UCRL - 74119
PREPRINT
Conf-720908--1

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A WINDING TECHNIQUE FOR SUPERCONDUCTING TAPE IN MULTI-AXIS MAGNETS

Arthur R. Harvey

August 30, 1972

This paper was prepared for publication in the Proceedings of the Fourth International Conference on Magnet Technology

A WINDING TECHNIQUE FOR SUPERCONDUCTING TAPE IN MULTI-AXIS MAGNETS*

Arthur R. Harvey
Lawrence Livermore Laboratory, University of California
Livermore, California 94550

Abstract

A superconducting magnet is in use at Lawrence Livermore Laboratory for a plasma confinement experiment. This magnet, weighing 13 tons, is wound in a four-arc configuration with a mean diameter of 1 m, resembling the seam of a baseball. The conductor is copper-stabilized niobium-titanium sustaining a field of 75 kG within the conductor bundle. Magnets of similar configuration with fields approximating 120 kG at the conductor are being contemplated, requiring nonductile superconducting tapes in lieu of the present multifilament conductor. Winding the tapes into complex shapes presents problems heretofore unconfronted. Investigations are now underway. Topics such as conductor lay, types of insulation, conductor splices, and the expected packing fraction are among those discussed.

Introduction

Multi-axis magnets are hardly innovations to magnet technology, nor are strip-wound solenoids. However, strip-wound multi-axis magnets are indeed new, emerging in response to our need for the higher current-carrying capabilities of nonductile superconducting tapes.

Superconducting Baseball II (Fig. 1),[1-3] now being used in a plasma confinement experiment at Lawrence Livermore Laboratory, is a four-arc magnet with four axes. We gained a lot of experience winding this configuration with a conductor of niobium-titanium filaments embedded in a copper matrix, as documented in Ref. 1.

Our major concern in this paper is with the fundamental requirements and properties of strip wound into baseball and similar shapes. We assume enough planar section between the arcs to provide a "transition region."

Winding Surface

A nonductile strip must not reach the fracture strain while being wound. This is a primary requirement. The surfaces on which the strip is wound must therefore be two-dimensional in nature. A planar surface is two-dimensional and so are two curved surfaces (cylindrical and conical):

- Cylindrical surface: one composed of parallel, straight-line elements with varying or constant radii normal to the elements.

- Conical surface: one composed of straight-line elements inclined with respect to each other such that no two line elements cross each other.

These surfaces — planar, cylindrical, and conical — are the only ones on which a strip can be wound without excessive strain.

When strip is wound on a planar surface or on a cylindrical surface with an edge normal to the surface elements, a plane may be passed through the edge configuration. Where a different arrangement is required, a conical or inclined cylindrical surface must be provided.

The four-arc, four-axis magnet at LLL requires four of these rather abrupt changes. We shall refer to these locations henceforth as 90-deg rotational transitions (or more simply, as transitions). All other winding surfaces are cylindrical only or with planar terminations.

Conductor Lay

A 90-deg rotational transition region is shown in Fig. 2. It consists of three layers of stacked strips. If we number the layers from the bottom, layers one and three each contain 24 strips; layer two contains 48 strips. The winding surface for the strip preceding the transition is the left plane. The corresponding winding surface following the transition is the lower horizontal plane.

The inclination of the layers is noteworthy. For example, if the front cross section of the

Fig. 1. Baseball II magnet.

*Work performed under the auspices of the U. S. Atomic Energy Commission.

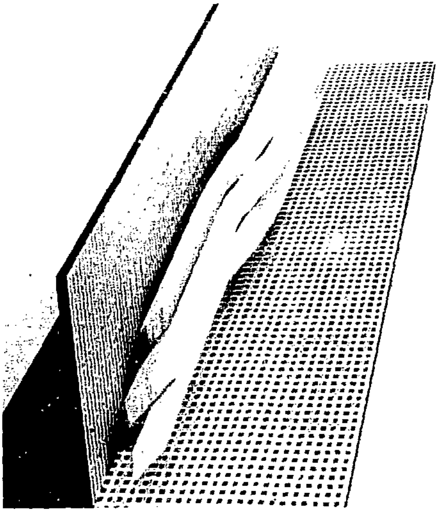

Fig. 2. Transition region.

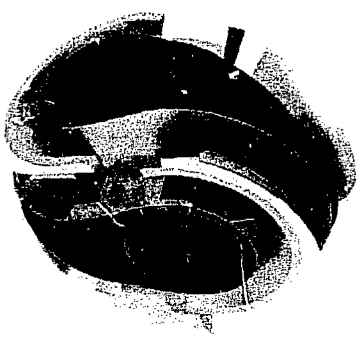

Fig. 3. Partial layer configuration (excluding transitions).

second turn of the third layer is viewed with respect to the first turn of the same layer, we see that it is spaced one thickness to the right of the winding surface. Not so obvious is the continuation of this displacement at the conductor edge in the region following the transition.

A similar observation could be made for the vertical displacement if the transition were viewed from the opposite end. An edge displacement of one thickness up and one thickness over leads one to the obvious conclusion that the layers are inclined at an angle of 45 deg with respect to the winding surfaces.

Because this inclination is at an angle of 45 deg, a plane through the stacked edges leading the transition is parallel to a similar plane through the same edges following the transition. Except for the transition itself, a layer is uniquely defined. Figure 3 depicts the layer arrangement in a baseball configuration in all locations outside the transition region.

Transition

The conventional way to rotate a strip 90 deg is by a simple twist. A model of this is shown in Fig. 4(A), where a rod depicts an axis of rotation through the center of the strip. An edge follows a helical path on a cylinder with a radius of half the strip width. The edge length may be expressed as follows:

$$L_e = [L_T^2 + (\pi W/4)^2]^{1/2}$$

where

L_e = edge length,

L_T = transition length, and

W = strip width.

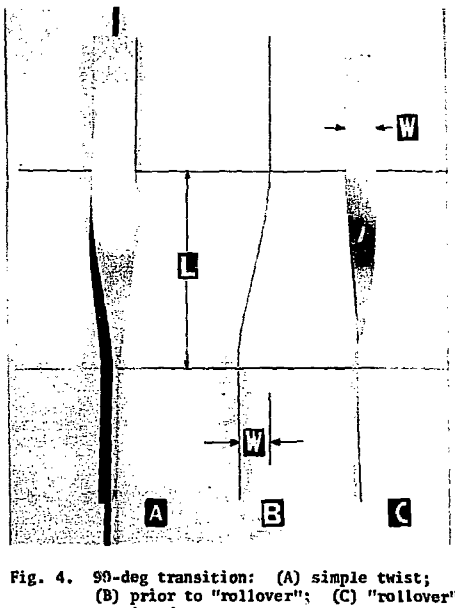

Fig. 4. 90-deg transition: (A) simple twist; (B) prior to "rollover"; (C) "rollover" completed.

Clearly, the edge strain in this case is proportional to $\sqrt{1 + [(\pi/4)(W/L_T)]^2}$, which could be excessive.

Fortunately, we can perform this 90-deg rotation while limiting the strain to one which is proportional only to the thickness of the strip and the length of the transition. If the strip is placed on edge as shown in Fig. 4(B), with one end fixed and the other end rotated about an axis through the bottom edge, we accomplish a transition like that shown in Fig. 4(C). All surface line elements parallel to the edges are of equal length, which of course is the desired property. Using this "rollover" technique, we have produced a 90-deg rotation within a distance of 6 in. — without buckling — in a stainless steel strip 1.5 in. wide by 0.010 in. thick.

Additional properties of a layer may now be defined. Refer to Fig. 5. The parallel planes through the top edge of the strips in a layer (previously defined) are spaced at a distance of $W/\sqrt{2}$, which is the thickness of the layer excluding the transition. At the center of the transition, the strip rotates to a position such that the thickness of the layer at this point is equal to the full strip width. For the sake of volume continuity, the individual strips must separate from each other in this region, as clearly seen in Fig. 6.

This property also gives the individual strips in the transition region an independence allowing them to be placed one directly over the other. (There is no transition drift in a single layer.)

Splices and Junctions

Splices and junctions are relatively simple in strip-wound magnets when compared to the layer junctions of Baseball II. Splices within a layer are straightforward. A simple lap joint may be made much the same as in tape-wound pancake coils. Layer junctions can be made by one or more lapping strips, bridging two layers.

The circuit continuity may not be immediately apparent because of the angular nature of the layers and the need for placing junctions at right angles to each other on alternating sides of a transition. However, it is not difficult to prove that these junctions are basically the same as those in a series-wound pancake solenoid. Of course, all the same circuit options are also available.

Packing Fraction

For multi-axis magnets of uniform cross section, the packing fraction depends on three factors. Two of these influence the current density;[4] the third is a function only of the perimeter and conductor width.

Refer again to Fig. 2. The top edge of the conductors leading the transition are one width higher than the faces of the corresponding conductors following the transition. In like manner, the side edges of the conductors trailing the transition are one conductor-width wider than the faces of the corresponding conductors leading the transition. A series of triangular voids occurs at the top and bottom of the conductor bundle in a section leading the transition, and a similar group occurs at the sides of a section following the transition. The net result, in a cavity whose cross section is $(N \times W) \times (N \times W)$ (N being an integer), is that the conductor and insulation occupy an area of $(N-1)^2W^2$.

Figure 5 shows that the transitions are advancing, with respect to each other, by an increment needed to produce a minimum separation between layers. If this can be achieved, the interturn and interlayer insulation can be selected independent of geometry. The packing fraction which influences current density may then be calculated in a routine manner.

Insulation — Cooling Network

Several insulation schemes were used in the construction of Baseball II, which with modifications could be satisfactorily adapted to strip-wound insulation-cooling networks.

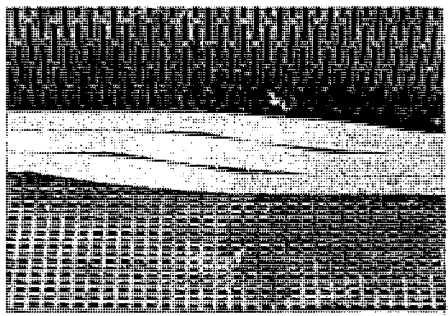

Fig. 5. Layer offset and advancing transitions.

Fig. 6. Strip separation in transition region.

Polyester film (Mylar) and epoxy glass laminate (NEMA G-10 or G-11) withstand high bearing stresses and exhibit good electrical insulation properties at cryogenic temperatures without shattering or cracking. Both are easily punched, sheared, and glued to form an insulation-cooling network. There has been some reluctance to using adhesives for bonding superconductors during winding, for fear that the cooling passages might be blocked. Yet bundle stability apparently would be improved if we were to use carefully metered amounts of a fast setting adhesive such as a cyanoacrylate to bond the turns.

Edge cooling alone is not enough for superconducting strip-wound magnets; allowance must be made, in the interturn insulation, for face cooling. Probably this can be accomplished best by bonding parallel strips of polyester film to a face of the conductor. Interlayer insulation may be slotted, grooved, or latticed; epoxy-glass laminate is an excellent choice here. Slotted and latticed insulation is shown in Figs. 2 and 5.

Winding Techniques

Adequate tension is a critical factor in winding any strip-wound magnet. Inadequate tension leaves voids which are not apparent until many turns later, when pressures on the first windings become sufficient to cause slippage and wrinkles of these turns. On the other hand, too much tension tends to cause lengthening of the transitions and, in multi-axis magnets, lateral slippage of the turns.

Our experience in winding Baseball II has shown that we need plenty of clamping and blocking during winding, carefully located. Clamps slow the winding process considerably, so every effort to make the clamps quick-acting pays off multifold. Bonding of the turns would greatly improve the winding speed as well as the bundle stability.

One encounters a problem of interference with this type of strip-wound magnet not normally experienced with more conventional conductors. Usually, layer two would be the first to be wound (see Fig. 2). Layers one and three then have to be positioned laterally on one side or the other of the transition, depending on which layer is being wound. To minimize the interference for strip-wound magnets, all layers should be step-wound. Interlayer insulation must be designed with this in mind.

Various voids may be seen in the several figures. These must be filled, of course, with shaped blocks in some cases and tapered strips in others. The voids are repetitive in nature and should be handled routinely by the placement of prefabricated materials.

Summary and Conclusions

Although strip winding on multi-axis surfaces is by no means a simple fabrication problem, it is not as complex as one might suppose. If the surfaces are two-dimensional, the layers, turns, and transitions may be uniquely defined. Layers are inclined with respect to the winding surfaces. Joints and junctions are much the same as in pancake-wound solenoids. Certain modifications in insulation-cooling networks are needed, as well as means to circumvent the winding interferences; however, these problems are by no means insoluble.

We have discussed a particular geometry with respect to strip winding. With a fundamental knowledge of strip behavior, it is not unreasonable to foresee geometry modifications to suit these properties. Perhaps some of them may even be used to advantage in the tailoring of magnet fields.

Acknowledgments

The author wishes to thank H. Harrison, R. Pendley, R. Shook, and D. Schiesser for construction of models and simulations used in this report.

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