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Coil End Design for the LHC Dipole Magnet

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Abstract

This paper describes the design of the coil ends for the Large Hadron Collider dipole magnets of the CERN European Laboratory for Particle Physics in Switzerland. This alternative to existing European designs was provided by Fermi National Accelerator Laboratory by agreement between CERN and the United States. The superconducting cable paths are determined from both magnetic and mechanical considerations. The coil end parts used to shape and constrain the conductors in the coil ends are designed using the developable surface, grouped end approach. This method allows the analysis of strain energy within the conductor groups, and the optimization of mechanical factors during the design. Design intent and implementation are discussed. Inner and outer coil design challenges and end analyses are detailed.

Introduction

Superconducting magnets typically use multiple-stranded cable in which the strands form a helical lay within the conductor. This conductor is then formed into a ribbon-like shape with a trapezoidal cross-section (see Figure 1). The conductor is wound along a cylindrical mandrel to produce a coil with a long straight section of conductors in closely specified positions (see Figure 2). These coil cross-section positions are defined by physicists to produce a precise and uniform magnetic field within the cylindrical bore of the assembled magnet (see Figure 3). At the ends of the coil, the conductors must leave the long straight section, rise up and over the mandrel, and rejoin the opposite side long straight section.

Individual conductors are tightly contained within the straight section of the magnet. This containment is desirable in the coil ends, but more difficult to obtain. Coil ends have proven to be a very difficult part of magnet design, and are a critical factor in magnet performance and reliability. The optimal coil end design provides consistent containment for each conductor in the end, while optimizing strain energy and minimizing mechanical and magnetic disturbances. Fermilab has progressed through many methods of specifying the positions of conductors in coil ends [1]. Starting with the SSC dipole program, in which Fermilab designed and produced several magnets, a method termed *developable surface, grouped end* was tried [2, 3].

Each coil cross-section contains subgroups of conductors that physicists refer to as current blocks (see Figure 2). The grouped end design approach treats each current block as a group of conductors that originate at the end of the coil straight section and maintain conductor-to-conductor contact as they wind around and over the mandrel. The group is a mathematically determined configuration that attempts to minimize the strain energy of individual conductors within the group, and is created by a computer program, BEND, written by Joe Cook [4, 5]. This program is the heart of a complete coil end design system which consists of using BEND to create and optimize the groups, combining the group boundary surface files into files which represent the coil end parts, and reading these files into a CAD package to produce the part geometry. This geometry is then used to produce drawings of the individual end parts, CAM toolpaths for manufacturing them, and computerized inspection paths for measuring them.

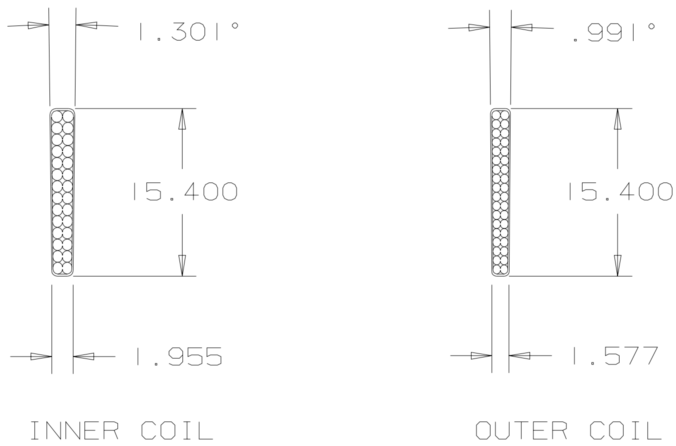

Figure 1: LHC Dipole Insulated Conductor

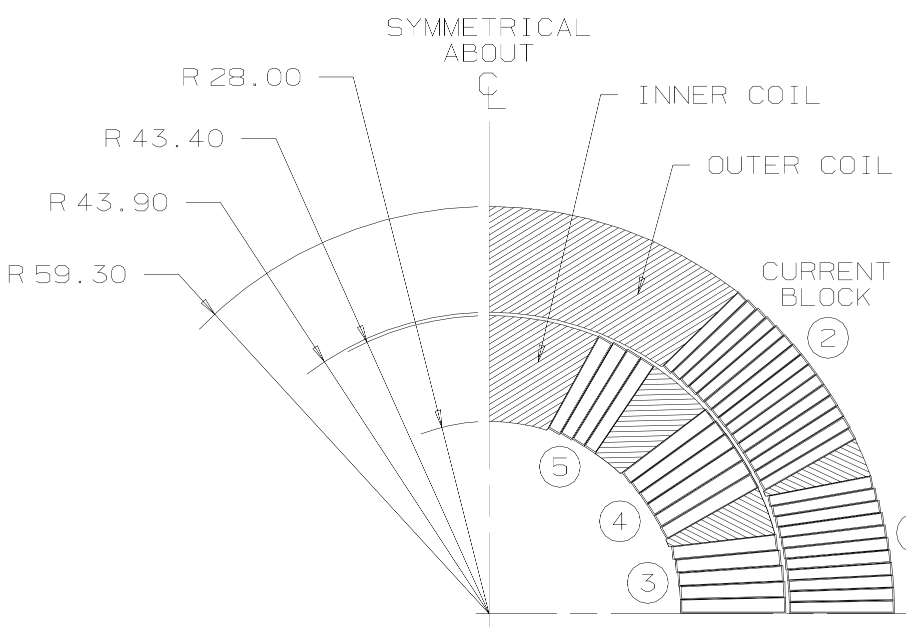

Figure 2: LHC Dipole Coil Cross-Section

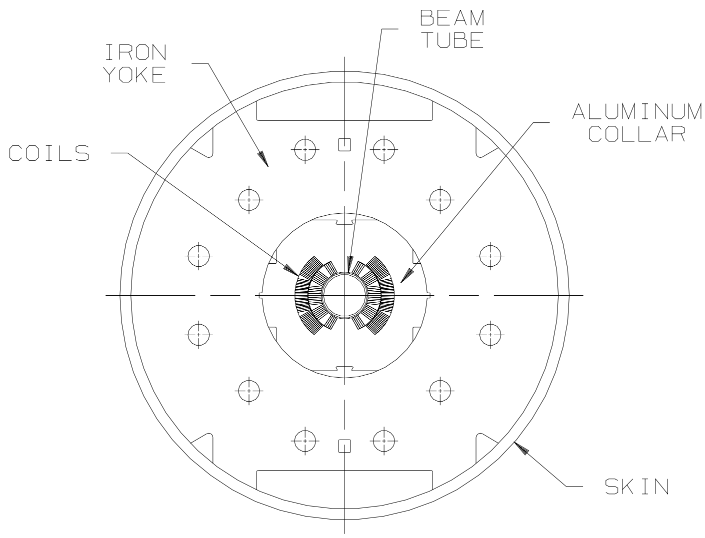

Figure 3: LHC Dipole Magnet Cross-Section

Group Definitions

Program BEND interactively accepts group-defining input from the user and constructs a least-strain group of conductors in space (see Figure 4). The group is defined within a right hand Cartesian coordinate system with a 0,0,0 origin located on the beam tube center line and the Z-axis coincident to it. The group originates in the X–Y plane at Z = 0 and terminates in the Y–Z plane at X = 0 where the conductors cross over the mandrel. Thus, only half an as-wound group is defined and is mirrored across the final Y–Z plane for return end groups or matched to different groups for the lead end. The group is constrained in four ways:

- The group's initial direction must be parallel to the positive Z-axis, as is the final direction of the coil straight section from which the group originates.
- The group's initial cross-section in the X–Y plane must match the cross-section of the straight section of the coil.
- The group's final direction must be parallel to the negative X-axis to provide a continuous curve after Y–Z plane mirroring.
- All the conductors in the group are defined to have their radially outermost edges on the outer surface of a cylindrical tube. The outer and inner radii of the tube are the same as the coil outer and inner radii.

The group is constructed around an infinitely thin strip in space called the *guiding strip* (see Figure 5). This surface is based on the rectifying developable, and is by definition the least-strain surface definable within the given constraints [4, 5]. The radially outer edge of the guiding strip lies on the outer surface of the tube and is called the *base curve*. The radially inner edge of the guiding strip is called the *free edge*. The free edge is mathematically determined and is not constrained to a tube surface. The *width* of the strip is specified by the user and is usually the difference between the outer and inner tube radii.

Fifty points are established on both the base curve and the free edge. Lines connecting like numbered points on each edge (e.g. point 30 to point 30) form a unique set of rulings, or *fold lines*, which, along with the base curve and free edge, define the surface of the guiding strip. The guiding strip surface can be located at any conductor surface of the group, including the group-inside and group-outside surfaces. Interactive output from program BEND will refer to all three of these group surfaces.

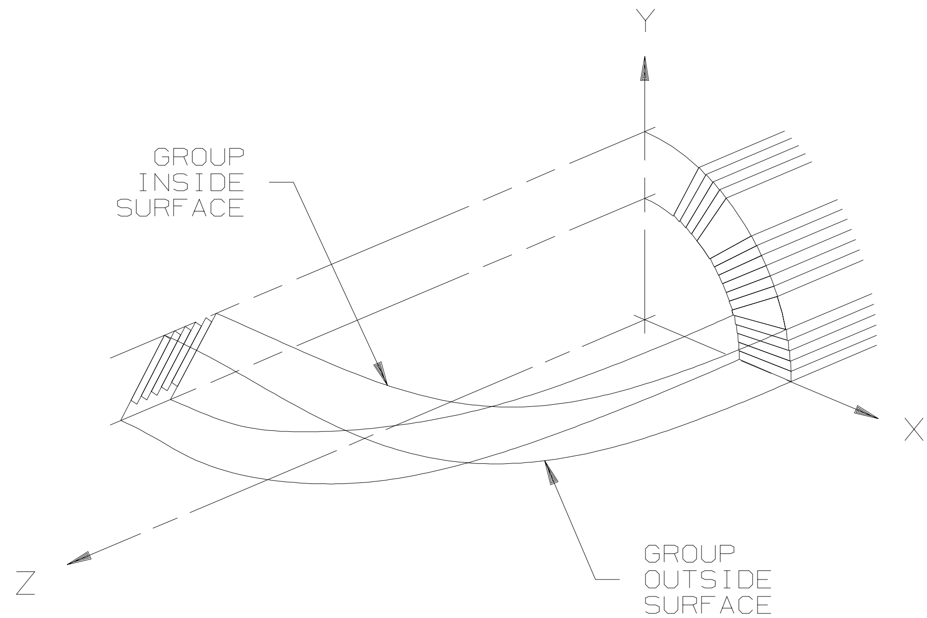

Figure 4: Group Surfaces

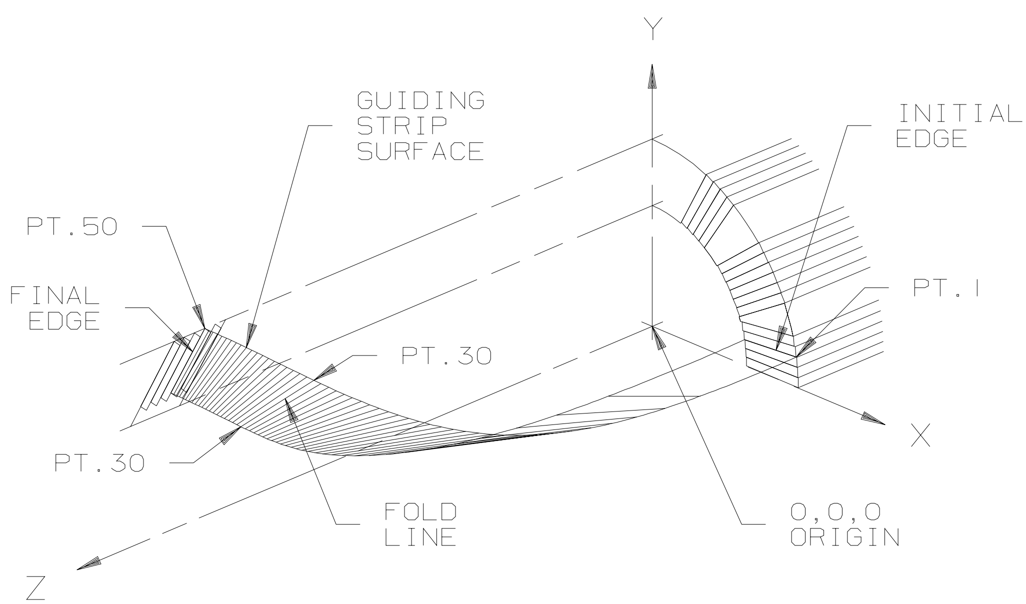

Figure 5: Guiding Strip

The number of conductors inside and outside the strip is a user-entered variable-set related to the coil cross-section and the selected guiding strip position. One-conductor groups to cross between current blocks can be constructed with the guiding strip defined to be on the inside or the outside group surface (see Figure 8). The group is constructed by stacking conductor-size trapezoids against the guiding strip with one trapezoid per conductor per guiding strip point. One edge of the trapezoids adjacent to the guiding strip are coincident to the fold line at that point. The guiding strip fold lines are transferred to the inside and outside group surfaces during this process.

Group Variables

The edge of a group surface that lies in the initial X–Y plane is called the *initial edge*, the edge that lies in the final Y–Z plane is called the *final edge*. The angles from vertical of these edges are called the *initial edge angle* and the *final edge angle*. The initial edge angle for any group is determined by the coil cross-section geometry at the chosen guiding strip location. Refinement of this angle may be necessary to insure that the inside and outside surfaces of the group match the related wedge surfaces in the cross-section.

The angle from vertical of a line passing through the 0,0,0 origin and through the intersection of the initial edge and the outer tube radius is called the *starting angle*. This angle is also determined from the geometry of the coil cross-section. Refinement of this angle on the guiding strip may be necessary to ensure proper azimuthal positioning of the group relative to the cross-section.

The user is given the chance to change the distribution of twist along the strip with a variable called *shift*. A shift of zero is the default value and produces an even distribution of twist. Positive values of shift cause more of the twist to be distributed early in the strip, negative values distribute more twist late in the strip. Another variable called *blunt* changes the radius of curvature of the free edge. A blunt of zero is the default and has no effect on the strip. Positive values of blunt pull the free edge of the strip out near its termination and are used to relieve sharp radii at the nose of the group, negative values tend to sharpen the nose radii. The variable *narrow* can be used to modify the effect of blunt. Positive values of narrow will concentrate the effect toward the nose, negative values concentrate the effect toward the initial edge.

The magnitude of the largest Z-coordinate of any group surface is referred to as the *A-length*. A-lengths are defined only for points that lie on the outer surface of the tube in the final Y–Z plane. Either the guiding strip A-length, the inside group A-length, or the outside group A-length may be specified by the user. This dimension is determined by both magnetic and mechanical considerations.

Relative positions of the conductor groups in a coil end can be determined to optimize magnetic field disturbances in the end. A-lengths may be desired to be as small as possible to shorten the magnetic length of the end. The 0,0,0 origin of a group does not have to be coincident to the 0,0,0 origin of the coil end, an *origin difference* may be applied. The origin difference of a group is the distance the X,Y,Z coordinate system of the group is translated along the Z-axis from the 0,0,0 origin of the coil end, effectively lengthening the straight section for that current block. Enough space must be supplied between conductor groups to produce a coil end part that adequately supports the group.

Certain mechanical considerations may require variation of the desired magnetic configuration. Program BEND distributes the twist in a group in an attempt to minimize the strain energy within the group. An A-length may be specified that is too short for a given group to smoothly distribute the group's twist. In some cases, the guiding strip buckles or folds back on itself due to crossing of fold lines. Usually, these conditions will produce a warning in BEND, cause output optimization data to be abnormally high or low, or cause the group to be resistant to attempts at optimization. The user should carefully analyze groups that are hard to optimize.

Conductor Variables

Conductor *width* will be the same as the specified guiding strip width. Conductor *mid-thickness* can be the same as the specified compressed, insulated conductor used in the coil (see Figure 1). For an exact coil cross-section match, however, the average mid-thickness of the conductors within each group should be estimated, and that value used as input to BEND. This mid-thickness typically needs to be refined to produce a group that exactly matches the cross-section (see Figure 6).

The conductor is typically insulated with a series of kapton film layers, the last layer containing a b-staged epoxy adhesive. After coil winding, the coil is installed in a fixed cavity curing mold and subjected to a heat and pressure cycle that sizes and bonds the coil. The forces applied to the ends of the coil during this curing process are less than those applied to the straight section.

Because of this, and because the shape of the conductor tends to change when wound around the coil end, *cable-thickening ratios* greater than one can be specified that increase the conductor mid-thickness at the middle of the group, at the termination of the group, or both. The mid-thickness at the origin of the group will remain unchanged, with the specified cable-thickening ratios smoothly applied from there.

The use of the group's average conductor keystone angle will result in exact matching to the appropriate wedge, pole, or parting plane surfaces. Just as the mid-thickness of the conductor can be altered, so can the keystone angle. *Keystone-widening ratios* less than one will decrease the conductor keystone angle (without affecting mid-thickness) according to the same constraints as outlined for mid-thickness.

Study of ends for the SSC magnets showed that the conductor keystone angle appeared to be less in the ends than in the straight section, and that the conductor compression at mid-group was different than where it terminates at the nose [6, 7]. Based on these observations, keystone-widening ratios of 0.100(mid-group) and 0.200(nose) and cable-thickening ratios of 1.064(mid-group) and 1.074(nose) were used in the LHC dipole design for both inner and outer coil groups. The effect of these changes to the conductor cross-section in the third-wound group of the LHC dipole inner coil is shown in Figure 6.

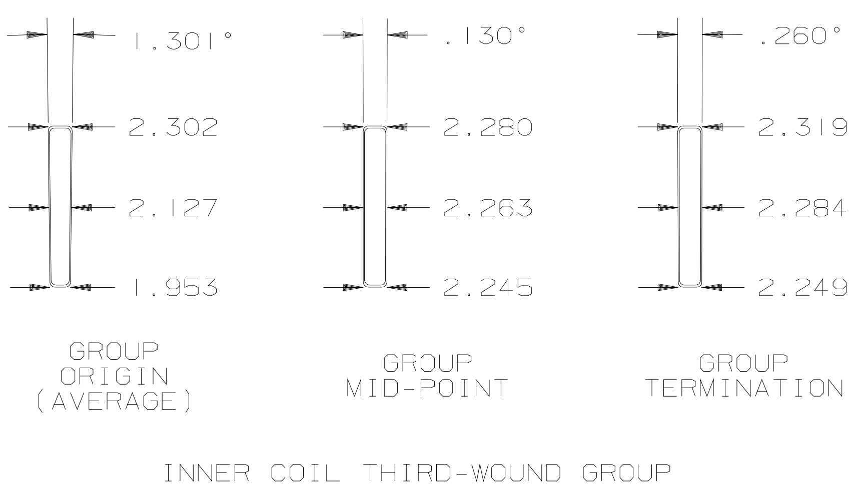

Figure 6: Designed Conductor Shape Changes

Group Optimization

The actual use of program BEND requires a substantial background in coil end design creation and optimization techniques. The user must have a clear understanding of the geometrical constraints of the coil end being designed, and some skill in picking group parameters such as guiding strip positions and A-lengths. Analysis of the interactive output of BEND requires a fair amount of experience, and a method of graphically viewing, measuring, and manipulating the geometry produced is a must. Many of the warnings produced by program BEND do not indicate a problem that will significantly affect the geometry. On the other hand, some true geometry problems are not easy to recognize in BEND output alone.

At Fermilab, all the necessary components for successful coil end design have been assembled and exhaustively tested. A paper has been written by Jeff Brandt documenting much of the background knowledge required to create and optimize groups of superconducting cables with program BEND [8]. The goals of optimization include minimizing the strain energy, maximizing the bend radii, and satisfying the geometric requirements of individual conductors within the group. The remainder of this paper discusses the specific challenges encountered during the LHC dipole coil end design, and an analysis of the results of this design effort.

Design Challenges — First-Wound Inner Coil Groups

The conductor picked for the LHC dipole inner coil has large strands and cross-sectional dimensions which make the conductor very stiff and potentially hard to wind. Because of this, maximizing the bend radii at the nose was the principal optimization goal for the first-wound groups. Experience has shown that the design of a return end group should be accompanied by the design of the lead end groups that must match it (see Figures 7 and 8). Often, the A-length chosen for the return end group cannot be used in the one-conductor group that transitions to the next current block.

An original goal for the Fermilab end parts was to use the same A-lengths found on the parts designed by CERN. This would keep each current block in the same general position and minimize disturbances to any magnetic optimization that had already been done by CERN. This goal was not possible to obtain in the first-wound inner coil groups. The A-length used by CERN was too short for the one-conductor lead end group, and the guiding strip buckled. The CERN 26.89mm inside group A-length was increased in increments until the lead end groups survived. The chosen inside group A-length for the Fermilab first-wound groups was 38.00mm. Because the Fermilab group does not contain additional spacer pieces between the turns, the outside group A-length increase was only 2.56mm for this group.

One of the features of the Fermilab end part design is the shelf (see Figure 9). When the angle of the conductor is shallow enough, relative to the normal to the mandrel, the conductors fail to fill up the space between the coil radii (see Figures 4 and 5). Program BEND places the radially outer edge of each conductor at the coil outer radius. This produces a gap between the conductor radially inner edge and the mandrel, which must be filled to provide the desired radial containment of the group.

Fermilab end parts fill this gap with a shelf, an extension to the part behind the group. Program BEND produced a final edge angle of 17.048° at the inside of the first-wound return end group. This was more than the CERN angle of 13.000°, but steep enough to preclude the need for a shelf. The shelf needs to be at least thick enough to survive cutter forces during machining, and conductor forces during winding and curing. Our experience has shown that around 0.70mm thick at the nose is the minimum shelf thickness .

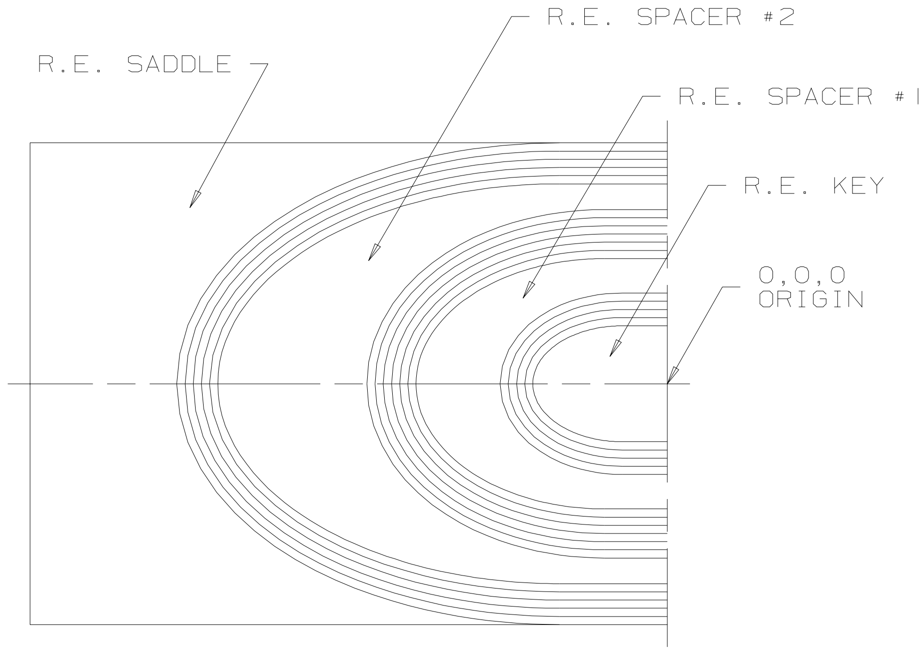

Figure 7: Inner Coil Return End Layout

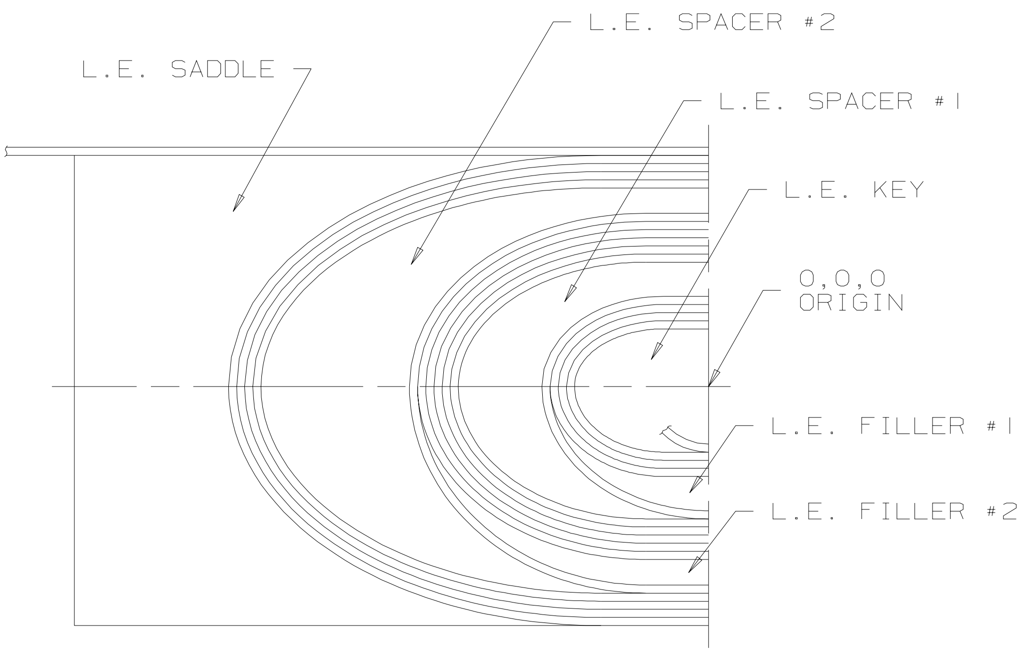

Figure 8: Inner Coil Lead End Layout

On the four-conductor return end group, the guiding strip was placed with 0 conductors inside and 4 conductors outside to provide the largest possible radii in the group, since conductors stacked on the inside of the guiding strip tend to force the radii smaller. No origin difference was used. The shift value used was 1.192, the blunt value was 0.270, and the narrow value was 0.000.

On the three-conductor lead end group, the guiding strip was placed with 0 conductors inside and 3 conductors outside. No origin difference was used. The shift value used was 1.230, the blunt value was 0.195, and the narrow value was 0.000. The inside group final edge angle was made 17.048° to match the return end group. On the one-conductor group, the guiding strip was placed with 0 conductors inside and 1 conductor outside. No origin difference was used. The shift value used was -0.420, the blunt value was 0.200, and the narrow value was 0.000. The outside group final edge angle was made 16.001° to match the return end group.

The inside-group surface of the one-conductor group had to be designed with the outside-group surface of the three-conductor group in mind. These two group surfaces define the geometry of the lead end filler #1 between them (see Figure 8). The filler must start at the 0,0,0 origin matching the wedge shape of the coil cross-section (see Figure 2), and feather to 0.00mm thickness at the nose. Because of the relatively wide wedge shape, this filler was fairly easy to design. The free edges of the two groups sometimes cause trouble, with the inside filler surface crossing through the outside surface in the middle of the group. This did not happen with this filler, but it took some work with the variables blunt and shift to get a smooth transition of the part thickness at the free edge.

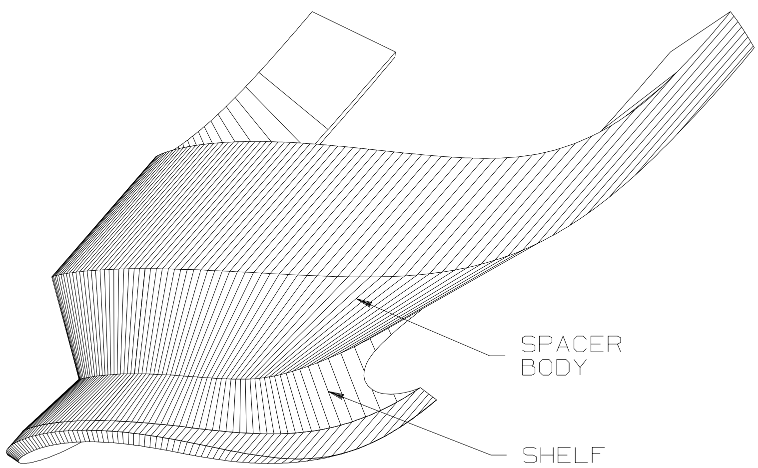

Figure 9: Inner Coil R.E. Spacer #2

Design Challenges — Second-Wound Inner Coil Groups

Shelf considerations were a primary concern for the second-wound groups. The first run of program BEND produced a 31.342° inside group final edge angle, making the shelf under these groups around 1.05mm thick at the nose. Although this thickness was greater than the minimum manufacturable, it was thin enough to consider the alternatives. The addition of a shelf adds much to the cost of the part. There are extra surfaces to machine and these surfaces must be cut without violating adjacent part surfaces. Also, the stiff conductor used appears to be very resistant to twist. Steepening the final edge angle of this group would eliminate the need for a shelf, and would also eliminate some of the twist in the conductor.

Based on these considerations, we decided to steepen the final edge angle for these groups to 19.000°. The shelf needed under conductors at this angle would only be around 0.09mm thick at the nose, and could be neglected. When the one-conductor transition group was created to match this revised angle, it behaved very well and looked good. Some additional confirmation for this decision was also provided by studying the CERN coil end design. The corresponding current block in CERN's design has a final edge angle of 21.000° that was determined empirically, and seemed to be what the conductor wanted to do in this position. These second-wound groups are the only groups in the inner coil that we varied the final edge angle from what BEND suggested.

The chosen inside group A-length was 71.00mm to make the body length of the spacers behind them the same as in the CERN design. Because of the change to the first-wound groups A-length, the second-wound groups were shifted forward around 3.20mm as compared to the CERN end. The steeper final edge angle, and the elimination of the additional thin spacer pieces between each turn produced an outside group A-length was only 2.46mm larger than the CERN design. These groups optimized easily, and even though the amount of hard-way bend in the conductor was increased, the values were low and within reason.

On the six-conductor return end group, the guiding strip was placed with 0 conductors inside and 6 conductors outside to maximize the bend radii in the group. No origin difference was used. The shift value used was -1.050, the blunt value was 0.245, and the narrow value was 0.000.

On the five-conductor lead end group, the guiding strip was placed with 0 conductors inside and 5 conductors outside. No origin difference was used. The shift value used was -0.630, the blunt value was 0.230, and the narrow value was 1.000. The inside group final edge angle was made 19.000° to match the return end group. On the one-conductor group, the guiding strip was placed with 0 conductors inside and 1 conductor outside. No origin difference was used. The shift value used was -1.110, the blunt value was 0.360, and the narrow value was -10.000. The outside group final edge angle was made 17.439° to match the return end group.

The design of lead end filler #2 was one of the most difficult end part design problem we have ever faced. As seen in Figure 2, the wedge shape is very narrow at the coil inner radius. On the first try, the two group surfaces intersected each other badly — over half of the part disappeared. For the first time ever seen, even the base curves of the two group surfaces crossed each other. Over fifty different groups were created in an effort to find a combination that did not violate each other.

For the first time, the BEND option called *vary the base curve* had to be used in the creation of the one-conductor group to fix the crossing of the two base curves. This option, with a value of 0.1(final) and 0.0(mid-group), effectively made the guiding strip stiffer at the nose. This changed the way the strip bends and forced the base curve of the one-conductor group to stay outside of the base curve of the five-conductor group. After this small success, no amount of varying the normal BEND parameters in either group was enough to fix the free edge crossing problem. Again for the first time, the BEND option *perturb* had to be used to eliminate this problem.

Perturb is an option that forces the guiding strip out a specified amount between a given set of points on the strip. The given end points remain unmoved, with the full perturbation applied at the center of the range and smoothly tapering off in both directions. This option acts on the base curve as well as the free edge, and can dramatically affect the strain energy within the group. For this reason, the standard BEND variables should first used to create two groups with a minimum amount of free edge crossing. In this case, the one-conductor group was perturbed outward by 0.38mm between points 5 and 15. An underside view showing the long, thin free edge of this filler is shown in Figure 10.

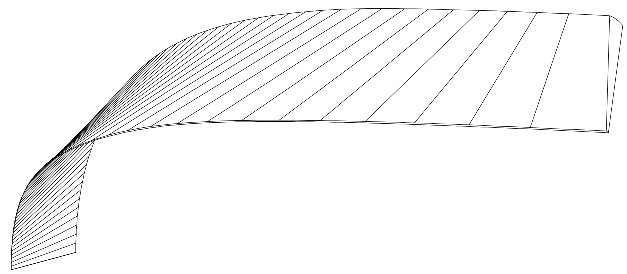

Figure 10: Inner Coil L.E. Filler #2

Design Challenges — Third-Wound Inner Coil Groups

The third-wound groups on the inner coil have the most twist to distribute, and are susceptible to guiding strip buckling if the A-lengths are not large enough. Again, we maintained the body length of the spacers behind the group. This gave an inside group A-length of 127.00mm, around 0.48mm smaller than the length of the corresponding CERN parts. This A-length turned out to be no problem for any of these groups. Because of the significant final edge angle difference, the outside group A-length was 1.55mm larger than the CERN design.

Several guiding strip positions were tried for the third-wound groups. On the return end, the strip was ultimately placed with 2 conductors inside and 3 conductors outside. All positions produced comparable bend radii and hard-way bend values, but this position had the best combination after optimization. No origin difference was used. The shift value used was 0.220, the blunt value was 0.070, and the narrow value was 0.000.

Program BEND produced a final edge angle of 40.919° on the inside of the third-wound groups. This provided a substantial shelf under these groups that could not be eliminated, but we debated long over whether we should steepen the final edge angles for these groups or not. The idea of eliminating some twist, and coming closer to the corresponding CERN angle of 27.000° was strongly considered. Even though the shelf and the guiding strip could have withstood a large amount of steepening, in the end we decided to leave this group as the program produced it. The decision to modify would have been arbitrary and would not have simplified the part. We also felt that these code-produced groups would provide a good comparison to the modified second-wound groups. The shelf thickness was 2.32mm at the nose, tapering down to 2.17mm thick at the extension.

No filler is required for the last-wound groups in a coil lead end, but the last turn exits the coil package at the parting plane instead of continuing around the end. Two additional groups were created for the lead end that used the same relative guiding strip position as used on the return end. One group had 1 conductor inside and 3 conductors outside. No origin difference was used. The shift value used was 0.630, the blunt value was 0.010, and the narrow value was 0.000. The group near the lead exit had 2 conductors inside and 2 conductors outside. No origin difference was used. The shift value used was 0.620, the blunt value was 0.070, and the narrow value was 0.000. All of the third-wound groups were easy to design and optimize.

Analysis of Results — Inner Coil Description

An LHC dipole inner coil was wound around Fermilab designed end parts the week of 31-Jul-95 through 04-Aug-95 at the CERN Laboratory in Geneva, Switzerland. A detailed trip report of the work done on this trip is entitled "Second Trip to CERN". It is dated October 13, 1995, and is available in Fermilab Technical Support files. Jeff Brandt and Imre Gonczy from Fermilab assisted CERN personnel during the entire production process. The coil was cured and measured before it was removed from the CERN tooling. The ends were then clamped to Fermilab tooling which would prevent any movement of the parts or conductors, and cut-off from the straight sections. These end assemblies were carried back to Fermilab where they were enclosed within a shell and vacuum-impregnated with a room cure epoxy mixture.

The epoxied assemblies were then cut in four places to expose the cross-section of the groups within the end (see Figure 11). The first cut was located so that one side of the cutting wheel would lie on the coil centerline in the Y–Z plane. The halves containing this plane were retained and polished, allowing us to view the conductor shape and behavior at the nose of each group. The other halves were cut in three more places each, at the midpoint of each group. Each of these cuts was normal to the tube and to the direction of the particular group, allowing us to view the conductor shape and containment at mid-group. All of the cut surfaces were polished to accentuate contrast.

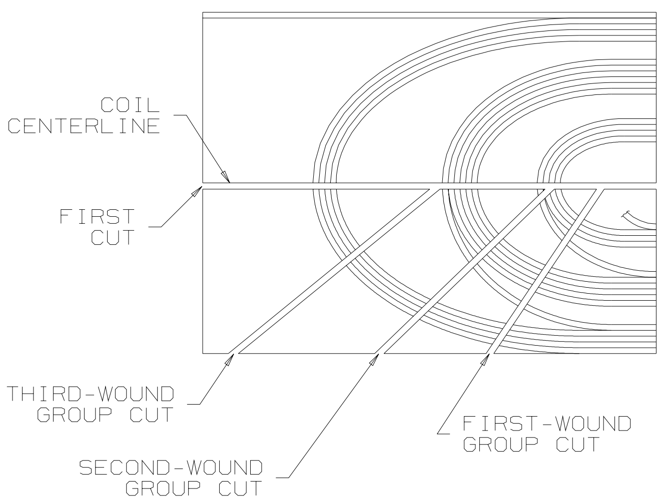

Figure 11: Epoxied Inner Coil Cut Layout

Analysis of Results — Inner Coil Y–Z Plane Sections

The inner coil return end Y–Z plane section is shown in Figures 12. The dimensions shown are the differences between the measured values and the designed values. This end did not close to the designed length by 3.25mm. Of this, an average of 0.70mm can be attributed to the parts being too big, and an average of 2.55mm can be attributed to the groups being too big. The inner coil lead end Y–Z plane section is shown in Figures 13. This end did not close to the designed length by 3.66mm. Of this, an average of 0.92mm can be attributed to the parts being too big, and an average of 2.74mm can be attributed to the groups being too big.

The conclusions that can be derived from this data are not completely clear for several reasons. Variations in the part dimensions, particularly in the spacers #2 and the saddles, are large enough to influence the compaction distribution of the third-wound groups. These groups appear to be tightly compacted at the conductor radially inner edge, and the measured dimensions average 0.52mm smaller than the designed space. At the conductor radially outer edge, the measured dimensions average 0.08mm larger than the designed space. Compaction appears to be somewhat less than desired at the radially outer edge of the return end, but good on the lead end. Some outer edge curl away from the parts behind them is evident in the first turn of each of these third-wound groups.

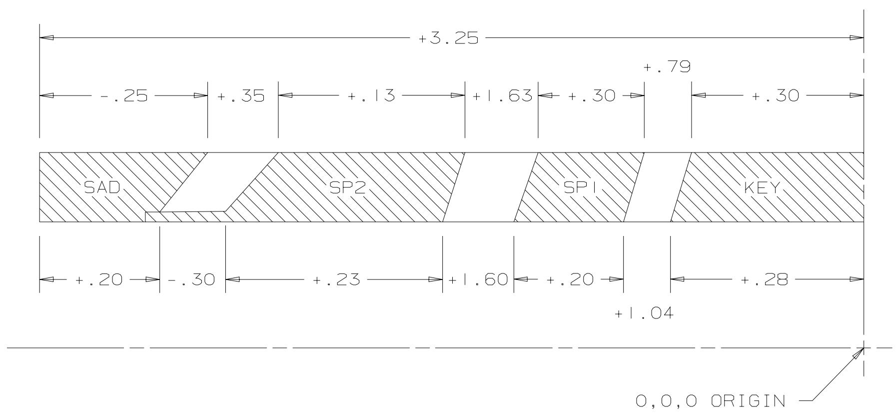

Figure 12: Inner Coil Return End Y–Z Plane Section

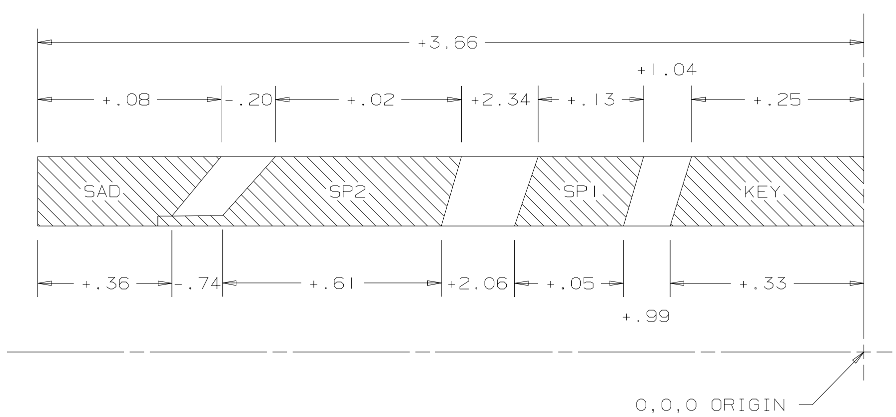

Figure 13: Inner Coil Lead End Y–Z Plane Section

Outer edge curl is a phenomenon that is seen in most stranded superconducting cable groups. It is the curling away of the radially outer edge of the conductor from the winding surface. It is localized in the turn near the nose, and is typically seen in only the first few conductors of a group. The curl is usually limited to the radially outer one-third or less of the conductor width — the inner two-thirds or more of the cable lies tightly against the winding surface. The condition seems to be exaggerated in groups with shallow final edge angles, and in the last-wound groups of a particular coil.

Conductor shape changes in the second-wound groups are very unusual. The conductor did not actually lay tightly against the part behind it, in spite of efforts to make it so, and winding feedback that it had. The conductors show an inner edge curl away from the parts behind them, unlike any group we have ever observed. Application of spacer installation force appears to have been concentrated at the conductor radially inner edge, causing an s-shape to be formed into the conductor. However, it is not certain that this s-shape did not exist in the conductor before the application of installation force.

At the conductor radially outer edge, the measured dimensions of the second-wound groups average 1.98mm larger than the designed space, with most of the difference showing up between the last-wound turn of the groups and the second spacers. At the conductor radially inner edge, the measured dimensions average 1.83mm larger than the designed space, with the difference appearing to be distributed in gaps between the first four wound turns.

The first-wound groups behaved more normally. At the conductor radially outer edge, the measured dimensions average 0.91mm larger than the designed space, with the difference appearing to be distributed in gaps between the first three wound turns. At the conductor radially inner edge, the measured dimensions average 1.02mm larger than the designed space, with the difference fairly evenly distributed between the four turns. Some evidence of part deformation is evident in the spacers #1 installed around these groups. This deformation appears to be localized around the tooling holes in the spacers at the nose, and may be part of the reason for lower compaction. Other potential reasons are the loss of tension during winding, and the combination of stiff conductor and small bend radii.

It is unfortunate that these conditions make the Y–Z plane sections difficult to analyze. This plane is the only one which contains all true conductor trapezoids of all the groups, and where the cable-thickening and keystone-widening ratios at the group termination can be observed. Because of the potential part variations of the third-wound groups, the final edge angle modifications of the second wound groups, and the potential winding variations of the first-wound groups, these coil sections are less able to provide meaningful data for the conductor shape change analysis required in an iteration #2 design.

Analysis of Results — Inner Coil Oblique Sections

Dimensional analysis of the oblique cuts of the coil ends is less exact because not all of the stacked trapezoids at any given point lie in a plane, and any cut through the middle of a group will show potentially distorted conductor shapes. We tried to make the cuts normal to the group as a whole, but it is not possible to make these oblique cuts follow the fold line of any conductor in the group. Because of this, measuring the width of the conductors or the group at these points is usually not conclusive. However, analysis of the containment of the group and the relative compaction of individual conductors is possible and very useful. In particular, the one-conductor groups reveal a lot about the design effectiveness.

The space for the turn in a one-conductor group is created from the surfaces of two different parts, machined in two different set-ups. If the space for conductors provided by program BEND were not correct, it would be easy to see in a section through a one-conductor group. All of the sections through one-conductor groups in these ends look excellent. The conductor paths conform very well to shape of the parts, and the compaction of the conductor across its width is uniform in all cases.

When the conductor is made, it is mechanically formed into a keystone shape, and strands at the radially inner edge of the conductor appear to be more tightly compacted. Because this variation across the width of the conductor can be deceiving, uniformity of compaction is best illustrated by the thickness of the insulation layers between turns. In the oblique sections through these coil ends, the insulation thicknesses across the width of the conductors are very uniform. This indicates that the keystone-widening ratio applied at mid-group is very close to representing the behavior of the actual wound conductor.

Analysis of the cable-thickening ratio is complicated. Axial forces applied in the curing process are much less than the applied azimuthal forces. From our experience, these axial forces are not transmitted through the coil end, but appear to be concentrated in the last-wound turns of the last-wound groups. Very little of the axial force, even very high axial force, makes it through the last spacers into the second-to-last-wound groups. We have found that if the coil end parts are not seated into their proper Z–axis position during the winding process, they will not be made to do so in the curing process.

One of the reasons for parts not being properly seated is the lack of seating of each wound turn against the part or turn behind it, and evidence of this problem shows up in the nose sections of the first and second-wound groups. The loss of winding tension and modification of final edge angles are potential explanations. However, since the author personally witnessed the attempt to seat each turn of this coil, it is likely that another reason for lack of Z–axis positioning is dominant in this coil.

If the cable-thickening ratio at mid-group does not allow the conductor enough room to affect its changes, then the parts will be tightly seated at mid-group before they are pushed back to their designed positions. Judging by the relative insulation thicknesses at mid-group and at the nose, it appears that this has been the case in this coil — the insulation gaps are noticeably more compressed at the mid-group sections than they are at the group termination sections. Even in the first-wound groups which see none of the curing axial forces, the compaction at mid-group is better than at the nose, though this effect is probably exaggerated by the combination of stiff conductor and small bend radii at the nose of the key.

Design Challenges — First-Wound Outer Coil Groups

The conductor picked for the LHC dipole outer coil has smaller strands and should be potentially easier to wind. In practice, this conductor bends easier but is less stable than the inner conductor. Strands become displaced from their normal positions quite easily, and this conductor must be handled with care during winding. The larger coil radii and the wider key width helped to minimize problems with these groups. Layouts of the Fermilab-designed outer coil ends are shown in Figures 14 and 15.

The chosen inside group A-length for the Fermilab first-wound groups was 67.00mm, around 0.56mm larger than the length of the corresponding CERN parts. This resulted in an outside group A-length that was 1.63mm larger than the CERN design. The increased difference is mostly the result of a shallower final edge angle. Program BEND produced an inside group final edge angle of 31.511° which was accepted, making the shelf under these groups 1.30mm thick at the nose, tapering down to 1.00mm thick at the extension. The CERN final edge angle for these groups is 21.0°.

On the fifteen-conductor return end group, the guiding strip was placed with 4 conductors inside and 11 conductors outside. Several other positions were tried and produced comparable bend radii and hard-way bend values, but this position had the best combination after optimization. No origin difference was used. The shift value used was 1.250, the blunt value was 0.138, and the narrow value was 0.000.

On the fourteen-conductor lead end group, the guiding strip was placed in the same relative position as used on the return end, with 3 conductors inside and 11 conductors outside. No origin difference was used.

The shift value used was 0.000, the blunt value was 0.150, and the narrow value was 1.000. The inside group final edge angle was made 31.511° to match the return end group. On the one-conductor group, the guiding strip was placed with 0 conductors inside and 1 conductor outside. No origin difference was used. The shift value used was 0.000, the blunt value was 0.300, and the narrow value was -0.562. The outside group final edge angle was made 28.539° to match the return end group.

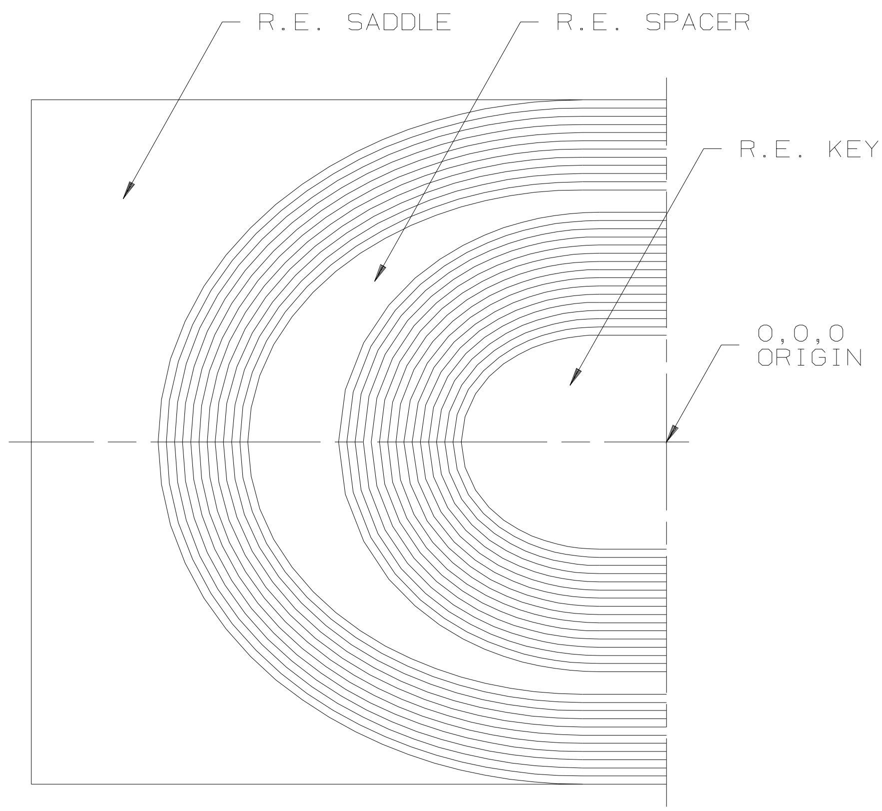

Figure 14: Outer Coil Return End Layout

The design of the outer coil lead end filler turned out to be even more difficult than the design for the inner coil lead end filler #2 described above. The wedge shape is even more narrow at the coil inner radius, and this filler was longer. On the first try, the two group surfaces intersected each other badly and again, the base curves of the two group surfaces crossed each other. The experience gained from the inner coil filler design did not minimize the work required, and over forty-five different groups were created before a combination was found that did not violate each other.

For the second time, the BEND option called vary the base curve had to be used in the creation of the one-conductor group to fix the crossing of the two base curves. This option, with a value of 0.3(final) and 0.0(mid-group), changed the way the strip bends and forced the base curve of the one-conductor group to stay outside of the base curve of the fourteen-conductor group. After this, many combinations were tried before the free edge crossing was minimized enough to use the BEND option perturb to eliminate it. In this case, the one-conductor group was perturbed outward by 0.89mm between points 4 and 20.

The outer coil lead end key requires a slot in its body for the inner to outer coil layer-jump splice (see Figure 15). Because splice forming and soldering fixtures already exist at CERN, we decided to incorporate this identical slot geometry into our key. We received the inside and outside slot surfaces in DXF format from CERN on a PC floppy disc. We were then able to read these DXF files in our Anvil CAD package and incorporate the surfaces into our two-piece lead end key design. These slot surfaces are the only ones in the Fermilab coil end design that were not produced by program BEND.

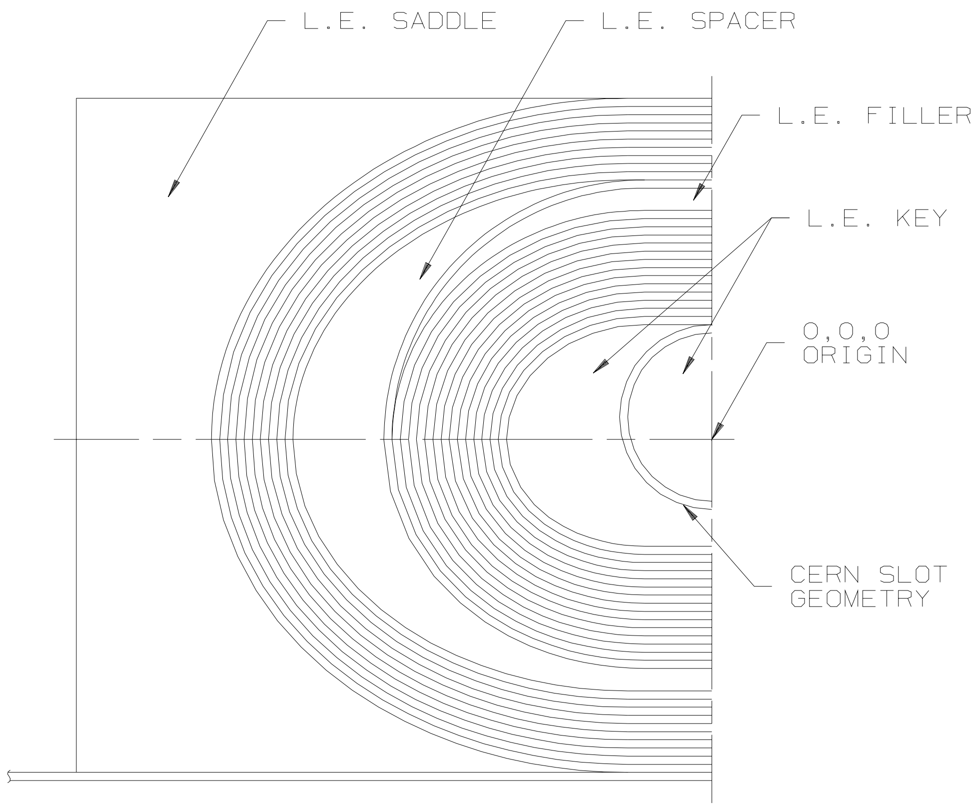

Figure 15: Outer Coil Lead End Layout

Design Challenges — Second-Wound Outer Coil Groups

By the time the second-wound outer coil groups were designed, we had some experience with winding LHC conductor. It was theorized that a relatively small steepening of the final edge angle might help to eliminate some of the conductor outer edge curl we had seen. For this reason, the final edge angle of these second-wound groups was steepened from the 40.777° produced by program BEND, to 35.000°. The modified final edge angle made the shelf under these groups 1.72mm thick at the nose, tapering down to 1.48mm thick at the extension.

The chosen inside group A-length for the second-wound groups was 119.00mm, around 2.89mm larger than the length of the corresponding CERN parts, to retain the relative body length of the spacers behind them. This resulted in an outside group A-length that was 3.29mm larger than the CERN design. The increased difference is mostly the result of the shallower final edge angle. The CERN final edge angle for these groups is 29.0°.

On the eleven-conductor return end group, the guiding strip was placed with 3 conductors inside and 8 conductors outside. Several other positions were tried and produced comparable bend radii and hard-way bend values, but this position had the best combination after optimization. No origin difference was used. The shift value used was 0.000, the blunt value was 0.056, and the narrow value was 0.000.

As on the inner coil lead end, no filler is required for the last-wound groups, and the last turn exits the coil package at the parting plane instead of continuing around the end. Two additional groups were created for the lead end that used the same relative guiding strip position as used on the return end. One group had 2 conductors inside and 8 conductors outside. No origin difference was used. The shift value used was 0.000, the blunt value was 0.067, and the narrow value was 0.000. The group near the lead exit had 3 conductors inside and 7 conductors outside. No origin difference was used. The shift value used was 0.000, the blunt value was 0.097, and the narrow value was 0.000. All of these groups were easy to design and optimize.

After completion of these groups, however, another problem was seen. As on the filler design mentioned above, the wedge shape is very narrow at the coil inner radius. The completed CAD objects revealed that the free edges of the first and second-wound groups intersected each other. This intersection was not severe, but was large enough to force us to revise the design. Because of the difficulty encountered in filler design, the decision was made to leave the first-wound groups alone and fix the crossing by revising the three second-wound groups. This is the first time we have seen free edge crossing between two groups that was not related to filler design.

The return end group with 3 conductors inside and 8 conductors outside was modified first using perturb. In this case, the group was perturbed outward by 1.78mm between points 1 and 12. This is a fairly large value for perturb, and caused a noticeable bulge in the base curve, seen on the outside surface of the outer coil spacer. We were not sure if this bulge would cause a significant winding problem or not. The lead end group with 2 conductors inside and 8 conductors outside was perturbed a total of 1.27mm between points 1 and 12, while the lead end group with 3 conductors inside and 7 conductors outside was perturbed a total of 1.65mm between points 1 and 12.

Analysis of Results — Outer Coil Description

An LHC dipole outer coil was wound the week of 27-Nov-95 through 01-Dec-95 at the CERN Laboratory in Geneva, Switzerland. A detailed trip report of the work done on this trip is entitled "Third Trip to CERN". It is dated December 8, 1995, and is available in Fermilab Technical Support files. Because conductor shape changes can add up very quickly in current blocks with many conductors, Fermilab decided to hold the production of outer coil lead end parts until the return end could be evaluated. Therefore, Fermilab-designed end parts were used only on the return end of this coil, and CERN-designed end parts were used on the lead end. Jeff Brandt assisted CERN personnel during the entire production process. The coil was cured and measured before it was removed from the CERN tooling. The ends were then clamped to Fermilab tooling which would prevent any movement of the parts or conductors, and cut-off from the straight sections. These end assemblies were carried back to Fermilab where they were enclosed within a shell and vacuum-impregnated with a room cure epoxy mixture.

The epoxied assemblies were then cut in three places to expose the cross-section of the groups within the end (see Figure 16). The first cut was located so that one side of the cutting wheel would lie on the coil centerline in the Y–Z plane. The halves containing this plane were retained and polished, allowing us to view the conductor shape and behavior at the nose of each group. The other halves were cut in two more places each, near the midpoint of each group. Each of these cuts was normal to the tube and to the direction of the particular group, allowing us to view the conductor shape and containment at mid-group. All of the cut surfaces were polished to accentuate contrast. The CERN lead end sections were measured and photographed before being sent back to Switzerland.

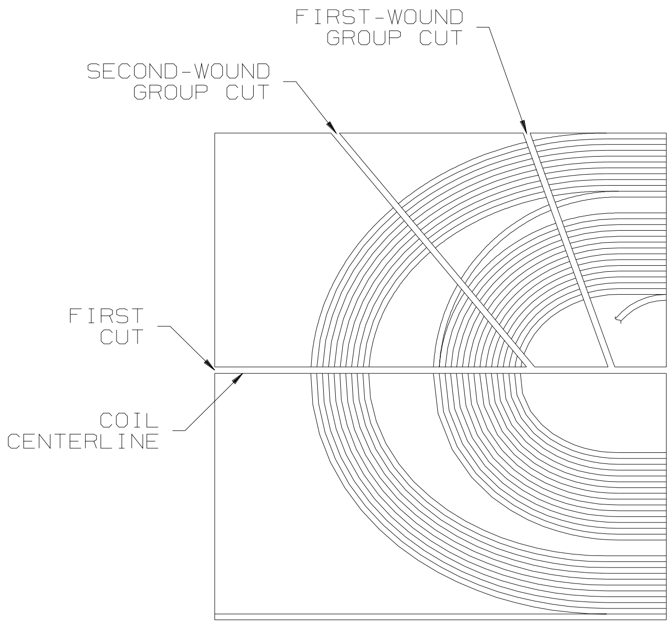

Figure 16: Epoxied Outer Coil Cut Layout

Analysis of Results — Outer Coil Y–Z Plane Sections

The Fermilab outer coil return end Y–Z plane section is shown in Figures 17. The dimensions shown are the differences between the measured values and the designed values. This end did not close to the designed length by 1.48mm. Of this, an average of 0.20mm can be attributed to the parts being too big, and an average of 1.28mm can be attributed to the groups being too big. The CERN outer coil lead end Y–Z plane section is shown in Figures 18. This end was shorter than the designed length by 7.61mm. Of this, an average of 13.46mm can be attributed to the parts being too small, and an average of 5.85mm can be attributed to the groups being too big.

The first-wound Fermilab return end group looks very well contained. The radially outer edges of the conductors are perhaps less tightly compacted than the radially inner edges. This would indicate that the conductors should be allowed to de-keystone at the group termination even more. However, there are many conductors in this group, and the insulation thicknesses across the width of the conductors appear to be uniform. Therefore, the keystone-widening ratio applied at group termination is very close to representing the behavior of the actual wound conductor.

The parts surrounding the Fermilab first-wound group were manufactured very close to the nominal dimensions, and the tolerance variations were in the same direction. This makes it much easier to analyze these sections. At the conductor radially inner edge, the measured group dimension was 1.02mm larger than the designed space. At the conductor radially outer edge, the measured group dimension was 0.92mm larger than the designed space. The small magnitude of these dimensions indicates that the cable-thickening ratio applied at group termination is also very close to representing the behavior of the actual wound conductor.

The radial positioning of this group was very good, with each turn contacting the shelf and aligned at the outer radius. There is a small amount of outer edge curl in this group, particularly in the first-wound conductor. Because curing end forces are not transmitted into this group, it appears that improvement could only be made by ensuring that the radially outer edge of each conductor was firmly tapped into place. If a redesign is considered, perhaps this group's final edge angle should be slightly steepened.

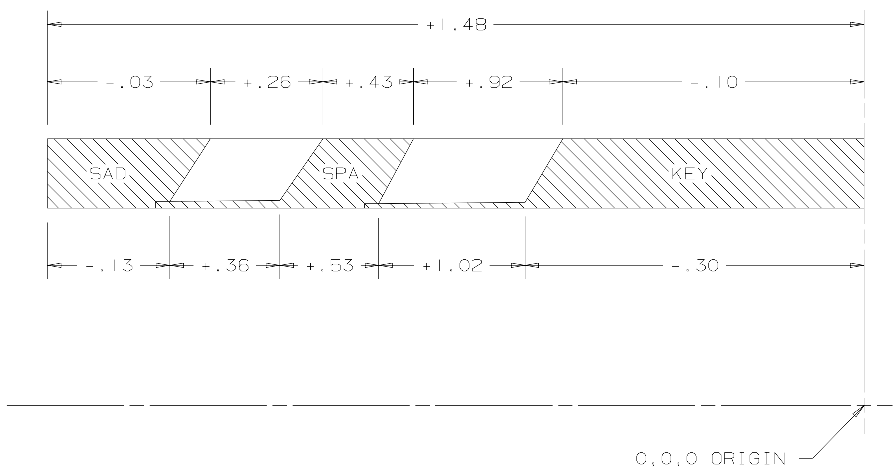

Figure 17: FNAL Outer Coil Return End Y–Z Plane Section

The second-wound Fermilab return end group wound extremely well. There is a noticeable reduction in the amount of outer edge curl in this group, that can probably be attributed to the slight steeping of the final edge angle. This steepening reduces the twist in the group, but increases the amount of hard-way bend. Experience has shown that this increase results in the widening of the conductor lower edge thickness. Therefore, a reasonable amount of steepening appears to reduce outer edge curl, but may require more de-keystoning at the group termination.

Analysis of the Y–Z plane section shows that this may be the case in the second-wound group. The radially inner edges of the conductors appear to be more tightly compacted than the radially outer edges. Insulation thicknesses across the width of the conductors appear to be smaller at the lower edges, indicating that the keystone-widening ratio applied at group termination should be increased. The required amount of increase is quite small, however, and the overall containment of the conductors in this group is very good.

The parts surrounding the Fermilab second-wound group were also manufactured very close to the nominal dimensions, and the tolerance variations were again in the same direction. At the conductor radially inner edge, the measured group dimension was 0.36mm larger than the designed space. At the conductor radially outer edge, the measured group dimension was 0.26mm larger than the designed space. The very small magnitude of these dimensions indicates that the cable-thickening ratio applied at group termination is extremely close to representing the behavior of the actual wound conductor.

The radial positioning of this group was also very good, with each turn contacting the shelf and aligned at the outer radius. However, the last-wound turn of this group shows some damage to the insulation at the conductor radially outer edge. The outer edge appears to have rubbed against the radius of the curing mold in the area between the mid-point of the turn and the nose. This turn is the one that moves axially the most due to application of curing end forces. The damage is minimal and localized, but care should be taken that this turn is tapped down radially during the winding of subsequent coils. Curing end forces appear to have been transmitted only into the three last-wound conductors of this group.

Analysis of Results — Outer Coil Oblique Sections

As mentioned above, dimensional analysis of the oblique cuts of coil ends is less exact. Analysis of the conformance of the conductor to the part shape, and the uniformity of insulation thickness across the conductor width are the most useful techniques for measuring design effectiveness at mid-group. There is some indication in the oblique section through the first-wound group that more mid-group de-keystoning would be in order. However, the Fermilab conductor paths conform very well to shape of the parts, and the compaction of the conductor insulation across its width is uniform. This indicates that the keystone correction factor applied at mid-group is very close to representing the behavior of the actual wound conductor.

If the cable-thickening ratio at mid-group does not allow the conductor enough room to affect its changes, then the parts will be tightly seated at mid-group before they are pushed back to their designed positions. Comparison of the insulation thicknesses at mid-group to those at group termination shows that the cable-thickening ratio applied at mid-group is extremely close to representing the behavior of the actual wound conductor. The bulge in the base curve from the large perturb values used did not seem to effect the winding of the second-wound groups at all. The conductors conform to the shape of the part in this area as well as they do in un-perturbed areas.

The only place the conductors do not conform well to the shape of the parts is seen in a localized area between the last turn of the first-wound group and the inside of the spacer, where a 0.60mm gap exists midway across the conductor width. This gap is seen in the first-wound group only in the cut through the second-wound group and exists between mid-group and group termination. The gap is not seen at the mid-group section of the first-wound group, or at the group termination section, a short distance from it. The cause of this gap is unknown, but it is possible that it exists in the machined inside surface of the spacer. We will closely inspect the surfaces of the parts used in a CERN model magnet.

The Fermilab design uses a shelf under the conductors to provide consistent radial containment of the group. The front edge of the shelf contains an arbitrary Z-axis extension of 3.18mm which extends around the entire front of the shelf. At the start of program BEND development, we felt that the as-wound conductor would be "fluffed" in the winding stage, and that this increased thickness would be eliminated by curing forces in the end. The extension was added to prevent the last-wound "fluffed" conductors from over-winding the shelf and becoming trapped between the shelf and the part in front of the group.

We have since learned that the conductor does indeed change in thickness during the winding process. However, except for the last-wound two or three conductors in the end, there is no mechanism to reduce the thickness. One important conclusion from these realizations is that if the conductors in the coil end are not made to lie in their proper positions during the winding process, they will not be made to do so by the curing process. Also, application of the proper keystone-widening and cable-thickening ratios should provide the proper amount of space for the group, and eliminate the need for a shelf extension.

These conclusions were supported by the winding of this outer coil. The conductor shape change ratios used provided a space for the conductors that was extremely close to the space required. The last-wound turn of each group ended right at the start of the shelf extension. Eliminating the shelf extension will reduce costs by simplifying the machining of the shelf, and eliminating the undercut required in the part in front of it. It would also eliminate the possibility of the shelf extensions of a first-wound group protruding through a thin spacer body into a second-wound group. This happened in this end design, and we hand-trimmed the shelf extension where it protruded. The undercut in the spacer, which broke through into the spacer outside surface during machining, would no longer be required.

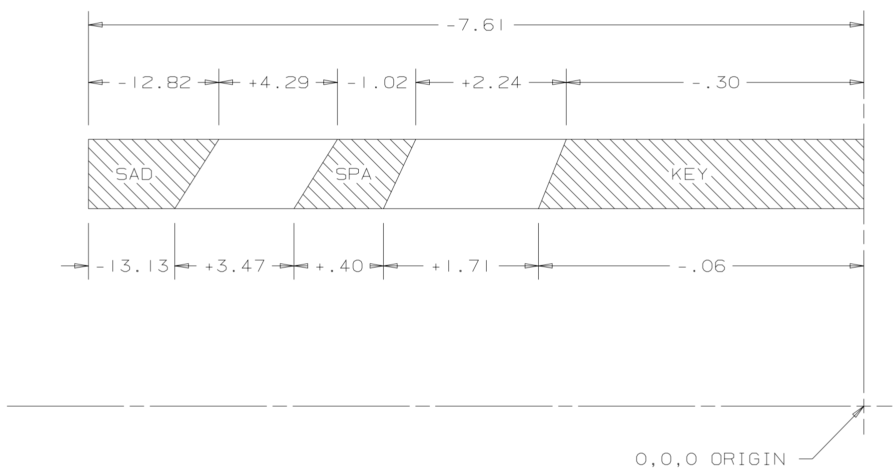

Figure 18: CERN Outer Coil Lead End Y–Z Plane Section

Analysis of Results — CERN Outer Coil Lead End

CERN end parts were used on the lead end of this coil. Because Fermilab did not design this end, we are not really able to analyze the success of the design. However, some general observations can be made. CERN decided to wind this coil without using the thin fanouts between each turn. The parts used, however, were designed to fit the current blocks with the fanouts in place. Because of this, the fit of the spacer and of the saddle around the grouped conductors cannot be expected to match as designed.

Measurements of the sectioned coil end showed that, at the nose, the CERN first-wound group was an average of 1.98mm bigger than the designed length, and the second-wound group was an average of 3.88mm bigger. This is somewhat surprising considering the total thickness of the fanouts that were not included. Because we have no other cured coils with fanouts to compare this to, we don't know if these parts would close to the designed length if wound as designed, but it is hard to imagine that these groups would have closed farther had the fanouts been used.

Based on comparison to the oblique sections, it appears that the conductor is better contained at mid-group than it is at the nose. It is possible that allowing the conductors to group resulted in large conductor shape changes that caused the parts to close first at mid-group, before they reached their designed position. However, the sections does not appear to show conductor shape changes large enough to have resulted in the Z-axis differences seen. CERN will have to compare this end with other ends wound in their traditional manner to understand the effects of this alternate winding technique.

While winding this coil, the CERN first-wound group behaved very similarly to the Fermilab first-wound group. Comparing the cut-up ends, the CERN oblique sections look very much like the Fermilab oblique sections. The conductors lie on the mandrel well in both designs and the mid-group containment is very much the same. The CERN Y–Z plane section is perhaps a little less compacted, but the absence of fanouts contributes to that. The conductors lie on the mandrel as designed in the CERN end, and on the shelf in the Fermilab end.

The second-wound groups wind around the outside spacer surfaces. The configuration of these surfaces of the two coil end designs was noticeably different, and the conductor responded quite differently. We were not able to get the conductor to lay on the mandrel in the mid-group section of the CERN end. The set of rulings on the CERN spacer surface did not appear to allow the conductor to bend in a way that kept it tangent to the mandrel. This resulted in a cured coil that will need filler material added on the inside as well as on the outside of the coil.

It also appeared that the CERN part rulings were the primary reason the group popped up off the mandrel when the winding hold-down tooling was removed. This tendency is difficult to deal with because the hold-down tooling must be removed before packaging the coil for curing. Both the Y–Z and oblique sections through this second-wound group show that the first turn suffered from being forced back into position. The Y–Z plane section shows that perhaps the radially inner edges of the conductors were less compacted. This could be explained by the absence of fanouts. The oblique section shows that the radially outer edges of the conductors were less compacted. In both sections, it is the first turn that does not depend on fanouts that is the most disturbed.

Second Iteration

Based on the analysis of these first two LHC dipole coils wound around Fermilab parts, a second iteration was limited to the second-wound current blocks of the inner coil only. These groups behaved poorly during the winding process and showed unusual conductor shape changes in the cut-up sections. This will result in five new iteration #2 end parts: return end spacer #1 and spacer #2, and lead end spacer #1, spacer #2, and filler #2. While the other groups in the Fermilab design could probably be improved in a second iteration, these groups wound well enough, and looked good enough to be used in a model magnet with confidence.

The second iteration of the inner coil second-wound current-blocks required the redesign of three groups: a six-conductor return end group, and two lead end groups to match it. Analysis was done on the cut-up sections to determine if the conductor shape change correction factors should be modified. This analysis showed that the keystone-widening ratios should be decreased from 0.100 to 0.000(mid-group), and from 0.200 to 0.135(nose), and that the cable-thickening ratios should be increased from 1.064 to 1.082(mid-group), and left unchanged at 1.074(nose).

As in the iteration #1 design, the A-length for these groups was set at 71.00mm to make the body length of the spacers behind them the same as in the CERN design. Because of the change to the first-wound groups A-length, the second-wound groups were shifted forward around 3.20mm as compared to the CERN end. This resulted in an outside group A-length that was 3.95mm larger than the CERN design. The increased difference is mostly the result of a shallower final edge angle.

On the six-conductor return end group, the guiding strip was placed with 0 conductors inside and 6 conductors outside. No origin difference was used. The shift value used was 0.371, the blunt value was 0.176, and the narrow value was 0.000. Program BEND produced a 31.342° inside group final edge angle which was accepted, making the shelf under these groups 1.05mm thick at the nose, tapering down to 0.96mm thick at the extension.

On the five-conductor lead end group, the guiding strip was placed with 0 conductors inside and 5 conductors outside. No origin difference was used. The shift value used was -1.000, the blunt value was 0.070, and the narrow value was -1.000. The inside group final edge angle was made 31.342° to match the return end group. On the one-conductor group, the guiding strip was placed with 0 conductors inside and 1 conductor outside. No origin difference was used. The shift value used was -0.990, the blunt value was 0.278, and the narrow value was -2.000. The outside group final edge angle was made 30.291° to match the return end group.

The iteration #2 design of inner coil lead end filler #2 was just as difficult as the iteration #1 design. Over forty different groups were created in an effort to find a combination that did not violate each other. Again, the BEND option called vary the base curve had to be used in the creation of the one-conductor group to fix the crossing of the two base curves. This option, with a value of 0.3(final) and 0.0(mid-group), forced the base curve of the one-conductor group to stay outside of the base curve of the five-conductor group. Then, the one-conductor group was perturbed outward by 0.74mm between points 4 and 18.

Conclusion

The coil end has proven to be one of the most complicated and difficult-to-define areas of magnet design. The Fermilab end design for the LHC dipole magnet uses the developable surface, grouped end approach provided by program BEND. This method allows the design of a coil ends that are not only the least-strain configuration, but also provide good placement and containment of each conductor in the coil cross-section. Mechanical considerations have been addressed and each group of conductors has been optimized. Inner and outer practice coils have been wound and cured on CERN tooling using Fermilab coil end parts. The ends of these coils have been epoxy impregnated and sectioned, and the resulting analysis has been used as input for a second iteration of coil end parts.

The second iteration was limited to redesign of the second-wound inner coil groups only. Analysis showed that the original configurations for all other inner coil groups will produce reliable and satisfactory coils. However, if an opportunity to redesign these other groups arises, the conductor shape change ratios used in the second iteration should be applied here as well. Because there are many conductors in the outer coil groups, the difference between designed and experienced conductor shape changes appears to be very small. Even so, refinement of the conductor shape change ratios should be considered in any redesign.

When the designed conductor shape change ratios match the behavior of as-wound conductors, the positions of the end parts in the cured coils become very close to the designed positions. This fact, along with the realization that curing forces do little to change the configuration of as-wound conductors, makes the usefulness of shelf extensions come into question. Eliminating the extensions would simplify the shelves, eliminate the need for undercuts, and eliminate the problem of the shelf extension of one part breaking through the body of the part in front of it.

The success of the second-wound outer coil groups in minimizing upper edge curl could perhaps be incorporated into other groups. Steepening the final edge angle a small amount eliminates some of the twist in the conductors, and appears to be beneficial. However, steepening the final edge angle too much can be quite detrimental, as shown in the second-wound iteration #1 inner coil groups. This factor in coil end design will need to be studied further.

Magnetic analysis of this coil end design may indicate the need for adjustment. In spite of efforts to minimize the differences, the configuration of the conductors within each group is different from the CERN design, and some of the group axial positions have been changed. Any re-design or continuation of this collaboration should consider this issue, as well as the conductor shape change, shelf extension, and final edge angle issues mentioned above.

We believe that the Fermilab-designed end parts can be used in a model magnet with confidence. Coils for the first LHC dipole model magnet using Fermilab-designed end parts were wound at CERN on the weeks of 15-Apr-96 through 26-Apr-96. A detailed trip report of the work done on this trip is entitled "Fourth Trip to CERN". It is dated May 13, 1995, and is available in Fermilab Technical Support files. This model magnet is scheduled to be ready for cold testing at the end of June, 1996. Both Norbert Siegel and Diego Perini at CERN expressed the desire to continue this collaboration to the point that Fermilab-designed end parts were production magnet ready. A shorter version of this paper covering only the inner coil design, has also been published at Fermilab [9].

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