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Nb_3Sn Cos(θ) Dipole Mirror Magnet, HFDM-04 Production Report

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1.0 INTRODUCTION

HFDM-04 is the fifth Nb_3Sn cosine theta dipole mirror magnet to be fabricated at Fermilab. 5 dipole 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 dipole	TD-00-069
HFDA02 dipole	TD-01-036
HFDA03 dipole	TD-01-064
HFDA04 dipole	TD-02-025
HFDA03A mirror	TD-03-001
HFDA03B mirror	TD-03-030
HFDM02 mirror	TD-03-029
HFDM03 mirror	TD-05-006
HFDA05 dipole	TD-04-048

The primary features of HFDM04 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 HFDM04

Inner/Outer Cable Strand Type	RRP
Inner/Outer Cable Strand No.	39
Strand Diameter	.7mm
Strand Manufacturer	Oxford Industries
Cable lay direction	Left Lay
Cable Cleaning Fluid	none
Inner and Outer Cable Insulation	125uM x 12mm wide dry ceramic tape wrapped with 30% overlap. 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	Hand made assembly, with (2) 25 micron thick x 9.5 mm wide stainless strips per quadrant bonded to a 75 micron kapton sheet. See section 4.3. Strip was placed between coil and 1st ground wrap layer, with kapton toward coil.
Coil Reaction Cycle	See section 4.1.
Voltage Tap Plan	See Section 4.3
Impregnation cycle	CTD101K epoxy, evacuated to 20-40 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 and 6.3.	
End longitudinal loading	None.	
Strain Gauges on Skin	Yes. See section 7.1.	
Other		
Coil Fabrication Start Date	11/15/04	
Cold Mass Completion Date	2/20/05	

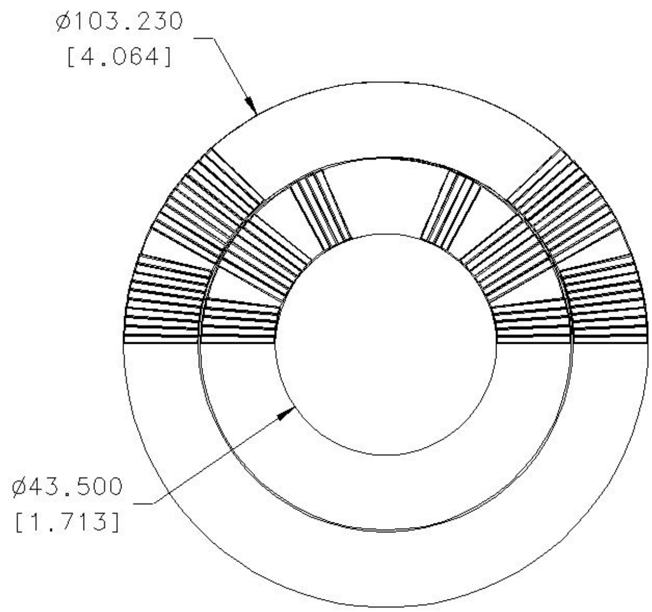


Figure 1.0.1 *HFDM04 cross section*

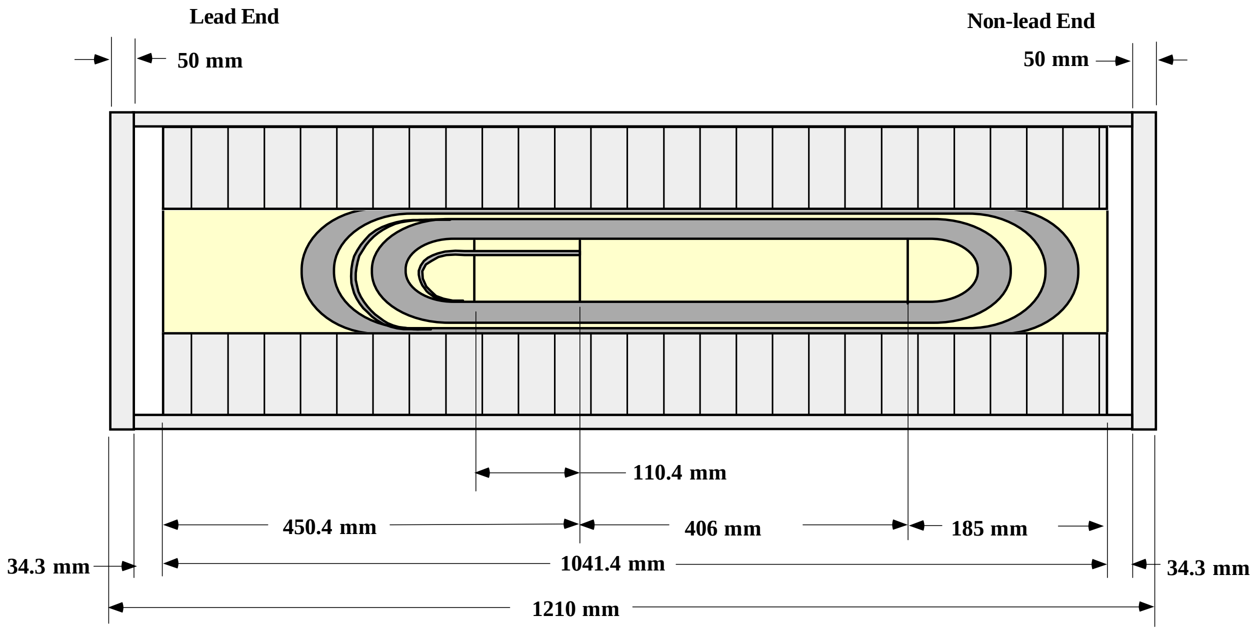


Figure 1.0.2: *Longitudinal parameters of HFDM-04*

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

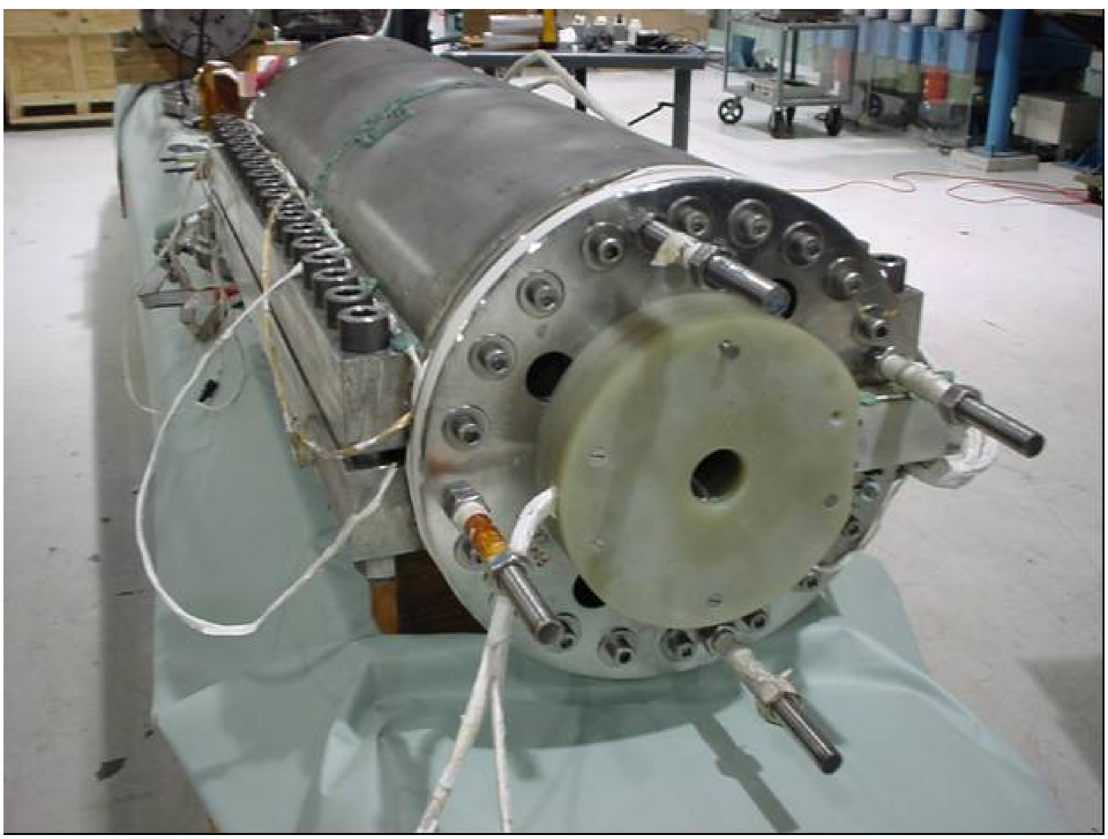


Fig. 1.0.3 *Photograph of HFDM-04 complete and ready for test*

Some important features of HFDM-04:

- The most significant change made between HFDA-05 and HFDM-04 is a change in strand from 1mm Powder in Tube made by SMI to .7mm RRP made by Oxford Industries. Modifications to the reaction cycle were therefore necessary.

- Cable and magnet cross section were changed from HFDA05, due to the change in strand diameter.

- Original design of cable for HFDD04 included a keystone angle of 1.3 degrees, with midthickness of 1.240 mm. All coil parts (end and straight section) were designed for cable of this cross section. This specification was subsequently changed, and the actual cable supplied had a keystone angle of .947 degrees, with a midthickness of 1.204 mm. See section 3.1 for more details.

- Cable was approximately one turn short, causing one turn to be eliminated from the inner coil current block nearest the mid-plane. Cable insulation was increased in this current block to compensate for the extra space. See section 3.2.

2.0 STRAND and CABLE

Strand for HFDM04 was made by Oxford Industries using the RRP Process. Billets numbers were 7054, 7060 and 6813. The nominal diameter of the strand was .7 mm. Strand parameters are described in table 2.0.1.

Table 2.0.1: Strand Description.

Billet ID	7054,7060,6813
Strand diameter, mm	0.7
I_c(12 T), A	~500
Cu fr., %	50
No. of filaments	54/61
D_{eff}, μm	85
Geometric filament size, μm	61-75
RRR	40
No. units	20
Total length, m	12,000
Average length/unit, m	600
Twist pitch, mm	12

2.1 Cable Mechanical Parameters

Rutherford type cable with 39 strands was manufactured at LBL. Cable reel number was F5O-F00891d. Cable mechanical parameters are listed in Table 2.1.1. Cable used in HFDM04 did not include a stainless steel core.

Table 2.1.1: *Cable parameters as provided by LBL.*

Parameter	Unit	Design Value	Measured Value
Strand Diameter	mm	.7 mm	.7029 mm
Mid-Thickness	mm	1.2 mm	1.2044 mm
Width	mm	14.34 +/-.025 mm	14.342 mm
Keystone angle	deg	0.95 deg	.947 deg
Pitch Length	mm	111 mm	N/A
Number of Strands		39	39
Lay Direction		left	left
Packing Factor	%	90	N/A
Reel Number		F5O-B00891d	

***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 the coil used in HFDM04 (HFDDH-001). Table 2.2.2 shows magnet quench currents at 4.5 and 2.2K. Figure 2.2.2 and Table 2.2.3 show self-field test results at 4.2 K for impregnated and non-impregnated keystoned RRP cables used as witnesses of the half-coil HFDDH01 (891-D’s) used in HFDM04. Results for the coil used in the following mirror HFDM05 (HFDDH02) (911’s) are also shown.

Table 2.2.1: Measured critical parameters of the witness samples of coil HFDDH-001.

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
HFDDH01				**Actual HT was 100 h at 210°C, 48 h at 400°C, 50 h at 650°C**								
Extr. #1 (annealed)		Q 134			**Q 176**		Q 301		Ti		280,2.38	8
Extr. #2 (annealed)*		Q 76			**Q 105**		Q 147		Ti			
Extr. #3*		Q 94			**Q 113**				Ti			
Extr. #4		Q 74			**Q 85**				Ti			
Extr. #5		(232)	Q 272	Q 308	**Q 336**	Q 407	Q 494	Q 528	Ti		325,2.53	33
Extr. #6		Q 228	Q 276	Q 333	**Q 382**	Q 495	Q 621	Q 494	Ti		320,1.37	16
Extr. #7 (annealed)		209,27	270	(345)	**Q 385**	Q 471	Q 552	Q 661	SS	1	300,1.47	14
Extr. #8 (annealed)		213,27	273	341	**422**	Q 510			SS	1	300,0.89	7

* Some resistivity observed

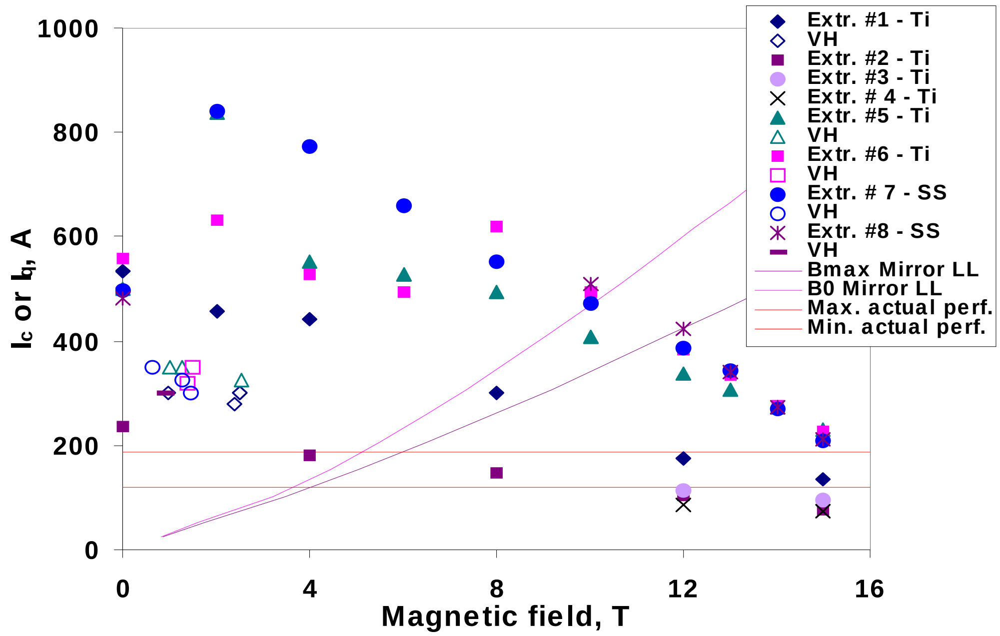


Figure 2.2.1: I_c or I_q as obtained through *VI* and *VH* measurement as a function of magnetic field for 0.7 mm 54/61 RRP strands extracted from cable 891-D and used as witnesses of half-coil HFDDH01. The red line shows actual performance of HFDDH01.

TABLE 2.2.2 *MAGNET QUENCH CURRENTS AT 4.5 K AND 2.2 K*

	Meas. I_{min}(4.5 K)-I_{max}(4.5 K), A	Meas. I_{min}(2.2 K)-I_{max}(2.2 K), A
HFDM04 (HFDDH01)	4690-7239	5609

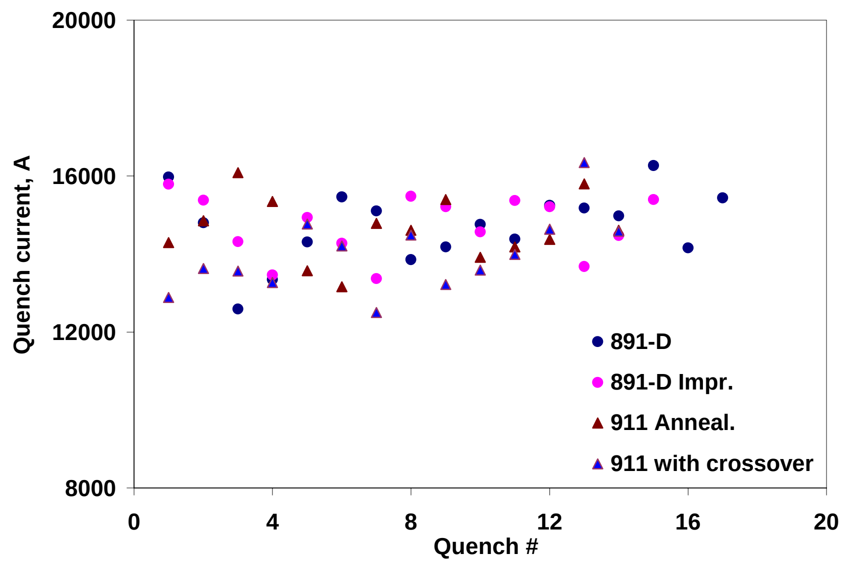


Fig. 2.2.2: Self-field test results at 4.2 K for impregnated and non-impregnated keystoned RRP cables used as witnesses of half-coils HFDDH01 (891-D's) and HFDDH02 (911

Table. 2.2.3: Witness Cable Test Results for HFDM04 and HFDM05

HEAT TREATMENT	Cable ID	Impregnation	Cable Ave. I_q, A	Cable Min. I_q, A	Min. I_q/strand, A
HFDDH01	891-D	N	14710	12588	322
"	"	Y	14731	13375	343
HFDDH02	911	N	14644	13166	337
"	"	N	13978	12500	320

Figure 2.2.3 shows the predicted short sample limits for coil HFDDH-001.

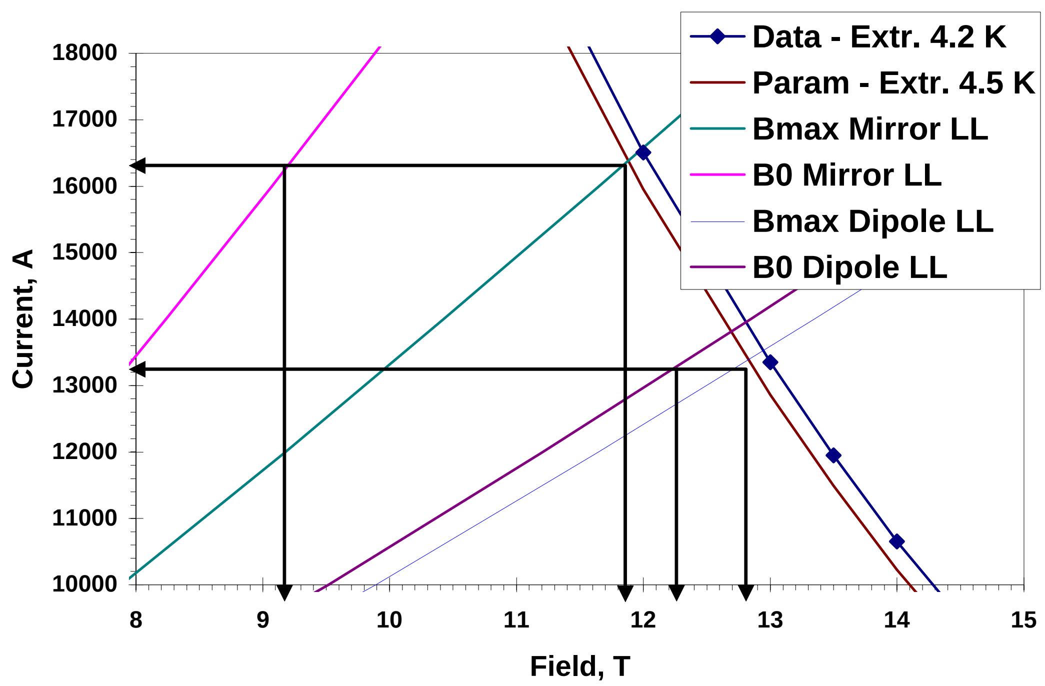


Fig. 2.2.3: *High field short sample limit for half-coil HFDDH01 in a mirror and dipole configurations.*

Table 2.2.4 shows the mirror maximum quench currents with SSL predictions for HFDM04..

Table 2.2.4 *Comparison of Mirror Maximum Quench Currents with Various SSL Predictions*

	T_0, K	Meas. I_{max}/B_{max}, kA/T	Meas. Min. I_q (self-field), kA	Calc. (strand) $I_{ssl}(B_{max},T_0)$, kA
HFDM04 (coil #01)	4.5	7.2 / 6	12.6	6.5 - 16.4

No formal cleaning process was used on the cable before insulating. Before insulating, the cable was heat-treated at 200 C for 30 min to reduce residual stresses in the cable. These stresses come from a combination of the strand and cable manufacturing processes.

3.0 COIL FABRICATION

3.1 Cable and Wedge Insulation

The original cable cross-section design for HFDM04 (coil HFDD01) included a keystone angle of 1.3 degrees, with mid-thickness of 1.240 mm. All coil parts (straight section and ends) were manufactured to accept this cross section. This specification was subsequently changed, and the actual cable supplied had a keystone angle of .947 degrees, with a mid-thickness of 1.204 mm, but coil parts as originally designed were used. The cable and wedge insulation was adjusted to help compensate for these differences. The amount of cable and wedge insulation used in HFDM04 and the reasons for choosing those values are described below:

The cable insulation system for HFDM04 is similar to the system used on HFDA05 (previous cos-theta PIT magnet), consisting of 125 micron (5 mil) thick x ½ inch wide dry ceramic tape with some overlap. Insulation thickness used for HFDA05 was 250 microns on all sides, as shown in Figure 3.1.1.

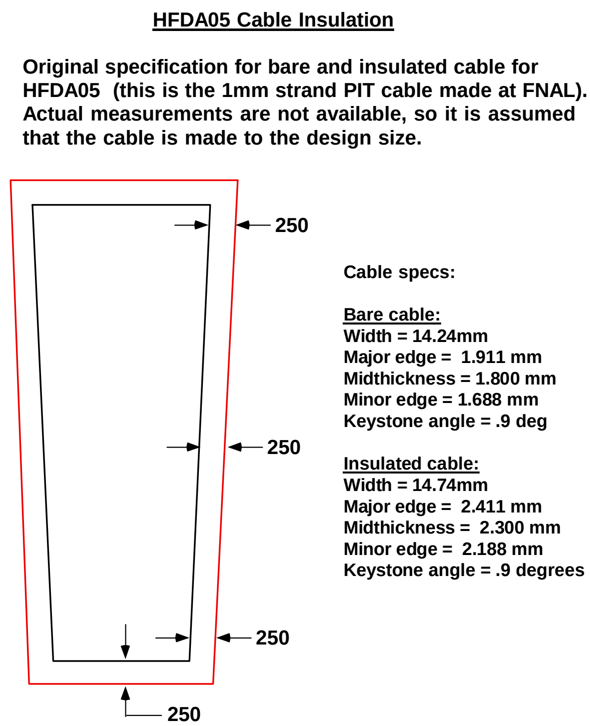
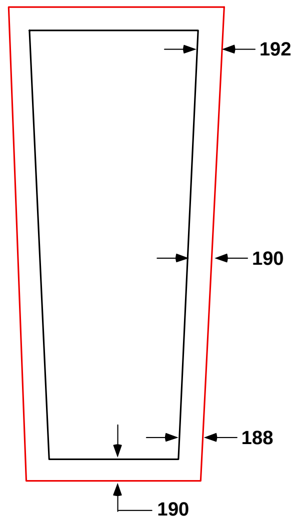


Fig. 3.1.1: HFDA05 Bare and insulated cable.

The original bare and insulated cable specifications for HFDM04 are shown in Figure 3.1.2. The total amount of insulation was to be approximately 190 microns all around. Figure 3.1.3 shows the actual bare cable size (black line) placed into a cavity which matches the design insulated cable size.

HFDM04 Cable Insulation Design

Original specification for bare and insulated cable for HFDM04 (this is the .7mm strand RRP cable for the magnets originally called HFDD dipoles).



Cable specs:

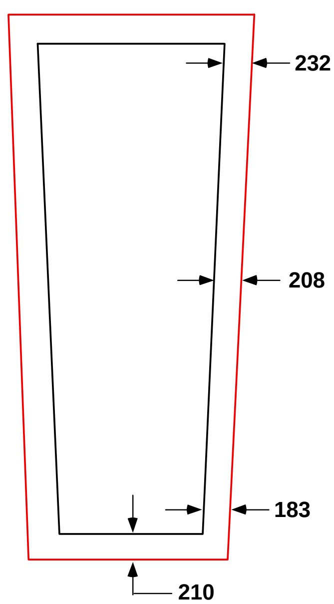
Bare cable:
Width = 14.36mm
Major edge = 1.403 mm
Midthickness = 1.240 mm
Minor edge =1.077 mm
Keystone angle = 1.3 deg

Insulated cable:
Width = 14.74mm
Major edge = 1.7873 mm
Midthickness = 1.620 mm
Minor edge = 1.4527 mm
Keystone angle = 1.3 degrees

Fig. 3.1.2: *HFDM04 bare and insulated original cable design.*

HFDM04 Cable Insulation Actual

Actual size of bare cable for HFDM04 (reel 891-D) placed inside the original insulated cable size (the parts and cavity are made to a size to accept the insulated configuration).



Cable specs:

Bare cable:
Width = 14.342 mm
Major edge = 1.323 mm
Midthickness = 1.2044 mm
Minor edge = 1.086 mm
Keystone angle = .947 deg

Insulated cable:
Width = 14.74mm
Major edge = 1.7873 mm
Midthickness = 1.620 mm
Minor edge = 1.4527 mm
Keystone angle = 1.3 degrees

Fig. 3.1.3: *HFDM04 Actual bare and insulated cable size*

Based on the above figures, with respect to the insulation system of HFDA05, the insulation amount should be decreased by 232/250 = 92% at the thick edge, 208/250 = 83% at the mid-thickness, 183/250 = 73% at the thin edge, and 210/250 = 84% on the radial surfaces.

75% was chosen as the overlap reduction percentage, because it is critical to not over-compress the cable in the fixture during reaction, and using a higher number might result in over-compression at the thin edge.

Insulation overlap of HFDA05 was 40% on the cable and 45% on the wedges. Overall, there were 24 turns and 4 wedges in the inner and outer coils combined. So there were 6 times as many turns as wedges. The average overlap percentage was therefore 40.7%.

The HFDM04 insulation overlap percentage is therefore (40.7)(.75) = 30.5%. ***The insulation system for HFDM04 was therefore chosen to be 5 mil x ½ inch wide dry ceramic tape, with a 30% overlap.***

After winding but before curing, the insulated cable was painted with CTD-1008 binder.

3.2 Coil Winding and Curing:

End part material was phosphor bronze. Parts were machined to fit the coil 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. The coil is therefore cured to a size which is 5 mils smaller than the nominal size per side.

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.

The hydraulic pressure used to close the press to the mold cavity size was taken during curing. These measurements indicated that the azimuthal pressure on the coil needed to close the mold was about 35 MPa.

At completion of the inner coil winding, it was discovered that there was not enough cable to complete the last turn of the inner coil. The final current block of the inner coil (nearest the midplane) was back-wound, then rewound with a double layer of 7.5 mil ceramic insulation placed between each turn, amounting to 15 x 5 = 75 mils of extra (uncompressed) insulation. This extra insulation replaced the azimuthal space normally taken by the final turn.

3.3 Coil Mechanical Measurements:

Coils are usually measured after curing, but before reaction, at various pressures to determine the shim size of the cavity in the reaction fixture. These measurements were not taken for coil HFDDH001, because the tooling was not available.

However, the hydraulic pressure used to close the press to the mold cavity size was taken during curing. These measurements indicated that the azimuthal pressure on the coil needed to close the mold was about 35 Mpa, the same as for the previous coils. The same shim (zero) was therefore used in the reaction cavity. The coil was therefore reacted with the cavity at the nominal size. Based on measurements of previous coils, (see section 3.3 of HFDM03 production report), coil HFDDH-01 was smaller than nominal azimuthal size at 3 MPa, therefore subjected to very low pressure in the fixture before reaction. During the reaction process, the coil is expected to grow in size to fill the reaction mold. Very low pressure is used to avoid tin leaks during reaction.

3.4 Coil Electrical Measurements:

Electrical measurements (L, Q and R) were taken on both the coil before placing into the reaction fixture. The data is shown in Table 3.4.1. The values match the theoretical estimates, which indicate that the coil is free of turn-to-turn shorts. The inductance, L and Q was measured at 1 kHz and at 20KHz. Resistance was measured using four-wire technique at 0.1 A. Measurements were done on a wooden table with no mandrel.

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

	Resistance mΩ	**Inductance μH @ 20 Hz**	**Inductance μH @ 1KHz**	**Q @ 20 Hz**	**Q @ 1KHz**
HFDDH001	120.9	576.35	501.441	.57	6.37

3.5 Ground Wrap System:

Inter-coil insulation consists of 3 layers of 5 mil (125um) ceramic sheet placed radially between inner and outer coil. Ground wrap consists of 3 layers of 5 mil (125um) ceramic sheet placed radially between outer coil and spacers. A quench protection (strip) heater, consisting of 2 stainless strips bonded to a 4 mil piece of kapton, is placed between the impregnated coil and the first sheet from the outer coil surface. The strip heater is inserted between the first and second layer of ground wrap after the coil is reacted but before it is impregnated.

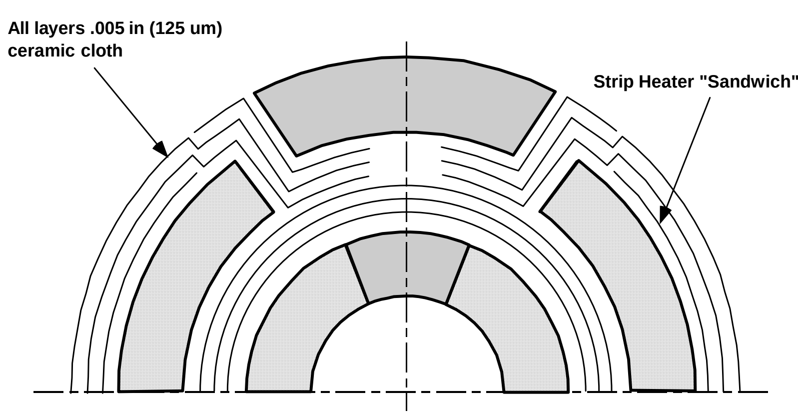


Fig. 3.5.1: *HFDM04 inter-coil and ground wrap insulation system*

The layers are "preformed" to the proper shape by painting with CTD-1008 and baking at 130C for 4 hours while wrapped onto a mandrel, which defines their shape. All layers are installed before the coils are reacted.

In fact, although the design calls for 15 mils of thickness for both the inter-layer and ground insulation, the sheets of "5 mil" being used measure about 6-7 mils each after curing.

4.0 COIL REACTION

4.1 Reaction Cycle

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

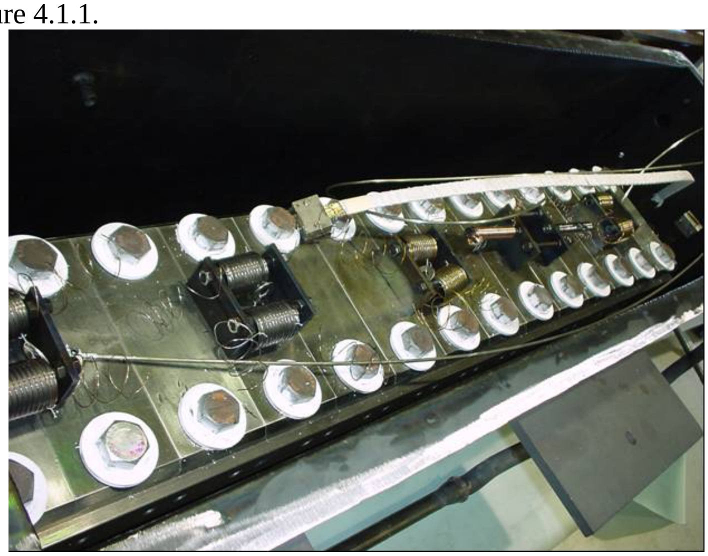


Figure 4.1.1: Coil HFDDH-001 in retort with witness samples

The reaction cycle of the coil HFDDH001 is described in detail below:

Oven used is the L & L oven in IB3. Based on recent heat treatment experiments, the oven settings were adjusted to compensate for three different parameters:

1. Vertical thermal gradient
2. Back-to-front thermal gradient
3. Lag time for the retort to reach the temperature of the programmed cycle.

1. Adjustment for vertical thermal gradient. Previous tests with an empty reaction fixture showed that the temperature of the oven at the position of the reaction fixture is lower than the oven control setting by approximately 10C at 210C, 10C at 340-400C and 10C at 650C. The soak steps at 210C and 650C will each be adjusted upward by 10C. The 400C step will not be adjusted, because it is critical to not overheat but being slightly under is not critical at this temperature.

2. Adjustment for back-to-front thermal gradient. The oven control is split into six "banks" of resistive coils. Each of these banks can be adjusted up or down individually, from settings of 0 to 999,

controlling the local variations in the oven. The banks were adjusted, based on recent heat treatment experiments, as shown in Table 4.1.1.

Table 4.1.1. *Heater Bank Settings*

Top sides	800
Bottom sides	999
Top door	700
Bottom door	800
Top back	950
Bottom back	950

3. Length of steady state steps (called soak steps) are also extended to compensate for the lag time for the retort to reach the temperature of the programmed cycle, as was done on the recent tests. Based on previous oven tests, the lag time is 20 hours at 210 degrees, 12 hours at 400 degrees, and 6 hours at 650 degrees.

The “ideal” (unadjusted) cycle for the coil is shown in table 4.1.2:

Table 4.1.2. *Unadjusted cycle for HFDDH-001*

Beginning set point: 20C			Time (hr:min)
Step 1	Ramp	from 20C to 210C at 25C/hr.	8:00
Step 2	Soak	210C	100:00
Step 3	Ramp	from 210C to 400C at 50C/hr.	3:36
Step 4	Soak	400C	48:00
Step 5	Ramp	from 400C to 650C at 75C/hr.	3:28
Step 6	Soak	650C	50:00
Step 7	Ramp	From 650C to 20C	48:00
Step 8	Soak	20C	till removed

The exact cycle (as programmed) for HFDDH01 is shown in Table 4.1.3:

Table 4.1.3. *Adjusted reaction cycle for HFDDH-001*

Beginning set point: 20C			Time (hr:min)
Step 1	Ramp	from 20C to 220C at 25C/hr.	8:00
Step 2	Soak	220C	90:00
Step 3	Ramp	from 220C to 221C at 1C/hr.	1:00
Step 4	Soak	221C	30:00
Step 5	Ramp	from 221C to 400C at 50C/hr.	3:36
Step 6	Soak	400C	60:00
Step 7	Ramp	from 400C to 660C at 75C/hr.	3:28
Step 8	Soak	660C	56:00
Step 9	Ramp	From 660C to 20C	48:00
Step 10	Soak	20C	till removed

Actual cycle for coil HFDDH001, as read by thermocouples, is shown in Figures 4.1.3 through 4.1.9. The horizontal axis in the figures represents the sampling rate for the data of 1 minute intervals. The three lines in the reaction cycle figure represent the readings from three thermocouples placed inside the reaction oven. Thermocouples were placed as shown in Figure 4.1.2.

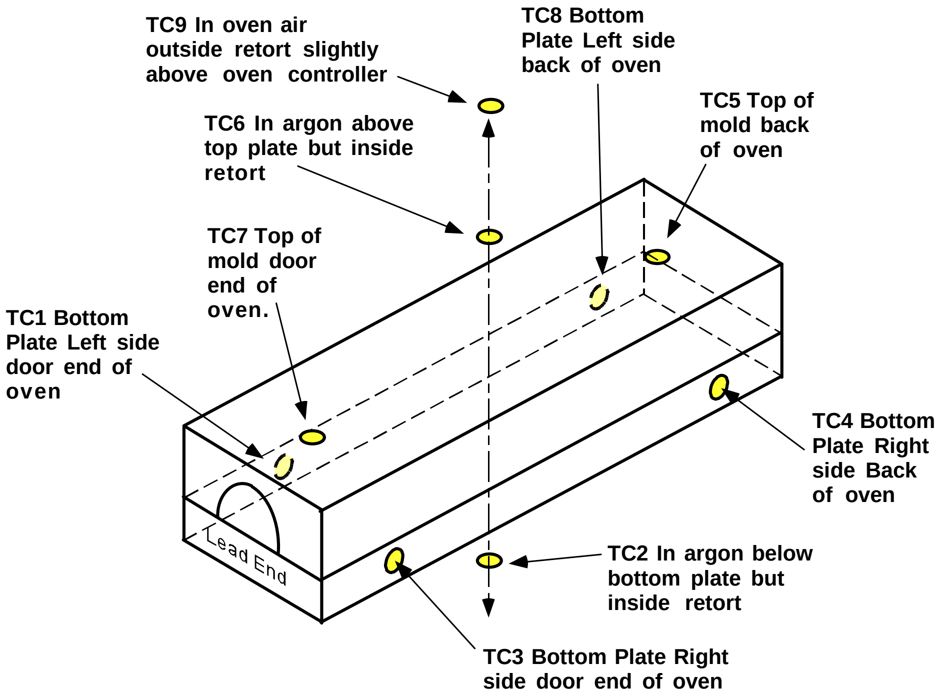


Figure 4.1.2: *Placement of Thermocouples*

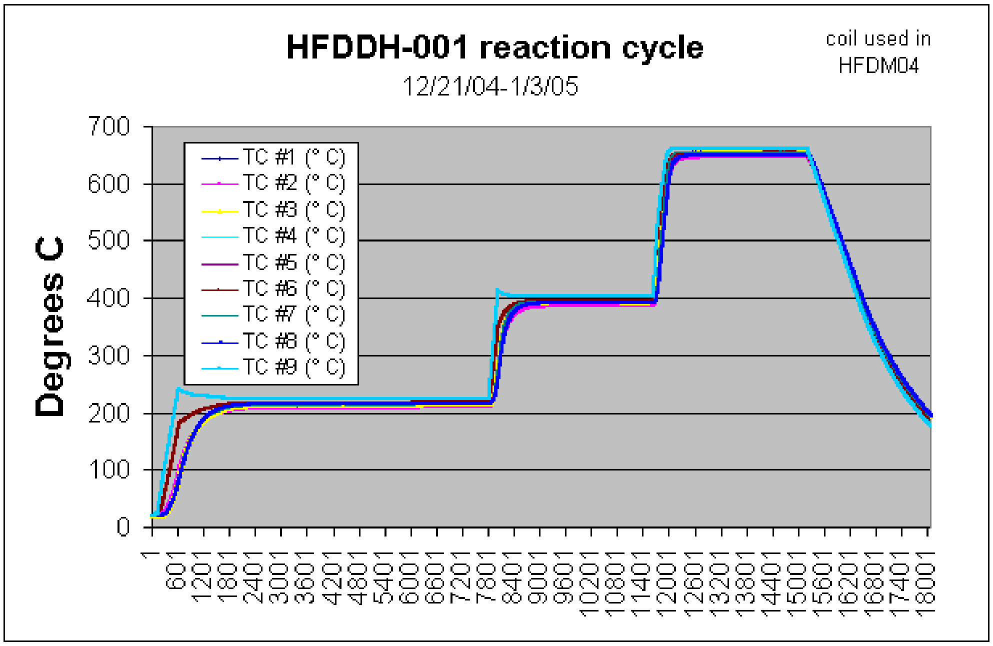


Figure 4.1.3: *Complete Reaction cycle of HFDDH01*

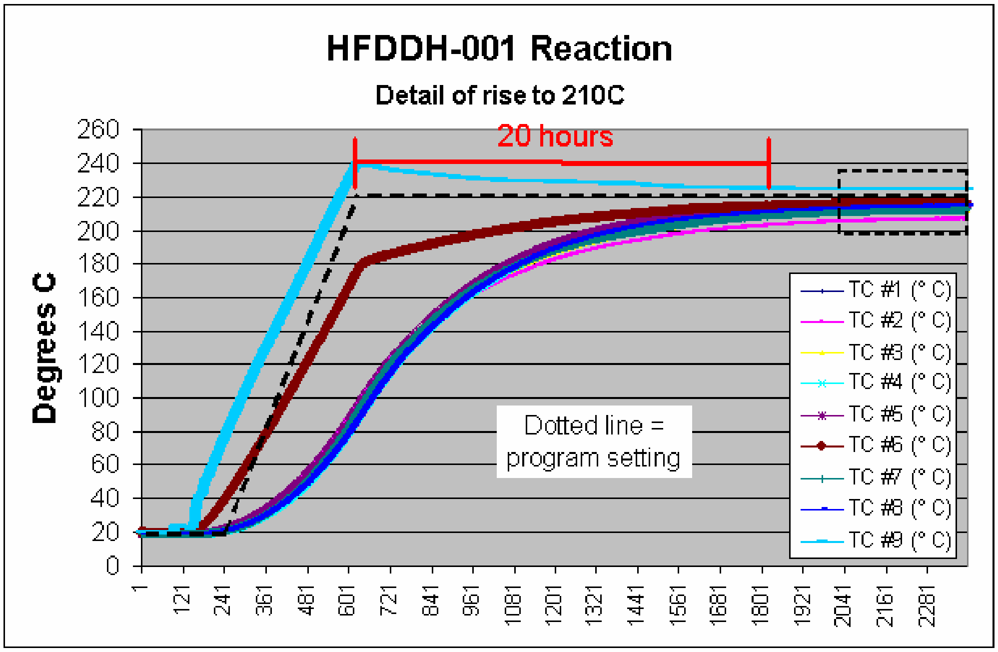


Figure 4.1.4: *Detail of rise to 210C*

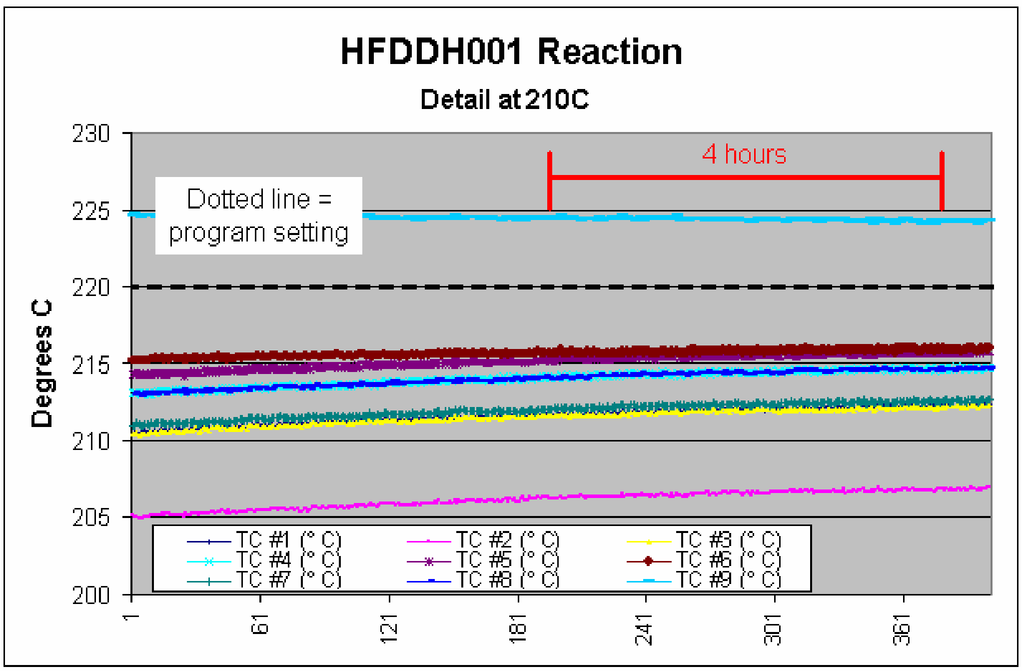


Figure 4.1.5: *Detail at 210C*

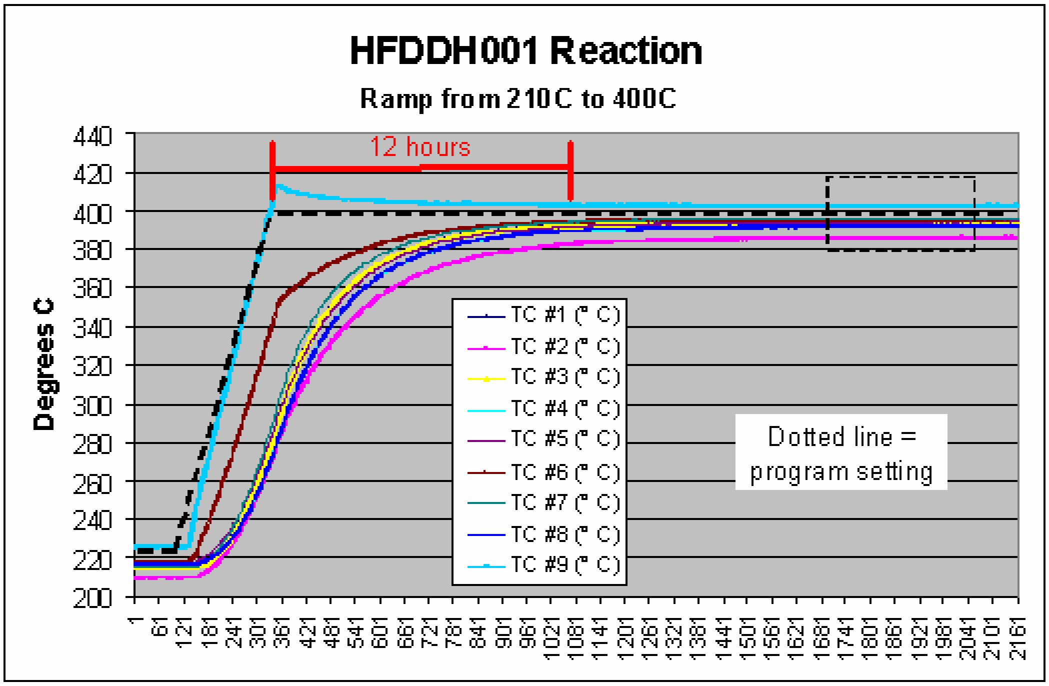


Figure 4.1.6: *Detail of rise from 210C to 400C*

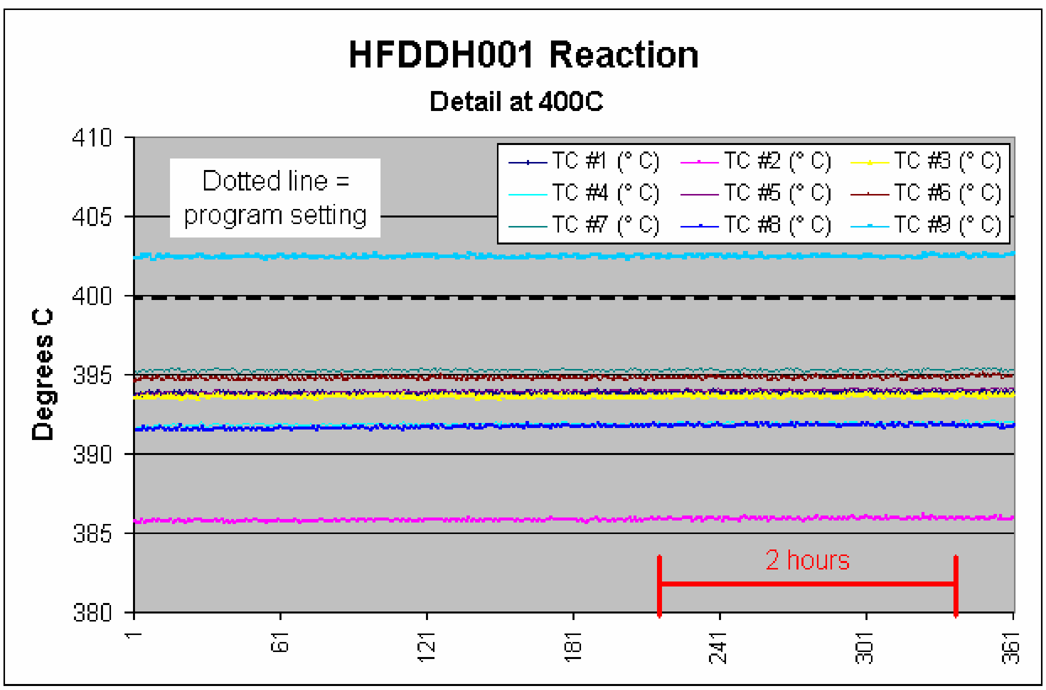


Figure 4.1.7: *Detail at 400C*

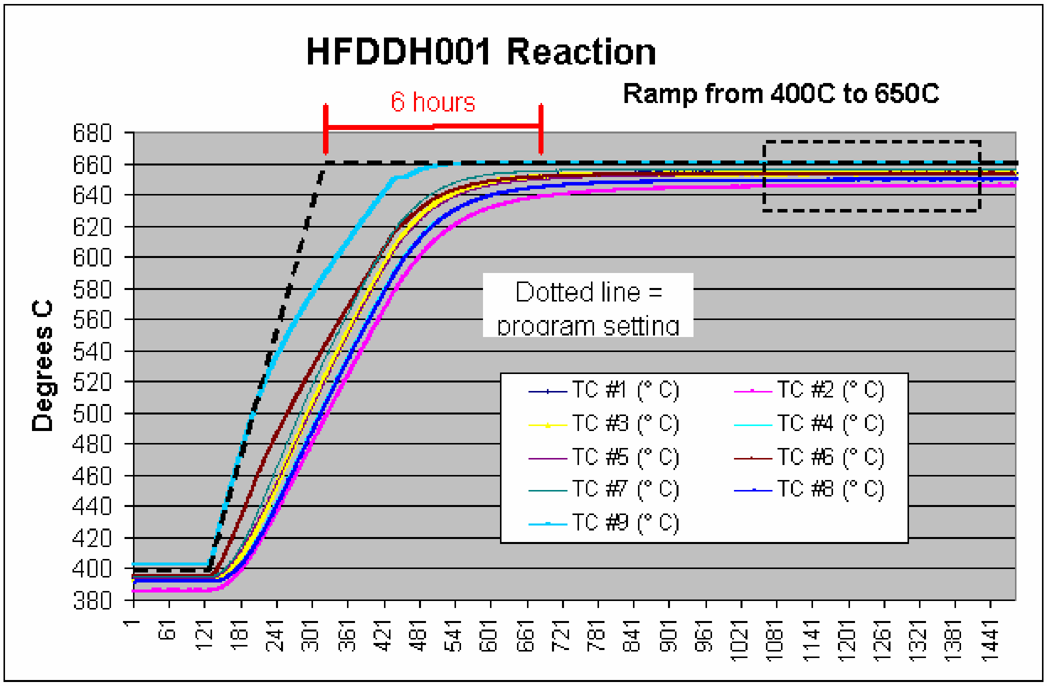


Figure 4.1.8: *Detail of ramp from 400C to 650C*

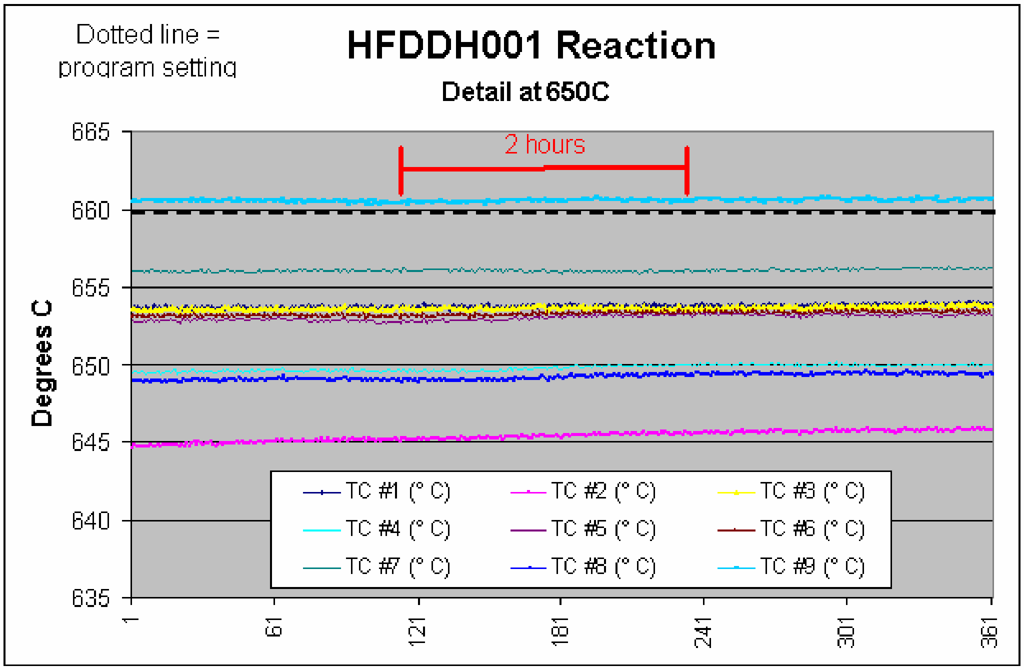


Figure 4.1.9: *Detail at 650C*

4.2 Voltage Taps and Spot Heaters

Voltage taps were mounted to the coils as shown in Figure 4.2.1. There were no voltage taps on the return end. HFDM04 did not contain spot heaters. Figure 4.2.1 shows coils as viewed from the inside (looking at concave surface).

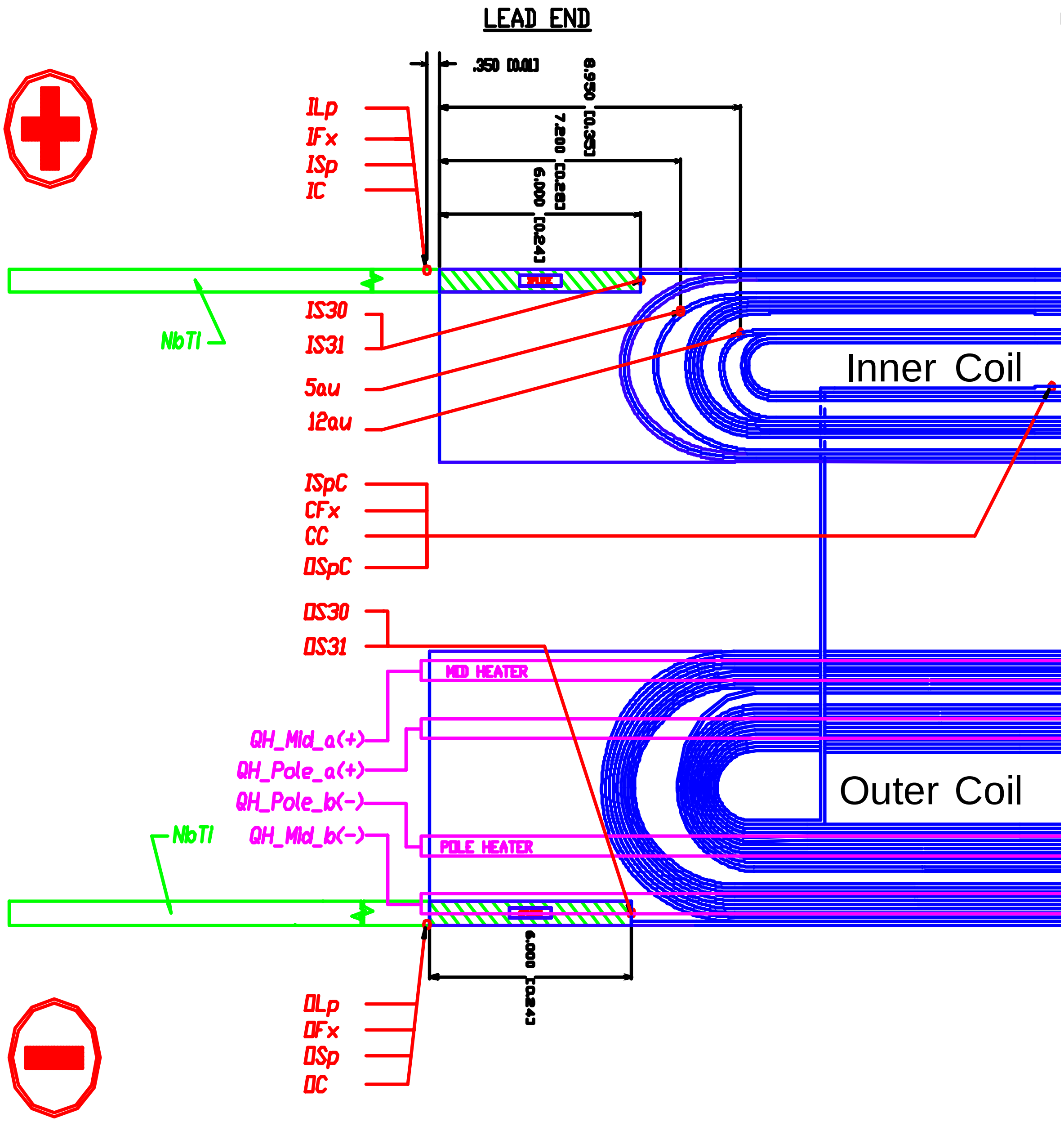


Figure 4.2.1: *Voltage Tap Layout.*

4.3 Strip Heaters:

Quench protection (strip) heaters were placed radially outside the outer coils, between the first and second layers of ground wrap, radially as shown in Figure 3.5.1 and azimuthally as shown in Figure 4.2.1. Each strip heater, consists of (2) 3/8 inch wide x 25 micron thick stainless strips bonded to a 4 mil piece of kapton. Each quadrant contained one assembly, with each strip placed approximately over the center of a current block. Strip heaters are inserted by hand, after reaction but before impregnation. The heater-wiring schematic is shown in Fig. 4.3.1.

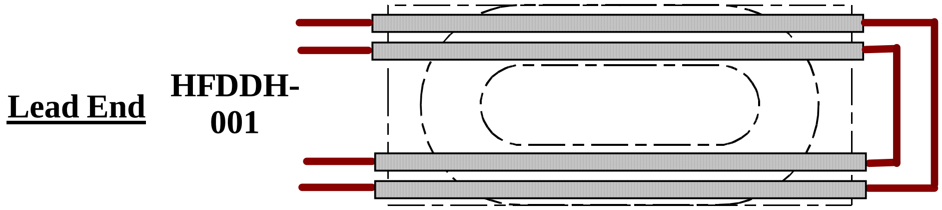


Figure 4.3.1: *Quench Protection heater wiring schematic.*

4.4 Parting plane Splices:

The midplane splices were done in the same manner as all Nb_3Sn dipoles have been done since HFDA-04 so that the splice joint is well supported, and the Nb_3Sn cable cannot be subjected to bending strain. This splice configuration is 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.

5.0 EPOXY IMPREGNATION

Coil HFDDH-001 was impregnated after splicing in the same fixture that was used for reaction. Figure 5.0.1 shows coil HFDDH-001 enclosed in the tooling and being prepared for impregnation.

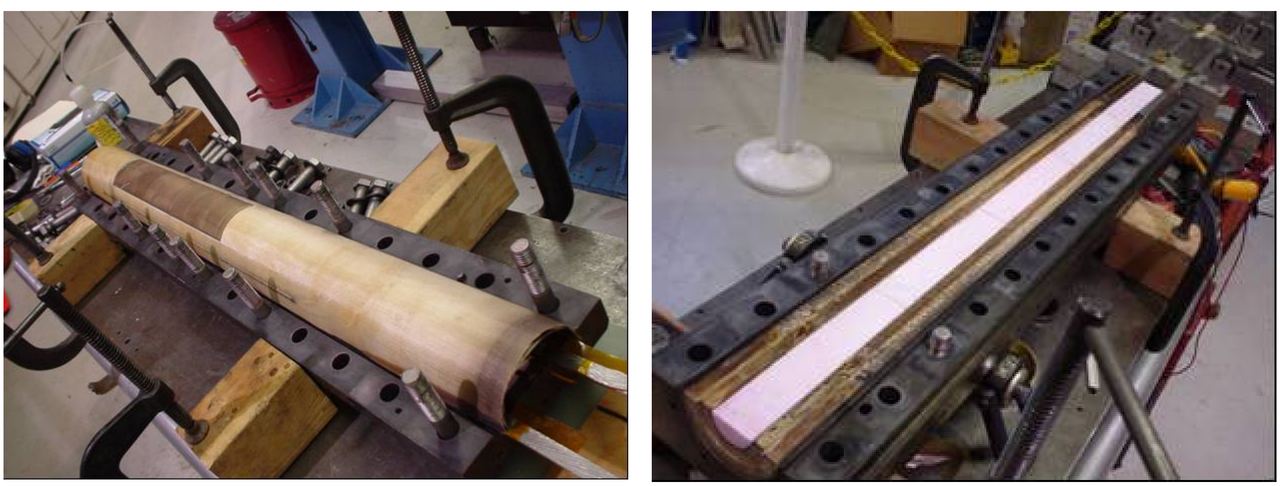


Fig. 5.0.1: *HFDDH-001 in reaction-impregnation tooling being prepared for impregnation*

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. The container of epoxy was heated to 55C and evacuated to about 115C. The epoxy flow rate into the coil was .04cc/sec (.5cm/sec linear flow in a tube of 3.2 mm inside diameter). Epoxy was flowed at this rate for 1 hour 40 minutes, the time it takes to fill about half the coil. Flow was then stopped for 2 hours to allow the epoxy to fill all spaces. Flow was then resumed. The coil took 2 more hours to fill, after which flow was continued for another 1 hour 15 minutes. Total time for the impregnation process was approximately 7 hours. After impregnation, the fixture was placed into an oven and cured at 125C for 21 hours.

Figure 5.1.2 *Coil assembly after impregnation.*

5.2 Mechanical Measurements:

The thickness, width and flatness of the coil were measured after impregnation (in the free state), as shown if Figures 5.2.1. and 5.2.2. Plots of these three measurements for HFDDH-001 are shown in Figures 5.2.3, 5.2.4 and 5.2.5. In the thickness and width measurement plots, yellow dots indicate points in the straight section, not covered by end parts.

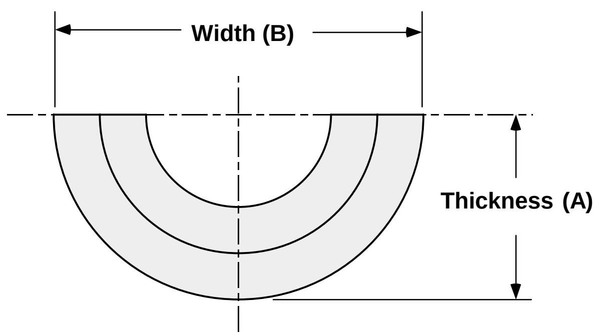


Figure 5.2.1 *Width and Thickness Measurements*

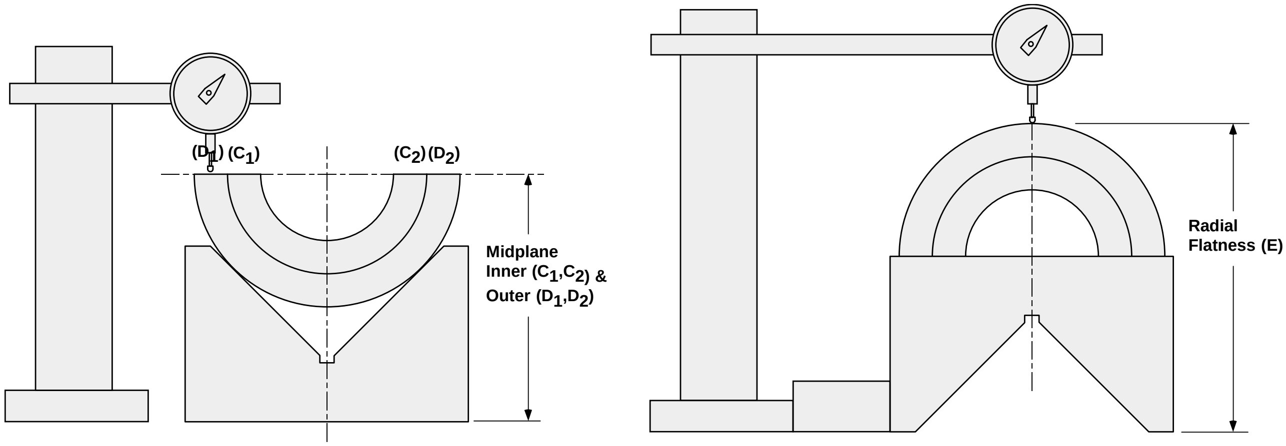


Figure 5.2.2 *Flatness Measurement Positions*

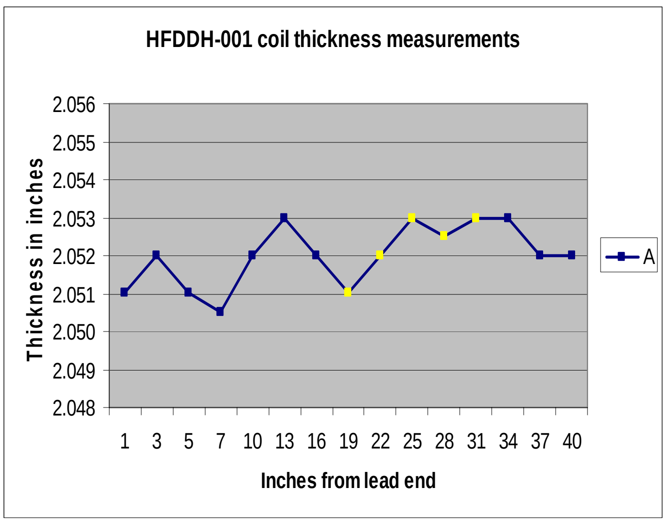


Figure 5.2.3 *Coil Thickness Measurements*

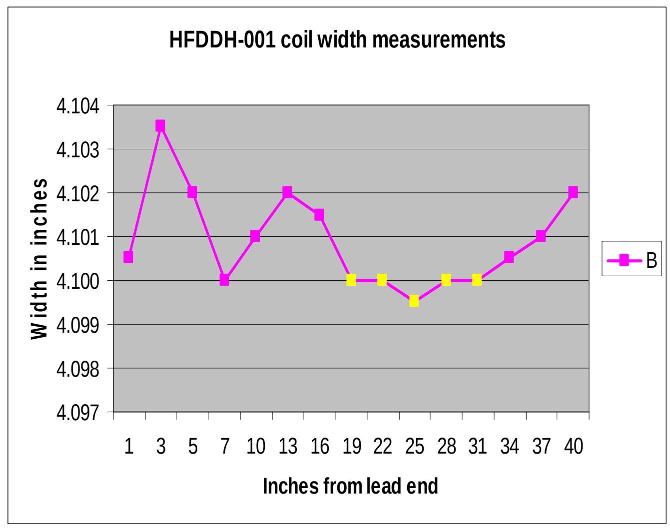


Figure 5.2.4 *Coil Width Measurements*

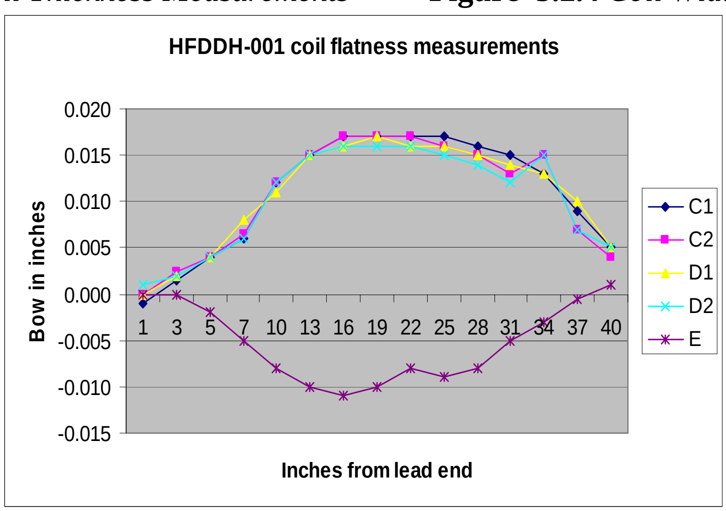


Figure 5.2.5 *Coil Flatness Measurements*

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:

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

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

Results for coil HFDDH001 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
001	2.0523	2.0500	3.28e-07	12.88760	12.88760	12.88760	12.88760	2.05113	2.052	.000087

The results show that the impregnated coil outside diameter is smaller than the design size by ~ 1.5-2 mil (35-50 microns). *Note: The measurements in section 5.2 were taken without the 2 mil kapton shim described in the beginning of section 6.3.*

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-coil.*

	Resistance mΩ	**Inductance μH @ 20 Hz**	**Inductance μH @ 1KHz**	**Q @ 20 Hz**	**Q @ 1KHz**
HFDDH-001	180.99	581.725	462.613	.39	4.12

6.0 YOKING

6.1 Magnet Structure

General structure of HFDM04 is shown pictorially in Figure 6.1.1. It has a horizontally split yoke. Aluminum-bronze spacers surround the coil inside the yoke, ending azimuthally at the coil parting plane, along the same plane as the yoke is split. The space which would normally be taken by the lower coil half is occupied by a solid steel “mirror”. Stainless steel strips are placed between the mirror and coil parting plane as shown in Figure 6.1.1. The stainless strip can be shimmed to a size appropriate to the particular magnet being assembled. 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 HFDM04. There is a gap between yoke halves, which remains open at all stages of construction and testing, even during cool-down and powering.

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 open, while the gap between the stainless strips and coil is exactly zero. The spacers are not under any stress, either azimuthally or radially.
2) Pressure is applied by the press to the yoke halves, reducing the yoke gap and applying radial stress to the coils through the spacers. The spacers are loaded radially, but not azimuthally, because there is a large azimuthal gap between the spacers and the mirror. Azimuthal compressive (hoop) stress is therefore applied to the coils, as the coil parting plane is pressed against the stainless steel strips.
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 still a gap between the yoke halves.
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 from step 3.
5) During cooldown, all components shrink (at different rates). The yoke gap remains open, and the tensile stress in the skin and yoke clamps increase.
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.

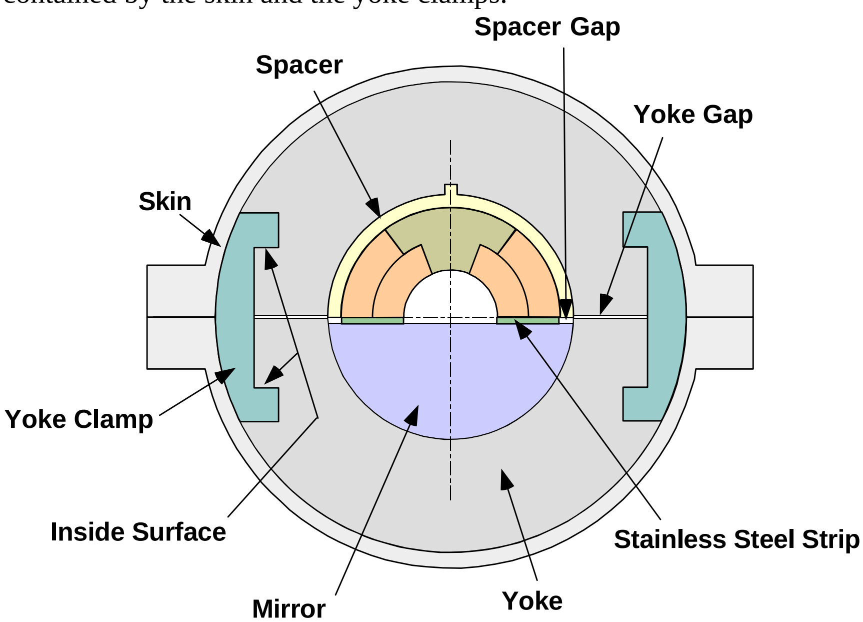


Figure 6.1.1 *HFDM04 General Structure*

6.2 Instrumentation

Both capacitance and traditional resistive beam strain gauges were used to measure coil azimuthal preload. Capacitance gauges (designated CG) and beam gauges (designated BG) were imbedded into the mirror at the midplane as shown in Figure 6.2.1. Gauges BG63 and BG64 measure preload at the inner and outer splices, respectively. BG61 and BG62 measure inner coil body preload. BG65, BG67, CG50 and CG51, measure outer coil body preload.

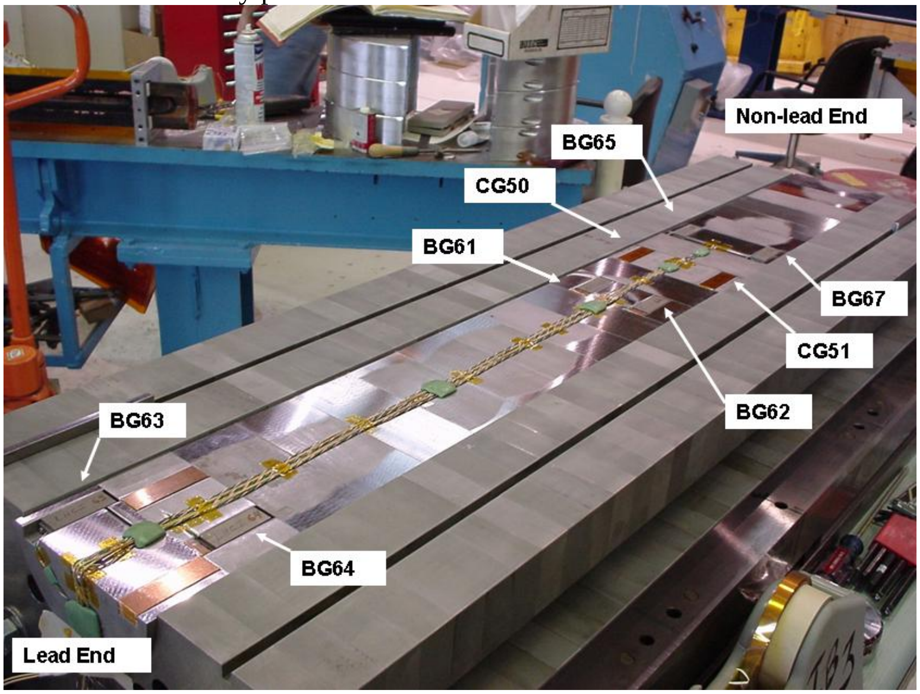
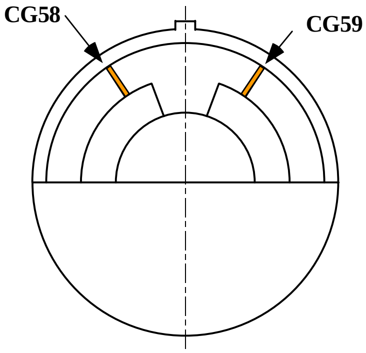


Figure 6.2.1 *Midplane gauges in HFDM04*

In addition to the midplane gauges, two capacitance gauges, CG58 and CG59, were placed at the outer pole in the body, at the same longitudinal position as gauges CG50 and CG51, with CG58 opposing CG50 and CG59 opposing CG51, as shown in Figure 6.2.2. To achieve this, the outer pole piece at this position was mold released before epoxy impregnation and removed afterwards, then replaced with a special outer pole piece modified to accept capacitance gauges. Resistive gauges were also mounted into circumferential grooves made on the aluminum bronze spacers at two positions as shown in Figure 6.2.3.



Looking from Lead End to Non-lead End

Figure 6.2.2. *Capacitance gauge layout at pole near center of magnet.*

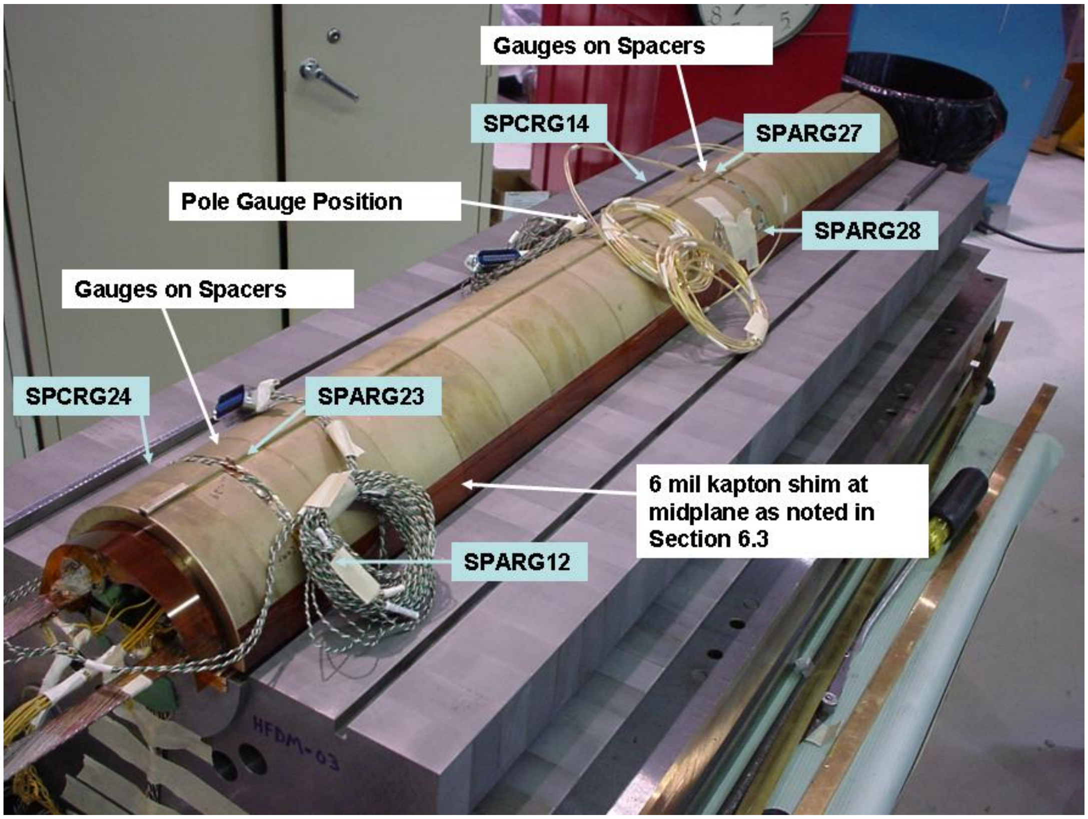


Figure 6.2.3: *Spacers with resistive gauges installed.*

Strain gauges were also mounted onto the inside surface of the coil, at the position s shown in Figure 6.2.4.

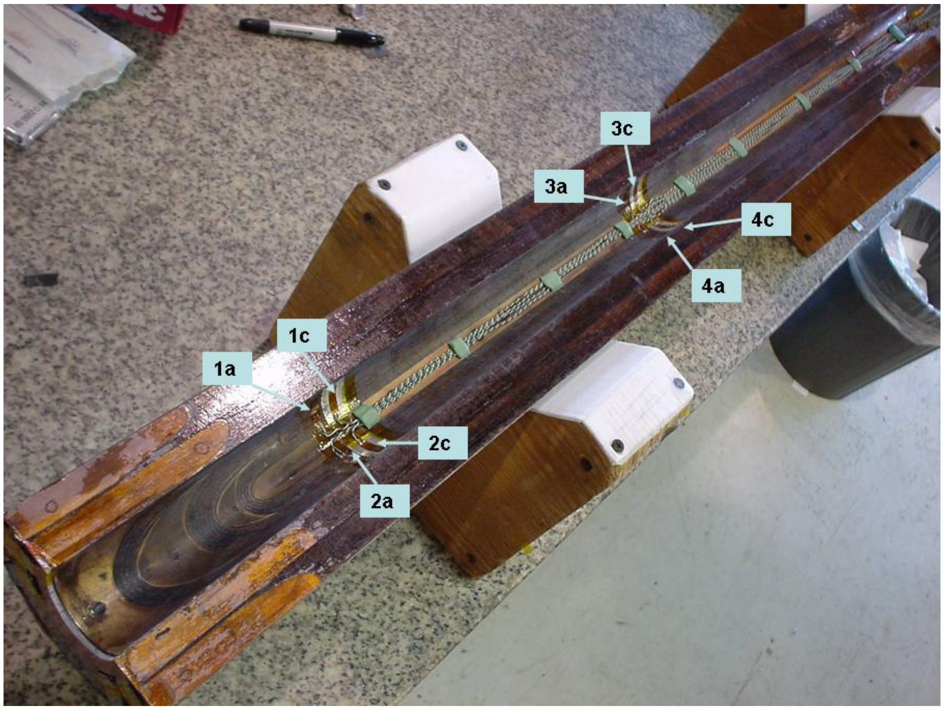


Figure 6.2.4: *Resistive gauges mounted to inside coil surface.*

6.3 Yoke Assembly

A sketch of the complete HFDM04 shim system is shown in Figure 6.3.1. The coil outside diameter, by design, should be at the nominal size to match the inside diameter of the spacers. Coil outside diameters and spacer inside diameters were measured (see sections 5.2 and 5.3). The measurements indicated that a radial shim of 2 mils was required between the coil and spacers. A 2 mil kapton sheet was used. Figure 6.3.2 shows the coil pair placed on the mirror with the 2 mil kapton layer installed and some spacers placed over the coil. The stainless steel strip at the mid-plane of the coil was shimmed to achieve an azimuthal interference of 5 mils (125 microns). Installation of this shim is shown in Figure 6.3.3. Aluminum bronze spacers were then placed around the coil. Finally, a 6 mil thick kapton layer was placed radially between the spacer and the coil near the midplane, as can be seen in Figure 6.2.3. This was done to increase the preload near the pole. The top yoke packs were then installed. The completed yoke assembly is shown in Figure 6.3.4.

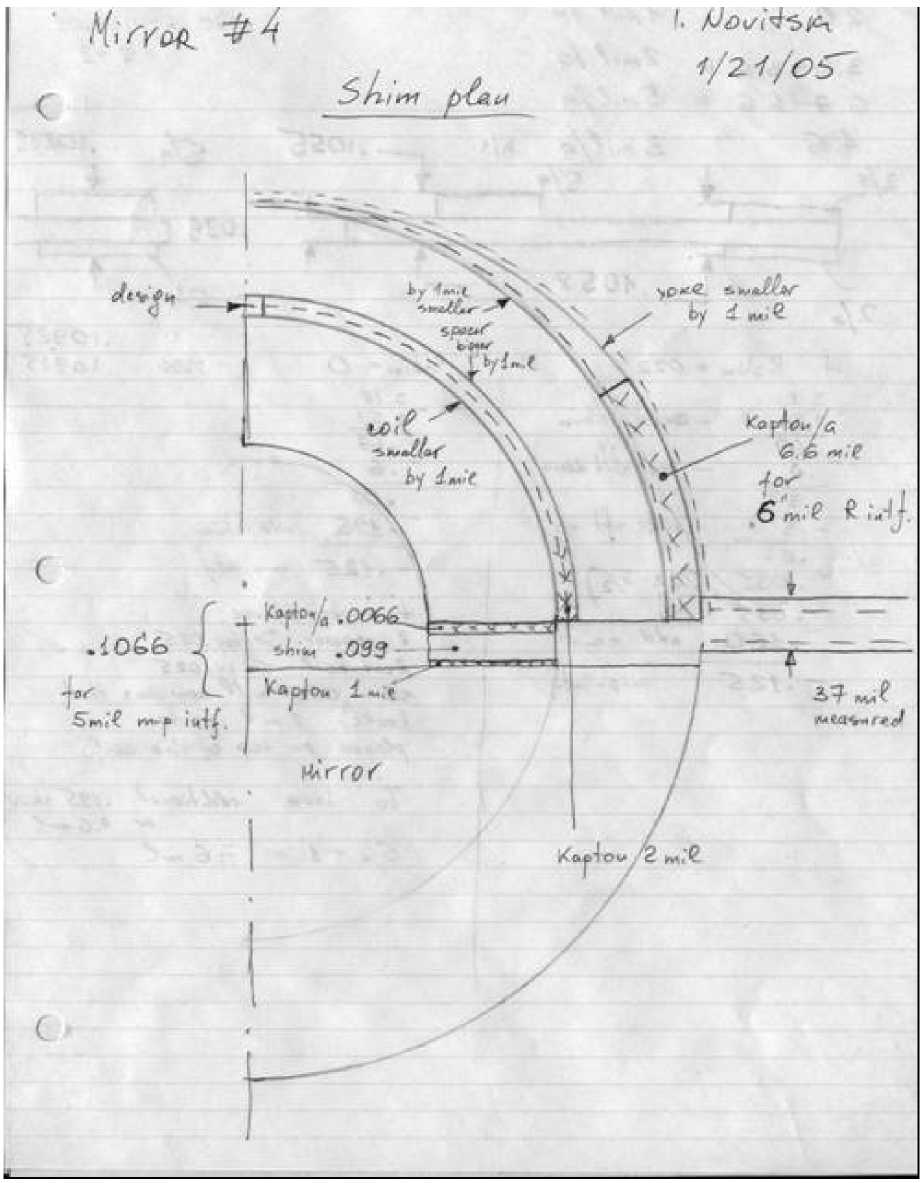
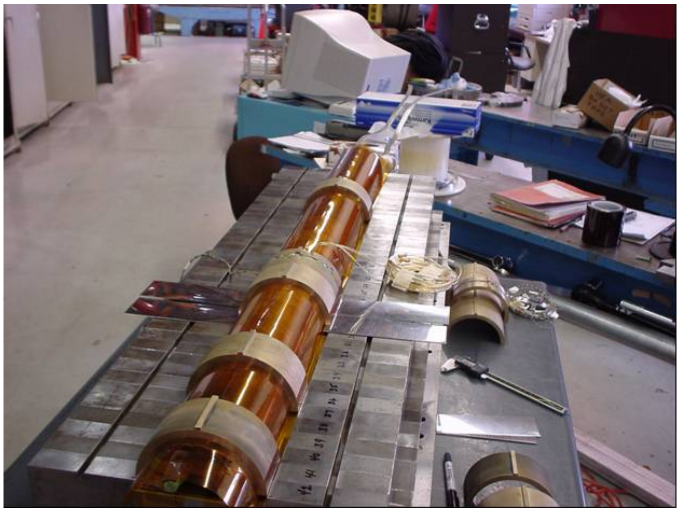


Figure 6.3.1 *HFDM04 shim system*



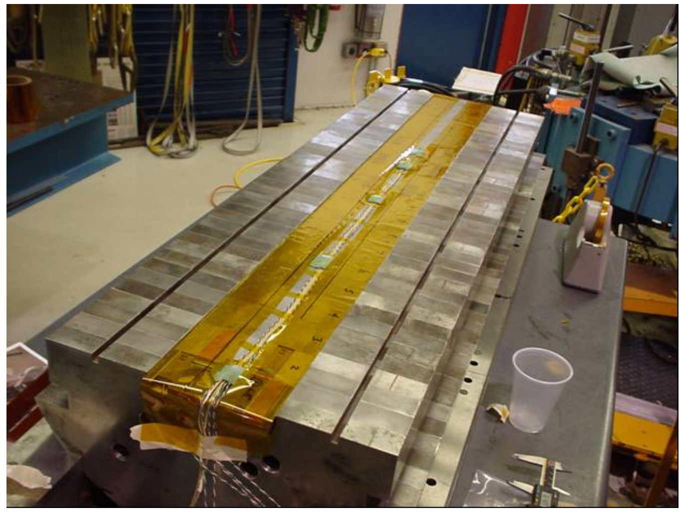


Fig. 6.3.2: *Coils on mirror with kapton installed*

Fig. 6.3.3: *Midplane shim being installed*

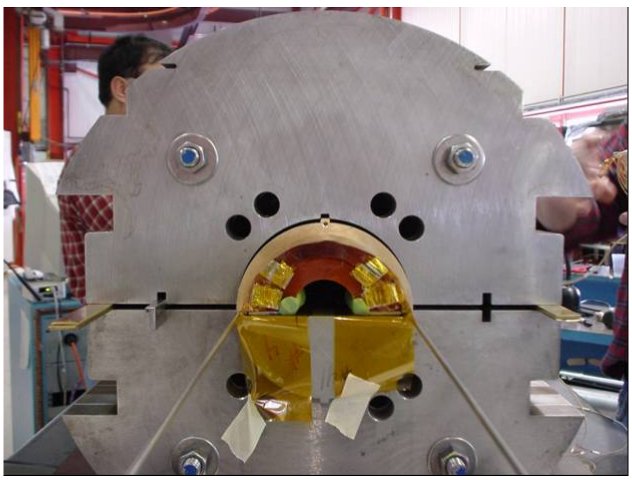


Figure 6.3.4 *HFDM04 in Yoke*

6.4 Pressing

Iron mirror blocks were placed in the lower yoke half. The coil was then installed onto the mirror as shown in Figure 6.2.3. After the upper yoke blocks were installed, the entire assembly was placed into the yoke press and compressed vertically. Once the nominal yoke gap was achieved, the press position was locked and the yoke clamps were inserted. After insertion of the yoke clamps all press pressure was released. Figure 6.4.1 shows HFDM04 in the yoke press.

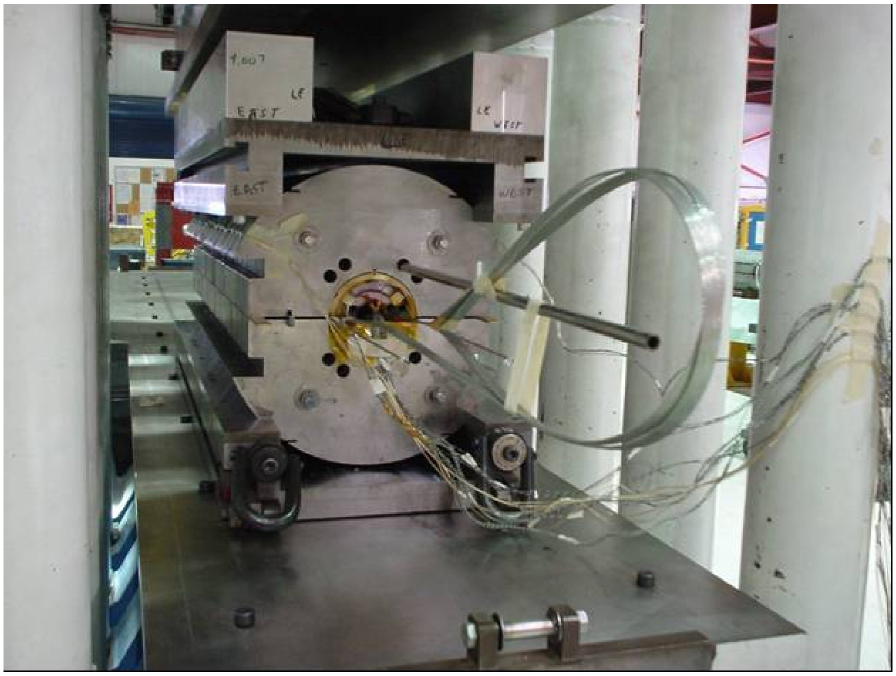


Figure 6.4.1 *HFDM04 in Yoke Press.*

Gauges were read during pressing and later assembly steps. Figure 6.4.2 shows outer coil capacitor guage readings through yoking and installation of skin. Figures 6.4.3 and 6.4.4, and 6.4.5 show readings of the midplane beam gauges, the resistive gauges mounted to the spacers, and the resistive gauges mounted to the coil inside radius during the same assembly steps. Horizontal axis describes press pump psi during yoking. Main cylinder force is 180 lbs. per pump psi across the entire magnet. "Bar Gap" is the distance between top and bottom flanges on the bolt-on skin during skin installation, as shown in Figure 6.4.6.

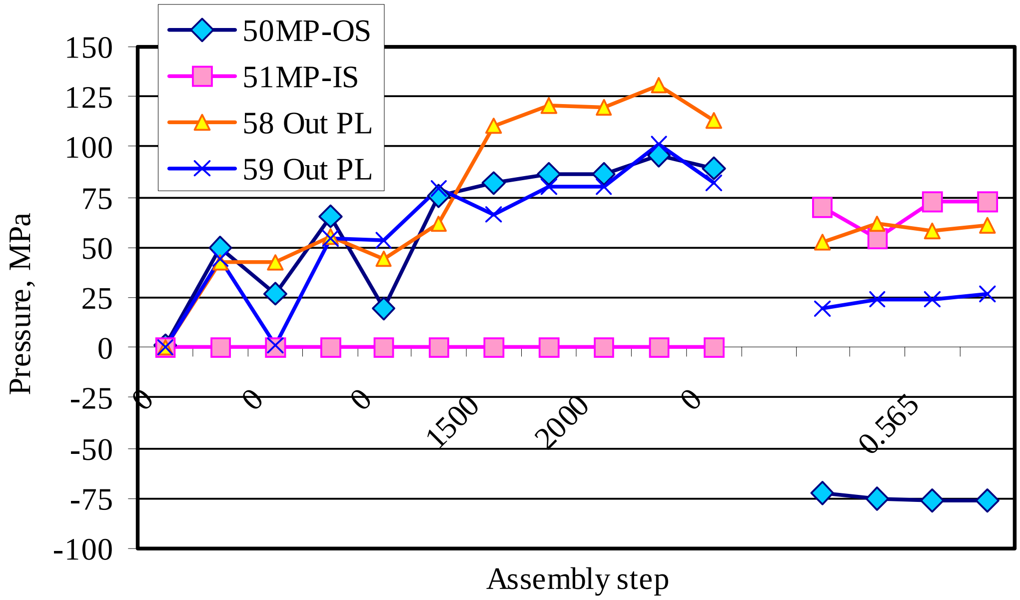


Figure 6.4.2 *Capacitor gauge readings on Outer Coil.*

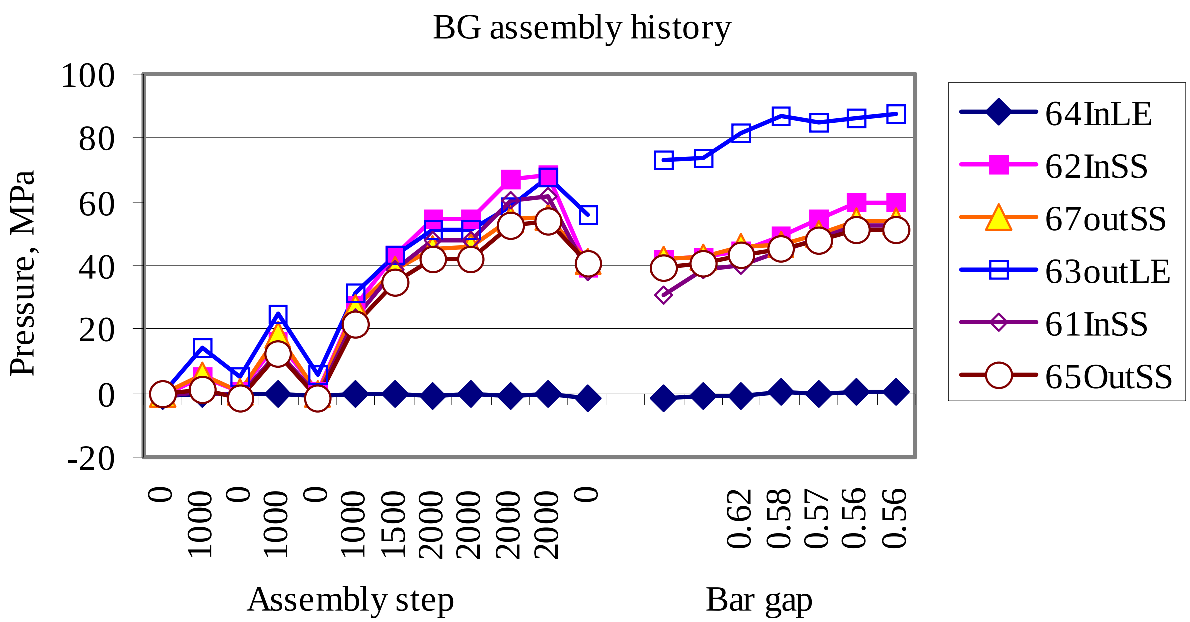


Figure 6.4.3 *Resistive beam gauge readings during Assembly.*

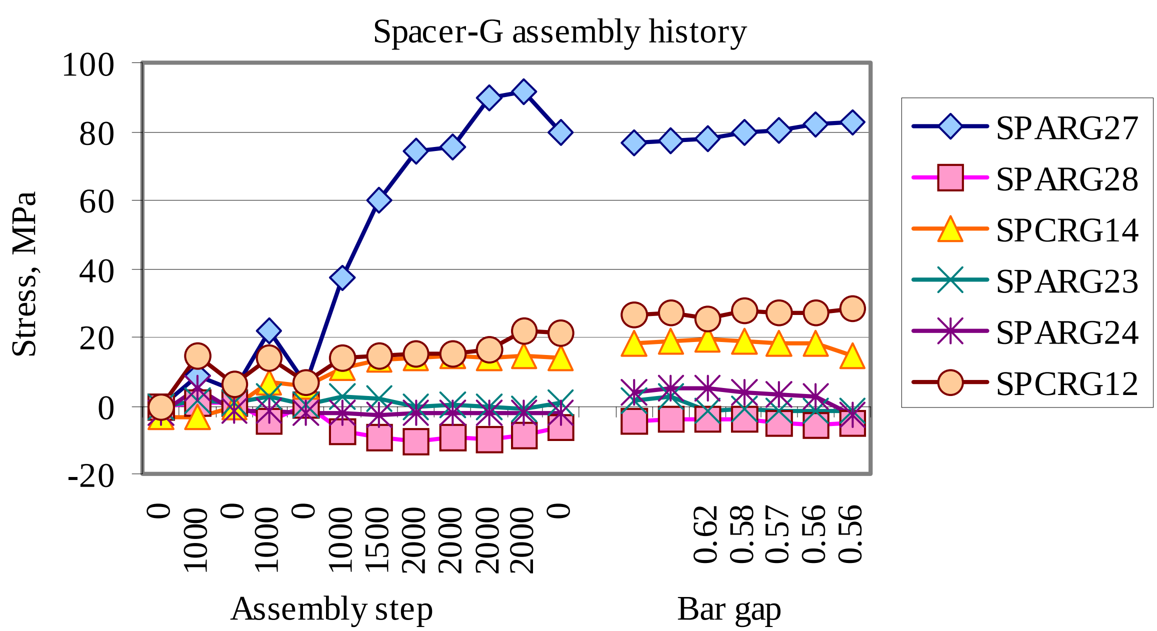


Figure 6.4.4 *Resistive gauges on spacers during Assembly.*

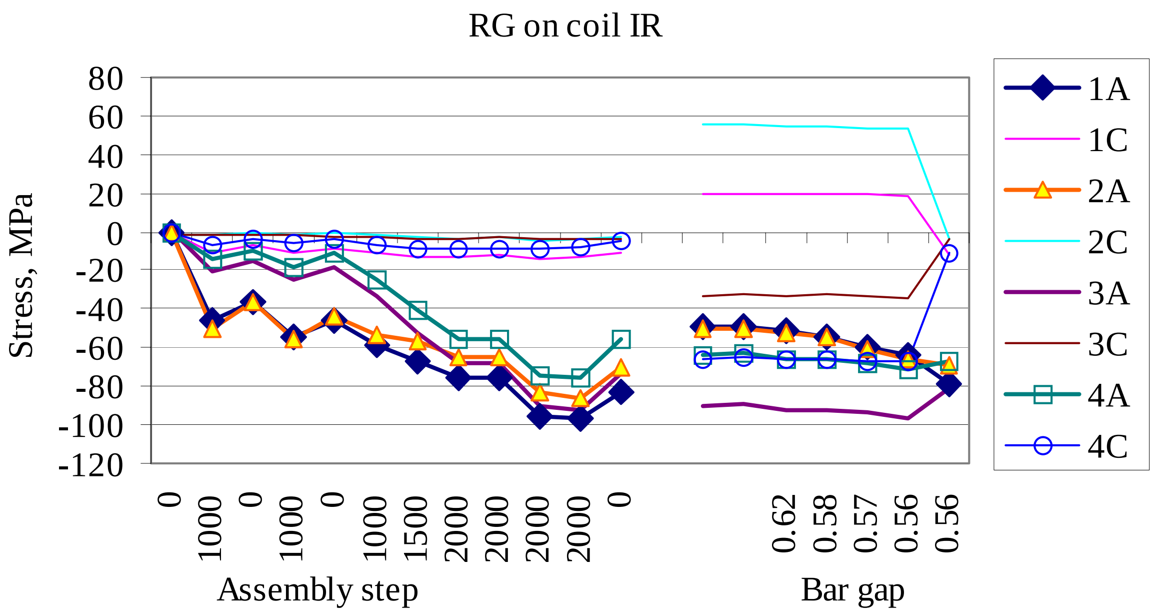


Figure 6.4.5 *Resistive gauges on coil inside radius during Assembly.*

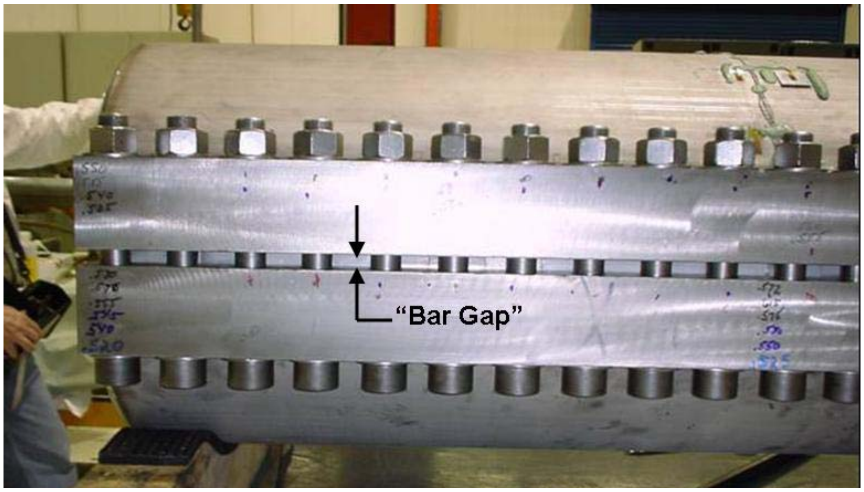


Figure 6.4.6 *Bar Gap.*

6.5 Electrical Measurements

Coil Electrical Measurements were taken after pressing, and are shown in Table 6.5.1. Resistance measurements were taken at .1 amp. Inductance and Q were taken both at 20 Hz and 1KHz.

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-001	182.12	1187.02	529.66	.76	1.77

7.0 Final Assembly

7.1 Skin Installation

Skin halves were placed around the yoked assembly and bolted together. Bolting was done in several steps, while stress in the coil and end spacers was monitored. Stresses during this operation are shown in the previous section 6.4.

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 7.1.4. These gauges were also monitored during the bolting operation. Figure 7.1.5 shows the average stress of the two skins during the seven bolting steps.

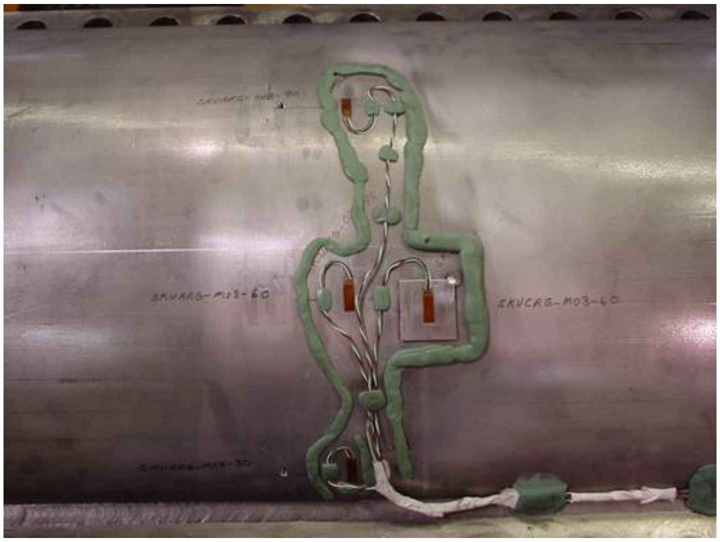


Figure 7.1.4: *Resistive strain gauges mounted on skin.*

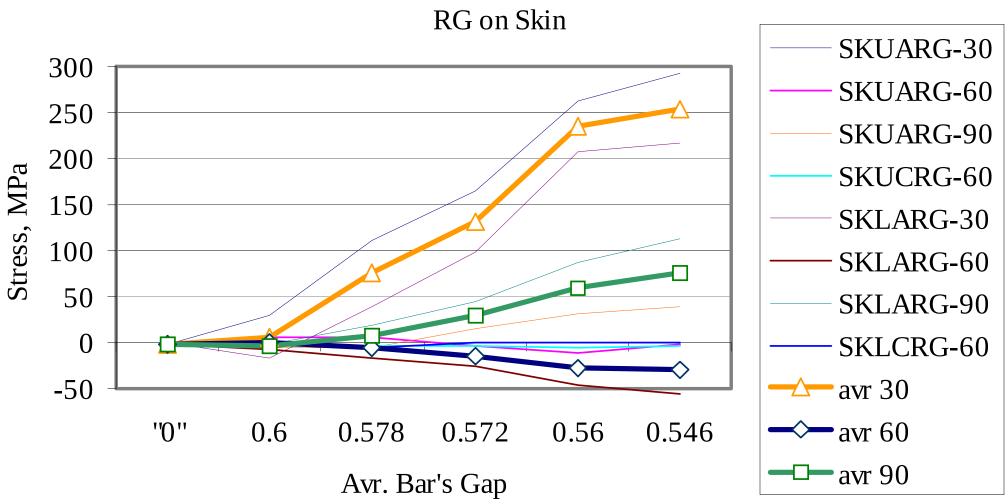


Figure 7.1.5: *Stress in skin during bolting operation.*

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 HFDM04. Consequently no bullets were installed.

7.3 Splices

Since HFDM04 has only one coil pair, no splicing at the midplane was necessary. Leads were bent into a configuration similar to that used for a full dipole, and clamped to the end plate with G-10 blocks. The leads therefore exit the magnet at a position similar to that for a dipole, allowing easy hookup at the Magnet Test Facility. Clamping with the G-10 blocks also provides strain relief for the lead. Voltage taps were installed on the lead cables.

7.4 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.

7.5 Final Electrical Measurements

Final electrical measurements were performed on the magnet just before shipping to VMTF for testing. Initially, a coil-to-ground short was found. It was identified as a short between the outer coil lead as it exited the magnet and the inside surface of a bronze spacer, caused by a small amount of solder flash on the lead. The solder flash was removed, kapton was placed between the lead and the spacer, and a small area of this spacer was relieved slightly. Subsequent electrical measurements showed the short to be eliminated. Table 7.5.1 summarizes the final measurements.

Table 7.5.1: *Electrical measurements on the total magnet.*

	Resistance	**Inductance, μH**		**Quality Factor**	
	mΩ	**At 20 Hz**	**At 1 kHz**	**At 20 Hz**	**At 1 kHz**
Total Magnet	181.94	1186.3	516.321	.76	1.73

Hi-Pot tests at 1000V were also performed on the final assembly to check current leakage between coil-to-ground, coil-to-heaters and heater-to-ground. The Table 7.5.2 shows these results.

Table 7.5.2: *Hi-Pot measurements on the yoked assembly.*

Test	**Leakage @ 1000V**
Coil to ground	.02 uA
Heaters to coil	.02 uA
Heaters to ground	.02 uA

Quench Protection (strip) heater resistance = 4.9 ohms per circuit, with each circuit consisting of two strips as shown in Figure 4.3.1.

8.0 SUMMARY

The fifth shell-type Nb_3Sn high field dipole mirror magnet, HFDM-04 was delivered to VMTF for testing on March 22, 2004.

HFDM04 had a 43mm bore diameter and a straight section approximately 1/2 meter long.

.7mm RRP strand manufactured by Oxford Industries was used. This is the first magnet to be produced at Fermilab with .7mm RRP strand.