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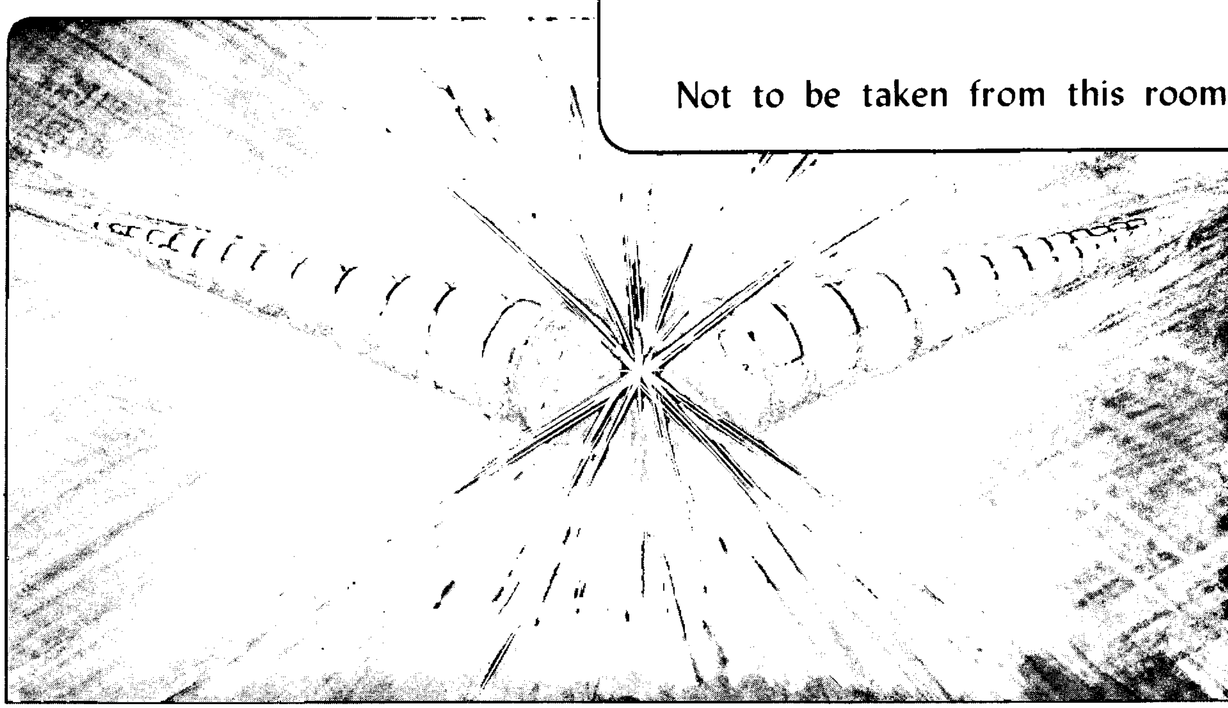

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Design and Fabrication of End Spacers for a 13 T Nb3Sn Dipole Magnet

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***Abstract*—A 13 Tesla R&D dipole magnet is currently being constructed using Nb3Sn superconducting cable. The four-layer "cosine-theta" magnet uses a wide cable (~15 mm) that will undergo a 650 C reaction after each layer is wound. About 75 bronze spacers at the magnet "ends" separate the winding blocks in such a way that the stored strain energy in the cable is minimized and the integrated field harmonics are reduced. Wax prototypes of the designed spacers were made on a 5-axis milling machine. This method of rapid prototyping required no tooling and enabled us to produce a large number of different end spacers that can be physically inspected and repeatedly modified before final prototypes are made. Spacers were originally machined from wax billets which were later cast in bronze.**

I. Introduction

The superconducting magnet D20 (50 mm bore, 1-m long) is intended for R&D of high field magnets made of Nb3Sn superconductor that are expected to reach a short sample field limit of 13 Tesla [1] A wind and react technique followed by epoxy impregnation of the fiberglass insulated coils was used. In order to be able to withstand a reaction temperature of 650 C, all spacers within the coils were made of bronze and shaped to fit precisely between conductor blocks. The four nested layers of the "cosine-theta" magnet will be assembled with a stainless steel collar and placed inside an iron yoke. A final outer stainless steel shell placed around the yoke will provide the final coil prestress. Two wide rectangular superconducting cable (1.58 mm and 1.12 mm) with 37 and 47 strands were tested and selected for layers 1,2 and 3,4 respectively. Within each layer several wedges have been placed to maintain field quality up to 13 Tesla (Fig. 1). With the large number of wedges (9 per quadrant) there will be a large number of end spacers used to produce a current distribution that will limit maximum field at the conductor, and minimize both unwanted harmonics and the possibility of electrical shorts.

II. Analysis

Conductor placement around the end of multipole magnets varies from an empirical approach [2], [3] to a purely mathematical one [4], [5]. Such a wide spectrum of solutions reflects the difficulties associated with conductor bending the "hard way" over the pole. Since stress analysis is usually not used, crude empirical cable dimensions in combination with a mathematical model are used to try and predict the shape and location of the first and last turn in each conductor block. Placement errors (including large accumulative errors) can cause the process to be highly iterative requiring close inspection, QA and additional "hand work" before all coils and spacers reach acceptable dimensions.

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Magnet D20 required bronze spacers to withstand a high reaction temperature. Additionally, spacers needed to accommodate a wide cable. Due to the large number of spacers required for the magnet, we have imposed two guidelines.

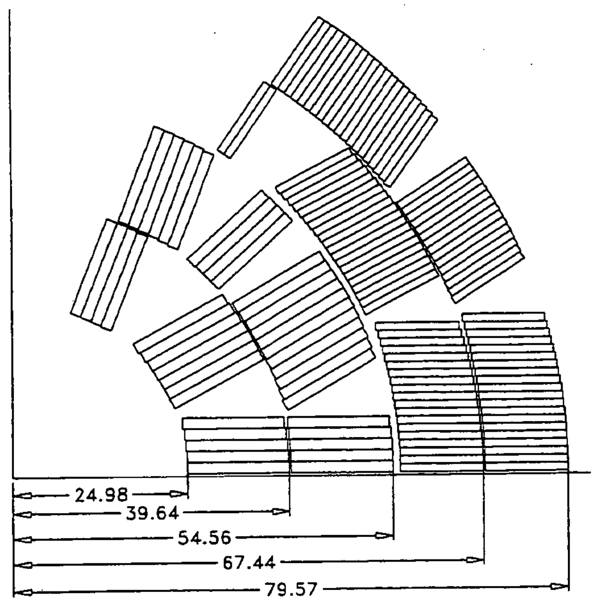

Fig. 1. Cross section view of dipole D20 - a 13 Tesla Nb3Sn magnet.

A) There will be no "shelves" underneath conductor blocks (i.e., conductor edge rests on the mandril); therefore, a conductor will be placed as close to a vertical position as possible without introducing kinks, reversals or loose strands. Any possible radial gaps will subsequently be filled with fiberglass insulation.

B) Conductor blocks and spacers will be designed by computer programs with a minimal use of CAD. A built-in process that will interface between conductor placements, magnetic design and CAD will enable CAD to be used primarily as a visual aid tool.

The end design was developed from an existing, optimized 2D cross-section. Each conductor block, handled separately, was extended from its current axial position toward the pole tip. A single guiding strip [6] was optimized to mark the path for each conductor block while maintaining a smooth cable path with a low average strain energy and torsion. A file that included conductor blocks of all four layers was used by the program "FIGEND" in a 3D harmonic analysis. The contribution from a high permeability axially symmetric iron yoke was also included. To minimize several sets of harmonics, the curved part of each coil block was left unchanged but the length of its straight section was allowed to vary. Although the coil cross-section was extended beyond the physical length of the iron, we considered the physical length of iron to be the same as its magnetic length, Lm=Lp=534.7 mm, and the physical length of the end, to be the length from the end of iron to the tip of layer 4 which is the one most extended (Fig. 2). The magnetic length of the end was calculated to be 150 mm.

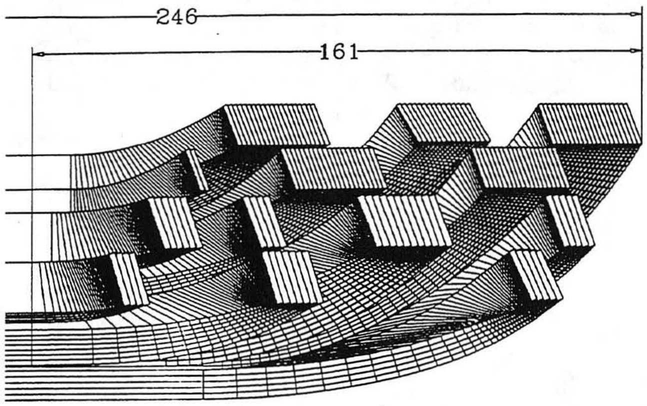

Fig. 2. Side view of end coils.

III. SPACERS

Once the size and position of all current blocks were determined, the surfaces adjacent to each block were made available as output from the program "BEND" (Fig. 3). Each surface was marked by two sets of x,y,z points along their inner and outer edges, with the area in between being determined by connecting lines ("rulings") between corresponding points. Since the spacing between rulings is small, there seems to be a sufficient set of suitable points for manufacturing the parts on a Numerical Controlled (NC) machine (no additional points are required). The data was transformed into vectors with their origin placed on the intersect between the rulings and the inner cylindrical surface of each layer pointing in the direction of the ruling. Files containing vectors of both inner and outer surfaces were e-mailed to the machine shop and processed on an EXCEL spread sheet before final submission to the 5 axis NC machine.

Rapid Prototyping

Spacers were made without specialized tooling. A solid cylinder made from Lucite or machinable wax with an outer diameter identical to that of the required layer was placed into the 5-axis chuck. With the cutting head rotating at a fixed vertical position the machine was capable of moving the cylinder along the horizontal xy plane and rotating it with respect to both the cylinder axis and the cylinder base. With the cylinder held fixed in the horizontal direction the cutter was initially oriented perpendicular to its axis with its tip extending below the required inner radius for the layer. A single pass in one direction was made to produce the inner surface and a single pass in the reverse direction was needed to complete the outer surface, with the spacer body remaining attached to solid core at all times. Stepping from one spacer to another was done on the same cylinder leaving only a small gap between adjacent spacers. In this way it was possible to fit several spacers on a single block and manufacture all spacers for a single layer from two 200 mm long cylinders.

At this point the gaps between the spacers were filled with epoxy (Shell product Epon 826 with 35-40% polyester micro balloons) and the inner diameter was bored out. Finally the epoxy bond was broken and the spacers removed (Fig. 4). The process was proven to be efficient and a large number of different wax spacers could be manufactured in a fairly short period of time. In most locations spacers were accurate to about 1/8 mm. The possibility of gouging along the inner surface, in those locations where the concentration of rulings was quite high, was minimized by the choice of a small cutter diameter.

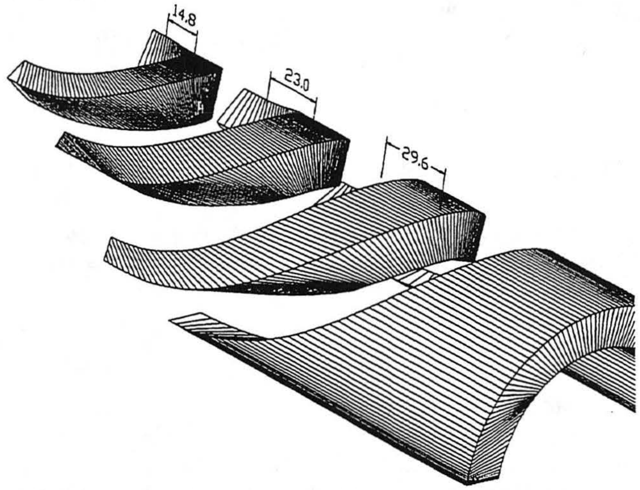

Fig. 3. CAD view of layer 2 return end spacers.

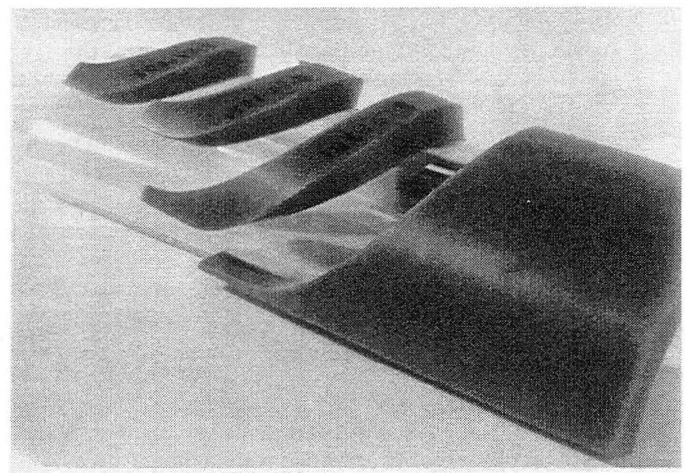

Fig. 4. View of WAX spacers machined by a 5-axis milling machine.

Bronze Casting

Individual wax models of spacers were used in the initial sand casting process, which proved to be imprecise and difficult to monitor. This method was abandoned in favor of a lost wax (investment) casting with a no tin, low iron bronze (C95300).

Better dimensional control as well as a lower per unit casting cost was achieved when several spacers were modeled on a single wax billet. A shrinkage allowance of 1.15% was introduced into all axial dimensions of the wax spacers leaving both the OD and ID of the wax billet intentionally oversized and undersized respectively.

After casting, all gaps between bronze spacers were filled with epoxy and the billet OD and ID machined to their final specified dimensions. Finally the epoxy bond between the spacers was broken and they were cleaned and inspected (Fig. 5). Although the dimensions of the spacers were acceptable, subsequent x-ray inspection revealed a large number of unacceptable voids due to gas pockets and other casting defects. These were attributable in some part to poor workmanship on the part of the caster. The majority of these spacers were unusable, although some were salvaged but needed considerable additional handwork in order to be usable. A final coat of ceramic plasma spray was applied to each spacer to provide extra electrical insulation. These salvaged parts were used in the construction of layers 3 and 4.

Alternative manufacturing options are currently under investigation. We have located a precision foundary willing to accept our specifications. A second option is machining the bronze spacers directly; this is being done on a 5-axis machine at Fermilab. A third alternative is to use a wire cutting EDM machine which has so far proven to be successful in cutting an aluminum spacer sample. Since the EDM machine imposes a limit on its cutting angle the process will require additional steps. A coordinate transformation must be imposed and the manufacture requires two separate passes as well as an operator manual rotation.

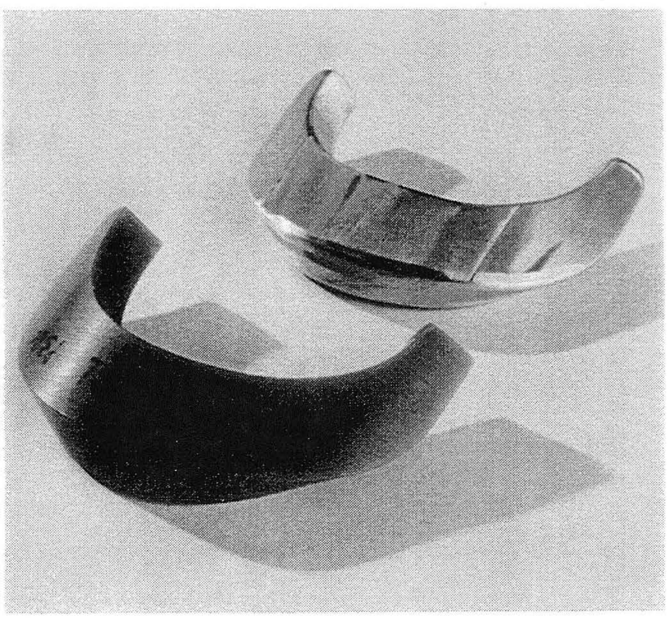

Fig. 5. View of a wax spacer and one casted out of bronze.

Lead End

The design of assymetric spacers for the lead end required special attention. We have made full use of the program BEND–which is capable of handling symmetrical return end parts–by generating a smooth left-right transition before a final rotation was imposed on all coordinates in order to produce a fully assembled lead end. By separating each conductor, including transitional turns, into two left-right non-symmetrical objects, we have generated the guiding strip with the program BEND in such a way that forced them to be continuous at their tip (Fig. 6).

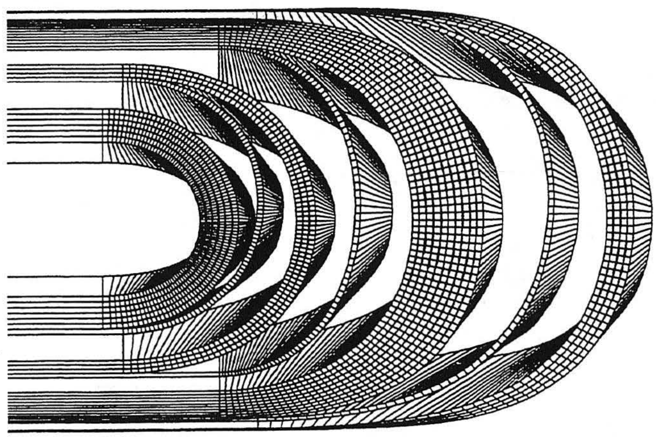

Fig. 6. Top view of lead end layer 2.

In order to insure the dimensional quality of all spacers, special templates were developed by drawing the contours of the spacers edges on a developable surface for both inner and outer diameters of each layer. Film plots of such drawings, with a 1:1 scale were generated with a regular HP plotter. These drawings were used as a visual inspection aide for the contours of the spacers. After inspecting the relative distance between contours of two adjacent spacers against the templates, minor corrections were made to the theoretical cable dimensions of each conductor block.

IV. MAGNETIC FIELDS

The physical length of the magnet end, Lp=246 mm, consists of 85 mm of straight coil and 161 mm of curved coils and spacers (Fig. 2). The magnetic and physical length of the magnet straight section is considered to be the same as and equal to the length of the iron. The iron does not extend over the end and therefore the part of the coil extending beyond the iron has a magnetic length less than its physical length. The magnetic length of the end, 138.4 mm, has been calculated by integrating the dipole field along its axis to a distance of over 200 mm beyond its physical end point (Fig. 7). A similar calculation (without any iron contribution) yielded a length of 162.8 mm. Since calculations were made with a high permeability iron we expect the magnetic length (at high field) to be around 150 mm, which is about 61% of its physical length. This low degree of compaction of the end was designed intentionally to reduce its peak field. The relative spacing between coils, spacers and iron was chosen to best reduce the integrated values of harmonics. Fig. 8 shows the variation of sextupole b2 along the end with similar plots available for higher harmonics. Since the current density of Nb_3Sn is sensitive to strain, and since we expect the area of increased strain to be located in the end regions, we have reduced the field in that part of the magnet by keeping it clear from any possible iron contribution to the field.

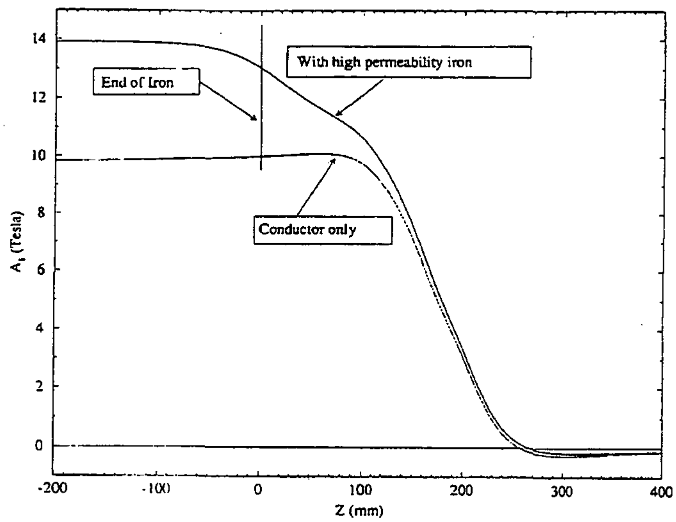

Fig. 7. Dipole field along its end axis (I=6000 A).

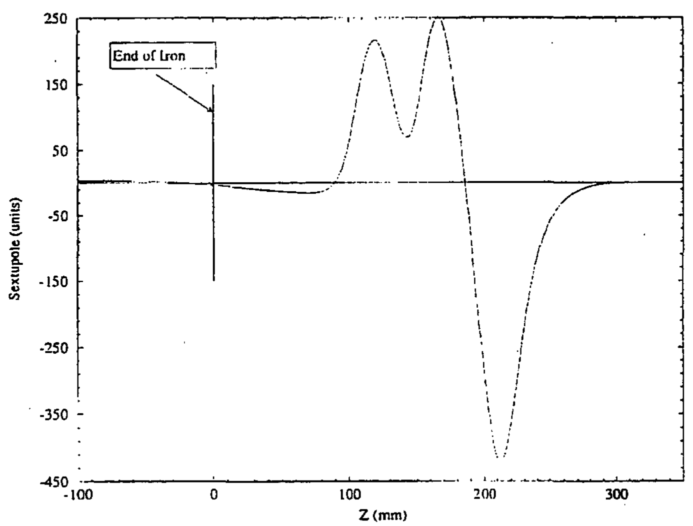

Fig. 8. Sextupole b2 as a function of axial position.

The maximum field at the conductor in the straight section which is located along the pole turn of layer 1 will normally rise as the curved portion of the end is approached (Fig. 9). By terminating the iron in advance of that point, a margin of 3 Tesla between the straight section and the end at low field and 1.2 Tesla at high field is obtained. This will cause the end to have an increased margin of at least 10% with respect to the straight section.

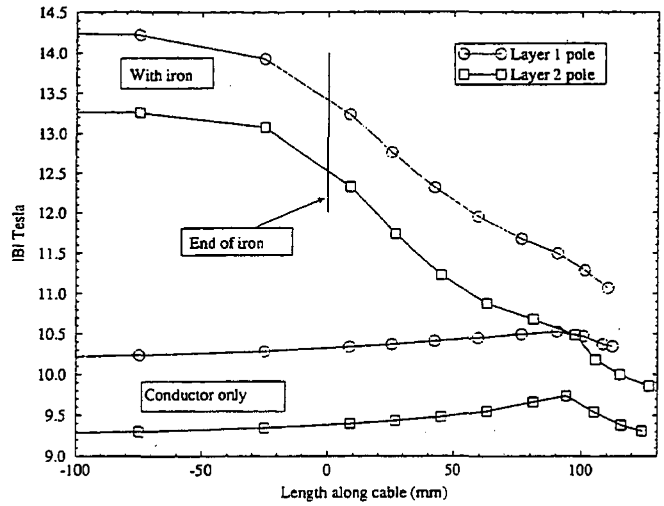

Fig. 9. Field magnitude at the conductor along pole turn of layer 1 and 2.

V. Conclusion

The manufacturing of end spacers and coil design could and should be better integrated. This would facilitate achieving an excellent fit between coils and spacers, and reduce costs and time in the development of future superconducting magnets.

Acknowledgment

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