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WINDING MANDREL DESIGN FOR THE WIDE CABLE SSC DIPOLE†

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Abstract

The 50 mm coil i.d. SSC dipole magnets use wider cables to give a greater operational margin between quench field and operating field. The cable used for the inner coil has 30 strands of the same size (0.808 mm) instead of 23 and the outer has 36 strands of the same size (0.648 mm) instead of 30 and the cable widths are increased in proportion. Although the coil inner diameter has been increased from 40 mm, the coil ends are noticeably harder to wind. This report describes the computational and experimental effort to design winding mandrels or center posts for the constant-perimeter ends.

Introduction

The changes in the SSC coil i.d. from 40 to 50 mm and in the number of strands from 23 to 30 for the inner cable and from 30 to 36 for the outer resulted in the effort described here to test the new cables for windability and to design new coil winding tooling. As the work progressed, analytically derived developable surfaces became available, but experimental results are the final arbiter of endpost design.

In the sections which follow, we describe the cable, coil and coil winding tooling, definitions of terms and description of processes, the theoretical design, minor modifications to it using CAD software, the experimental work and the final design.

Cable, Coil and Coil-Winding Tooling

Cable

The dimensions and other mechanical properties of the Rutherford-style cable are listed in Table 1. Cable lay direction is determined by the wires in the cable. When viewed lengthwise, a left lay cable has wires spiraling counterclockwise as threads in a left-hand screw. Cable pitch is the longitudinal distance in which a single wire makes one complete revolution around the cable.

Table I. Cable Parameters

Parameter	Inner	Outer
Number of wires in cable	30	36
Mid-thickness, *mm*	1.46	1.17‡
Width, *mm*	12.34	11.71
Keystone angle, *degree*	1.23	1.02
Lay direction	left	left
Lay pitch, *mm*	86	96
State of anneal	unannealed	unannealed

‡This was reduced to 1.16 mm subsequent to the present work.

The stability of the cable against wire "popping" (a single wire rising out of place) or against collapse, in which most of the wires fall out of place (also called "tubing"), is a function of wire diameter, number of wires in the cable, the aspect ratio (or ratio of cable width to mid-thickness), the springiness or hardness of the wire, and the lay pitch. All but the latter were fixed during the present studies. A large aspect ratio cable due to a large number of wires, or a cable with fine wires, is more prone to collapse during winding.

Twisting a cable axially against the lay will cause it to open up or "unlock". Unlocking occurs first on the outer (thick) edge, which is less compressed than the inner edge. A shorter lay pitch makes the cable more resistant to unlocking.

The insulation for the cable consists of two parts. Kapton is applied first with a 50% overlap to form the first two layers. The Kapton is overlayed with an epoxy-impregnated fiberglass tape applied as a nominal butt wrap. All of the coil winding studies began with bare (uninsulated) cable.

Coil

The 2-dimensional cross section of the coils in the straight section of the magnet is determined mainly by magnetic field purity requirements. A complication is that the superconductor cable cannot be rolled to a trapezoidal cross section having a sufficiently large angle to match the cable thickness and coil radius, that is, the cable is "partially keystoned". Insulated copper wedges, required for magnetic field shaping, are over-angled to compensate for the inadequate cable angle. The coil design for the present work is termed W6733. At the beginning of these studies, it became apparent that a shorter inner cable pitch would be desirable to increase cable mechanical stability. When the studies were nearly completed, the new inner cable with shorter pitch became standard. It's width was increased 0.23 mm requiring an altered coil design termed W6733A.

Coil Winding Direction

Winding direction is defined as the direction in which the cable is wound around the centerpost end when looking down on the tooling. Figure 1 shows the first turn of the inner coil being applied at the lead end. Winding direction affects the coil because the spiral cable lay makes it anisotropic in bending. Left lay cable winds best in the clockwise direction, and right lay cable in the counter clockwise direction. The inner coil must be wound in the opposite direction to that of the outer to facilitate making the joint between the coils. The inner coil winding direction is also influenced by the cable lay, but more so by the shape of the centerpost end, since the inner centerpost is much smaller than the outer.

Coil Winding Machine and Tooling

The coil is wound on a precision, cylindrical tool called a "mandrel" to which the centerpost is attached. Coil winding is done with the narrow edge of the trapezoidal cable facing the surface of the mandrel and the wide surface of the cable facing the centerpost. The azimuthal size of the centerpost determines the sharpness of cable bend at the ends. Inner coils, with a mean azimuthal centerpost size of 16.6 mm are more difficult to wind than outers, which use a centerpost 63.5 mm wide.

The coil winder used for the present studies has a movable carriage on which is mounted a spool of cable; the carriage rotates around the entire length of the

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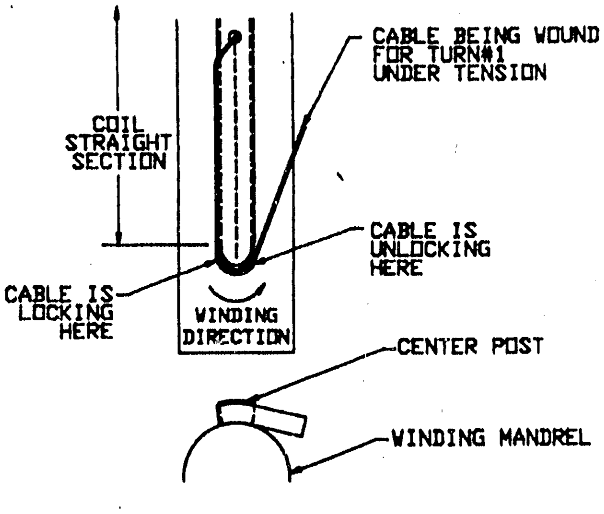

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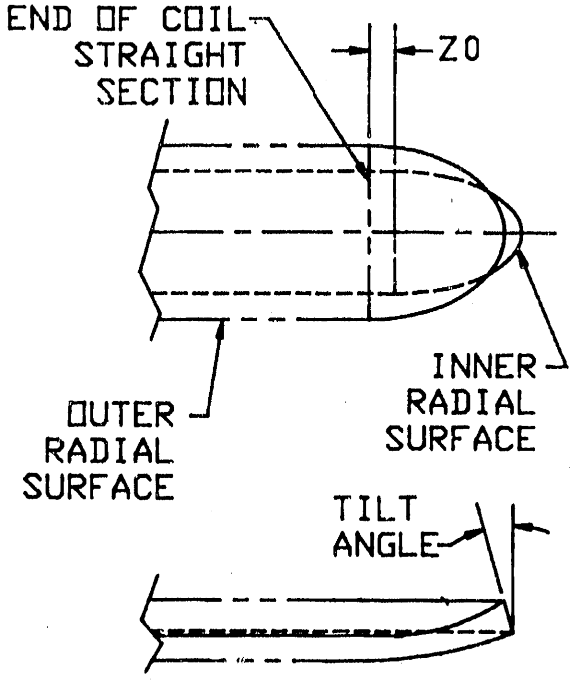

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As the carriage moves around the end of the mandrel, the mandrel is rotated azimuthally under the control of the technician, in such a way as to attempt to make the inner edge of the cable just touch the mandrel throughout the coil end.

Design of Centerpost End Shape

Constant Perimeter End

Approximate the cable by a ribbon of the same width but zero thickness, actually the inner surface of the pole-most turn of the coil. Assume the ribbon can bend in the "easy" direction, perpendicular to the plane of the ribbon, but cannot bend in the "hard" direction, in the plane of the ribbon. Fasten the two ends of the ribbon rigidly in the positions of the turn in the straight-section. The inner edge of the ribbon should lie on the circular cylinder (the "inner edge cylinder") having the same radius as the inner edge of the ribbon in the straight-section, and the same axis as the straight section. The axial extent of the outer edge of the ribbon will be less than that of the inner edge, i.e., where the ribbon crosses over the cylinder (at $\theta = \pi/2$ in circular cylindrical coordinates), it will tilt towards the straight-section. This is because the length of the two edges is the same (the perimeter is constant), but the outer edge is at a larger radius. The amount of tilt, or angle between the ribbon and a normal to the cylinder axis at $\theta = \pi/2$, is an important parameter of the endpost design. Figure 2 shows the tilt in an outer endpost.

A real end turn may be only approximately constant perimeter; because of it's helical structure, the cable can bend rather easily in the hard direction. Our definition of a developable constant perimeter end requires contact of the inner edge with the inner edge cylinder at all points, and allows some bending in the hard direction to accomplish this, but minimizes such bending along the entire length of the ribbon.

The Baseline Design

The mathematical treatment of an end follows, up to a point, a verbal description given by Bossert et al[1]. Space curves lying on the inner and outer edge cylinders define a surface *S*, containing the two curves. The ribbon lies on *S*, but it's edges may not coincide with the two defining curves, termed the "inner cylinder curve" and the "outer cylinder curve." The edges of the ribbon are assumed to be geodesics of the surface, that is, if *S* can be developed into a plane, the edges would be straight lines.

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We assume a form for the inner cylinder curve which satisfies all the constraints on the ribbon. With an arbitrary choice of this curve, even one which satisfies the constant perimeter condition, *S* is unlikely to be developable, so the inner cylinder curve is varied in a systematic way to wind up with *S* being "quasi-developable".

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at the i^{th} point, numerically with the centered-difference equation for the second derivative of y with respect to arc length,

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It should be noted that the baseline designs are actually pretty good; χ^2 for the outer baseline design is 0.165, whereas the final outer design has a χ^2 of 0.111. The inner baseline design has a χ^2 of 0.655 and the final inner design a χ^2 of 0.277.

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The inner and outer surfaces of the endpost are portions of cylinders having radii which are in general not the same as the radii of the "inner edge cylinder" and "outer edge cylinder" defined above. This is because the turn may not be "radial", i.e., may not be centered on a plane containing the z axis in the straight section of the coil. BNL 2-D coil cross-sections are designed so that the midpoint of the outer edge of each turn in a layer lies on a specified circle. This circle defines the endpost outer surface. If the turn is radial, the midpoint of the inner edge defines the radius of the endpost inner surface. The final step in the computer program is to extend the line passing through the coordinates C2(j,i) and C3(j,i) defined above, in the slant direction to the intersection with the mandrel. (The outer coordinates C3 are essentially correct.) The 3-D coordinates are then transformed back into developed (2-D) coordinates. The present version of the program is CNSTND6.

Interaction between CNSTND6, CAD and NC machining

The 2-D configuration generated by CNSTND6 is transferred electronically to a computer-aided design (CAD) machine in the design group, where dimensions are checked and minor alterations made as needed. For example, the endpost outer surface does not coincide exactly with the outer cylinder curve, but is slightly larger. Also, the inner cable width increase (0.23 mm) was not rerun on CNSTND6; the necessary changes were made using the CAD machine.

Flat patterns were used to construct (by hand) the experimental endposts for winding tests. For the production endpost, 3-D data from the CAD machine are transferred electronically to the central machine shop and used to program a numerically-controlled (NC) 5-axis milling machine.

Experimental Work

All experiments were conducted on the return end of the centerpost, which is symmetrical. The lead end, which is asymmetrical, is a modification of the return end.

A variety of observations were made during the experiments, mostly of a qualitative nature. These include unlocking, popped or raised wires, cable collapse, thick edge expansion, azimuthal gaps between the cable and centerpost, and gaps between turns at the coil end.

A new quantitative observation was developed during the present tests, called "cable lift". This is the distance, measured at specific positions along the z axis, between the winding mandrel and the inner cable edge. Although the mandrel is rotated during winding so as to maintain contact of the cable with the mandrel, a previous section of the cable may lift off while a subsequent section is being applied. Lift is measured after the first turn is wound and clamped to the centerpost, 150 mm inward of the end. It is measured at the end of the straight section and 25 mm inward of the end of the straight section, on both sides of the centerpost, by a feeler gage or pin gage between the cable edge and the mandrel. Those parameters affecting the amount of lift are winding tension, winding direction, cable pitch, cable insulation, endpost tilt angle and end shape. Lift measurement is most useful when varying a single parameter; when several parameters have been varied, the lift measurements may not be consistent.

Left lay cable wound clockwise tends to unlock as it is applied entering the end, and tends to lock while exiting the end. While entering the end, pressure of the cable against the endpost helps to maintain wire registration. Since there is no such assistance after exiting the end, a right lay cable is harder to wind successfully clockwise. Both cables have left lay, but the outer cable, which has a higher aspect ratio than the inner, is more prone to failure. Tests showed the outer cable had to be wound clockwise. The final version of the inner cable, with a shortened pitch, is robust enough to wind in either direction.

As might be expected, the Kapton wrap helps to bind the cable together and improve resistance to unlocking and raised wires. However, although it is a high strength material, it can be damaged during coil winding if the cable is prone to unlocking. Kapton breakage on the thick edge and also near the middle of the side facing the centerpost was found after winding such cables. Examination of a cable after winding without Kapton revealed thick edge expansion, and it is supposed that stretching of the Kapton there was responsible for the breaks in the Kapton-wrapped cables. Tests showed that changing the wrap direction did not improve matters. Kapton breakage was seen while using the initial, longer pitch (94 mm) inner cable and in outer cable wound counterclockwise. Neither the long-pitch inner nor the outer cable could be successfully wound counterclockwise without the Kapton. The improved inner wider cable with shorter pitch did not cause Kapton breakage when wound in either direction.

The older, 40 mm i.d. SSC coils were made with smaller cables and were wound with 0.16 to 0.18 kN (35 to 40 lbs) tension. The present experiments were done at 0.18, 0.22 and 0.27 kN (40, 50 and 60 lb). With too little tension, the coil is loose, and it may be difficult to get the larger, fluffier coil into the curing mold. Also, the cable may not conform to the endpost. Too high a tension can cause the cable to collapse or pop a wire, and the insulation may be damaged by scuffing on the mandrel. The new, wider outer cable can be wound with 0.16 kN tension, but the inner requires a minimum of 0.18 kN to wind around the narrow endpost. A tension of 0.27 kN on the inner is a bit high; although it improves conformity of the cable to the endpost and decreases lift on the exiting side, it increases lift on the entering side. With a lower tension, lift was equal on both sides. The final choice for both inner and outer was 0.22 kN.

Gaps tend to occur between the centerpost and the cable along the straight section, but are not a problem; the turns are held in place during winding of long coils by clamps, and gaps are closed during curing. Gaps that occur between turns in the ends are caused by improper endpost tilt. These gaps leave voids after curing and are undesireable.

The initial endpost model for the inner was the baseline design, with a 40° ellipse on the outer edge and a 40° ellipse plus straight section on the inner edge. Endpost tilt angles from 0° to 13° were tried and it was found that the proper tilt was between 5° and 9°. Endpost shapes designed using CNSTND6, with outer edge ellipses of 40°, 38°, 36° and 34°, and tilt angles from 8.3° to 9.1°, were tried next. The 36° outer-edge ellipse, with a tilt of 8.6°, gave the least cable lift and was chosen.

The outer coil winding tests were not as lengthy as those on the inner coil; the larger mandrel and wider centerpost make winding easier. The first test was with a model computed using an early version of CNSTND; the model was wound with bare cable using 0.22 kN tension. The cable lifted 0.7 mm at the beginning of the straight section and 1.24 mm, 25 mm before the straight section. After 3 turns, there were 0.5 mm gaps between turns at the crossover point; the endpost angle was too large, 32.3°. The endpost angle was modified to 20°, without regard to maintaining constant perimeter. Wound clockwise, with 0.22 kN tension, there were no raised wires, and seven turns were wound without problems. Wound counterclockwise, the cable collapsed. Tests were then made on five more endposts having angles in the range 20° to 26.3°; the last three of these were obtained with CNSTND6. The final choice was a 40° ellipse outer edge, 36.8° ellipse inner edge and a tilt of 24.7°, a slight modification of a CNSTND6 design. With this endpost, eleven turns were wound clockwise with 0.22 kN tension without problems, on an open mandrel with no guide for the cable.

Final Design

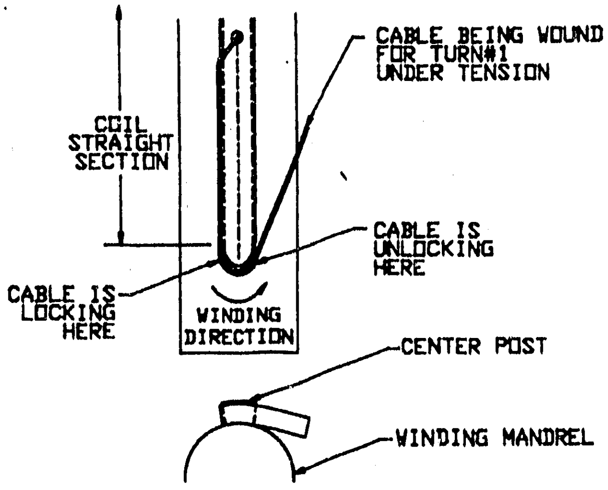
The endpost configurations finally arrived at are given in Table 2.

References

[1] R.C. Bossert, J.S. Brandt, J.A. Carson, H.J. Fulton, G.C. Lee and J.M. Cook, "Analytical Solutions to SSC Coil End Design", Proc. International Industrial Symposium on the Supercollider, (Feb. 1989), New Orleans, p.387.

Table II. Final endpost configurations; linear dimensions are in mm and angles in degrees.

Coil	Radial Surface	Straight Section	Degree Ellipse	Major Axis	Minor Axis	Tilt Angle
inner	inner	7.70	32.6	11.68	6.30	8.6
inner	outer	0.00	36.0	17.45	10.26	
outer	inner	19.35	36.8	43.66	26.19	24.7
outer	outer	0.00	40.0	57.51	36.96	



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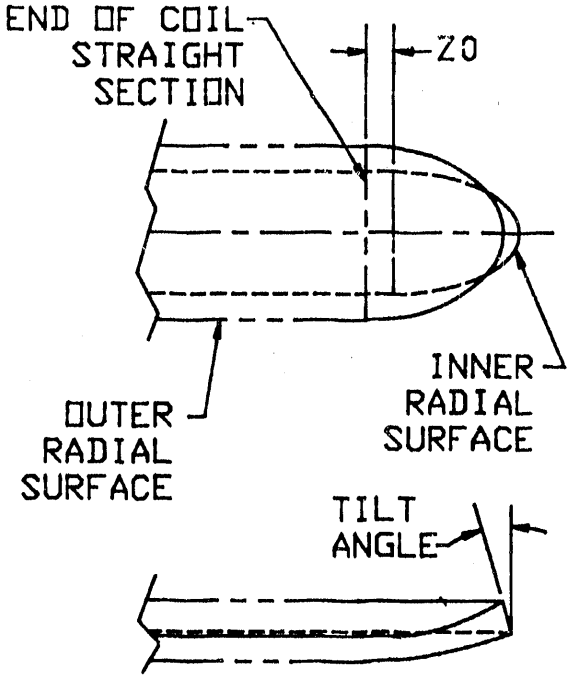

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Flat patterns were used to construct (by hand) the experimental endposts for winding tests. For the production endpost, 3-D data from the CAD machine are transferred electronically to the central machine shop and used to program a numerically-controlled (NC) 5-axis milling machine.

Experimental Work

All experiments were conducted on the return end of the centerpost, which is symmetrical. The lead end, which is asymmetrical, is a modification of the return end.

A variety of observations were made during the experiments, mostly of a qualitative nature. These include unlocking, popped or raised wires, cable collapse, thick edge expansion, azimuthal gaps between the cable and centerpost, and gaps between turns at the coil end.

A new quantitative observation was developed during the present tests, called "cable lift". This is the distance, measured at specific positions along the z axis, between the winding mandrel and the inner cable edge. Although the mandrel is rotated during winding so as to maintain contact of the cable with the mandrel, a previous section of the cable may lift off while a subsequent section is being applied. Lift is measured after the first turn is wound and clamped to the centerpost, 150 mm inward of the end. It is measured at the end of the straight section and 25 mm inward of the end of the straight section, on both sides of the centerpost, by a feeler gage or pin gage between the cable edge and the mandrel. Those parameters affecting the amount of lift are winding tension, winding direction, cable pitch, cable insulation, endpost tilt angle and end shape. Lift measurement is most useful when varying a single parameter; when several parameters have been varied, the lift measurements may not be consistent.

Left lay cable wound clockwise tends to unlock as it is applied entering the end, and tends to lock while exiting the end. While entering the end, pressure of the cable against the endpost helps to maintain wire registration. Since there is no such assistance after exiting the end, a right lay cable is harder to wind successfully clockwise. Both cables have left lay, but the outer cable, which has a higher aspect ratio than the inner, is more prone to failure. Tests showed the outer cable had to be wound clockwise. The final version of the inner cable, with a shortened pitch, is robust enough to wind in either direction.

As might be expected, the Kapton wrap helps to bind the cable together and improve resistance to unlocking and raised wires. However, although it is a high strength material, it can be damaged during coil winding if the cable is prone to unlocking. Kapton breakage on the thick edge and also near the middle of the side facing the centerpost was found after winding such cables. Examination of a cable after winding without Kapton revealed thick edge expansion, and it is supposed that stretching of the Kapton there was responsible for the breaks in the Kapton-wrapped cables. Tests showed that changing the wrap direction did not improve matters. Kapton breakage was seen while using the initial, longer pitch (94 mm) inner cable and in outer cable wound counterclockwise. Neither the long-pitch inner nor the outer cable could be successfully wound counterclockwise without the Kapton. The improved inner wider cable with shorter pitch did not cause Kapton breakage when wound in either direction.

The older, 40 mm i.d. SSC coils were made with smaller cables and were wound with 0.16 to 0.18 kN (35 to 40 lbs) tension. The present experiments were done at 0.18, 0.22 and 0.27 kN (40, 50 and 60 lb). With too little tension, the coil is loose, and it may be difficult to get the larger, fluffier coil into the curing mold. Also, the cable may not conform to the endpost. Too high a tension can cause the cable to collapse or pop a wire, and the insulation may be damaged by scuffing on the mandrel. The new, wider outer cable can be wound with 0.16 kN tension, but the inner requires a minimum of 0.18 kN to wind around the narrow endpost. A tension of 0.27 kN on the inner is a bit high; although it improves conformity of the cable to the endpost and decreases lift on the exiting side, it increases lift on the entering side. With a lower tension, lift was equal on both sides. The final choice for both inner and outer was 0.22 kN.

Gaps tend to occur between the centerpost and the cable along the straight section, but are not a problem; the turns are held in place during winding of long coils by clamps, and gaps are closed during curing. Gaps that occur between turns in the ends are caused by improper endpost tilt. These gaps leave voids after curing and are undesireable.

The initial endpost model for the inner was the baseline design, with a 40° ellipse on the outer edge and a 40° ellipse plus straight section on the inner edge. Endpost tilt angles from 0° to 13° were tried and it was found that the proper tilt was between 5° and 9°. Endpost shapes designed using CNSTND6, with outer edge ellipses of 40°, 38°, 36° and 34°, and tilt angles from 8.3° to 9.1°, were tried next. The 36° outer-edge ellipse, with a tilt of 8.6°, gave the least cable lift and was chosen.

The outer coil winding tests were not as lengthy as those on the inner coil; the larger mandrel and wider centerpost make winding easier. The first test was with a model computed using an early version of CNSTND; the model was wound with bare cable using 0.22 kN tension. The cable lifted 0.7 mm at the beginning of the straight section and 1.24 mm, 25 mm before the straight section. After 3 turns, there were 0.5 mm gaps between turns at the crossover point; the endpost angle was too large, 32.3°. The endpost angle was modified to 20°, without regard to maintaining constant perimeter. Wound clockwise, with 0.22 kN tension, there were no raised wires, and seven turns were wound without problems. Wound counterclockwise, the cable collapsed. Tests were then made on five more endposts having angles in the range 20° to 26.3°; the last three of these were obtained with CNSTND6. The final choice was a 40° ellipse outer edge, 36.8° ellipse inner edge and a tilt of 24.7°, a slight modification of a CNSTND6 design. With this endpost, eleven turns were wound clockwise with 0.22 kN tension without problems, on an open mandrel with no guide for the cable.

Final Design

The endpost configurations finally arrived at are given in Table 2.

References

[1] R.C. Bossert, J.S. Brandt, J.A. Carson, H.J. Fulton, G.C. Lee and J.M. Cook, "Analytical Solutions to SSC Coil End Design", Proc. International Industrial Symposium on the Supercollider, (Feb. 1989), New Orleans, p.387.

Table II. Final endpost configurations; linear dimensions are in mm and angles in degrees.

Coil	Radial Surface	Straight Section	Degree Ellipse	Major Axis	Minor Axis	Tilt Angle
inner	inner	7.70	32.6	11.68	6.30	8.6
inner	outer	0.00	36.0	17.45	10.26	
outer	inner	19.35	36.8	43.66	26.19	24.7
outer	outer	0.00	40.0	57.51	36.96	

END

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