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Nb_3Sn Cos(θ) Dipole Magnet, HFDA-05 Production Report

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1.0 INTRODUCTION

HFDA-05 is the fifth Nb_3Sn cosine theta dipole magnet to be fabricated at Fermilab and the fourth to be tested. 4 dipole mirror magnets of this style were also built and tested. Table 1.0.1 lists the previous models in the HFDA series and the numbers assigned to the production reports that describe them.

Table 1.0.1 *HFDA Model Magnet Production Report Numbers*

Model number	Fabrication Report Number
HFDA01	TD-00-069
HFDA02	TD-01-036
HFDA03	TD-01-064
HFDA04	TD-02-025
HFDA03A mirror	TD-03-001
HFDA03B mirror	TD-03-030
HFDM02 mirror	TD-03-029
HFDM03 mirror	TD-05-006

The primary features of HFDA05 are listed below in Table 1.0.2. The magnet cross-section is shown in Figure 1.0.1.

Table 1.0.2 Primary Features of HFDA05

Inner/Outer Cable Strand Type	PIT
Inner/Outer Cable Strand No.	28
Strand Manufacturer	ShapeMetal Innovation
Cable lay direction	Left Lay
Cable Cleaning Fluid	None
Inner and Outer Cable Insulation	125uM x 12mm wide ceramic pre/preg with .75mm gaps surrounded by 125uM thick x 12.5mm wide ceramic pre/preg with .75mm gaps. Outer layer is wrapped to straddle gap in inner layer. Before curing, CTD-1008 binder is painted onto coil.
Bore Diameter	43.5 mm
Coil curing temp.	150C
Inter-layer insulation	3 layers of 125 micron thick ceramic sheet
Ground Wrap	3 layers of 125 micron thick ceramic sheet
Strip Heater design	25 micron thick x 13 mm wide stainless strips. Placed between ground wrap layers.
Coil Reaction Cycle	25C/hr. to 655C, hold for 170 hours
Voltage Tap Plan	See Section 4.3
Impregnation cycle	CTD101K epoxy, evacuated to 20-75 microns, heated to 60C, .04cc/sec flow rate, cure for 21 hours at 125C. See section 5.1
Strain Gauges	Resistive gauges on spacers, both in straight section and at lead end. Capacitive gauges at upper and lower outer pole, in straight section.
Spot Heaters	None.

Spacer Style	Aluminum Bronze half round.
Mechanical shim system	See sections 6.1, 6.3 and 6.4.
End longitudinal loading	None.
Strain Gauges on Skin	Yes. See section 7.1.
Other	
Coil Fabrication Start Date	3/16/04
Cold Mass Completion Date	8/02/04

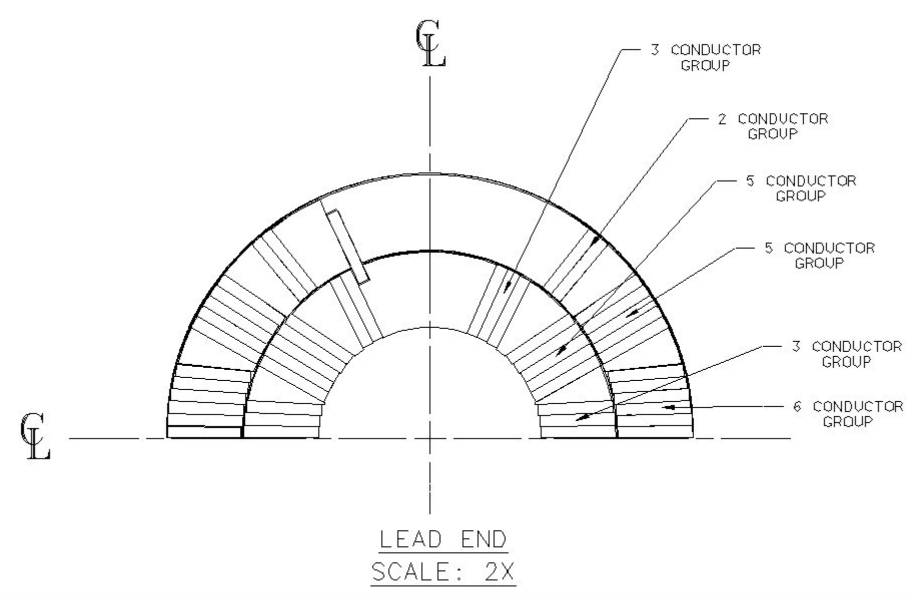


Figure 1.0.1 *HFDA cross section*

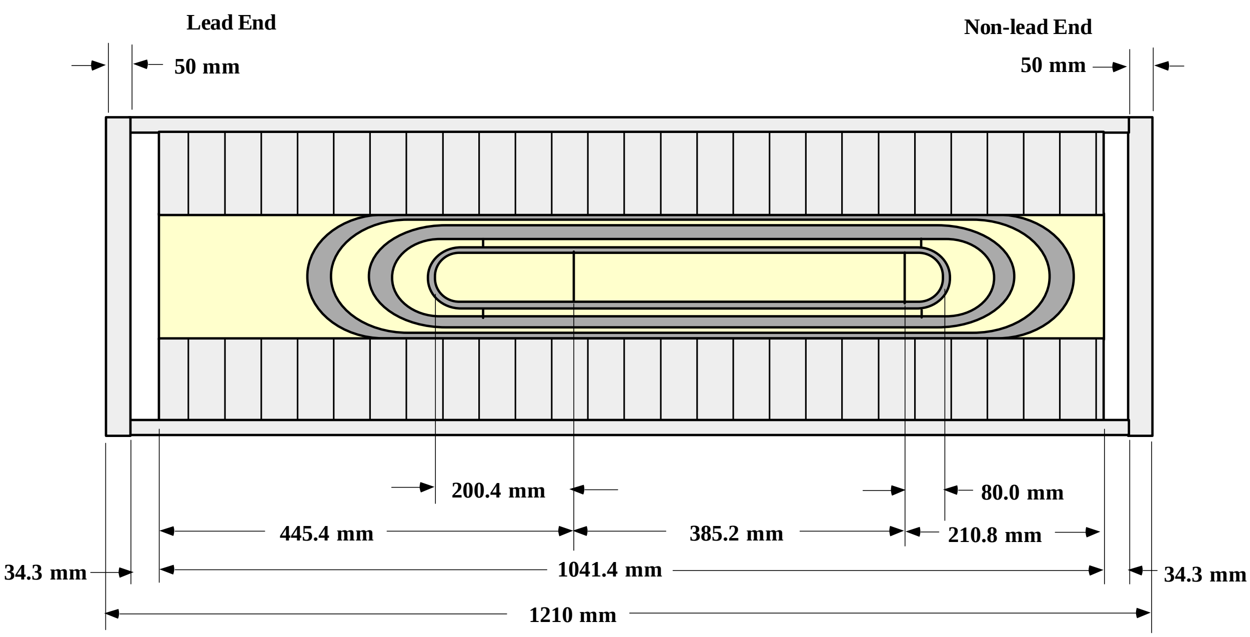


Figure 1.0.2: *Longitudinal parameters of HFDA-05*

Fig. 1.0.3 shows the completed magnet ready to be tested.

Fig. 1.0.3 *Photograph of HFDA-05 ready to be shipped to VMTF*

<u>Some important features of HFDA-05</u>:

Most specific features of HFDA-05 are similar to those for HFDA-04 and are listed in the production report for that magnet. Important features of HFDA-05 are listed below.

- The most significant change made between HFDA-04 and HFDA-05 is a change is strand from Modified Jelly Roll made by OST to Powder in Tube made by SMI, as had been done for the previous mirror magnet HFDM-03. Modifications to the reaction cycle were therefore necessary.

- The lower coil-half (HFDAH-012) was reused from the previous mirror magnet HFDM-03. Only one new coil half was produced for this magnet. The two half-coils were therefore reacted and impregnated separately.

- The end-saddles were configured so that the lead cable comes out in the mid-plane, as in HFDA-04. The entire splice joint is therefore well supported at all stages of the magnet operation. See Section 5 of the HFDA-04 production report for more details on splice joints.

- None of the outer pole pieces had extensions to connect them to the spacers. There is therefore no accurate azimuthal alignment between the coils and the yoke. Alignment was done by hand, using "scale" measurements while installing spacers. This was done to prevent large variations in azimuthal stress between the left and right sides of the coil assembly during and after yoking. (see also section 6.4).

- HFDA05 yoke gap was, by design, closed after cooldown. Previous HFDA models had an open yoke gap during cooldown and excitation.

2.0 STRAND and CABLE

Strand for HFDA05 was made by ShapeMetal Innovation (SMI) using the Powder in Tube Process. Billets numbers were SMI#170, 171, 173A and 173B. The nominal diameter of the strand was 1.00 mm. The Cu to non-Cu ratio was 1.15. Strand description is shown in table 2.0.1.

Table 2.0.1: *Strand parameters for HFDA05.*

Billet ID	170's
Strand diameter, mm	1
I_c(12 T), A	~700
Cu fr., %	53.6
No. of filaments	192
D_{eff}, μm	50
Geometric filament size, μm	-
RRR	>250
No. units	5
Total length, m	4000
Average length/unit, m	1000
Twist pitch, mm	20

2.1 Cable Mechanical Parameters

Rutherford type cable with 28 strands was manufactured at Fermilab. Cable reel number was HFDA-30609-28-2. Cable mechanical parameters are listed in Table 2.1.1. Cable used in HFDA05 did not include a stainless steel core.

Table 2.1.1: *Cable parameters as provided by FNAL TD.*

Parameter	Unit	Design Value	Measured Value
Strand Diameter	mm	1.00 mm	N/A
Mid-Thickness	mm	1.8 mm	N/A
Width	mm	14.24 +/-.025 mm	N/A
Keystone angle	deg	0.9 deg	N/A
Pitch Length	mm	110	N/A
Number of Strands		28	28
Lay Direction		left	left
Packing Factor	%	88.6	N/A
Reel Number		HFDA_030609_28-2	

2.2 Cable Electrical Parameters

During magnet fabrication, both virgin extracted strand samples were placed as witness samples, first in the oven when the cable was pre-annealed, then on the reaction fixture inside the retort, along with the coil assembly, during the reaction cycle (see section 4.1 for reaction cycle details).

Electrical tests were performed on the witness sample strands after reaction of the coils. Table 2.2.1 shows measurements made on these samples at SSTF for coils HFDAH-012 and HFDAH-013. Figures 2.2.1 and 2.2.2 show measurements made on these samples at SSTF for coils HFDAH-012 and HFDAH-013, respectively. Figures 2.2.3 and 2.2.4 show the predicted short sample limits for coils HFDAH-012 and HFDAH-013, respectively.

Table 2.2.1: Measured critical parameters of the witness samples of coils HFDAH-012 and HFDAH-013.

Strand ID	I_c(A),n at	15 T	14 T	13 T	**12 T**	10 T	8 T	6 T	Barrel	Probe	I_s(A),B_s(T)	RRR
HFDA012 (HFDM03)					Actual HT was 170 h at 655°C							
VG. 173B			412,44	502,48	**603,49**	857,53	1195	1702	SS	2		81
VG. 171			403	Q 468	**Q 551**	Q 757	Q 1019		SS	2		
Extr. #1			354	Q 401	**Q 462**	Q 609	Q 785	Q 800	SS	2		65
Extr. #2			378,34	460,36	**554,35**	781,38	1096,39	1560	SS	2		125
Extr. #3			398	493	**589**	831			Ti	2		
Extr. #4			Q 273	Q 314	**Q 361**	Q 470			Ti	2		90
HFDA013					Actual HT was 170 h at 655°C							
VG. 173A		312,49	381,48	462,51	**550,48**	783,51			SS	1		223
VG. 170		337,48	412,49	498,51	**595,51**	839,57			Ti	2		51
Extr. #1		281,22	366,22	480	**600**	895			SS	1		305
Extr. #2 (171)		308	404	520	**660**				Ti	1		4?
Extr. #3		308,25	407,25	515					Ti	2		5

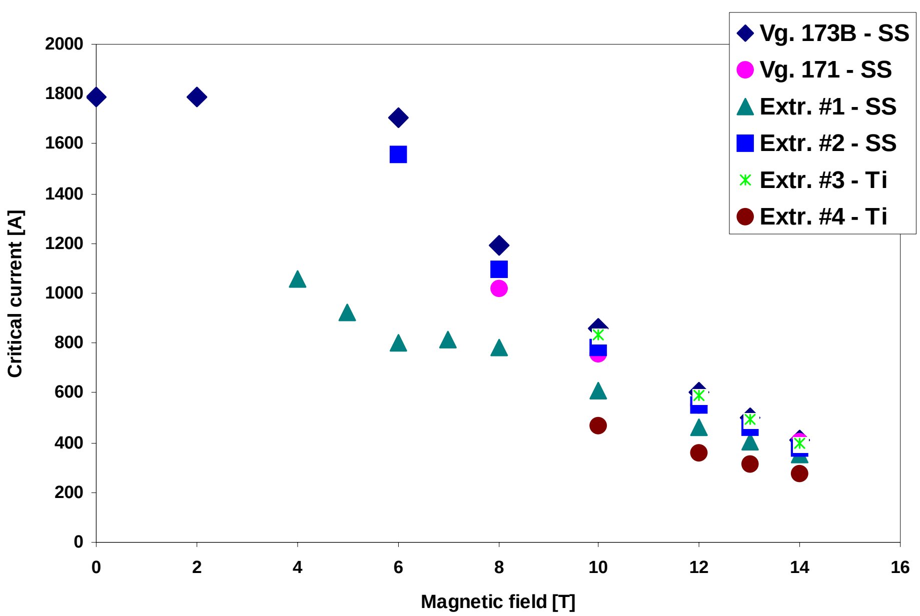


Figure 2.2.1: *I_c of witness samples of coil HFDAH-012.*

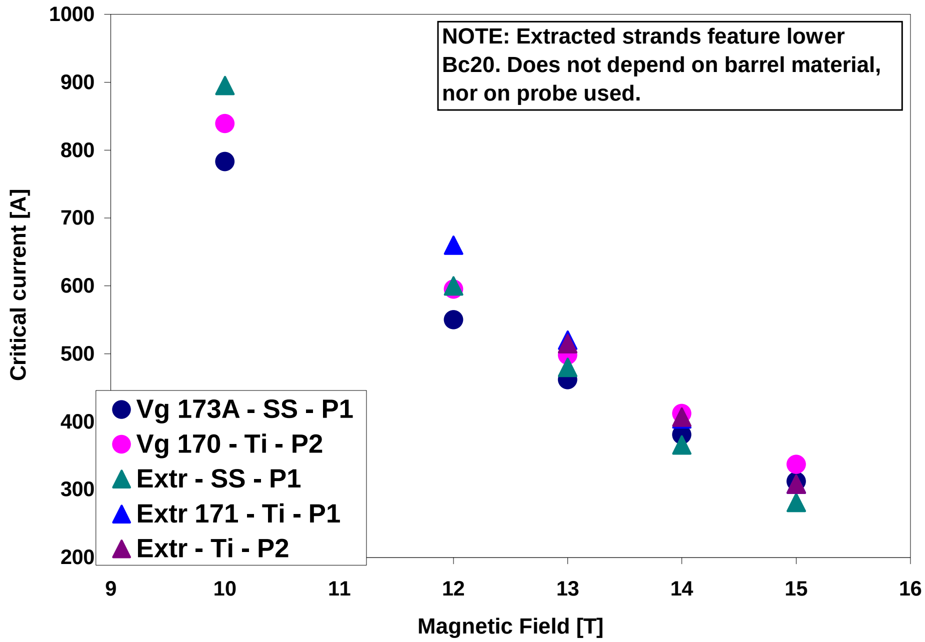


Fig. 2.2.2: *I_c of witness samples for coil HFDAH-013.*

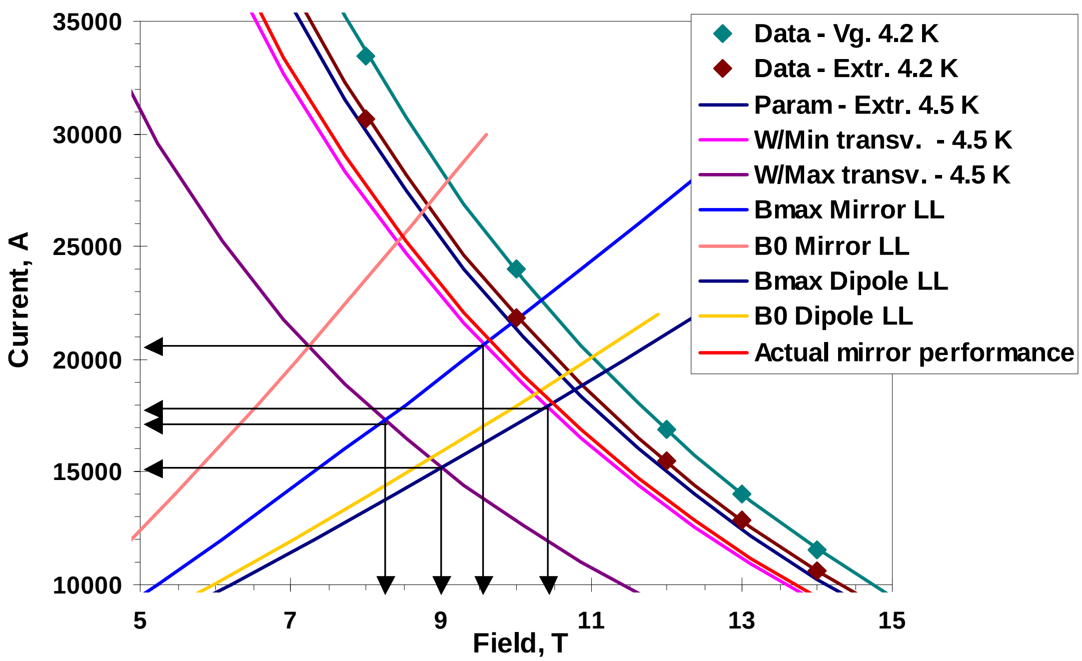


Fig. 2.2.3: *Short sample limit range for half-coil HFDA012 in a mirror and dipole configurations. Maximum transverse pressure was assumed to be 100 MPa. According to strand tests, this leads to an I_c degradation of 10 to 40%. The mirror performance was consistent with a 7% I_c transverse pressure degradation.*

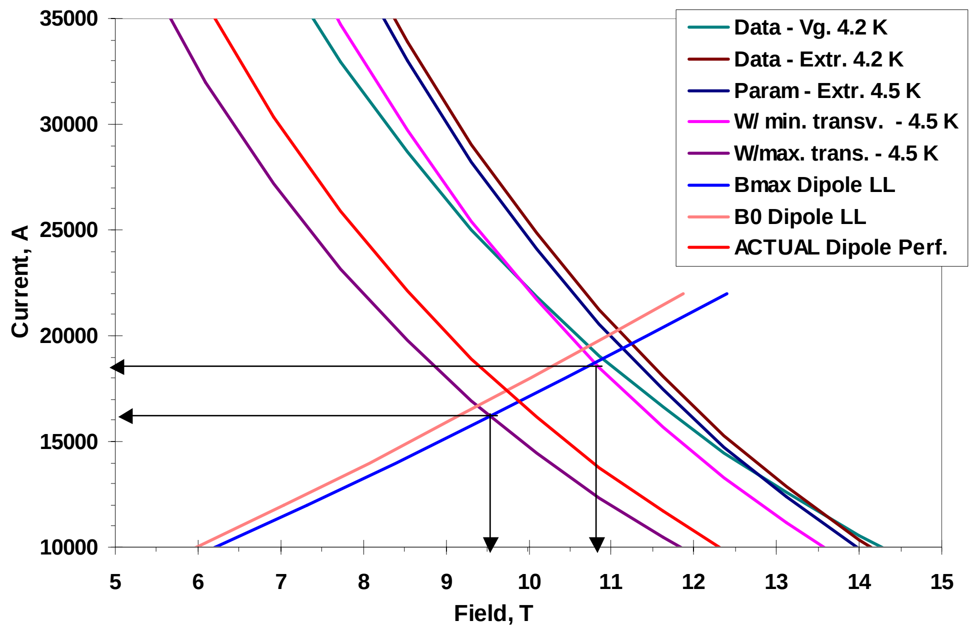


Fig. 2.2.4: *Short sample limit range for half-coil HFDA013 in a dipole configuration. Maximum transverse pressure was assumed to be 100 MPa. According to strand tests, this leads to an I_c degradation of 10 to 40%. The dipole performance was consistent with a 33% I_c transverse pressure degradation on coil HFDA013, which limited the magnet.*

3.0 COIL FABRICATION

3.1 Cable and Wedge Insulation

No formal cleaning process was used on the cable before insulating.

Before insulating, the cable was heat-treated at 200 ^{o}C for 30 min to reduce residual stresses in the cable. These stresses come from a combination of the strand and cable manufacturing processes.

HFDA-05 coils were the first to use ceramic insulation with binder applied by an outside manufacturer (CTD). Previously, cable was wrapped with dry ceramic insulation, then painted before curing with CTD-1008 binder.

Standard 5 mil (125 micron) ceramic tape was used, wrapped in two layers. The first layer was dry (i.e., no binder) 5 mil woven ceramic tape wrapped with .75 mm gaps. The second layer consisted of the same ceramic tape, but with CTD-1008 binder added by the manufacturer. It was also wrapped with .75 mm gaps, with the tape straddling the gaps from the first layer. The first layer was dry so that the binder would not be in direct contact with the cable.

Both coil halves (HFDAH-012 and HFDAH-013) were wrapped with the same insulation system. HFDAH-012 was fabricated, then used in mirror magnet HFDM03. After testing, it was removed and paired with HFDAH-013 to make HFDA05. As a result, several months passed between the insulation of HFDAH-012 and HFDAH-013. During that time, the factory pre-preg ceramic binder had become somewhat cured, causing coil HFDAH-013 to be larger azimuthally than HFDAH-012. On both coils, CTD-1008 ceramic binder was painted on the outside surface of the coil before curing.

3.2 Coil Winding and Curing:

End part material was bronze. Parts were machined to fit the coils in the final, compressed state. In order to allow the parts to fit onto the uncompressed coil during winding, they were reworked by hand from the original design. This resulted in spaces between coil end turns and end parts after curing, which were filled with a mixture of ground ceramic tape and CTD-1008 binder.

Also, a layer of 2 mil thick mica was placed between each wedge surface and the insulation. The mica is used so that the cable does not stick azimuthally to the wedges. It is believed that, during excitation, if the wedges are bonded to the turns, the epoxy can crack between the wedges and turn, causing possible quenches. An identical mica sheet is also placed over the pole piece on the inner coil, along the straight section, from back of key to back of key, for the same reason.

Curing is done in a closed cavity mold manufactured to the nominal coil size. Curing is done at 150 degrees C for 1/2 hour. A 5 mil azimuthal shim made of kapton, placed on the sizing bar, and no radial shims, were used during curing.

After curing the inner coil, inter-layer insulation was installed on the outside perimeter. Inter-layer insulation consisted of 3 layers of 5 mil thick ceramic cloth. The outer coil was then wound and cured at 150C. The inner coil is consequently cured twice.

3.3 Coil Mechanical Measurements:

Each coil half was measured after curing, but before reaction, at various pressures. Azimuthal coil size data is shown in Figure 3.3.1. Coil size shown is "with respect to a steel master of the nominal (design) coil size." Coil size data is used to determine the shim size of the cavity in the reaction fixture. In the case of both coils 012 and 013, no shimming was done to the cavity. The coils were therefore reacted with the cavity at the nominal size. Since in both cases the coils are smaller than nominal azimuthal size at 3 MPa, the coils are subjected to very low pressure in the fixture before reaction. During the reaction process, they are expected to grow in size to fill the reaction mold. Very low pressure is used to avoid tin leaks during reaction.

Although both coils 012 and 013 were wound and cured under the same conditions, coil 013 is larger than coil 012. This is due to the partially cured adhesive of coil 013 (see also section 3.1).

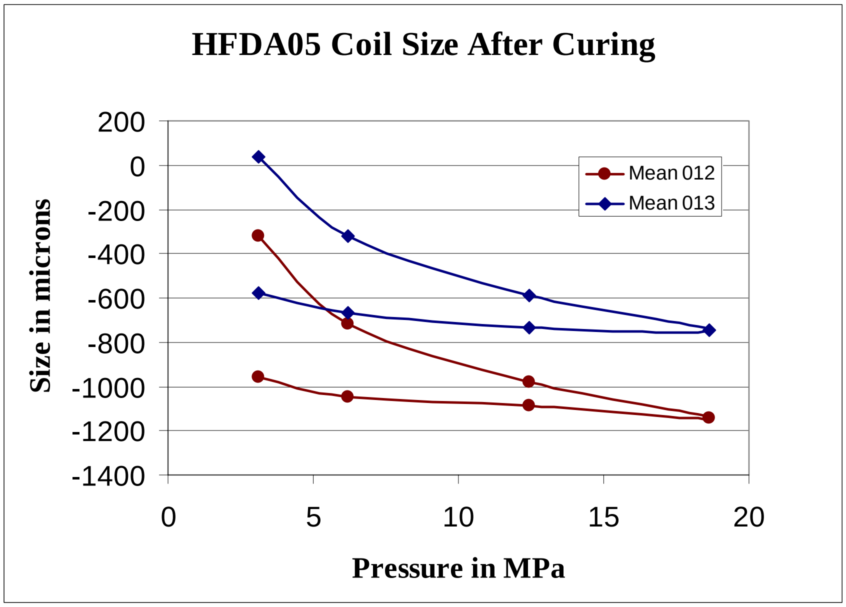


Fig. 3.3.1: *Coil size after curing.*

3.4 Coil Electrical Measurements:

Electrical measurements (L, Q and R) were taken on both the half coils before placing them into the reaction fixture. The data is shown in Table 3.3.1. Both the coils have similar values and match the theoretical estimates, which indicate that the coils are free from turn-to-turn shorts. The inductance, L and Q were measured at 1 kHz and at 20KHz. Resistance was measured using four-wire technique at 0.1 A. Coil 012 was measured on a wooden table with no mandrel. Coil 013 was measured on a wooden table with an aluminum mandrel.

Table 3.4.1: *Electrical measurements on the cured half-coils*

	Resistance mΩ	Inductance μH @ 20 Hz	Inductance μH @ 1KHz	Q @ 20 Hz	Q @ 1KHz
HFDAH-012	57.8	242.618	220.489	.42	6.21
HFDAH-013	57.1	236.887	242.747	.49	6.00

3.5 Ground Wrap System:

Ground wrap, consisting of three layers of 125 micron ceramic cloth, was placed around the outer coil.

4.0 Coil Reaction

4.1 Reaction Cycle

Each half-coil was placed into an individual reaction fixture as shown in Figure 4.1.1. The reaction fixture was installed into a retort as shown in Figure 4.1.2.

Figure 4.1.1: HFDAH-013 in reaction fixture.

Figure 4.1.2: In retort with witness samples

The reaction cycle for HFDA-05 is shown in table 4.1.1. Actual cycles for coils HFDAH-012 and HFDAH-013 are shown in Figures 4.1.3 and 4.1.4. The horizontal axis in the figures represents the sampling rate for the data of 2 minute intervals for coil 012 and 1 minute intervals for coil 013 respectively. The three lines in the reaction cycle figures represent the readings from three thermocouples placed inside the reaction oven. Thermocouples were placed:

- Inside the oven but outside the retort.
- Inside the retort but in the space outside the reaction fixture
- Attached directly to the surface of the reaction fixture.

Table 4.1.1: *Reaction cycle used in HFDA-05*.

	Ramp Rate **^oC/hr**	**Temperature** **^oC**	**Dwell Time** **hr**
Step – 1 ramp up	25	28-655	
Step – 2 soak		655	170
Step – 3 ramp down	-15	655-28	

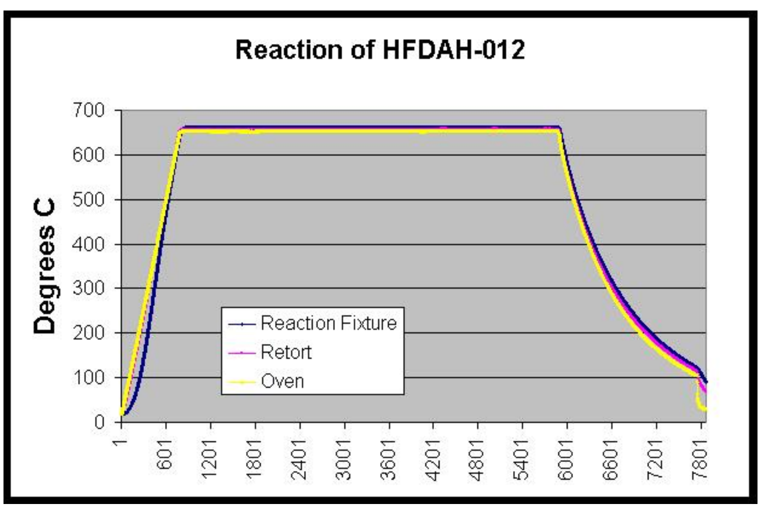


Figure 4.1.3: *Reaction cycle of HFDAH-012*.

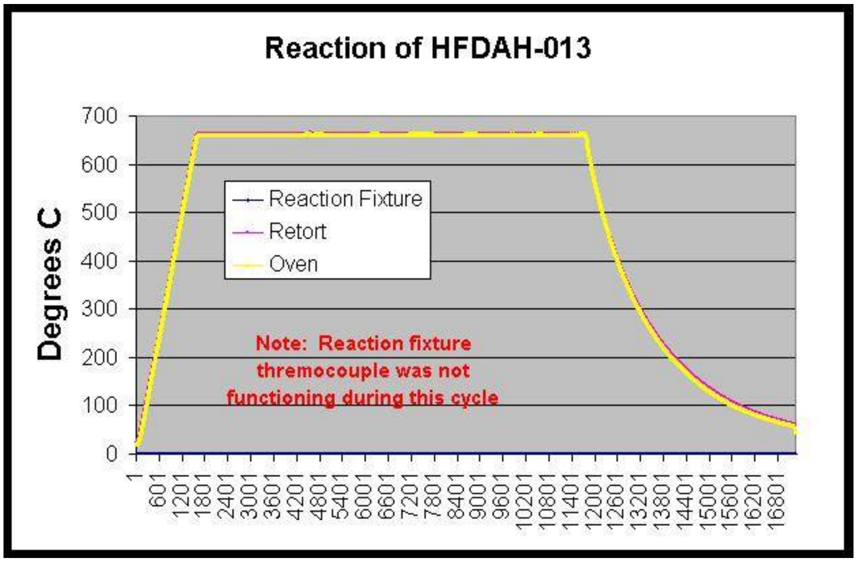


Figure 4.1.4: *Reaction cycle of HFDAH-013.*

4.2 Strip Heaters:

Ground wrap consisted of 3 layers of .005 inch (125 micron) thick ceramic cloth. Quench protection (strip) heaters were placed radially outside the outer coils, between the first and second layers of ground wrap. They consisted of 25 micron thick by 12.7mm wide stainless steel strips. Each quadrant contained one strip, placed approximately over the center of the largest current block. Strip heaters are inserted by hand, after reaction but before impregnation. The heater-wiring schematic is shown in Fig. 4.2.1.

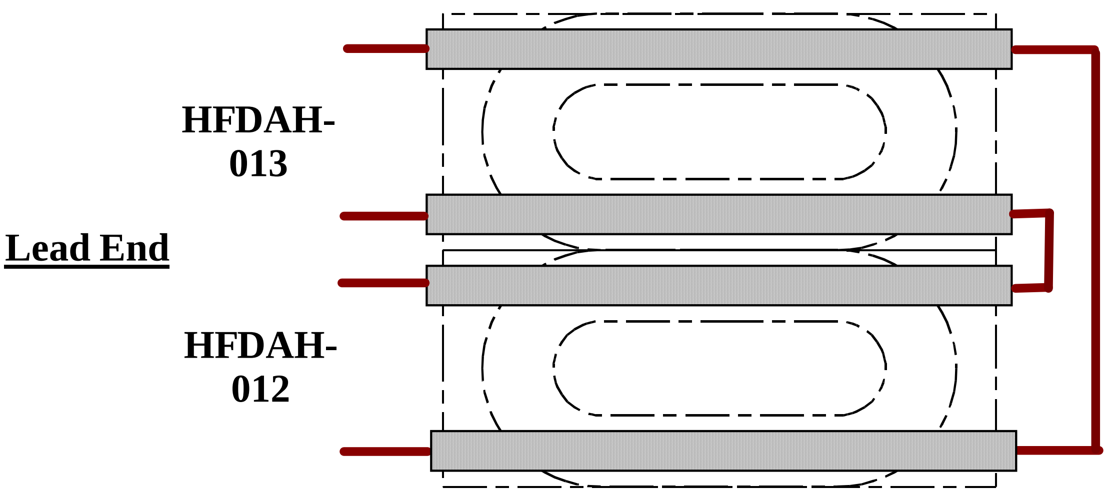


Figure 4.2.1: *Quench Protection heater wiring schematic.*

4.3 *Voltage Taps and Spot Heaters*

Voltage taps were mounted to the coils as shown in Figure 4.3.1. HFDA05 did not contain spot heaters. Figure 4.3.1 shows coils as viewed from the inside (looking at concave surface).

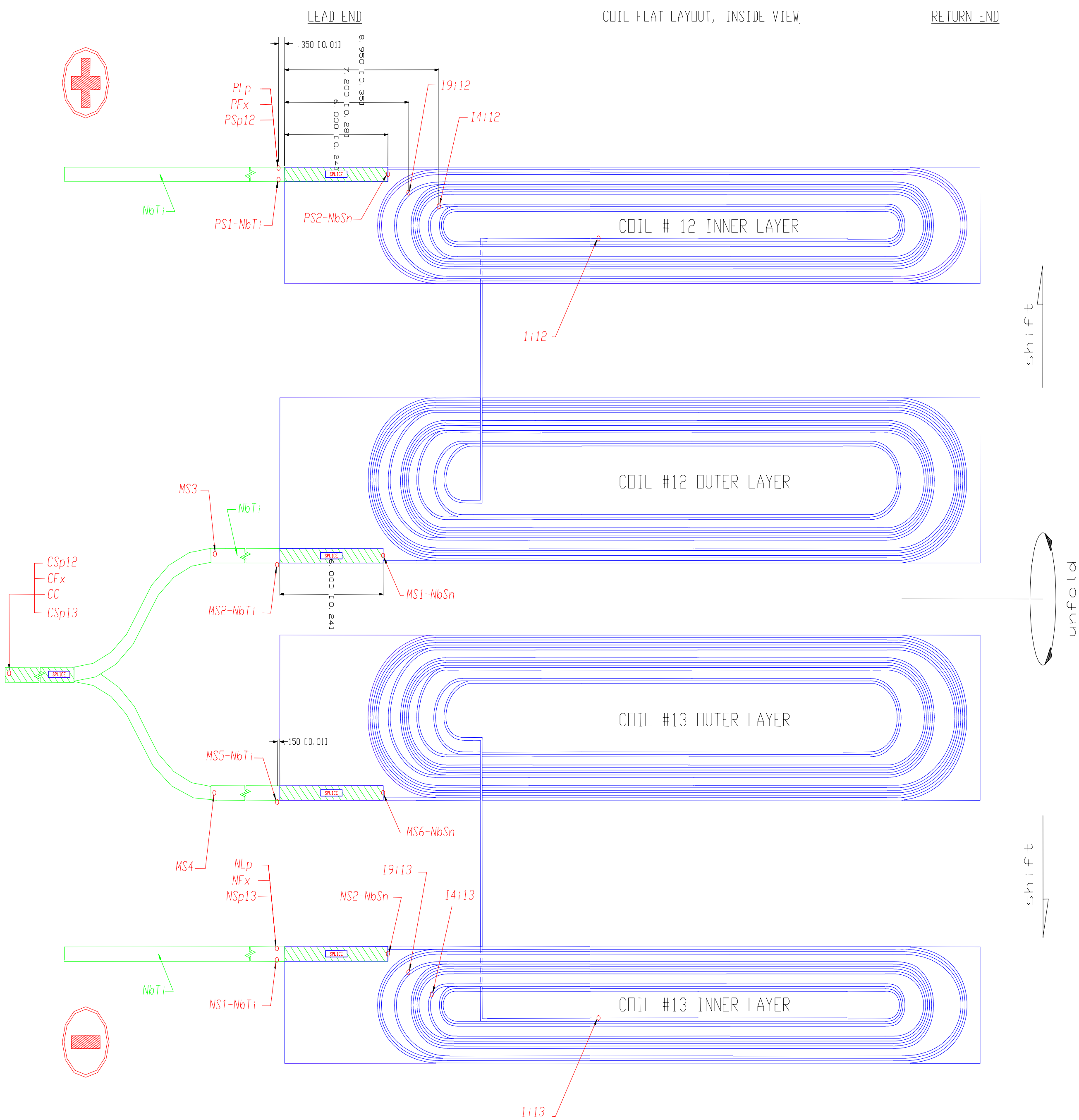


Figure 4.3.1: *Voltage Tap Layout.*

4.4 Parting plane Splices:

Beginning with the previous magnet, HFDA-04, the splice configuration at the parting plane was redesigned so that the splice joint is better supported, and the Nb_3Sn cable cannot be subjected to bending strain. This splice configuration is shown in Figure 4.4.1 and explained in detail in the HFDA-04 production report, TD-02-025. Splicing was done after reaction with the coil still housed in the same tooling used for reaction. On HFDA05, new tooling, improved from that used for HFDA04, was used. Solder was 70%/30% lead/tin with Kester 44 flux. Solder is heated to a temperature of approximately 230C.

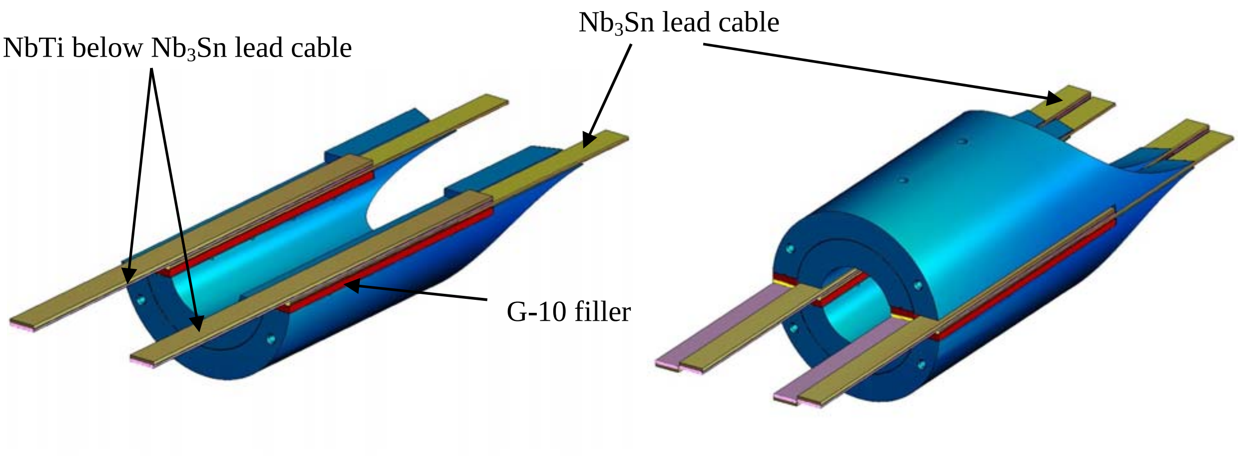


Fig. 4.4.1: *End-saddle and the splice geometry for magnet HFDA-05*

5.0 EPOXY IMPREGNATION

Each half coil in HFDA05 was impregnated separately after splicing, in the same fixture that was used for reaction. Figure 5.0.1 shows half coil HFDAH-012 enclosed in the tooling and being prepared for impregnation.

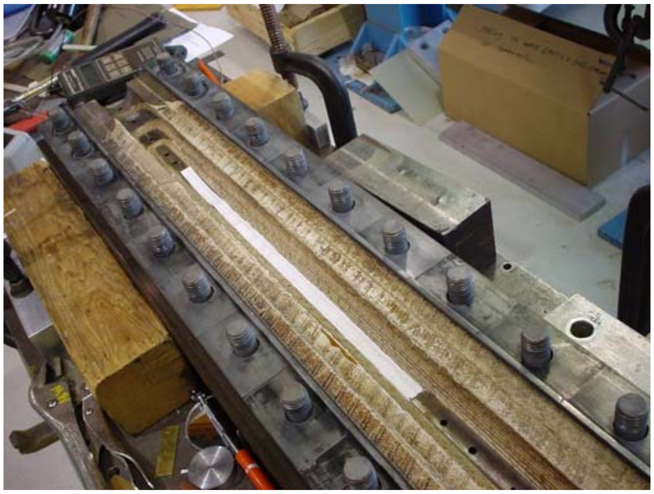


Fig. 5.0.1: *HFDAH-013 in reaction-impregnation tooling being prepared for impregnation*

5.1 Impregnation Cycle:

Coils were impregnated with CTD101K epoxy. The impregnation fixture was placed in a large oven, heated to 60C and evacuated to 75 microns for HFDAH-012 and 20 microns for HFDAH-013, respectively *(small vacuum leaks in the oven were corrected between coils 012 and 013, allowing a better vacuum to be achieved for the second coil).* The container of epoxy was heated to 55C and evacuated to about 115 microns for HFDAH-012 and 60 microns for HFDAH-013. *(In both cases, the vacuum in the reaction oven is held at 40 microns higher than in the epoxy container).* The epoxy flowed into the coil at a flow rate of .04cc/sec (.5cm/sec linear flow in a tube of 3.2 mm inside diameter). Impregnation took approximately 3-4 hours. After impregnation, the fixture was placed into an oven and cured at 125C for 21 hours. Figure 5.1.1 shows coil HFDAH-013 after impregnation.

Figure 5.1.1 *Impregnated coil assembly*

5.2 Mechanical Measurements:

The thickness, width and flatness of each coil were measured after impregnation (in the free state), as shown if Figure 5.2.1. and 5.2.2. Plots of these three measurements for HFDAH-012 are shown in Figures 5.2.3, 5.2.4 and 5.2.5 (both before and after being cold tested in HFDM03). Figures 5.2.6, 5.2.7 and 5.2.8 show the same measurements for HFDAH-013. In the thickness and width measurement plots, yellow dots indicate points in the straight section, not covered by end parts.

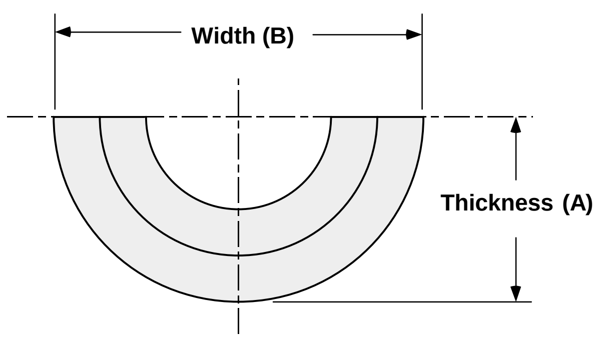


Figure 5.2.1 *Width and Thickness Measurements*

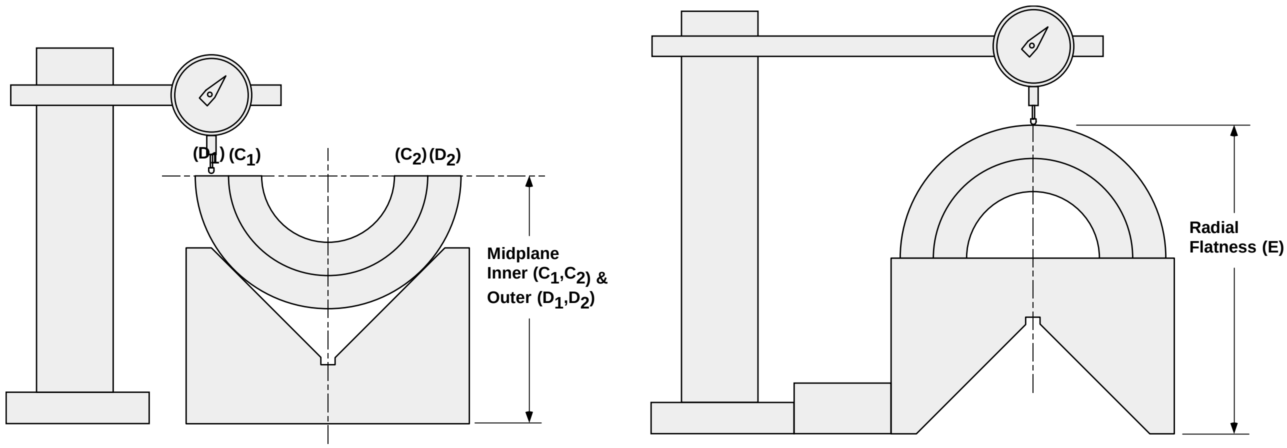


Figure 5.2.2 *Flatness Measurement Positions*

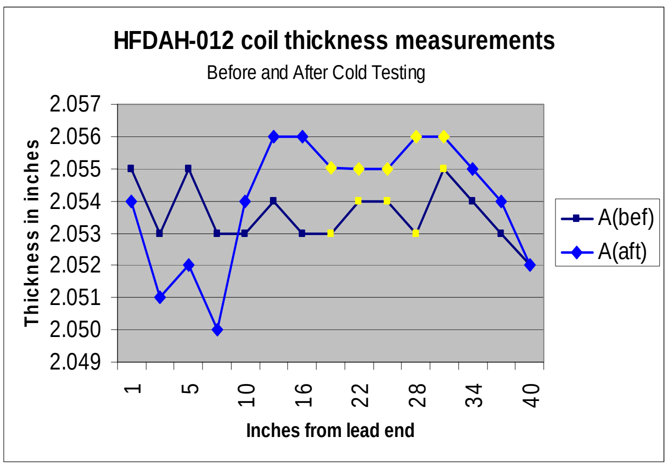


Figure 5.2.3 *Coil Thickness Measurements*

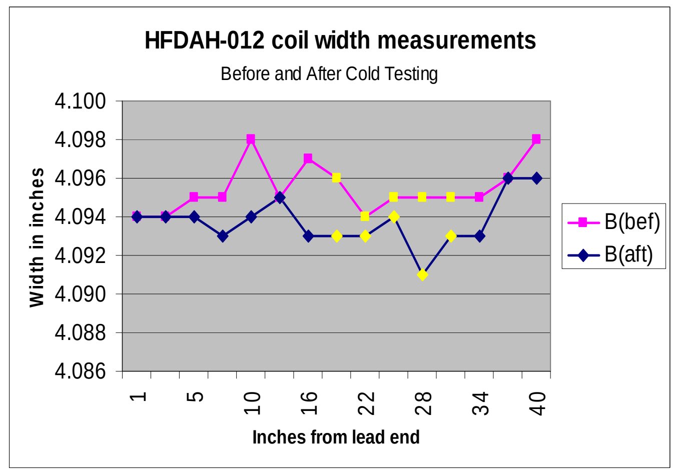


Figure 5.2.4 *Coil Width Measurements*

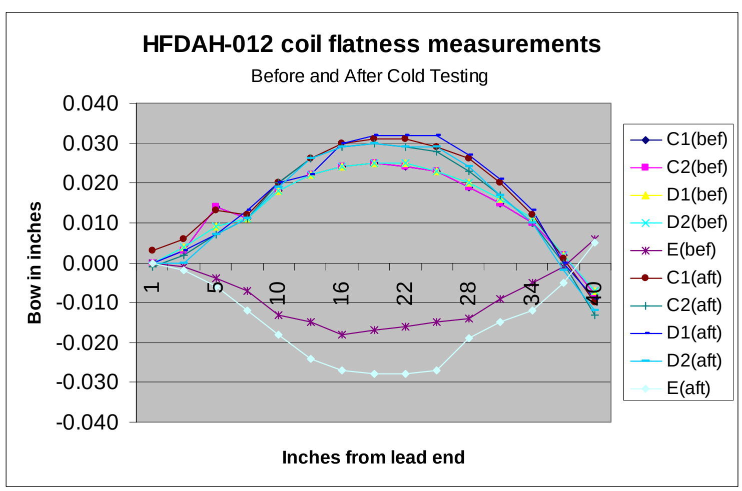


Figure 5.2.5 *Coil Flatness Measurements*

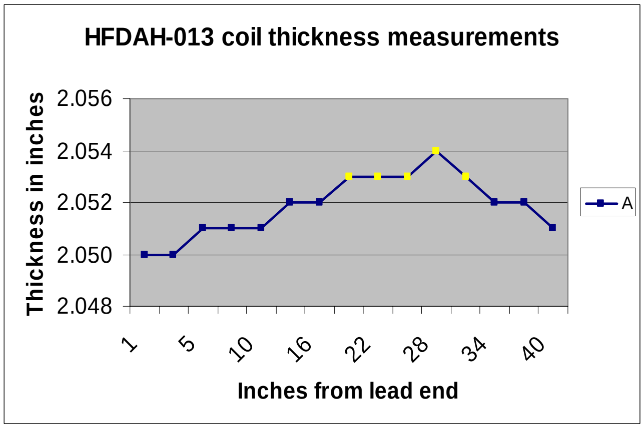


Figure 5.2.6 *Coil Thickness Measurements*

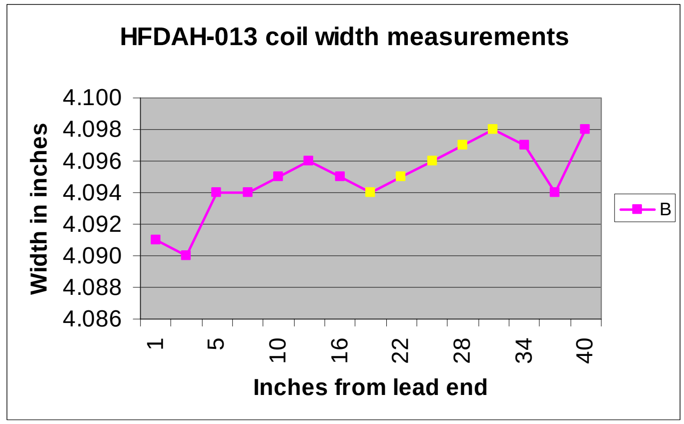


Figure 5.2.7 *Coil Width Measurements*

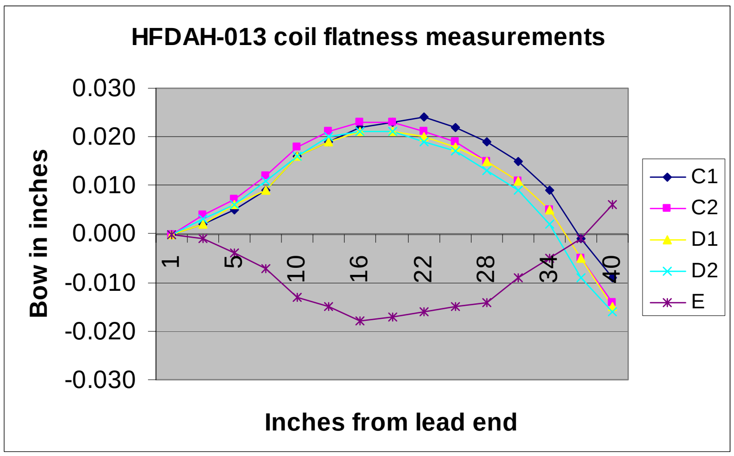


Figure 5.2.8 *Coil Flatness Measurements*

5.3 Calculation of Coil Radial Shim:

Radial shims may be placed around the outside of the coils, to compensate for differences between coil radial actual and design size. These shims are calculated based on the measurements taken in section 5.2.

After extraction from the impregnation mold, the coil deflects. The shape it takes is modeled as half of an ellipse in 2D cross-section. The coil outer radius is re-calculated based on the assumption that the perimeter the ellipse and circle for the outside surface of the outer coil are equal. The ellipse perimeter can be computed using the rapidly converging Gauss-Kummer series as follow:

$$p = \pi(a+b)\sum_{n=0}^{\infty}\binom{\frac{1}{2}}{n}^2 h^n = \pi(a+b)\left(1+\tfrac{1}{4}h+\tfrac{1}{64}h^2+\tfrac{1}{256}h^3+\ldots\right)$$

where $h \equiv \left(\frac{a-b}{a+b}\right)^2$.

Results for coils HFDAH012 and HFDAH013 are shown in Table 5.3.1. Coil 012 was measured both before and after it was used in mirror magnet HFDM03. Table 5.3.1 shows both measurements.

Table 5.3.1 *Coil Radial Shim Calculations*

Coil	a=A	b=B/2	h= ((a-b)/(a+b))^2	Pe(n=0)	Pe(n=1)	Pe(n=2)	Pe(n=3)	Rcycle = Pe/pi/2	Radius design	Radial Shim
12bef	2.0538	2.0475	2.3596e-06	12.88461	12.88462	12.88462	12.88462	2.05065	2.052	.00135
12aft	2.0554	2.0464	4.82181e-06	12.88620	12.88622	12.88622	12.88622	2.05091	2.052	.00109
13	2.0532	2.0480	1.60763e-06	12.88430	12.88430	12.88431	12.88431	2.05060	2.052	.00140

The results show that the impregnated coil outside diameter is smaller than the design size by ~ 2-2.5mil (50-70 microns).

5.4 Electrical Measurements:

Coil Electrical Measurements were taken after impregnation, and are shown in Table 5.4.1. Resistance measurements were taken at .1 amp. Inductance and Q were taken both at 20 Hz and 1KHz.

Table 5.4.1: *Electrical measurements on the impregnated half-coils.*

	Resistance mΩ	Inductance μH @ 20 Hz	Inductance μH @ 1KHz	Q @ 20 Hz	Q @ 1KHz
HFDAH-012	60.6	224.506	188.377	.5	1.88
HFDAH-013	60.1	242.041	187.296	.5	1.89

6.0 YOKING

6.1 Magnet Structure

General structure of HFDA05 is shown pictorially in Figure 6.1.1. It has a vertically split yoke, although it is pressed in the horizontal position shown in Figure 6.1.2. Aluminum-bronze spacers surround the coil inside the yoke, and are split at the coil pole, along the same plane as the yoke. Preload is achieved by a combination of the aluminum yoke clamps and skin. The skin may be either welded or bolted, and is bolted in the case of HFDA05. There is a gap between yoke halves, which remains open at all stages of construction (300K), but closes when cooled to 4K.

By design, the coil preload and internal stresses of the components vary during construction, cool-down and operation, approximately as described below:

1) When the magnet is at room temperature, and the coil preload is zero, the yoke gap by design is 1.5mm, while the spacer gap is exactly zero, with no stress on the spacers.
2) Pressure is applied by the press to the yoke halves, reducing the yoke gap and increasing azimuthal compressive (hoop) stress to the spacers, decreasing their inside diameter and applying preload to the coils.

3) The yoke clamps are inserted and the press pressure is released, transferring the press pressure to tensile stress in the yoke clamps. The inside surfaces of the yoke clamps are now in contact with the yoke, and there is a gap between the yoke halves. Shims are placed in the gap between the yoke halves to control the preload after cooldown, as shown in Figure 6.1.2.
4) The skin is bolted onto the yoke, applying preload to the coils, relieving some but not all of the stress from the yoke clamps. The skin is now in azimuthal tension, and the inside surfaces of the yoke clamps are still in contact with the yoke. Stress on the spacers and coil is unchanged.
5) During cooldown, all components shrink (at different rates). The yoke gap closes (yoke halves close onto the shims), and the tensile stress in the skin and yoke clamps increase. Coil preload after cooldown is determined by the size of the yoke gap shims.
6) During excitation, Forces are applied radially outward by the coils at the parting plane. These forces are contained by the skin and the yoke clamps, and the yoke gap remains closed.

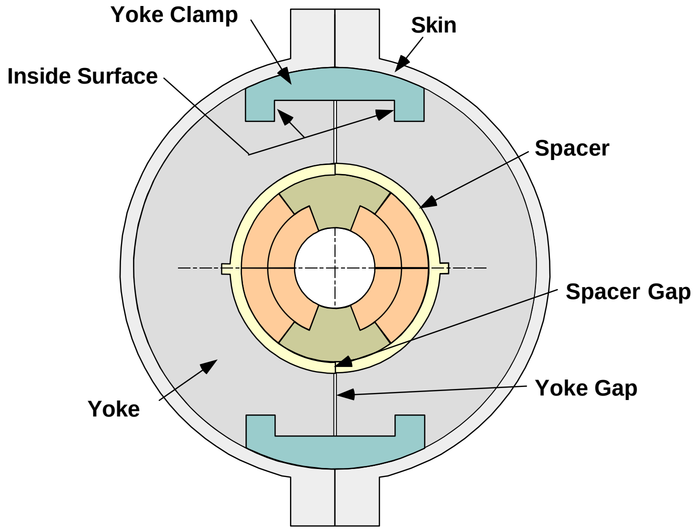


Figure 6.1.1 *HFDA05 General Structure*

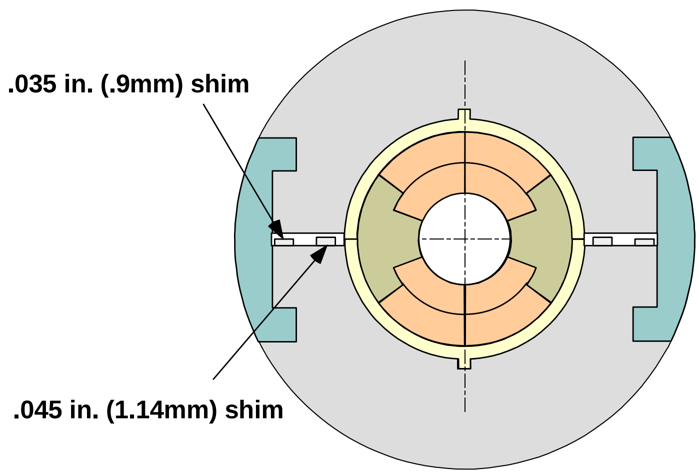


Figure 6.1.2 *Yoke gap shims*

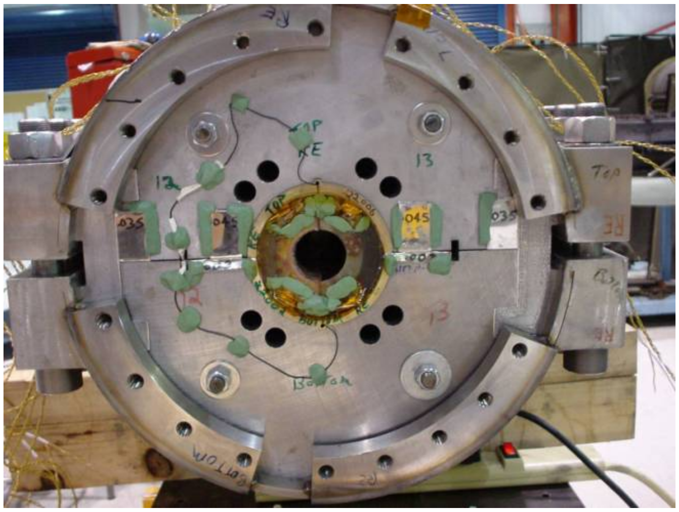


Figure 6.1.3 *HFDA05 in Yoke*

HFDA05 is the first HFDA magnet to feature a closed yoke gap during cooldown and excitation.

6.2 Instrumentation

Both capacitance and traditional resistive strain gauges were used to measure preload. The capacitance gauges measure the azimuthal stress in the outer coil layer while the resistive gauges measure the azimuthal stress in the aluminum spacers.

One outer pole piece on each half-coil was mold released before epoxy impregnation and removed afterwards. These pieces were replaced with special outer pole pieces modified to accept capacitance gauges. Resistive gauges were mounted into circumferential grooves made on the aluminum bronze spacers. Capacitance gauges were as placed as shown in Figure 6.2.1, longitudinally near the center of the straight section. A spacer instrumented with resistive gauges, as shown in Figure 6.2.2, was placed longitudinally next to the capacitor gauges, also near the center of the straight section. In order to estimate the stress distribution near the splice joint, another spacer instrumented with resistive gauges as shown in Figure 6.2.3, was placed near the lead end.

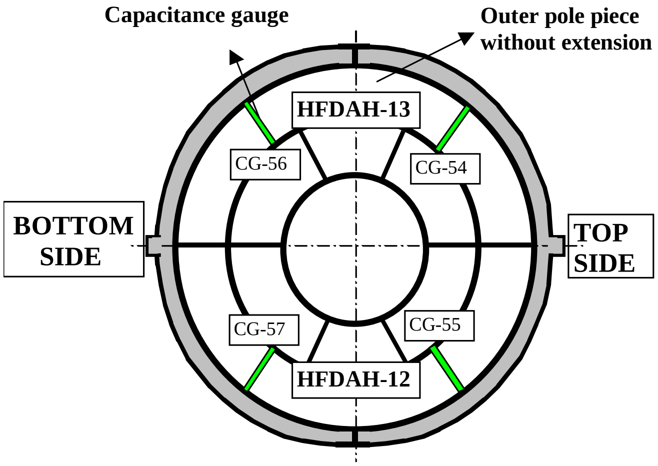
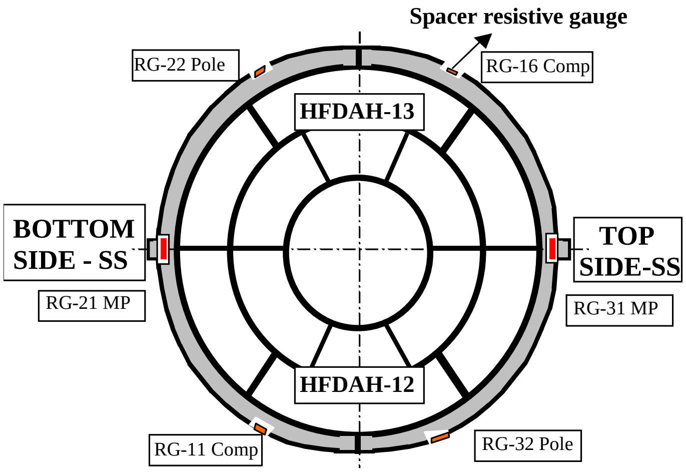


Figure 6.2.1. *Capacitance gauge layout near center of magnet during magnet assembly.*



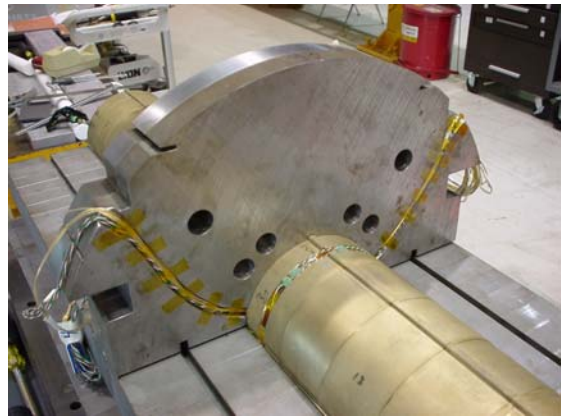


Figure 6.2.2: *Layout of spacers with resistive gauges in the magnet straight section.*

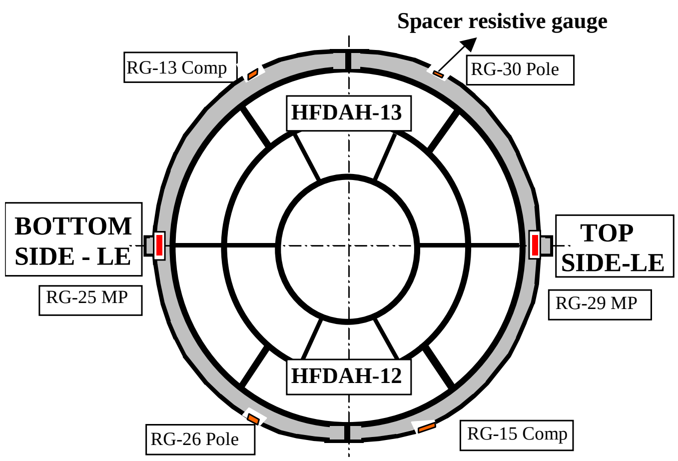


Fig. 6.2.3: *Layout of resistive gauges at the magnet Lead End.*

6.3 Yoke Assembly

To achieve the proper preload, coil outside diameters should be at the nominal size to match the inside diameter of the spacers. For HFDA05, the design included placing a 2 mil (50 micron) layer of kapton around the outside surface of the coils as added ground wrap. Coil outside diameters were measured (see sections 5.2 and 5.3). The measurements indicate that no radial shim other than the 2 mil kapton would be required. Nevertheless, it was decided to start with a 5 mil (125 micron) layer of kapton (i.e., 3 mils more than the design). This decision was made because coil HFDAH012, when previously used in HFDM03, had included a 5 mil sheet of kapton, and HFDM03 had acceptable coil preload. HFDAH013 measurements were virtually identical to HFDAH012. Figure 6.3.1 shows the coils with the kapton layer installed. The aluminum bronze spacers were then placed around the coils. The assembly was lowered into the bottom yoke packs, followed by the installation of the top yoke packs.

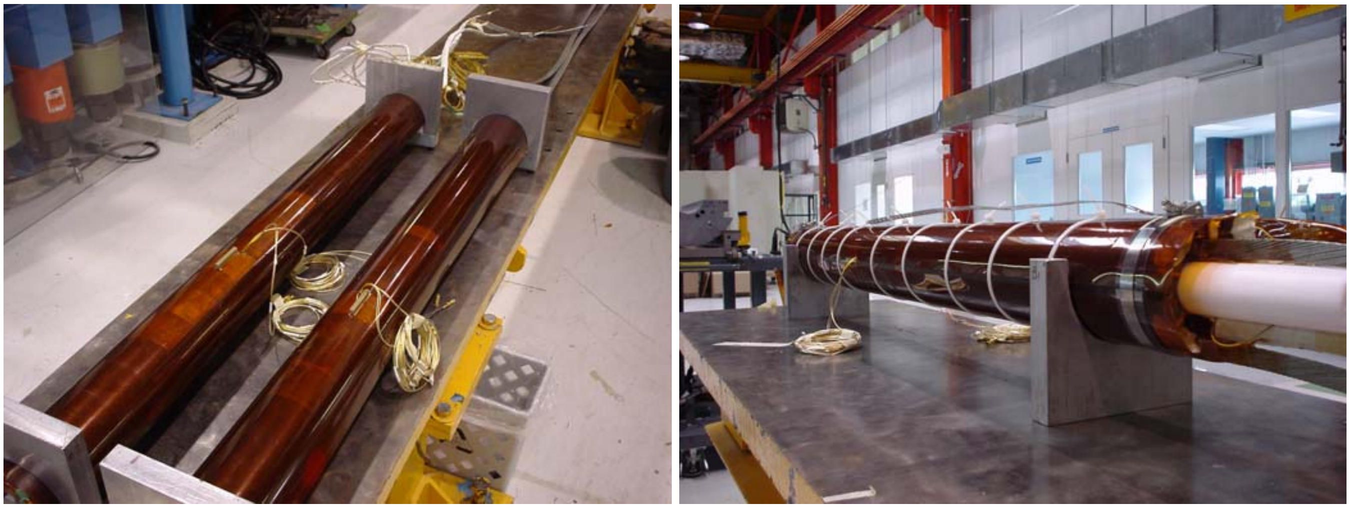


Fig. 6.3.1: *Kapton shim placed around impregnated coils.*

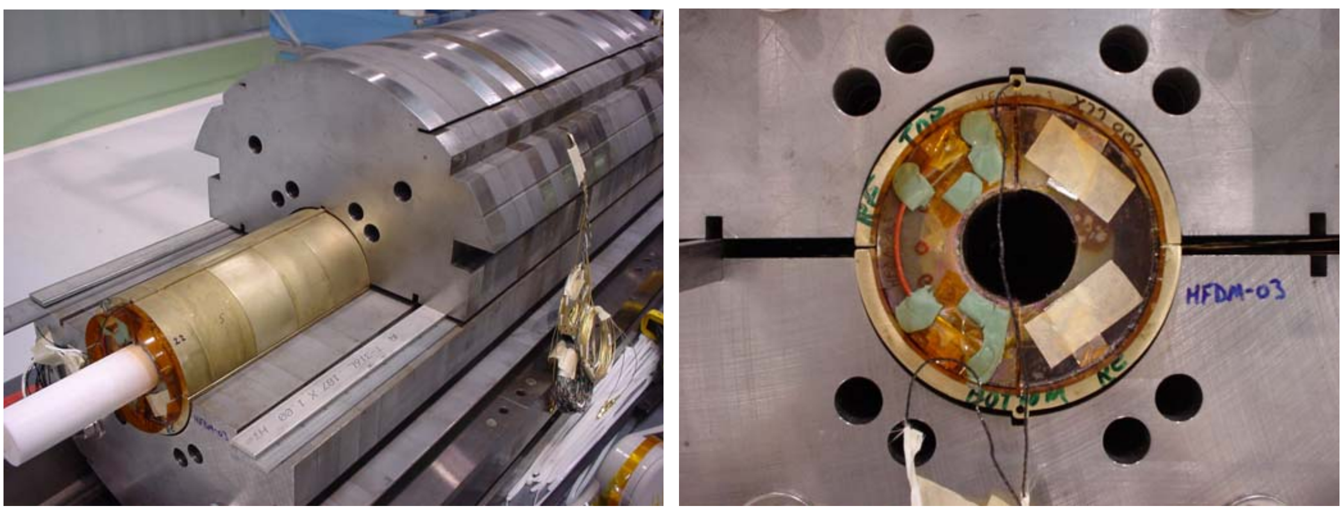


Fig. 6.3.2: *Assembly of HFDA05.*

HFDAH-013 was used as the upper coil and HFDAH-012 as the lower coil.

6.4 Alignment

An alignment operation, or "dry run" in the press, was done to determine if all shims and coil sizes were appropriate. During the alignment operation, a special instrumentation pack was installed, which included extensions on the outer pole pieces, as shown in Figure 6.4.1. The spacer with extension was placed only in one place, in the middle of the straight section. Originally, this special spacer was intended to be used during the final assembly as well as just the alignment operation, to provide azimuthal alignment between the coils and yoke. However, strain gauge readings during the alignment process revealed asymmetrical coil loading in this area. This could have been caused by the fact that the azimuthally unaligned sections were being locked in place by radial friction before the alignment pack began moving into position. To avoid the risk of undue stress on the coils, it was decided to use only spacers without extensions for the final assembly.

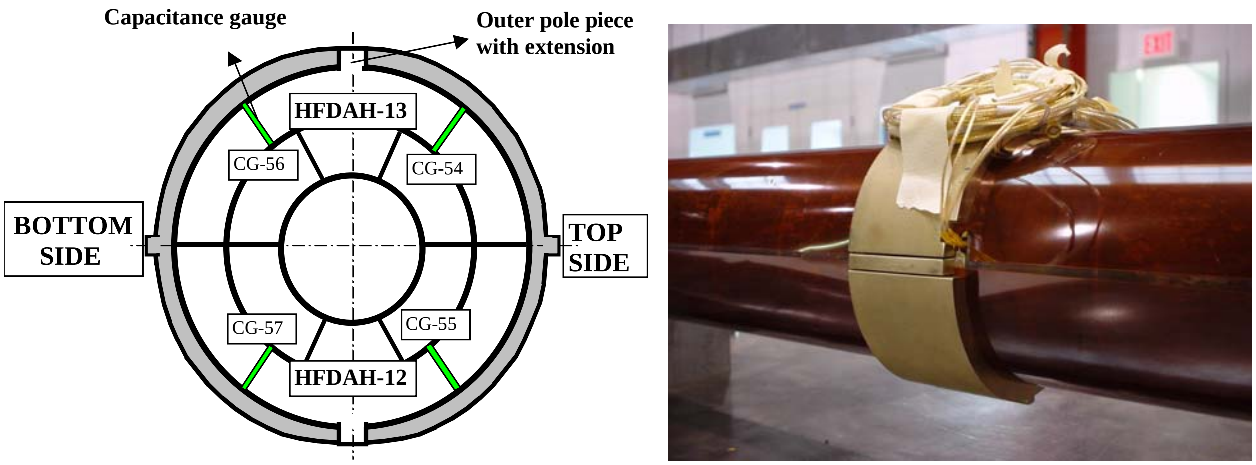


Figure 6.4.1: *Capacitance gauge layout during alignment operation.*

By design, the spacers should be in contact at the “0 preload point” during pressing, when the yoke gap reaches 1.5 mm or .059 inches. At the same time, the coil pressure and the spacer azimuthal stress should be minimal or zero. As pressure is applied, internal stresses in all components should increase. Strain should increase, therefore, in both the resistive as well as the capacitor gauges.

Spacer strain gauge and pole capacitor gauge readings during the alignment operation (dry assembly run) are shown in Figures 6.4.2 and 6.4.3, respectively. Both plots show yoke gap size in inches vs. stress in Mpa. Shims were placed in the yoke gap to control the yoke gap size and avoid press over-compression during the alignment operation. The “yoke shim size” shown on the horizontal axis in Figure 6.4.2. is therefore equivalent to the yoke gap size.

Press loads up to 2500 pump psi (equivalent to 450000 total lbs force) were applied. When the yoke gap was decreased to .06 inches, (1.5mm) no strain was observed in the spacers. However, the coil capacitor gauges located at the pole near this spacer recorded loads varying from 40 to 140MPa. This meant that the spacers had not yet contacted each other at the parting plane, but were loading the coils radially. In addition, the large variations between capacitor gauge readings indicated that asymmetrical loading of the coils was taking place.

As a result, the coil outside shim was reduced from 5 mils to 2 mils, conforming to the measurements taken in section 5.3. 3 mil stainless steel shims were also added at each spacer gap. Also, the spacer with the alignment tab was removed and replaced with one that did not have a tab.

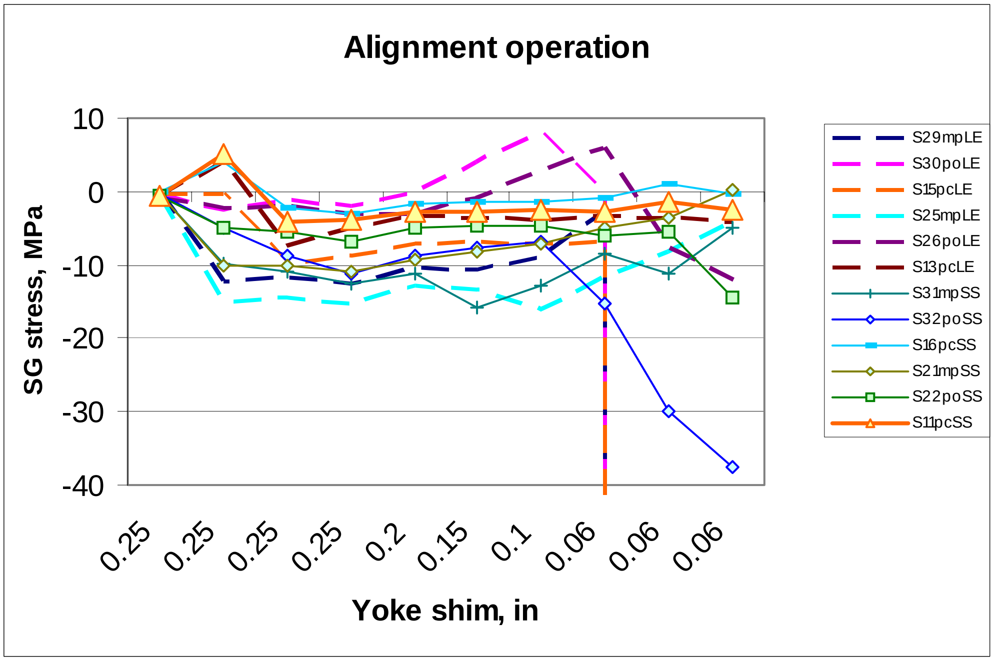


Figure 6.4.2: *History of resistive gauges on spacers during alignment operation.*

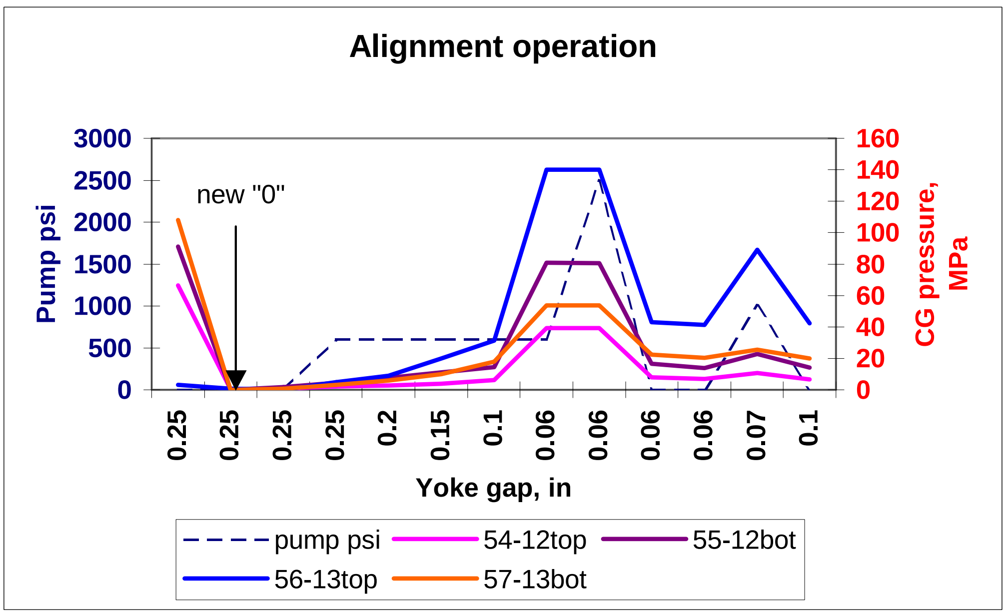


Fig. 6.4.3: *History of capacitance gauges at outer poles during alignment operation.*

6.5 Pressing

After reassembling, the magnet was put back into the press for yoke installation, as shown in Figure 6.5.1. The yoke halves were loaded vertically with main press pressure. The yoke clamps were inserted by hydraulic side pushers.

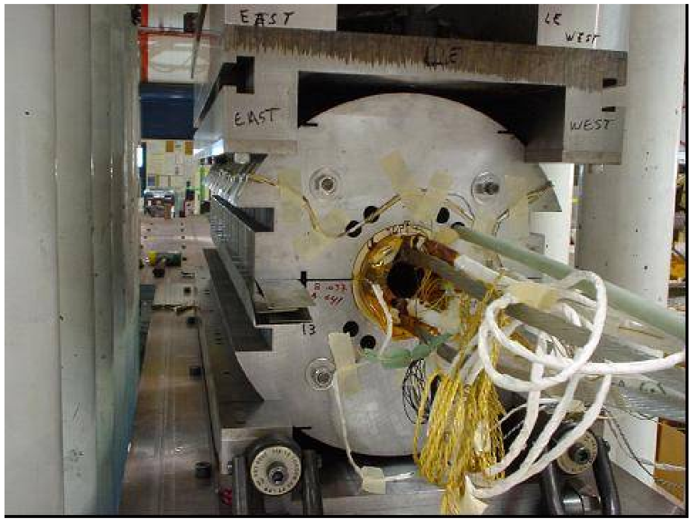


Fig. 6.5.1 *Magnet installed in the yoke press*

During the yoking operation, shims were placed between the yoke gaps to avoid accidental over-compression of the coils. The yoking operation began with shims .070 inches thick. Hydraulic pressure was applied until the shims were contacted, and strain gauges readings were taken. Then the shims were removed and replaced with smaller shims, and the process repeated until the shim size was reduced to .050 inches. Main pump hydraulic pressure of 4000 psi was required to reach the .050 shims. The aluminum clamps were then partially inserted with 400 pump psi hydraulic pressure on the side cylinders. Then, the clamps were fully inserted using 1000 psi main pump pressure and 4000 psi side pressure. The final yoke gap, after the side clamps were fully inserted, was .057 inches. The temporary shims were then removed and replaced with the final shim system as shown in Figure 6.1.2. Main cylinder force is 180 lbs per pump psi across the entire magnet, and side cylinder force is 4.5 lbs per pump psi, applied per clamp. Side clamps are 2 inches thick.

Figure 6.5.2 shows capacitor gauge readings at the poles during yoking and skin bolting. Figure 6.5.3 shows resistive gauges on the spacers during yoking and skin bolting.

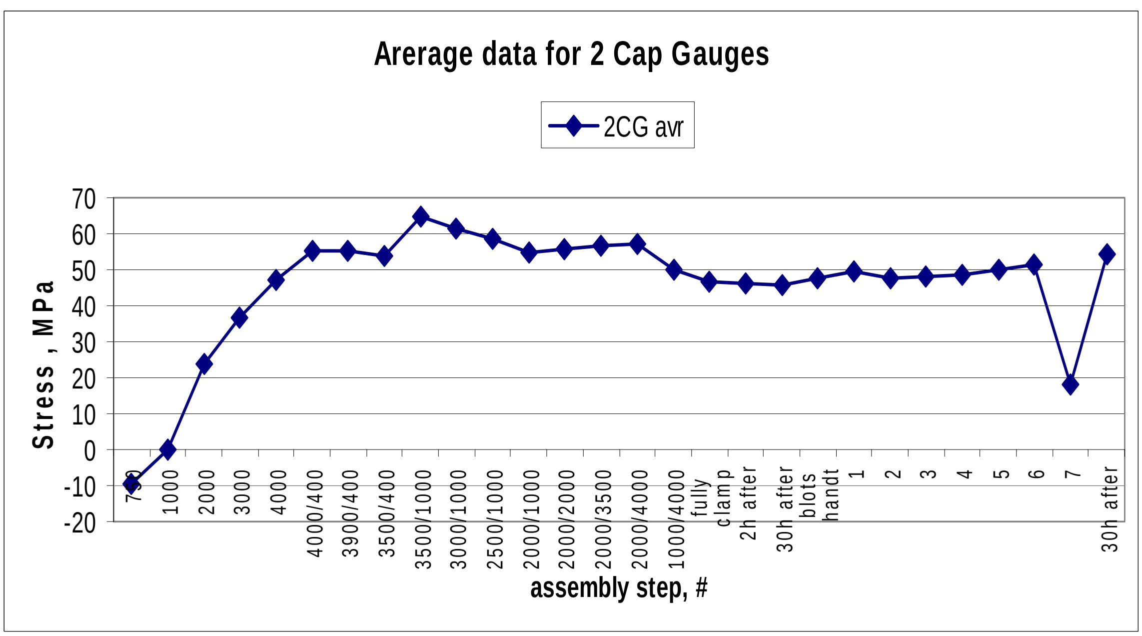


Figure 6.5.2: *Azimuthal stress in the coil outer layer during yoking and skin bolting operation (from capacitor gauges at outer pole)*

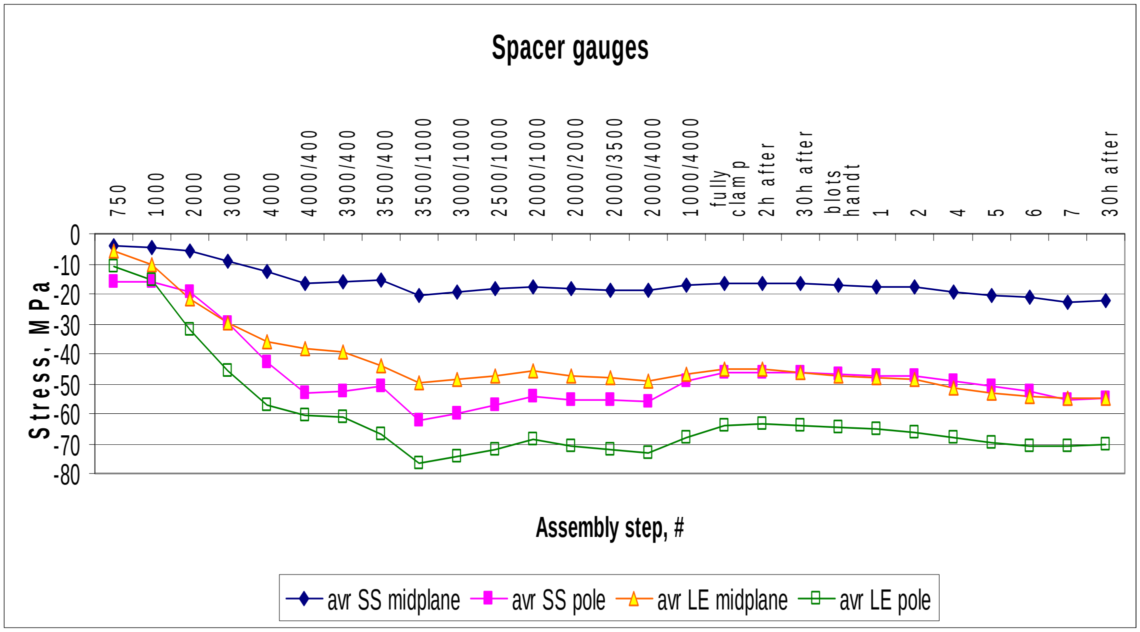


Figure 6.5.3: *Azimuthal stress in the spacers during yoking and skin bolting operations from resistive gauges.*

6.6 Electrical Measurements

Coil Electrical Measurements were taken after pressing, and are shown in Table 6.6.1. Resistance measurements were taken at .1 amp. Inductance and Q were taken both at 20 Hz and 1KHz.

Table 6.6.1: *Electrical measurements on the yoked assembly.*

	Resistance mΩ	**Inductance µH @ 20 Hz**	**Inductance µH @ 1KHz**	**Q @ 20 Hz**	**Q @ 1KHz**
HFDAH-012	60.7	334.393	101.608	.64	1.03
HFDAH-013	61.4	334.816	101.851	.64	1.04

Hi-Pot tests at 500V were also performed on the yoked assembly to check current leakage between coil-to-coil, coil-to-ground, coil-to-heaters and heater-to-ground. The Table 6.6.2 shows these results.

Table 6.6.2: *Hi-Pot measurements on the yoked assembly.*

Test	**Leakage @ 500V**
Coil to coil	.068 uA
Coil to ground	.064 uA
Heaters to coil	.056 uA
Heaters to ground	.020 uA

7.0 FINAL ASSEMBLY

7.1 Skin Installation

Skin halves were placed around the yoked assembly and bolted together. Bolting was done in seven steps, while stress in the coil and end spacers was monitored. Stresses during this operation are shown in Figures 6.5.4 and 6.5.5 of the previous section.

Resistive gauges were also installed onto the surface of the skin. Gauges were mounted near the longitudinal center of the skin, positioned to measure the azimuthal strain in the surface. They were mounted on both the upper and lower skins, at azimuthal positions of 30, 60 and 90 degrees from the yoke/skin gap, as shown in Figure 7.1.1. These gauges were also monitored during the bolting operation. Figure 7.1.2 shows the average stress of the two skins during the seven bolting steps.

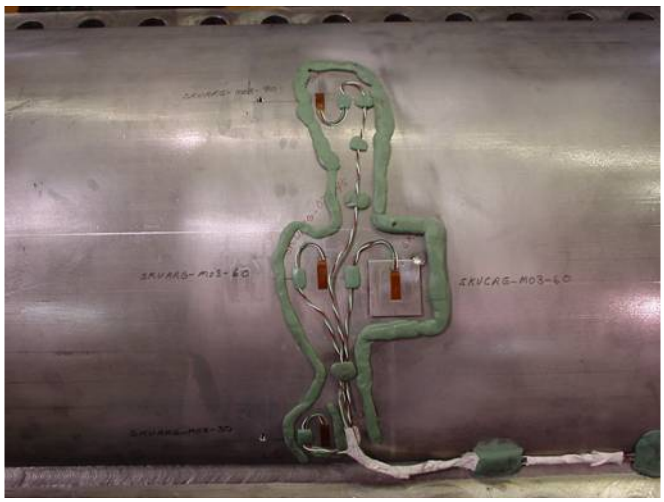


Figure 7.1.1: *Resistive strain gauges mounted on skin.*

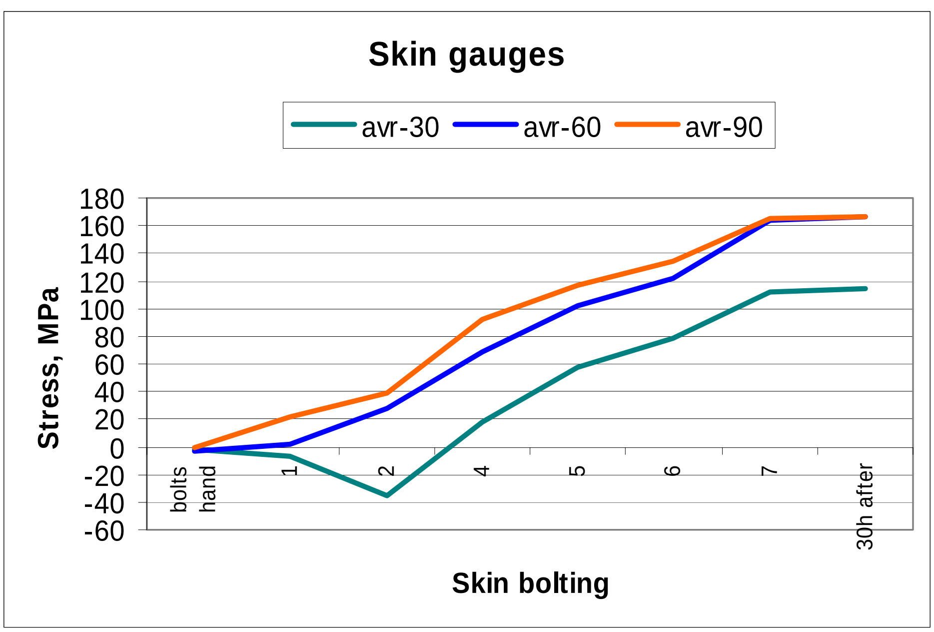


Figure 7.1.2: *Stress in skin during bolting operation.*

Yoke gaps were also measured while the skin was being bolted, using filler gauges. Measured gaps during the seven bolting steps are shown in Figure 7.1.3.

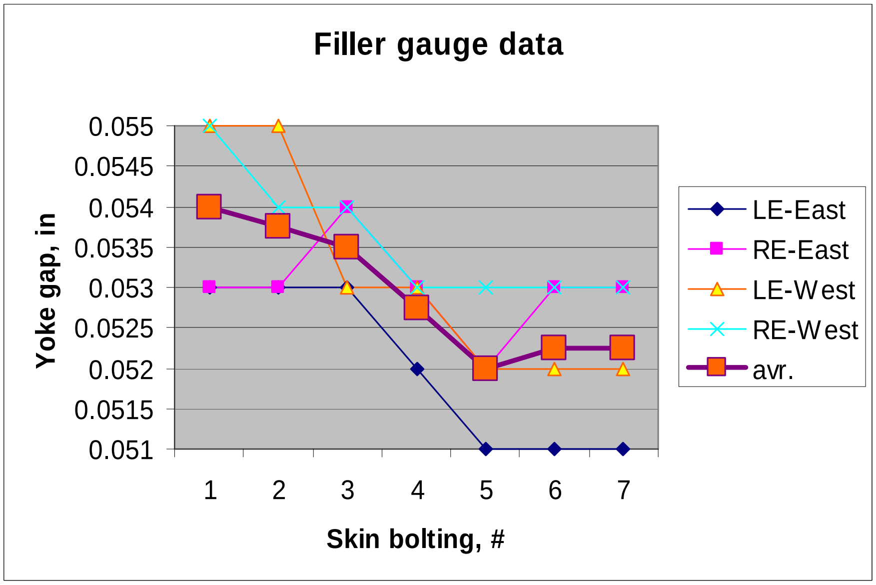


Figure 7.1.3: *Measured yoke gaps during bolting operation.*

7.2 End Plate Installation

After the skin is installed, RTD's to measure the temperature during testing are installed. One RTD is installed in a hole on the spacer on each end.

An end plate is then bolted onto each end. Since this assembly was bolted, not welded, no twist measurements were taken.

The ends were not loaded longitudinally on HFDA05. Consequently no bullets were installed.

7.3 Splices

After the end plate is installed, the half-coil splices are made. The outer layer leads from both the half-coils were spliced together and captured in a G-10 box. The inner layer leads were used as power leads for the magnet. The half-coil splice assembly was achieved without using "green putty" to fix the leads to the G-10 spacers. This would enable the leads to move under Lorentz forces if necessary. Voltage taps were installed on the lead cables before installing the splice box assembly. Figure 7.3.1 shows the lead configuration, before and after the cover is installed onto the splice housing.

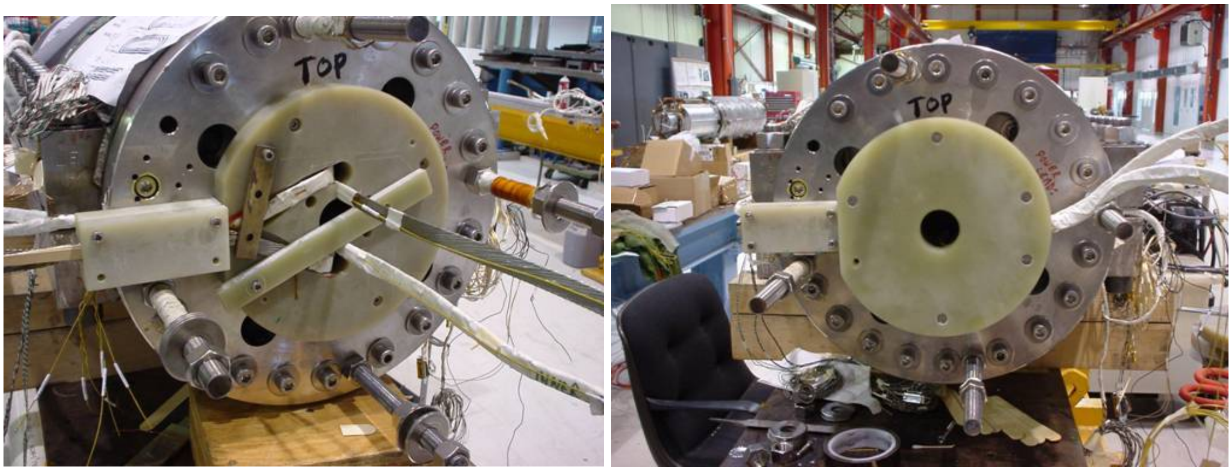


Figure 7.3.1: *Lead and Splice configuration.*

7.4 Electrical Measurements

Electrical measurements were performed on the magnet after making splices, but just before installing the hypertronics connectors. Table 7.4.1 summarizes these measurements.

Table 7.4.1: *Electrical measurements on the half-coils and the total magnet.*

	Resistance	**Inductance, mH**		**Quality Factor**	
	mΩ	**At 1 kHz**	**At 20 Hz**	**At 1 kHz**	**At 20 Hz**
HFDAH-012	60.8	0.123	0.344	1.53	0..65
HFDAH-013	61.5	.125	0.342	1.54	0.65
Total Magnet	122.5	0.345	1.095	1.41	0.99

Quench Protection (strip) heater resistance = 4.9 ohms per circuit, with one circuit consisting of two strips as shown in Figure 4.2.1.

7.5 Connectors

Wires were terminated into 3 separate hypertronics connectors, one for quench characterization voltage taps, one for quench protection heaters, and one for resistive strain gauges (spacers and skin). A separate connector was used for RTD's (thermometers). Capacitance gauges are terminated using separate wires, with individual SMC female connectors.

7.6 Final Electrical Measurements

Final electrical measurements were performed on the magnet just before shipping to VMTF for testing. Table 7.6.1 summarizes these measurements.

Table 7.6.1: *Electrical measurements on the half-coils and the total magnet.*

	Resistance	**Inductance, mH**		**Quality Factor**	
	mΩ	**At 1 kHz**	**At 20 Hz**	**At 1 kHz**	**At 20 Hz**
Total Magnet	120.5	0.341	1.094	1.40	0.99

Hi-Pot tests at 500V were also performed on the final assembly to check current leakage between coil-to-ground, coil-to-heaters and heater-to-ground. The Table 7.6.2 shows these results.

Table 7.6.2: *Hi-Pot measurements on the yoked assembly*.

Test	Leakage @ 500V
Coil to ground	.01 uA
Heaters to coil	.02 uA
Heaters to ground	.016 uA

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8.0 SUMMARY

The fifth shell-type Nb_3Sn high field dipole magnet, HFDA-05 was delivered to VMTF for testing on August 2, 2004.

HFDA05 had a 43mm bore diameter and a straight section approximately 1/2 meter long.

1mm PIT strand manufactured by ShapeMetal Industries was used, substituted for the Modified Jelly Roll cable used in previous HFDA models, because it was found to be unstable at low fields.

One coil from HFDA05 was re-used from a previous mirror model, while one was manufactured new for this magnet.

HFDA05 was tested at VMTF, achieving a field of 10 Tesla.