets had been lined with 0.15 mm-thick *Dacron-Mylar-Dacron* insulator sheets.

Two potted pancakes form each 16 turn coil. Their leads are connected through three solid-copper buses so that the incoming current is split into two parallel pancakes, one in the top and one in the bottom coil. This circuit is connected in series to the remaining pair of pancakes. The coil leads are TIG welded with ***sil-fos*** braze to the buses. Each pancake is an independent cooling circuit protected by a thermal switch. The coils are kept in place by 4 G10 adjustable wedges driven between them. The completed magnet is shown in Fig. 6.

VII. CONCLUSIONS

Following are our conclusions regarding the use of a vertical stacking fixture:

1. ***Easier to meet the flatness tolerances:*** we did not meet the two flatness tolerances; most of each datum surfaces was flatter than .1 mm (0.004 in)—there was a 254 mm-long section that varied up to −0.23 mm.
2. ***Easy to stack the lams:*** yes, it was.
3. ***Easier to weld the angle supports:*** yes, very good access to the welded areas. A horizontally stacked core would have to have been rolled over, possibly disturbing the positions of the lams.
4. ***Flatness achieved when core was vertical same when it was horizontal:*** yes, hardly any change.
5. ***The core length the same when vertical or horizontal:*** no, this was not the case. The length was up to 1.35 mm longer when it was laid flat. This difference, caused by the weight of lams when vertical, would have to be taken into account to achieve the length tolerance of ±0.5 mm.
6. ***Easy to measure the height and change it by varying compression load:*** yes, to both. The heights on the sides touching the straight edges were about 1.5 mm taller than the other two sides.
7. ***Packing factor value would be consistent thoroughout the stack:*** it was, at 97.8%.
8. ***Specs on the perpendicularity of the core ends could be met:*** yes, they were.
9. ***Fixture could be made to withstand a 3 g static horizontal force:*** assumption not tested—no large earthquakes occurred while fixture was in use!

We believe the lessons learned on this prototype core will yield satisfied tolerances on future cores. Whether or not these tolerances are necessary will be revealed by magnetic measurements starting in September 1993.

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