Design Issues for Coil End Parts for the High Field Dipole at Fermilab

S. Yadav & I. Terechkine

***Abstract*—A one-meter long model of a high field dipole magnet is being fabricated at Fermilab. The design is based on a two-layer, shell-type coil made of Nb_3Sn Rutherford-type cable (with a keystoned shape). The cable is wrapped with a ceramic tape, treated with a binder, and cured to form a strong insulation system. This paper presents specific issues related to the design of end spacers for the Nb_3Sn superconducting magnet coils.**

***Index Terms*—end parts, rapid prototyping, Nb_3Sn dipole magnet**

I. Introduction

As a next logical step on energy frontier after the Large Hadron Collider (LHC), Fermilab is involved in conducting R&D work for a future Very Large Hadron Collider (VLHC) with 100 TeV center-of-mass energy using superconducting magnets in the field range of 11-12 T [1]. One of the main challenges for the feasibility of such a collider is to make technological advances and to find cost reduction strategies to significantly reduce the overall cost of the machine. Since superconducting magnets are the most costly and technically challenging components of a hadron collider, a large effort is being made to optimize magnet design between cost and performance. Since Fermilab has the necessary tooling and expertise gained from building NbTi cosine-theta magnets for the Tevatron and LHC, it is logical to use this existing expertise and tooling for building high field Nb_3Sn magnets in a two-layer cosine-theta structure [2]. It should be noted that a cosine-theta design is the most efficient one in its use of superconductor, iron and steel [3]–materials that add significantly to the overall cost of a superconducting magnet. Another magnet cost driving factor is the fabrication cost of the coil end parts that must provide sufficient support to the conductors at the ends. Alternate magnet designs based on the common coil methodology [4] have been proposed with the presumed potential of significantly reducing the cost of the magnets due to their relatively simple design of two-dimensional end spacers and wedges. However, as discussed later in this paper, recent technological advances in the manufacturing processes have made it possible to fabricate coil end parts for the cosine-theta design at a very economical and competitive price. In this paper, we present some issues related to the design of end parts for the Nb_3Sn superconducting magnet coils and discuss manufacturing technologies to reduce the fabrication costs. Note that the current Fermilab efforts are focused on making a dipole of 43.5 mm bore diameter. Further details of the dipole magnet fabrication and other coil related issues could be found in [5].

II. Coil Design

A. End Parts Inclination Angle

Fig. 1 shows the XY cross-section of the first dipole model. The coil end parts have been designed using program BEND developed by Joe Cook from Fermilab [6]-[7]. Fig. 2 shows the YZ cross-section of the lead and return ends of the Fermilab dipole model. The *inclination angle* (from vertical) of the conductor in the YZ plane is a parameter that can be varied within program BEND. Note that the inclination angle

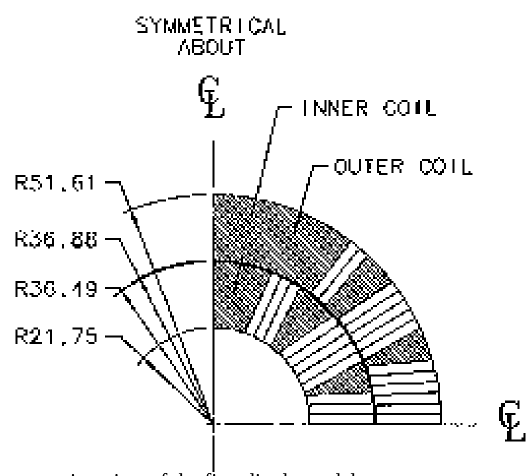

Fig. 1. Cross-section view of the first dipole model magnet.

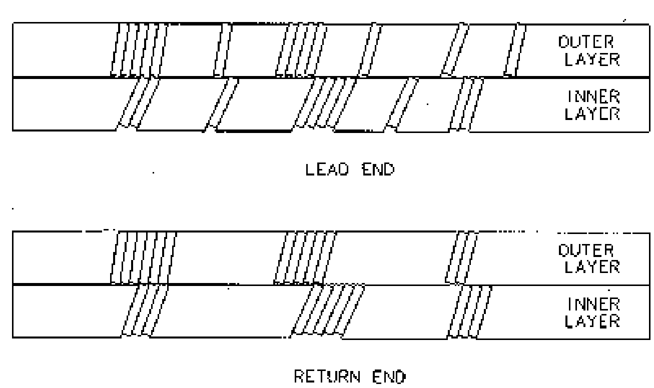

Fig. 2. Lead end and return end cross-sections.

obtained from program BEND is based upon a rectifying developable surface (that is twisted by a small angle to match the inclination angle of the conductor in the straight section), and represents a configuration of minimum strain energy within the given geometrical constraints. Generally, the inclination angle obtained from program BEND increases for the conductor groups that are closer to the mid-plane. Large inclination angles result in gaps that appear on the inside (or outside) radius. This happens because the cables are positioned at an angle and no longer require as much radial clearance as they would if they were stacked vertically. This problem has been tackled in the past by having a *shelf* as an integral part of an end spacer (Fig. 3) attached to the inside radius and thus filling the empty space. These parts are machined by a 5-axis milling machine using a ball-end milling cutter. The use of *shelves*, although useful, increases the cost of end parts fabrication. As part of the VLHC program efforts to bring down the overall cost of such a machine, efforts are underway to explore different manufacturing technologies to reduce the cost of end parts fabrication. Therefore, we are investigating EDM, waterjet machining, and rapid prototyping techniques as an alternative to the conventional 5-axis milling operation. Since *shelves* can not be fabricated using EDM or waterjet machining, inclination angles were used that were smaller than that suggested by program BEND based on strain-energy minimization concepts. Smaller inclination angles help to avoid large gaps at the top or bottom of the conductor groups that are filled with epoxy during coil impregnation. Note that having relatively large volumes of unsupported epoxy can result in cracks at cryogenic temperatures leading to possible quenches at the magnet ends.

A study was conducted at Fermilab to investigate the effect of changing the *inclination* angle of the conductor groups. Two practice coils were wound. The first practice coil was wound using aluminum bronze end parts that were fabricated using the wire EDM technology. In an effort to reduce the cost of R&D coils, the second practice coil was wound using parts made of copper-duraform using the selective laser sintering (SLS) technology. SLS is a rapid prototyping technique that uses powder to make prototype parts. The powder is melted, layer by layer, by a computer-directed heat laser. Additional powder is deposited on top of each solidified layer and again sintered. Fig. 4 shows photographs of the inner and outer layer coil end parts made using this

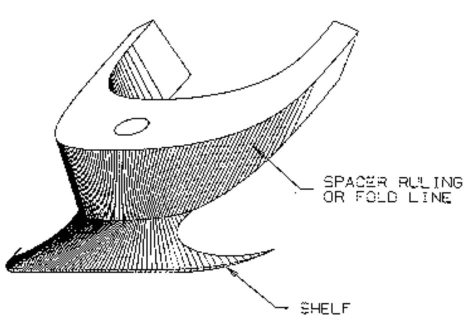

Fig. 3. An end-spacer with a shelf as an integral part.

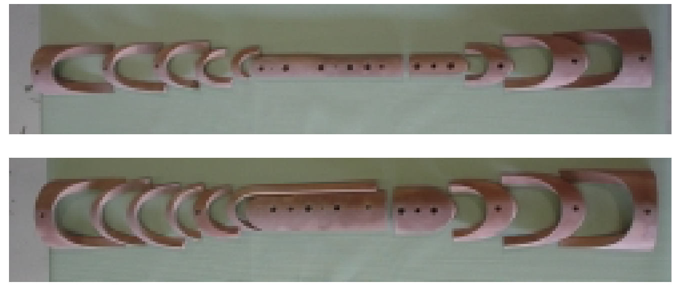

Fig. 4. Photographs of the inner and outer layer coil end parts fabricated using the selective laser sintering technology.

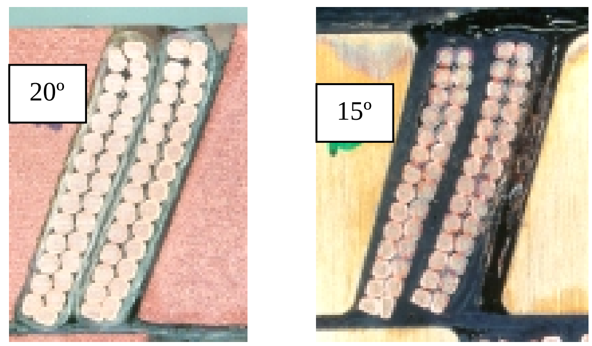

Fig. 5. Return end, outer layer, two-conductor group. Inclination angle of 20° for the SLS part and 15° for the EDM part were used, as opposed to the angle of 28.9° suggested by program BEND.

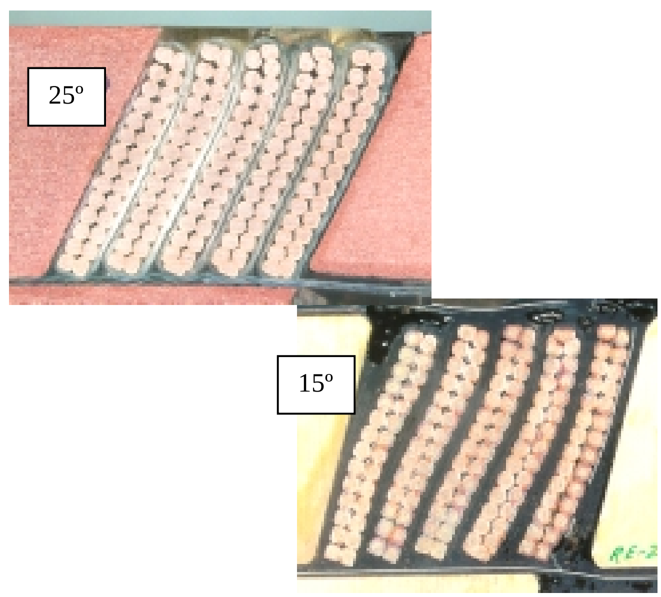

Fig. 6. Return end, outer layer, five-conductor group. Inclination angle of 25° for the SLS part and 15° for the EDM part were used, as opposed to the angle of 36.3° suggested by program BEND.

process for the second practice coil winding.

Figures 5 to 7 show the effect of changing the *inclination* angles from those values suggested by program BEND based on minimization of strain energy within the given constraints. It is observed that if the inclination angle is made too small (to avoid using shelves), then the conductor positioning at the ends is not good and that the conductors tend to take a

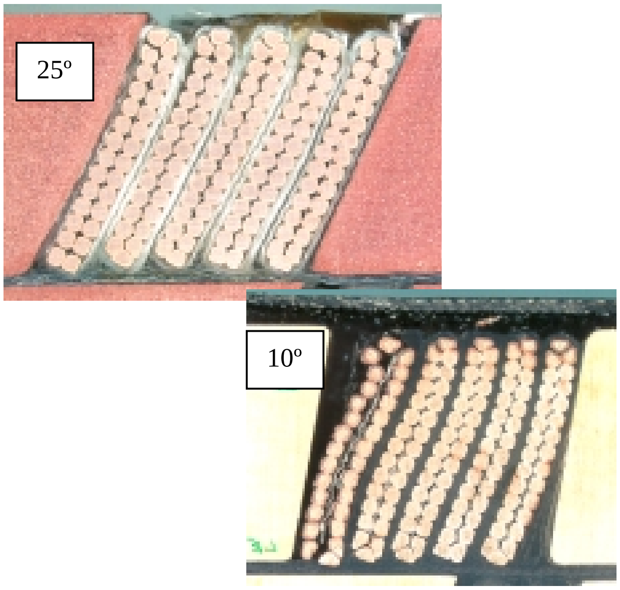

Fig. 7. Lead end, outer layer, five-conductor group. Inclination angle of 25° for the SLS part and 10° for the EDM part were used, as opposed to the angle of 43.2° suggested by program BEND.

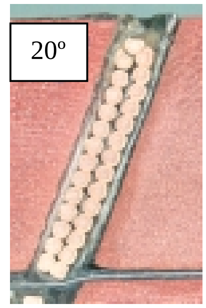

Fig. 9. Lead end, outer layer, one-conductor group. Inclination angle of 20° was used, as opposed to the angles of 37.4° suggested by program BEND. Inside radial movement of the conductor is observed for this group.

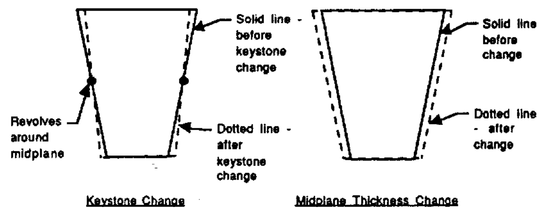

Fig. 10. Schematic representation of de-keystoning and increase in cable mid-thickness during winding around the magnet end parts.

position with a larger inclination angle to minimize their strain energy. However, sections from the second practice coil made using SLS end parts show that some deviation from the angle suggested by program BEND could be used with still good positioning of the conductors in the end. Note that some upper edge swirl of the conductors is observed, a phenomenon that is more prominent for the first practice coil that had larger deviations of the inclination angle from that suggested by program BEND. This upper edge (and for some cases lower edge) swirl of the conductors is due to their tendency to relieve internal stresses that arise in them due to deviations from the surface of minimum strain energy based on the concept of a developable surface. We plan to further investigate this issue and develop a mechanics-based understanding using finite element techniques.

Another reason for using shelves in the past was to provide internal support for the conductors to avoid the tendency of the turns to move into the bore after curing. This was observed for some of the early SSC magnets built at Fermilab, where some of the end turns had protruded into the bore after curing. For the present case, it is instructive to note that when the conductors are well supported at the inside surface (for example, during the winding of the inside layer when the support is provided by the winding mandrel), no inside movement of the conductors into the bore is observed (Fig. 8). However, as seen from Fig. 2, some of the outer layer turns lie on top of the inner layer turns at the end. For some of these turns there was no sufficient radial support at the inside surface of the conductors, and a small radially inward movement of the conductor was observed for such cases (Fig. 9). This problem can be avoided by filling the void space on top of the inside layer conductor groups using filler materials such as glass fibers or a ceramic based putty.

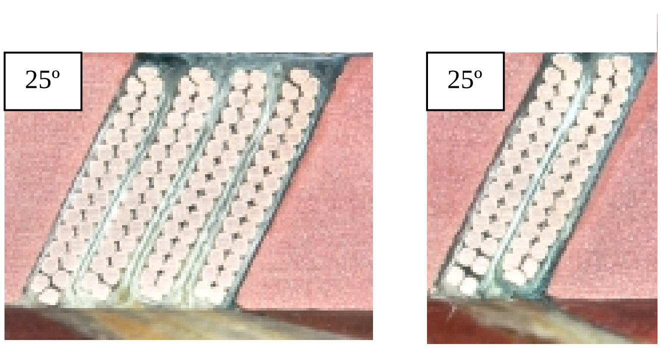

Fig. 8. Lead end, inner layer, four-conductor and two conductor groups. Inclination angle of 25° for both parts was used, as opposed to the angles of 33.5° and 41.2° respectively suggested by program BEND. No inside movement of the conductors into the bore is observed for these groups.

B. Cable Shape Change

As the cable is formed around the end spacers during magnet coil winding, dekeystoning of the cable is observed along with an accompanying increase in the cable mid-thickness (Fig. 10). A-priori quantitative knowledge of this cable shape change is necessary for designing end spacers that are able to ensure a proper conductor placement at magnet ends without significant gaps. At present, there is a good understanding of the cable shape change parameters for the widely used NbTi cable with kapton insulation. However, such an understanding is lacking for the Nb_3Sn cable wrapped with advanced high temperature insulation materials. This lack of knowledge of the cable shape change parameters along with the necessity to optimize the inclination angles makes the design of end spacers to be an iterative process. The SLS technique described earlier helps in reducing the design optimization time. The advantage of this technology is that the parts can be made at a very economical price and in a very short time, using solid models of the parts created in a solid modeling program such as SDRC's I-DEAS. We have further developed a program file in I-DEAS that can read output data from program BEND and generate solid models of all the end parts automatically. This data is then communicated to the vendor electronically to get the parts fabricated in less than a week's time and at a cost fifteen to twenty times less than the cost of the conventional 5-axis milling.

C. Manufacturing Technologies

Beside selective laser sintering (SLS) and electric discharge machining (EDM) that have been used to fabricate coil end parts for the practice coil windings, we are looking into alternative manufacturing technologies to bring down the fabrication costs. A technology that looks very promising is 5-axis waterjet machining. We have fabricated and inspected a few sample end spacers machined using waterjet with satisfactory results. The sample end spacers were fabricated from both metal and ceramic materials. The waterjet nozzle used for this application had an inside diameter of 1.07 mm (.042") and used water at a pressure of 378 MPa (55,000 psi), mixed with a garnet abrasive. The next step is to fabricate all the end parts for a coil using this technology and we would report the results in future publications. Note that the waterjet machining has a significant advantage of reducing both the cost and time of end parts fabrication. It also offers us the opportunity to use different materials such as ceramics for end parts fabrication. We believe that this technology could bring down the cost of end parts fabrication to one-fourth of the present cost obtained using 5-axis milling.

III. CONCLUSIONS

To enable the use of cost saving technologies such as waterjet machining, we have investigated the influence of conductor inclination angle at the ends. We have shown that smaller inclination angles at the ends can be used to avoid the necessity of using shelves. Also, since the design of end spacers is an iterative process, we have used technologies such as selective laser sintering (SLS) for end parts fabrication (for R&D coil windings) to reduce both the fabrication cost and time. We are confident that with these enabling technologies, the cost of end parts fabrication would be a small fraction of the overall cost of the Nb_3Sn superconducting magnet. To increase the reliability of electrical insulation at magnet ends, efforts have started to investigate the feasibility of using ceramic materials for end parts fabrication.

ACKNOWLEDGMENT

S.Y. would like to thank Rodger Bossert, Jeff Brandt, and Joe Cook of Fermilab for several helpful discussions on the design of end parts and on program BEND. We would also like to acknowledge the great efforts of the above mentioned personnel in organizing Fermilab Bend Workshop in May 1999. Thanks are also due to Jay Hoffman for taking the photographs of the end cross-sections of the practice coils.

REFERENCES

[1] G. Ambrosio, et al., "Conceptual design of the Fermilab Nb_3Sn high field dipole model," Proceedings of the *1999 Particle Accelerator Conference*, pp. 174-176, New York, 1999.

[2] N. Andreev, et al., "Development of the 11 T Nb_3Sn dipole model at Fermilab," *IEEE Trans. on Appl Superconductivity,* vol. 10, pp. 298-301, March 2000.

[3] A. V. Zlobin and V. V. Kashikhin, "Magnetic designs of Fermilab 2-in-1 Nb_3Sn dipole magnets for VLHC," *IEEE Trans. on Appl Superconductivity,* submitted for publication.

[4] R. Gupta, et al., "A high field magnet design for a future hadron collider," *IEEE Trans. on Appl Superconductivity,* vol. 9, pp. 701-704, June 1999.

[5] N. Andreev, et al., "Fabrication and testing of the Nb_3Sn dipole magnet at Fermilab," *IEEE Trans. on Appl Superconductivity,* submitted for publication.

[6] J. M. Cook, "An application of differential geometry to SSC magnet end winding," Fermilab Technical Division Note TM-1663, 1990.

[7] J. M. Cook, "Strain energy minimization in SSC magnet winding," *IEEE Trans. on Magnetics*, vol. 27, pp. 1976-1980, Mar. 1991.