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Nb_3Sn Cos(θ) Dipole Magnet, HFDA-06 Production Report

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1.0 INTRODUCTION

HFDA-06 is the sixth Nb_3Sn cosine theta dipole magnet to be fabricated at Fermilab and the fifth 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
HFDA05	TD-04-048
HFDA03A mirror	TD-03-001
HFDA03B mirror	TD-03-030
HFDM02 mirror	TD-03-029
HFDM03 mirror	TD-05-006
HFDM04 mirror	TD-05-023
HFDM05 mirror	TD-05-038

The primary features of HFDA06 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 HFDA06

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	1/15/05
Cold Mass Completion Date	7/10/05

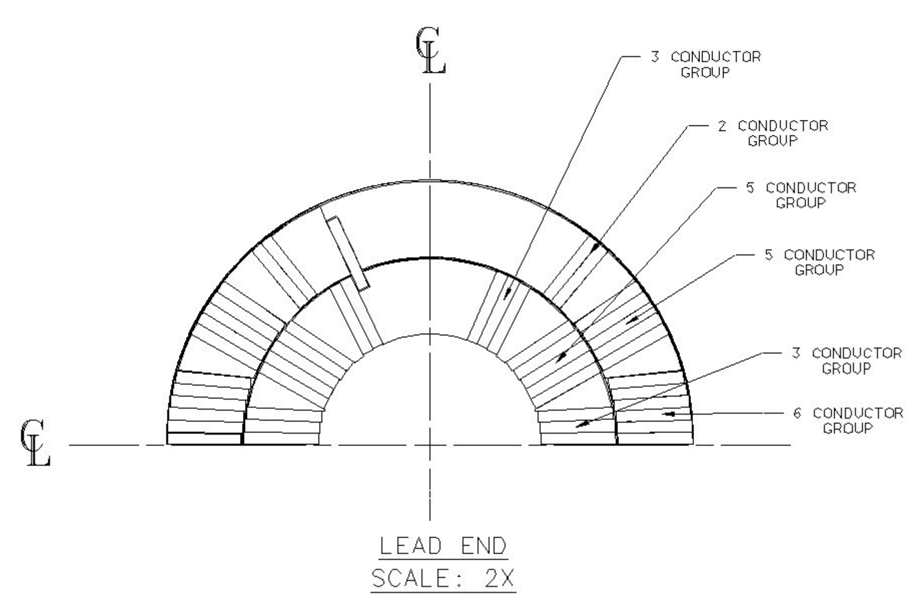


Figure 1.0.1 *HFDA cross section*

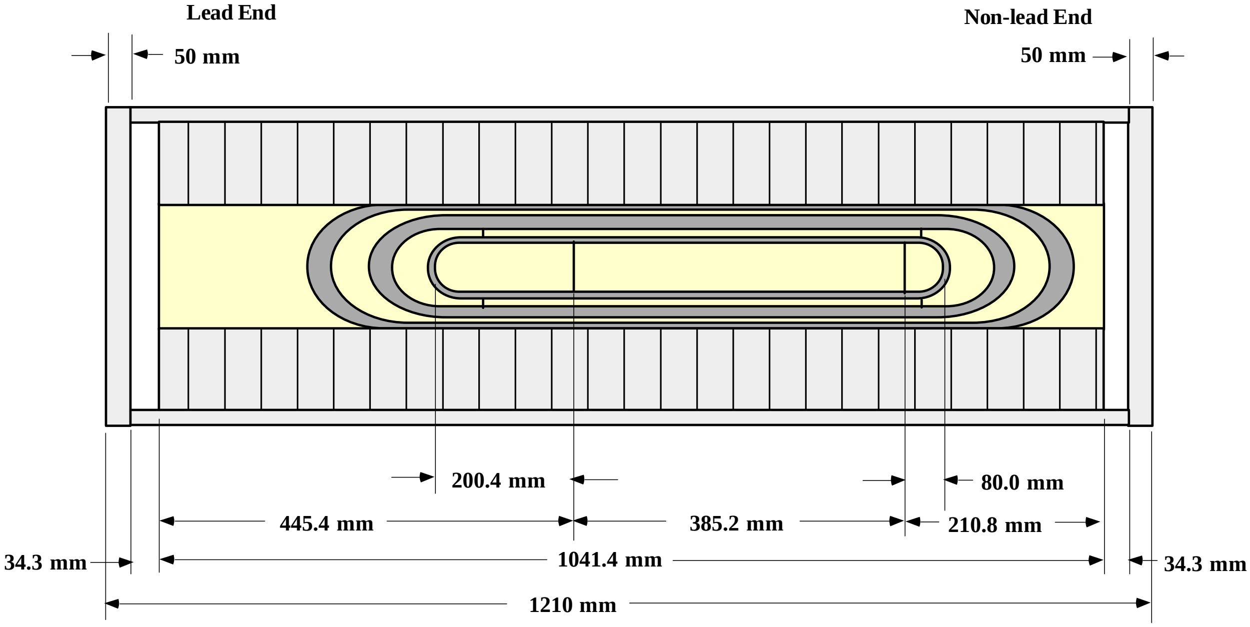


Figure 1.0.2: *Longitudinal parameters of HFDA-06*

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

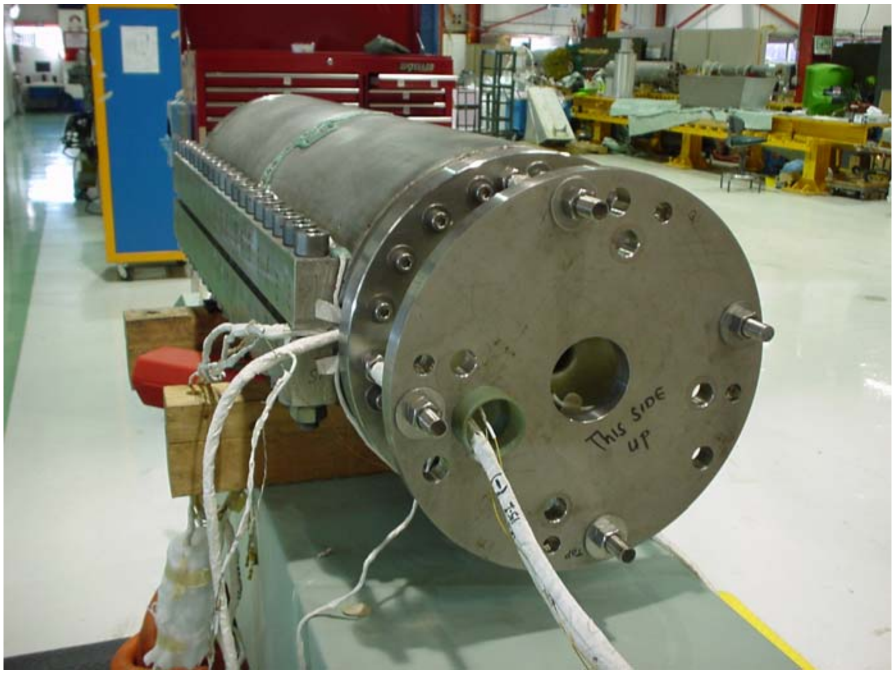


Fig. 1.0.3 *Photograph of HFDA-06 ready to be shipped to VMTF*

2.0 STRAND and CABLE

Strand for HFDA06 was made by *ShapeMetal Innovation (SMI*) using the Powder in Tube process. The nominal diameter of the strand was 1.00 mm.

TABLE 2.0.1

STRAND DESCRIPTION

Billet ID	180's
Strand diameter, mm	1
I_c(12 T), A	~700
Cu fr., %	52
No. of filaments	192
D_{eff}, μm	45
Geometric filament size, μm	50-57
RRR	>250
No. units	2
Total length, m	3507
Average length/unit, m	1754
Twist pitch, mm	20

2.1 Cable Mechanical Parameters

Rutherford type cable with 28 strands was manufactured at Fermilab. Cable reel number was HFDA-040519-28-2. Cable mechanical parameters are listed in Table 2.1.1.

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

CABLE ELECTRICAL PARAMETERS **TABLE II**

CABLE DESCRIPTION

Coil ID	HFDA014, HFDA015
Cable Traveler ID*	HFDA_040519_28-2
Strand billets	181, 182B
No. of strands	28
Strand diameter, mm	1.0
Pitch length, mm	110
Cable average thickness, mm	1.8
Cable width, mm	14.24
Keystone angle, °	0.9
Packing factor, %	88.6

*Traveler provides cable map.

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 and Figure 2.2.1 show measurements made on these samples at SSTF for coil HFDAH-014. Table 2.2.2 and Figure 2.2.2 show measurements made on these samples at SSTF for coil HFDAH-015. Figures 2.2.3 and 2.2.4 show the predicted short sample limits for coils HFDAH-014 and HFDAH-015, respectively.

Table 2.2.1: *Measured critical parameters of the witness samples of coil HFDAH-014.*

Sample Billet	Sample State	Barrel Material	Ic (@ 12T) A	n	RRR
182B	Virgin	Stainless Steel	550	56	123
181	Virgin	Titanium	522	n/a	93
182B	Virgin	Titanium	579	54	101
1 (182B)	Extracted	Stainless Steel	504	38	81
2 (181)	Extracted	Titanium	504	37	80
3 (181)	Extracted	Titanium	523	36	90

* premature quench

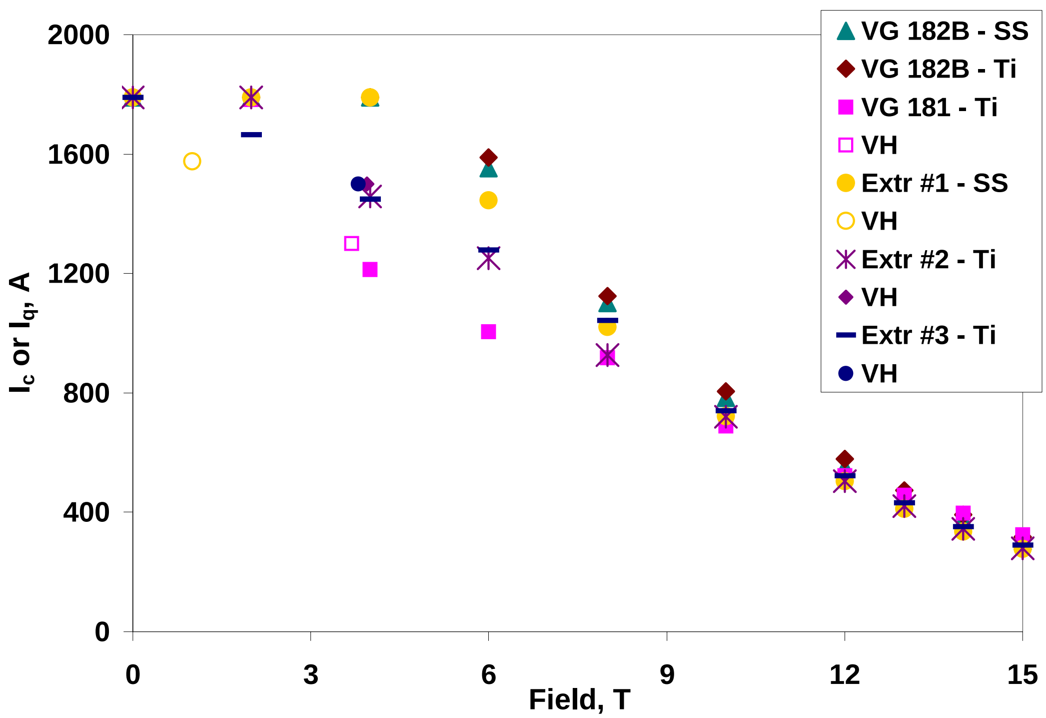


FIGURE 1. I_c or I_q as obtained through *VI* and *VH* measurement as a function of magnetic field for PIT round and extracted strands used as witnesses of half-coil HFDA014.

Table 2.2.2: *Measured critical parameters of the witness samples of coil HFDAH-015.*

Sample Billet	Sample State	Barrel Material	Ic (@ 12T) A	n	RRR
182	Virgin	Stainless Steel	510	510	146
182B	Virgin	Titanium	536	n/a	94
1 (182B)	Extracted	Stainless Steel	467	41	135
2 (182B)	Extracted	Stainless Steel	456	37	87
3 (181)	Extracted	Stainless Steel	464	37	98
4 (181)	Extracted	Titanium	469	31	89

* premature quench

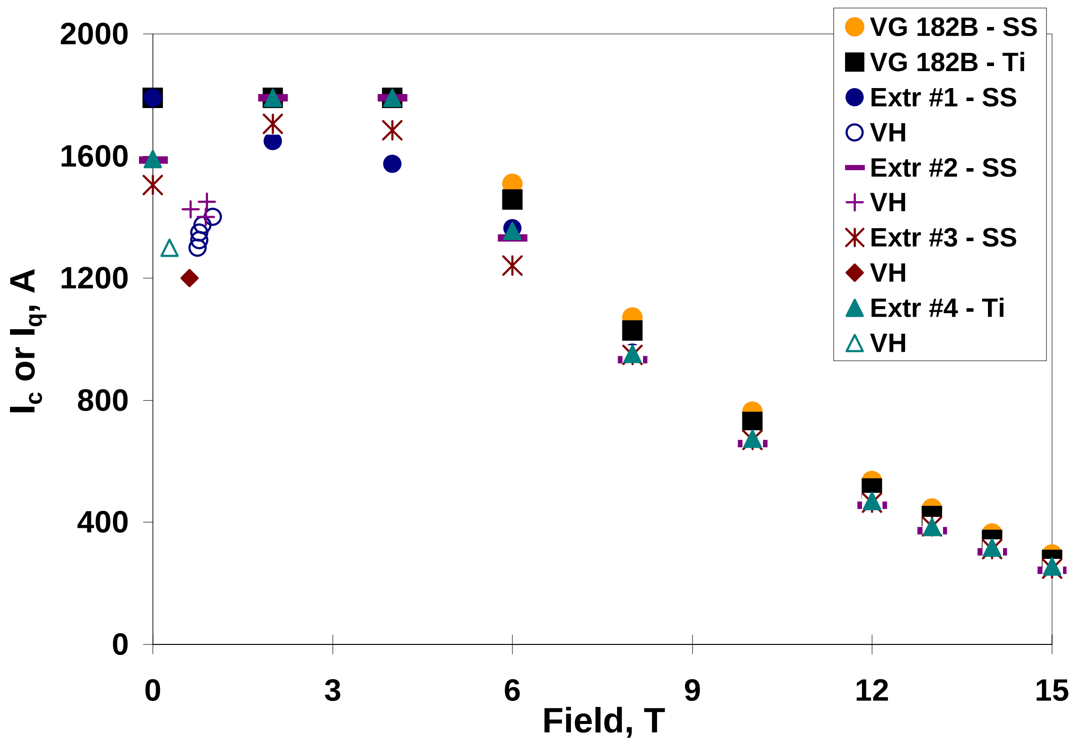


FIGURE 2.2.2 I_c or I_q as obtained through *VI* and *VH* measurement as a function of magnetic field for PIT round and extracted strands used as witnesses of half-coil HFDA015.

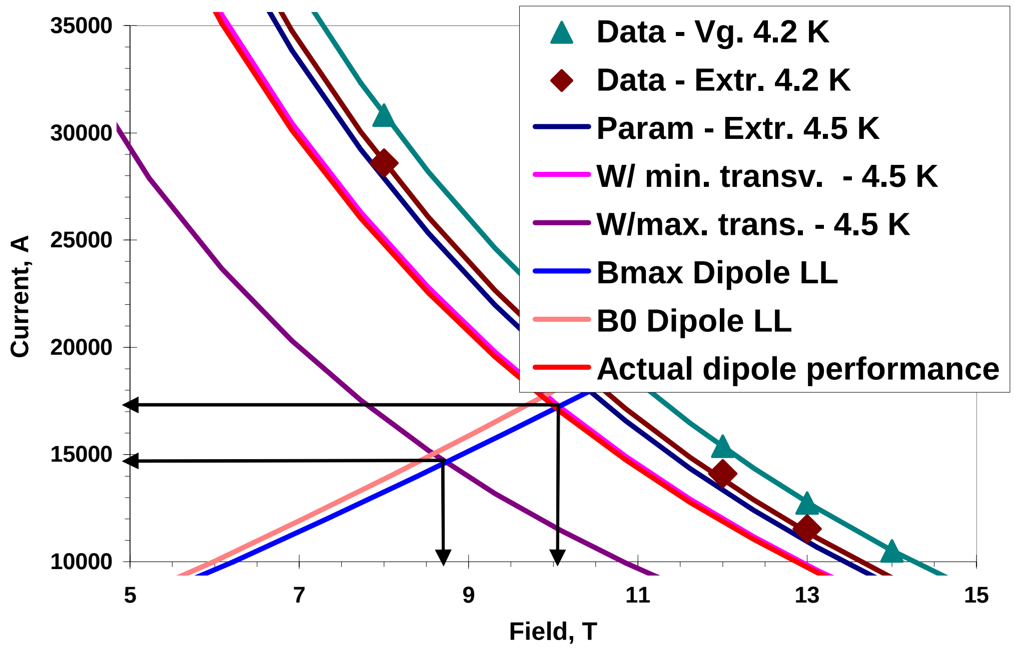


FIGURE 2.2.3 Short sample limit range for half-coil HFDA-014 in a dipole configuration. Maximum transverse pressure was assumed to be 100 MPa. According to strand tests, this leads to an I_c degradation of 10 to 40%.

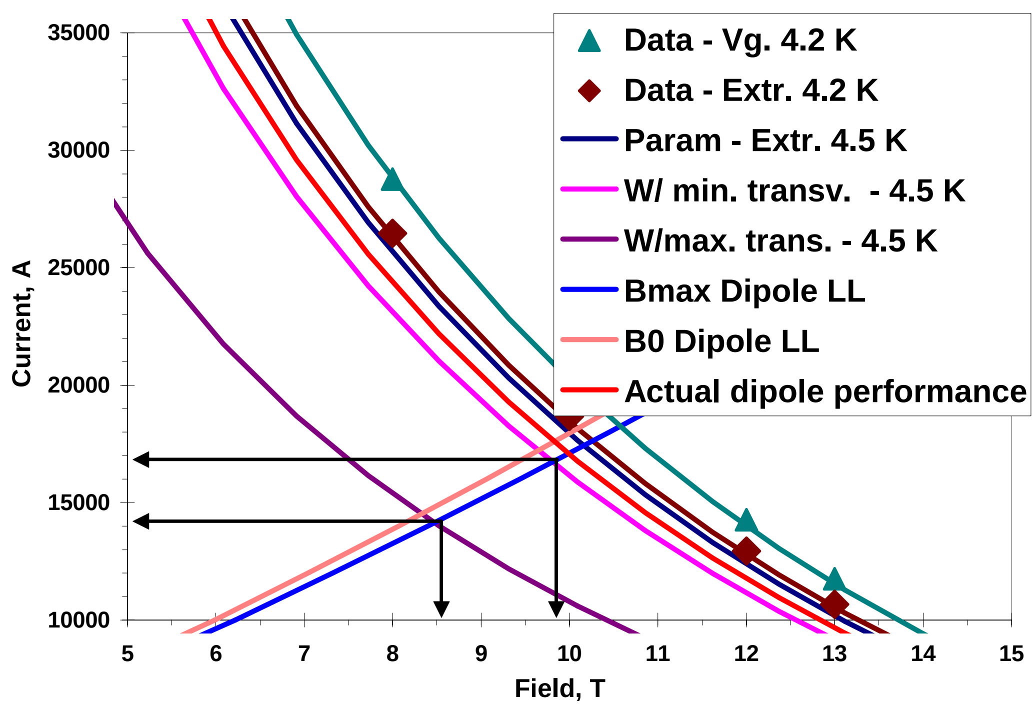


FIGURE 2.2.4 Short sample limit range for half-coil HFDA-015 in a dipole configuration. Maximum transverse pressure was assumed to be 100 MPa. According to strand tests, this leads to an I_c degradation of 10 to 40%. The dipole performance was consistent with a 5% I_c transverse pressure degradation on coil HFDA015, 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.

Standard 5 mil (125 micron) ceramic tape was used, wrapped in two layers. Both layers were wrapped dry, and then CTD 1008 binder was added just before curing. The 125uM x 12mm wide ceramic pre/preg with .75mm gaps is surrounded by 125uM thick x 12.5mm wide ceramic pre/preg with .75mm gaps. The Outer layer is wrapped to straddle the gap in the inner layer. Before curing, CTD-1008 binder is painted onto the coil. The wedges and cable are wrapped identically.

3.2 Coil Winding and Curing:

End part material was aluminum 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 014 and 015, 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.

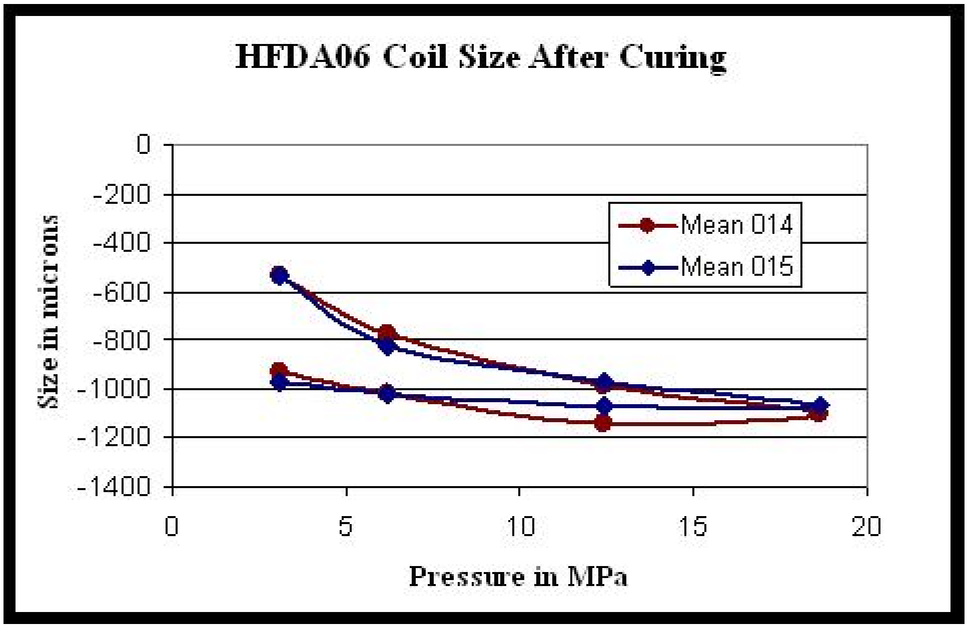


Fig. 3.3.1: *Coil size after curing.*

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 3.4.1. 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 014 and Coil 015 were measured on wooden V-blocks before spacers.

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-014	5.7100	236.887	242.747	.49	6.00
HFDAH-015	5.6863	251.016	212.207	.54	5.68

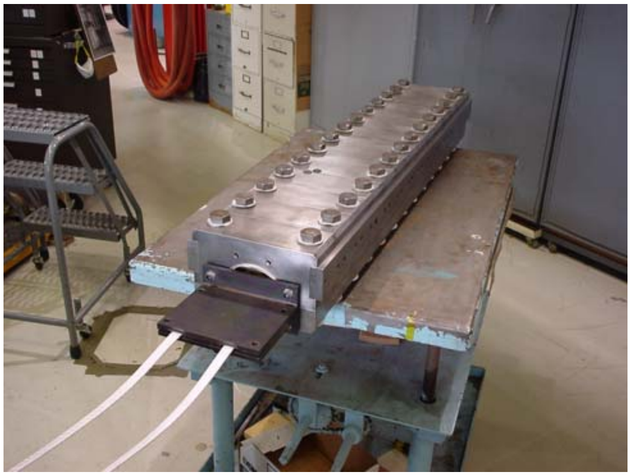
3.5 Ground Wrap System:

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.



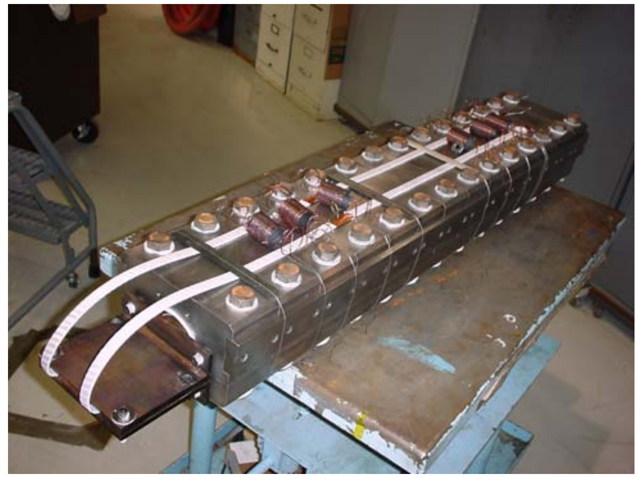


Figure 4.1.1: HFDAH-014 in reaction fixture. **Figure 4.1.2**: In retort with witness samples

The reaction cycle for HFDA-06 is shown in table 4.1.1. The actual cycles for coils HFDAH-014 and HFDAH-015 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 1 minute intervals for coils 014 and 015. 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.

<u>Summary of Reaction Data for HFDAH-014 and HFDAH-015</u>

Coils HFDAH-014 and HFDAH-015 were made from 1mm PIT strand and were used in short model dipole HFDA06. They were reacted in September and October 2004, respectively.

HFDAH-014:

Intended reaction cycle:

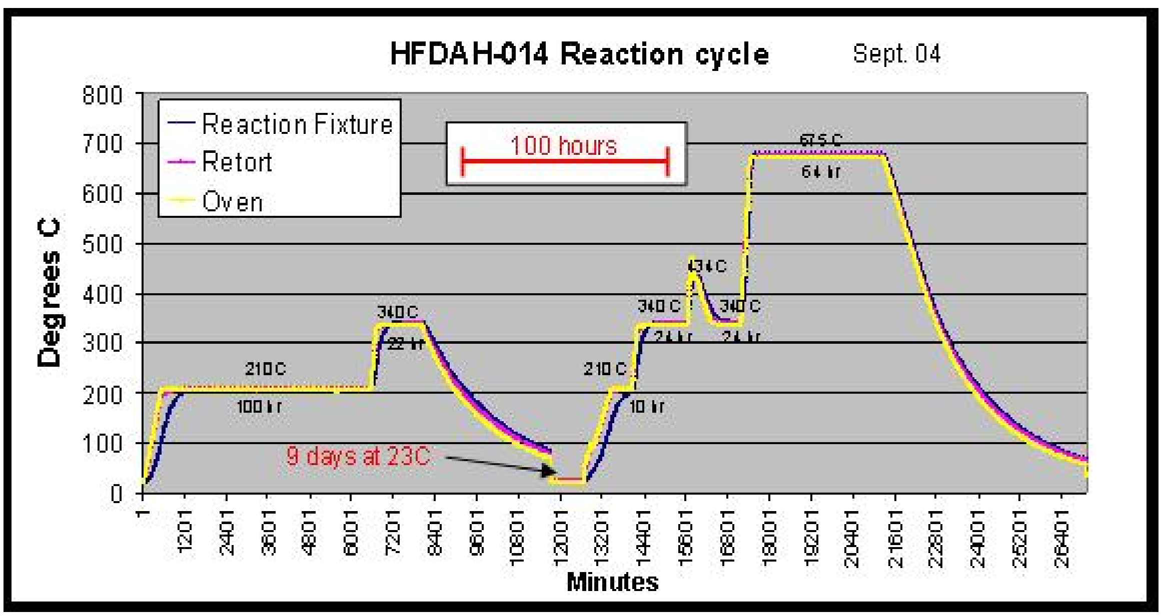
100 hours at 210°C
48 hours at 331°C
64 hours at 675°C

Actual reaction was aborted and restarted several times, because of malfunctions in the oven.

Actual cycle was:

100 hours at 210C
22 hours at 340C
9 days at 23C
10 hours at 210C
24 hours at 340C
Brief momentary ramp to 434C, then back to 340C
24 hours at 340C
64 hours at 675C

It is shown pictorially below. All ramps were 25°C/hr from 0 to 210°C, 50°C/hr from 210 to 340C and 75°C/hr between 340 and 675°C. No adjustments were made to the programmed oven temperature or heater banks to compensate for offsets in oven vs. coil temperature or temperature gradients.



HFDAH-015:

Intended reaction cycle:

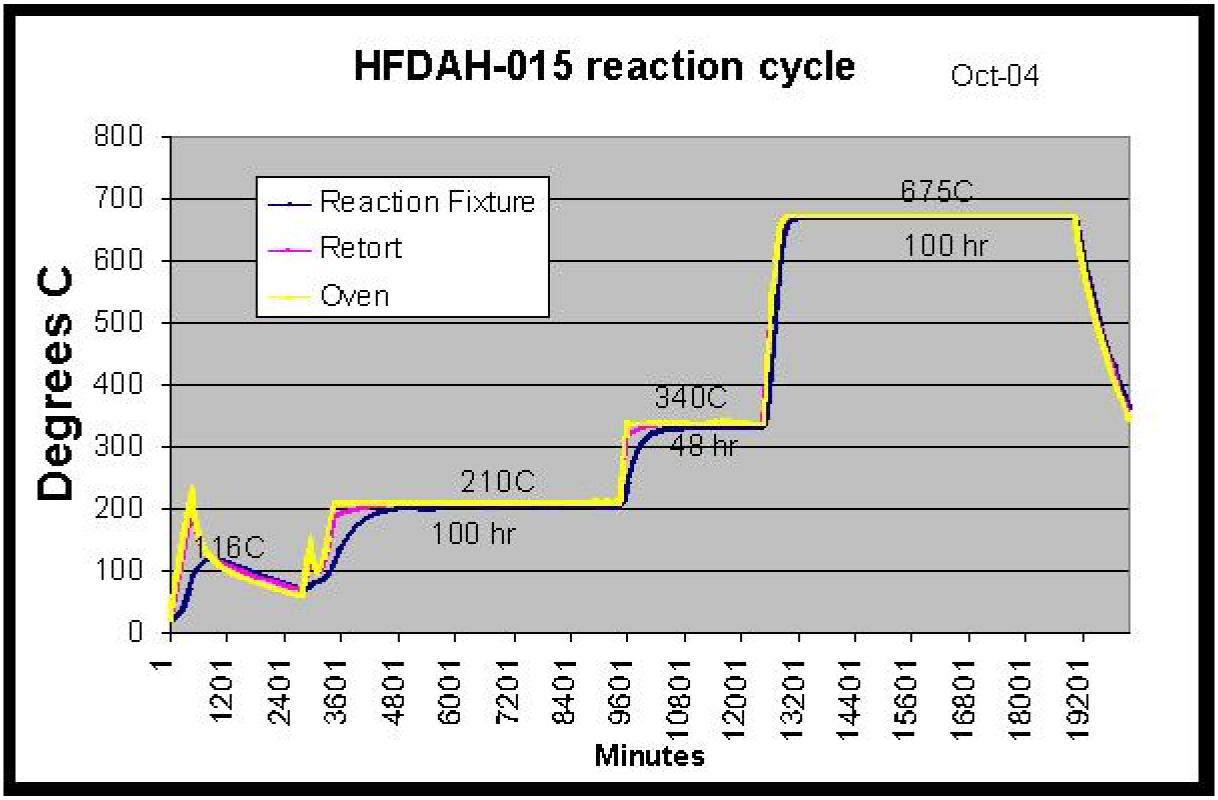
100 hours at 210°C
48 hours at 331°C
100 hours at 675°C

Actual reaction was aborted and restarted once, during the initial ramp to 210C.

Actual cycle was:

Initial ramp to 116C, slowly cooling to about 80C over about 40 hours.
100 hours at 210C
48 hours at 340C
100 hours at 675C

It is shown pictorially below. All ramps were 25C/hr from 0 to 210C, 50C/hr from 210 to 340C and 75C/hr between 340 and 675C. No adjustments were made to the oven temperature or heater banks to compensate for offsets in oven vs. coil temperature or temperature gradients.



Note: Temperatures were recorded during both reactions with one thermocouple attached to the reaction fixture. Temperatures read during each reaction varied, although the conditions were the same, and are not considered reliable, so the nominal temperatures of 210C, 340C and 675C are used. Temperatures recorded during the two reactions by the thermocouple are shown in the table below:

Programmed Temp	HFDAH-014	HFDAH-015
210°C	212	202
340°C	343	331
675°C	680	670

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.

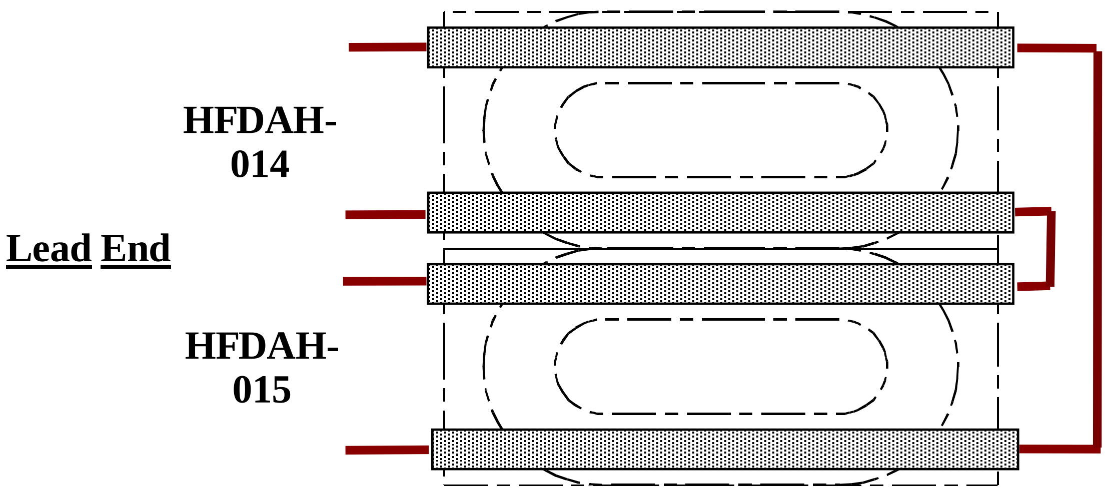


Figure 4.2.1: *Quench Protection heater wiring schematic.*

4.3 Voltage Taps and Spot Heaters

Voltage taps were mounted to the coils as shown in Figure 4.3.1. HFDA06 did not contain spot heaters. Figure 4.3.1 shows coils as viewed from the inside (looking at concave surface).

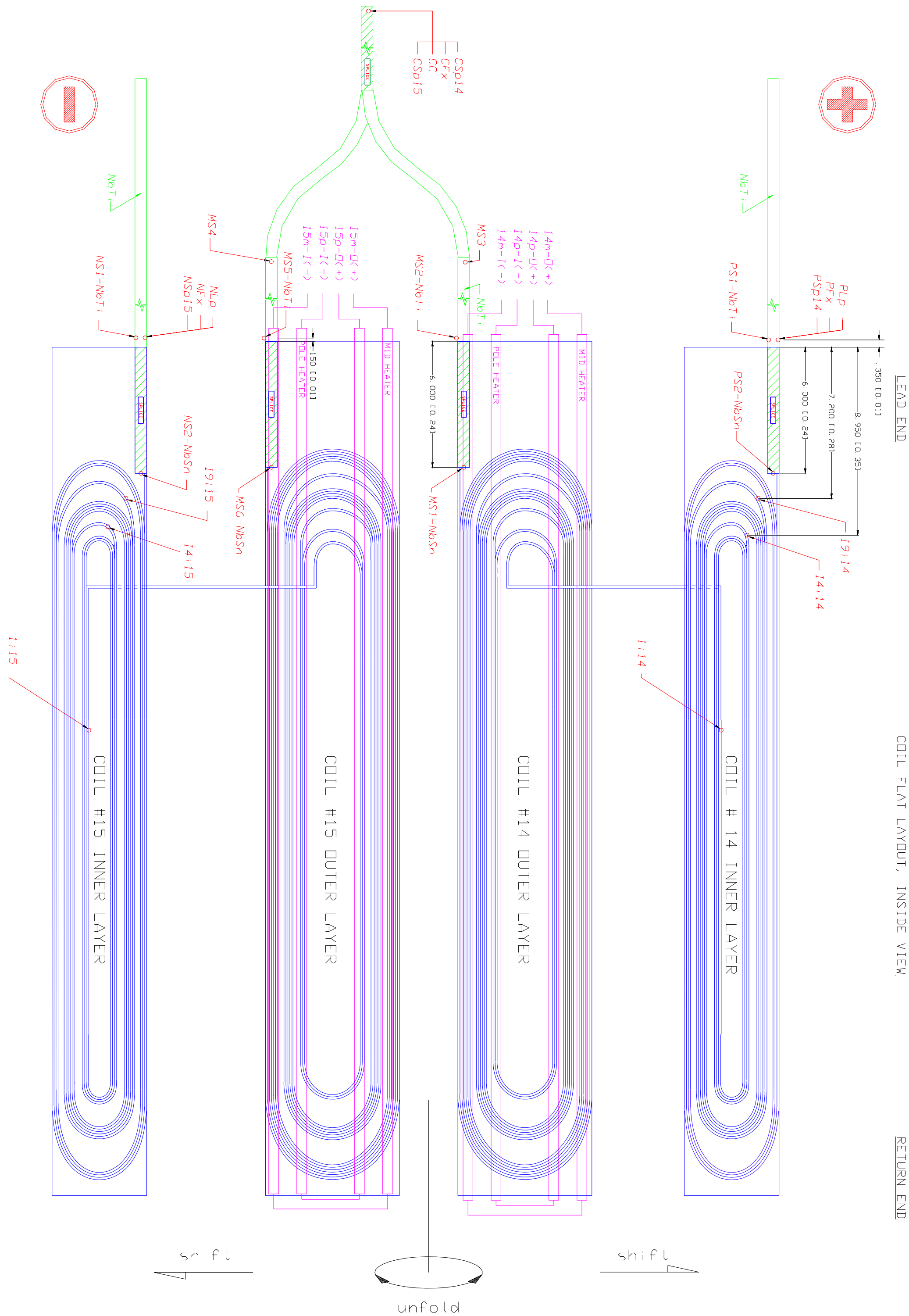


Figure 4.3.1: *Voltage Tap Layout.*

4.4 Parting plane Splices:

Beginning with 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. Solder was 70%/30% lead/tin with Kester 44 flux. Solder is heated to a temperature of approximately 230C.

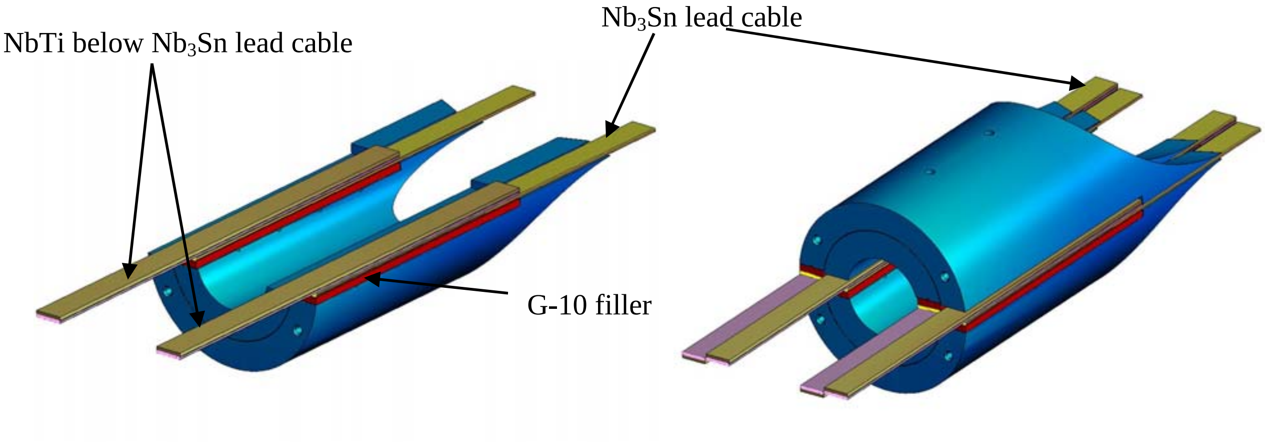


Fig. 4.4.1: *End-saddle and the splice geometry for magnet HFDA-06*

5.0 EPOXY IMPREGNATION

Each half coil in HFDA06 was impregnated separately after splicing, in the same fixture that was used for reaction. Figure 5.0.1 shows half coil HFDAH-014 enclosed in the tooling and being prepared for impregnation.

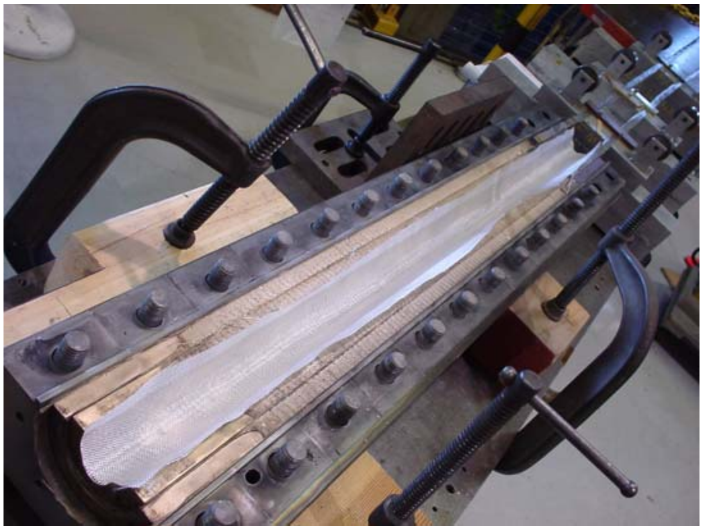


Fig. 5.0.1: *HFDAH-014 in reaction-impregnation tooling being prepared for impregnation*

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 20 microns. The container of epoxy was heated to 55C and evacuated to 60 microns. 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-014 after impregnation.

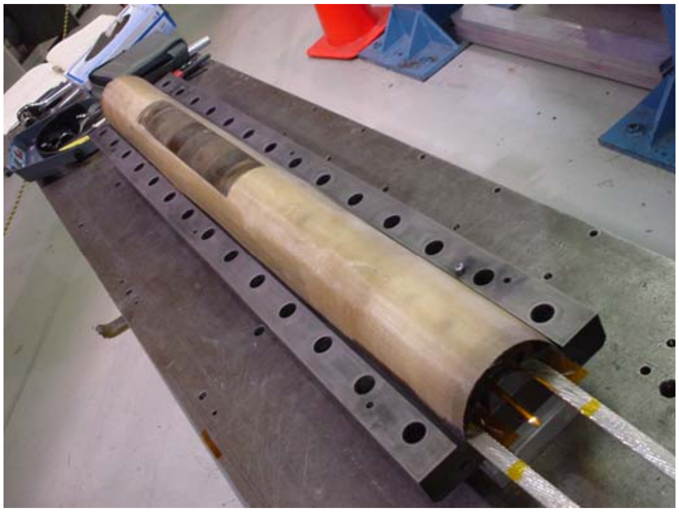


Figure 5.1.1 *Impregnated coil assembly*

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-014 are shown in Figures 5.2.3, 5.2.4 and 5.2.5. Figures 5.2.6, 5.2.7 and 5.2.8 show the same measurements for HFDAH-015. In the thickness and width measurement plots, yellow dots indicate points in the straight section, not covered by end parts.

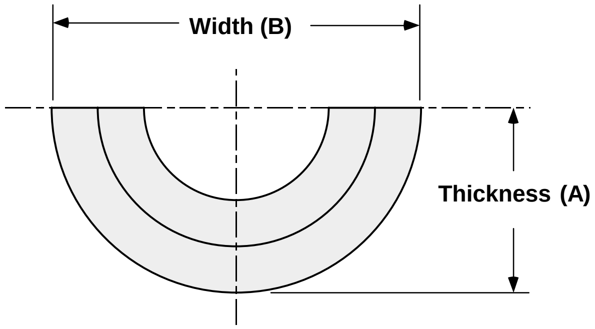


Figure 5.2.1 *Width and Thickness Measurements*

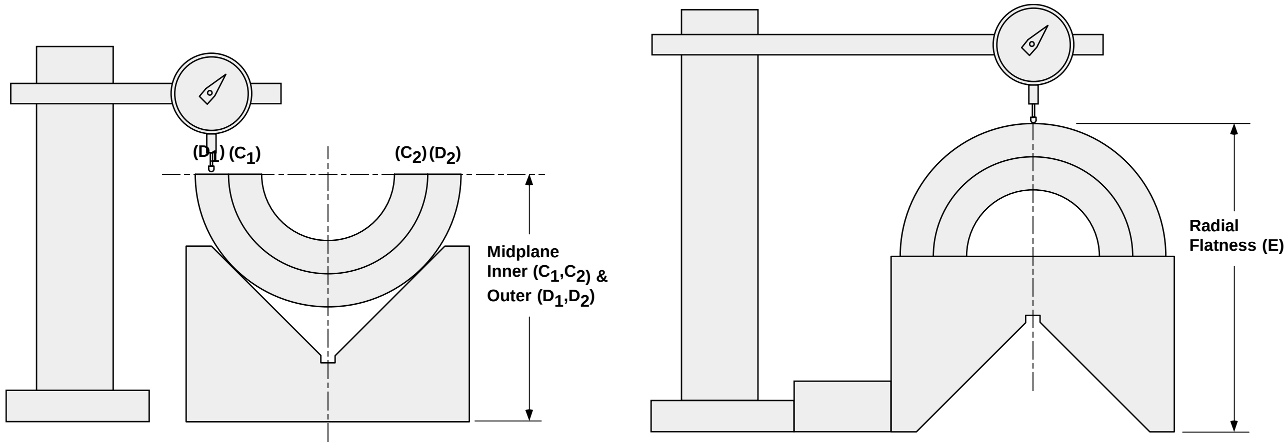


Figure 5.2.2 *Flatness Measurement Positions*

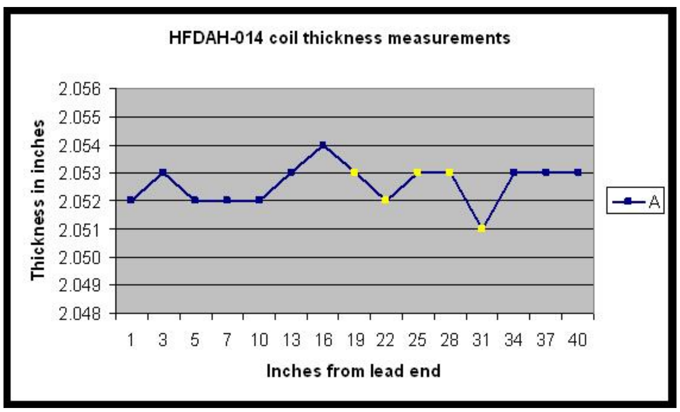


Figure 5.2.3 *Coil Thickness Measurements*

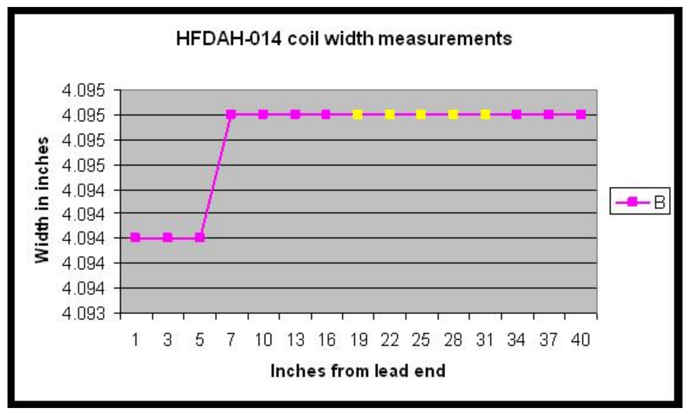


Figure 5.2.4 *Coil Width Measurements*

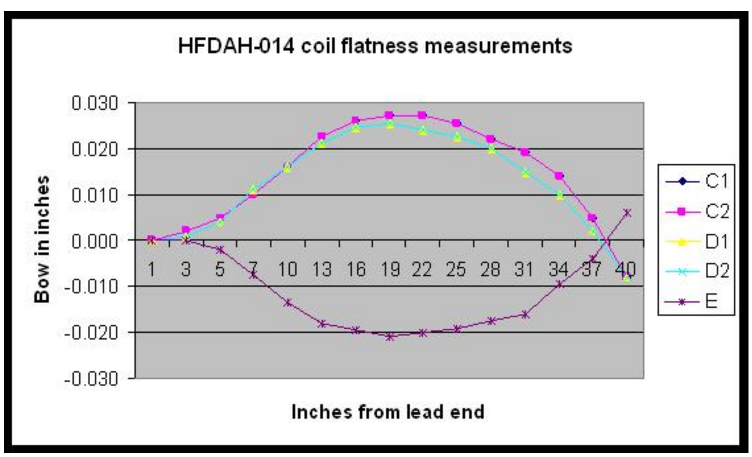


Figure 5.2.5 *Coil Flatness Measurements*

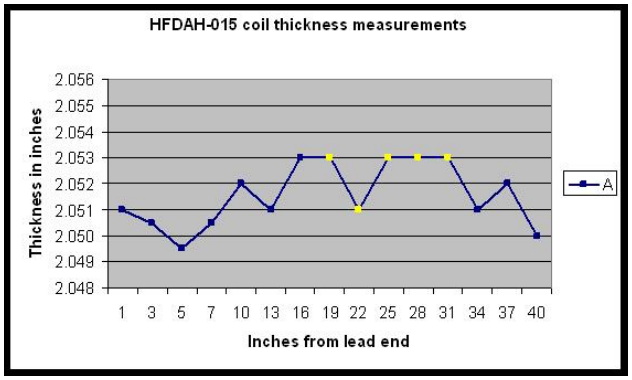


Figure 5.2.6 *Coil Thickness Measurements*

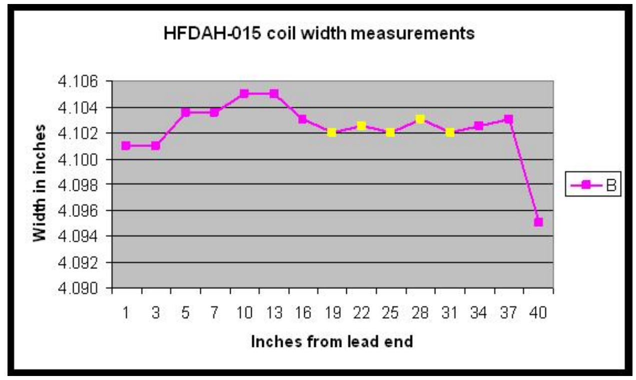


Figure 5.2.7 *Coil Width Measurements*

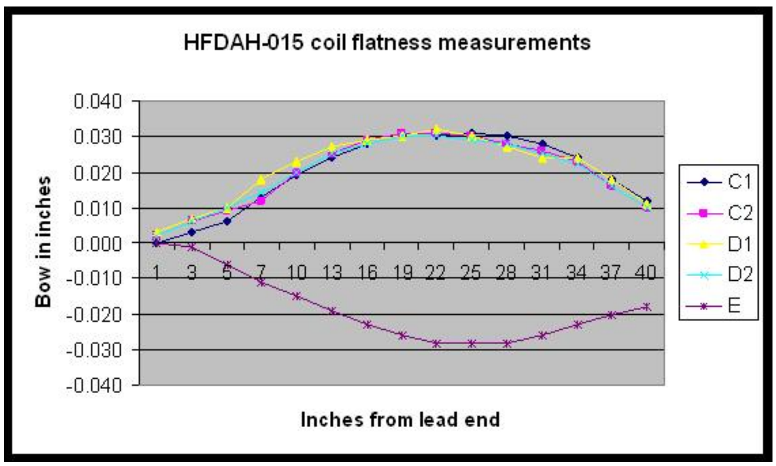


Figure 5.2.8 *Coil Flatness Measurements*

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 of an 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 follows:

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

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

Results for coils HFDAH014 and HFDAH015 are shown in Table 5.3.1

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
014	2.052	2.0475	1.20493e-06	12.87895	12.87895	12.87895	12.87895	2.049751	2.052	0.0022
015	2.0526	2.051	1.52023e-07	12.89183	12.89183	12.89183	12.89183	2.0518	2.052	0.0002

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@1A	Inductance μH @ 20 Hz	Inductance μH @ 1KHz	Q @ 20 Hz	Q @ 1KHz
HFDAH-014	6.0041	248.287	197.245	.51	4.26
HFDAH-015	6.1177	249.893	198.794	.5	4.24

6.0 YOKING

6.1 Magnet Structure

General structure of HFDA06 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 HFDA06. 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.

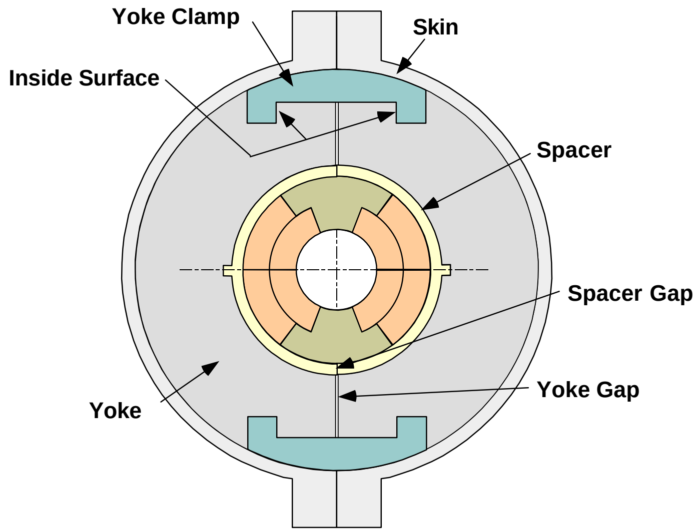


Figure 6.1.1 *HFDA06 General Structure*

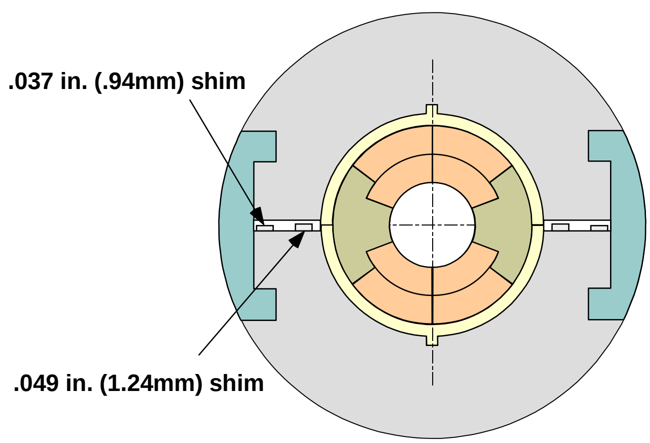


Figure 6.1.2 *Yoke gap shims*

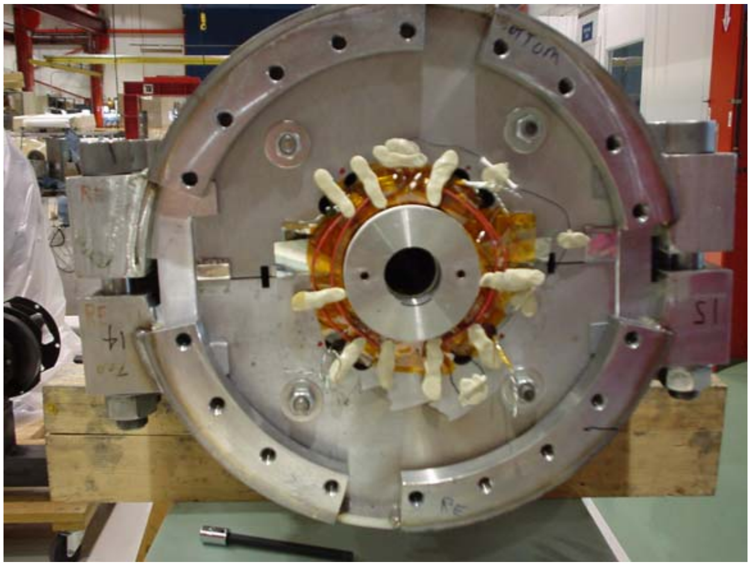


Figure 6.1.3 *HFDA06 in Yoke*

HFDA06 features a closed yoke gap during cool down and excitation, as did HFDA05. During construction, full-length shims were paced in the yoke midplane gaps. This was done to protect the coils from over compression during yoke clamp insertion. Shim size was based on a Finite Element calculation {TD-04-50].

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.

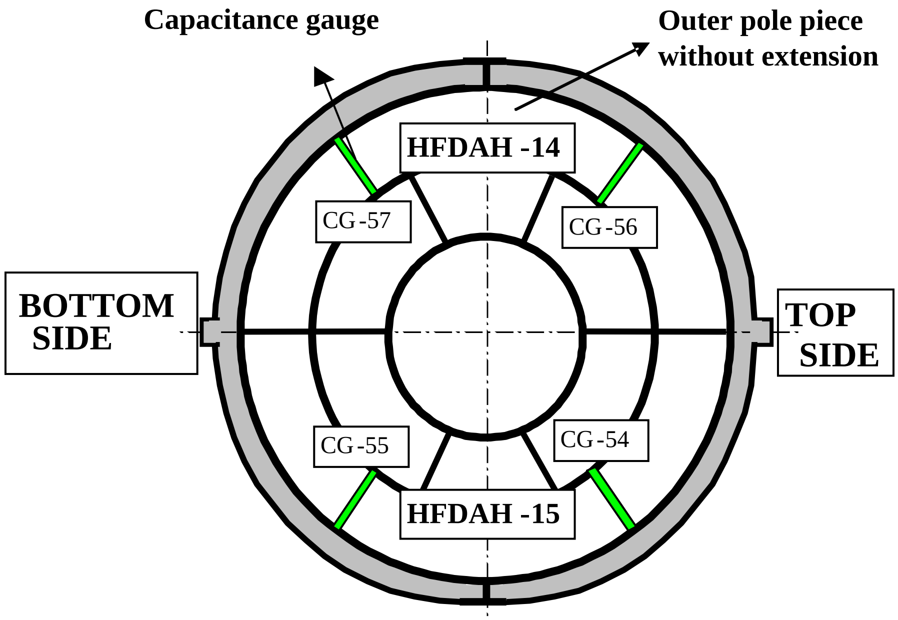


Figure 6.2.1. *Capacitance gauge layout near center of magnet during magnet assembly.*

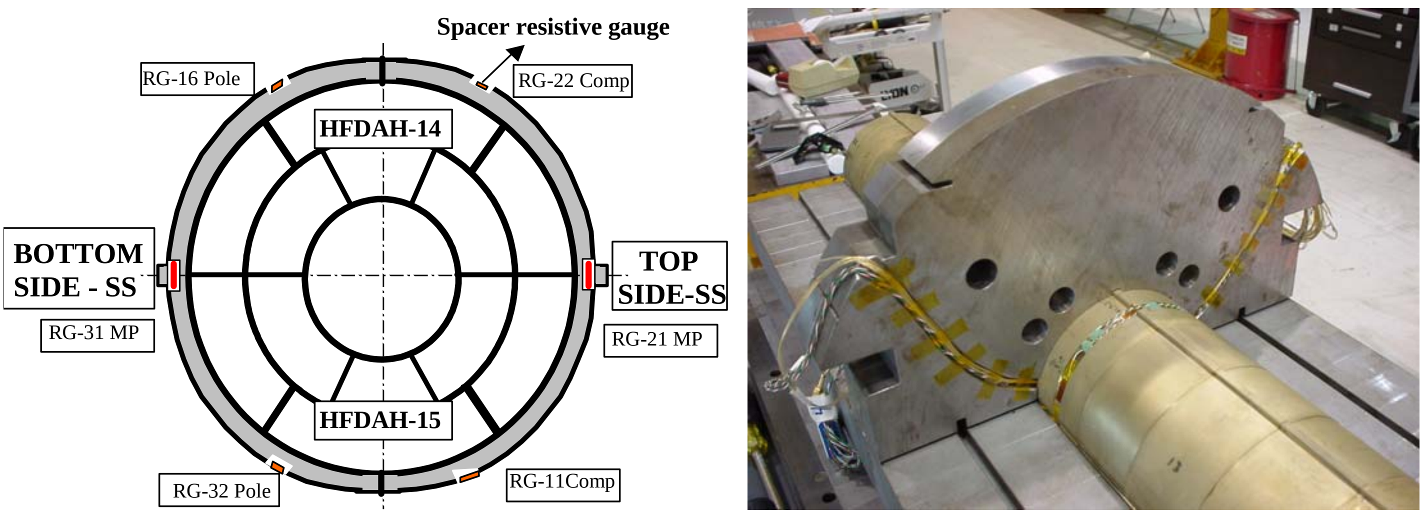


Figure 6.2.2: *Layout of spacers with resistive gauges in the magnet straight section.*

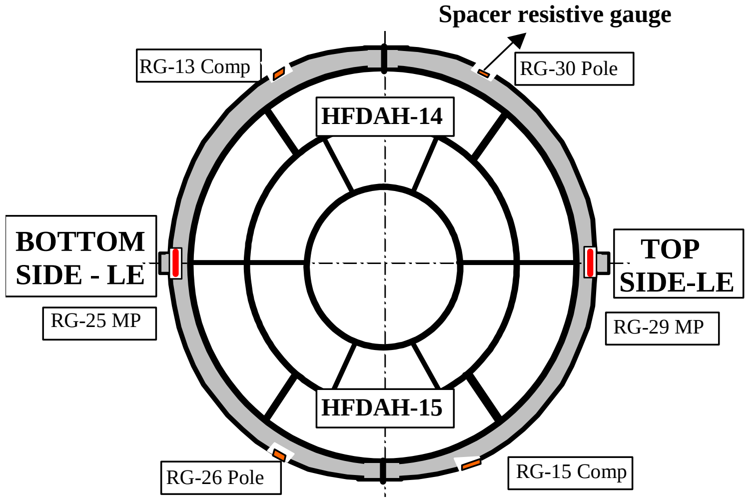


Fig. 6.2.3: *Layout of resistive gauges at the magnet Lead End.*

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 HFDA06, 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. Therefore, a radial shim of 2 mils (50µm) was used around each coil. Two 3 mil (75µm) thick SS shims were added azimuthally at the spacer midplanes to compensate for smaller manufactured size of the spacers. 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.

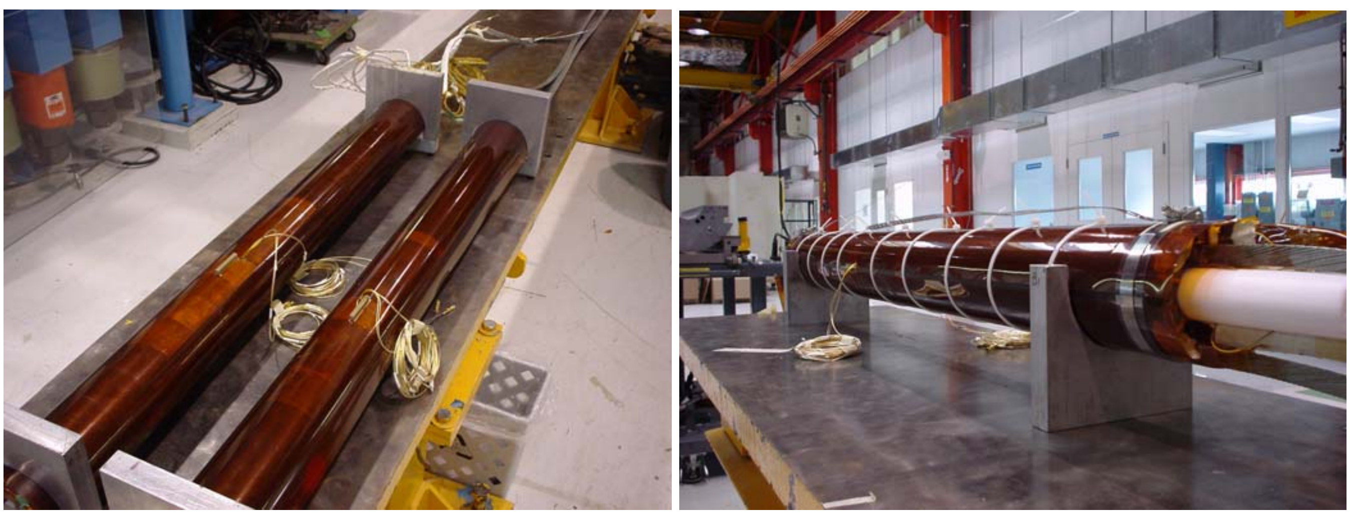


Fig. 6.3.1: *Kapton shim placed around impregnated coils.*

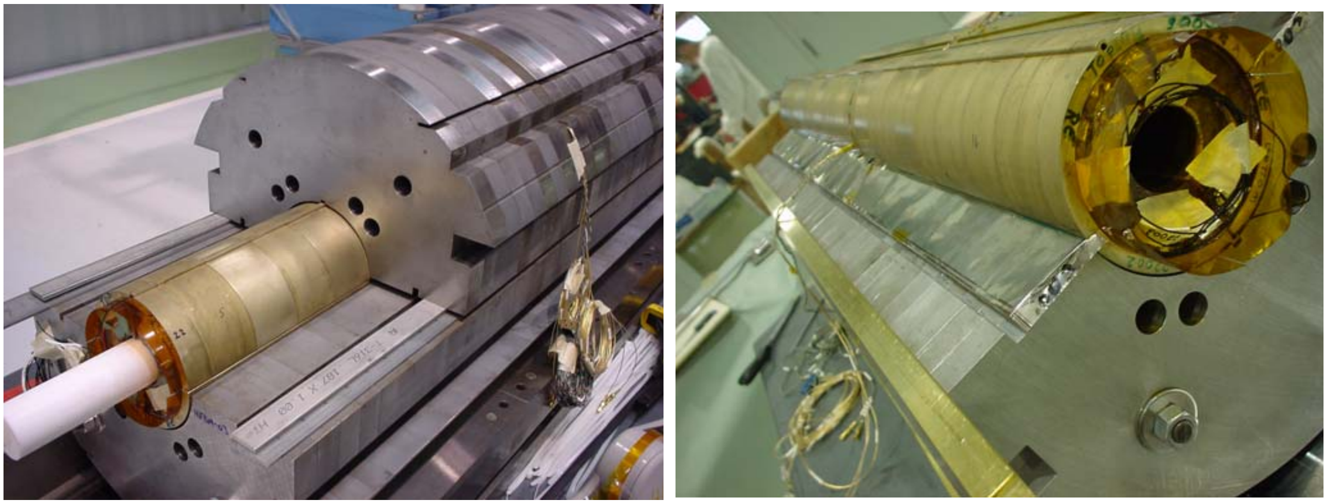


Fig. 6.3.2: *Assembly of HFDA06.*

HFDAH-015 was used as the upper coil and HFDAH-014 as the lower coil.

6.4 Pressing

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.

The magnet was placed into the press for yoke installation, as shown in Figure 6.4.1. The yoke halves were loaded vertically with main press pressure. The yoke clamps were inserted by hydraulic side pushers.

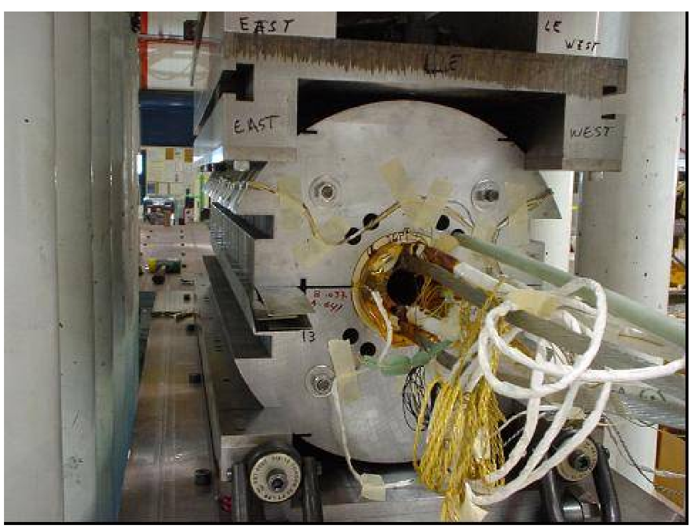


Fig. 6.4.1 *Magnet installed in the yoke press (HFDA05 shown)*

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.

Spacer strain gauge and pole capacitor gauge readings during yoking and bolting of the skins are shown in Figures 6.4.2 and 6.4.3, respectively. Yoke gap vs. Press pressure is shown in Figure 6.4.4.

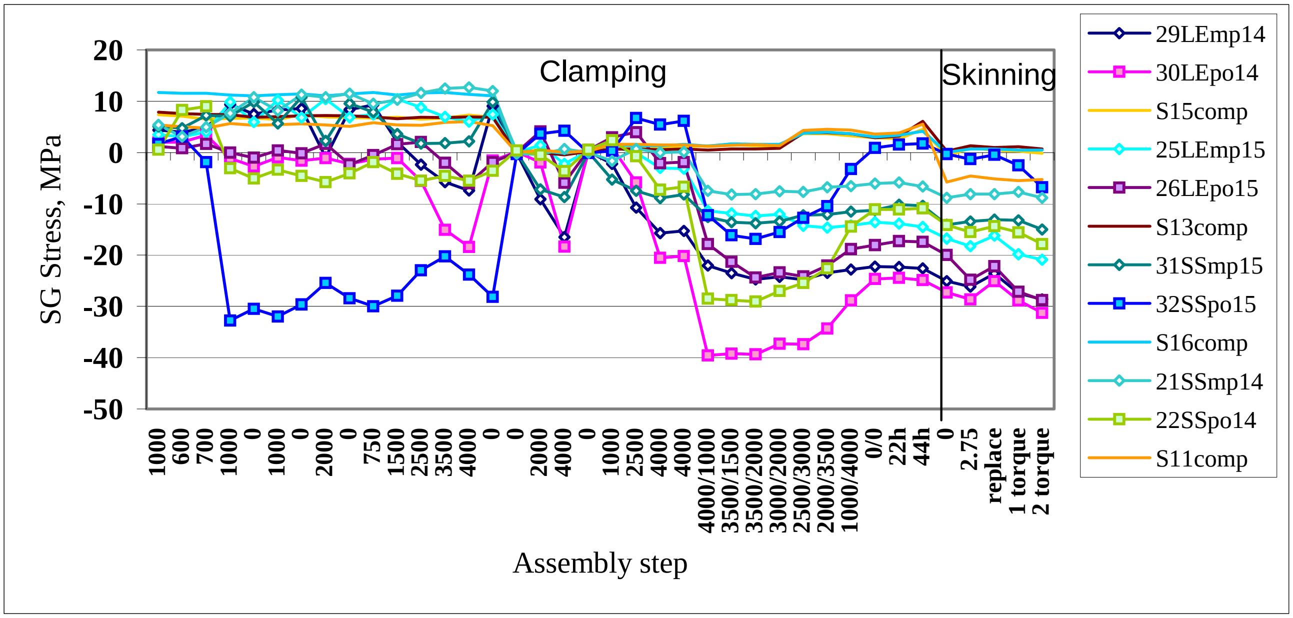


Figure 6.4.2: *Azimuthal stress in the spacers during yoking and skin bolting operations from resistive gauges.*

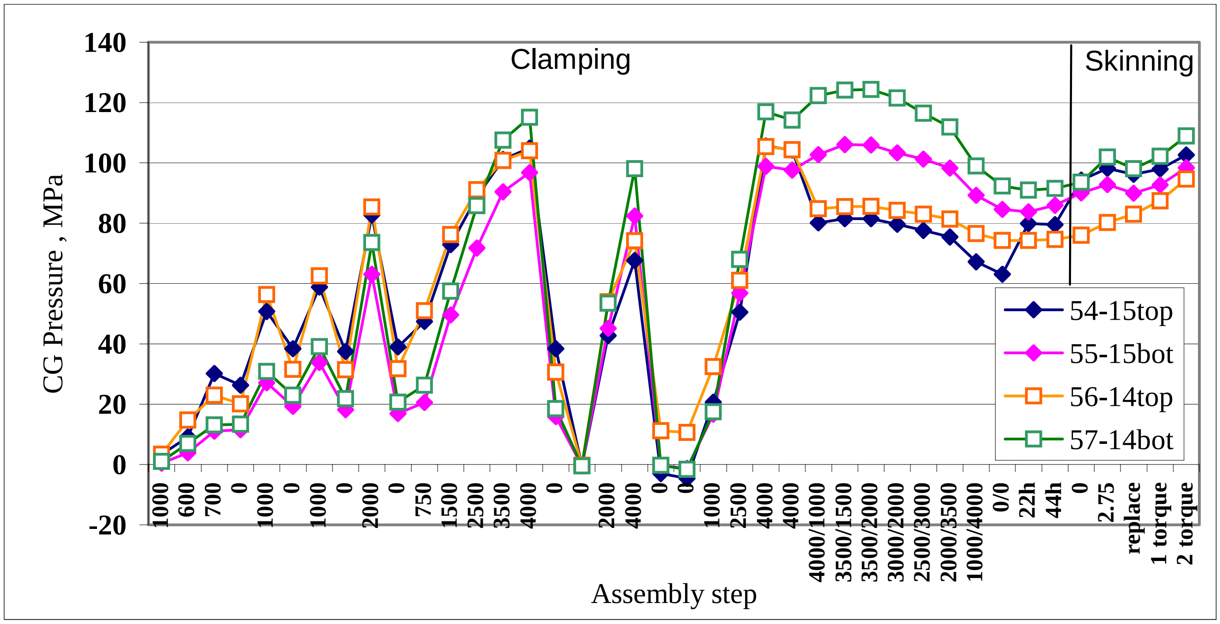


Fig. 6.4.3: *History of capacitance gauges.*

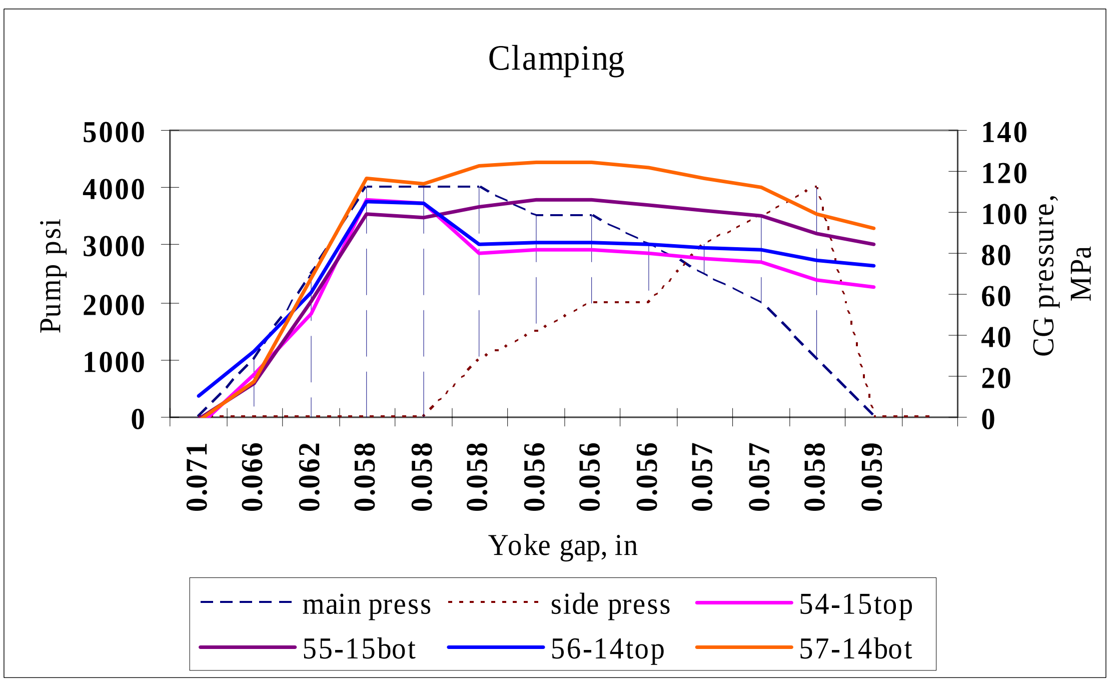


Figure 6.4.4: *History of capacitance gauges.*

6.5 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 1 KHz.

Table 6.5.1: *Electrical measurements on the yoked assembly*

	Resistance mΩ	Inductance μH @ 20 Hz	Inductance μH @ 1KHz	Q @ 20 Hz	Q @ 1KHz
HFDAH-014	60.661	344.535	137.947	.67	1.59
HFDAH-015	61.895	344.796	137.814	.66	1.58
Total	122.420	1105.75	397.173	1.02	1.48

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 6.5.2: *Hi-Pot measurements on the yoked assembly*

Test	Leakage @ 1KV
Coil to coil	.16 uA@250V
Coil to ground	.02 uA
Heaters to coil	.06 uA
Heaters to ground	.02 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 bolting steps.

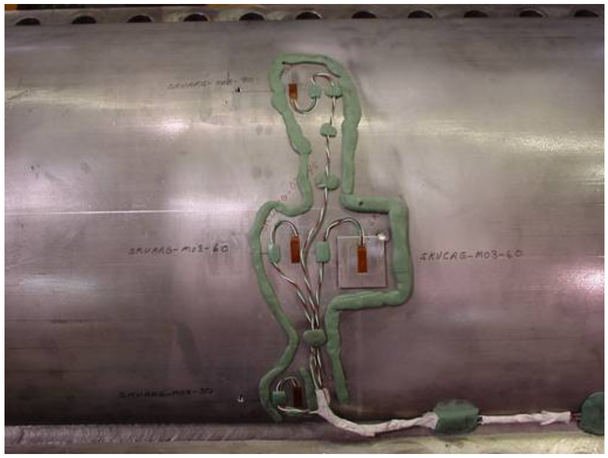


Figure 7.1.1: *Resistive strain gauges mounted on skin.*

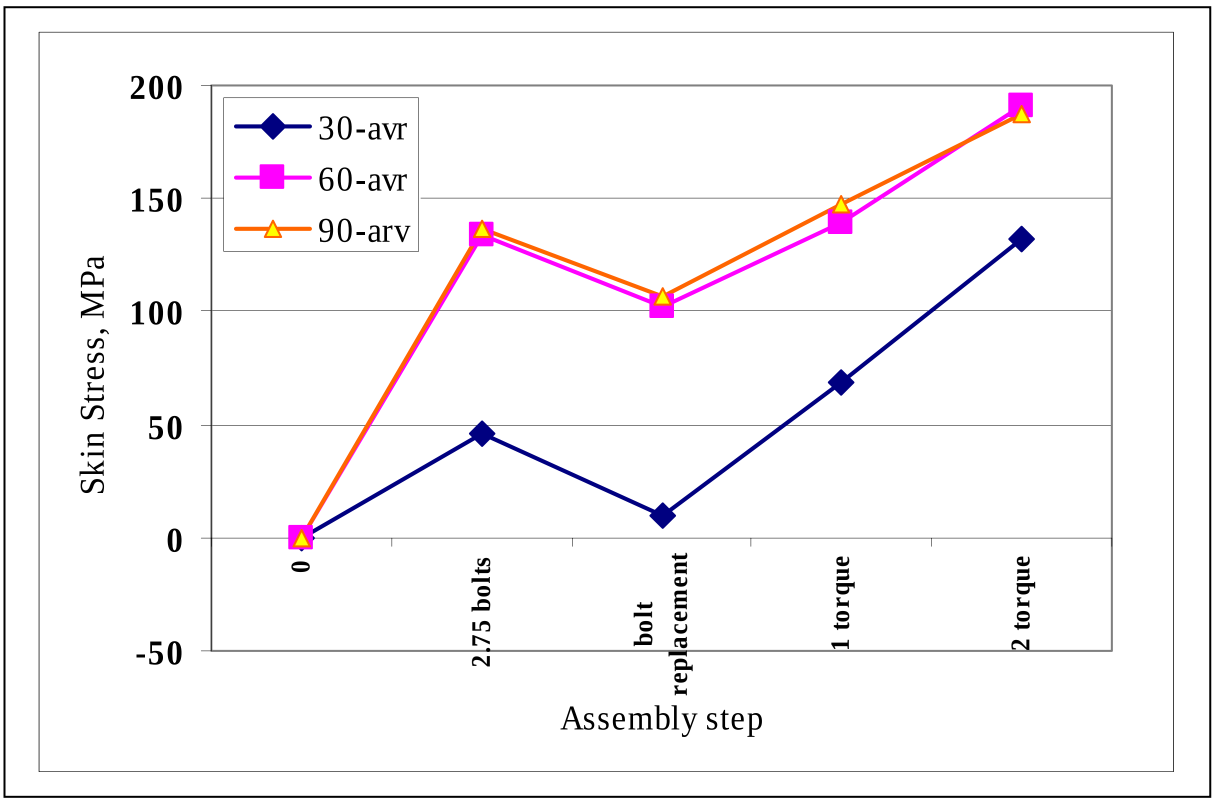


Figure 7.1.2: *Stress in skin during bolting operation, first with ¾"bolts then replaced with final 1" bolts*

Yoke gaps were measured after the skin was bolted. Measured gaps after the bolting operation are shown in Figure 7.1.3.

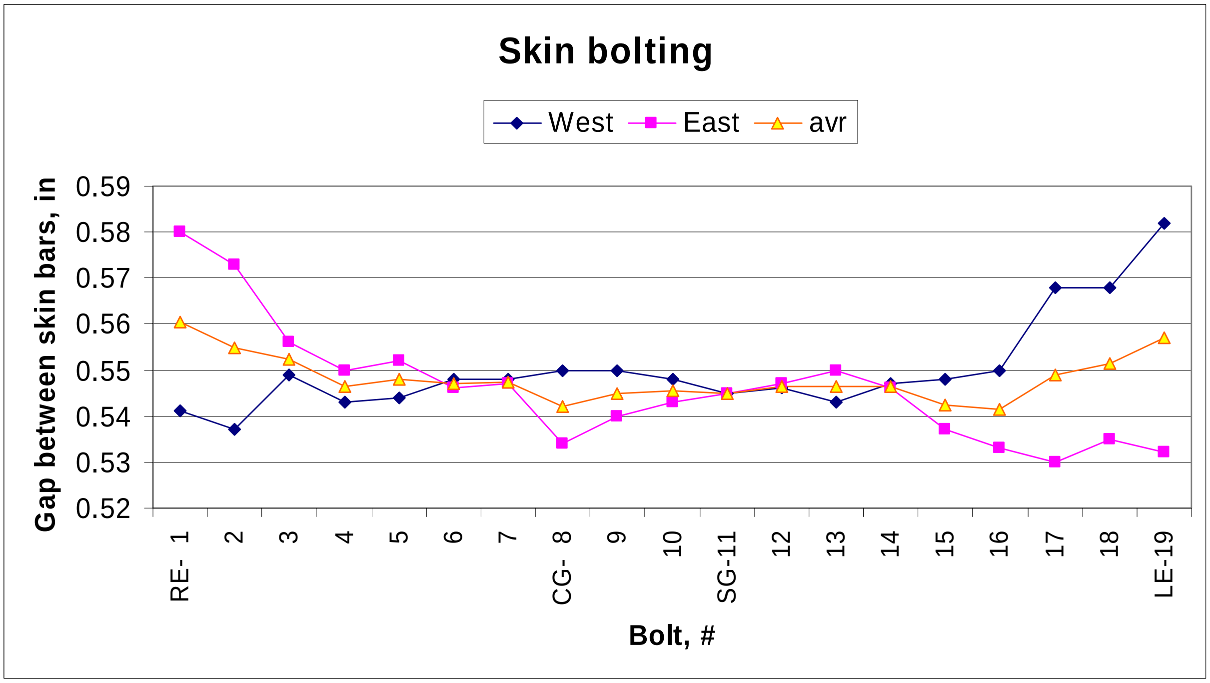


Figure 7.1.3: *Measured yoke gaps after bolting operation*

7.2 End Plate Installation

After the skin is installed, RTDs to measure the temperature during testing are installed. One RTD is installed near each end. An end plate is then bolted onto each end. Since this assembly was bolted, not welded, no twist measurements were taken.

Four preload bolts (bullets) were installed into each end plate. These bolts were used to apply longitudinal load to the coils. Figures 7.2.1 and 7.2.2 show bullet load in pounds during installation for the lead and return (non-lead) end, respectively.

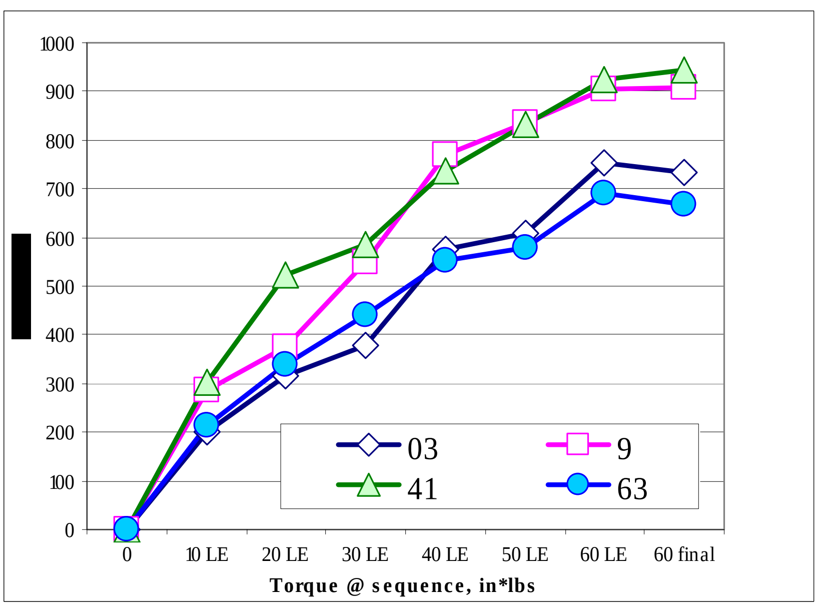


Figure 7.2.1

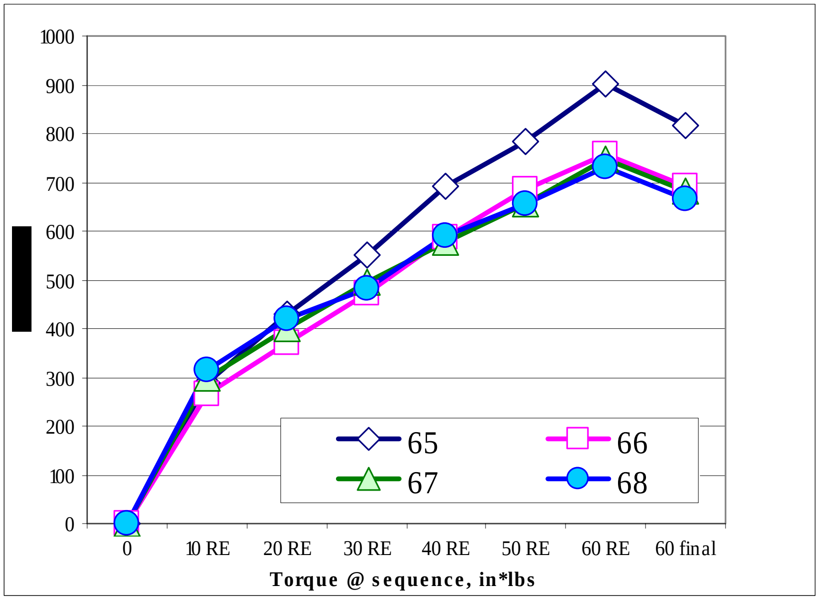


Figure 7.2.2

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 done 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. HFDA05, which is identical to HFDA06, is shown.

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 taken with 1 Amp applied.

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

	Resistance mΩ	**Inductance, μH**		**Quality Factor**	
		At 20 kHz	**At 1 Hz**	**At 20 kHz**	**At 1 Hz**
HFDAH-014	60.4506	342.311	131.071	.66	1.56
HFDAH-015	61.4909	343.693	132.931	0.65	1.57
Total Magnet	121.2415	1100.22	375.251	1.02	1.45

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

Test	**Leakage @ 1KV**
Coil to coil	.04 uA@250V
Coil to ground	.04 uA
Heaters to coil	.06 uA
Heaters to ground	.02 uA

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, skin and bullets). 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 mΩ	**Inductance, μH**		**Quality Factor**	
		At 20 Hz	**At 1 Hz**	**At 20 Hz**	**At 1 Hz**
Total Magnet	121.186	1099.7	374.428	1.02	1.45

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 @ 1KV**
Coil to ground	.02 uA
Heaters to coil	.02 uA @800V
Heaters to ground	.02 uA

8.0 SUMMARY

The sixth shell-type Nb_3Sn high field dipole magnet, HFDA-06 was delivered to VMTF for testing on July 10, 2005.

HFDA06 had a 43mm bore diameter and a straight section approximately 1/2 meter long.

1mm PIT strand manufactured by ShapeMetal Industries was used, identical to the cable used in HFDA05.

HFDA06 was tested at VMTF, achieving a field of 10 Tesla.