Fermi National Accelerator Laboratory

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SSC 40 mm Short Model Construction Experience*

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ABSTRACT

Several short model SSC magnets have been built and tested at Fermilab. They establish a preliminary step toward the construction of SSC long models. Many aspects of magnet design and construction are involved. Experience includes coil winding, curing and measuring, coil end part design and fabrication, ground insulation, instrumentation, collaring and yoke assembly. Fabrication techniques are explained. Design of tooling and magnet components not previously incorporated into SSC magnets are described.

INTRODUCTION

A series of short model dipoles are being built for the purpose of analyzing the Fermilab SSC magnet design. Changes in design as well as methods of construction can be implemented rapidly by testing them in short models before incorporating them into the more costly and time consuming long magnets. The Fermilab short magnet program attempts a number of design alternatives to the already established "baseline" 40 mm SSC dipole. Manufacturing methods are also incorporated which should facilitate the eventual mass production of SSC magnets. Table 1. lists the design features unique to the Fermilab short models. None of these are currently used in the baseline SSC dipoles. All are being analyzed during the construction of short models for their effect on manufacturability, magnet to magnet consistency and ultimate magnet performance.

EARLY CONSTRUCTION EXPERIENCE

Several SSC short models at Fermilab were built according to a different cross section, the NC9[11], than the baseline. This cross section had the same 40 mm bore diameter and cable sizes, but had slightly different conductor placement and wedge sizes. NC9 magnets had many other design differences, including aluminum collars. As a result many of the design variations cannot be meaningfully compared to the baseline. Nevertheless there are some areas in which the NC9 experience is relevant to the present magnets. Analytically designed coil ends were used in NC9 magnets. Winding and curing techniques are identical. Conductor placement has been observed and analyzed. Various ground wrap systems were attempted. NC9 magnets were built both with and without the addition of teflon as a slip plane for coils in the cross section. They were also built both with and without collaring shims and shoes.

COIL WINDING

All coils are wound on laminated mandrels (see Fig. 1). Steel pole keys made by an EDM process are bolted to the mandrel. Turns are wound around the pole keys and around steel winding keys. The steel winding keys are replaced by G-10 end keys after the coil is cured.

Winding tension is a major concern. Tension must be kept within certain limits. These limits vary depending on the type of coil being wound. Upper and lower winding tension boundaries are dependent on three physical restraints. First, the tension must be high enough that no more than a reasonable amount of effort is required to lay the turns into position as they are wound around the end parts. Second, the cable must be wound tightly enough that the uncured coil can be inserted into the curing mold without an undue amount of pressure. If winding tension is too low the coil will sag by an unacceptable amount making it more difficult to insert into the curing mold. On the 4 cm bore SSC short models it is this cable sag which defines the lower boundary for winding tension. The upper boundary is controlled by the mechanical stability of the cable. If tension is too high, the individual strands will try to take a less stressful shape, causing them to come out of lay. The exact values of these boundaries are usually found by trial and error during the initial coil winding. The winding tension for the SSC 4 cm short models is kept between 70 and 75 lbs. on the inner and 80 and 85 lbs. on the outer coils.

COIL END CONSTRUCTION

Fermilab coil ends are made from an analytically derived geometry.[1,5] The goal in creating these geometries is to cause the cable as it is wound around the end to be subject to as little stress as possible. The need for new end geometries developed because the past SSC ends have been difficult to wind and impossible to maintain conductor placement consistency from magnet to magnet. Some magnets have failed due to end problems.

Table 1. Fermilab SSC Short Model Design Features

1. Coils cured using closed cavity mold with hydraulic pressure on ends.

2. Coil ends consisting of:

   a. All parts manufactured from solid G-10.
   b. G-10 keys, saddles and spacers made from an analytically derived geometry.[1] Surface shapes are produced by NC machining using output from computer programs developed at Fermilab.[2,3]
   c. Turns are separated only between current blocks.
   d. Wedges are terminated by solid G-10 spacers.
   e. Spacers incorporate shelves for internal support.
   f. Both "grouped" and "individually determined" options are being tried.[1]
   g. Several manufacturing options are being persued, including machining and molding of different materials.

3. External inner-to-outer coil splice with collet style end clamp system.

4. Kapton only coil insulation and ground wrap system.

5. Elimination of all collaring shims and shoes.

6. Pro-ovalized collar.

7. Square key insertion method.

8. Use of yoke and skinning press.

9. Full length fiducial on skin.

Two different methods of creating cable paths have been developed at Fermilab. These are called the "ellipse on cylinder"[2] and the "developable surface"[3,4] methods. In either case the surface is created by a computer program which automatically generates a surface from the input parameters given by a designer.

Independent of the method of creating the cable paths is the method of stacking the cables within a current block. These are the "individually determined" and the "grouped" methods (see Fig. 2.).

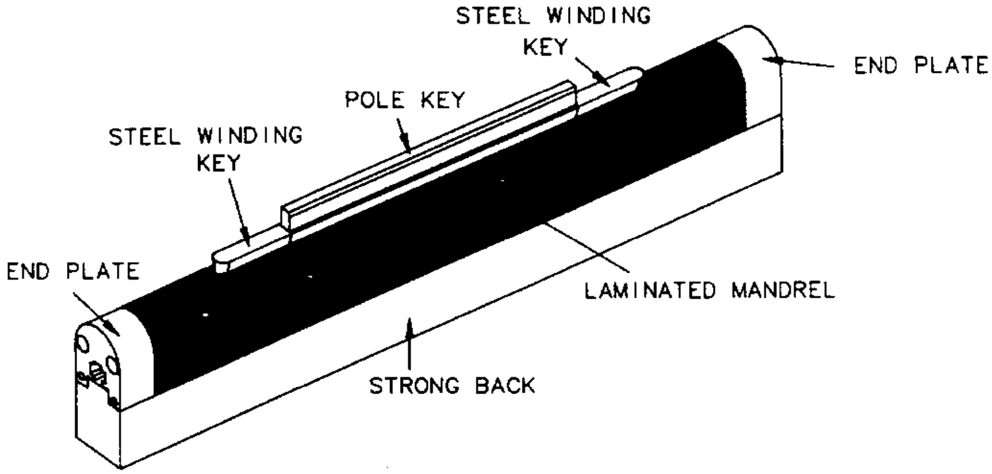


Fig. 1. Laminated Mandrel

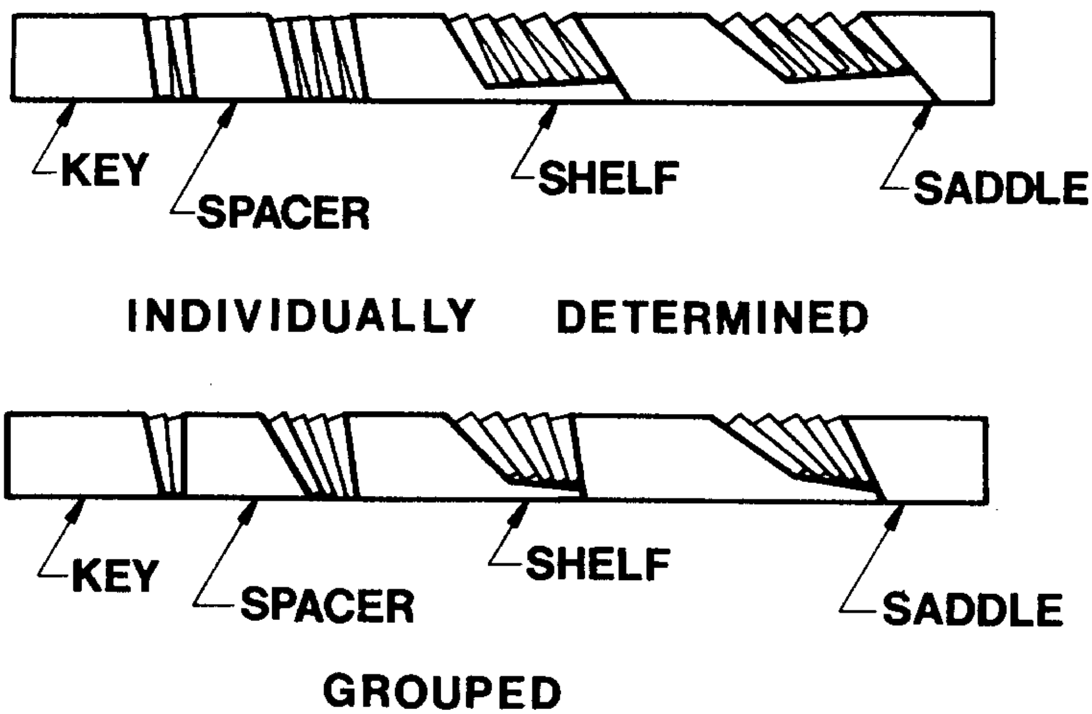


Fig. 2. Cable Stacking Methods

Individually Determined. The minimum stress surface for each turn is calculated individually. This results in the turns not laying directly upon each other. As turns get farther from the pole, the geometry requires that they be stacked at an increasingly larger angle (see Fig. 2.) Small spaces develop between each turn. These spaces typically become filled with epoxy.

Grouped. In the grouped method only the center of each current block is a calculated surface. The turns within each block are layed directly upon each other with no spaces between them. As the turns get farther away from the center or "guiding strip", their internal stresses become progressively higher.

The advantage to the individually determined method is that the stress in each turn is minimized. The advantage of the grouped method is that the spaces between turns are eliminated, further restricting cable movement. There are therefore four different types of ends which can be used on a magnet:

1. Ellipse on Cylinder/Individually Determined

2. Ellipse on Cylinder/Grouped

3. Developable Surface/Individually Determined

4. Developable Surface/Grouped

One objective of the Fermilab short model program is to determine what type of end design is most desirable for the SSC magnet.

Three NC9 magnets were built with Ellipse on Cylinder/Grouped ends. One was cold tested. Two were potted and sectioned. Fig. 3. shows an image of the sectioned end from one of these magnets (F5). These ends were very easy to wind. Conductor placement is consistent between magnets. Some problems still remain. The first turn in each current block has often pulled slightly away from the key around which it is wound, causing gaps as shown. This could be due to an inherent weakness in the grouped method in that it attempts to stack the first cable at a more extreme angle with respect to vertical than a minimum stress condition would dictate. It could also be due to the incompleteness of the model. The model assumes the cable is a homogeneous, infinitely thin strip and not the composite of shapes and materials that really make up a cable. It could also be due to the weakness of the ellipse on cylinder format.[1,5] The developable surface format attempts to correct these weaknesses.

Four magnets have been wound with Ellipse on Cylinder/Individually Determined ends. All four are C358 cross section. A total of five short magnets will be made with these ends of which four will be tested cold. Fig. 4. shows an image of the sectioned end of one of these magnets (DS0307). The end windings do not appear to conform to the individually determined format as readily as they do to the grouped. Conductor placement was poorer than in the grouped case. Winding was also more difficult.

The grouped method of stacking cables appears superior. More work still needs to be done to determine the viability of the grouped format. Developable Surface/grouped ends have been designed which will be incorporated into at least three 40 mm short magnets.

All ends incorporate shelves beneath keys and spacers to radially support the end windings. The shelves function very well as shown on Figs. 3 and 4. End turns no longer protrude into the bore as has been common in past SSC magnets.

When implementing any new end design it is necessary to demonstrate that the coil ends will not have turn-to-turn shorts in operation. Turn to turn hipots were performed on the ends from two magnets (one grouped and one individually determined). Each turn was hipotted successively

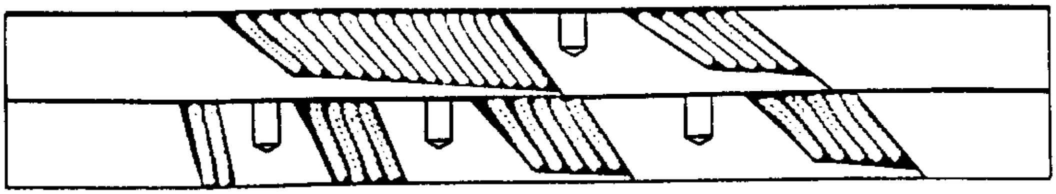


Fig. 3. Ellipse on Cylinder/Grouped End

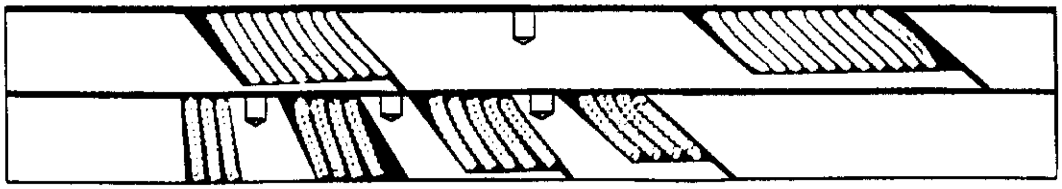


Fig. 4. Ellipse on Cylinder/Individually Determined End

to 100V, 300V, 500V, and then to breakdown. Approximately 100V is required in operation. All turns in F5 passed the 500V hipot and the lowest breakdown voltage was 1700V. On DS0307 all turns passed the 100V hipot. One turn failed at 300V but the next lowest breakdown voltage was over 1200V. The low breakdown voltage was on the first inner coil wound (#101). This coil had been used extensively over a period of several weeks to calibrate and cross check long coil size measurements. It was subject to many compressions in the size measurement fixture and was probably subjected to some mishandling by inexperienced technicians. Just before assembly of the magnet end a turn-to-turn short was found that had not been present immediately after curing. The short was not present, however, after the coil end was clamped and at this point passed the 100V hipot. Because of the unusual handling of this coil we do not believe that its performance is representative of coils manufactured under normal circumstances.[10]

Consequently it does not appear that the Fermilab ends are likely to have a turn-to-turn failure problem. This will be verified by cold testing many magnets.

CURING COILS

Fermilab short coils are cured in a closed cavity mold. Two separate sets of cylinders apply load to the coil (see Fig. 5). The mandrel cylinders apply a radial load to the coil through the mandrel. The platen cylinders apply the azimuthal load to the coil through the sizing bars.[6] The coil is pressed in a two stage process. First the load is applied to the mandrel and then to the sizing bars. The position of the sizing bars is set by stops on the curing mold.

The closed cavity mold is expected to create a uniform coil in both the radial and azimuthal directions. Many short SSC coils have been wound and cured with this process. Six NC9 inner coils and six NC9 outer coils have been produced. Eleven C358 inner coils and eight C358 outer coils have been produced to date.

A problem with the laminated mandrel became evident upon curing. B-stage epoxy from the glass tape extruded into the gaps between the mandrel laminations. This gave the inside surface of both the inner and outer coils a serrated effect. This is unacceptable on the outer coil since it is this surface which contacts the inter-coil ground insulation. A "sheath", or a .015 thick layer of steel was permanently attached to the surface of the outer coil mandrel, giving the cured outer coils a smooth inside surface. This could be done for the inner coil if necessary.

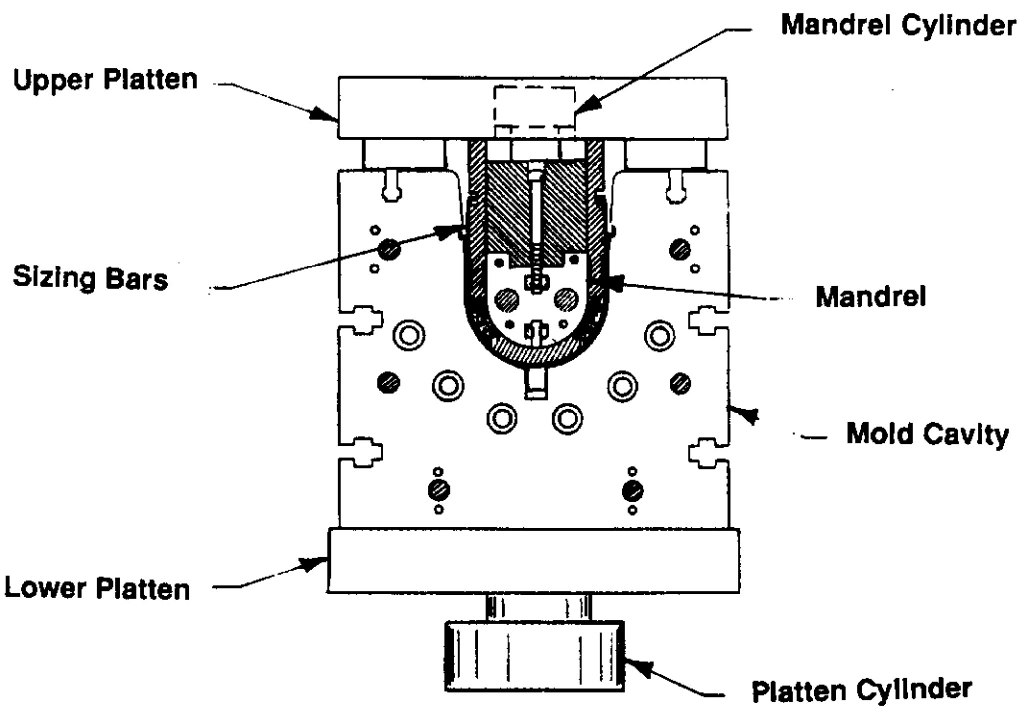


Fig. 5. Closed Cavity Mold

CURING ENDS

When a coil is cured, the curing tooling establishes the inside and outside coil diameters and applies azimuthal pressure to the straight section of the coil. The ends of the coil are also preloaded at this time. End preloading is intended to move the G-10 end parts to their proper positions, thereby compressing the end conductor groups and closing the gaps between the G-10 parts and wedges.

End preloading has been accomplished in two different ways. The long model tooling uses hydraulic force. Fermilab short model tooling will ultimately use hydraulic force as well. Currently three small screws are used to apply end pressure on short coils. Short model experience has shown it to be difficult to achieve proper G-10 end part positioning. The force generated by the small screws has not been sufficient to close the gaps between the G-10 end parts and wedges. Any remaining gap leaves an area in the coil that is not directly compressed by the curing tooling. This also creates end conductor groups that are not completely compressed. This can be seen in coil end sections and is shown in Figs. 3 and 4 where end parts are sometimes not completely pushed back to meet the shelves behind them. Fermilab long model tooling has produced more satisfactory small wedge gaps, although another problem has become evident. The end force is not equally distributed throughout the end parts and does more to compress the last wound end group than the first.

A new approach to these problems is now in the design stage. Each end part will be pushed to its proper position and pinned in place during the winding operation. This will close the wedge gaps and allow the next wound conductor group to be more correctly positioned.

The Fermilab magnet testing program has not shown the lack of end compression or presence of wedge gaps to be a problem. Nevertheless the potential for problems have caused this to be an area for design consideration.

COIL SIZE

All coils are measured before collaring. Coil measurements are used to determine what the expected preload will be. The measurements compare the azimuthal or "arc length" of a quadrant to a steel master of the correct size. Measurements of Fermilab short coils are made on a small portable fixture. The cross section and basic design features of this fixture are shown in Fig. 6. Both coil and master are individually placed in a steel cavity and a load is applied with a hollow bore hydraulic cylinder. The coil size is measured with an LVDT which contacts the back of the cylinder plunger. The master measurement is subtracted from the coil.

The coil is divided for measuring purposes into 24 positions (see Fig. 7). Each of these positions is measured at 12000 coil psi. This measurement determines the average coil size as well as the consistency in size within the coil. Eight of these positions are measured at several different pressures (6000, 8000, 10000 and 12000 psi.) This measurement determines the modulus of elasticity of the coil.

Eleven inner and eight outer C358 coils have been cured and measured. Complete measurements of the most recently cured coil are shown in Figs. 8 and 9. Table 2. lists the relevant data for all C358 short coils currently produced.

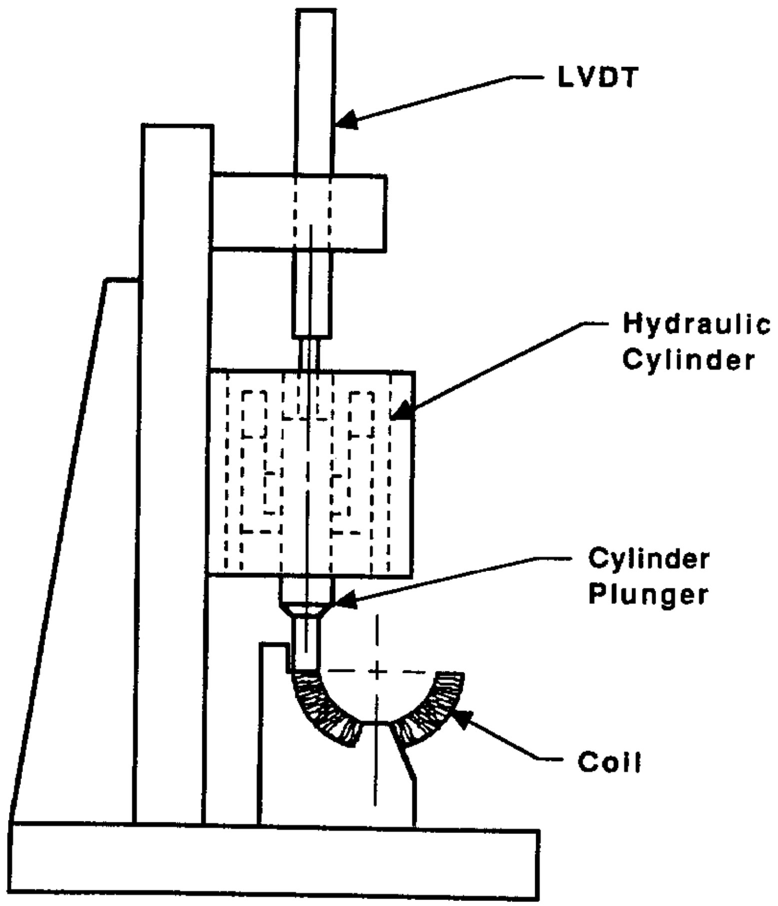


Fig. 6. Coil Measuring Fixture

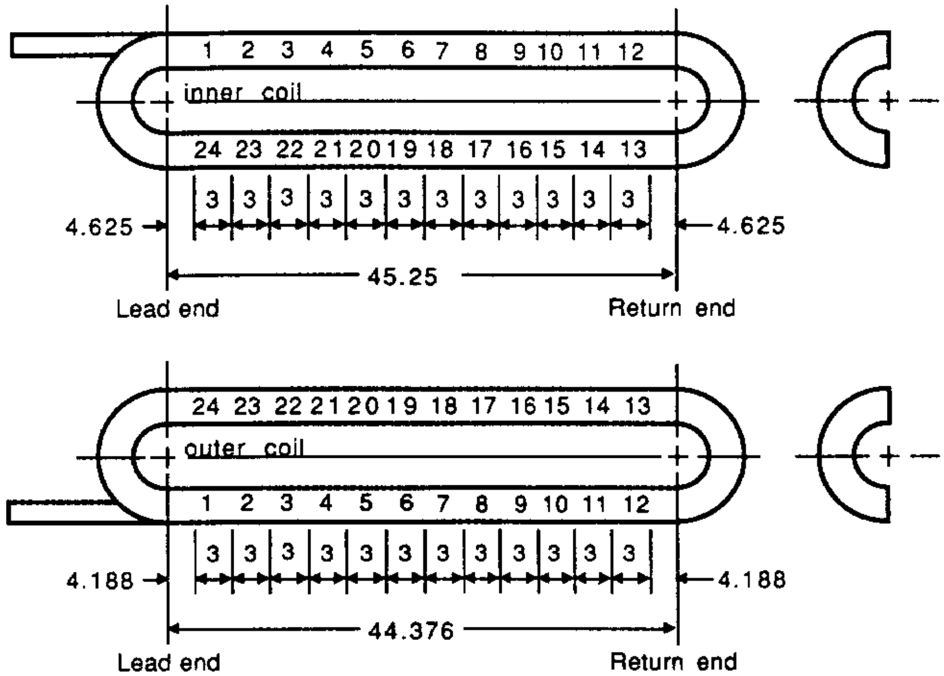


Fig. 7. Coil Measuring Positions (C358 coils)

Table 2. Short Coil Size Measurements

Measured at 12000 psi		Side A			Side B		
Coil No.	Type	Mean Coil size with respect to Master	Range	Std. Dev.	Mean Coil size with respect to Master	Range	Std. Dev.
101	Inner	.0018	+/-.0027	.0019	.0011	+/-.0016	.0013
102	Inner	.0027	+/-.0012	.0008	.0022	+/-.0016	.0001
103	Inner	.0023	+/-.0013	.0008	.0014	+/-.0027	.0016
104	Inner	.0044	+/-.0013	.0008	.0034	+/-.0028	.0015
105	Inner	.0044	+/-.0021	.0013	.0067	+/-.0027	.0019
106	Inner	.0018	+/-.0018	.0010	.0015	+/-.0019	.0012
107	Inner	.0004	+/-.0012	.0008	.0026	+/-.0023	.0012
108	Inner	.0038	+/-.0013	.0008	.0020	+/-.0012	.0007
109	Inner	.0031	+/-.0023	.0011	.0031	+/-.0020	.0013
110	Inner	.0021	+/-.0011	.0006	.0042	+/-.0018	.0010
111	Inner	.0043	+/-.0011	.0007	.0034	+/-.0008	.0005
301	Outer	-.0028	+/-.0013	.0009	-.0010	+/-.0020	.0010
302	Outer	-.0012	+/-.0039	.0020	-.0020	+/-.0021	.0012
303	Outer	-.0011	+/-.0020	.0011	.0012	+/-.0013	.0008
304	Outer	-.0022	+/-.0018	.0011	-.0008	+/-.0016	.0011
305	Outer	-.0016	+/-.0010	.0007	-.0030	+/-.0011	.0007
306	Outer	.0030	+/-.0016	.0008	.0021	+/-.0012	.0007
307	Outer	.0021	+/-.0010	.0006	.0030	+/-.0016	.0010

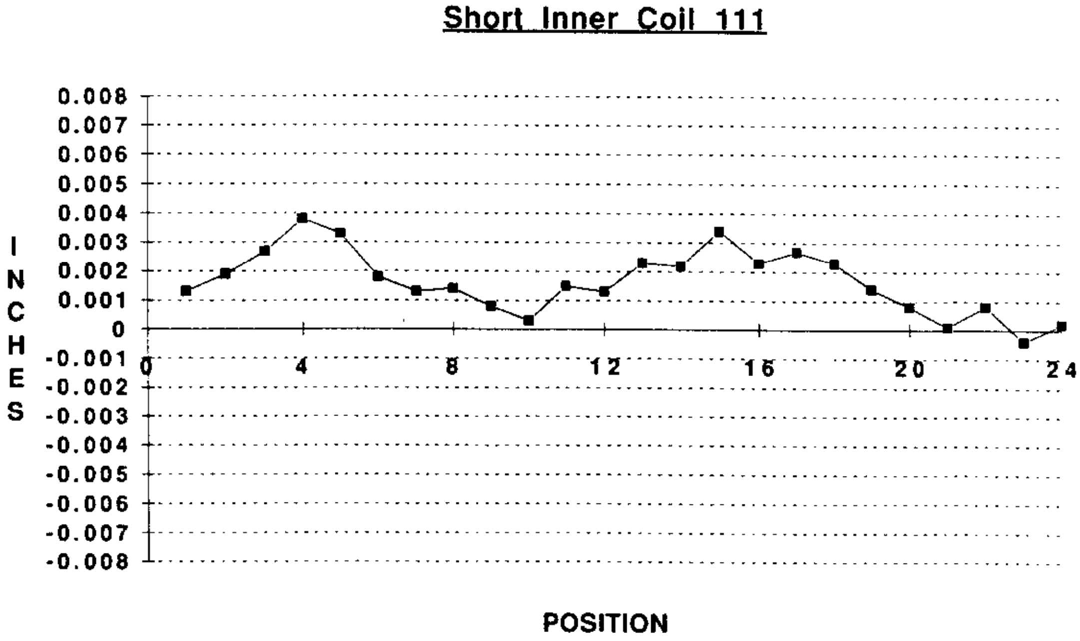


Fig. 8. Inner coil Size Measurements (at 12000 psi.)

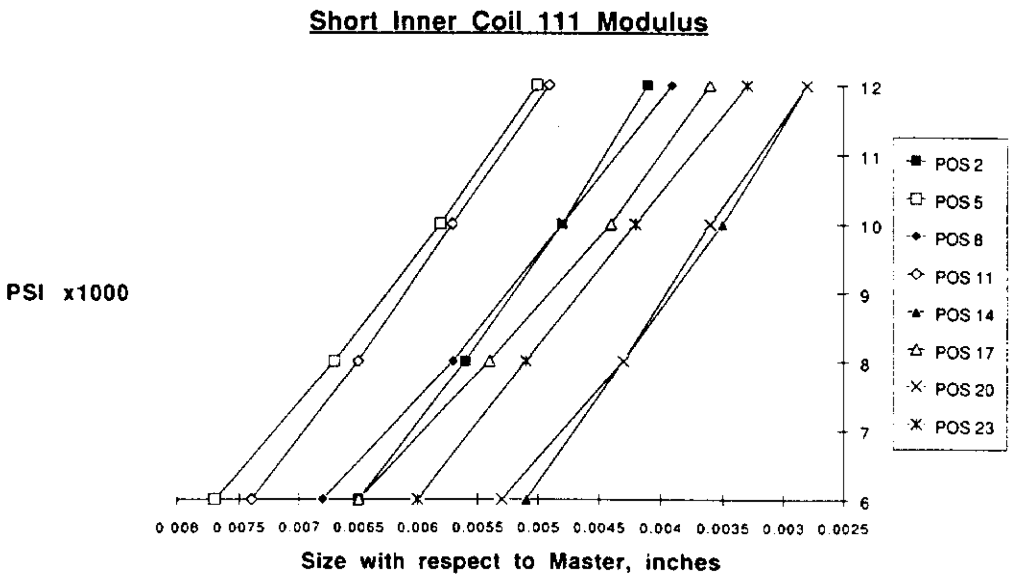


Fig. 9. Inner coil Modulus Measurements

Variations in coil size do not appear to be due to any systematic effects. This could represent a limit on how consistent coils can be made given the component parts (cable, glass tape, wedges and kapton). If so, cable variations of this magnitude will have to be considered in the design of SSC dipoles. Modulus of elasticity for both inner and outer coils is approximately 2×10^6 psi.

It is necessary to know the modulus of elasticity as well as the size of coils when making production magnets. Cured coils in production need to be made in large numbers and matched into pairs according to their size and modulus. Coils with similar sizes are paired together to avoid having errors in the position of the parting plane. This is in contrast to prototype programs in which coils are wound and then immediately put into magnets in the order in which they are wound. For this reason it is necessary to have a production method of measuring coils. The fixture currently being used for short models operates well, but is very labor intensive and could not be used as a production device. Fermilab is therefore developing a measuring system in which load cells and LVDT's are mounted onto the curing press and are used to measure each coil immediately after curing.[13] The short SSC curing press has been instrumented with this equipment. Measurements have been taken on two outer coils and one inner coil.

SPLICES

Inner to outer coil splices in Fermilab short models are located exterior to the coil. The configuration is shown in Fig. 10. This has been done previously in SSC short models built at LBL and Low Beta Quadrupoles made at Fermilab. Locating the splice in this position eliminates the need to break the pole turn away from the rest of the coil when making the splice. Breaking the pole turn away after curing is undesirable because the pole turn is never recured to the rest of the coil. The possibility of damaging the rest of the coil is also decreased since the splice is made farther from the coil body. Quenches in the splice area are also made less likely because the splice is in a lower field area than it would be in the coil body.

The coil end and splice are enclosed in a collet style clamp assembly (see Fig. 11). The lead end configuration is shown. The return end clamp is identical except that there are no splices. The coil is surrounded by a four piece G-10 collet. The G-10 collet is closed by driving on a stainless steel tapered sleeve, thereby compressing the end sections of the coil.

One objective of the Fermilab short model program is to analyze the end clamp system to see if it provides enough preload to the coil. Measurements are taken of the outside diameter of the stainless steel ring before and after the collet is closed. The measured deflections are compared with a finite element analysis of the return end to determine whether the preload in the end is adequate. Fig. 12. shows these measurements for the return end clamp of magnet DS0308. The calculations indicate that these deflections are comparable to a preload of 4000 psi. It appears that the stainless steel shell needs to be made more rigid. Measurements of the deflection of the clamp are also taken during magnet cooldown and powering.

The outer shell, being made of stainless steel, has a relatively low coefficient of thermal expansion. It seems likely that the outer shell will therefore be changed to aluminum and made thicker to maintain higher preloads. A combination of finite element calculations and measurements of end clamps in assembled magnets will be used to determine the thickness used in the final design.

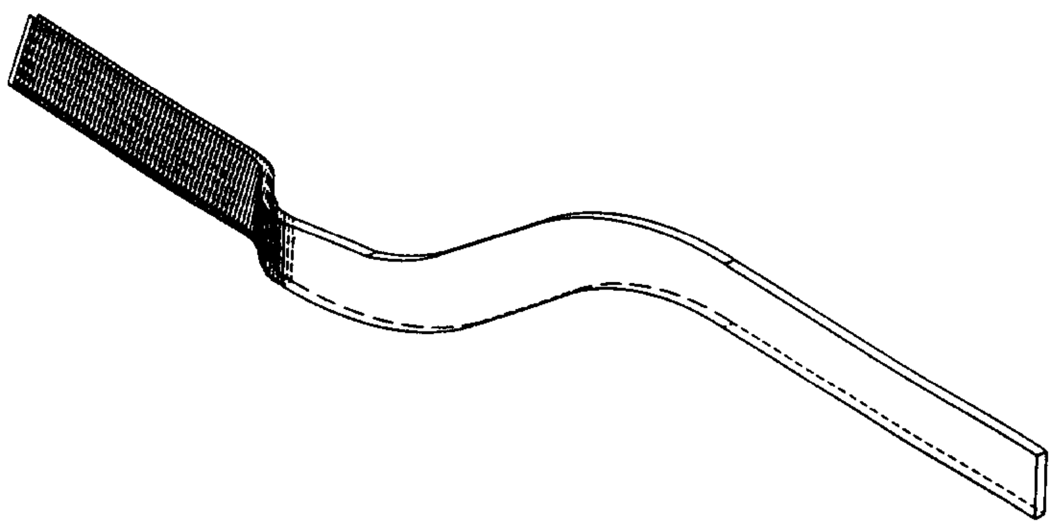


Fig. 10. Exterior Splice Configuration

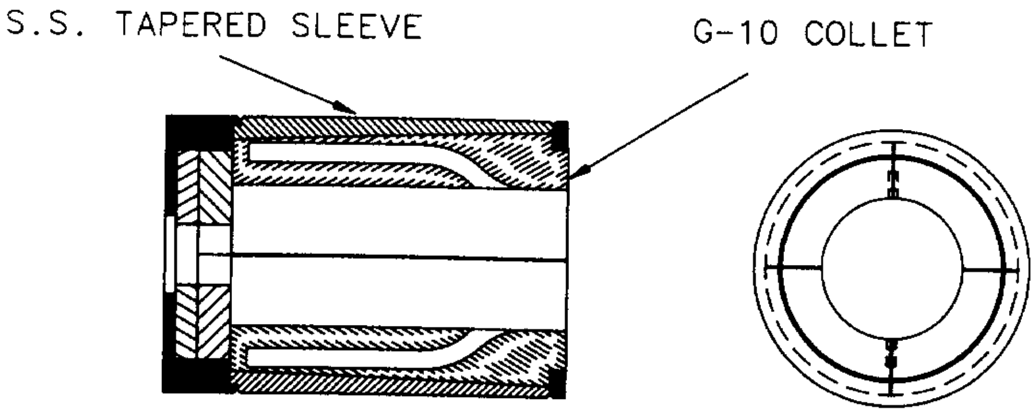
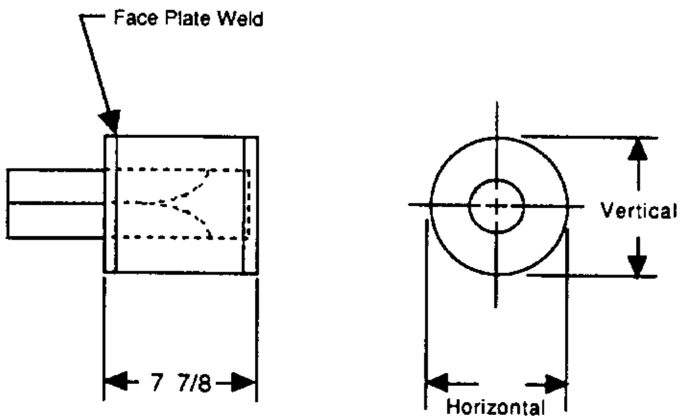


Fig. 11. Collet Style End Clamp



DS0308 Return End Clamp Deflections with Magnet in Warm Free State

Distance from face plate weld	Horizontal	Vertical
.5 inches	-.011	+.010
1.5 inches	-.010	+.009
2.5 inches	-.008	+.007
3.5 inches	-.006	+.006
4.5 inches	-.005	+.005
5.5 inches	-.005	+.006
6.5 inches	-.001	+.002

Nominal Diameter = 6.250 inches

Fig. 12. Return End Clamp Deflections

COIL GROUND INSULATION

The Fermilab short model coil and ground insulation system is shown in Fig. 13. It has several features which are unique to SSC magnets. They are listed in Table 3.

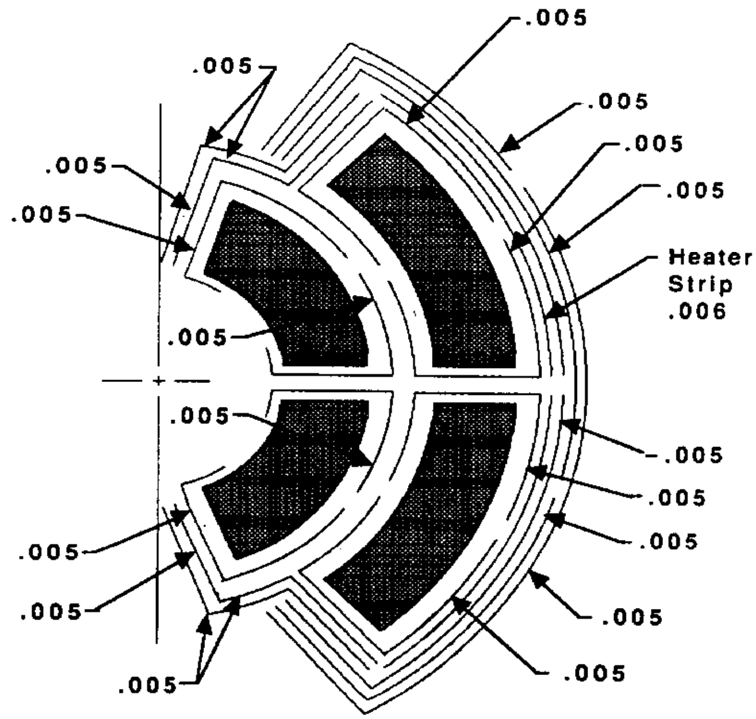


Fig. 13. Fermilab Coil Insulation System

Table 3. Coil Insulation Features

1. All insulating material is .005 kapton. This is the most simple configuration. All previous Fermilab magnets have been built this way.

2. No collaring shims are used. Collaring shims have created many problems in the construction of SSC magnets. They frequently fall out of place. Their primary function is to protect the kapton ground wrap at the poles from deterioration due to contact with the serrated edges of the collar. If this contact does not prove to be a problem, then they are an unnecessary extra part and can be eliminated.

3. No collaring shoes are used. The function of the collaring shoes is also to protect the kapton ground wrap from the serrated edges of the collar. If it is unnecessary, then it should also be eliminated.

4. There is no teflon or any other material except kapton used to provide a slip plane between the radial surfaces of the coils. Fermilab has built many magnets with kapton only insulation. No problems have been encountered in these magnets. It is desirable to eliminate as many low modulus materials inside the coil area as possible. There is also some uncertainty about the stability of teflon in a radiation environment.

The Fermilab coil insulation has been designed to simplify the configuration as much as possible. Tevatron has been used as an example, with consideration given to special SSC problems when necessary. Three C358 magnets (DS0307, DS0308 and DS0309) and one NC9 magnet

(F5) have been built with this insulation system. The NC9 magnet has been cold tested. Questions to be asked concerning the system include:

1. Will the absence of collaring shims allow excessive stress on the kapton insulation at the poles, causing ground shorts during either collaring or powering?

2. Will the lack of collaring shoes allow excessive stress on the kapton insulation at the radial surface of the outer coil, causing ground shorts during either collaring or powering?

3. Will the absence of a teflon slip plane cause any problems related to coil preload or training behavior?

Tests of insulation integrity at the poles and outer surface of the coils without collaring shims and shoes have been completed on one short model (DS0307). The magnet was placed in the press. Full press pressure was applied to the collared coil. At full press pressure the coil was .010 inches beyond closed and the azimuthal coil preload (calculated from pump psi) averaged in excess of 15000 psi in both inner and outer coils. Each coil was hipotted to ground at 5000V. Upper to lower coils were hipotted to each other at 3000V. Hipots were done at the maximum pressure and at several intermediate pressures while the load was being applied. No shorts were detected. This insulation test will be repeated on future magnets.

During cold testing the magnets will be cycled many times to determine if any insulation deterioration will occur during the life cycle of the magnet. One NC9 magnet (F5) has been current cycled 4500 times. No failures developed in the ground insulation.

Experiments are being done to determine whether the kapton only system can provide an adequate slip plane for the layers of ground insulation. One magnet (DS0307) is being assembled and collared three different ways: with kapton insulation only, with teflon added between kapton layers in the same manner as the baseline dipole and with teflon applied directly to the coils. Measurements are taken of two different values: coil psi at the poles and press load. Coil psi at the poles can be measured directly by the strain gages. The press load can be used to determine the approximate parting plane coil psi. Knowledge of these values then allows one to understand the relationship between preload at the parting plane and preload at the poles. This relationship will determine whether the coefficient of friction between the insulation layers is small enough to allow sufficient preload at the poles.

Two magnets (DS0308 and DS0309) have been assembled and will be cold tested with the kapton only insulation system. Another magnet (DS0310) will be tested with teflon slip planes added. Training behavior of the magnets will be compared. If they are significantly different, any of the magnets can be reassembled and retested with an alternate coil insulation system. Results should indicate whether teflon is a necessary part of the ground insulation system.

COLLARING

Fermilab short models are collared using laminated collaring tooling. The tooling consists of several components (see Fig. 14). They are: a laminated structure into which the collared coil is placed, a hydraulic system to drive in the tapered collaring keys, "key supporting bars" to support the tapered keys as they are being inserted into the collars and a transport mechanism to aid in rolling the tooling in and out of the press.

COLLARING METHODS

The tooling provides for two different methods of collaring a coil. Both have been used at various times in SSC magnet fabrication. They are called the "tapered key method" and the "square key method". In the tapered key method a vertical load is applied with the press until the collars are closed just enough to allow the tapered keys to engage. The final portion of closing is

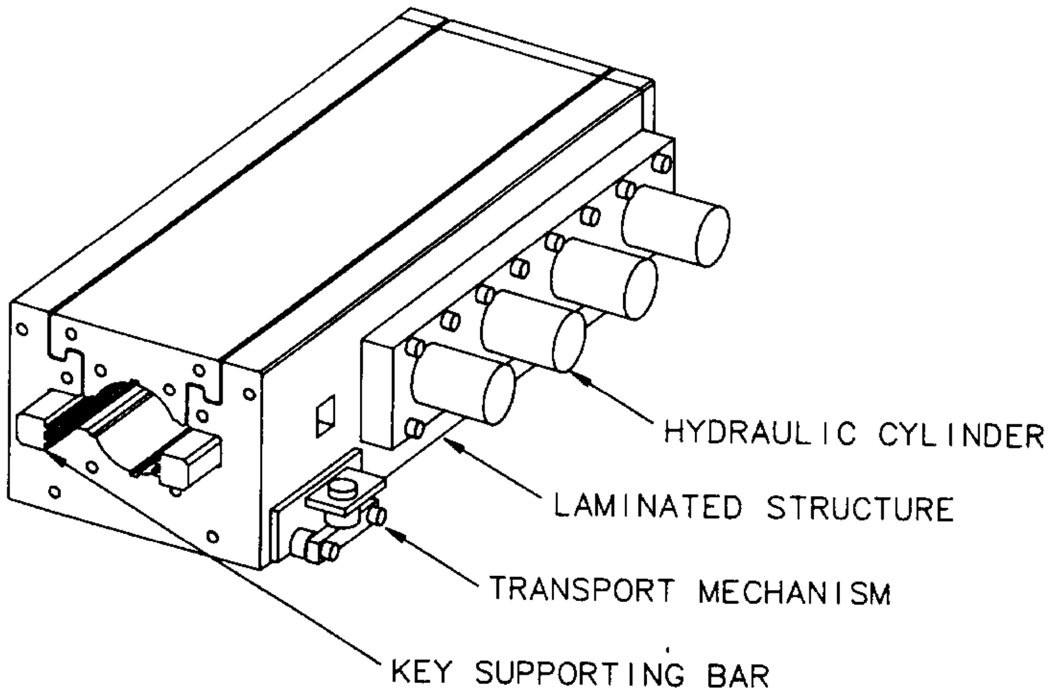


Fig. 14. Collaring Tooling

done by driving in the tapered keys. In the square key method the vertical load is applied with the press until the collars are completely closed. The keys are then pushed in from the side. Very little side force is needed to push in the keys. Either square or tapered keys can be used with this method. The advantage of the tapered key method is that a minimum amount of overcompression of the coils is necessary to collar the magnet. The square key method requires temporary higher preloads during collaring (see Fig. 15). The advantage of the square key method is that the keys are not damaged or "grooved" during collaring. A more consistent relationship between coil size and preload can therefore be achieved.[9] The Fermilab collaring tooling can be used to collar a magnet by either method.

Fermilab short models are collared using the square key insertion method. The collaring procedure is described in Table 4.

Three short models have currently been collared with the square key method. All were overcompressed by .005 before inserting the keys. No turn-to-turn shorts or ground insulation failures have resulted from stresses due to overcompression.

COLLAR/YOKE INTERFACE

All SSC magnets currently use the iron yoke as a mechanical support for the collared coil. Collars alone have proven to be mechanically insufficient to keep the coils adequately contained. Contact between the collar and yoke is necessary to maintain preload, decrease collar deflection under excitation and to transfer the axial component of the Lorentz force to the skin via coil-collar-yoke friction.[8] This can be difficult because the collar material has a higher coefficient of thermal expansion than the iron yoke.

Fermilab short models have a horizontally split yoke with a line-to-line fit between the collar and yoke when cold. This is accomplished by designing the collar configuration such that,

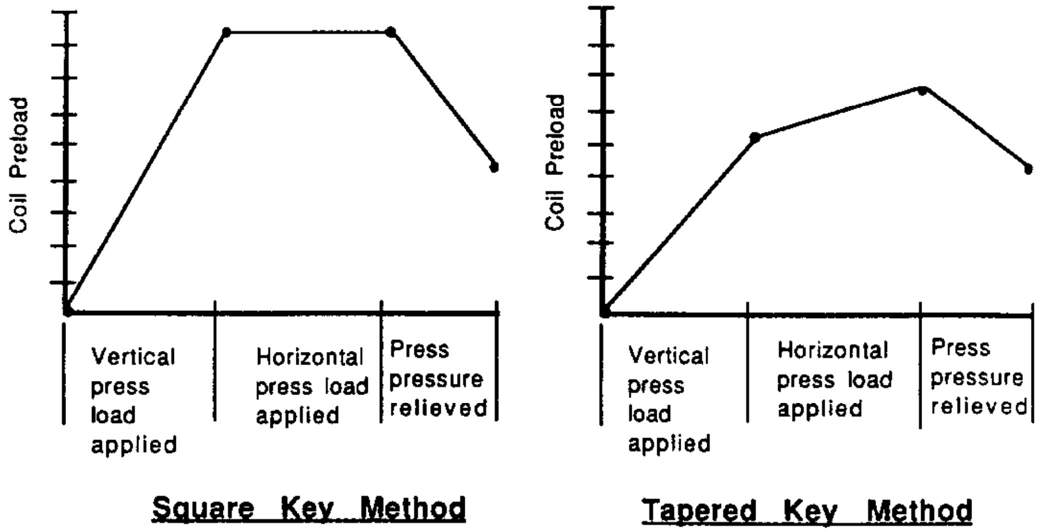


Fig. 15. Preloads from Square and Tapered Key Methods

Table 4. Collaring Procedure (square key method)

1. Place tapered keys on key support bar. They are held to the bar by a spring clip assembly as shown in Fig. 16.

2. Place the preassembled collared coil in the bottom half of the collaring tooling.

3. Roll the assembled tooling (with the collared coil inside it and the cylinders attached to it) into the press. It is supported vertically by belleville washers and guided horizontally by camrollers.

4. Activate the vertical cylinders. The press closes until it bottoms out against the lower laminations. The collars are now completely closed.

5. Activate the horizontal cylinders. The tapered keys are then pushed in until the horizontal cylinders reach their stops. Since the collars are already completely closed, it takes minimal force to place them in their slots. The collared coil is then complete.

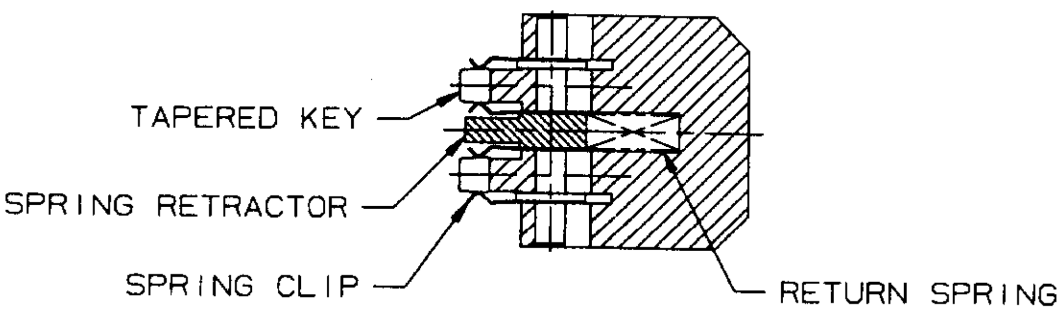


Fig. 16. Key Support Bar

when the collared coil is in the undeflected state it is vertically oval. When the collars are in an undeflected state the centerlines of the two collar halves are separated by .004 (see Fig. 17). This allows the collared coil, after deflections caused by coil preload and changes in size caused by thermal contraction of components, to still contact the yoke when cold.[9] Two magnets (DS0308 and DS0309) have been completed with this design. Several more will be built.

A vertically split yoke has also been designed. It will be used in some short models. The vertically split yoke has certain advantages relative to the horizontal.[7] Since the iron laminations are drawn onto the collars from the horizontal direction, the collared coil can be inserted easily into the yoke while still maintaining the appropriate horizontal interference necessary at room temperature. The vertically split yoke requires a different collar design to achieve the same line-to-line fit when cold.

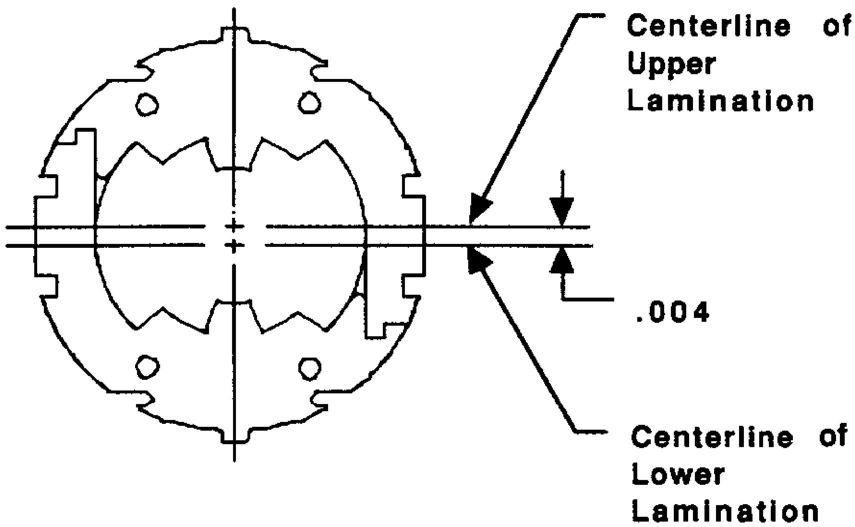


Fig. 17. Pro-ovalized Collar Configuration

YOKE AND SKIN DESIGN

The baseline SSC magnets are contained in a 3/16 inch thick 304 stainless steel skin. Alignment is achieved by use of intermittent fiducial balls.

The Fermilab yoke and skin system is designed to improve the straightness and angular alignment of the magnet as well as completely close the parting plane gap in the iron. To properly close the parting plane gap requires that the skin must also be longitudinally straight. If not, the skin will merely contact the laminations at the high points leaving the intermediate laminations unsupported.

Neither the collared coil nor yoke assembly offer either beam or torsional stiffness. It is therefore necessary to index each and every lamination during the assembly process. This is accomplished by using a full length alignment key. The key indexes to each yoke lamination. It also indexes to the assembly tooling to properly align the angularity of all laminations. The tooling plays an important roll in accomplishing the design goals. It must precisely define the geometry of the assembly prior to welding. Once welded, the shape is fixed.

One SSC short model (DS0308) has been completed with this yoke design. Welding of alignment keys was done by hand. Fermilab's internally developed requirement for twist over the iron length is a maximum of 1 milliradian. Measurements of the fiducial bar indicate that twist in DS0308 is approximately 5 milliradians. This was caused by an out-of tolerance condition in the alignment key. This condition will be corrected by the next short model. Similar magnets produced at Fermilab with alignment keys that are within the specified tolerance have no more twist than the design specifications.

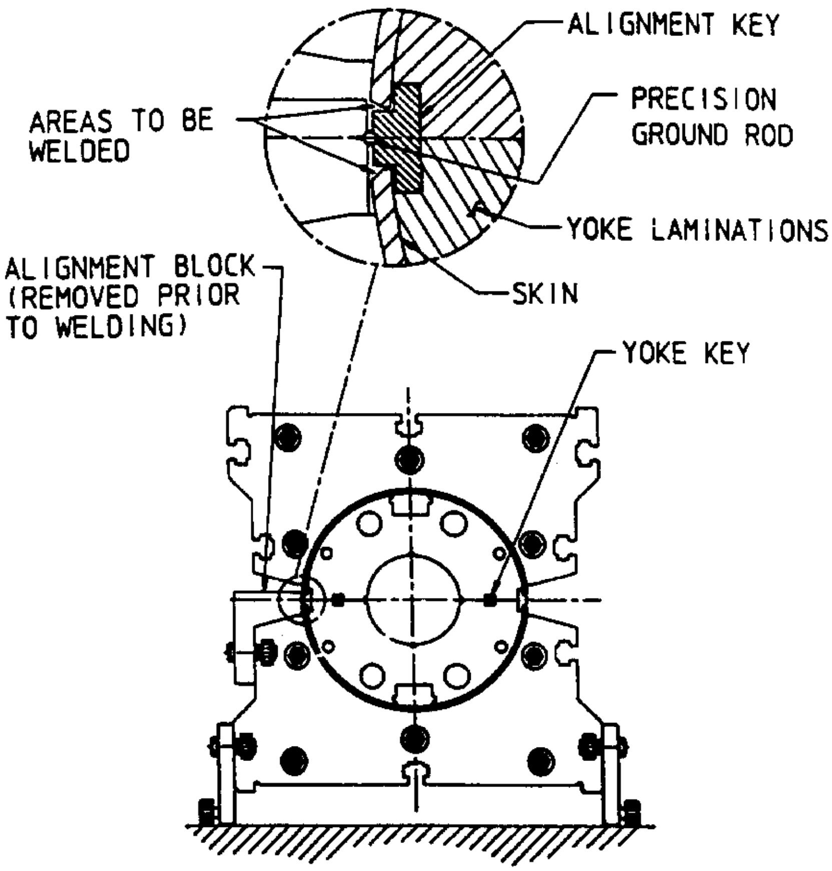


Fig. 18. Yoke and Skinning Tooling

INSTRUMENTATION

Fermilab short models are instrumented with resistive strain gage load cells to measure the coil preload at the poles both during collaring and cold testing. The strain gage system is identical to that used in the baseline design at BNL.[12]

Capacitance load cells are also being mounted in the collars.[14] The capacitance of these cells changes by a measurable amount when they are subjected to an external load, hence a correspondence between pressure and capacitance can be established and used to measure the load applied to these devices. These gages are still in the developmental stage and their inclusion in the short magnets has been primarily to learn what difficulties their use presents. If a reliable capacitance load cell can be produced, they will have the advantage of being very thin (less than 0.030 inches with insulation), and therefore can be used to measure coil stress in places which are currently unreachable, such as inside wedges or at the parting plane.

Strain gages are applied to the skin on magnets to be tested cold. These gages will measure stresses in the skin during many phases of construction and testing. Knowledge of skin stresses during cooldown and coil excitation is needed to make decisions involving the yoke/collar interface design.

CONCLUSION

The Fermilab short model program has been implemented to achieve two objectives: to prove that the Fermilab tooling can produce a working magnet and to test design alternatives which could improve the performance of the established baseline SSC dipole. Several magnets have been built and tested. Continuing development is necessary concerning both design of magnet components and production manufacturing methods. The short magnet program is equipped to continue this process and proceed from it into the next SSC dipole design.

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