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HFDB-03 *"3nd Racetrack"* production report

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Abstract:

In the R&D effort toward a post-LHC hadron collider, Fermilab is developing a 10-11 T block-type, common-coil dipole magnet operating at 4.5 K using Nb_3Sn superconductor with the React-and-Wind technology [1]. As part of the development of the React-and-Wind technology, flat racetrack coils have been tested in the so-called "Racetrack magnet"[2]. This note is the production report of HFDB-03 (Racetrack #3). The design of HFDB-03 is similar to the one of HFDB-02 with a few modifications described in [3]. The mechanical design has been studied with FE models presented in [3,4]. Because of its purpose and characteristics HFDB-03 wasn't fabricated using a traveler. Fabrication procedures were prepared before each operation was performed. These procedures were prepared starting from the fabrication report of HFDB-02 [5] and taking into account the new features of HFDB-03. Comments have been added after some steps of the fabrication. These procedures constitute the main body of this report. In the appendixes some more documents and some pictures taken during the fabrication have been added.

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CABLE PREPARATION

The Nb_3Sn cable used in HFDB-03 had 41 strands with 0.7 mm diameter. Details about the strands may be found in the paragraph “witness samples”. The cabling was performed at LBNL. The cable data log is reported in Appendix 1. The procedure for the preparation of the cable to the heat treatment is described in the following.

Procedure for cable preparation

Synthetic oil: Use **Mobil 1 formula 0W-30** oil because it has the lowest viscosity (53 cSt at 40 C and 10 cSt at 100 C) among Mobil 1 oils.

Cable preparation:
- cut two pieces of Nb3Sn cable (from spool: R1O-00824),
- length: 70 m each,
- weld ends of each cable,
- wind each cable on a metallic spool,

Oil “impregnation” (to be performed at the Material workshop):
- each cable should be ‘impregnated separately’ in a plastic bag (polyvinyl 5 mil thick) with two ports (one for vacuum, one for oil inlet)
- de-gas the oil in a vacuum chamber (use about 2 liters of oil per bag),
- prepare the bag and set felt bleeder-breather to avoid closing the ports,
- keep cable under vacuum overnight,
- slowly input the oil in the bag (it should take about 2 hours),
- stop when the spools are completely filled by oil (no more difference between inner and outer pressure),
- wait a few hours for a uniform distribution of the oil in the bag,
- close vacuum pump when it start sucking oil into the pipe
- heat up the spool (100 C for 3 hours).

Cleaning:
- make the spool stand in vertical orientation above the tank in order to let the extra oil drip in the tank,
- remove the cables form the spools and clean them with wiping rolls and paper,
- clean the spools,
- dispose oil and papers.

HEAT TREATMENT

The cable for each coil was reacted on a single layer stainless steel spool inside a reaction retort. Each spool had a diameter of 360 mm. Two extra turns were set around the metallic spool before winding the cables. They were removed after winding leaving a gap of about 2 mm.
The heat treatment used was the standard HT suggested by the wire manufacturer (Oxford Superconducting Technology) performed in Argon atmosphere. Because of some scratches on the surface of the cables a plateau at 225 C was added to the standard OST heat treatment.

			TOTAL hours	TOTAL days
starting temperature	C	25		
Rate	C/h	25		
1st temperature	C	**210**	7.4	
const. temp time	h	100	100	
Rate	C/h	10		
2nd temperature	C	**225**	1.5	
const. temp time	h	20	20	
Rate	C/h	25		
2nd temperature	C	**340**	4.6	
const. temp time	h	48	48	
Rate	C/h	25		
4th temperature	C	**650**	12.4	
const. temp time	h	180	180	
Rate	C/h	75		
cooldown	C	25	8.3	
const. temp time	h	0	0	
			382.2	**15.9**

Notes:

At 210 C there was a difference between the temperature shown by the thermocouples and the set temperature (readings: 203, 204, 206 C) while the over-temperature control of the oven was reading 207 as the termocouple set outside of the retort. Therefore the set temperature was increased to 214 C after 37 hours from the beginning of the plateau, and subsequently to 218 C after 32 hours at 214.

WITNESS SAMPLES RESULTS AND SHORT SAMPLE LIMIT

The following samples have been reacted with the cable:
Virgin samples:

- 2 from ORE 164,
- 1 from ORE 159,
- 1 from ORE 166,

Extracted samples:

- 3 from cable R1O-00824

COMMENT: The cable was made of OST-MJR strands from three billets (159, 164 and 166). The head of the cable was marked to show the stand map. When the cable spool was inspected before starting the fabrication of this magnet the head wasn't there anymore and the correlation with the strand map was lost.

Test results are shown in the following table

TEST RESULTS							
	R1OOO824-1	R1OOO824-2	R1OOO824-3	159 FE	164 FE	164 BE	166 FE
B (T)	Ic (A), n-value	Ic (A), n-value	Ic (A), n-value	Ic (A), n-value	Ic (A), n-value	Ic (A), n-value	Ic (A), n-value
15	184	171, 32	~ 175	228, 32	212, 29	211, 31	168
14	q	229, 36	Q	290, 39	271	274, 44	229
13	q	296, 47	Q	358 (at 4.33 K)	340	346	294
12	q	q (at 327)	q (at 332)	q (at 380)	422	428	375
10	q	Q	q	Q	q	q	q
8	q	Q	q	Q	q	q	Q
6	q	-	-	-	-	-	Q
RRR	4	7	11	11	11	6	35

PAREMETERIZED DATA							
	R1OOO824-1	R1OOO824-2	R1OOO824-3	159 FE	164 FE	164 BE	166 FE
B (T)	Ic (A), n-value	Ic (A), n-value	Ic (A), n-value	Ic (A), n-value	Ic (A), n-value	Ic (A), n-value	Ic (A), n-value
15	184	171, 32	~ 175	228, 32	212, 29	211, 31	168
14	*236-246 **	229, 36	*228-234 **	290, 39	271	274, 44	229
13	*299-321 **	296, 47	*288-306 **	*369*	340	346	294
12	***372-411 ***	***382***	***359-391 ***	***460***	**422**	**428**	**375**
10	*560-643 **	*598*	*539-613 **	*692*	*640*	*645*	*590*
RRR	4	7	11	11	11	6	35
Bc20 (T)	-	23.5	-	25	25	25	23.5

* Ic range within a Bc20 range of 25 to 23.5 T

Short sample limit estimation

The measured Ic of the virgin strand from billet 166 is lower than the measured Ic of any extracted strand. It is not known if any measured extracted strand was from billet 166. Therefore, assuming that strands from billet 166 have the lowest Ic under the heat treatment performed, the short sample limit should be computed from the Ic of the virgin strand from billet 166. Taking into account a "standard" cable degradation of 6% and a bending degradation of 14% (for 0.47% maximum bending strain), HFDB-03 short sample limit is 16527 A at 10.03 T and 4.5 K.
Assuming that the virgin strand from billet 166 was damaged, the extracted strands show the lowest Ic. Taking the lowest values given by the parameterizations of the extracted strands and a bending degradation of 14% (for 0.47% maximum bending strain), HFDB-03 short sample limit is 16589 A at 10.06 T and 4.5 K.

CABLE INSULATION

The cable insulation consisted in two tapes (a 6.5 mil pre-impregnated fiberglass tape and a 3 mil Kapton tape) wound together with the coil in order to form a continuous spacer between each couple of turns. See [5,6] for more details.
The Kapton tape was procured in unit length longer than the coil in order to have a continuous insulation and to keep it under tension during the whole winding. The pre-preg tapes were

selected among several tapes on stock. Some tapes were already cut to width (0.6 inch) many more were not. In the following is reported the procedure to inspect the tapes cut to width. In the appendix a summary sheet with the best tapes is shown.

Procedure for pre-preg roll selection

Measure thickness, width and length of the rolls in the cardboard box marked "**0.6 rolls**"

- Use a micrometer to measure the thickness (this is the most important measurement, be very accurate),
- Use a caliber to measure the width,
- Measure thickness and width every 4 feet.
- The total length will be given by the number of the measurement (* 4 feet) + the remaining length.
- Report every defect in the tapes (junctions, holes, cuts, …) writing the type of defect and the distance from the beginning of the tape
- Put a new tag on each measured roll (same name as on the data sheet)
- Tags: 3RT-1, 3RT-2, 3RT-3, 3RT-…

TEMPERATURE SENSORS

The temperature sensors used are: CX-1050-SD-HT Cernox by LakeShore, which can withstand temperatures up to 420 K. They have been calibrated at Fermilab in the Engineering Laboratory. We used the wire commonly used in IB3 for RTDs. It's produced by California Fine Wire (phone 805-489-5144) consists of four manganine wires with individual insulation, twisted and insulated by a Tefzel jacket. The Tefzel jacket is rated up to 200 C, the insulation on each wire up to 220 C.

MAGNET FABRICATION

The magnet was fabricated according to the following procedures:

- Prepare insulation:
  - Insulation consists of two tapes:
    - Pre-preg tape with low epoxy content (6.2 – 6.3 mil thick)
    - 3 mil Kapton tape
  - Select the best rolls of pre-preg tape (check thickness and length):
  - Reduce the width of the selected tapes to 0.6 inch (+/- 0.008 inch)

- INSULATION FOR THE FIRST COIL:
  - Kapton: use 59 m
  - Pre-preg: use roll RT3-2 (all) and RT3-6 (all)
  - The tapes should be wound on the insulation spool (made of wood) with pre-preg inside and Kapton outside,
  - Pre-preg roll RT3-6 should be put first on the spool (so that we will start using roll RT3-2 on the coil first)
  - The pre-preg rols should be glued to the Kapton at the beginning and at the end of each roll (NO overlap at the junction between the two pre-preg rolls)

- Prepare G10 coil parts:
  - End parts:
    - do cuts in order to make them flexible (should open when coils spring back)
    - Make notches for VTs
      - Dimensions: 2 mm deep, 5 mm long, 4 mm large
      - Position: see marks on the parts
  - Straight parts: do grooves for instrumentation
    - same as in HFDB-02 for VTs in the straight part and close to the splice,
    - new design for VTs in the ends (i.e. notches for brass strips and grooves for soldering of wires to strips)
    - COMMENT from previous Racetrack: the channels in the G10 coil part should be deeper, the channels in the end should be larger in order to accommodate all the wires,
  - Precise grooves for spot heaters and temperature sensors:
    - spot heaters: 0.25 mm deep, 32 mm long
    - temperature sensor: 3 mm deep, 2 mm long, 8.6 mm wide from the top surface of the G10 part

- Mechanical structure preparation for winding:
  - install bottom plate on winding table,
  - prepare and check the tensioners,
  - apply the ground insulation on the main plates:
    - four layers of 5 mil adhesive Kapton
  - set bottom-coil inner parts; before installing them:
    - check pins and holes (in case they don't fit make holes a bit larger)
    - make the holes for the outermost pins larger than the pin, in order to compensate for the different thermal contraction (Giorgio will check them)
      - 30 micron close to splice end

        - 70 micron return end

- ❖ Practice winding (using the beginning of the cable for the first coil: SPOOL #2):
  - ➢ set the roller table (fix the legs!)
  - ➢ remove the gap between the cable and the metallic spool
    - rotate the core of the spool in the direction opposite to the winding direction,
    - **<u>BE VERY CAREFUL !!!</u>**
  - ➢ install the spool with the cable on the 2nd tensioner (clockwise),
  - ➢ install the spool with the cable insulation on the 1st tensioner.
  - ➢ wind a turn of insulation (both tapes) around the G10 parts (in order to have insulation between the cable and the G10 parts)
    - glue the beginning of the insulation to the G10
    - start the insulation from the channel where the NbSn cable comes out of the splice
  - ➢ make splice using the same fixture used for HFDB-02
    - pre-tin the NbTi cable and the copper shims (only on one side)
    - pre-tin the NbSn cable (**<u>be careful: DON'T BEND THE CABLE</u>**)
    - use a 10 mil solder strip between the cables
    - use a 5 mil solder strip between a cable and a copper strip
    - a Kapton film in order to avoid to splice the cables where they should separate (outside of the fixture),
    - splice fixture should be strongly tight, but not at the maximum,
    - clean the soldering coming out during the splicing in order to avoid that the splice doesn't fit,
    - <u>add 3-mil Kapton strip on the bottom of the splice</u>,
    - check splice thickness and compare with the distance between G10 teeth,
      - thickness of splice parts in mm: NbSn cable 1.20, NbTi cable 1.30, shims 4.70, TOTAL 7.2 mm
    - set the splice, the Nb_3Sn cable start and the NbTi cable,
  - ➢ wind 3 turns without side pushers (we may use up to 8 m of cable = 26 feet)
    - tension on the cable: 20 lbs.,
    - tension on the tape: 30 lbs,
    - measure cable and coil dimensions,
  - ➢ put voltage taps (practice in putting voltage taps after winding!!!)
    - the tapes should have a "U"cut ➔ do it during the winding,
    - practice with brass strips
      - the brass strips may be soldered when the cable is in position, if the groove is large enough
      - thickness of solder + strip = 75 micron (50 strip + 25 solder)
  - ➢ splice to NbTi current leads: use two NbTi cables with copper stabilizing strips,
    - two copper strips 0.5 mm thick and 8 inch long on each side,
    - set splice partially outside the plate for better cooling (1.75 inch),
    - set the voltage tap (BLRS2),
  - ➢ check the splices:
    - measure their thickness, open them and check cable bonding
    - Previous experience: 5 mil soldering strip is enough if all cables are pre-tinned but 10 mil helps to fill the cables inside (➔ use 10 mil between the cables)

- ❖ Prepare for first coil winding
  - ➢ Increase depth of groves for VTs (solder shouldn't touch the G10)

- paint with mold-release all parts which need it: bottom plate, G10 inserts and end parts (note: <u>also the sides of the G10 inserts and the sides of the end parts</u>),

- Coil-coil connection cable:
  - use HGQ inner cable,
    - length: 35 inches
  - pre-tin the cable where it will be soldered to the coils,
  - pre-bend it,

- 1st coil winding:
  - use SPOOL # 2
  - inspect the extra turns
    - inspect the first 33 feet of the cable: check if there was any tin leakage (scratch locations)
    - Inspection report: NO tin leakage
    - <u>Starting point for splice: 4 inches from the orange mark (toward the center of the spool)</u>
  - Insulation:
    - fix the beginning of the tape (glue it before inserting the splice and the cable)
    - make one turn around the G10 parts and cut U-shaped gaps to be used for VTs
      - do this before the splice!!!
  - splice with NbTi cable:
    - add copper shims as stabilizers (2.35 mm thick),
    - pre-tin all the cables,
    - pre-bend the NbTi cable so that it will fit more easily inside the groove
    - splice fixture should be strongly tight, but not at the maximum,
    - use a Kapton film in order to avoid to splice the cables where they should separate (outside of the fixture),
    - clean the soldering coming out during the splicing in order to avoid that the splice doesn't fit,
    - <u>add 3-mil Kapton strip on the bottom of the splice</u>,
    - check splice thickness and compare with the distance between G10 teeth,
    - thickness of splice parts in mm: NbSn cable 1.20, NbTi cable 1.30, shims 4.70, TOTAL 7.2 mm
      - measured thickness: 7.78 mm (top) - 7.52 mm (bottom)
  - set the splice, the Nb_3Sn cable start and the NbTi cable,
    - paint with mold release the NbTi cable before you put it into the groove
  - start winding:
    - setup or re-set up the tensioner (tension, spool diameter, thickness)
    - tension on the cable: 20 lbs.,
    - tension on the tape: 30 lbs,
    - don't use the side pushers (use them only to install the end inserts),
    - use the T-shaped parts or check the ends during winding
      - Comment after winding: we used the T-shaped parts only to keep the end inserts in position, and used hands and a light G10 hammer to set each new turn in place
    - number of turns: 28 (14+14 - check the cable thickness after reaction and compare with drawing),
    - DON'T GO BACK DURING WINDING !!!
    - measure the coil thickness after turn #14
      - STOP winding before turn # 14 goes on the lead end

- compact the coil with side pushers
- measure coil thickness (6 locations on each side)
- compare with nominal dimension and decide if to put the lead end part or add an additional turn
- COMMENT: 14+14 is OK

- end inserts:
  - use screws in order to keep end parts in place during winding
    - these screws should end with a conical tip
  - **add 3 mil Kapton strip on the outer side of the end spacer**
    - this strip should be 3/8 of inch longer then the end part on each side
    - apply mold-release on the surface looking at the end spacer,
- end shoes:
  - Put ground insulation on the end shoes, it should be:
    - 2 layers of 5 mil kapton with adhesive, on the coil side
      - at the end of the winding measure the coil thickness to double-check that this is the right ground insulation thickness
    - the ground insulation should extend behind the tip by ¼ of inch for the inner layer, and a bit more for the outer layer
    - COMMENT AW: the diameter of the return end is smaller than that of the lead end ==> we removed the kapton between the end shoes in the return end
- end of winding:
  - apply mold-release on the insulation covering the last turn
- splice: use two NbTi cable with copper stabilizing strips,
  - two copper strips 0.5 mm thick and 8 inch long on each side,
  - set splice partially outside the plate for better cooling (one inch),
  - set the voltage tap (BLRS2)
  - set temperature sensor
  - insulate splice: 3 mil Kapton 50% overlap
  - measure the thickness of the insulated splice and compare with the indentation in the end shoe
    - RESULT: the thickness of insulated splice is 7.5 mm
    - add extra ground insulation so that the NbSn cable will remain straight
    - COMMENT: we added 5 10-mil G10 strips
  - fill the gap between the beginning of the indentation and the beginning of the splice
    - use some soft material (fiberglass tape) because we don't want to push on the Nb3Sn cable during assembly before impregnation
    - COMMENT: we wound a fiberglass tape around a G10 piece (total thickness 17 mil)
- set splice in place
  - fix it using a side pusher

- Instrumentation:
  - All instrumentation wires should be 12 feet long
  - install the spot heater:
    - reduce the length of its leads
    - it should be installed with the wires already spliced to the ss leads,
    - fix the wires with green putty
  - put VTs
    - put VTs only on the top of the large face of the cable (to avoid stress concentrations),

        - keep a Kapton piece on the top of the G10 groove during the soldering and remove it after soldering (to avoid bonding between the solder and the G10)
      - solder brass strips
      - put green putty for strain-release **<u>and gray RTV close to the cable</u>**
  - Set HT-Cernox,
      - check their resistance (about 60 ohm + 30 ohm in the wires)
      - put red RTV in the groove behind the Cernox
  - put labels for VTs and Cernox wires

- Measure coil thickness
  - compact both sides
  - measure coil thickness (7 points on each side = where there are the holes for the bolts)
      - RESULTS: see file "*coil dimension.xls*"
  - Measure the distance between the coil or the end-shoes and the edge of the bottom plate
      - actually we measured the distance between the pusher bar and the edge of the plate (9 points on each side = where there are the holes for the bolts)
      - RESULTS: see file "*coil dimension.xls*"
  - Measure block thickness in the ends
      - RESULTS: see file "*coil dimension.xls*"
  - Compute the thickness of G10 side shims:
      - RESULT: we may use shims of HFDB-02 (6 mm on the NON-lead side and 3.5 mm on the lead side)
  - Do we need to compensate/fix coil displacements?
      - YES: we will oversize the holes for the pins of the G10 inserts for the top coil, in the return end and we will use a bolt as a new centering pin to control both the gap dimension and the alignment
  - Keep/remove kapton on the side of the end shoes on the non-lead side?
      - NO, we removed the Kapton between the two end shoes in the return end

Procedure to install the G10 side shims
- Preparation:
  - Make grooves in G10 side shims
      - Grooves for SH, TS on lead side
      - Grooves for CAP GAUGE and wires, on the non-lead side
      - Check dimensions of grooves for Spot Heater and Cap Gauge
  - Prepare instrumentation:
      - Solder leads to Spot Heater (at 90 degress)
      - Pre-bend leads of temperature sensor (may be done at the end)
  - <u>Mark position of VTs on lead-side</u>
  - Put mold release again on machined shims
  - Make filler for groove of the Cap Gauge an its leads
  - <u>Tension on the cable: 20 lbs</u>
  - Check that:
      - Side pushers are tight
      - Two main bolts are tight
  - <u>Remove the pusher on the splice and the opposite pusher</u>
- NON-LEAD SIDE
  - Remove the pushers and side bar on the NON-LEAD SIDE
      - <u>Measure the spring back at end-shoe tips</u>

    - RESULTS: -3 mil RE, -1 mil LE
  - Install the 6-mm thick G10 shim
    - The groove should be on the outside (i.e. NOT facing the coil)
  - Put bar back and tight pushers
  - NOTE: we put the shim on the lead side first
- LEAD SIDE
  - Remove the pushers and side bar on the LEAD SIDE
    - <u>Measure the spring back at end-shoe tips</u>
    - RESULTS: 44 mil RE, 16 mil LE
  - Solder VTs
  - Make notches in the 3.5 mm shim in the position of VTs
  - Put mold release where notches were made
  - Install 3.5 mm thick G10 shims
    - The groove should be facing the coil
  - Install spot heater
  - Put bar back and tight pushers
- Final set up
  - Tight pusher on the splice (and the opposite one)
  - Remove cable tension
  - Install temperature sensor
    - The leads should be pre-bent
      - <u>BE VERY CAREFUL (follow procedure by LakeShore)</u>

- Quench heaters fabrication (see Appendix 5):
  - fabricate two quench heaters consisting of:
    - stainless steel strip (1 mil thick) glued on a 3 mil Kapton foil
    - 5 mil Kapton strips (with gaps for epoxy flow) glued on another 3 mil Kapton foil,
  - quench heater for bottom coil:
    - <u>Add holes to help epoxy flow from the grooves in the G10 plate,</u>
    - <u>holes should be at least 3/16 of inch from the stainless steel strips (to avoid shorts!)</u>
    - glue the two layers of 3 mil kapton
    - measure the thickness of the Kapton + glue layers after fabrication
    - RESULT: average thickness 13.2 mil (0.335 mm)
  - make cuts where the brass strips go up (small cut) and down (large cut to have room for solder wires)

- **<u>Install the bolt that will be used to center the G10 inserts of the top coil</u>**
  - Check the position and thickness of the kapton on the bolt (should be a tight fit with the G10 inserts of the bottom coil), the kapton should extend to the top coil
  - Paint it with mold release
  - <u>Install it with the head on the bottom</u>
  - <u>Add washer (the washer with a cut for epoxy flow)</u>
  - <u>NOTE: this bolt will NEVER be removed before impregnation</u>

- Before the installation of the quench heater:
  - <u>Put RTV on the NbTi cable inside the groove and in the holes for splice cooling,</u>
    - <u>Also in the holes in the bottom plate behind the splice</u>
  - <u>Put fiberglass tape in the gap close to the coil at the end of the inner splice</u>
  - check Cernox resistance (about 60 ohm + 30 ohm in the wires)
  - put labels for VTs and Cernox wires

- <u>Install keys in the end shoes</u>
- Check for short to ground
  - NO shorts
- Put soft filler close to the splice

- Check procedure to have same geometry in the top coil
  - Measure again ID in both ends
    - RESULTS: RE 180-180.1 mm, LE 181.5-181.6 mm
    - Distance between innermost edge of holes (numbered starting from lead end): #2: 88.3 mm, #4: 88.66 mm, #9: 88.0 mm
  - Install G10 inserts for top coil
  - Check their position with respect to the bottom coil
    - Same ID in RE???
      - YES, within the accuracy of the measurement (0.1 mm)
    - Do we need a pin-bolt also for LE or the splice does the job???
      - YES, we need: we put some kapton around the central bolt of the lead end to use it as pin-bolt during the winding of the top coil; this bolt will be removed before impregnation
      - We also need 18 mils of kapton in the hole for the pin close to the lead end in the lead side G10 part
    - Longitudinal position???
      - It's fine
  - The procedure for the installation of these parts should be decided before we put the QH!!!
    - The pin-bolts will take care of centering the parts, we will add the kapton shims in one hole

- Quench Heater (QH) installation
  - Remove all bolts
  - Put QH
    - <u>BE CAREFUL with the instrumentation on the outer turn of the lead side</u>
  - Trim QH on the lead side for instrumentation
    - <u>Note: just the minimum, the QH should cover the cables</u>
  - Fix the position of the QH with bolts
  - Check holes for strips
    - Make holes larger if needed
  - Have strips going through the holes
  - Insulation of strips:
    - Put 3 mil insulation on the cables (in the window made by the hole)
      - Avoid overlap with the quench heater
    - Put 1 mil behind the strips
    - Put 1 mil on the top of the strip close to the end shoes
  - Solder strips to wires
    - Put kapton to avoid contacts among strips or wires
  - Paint the top surface (everything included) with mold release

- Inter-layer plate:
  - file the edges,
  - make tapered grooves for Nb3Sn cable going from the inner splice to the coil
  - make grooves where the instrumentation wires make bumps above the top surface of the G10 inserts

- make or enlarge cuts on the edges (for Cap gauge wires, SH and TS)
- mold release both faces,
- install the G10 plate,
- set the instrumentation wires inside the groove
  - do we have room for a temperature sensor in the top coil???
    - We will decide after the instrumentation for the top splice is in
- add one layer of 3 mil Kapton (to prevent large amount of epoxy to be close to the cables)
  - the Kapton should have mold-release on both surfaces, so that cracks in the epoxy will not propagate to the epoxy close to the coil,
  - it should have small holes to let epoxy go to the cables
  - it should be ½ inch larger and longer than the G10 plate

- cut the Nb_3Sn cable
  - keep **seven feet** of Nb_3Sn cable between NbTi leads
    - fix the leads of the bottom coil to the bottom plate

- INSULATION FOR THE SECOND COIL:
  - Kapton: 3 mil without adhesive 0.6 inch width (should be a continuous piece as long as the two pre-preg rolls, i.e. about 220 feet)
  - Pre-preg: use roll RT3-31 and RT3-34
    - Cut to width: 0.6 +/- 0.008 inch
  - The tapes should be wound on the insulation spool (made of wood) with pre-preg inside and Kapton outside
  - Pre-preg roll RT3-34 should be put first on the spool (so that we will start using roll RT3-31 on the coil)
  - The pre-preg rolls should be glued to the Kapton at the beginning and at the end of each roll (NO overlap at the junction between the two pre-preg rolls)
    - Glue pre-preg and kapton along 1.5 inch (all width)
  - TOTAL LENGTH: 196 feet (59.7 m)

- preparation for 2nd coil winding:
  - paint with mold-release all parts which need it
    - (Note: also the sides of the G10 inserts and end parts),
  - Set up insulation and cable as for the winding of the first coil

- 2nd coil winding:
  - use SPOOL # 1
  - inspect the extra turns
    - inspect the first 30 feet of the cable: check if there was any tin leakage (scratch locations)
    - Inspection report: NO tin leakage, a strand a bit out of the cable in the first turns of the spool
    - Starting point for splice: 30 feet from the end of the cable
  - Insulation:
    - fix the beginning of the tape (glue it before inserting the splice and the cable)
    - make one turn around the G10 parts and cut U-shaped gaps to be used for VTs
      - do this before the splice!!!
  - splice with NbTi cable:
    - add copper shims as stabilizers (2.35 mm thick),
    - pre-tin all the cables,

- pre-bend the NbTi cable so that it will fit more easily inside the groove
- splice fixture should be strongly tight, but not at the maximum,
- use a Kapton film in order to avoid to splice the cables where they should separate (outside of the fixture),
- clean the soldering coming out during the splicing in order to avoid that the splice doesn't fit,
- <u>add 3-mil Kapton strip on the TOP of the splice</u>,
- check splice thickness and compare with the distance between G10 teeth,
- thickness of splice parts in mm: NbSn cable 1.20, NbTi cable 1.30, shims 4.70, TOTAL 7.2 mm
  - measured thickness: 7.87 mm (top) - 7.72 mm (bottom)
    - in the bottom coil it was:7.78 mm (top) - 7.52 mm (bottom)

- set the splice, the Nb_3Sn cable start and the NbTi cable,
  - paint with mold release the NbTi cable before you put it into the groove
  - <u>add a U-shaped kapton piece where the NbTi cable exits out of the G10 parts</u>
  - <u>put a 5 mil kapton on the top plate close to the NbTi cable in the same point</u>
- start winding:
  - setup or re-set up the tensioner (tension, spool diameter, thickness)
  - tension on the cable: 20 lbs.,
  - tension on the tape: 30 lbs,
  - don't use the side pushers (use them only to install the end inserts),
  - use the T-shaped parts or check the ends during winding
    - Comment after winding of bottom coil: we used the T-shaped parts only to keep the end inserts in position, and used hands and a light G10 hammer to set each new turn in place; we didn't use the side pushers until the end of the winding
  - number of turns: 28 (14+14)
  - DON'T GO BACK DURING WINDING !!!
- end inserts:
  - use screws in order to keep end parts in place during winding
    - these screws should end with a conical tip
  - **<u>add 3 mil Kapton strip on the outer side of the end spacer</u>**
    - this strip should be 3/8 of inch longer then the end part on each side
    - apply mold-release on the surface looking at the end spacer,

- End of 2nd coil winding:
  - end shoes:
    - <u>Put ground insulation on the end shoes, it should be:</u>
      - 2 layers of 5 mil kapton with adhesive, on the coil side
        - at the end of the winding measure the coil thickness to double-check that this is the right ground insulation thickness
      - the ground insulation should extend behind the tip by ¼ of inch for the inner layer, and a bit more for the outer layer
      - COMMENT AW of the bottom coil: the diameter of the return end is smaller than that of the lead end ==> we removed the kapton between the end shoes in the return end
  - end of winding:
    - apply mold-release on the insulation covering the last turn
  - splice: use two NbTi cable with copper stabilizing strips
    - two copper strips 0.5 mm thick and 8 inch long on each side
    - set splice partially outside the plate for better cooling (1.75 inch)

        - during the splicing keep the tensioner ON with 0 lbs (just to keep the cable straight)
        - splice thickness: 6.88 – 6.61 mm
    - set the voltage tap (TLRS2)
    - set temperature sensor
    - insulate splice: 3 mil Kapton 50% overlap
    - measure the thickness of the insulated splice and compare with the indentation in the end shoe
        - insulated splice thickness: 7.1 +/- 0.1 mm
        - <u>add extra ground insulation so that the NbSn cable will remain straight</u>
        - COMMENT AW: we put 3 10-mil G10 strips
            - In the bottom splice we added 4 10-mil G10 strips
    - fill the gap between the beginning of the indentation and the beginning of the splice
        - use some soft material (fiberglass tape) because we don't want to push on the Nb3Sn cable during assembly before impregnation
        - the filler shouldn't be thicker than 0.1 inch
        - COMMENT AW: we used 3 G10 layers 12 mil thick, one of them wrapped by fiberglass tape
            - In the bottom coil we wound a fiberglass tape around a G10 piece
- set splice in place
    - fix it using the side pushers
    - COMMENT: at the beginning we used clamps because the additional pushers were not available

- Make second quench heater
    - Same as the one for the bottom coil, except for the pin-holes: <u>only one row</u> instead of two

- Instrumentation:
    - All instrumentation wires should be <u>12 feet long</u>
    - install the spot heater:
        - reduce the length of its leads
        - it should be installed with the wires already spliced to the ss leads,
        - fix the wires with green putty
    - put VTs
        - put VTs only on the top of the large face of the cable (to avoid stress concentrations),
            - keep a Kapton piece on the top of the G10 groove during the soldering and remove it after soldering (to avoid bonding between the solder and the G10)
        - solder brass strips
        - put green putty for strain-release **<u>and gray RTV close to the cable</u>**
    - Set HT-Cernox,
        - check their resistance (about 60 ohm + 118 ohm in the wires)
        - put red RTV in the groove behind the Cernox
    - put labels for VTs and Cernox wires
    - install the G10 tubes for the VTs
        - may have a cut in order to introduce the wires keeping the loops
        - COMMENT AW: we used a tube (with longitudinal cut) for the wires close to the return end, shrink tape for the wires close to the lead end
    - set VTs on the NbTi connection cable:
        - one for quench protection (use a 22 gage wire) and one for back up (30 gage)
    - set the wires (VTs and Cernoxes) in the groove of the G10 plate between the splices

        - we may do it now because we are not going to add any instrumentation on the top coil lead side
        - be careful that the NO wire goes above or under the groove (it would be cut by the side pusher!)

- Measure coil thickness
    - compact both sides
    - measure coil thickness (7 points on each side = where there are the holes for the bolts)
        - RESULTS: see file "*coil dimension.xls*"
    - Measure the distance between the pusher bar and the edge of the plate (9 points on each side = where there are the holes for the bolts)
        - RESULTS: see file "*coil dimension.xls*"
    - Measure block thickness in the ends
        - RESULTS: see file "*coil dimension.xls*"
    - <u>Do we need to compensate/fix coil displacements???</u>
    - <u>Keep/remove kapton on the side of the end shoes on the non-lead side???</u>
        - <u>See in the following</u>

Procedure to install the G10 side shims

- Preparation:
    - Install the double clamps on the lead end to push on the splice (and react on the other side)
    - Install the end shoes
        - COMMENT AW: on the Lead End we removed the kapton (13 mils) on the non-lead side (now the end shoes fit well)
        - COMMENT AW: on the Return End we removed the kapton (13 mils) on both sides (still the end shoes don't fit!!!)
    - Take a decision about the temperature sensor on the lead side
        - <u>We are NOT going to install the temperature sensor on the outer turn of the lead side (TS-T3)</u>
    - <u>Tension on the cable: 10 lbs</u>
    - Check that:
        - Side pushers are tight
        - Two main bolts are tight
    - <u>Remove the pusher on the splice and the opposite pusher</u>
- NON-LEAD SIDE
    - Remove the pushers and side bar on the NON-LEAD SIDE
        - <u>Measure the spring back at end-shoe tips</u>
        - RESULTS: 8 mils at the LE, 4 mils at the RE
    - <u>Trim the 3 mil kapton foil at 4 mm from the edge of the coil</u>
    - Install the 6-mm thick G10 shim
        - The groove should be on the outside (i.e. NOT facing the coil)
    - Put bar back and tight pushers
- LEAD SIDE
    - Remove the pushers and side bar on the LEAD SIDE
        - <u>Measure the spring back at end-shoe tips</u>
        - RESULTS: 12 mils at the LE, 6 mils at the RE
    - <u>Trim the 3 mil kapton foil at 2 mm from the edge of the coil</u>
    - Install 3.5 mm thick G10 shims
        - Fill the grove with green putty (no bumps!!!)
        - The groove should NOT be facing the coil
    - Put bar back and tight pushers

- Final set up
  - Tight pusher on the splice (and the opposite one)
  - Remove cable tension

- Final set-up before the installation of the quench heater:
  - Trim the pre-preg insulation in excess (where the tape was wider then nominal)
  - Put RTV on the NbTi cable inside the groove
  - Put fiberglass tapes in the gap close to the coil at the end of the inner splice
  - Put fiberglass tapes in the gaps in the end inserts
  - <u>Install keys in the end shoes</u>
  - fill gaps in the coil at the tips of the end inserts (<u>Giorgio</u>),
    - use 3 or 4 layers of pre-preg tape with different lengths in order to have a tapered spacer
  - Splice region (<u>both bottom and top coil</u>):
    - Put soft fillers (<u>fiberglass tape</u>) between the end of the G10 shim and the beginning of the splice
    - Put spacers in order to have the same thickness at the splice and at the G10 shim
      - use strips of pre-preg tape (at least 3 layers) and G10
      - in the top coil the thickness should be 0.85 mm
      - in the bottom coil it should be 0.65 mm
    - COMMENTS: we used a G10 strip with fiberglass tape wound around it
  - Shimming in order to compensate top/bottom coil differences
    - Do we need it?
    - COMMENTS: we decided NOT to do any compensation and to compute the shim thickness according to the wider coil on each side

- Final set-up that may be done before or after the QH installation:
  - Put the Teflon rods and RTV in the holes for splice cooling
    - <u>We need RTV especially between the rods and the splices</u>
  - <u>fill holes in the end pushers with gray RTV (to avoid epoxy to fill them)</u>
    - apply mold-release on the sides of the holes before putting gray RTV
    - make a Kapton cylinder around each bolt and leave it in the hole

- Quench Heater (QH) installation
  - Remove all bolts
  - Put the QH
  - Fix the position of the QH with bolts
  - Check holes for strips
    - Make holes larger if needed
  - Have strips going through the holes
  - Insulation of strips:
    - Put 3 mil insulation on the cables (in the window made by the hole)
      - Avoid overlap with the quench heater
    - Put 1 mil behind the strips
    - Put 1 mil on the top of the strip close to the end shoes
  - Solder strips to wires
    - Put kapton to avoid contacts among strips or wires
  - Paint the top surface (everything included) with mold release

- Electric tests

- Check for shorts to ground
  - RESULT: OK
- cut the cable
  - keep 7 feet of Nb3Sn cable between NbTi cables,
- measure resistance and inductance of the coil:
  - COMMENT: this was postponed in order to perform the impregnation on time

- Mechanical structure assembly:
  - Prepare the main bolts (1 inch diameter) for impregnation
    - Clean, apply mold release and **grease** on 45 main bolts
    - Keep 12 bolts clean for the initial set up
  - Prepare the main plates
    - Put mold release and **grease** on the threads
  - Prepare the end plates
    - Put mold release and **grease** on the bullets and threaded parts
    - paint with mold release
  - Install the top plate
    - Remove the kapton layers (used for ground insulation) from the side of both bottom and top plate on the return end (we keep it on the lead end because there we have the leads of the quench heaters)
  - Install the Return End plate
    - Use washers/spacers to have some clearance for the wires of the spot heater
  - Install the Lead End plate
    - This is a dry fit: don't put RTV in the groove
    - Use washers to have some clearance for the leads of the quench heater
  - Top place centering
    - Tighten the bolts in the Return and Lead end plates in order to use them to center the top plate
    - COMMENT: we used only the return end plate for this
    - Fix the position of the top plate by hand-tightening a few main bolts
  - RTV around the leads
    - Pull back the Lead End plate
    - Stuff with RTV the groove for the leads in the Lead End plate
    - Tighten the bolts in the Lead end plate permanently
  - Side pusher installation
    - Clamp the leads in such a way to keep the coils under tension
    - COMMENT: we used wood slabs, C clamps and G10 wedges
      - **DO IT WELL – IT'S CRUCIAL NOT TO LOOSE THE TENSION**
    - Remove the side clamps from the splices
    - Remove the clamps and side bar from the lead side
    - Remove the clamps and side bar from the non-lead side
    - <u>Clean mold release from the outer surface of the G10 shims</u>
      - We want epoxy to remain on the magnet
    - Install the side pushers
      - use spacers in order to avoid over squeezing the coil
      - <u>spacer thickness: 3.1 mm on non-lead side, 3.6 mm on lead side</u>
        - in HFDB02 we used: 3.1 mm on non-lead side, 3.4 mm on lead side,
    - don't use Al bolts, use the old ss bolt (Al bolts will be used after impregnation)
    - the **torque** on the bolt shouldn't exceed 10 inch*lbs
      - **STOP if you cannot close the gap without exceeding this torque!!!**

  - If so we have to think about different shims (for instance different between LE and RE)
  - COMMENT: First we hand tightened the non-lead side to the nominal gap, then we tried to install the lead side pusher but found that the main bolts didn't go trough in the lead end. Therefore we opened more the gap in the non-lead side and tried again to install the lead side pusher using the side bolts after having increased the thickness of the side shim closer to the lead end by 10 mil. It worked and we could install the main bolts.
- ➢ Install all main bolts
  - ▪ Washers with cut should be both in the bottom and top
- ➢ Tighten gradually the bolts and the bullets
  - COMMENT: first we slightly tightened the bolts in the main plate (to have coils flat), secondly we had bullets just in contact with the end shoes, thirdly we tightened the side bolts (going from the from center to the ends) to 10 inch*lb. We could close the gap to the shim dimensions on the lead side. On the non-lead side the gap was larger. We tightened the bolts to 20 inch*pound but the gap didn't change significantly. Therefore we decided to stop.
  - GAP dimensions: 3.8 mm on the lead side (from 3.6 Return End to 4.0 Lead End) and 4.0 mm on the non-lead side

❖ Preparation for impregnation:
- ➢ preparation for impregnation:
  - ▪ on all bunches of wires: apply mold-release, put shrink tape, mold-release again, add RTV at the beginning
  - ▪ on the cables: mold-release, put shrink tube (2 tubes if possible), mold-release, add RTV at the beginning
  - ▪ put mold-release, grease and the bolts in the holes for G10 box support,
  - ▪ mold-release, grease and RTV on all bolts
    - RTV shouldn't prevent epoxy to go into the holes of the main bolts
  - ▪ mold release on all surfaces (also bottom plate and the surfaces now in contact with the supports)
- ➢ clean and apply mold release on the impregnation tank and on the aluminum spacers
- ➢ Prepare epoxy level meter (a ruler with easy-to-see marks)
- ➢ Put the magnet in the impregnation box
  - ▪ Fill the tank with aluminum and Teflon spacers
  - ▪ Use epoxy blocks as additional fillers
  - ▪ Put some kapton foils with mold release in order to have plans that will help to free the magnet from epoxy after impregnation

❖ Impregnation
- ➢ See procedure and details in the appendix

❖ Electric tests
- ➢ Measure resistance and inductance of the coil:
  - ▪ RESULTS:
    - R = 280 mohm (R from lead + to CF = 140 mohm)
    - L = 0.2905 mH @ 20 Hz (Q=0.12); 0.2063 mH @ 1 kHz (Q=2.18).
  - ▪ For reference HFDB-02 had:
    - R = 221.8 mohm (R from lead + to CF = 110.7 mohm)
    - L = .329 mH @ 20 Hz (Q=0.18); .287 mH @ 1 kHz (Q=4.67)

- Hi-pot test
  - Coil to ground
  - Heaters to Coil
  - Heater to Ground
  - RESULTS AND COMMENTS:
    - After the impregnation the Hi-Pot test revealed some current leakage COIL to GROUND (0.15 uA at 500 V) and from the Top_Right Quench Heater to COIL and to GROUND (0.36 uA at 100 V). The other Quench Heaters had NO leakage above the detectable threshold (0.05 uA) at 1000 V.
    - After cleaning and reassembly the leakages were much higher: above 0.5 uA at 200 V for any combination of COIL, GROUND and Quench Heaters.
    - Bolts, side pushers, and end plates were removed while performing Hi-Pot tests at every stage. It was found that some current was leaking through the end-shoes of the bottom coil in the return end (0.25 uA at 100 V). It was decided to insulate all end shoes from ground, by adding a G10 shim in the bottom of each end shoe and by insulating with Kapton all main bolts going through the end shoes.
    - The Hi-Pot performed after these modifications gave NO detectable current leakages at 1000 V for any combination of COIL, GROUND and Quench Heaters.
    - Some current leakages appeared again just before pre-stress application. The insulation on the leads was partially removed at that moment (in order to set back two voltage taps that came off). The un-insulated parts of the cables were in air and far from the ground. Still we think this was the source of the problem because it disappeared when the cables were completely insulated.

- Cleaning
  - Clean all bolts and threads
  - Remove and clean the side pushers and the end plates
    - Mark the side pushers in order to set them back in the same position they had during impregnation
  - Try not to remove the thin epoxy layer on the G10 coil shims

- Cap-gauges:
  - Set Cap gauges in the grooves in the G10 coil shims (Non-lead side)
  - Their thickness should match the thickness of the groove in the G10 shims
  - Set the wires in the groove in the G10 plate
    - Fix them to avoid being cut by the side pusher

- Before preloading:
  - Install additional kapton around leads
  - Install lead end plate along with alignment shims
  - Install all bullets in both lead and return end plate (including instrumented as per the layout on the wall)
  - Snug all bolts/bullets on side pushers, end plates and main plate
  - Make measurements of coil inductance (L), resistance (R) and Q factor
  - Perform Hi-Pot test of the magnet (coil to ground, coil to heaters and heaters to ground)
    - See results in the Appendix

- Insulation of the end-shoes from ground

- COMMENT: this part was added to the procedure because some current leakage (3 uA at 100 V) Coil-Ground was measured after cleaning. The G10 shims will insulate the end-shoes and the brass shims will distribute the load applied by the bullets
- Set G10 shims at the end of each end-shoe
- Make brass shims 5 mm thick
  - Should be slightly undersized with respect to the G10 shims
  - Cover their face toward the G10 shim with 3 mil Kapton,
- Set brass shims at the center of each G10 shim
- Cover with 3 mil Kapton the body of the main bolts located in the magnet ends in order to insulate them from the end shoes
  - COMMENT: also several bolts going through the G10 island were insulated the same way

- Electric tests
  - Measure resistance and inductance of the coil:
    - RESULTS:
      - R = 281 mohm
      - L = 0.292 mH @ 20 Hz (Q=0.12); 0.2063 mH @ 1 kHz (Q=2.17).

- Pre-load procedure:
  - Connect selected strain gauges to the cart used to read the load during pre-stressing
  - Follow pre-load procedure (see in Addendum)
  - Hi-Pot test should be performed four (4) times during pre-stress application
    - RESULTS: NO detectable current leakage at 1000 V for any combination of COIL, GROUND and Quench Heaters
  - In the days following the pre-load application, check the torque on all bolts and keep it at nominal values

- Final assembly:
  - Install bridges supporting the G10 box there the NbTi cable is set
  - Check all instrumentation
  - Solder wires to the connectors according to: HFDB-03 Magnet/DAQ System Interface
    - Connectors should be at 4 feet from the lead end of the magnet
    - <u>Warning</u>: fixed voltage taps should be soldered to their connector only after the top plate installation
  - Copper radiators for lead splices:
    - Clean them from RTV and epoxy
    - Set them in the appropriate position,
    - Insulate top from bottom and surrounding parts
    - Insulate the top-plate face close to the radiators
  - Set G10 end plate
  - Set top-plate (<u>check the orientation</u>)
  - Fix instrumentation wires to the magnet using green putty
  - Label positive and negative lead

- Delivery
  - After removing the magnet from the posts, set the four missing bolts in the ends
  - Deliver to IB1 in horizontal position

- At VMTF

- Spot heater Hi-Pot test at 500 V
- RESULTS: NO detectable current leakage

INSTRUMENTATION CHECK BEFORE DELIVERY

❖ Voltage taps: TOTAL ~~40~~ 38

- lead end: 4 (x 2)
- return end: 4 (x 2)
- inner splice: 2 (x 2)
- outer splice: 3 (x 2)
- inner spot heater: 3 (x 2)
- outer spot heater: 2 (~~x 2~~ NOT INSTALLED on top coil)
- quench characterization and lead protection: 2 (x 2)
  - BLp, BLqc, TLp, TLqc

❖ QDS voltage taps: 3 (+ a back-up wire)

- lead: 1 (x 2)
  - BLF
  - TLF
- between bottom and top coil: 1 (+ a back-up wire)
  - CF

❖ Temperature sensors: TOTAL ~~8~~ 5 OK, 1 has a jumper in the connector

- Bottom coil:
  - TS-B1 (serial # X25564) inner left side (non lead side),
  - TS-B2 (X25565) inner right side (lead side),
  - ~~TS-B3 (X25566) outer right side (lead side)~~, DEAD
  - TS-B4 (X25567) lead splice
- Top coil:
  - TS-T1 (X25568) Inner left side (non lead side),
  - TS-T2 (X25569) Inner right side (lead side), JUMPER BETWEEN I- AND V-
  - ~~TS-T3 (X25570) outer left side (non lead side)~~, NOT INSTALLED
  - TS-T4 (X25571) lead splice
- color code:

	V+	I+	I-	V-
	G	R	B	Y

❖ Spot heaters: TOTAL 3

- bottom coil, innermost turn, straight section: 1
  - labels: BISH+, BISH-
- bottom coil, outermost turn, straight section: 1
  - labels: BOSH+, BOSH-
- top coil, innermost turn, straight section: 1
  - labels: TISH+, TISH-
- ~~top coil, outermost turn, straight section: 1~~
  - ~~labels: TOSH+, TOSH-~~ NOT INSTALLED

❖ Strip heaters: TOTAL 4

- Bottom coil, inner face, right (lead) side:
  - labels: BRQH+, BRQH-
- Bottom coil, inner face, left (non lead) side:
  - labels: BLQH+, BLQH-

- Top coil, outer face, right (lead) side:
  - labels: TRQH+, TRQH-
- Top coil, outer face, left (non lead) side:
  - labels: TLQH+, TLQH-

Strain gauges: TOTAL ~~39~~ 38

- on main plate bolts: 8 (+2 compensators)
  - mainL1A, mainL1B,
  - mainL2A, mainL2B,
  - mainR3A, mainR3B, ~~mainR3C~~ DEAD
  - mainR4A, mainR4B, mainR4C.
- on side pusher bolts: 12 (+1 compensator)
  - sideLE1A, sideLE1B,
  - sideLE2A, sideLE2B,
  - sideRE3A, sideRE3B,
  - sideRE4A, sideRE4B ???,
  - sideLS1A, sideLS1B, sideLS1C
  - sideRS2A, sideRS2B,
- on end bullets: 16
  - lend1A, lend1B,
  - lend2A, lend2B,
  - lend3A, lend3B,
  - lend4A, lend4B,
  - rend1A, rend1B,
  - rend2A, rend2B,
  - rend3A, rend3B,
  - rend4A, rend4B.
- color code:

color code:	V+	I+	I-	V-
	G	R	B	W

Capacitance gauges: TOTAL 2

- on the bottom coil, lead side
  - capLB
- on the top coil, non lead side
  - capNLT

REFERENCES

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2) G. Ambrosio et al., "Development and test of a Nb_3Sn Racetrack Magnet using the React and Wind Technology", *Advances in Cryogenic Engineering 47A*, pp. 329-336 (2002).
3) G. Ambrosio, N. Andreev, P. Bauer, S. Bhashyam "2D mechanical analysis of the straight section of HFDB-03 Racetrack #3", TD-03-017
4) S. Bhashyam, G. Ambrosio and N. Andreev, "2D Mechanics of HFDB-03 – Straight Section and Ends" TD-03-026
5) G. Ambrosio et al., "Study of insulating materials for HFDB-02 "Racetrack Magnet" using Nb3Sn and the React-and-Wind technology" TD-02-008.
6) G. Ambrosio et al., "Fabrication and Test of a Racetrack Magnet Using Pre-Reacted Nb_3Sn Cable", to be published in ASC 2002 proceedings (Houston, TX).

Appendix 1: Cable log sheet

CABLE No. **FNL R&W-R1O-00824**
MFG. 11/15/01 LBNL
OPERATOR: H.Higley, E. Palmerston

CABLE LOG SHEET
LBNL-SUPERCON-AFRD
SUPERCONDUCTING MAGNET MATERIALS
BLD 52

Objective:

1) **Nb3Sn 41 strand cable Identical to LBNL Cable # R1I-00811 using Oxford strand. Giorgio Ambrosio of FNAL, observed entire cable run.**

- STRAND INFORMATION -

MANUFACTURER :	Oxford		
BILLET #:	Ore-159, 164 & Ore-166		
SPOOL #:	See Respool Map. "stmpRAW1-O-B0824_Ore159_164_166.xls"		
COMPOSITION :	Nb3Sn		
STRAND Dia.. NOMINAL :	0.7 mm	INSP. DIA..:	0. 0.7029 mm avg.
Cu/SC RATIO NOMINAL :		INSP. RATIO :	
FILAMENT TWIST/LENGTH :		DIRECTION :	Right
SHARP BEND TEST :			
LENGTH PER SPOOL :	250m, without leaders or trailers.		

- CABLING SPECIFICATIONS -

TYPE or SPEC.:	FNAL R&W -R1				
No. of STRANDS:	41				
PITCH DIRECTION:	LEFT	PITCH LENGTH:	109.8		
PLANETARY RATIO:	-.57				
ROLLER ID #:	P29 & 30	WIDTH:	15.006 mm	ANGLE::	**0**
MANDREL ID #:	39B	WIDTH:	14.32 mm	THICKNESS::	.58 mm
LUBRICATION :	MOBIL-1 15w-50 , 20% + Naphtha as thinner, approximately 2 drops/ pitch.				
STRAND TENSION:	2.4kg. +/- .05	TURKS HEAD LOAD "SGM":	-68kg. = 30kg. Cable tension		

- FINISHED CABLE -

	R1O-00824
FINISHED LENGTH:	239m
Avg. THICKNESS:	1.2230 mm
Avg. WIDTH:	15.0714 mm
Avg. ANGLE:	-0.028 deg.

RESIDUAL TWIST/Mtr.:	90 deg. under twist " good direction"
ETCH for FILAMENT DAMAGE:	

Notes: This cable looks very good. It has a very uniform surface finish and minimal residual twist.
Over sized cable at startup of run was not removed, see graphs on page 3.
Sample taken from tail end for metallography at LBNL.
Cable shipped to FNAL IB4 11/16/01.

Note: statistics are for length from 14m… 239m at top of spool as delivered and labeled "Tail End"

[CABLE RUN   CME R1000824]

Date: 11-15-2001 FNL R&W .7mm x 41st Time: 09:15:41

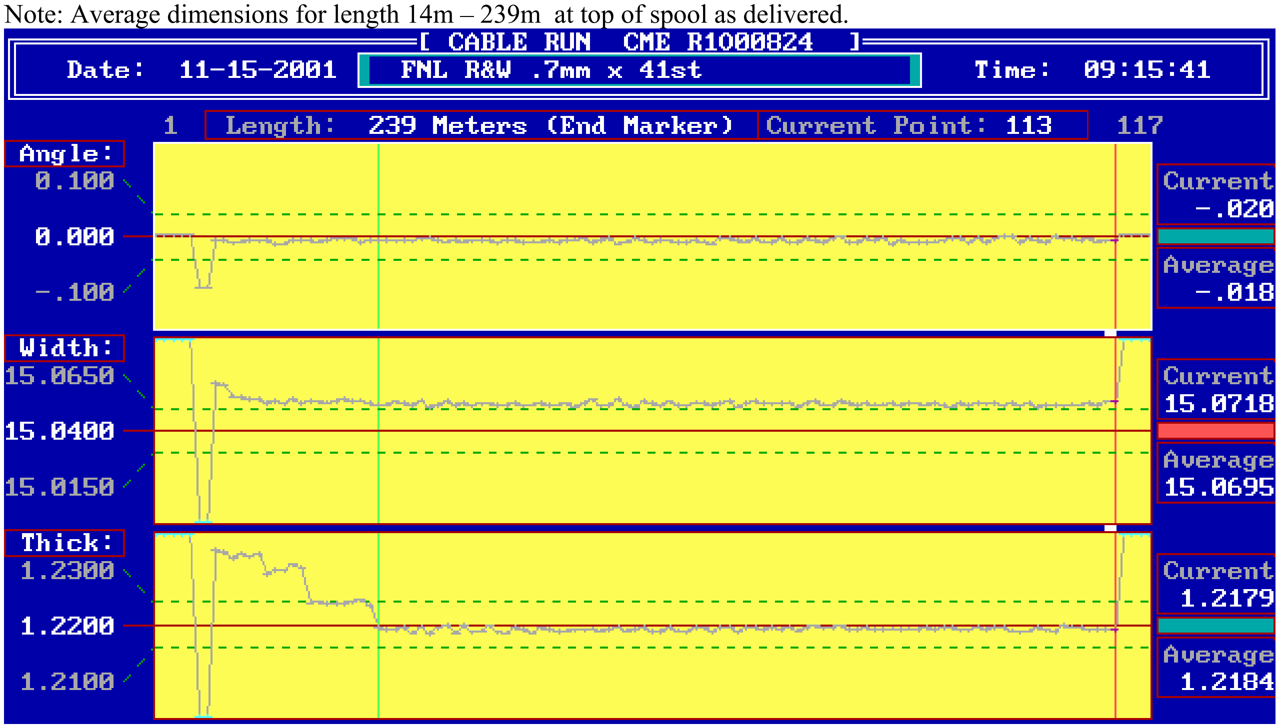
Statistics for CME R1000824
Cable Section from length = 15 to length = 239 (224 Meters)

	kPa	ANGLE	WIDTH	THICK
AVERAGE	17,422	-.018	15.0695	1.2184
MINIMUM	17,391	-.037	15.0660	1.2165
MAXIMUM	17,449	0.002	15.0742	1.2199
STANDARD DEVIATION	24	0.008	0.0018	0.0008

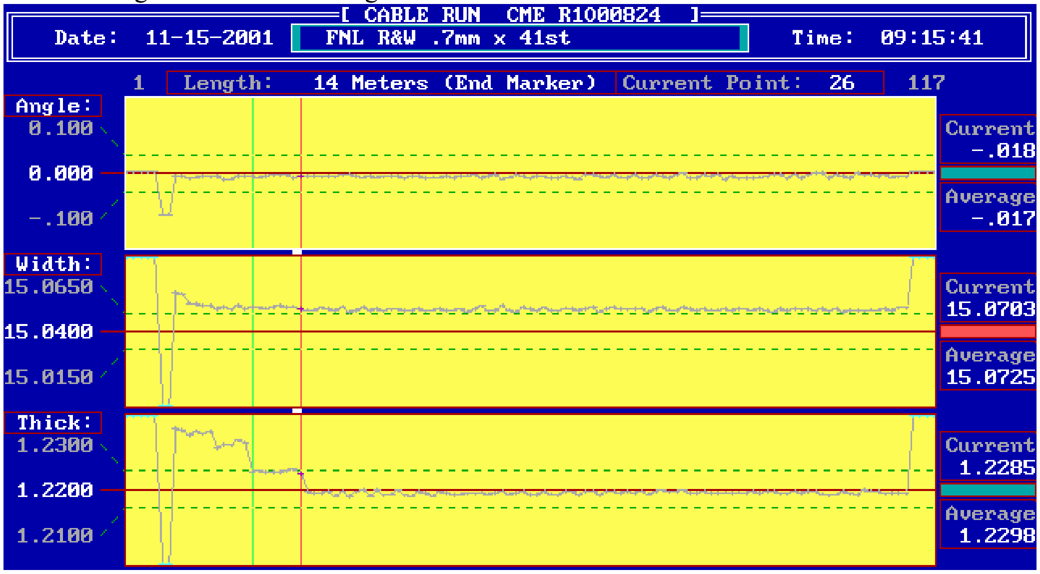
Cable Type : FNL R&W .7mm x 41st
Run Title : RAW-1-0-00824
Run Date : 11-15-2001
Supervisor : HUGH HIGLEY
Operator : EVAN PALMERSTON
Cable Data File : CMECTYPE.R1
Reel Number : -
Total Run Length : 239
Number of DataPts : 113
Clamp Time : 4
Clamp Interval : 4

F10 to Quit

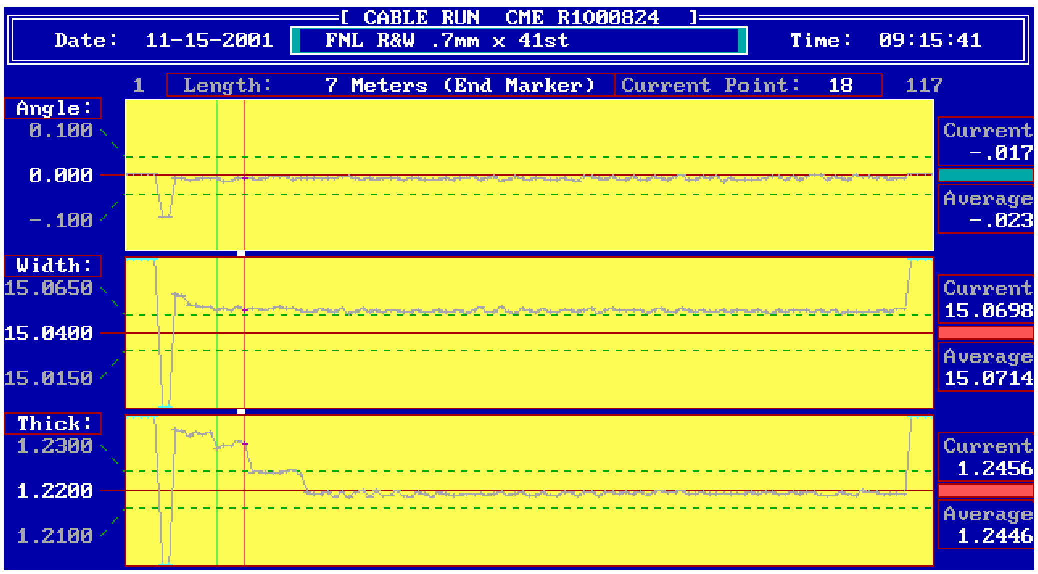
Note: Average dimensions for length 14m – 239m at top of spool as delivered.



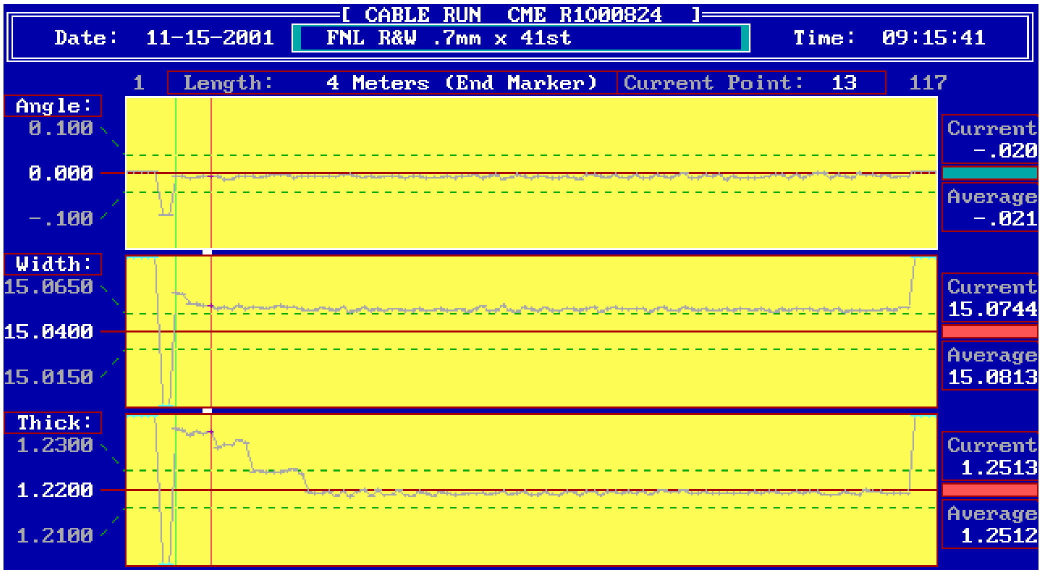
Note: Average dimensions for length 7m – 14m



Note Average dimensions for length 4m – 7m.



Note: Note: Average dimensions for length 0m-4m at "Hub" of spool as delivered.


[CABLE RUN CME R1000824]
Date: 11-15-2001
FNL R&W .7mm x 41st
Time: 09:15:41
1
Length: 4 Meters (End Marker)
Current Point: 13
117
Angle:
0.100
0.000
-.100
Current
-.020
Average
-.021
Width:
15.0650
15.0400
15.0150
Current
15.0744
Average
15.0813
Thick:
1.2300
1.2200
1.2100
Current
1.2513
Average
1.2512

Summary of good pre-preg roll measurement
(best rolls only)

			Selected for the FIRST COIL			Selected for the SECOND COIL					
roll number			**2**	**6**	**10**	**31**	**34**	**41**	**39**	**51**	**52**
Length	Total	m	31.7	24.4	32.9	29.3	28.0	30.5	18.3	31.7	31.7
Thickness	Average	mil	**6.29**	**6.41**	**7.10**	**6.27**	**6.22**	**6.89**	**6.90**	**6.04**	**6.88**
	St. Dev.		0.53	0.37	0.50	0.66	0.52	0.86	0.52	0.20	0.22
	Max		8.25	7.45	8.05	7.80	7.40	8.95	7.95	6.40	7.45
	Minimum		5.85	5.75	6.10	5.40	5.40	5.75	6.25	5.55	6.20
Width	Average	inch	0.601	0.597	0.617	0.598	0.602	0	0	0.594	0.596
	St. Dev.		0.001	0.004	0.014	0.009	0.015	0	0	0.016	0.014
	Max		0.603	0.603	0.641	0.615	0.622	0	0	0.634	0.622
	Minimum		0.600	0.586	0.571	0.588	0.588	0	0	0.568	0.550
Width	Average	mm	15.28	15.17	15.66	15.19	15.30	0.00	0.00	15.08	15.14
	St. Dev.		0.02	0.11	0.36	0.22	0.38	0.00	0.00	0.41	0.35
	Max		15.30	15.32	16.27	15.62	15.80	0.00	0.00	16.10	15.80
	Minimum		15.24	14.88	14.50	14.94	14.94	0.00	0.00	14.43	13.97
Use these rools:			1A	1B		2A	2B				
Average thickness		mm	0.161			0.159					

Giorgio Ambrosio:
Width: one bad spot 0.655

Impregnation procedure for 3rd Racetrack

31-Mar-03 Version 2

	Set	Read	
C	F	F	
60	**140**	…	temperature during pumping (42 hrs)
60	**140**	…	temperature during impregnation
125	**257**	…	temperature during curing

Epoxy component and total weight

	volume	45.42	l	*12.00*	*gallon*
	density	1.20	kg/l		
	weigth	54.504	kg		
	one part	0.284616	kg		
parts:					
100	part A	**28.46**	**Kg**	62.76	lb
90	part B	**25.62**	**Kg**	56.48	lb
1.5	part C	**0.427**	**Kg**	0.94	lb
	Total	**54.50**	**Kg**	120.19	lb

Mixing temperature: 140 F (60 C)

Degassing: 1hour 15 minutes (starts when temperature is above 40 C)

impregnation procedure:

magnet at 140 F, epoxy at 140 F (60 C)

oven pressure: 30 Hg micron (during all process)

- first filling to reach coil bottom (at 2.5 inch from the bottom of the tank),
- slow filling: increase the level of 1 inch/hour ut to 7.25 inch

curing procedure:

20 hours at 257 F (125 C)

Appendix 4: data recorded during impregnation

Impregnation of 3rd Racetrack

March 31, 2003

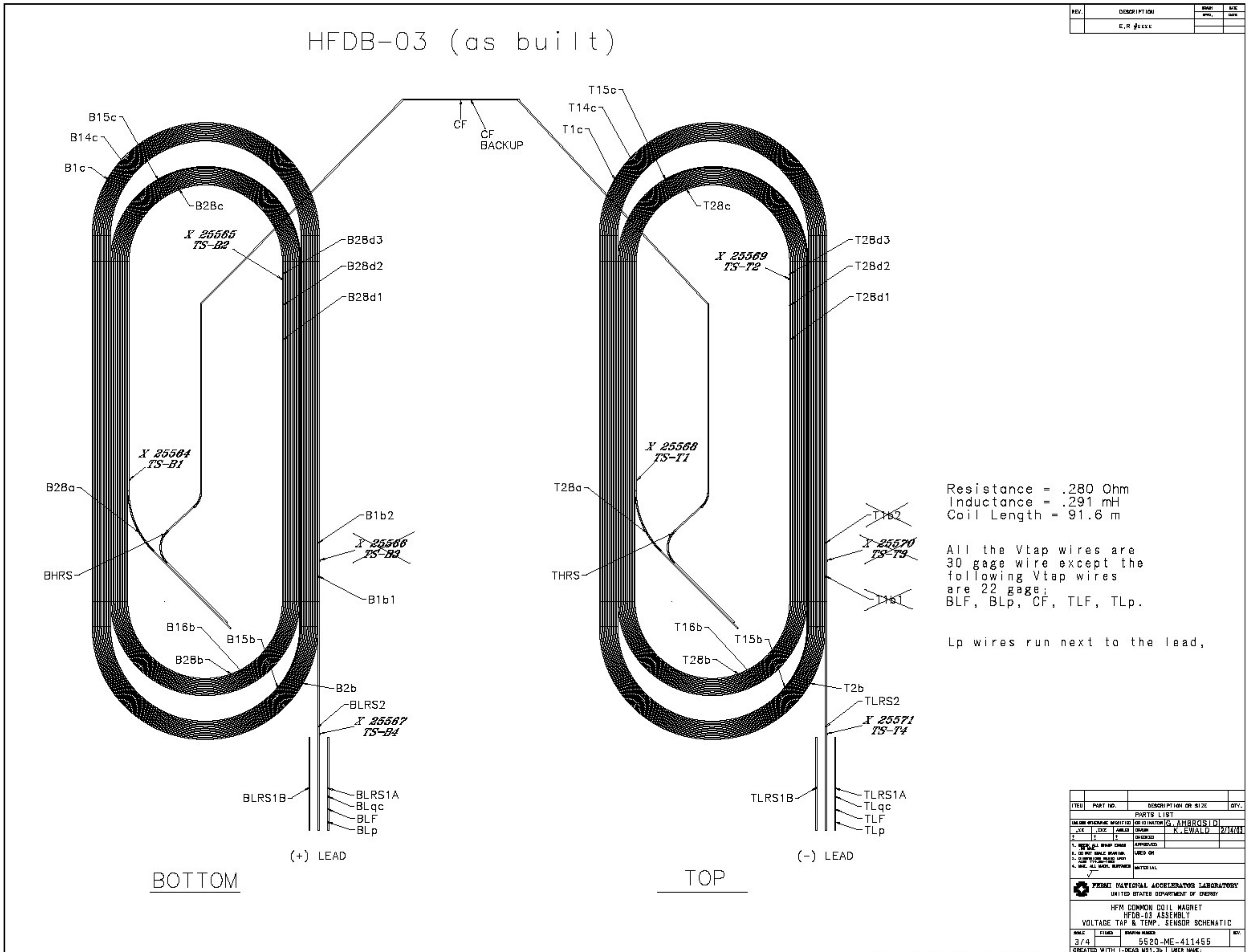
Technicians: Dean and Adam

time	temperatures			Epoxy level	Action
	Epoxy (C)	Magnet (F)	Oven (F)	(in)	
					pump and heat started on the 29th at 2:30pm - oven set at 140 F
8:30		120	140		oven set at 150 F
9:30					start mixing
10:40	60				start degassing
11:15		124	150		
11:53	62	124.2	150/151		Start impregnation (fast filling up to 2 inches)
12:05	60				
12:21	61	124.7	151	3	Vacuum 28 um Hg
13:00	54	125.5	151	4	Vacuum 28 um Hg
13:30	59	126.2	151	5	Vacuum 28 um Hg
14:00	59	126.3	150	5	Vacuum 28 um Hg
14:30	60	125.9	157		Vacuum 28 um Hg
15:00	59	127	156	6	Vacuum 28 um Hg
15:30	60	127.8	155		Vacuum 28 um Hg
16:00	58	128.9	162		Vacuum 28 um Hg
16:30	59	128.9	160	6 3/4	Vacuum 28 um Hg
17:00	58	129	161	7	Vacuum 28 um Hg
17:25	60	128.4	160		END of filling (we used all epoxy)

Vacuum: pressure < 30 um Hg all time

Note: coils should have been between 2.5 and 7 inch

Appendix 5: voltage tap plot and distances



HFDB-03 "3rd Racetrack" as built

Voltage taps: list and position

T1b1 and T1b2 have been removed

	ΔI	Total	Dead/Alive	Note
BLqc	0	0		
BLRS1A	0	0		
(BLRS1B)	0	0		same locat
BLRS2	200	200		
B1b1	180	380		
B1b2	90	470		
B1c	588	1058		
B2b	1136	2194		
B14c	21165	23359		
B15b	837	24196		
B15c	746	24942		
B16b	755	25697		
B28b	18700	44397		
B28d1	295	44692		
B28d2	90	44782		
B28d3	90	44872		
B28c	156	45028		
B28a	469	45497		
BHRS	70	45567		
THRS	450	46017		
T28a	70	46087		
T28c	469	46556		
T28d3	156	46712		
T28d2	90	46802		
T28d1	90	46892		
T28b	295	47187		
T16b	18700	65887		
T15c	755	66642		
T15b	746	67388		
T14c	837	68225		
T2b	21165	89390		
T1c	1136	90526		
TLRS2	858	91384		
TLRS1A	200	91584		
(TLRS1B)	0	91584		same locat
TLqc	0	91584		

Appendix 6: Quench heaters have the same design of those used in RT2; the legs were slightly shorter.

Racetrack 2

all heaters in series

magnet length	**0.8**	m
N. of Strips per Heater	4	
Strips in parallel	1	
N. of Heater in parallel	**1**	
N. of Heater in series	2	

Heater strip:	at 4 K			at 296 K	at 4 K
Strip width	1.0E-02	m		1.0E-02	1.0E-02
Strip thick	2.5E-05	m		2.5E-05	2.5E-05
rho aisi304	4.9E-07	ohm*m		7.2E-07	**4.9E-07**
rho aisi316	5.3E-07	ohm*m		7.7E-07	5.3E-07
A strip	2.5E-07	m2		2.5E-07	2.5E-07
R/length	1.96	ohm/m	(without Cu)	2.88	1.96
Cu cladding		**0 :1**			
Cu length	0.0E+00	m		0.0E+00	0.0E+00
SS length	1.2E-01	m	100%	1.2E-01	1.2E-01
SS length/strip	0.8	m	145%	1.2	1.2
R 1 strips	1.6	ohm		3.3	**2.274**
Tot heater R	6.3	ohm		13.36	9.1
Rwires	0.3	ohm		0.4	0.8
Rtot	**12.8**	**ohm**		**27.1**	**19.0**

SSC Capacitor Bank:		
C tot	1.44E-02	F
U tot	400	V
Vmax(V)	450	89%
E tot	1.2E+03	J
Po	8.4E+03	W
Po-Pleads	8.1E+03	W

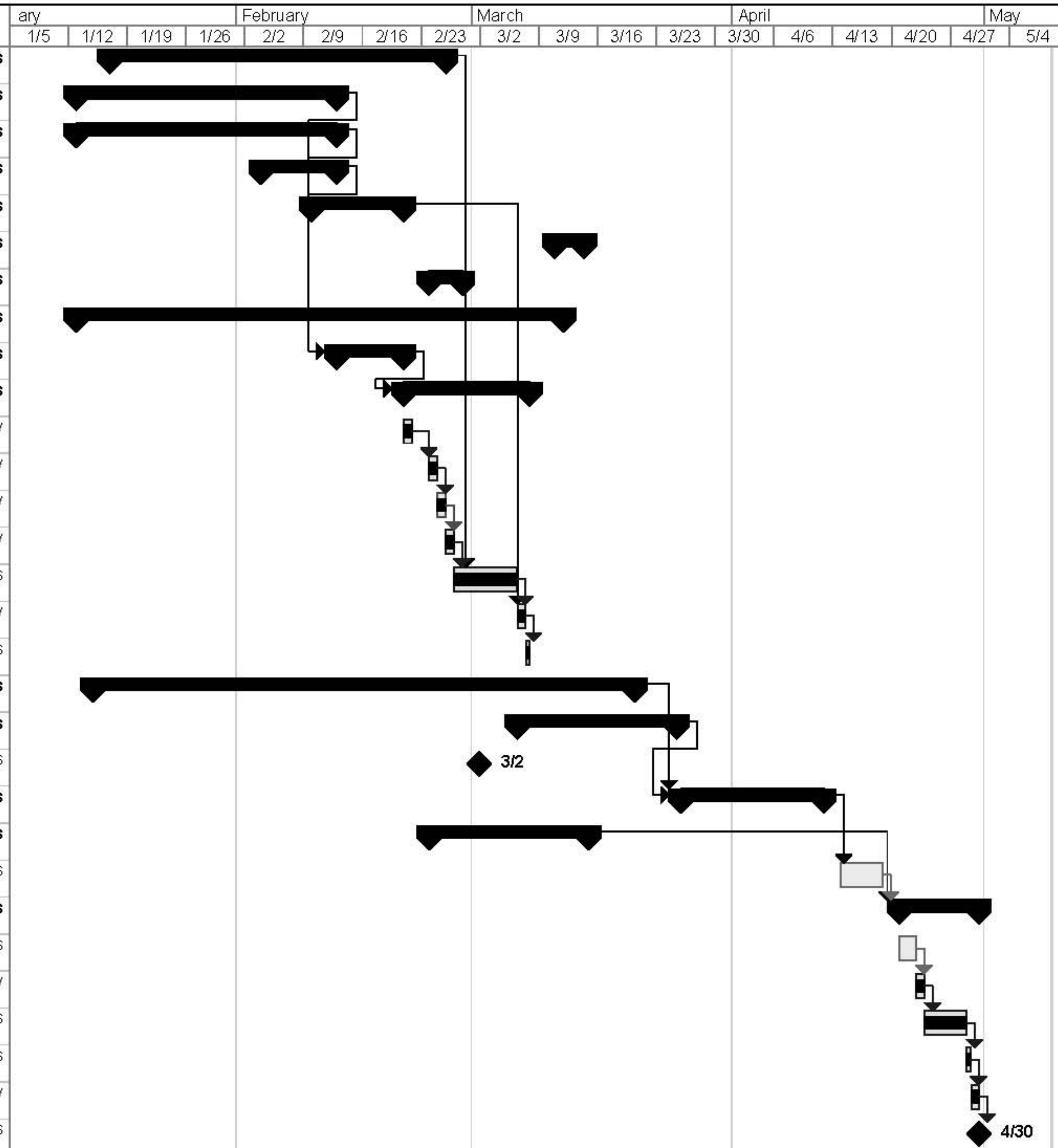
P/A	**8.7**	W/cm2
decay time	**0.273**	s
Io	**21**	A
gen=Po/vol	3.6E+09	W/m3

ansys	
gen (W/m3)	T (K)
5.5E+10	10.4
2.8E+10	9.8
1.0E+10	9.5

Cable dimensions:								
ins	1.00E-04	m	drheated	1.40E-03	m	E/S	1.2E+04	J/m2
drcab	0.00144	m	ins	5E-04	m	**E/V**	4.4E+06	J/m3
dhcab	0.01516	m	DH	2E+05	J/m3	**E/V w ins**	3.3E+06	J/m3
strand	7.00E-04		DH	5E+05	J/m3	**diff**	177%	
						diff	147%	

Appendix 7: Schedule of cable preparation and magnet fabrication

ID	Task Name	Duration
1	**New instrumentation plan**	**27 days**
6	**Cable preparation**	**22 days**
14	**Insulation preparation**	**22 days**
19	**winding preparation**	**7 days**
24	**Heaters for Bottom coil**	**9 days**
27	**Heaters for Top coil**	**3.5 days**
30	**Cap gauges**	**4 days**
33	**New parts**	**41 days**
49	**practice winding**	**6 days**
56	**1st coil**	**11 days**
57	Starting splice	1 day
58	Prepare for winding	1 day
59	1st coil winding	1 day
60	Current lead splice	1 day
61	VTs and Cernox	5.5 days
62	Instrumented side shims	1 day
63	Install quench heater	0.5 days
64	**New NbTi support box**	**45.5 days**
67	**2nd coil**	**13 days**
76	Book IB2 for impregnation	0 days
77	**impregnation & cleaning**	**15 days**
82	**bolts instrumentation**	**15 days**
86	**Delay due to Hi-Pot problem**	5 days
87	**prestress & instrumentation**	**7.5 days**
88	Delay due to new cart set-up	2 days
89	Apply prestress	1 day
90	Hypertronics connectors	3 days
91	Check-out before delivery	0.5 days
92	Set up for delivery to IB1	1 day
93	Delivery to IB1	0 days



Page 1

Appendix 8: Photos during fabrication

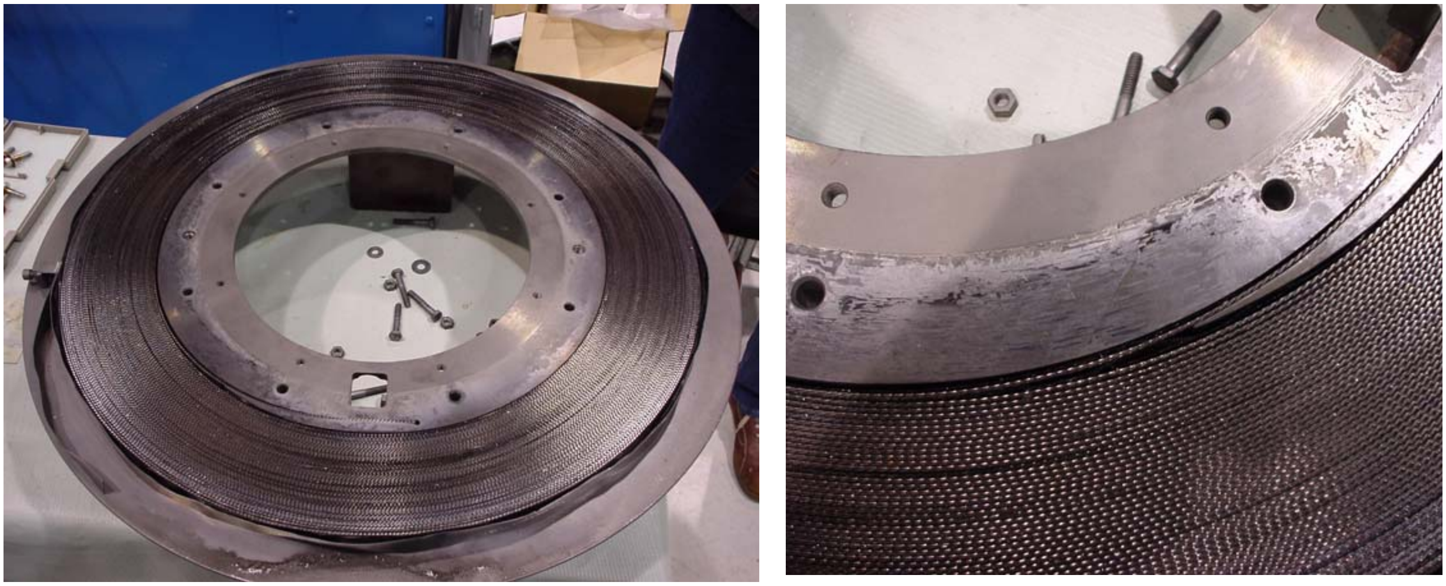


Figure 1: reaction spool with reacted cable. On the right detail of the gap left by the cables removed before heat treatment in order to avoid bumps at the clamp

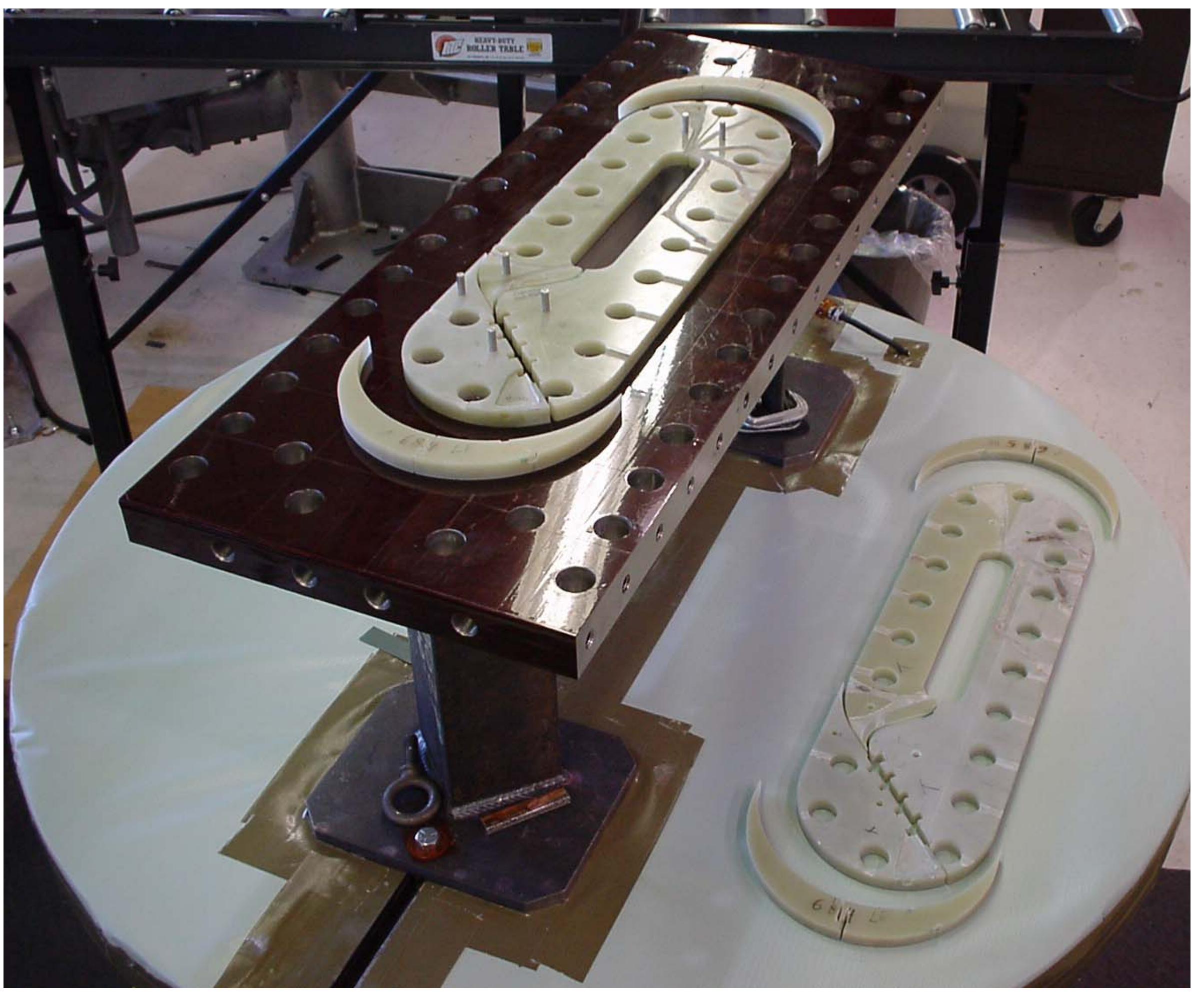


Figure 2: G10 coil parts and bottom plate used as winding table

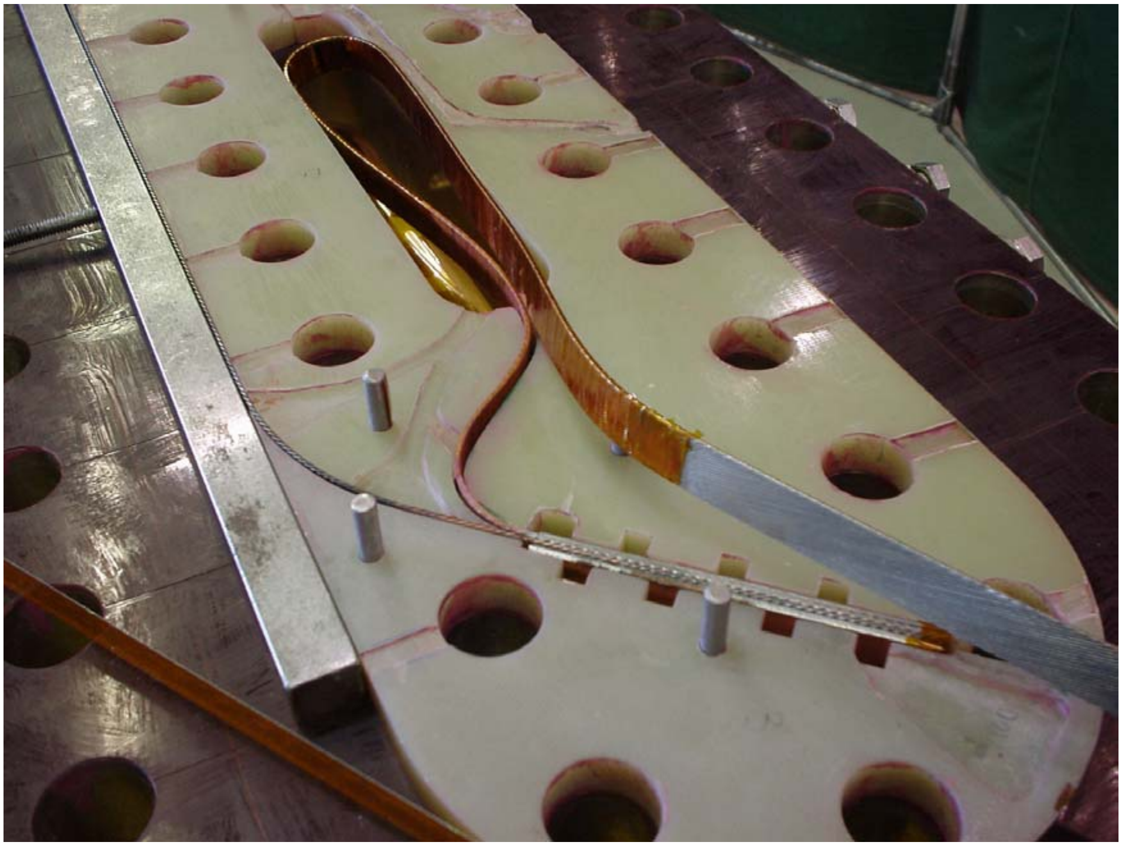


Figure 3: Splice of the Nb_3Sn cable to the NbTi cable

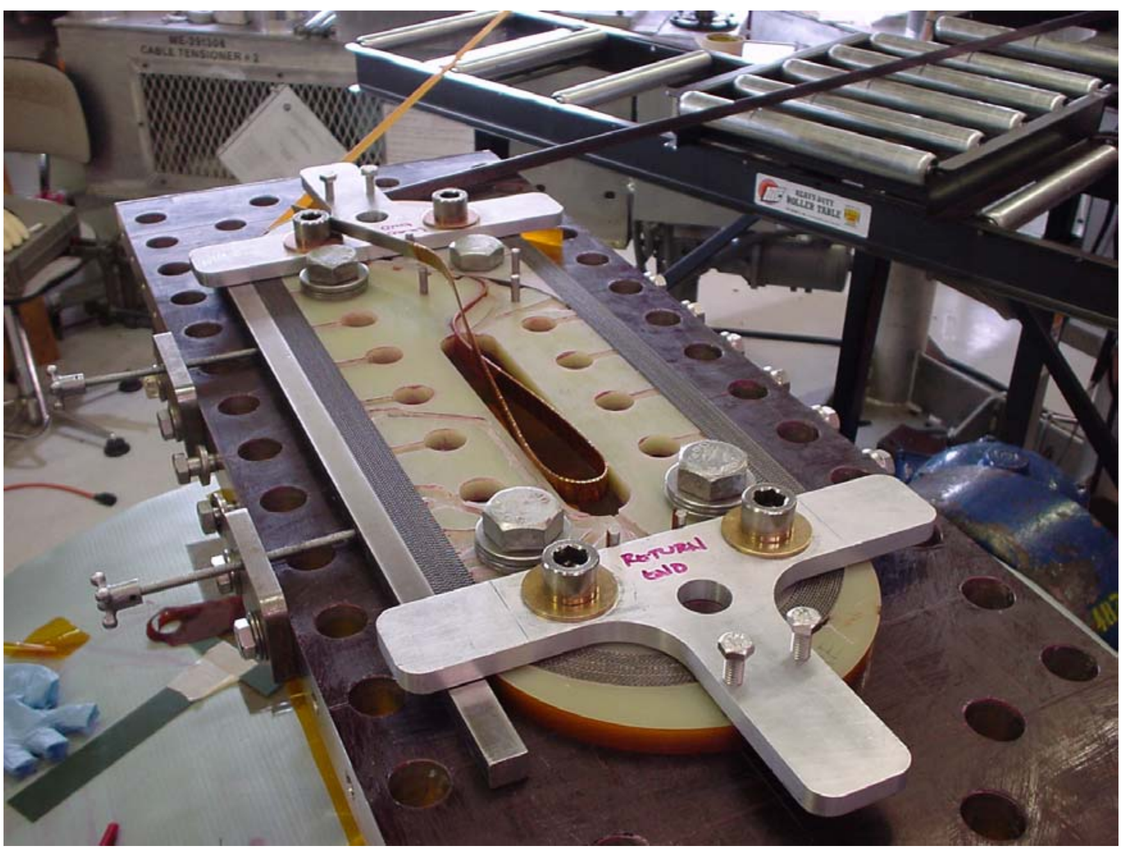


Figure 4: Winding of the bottom coil

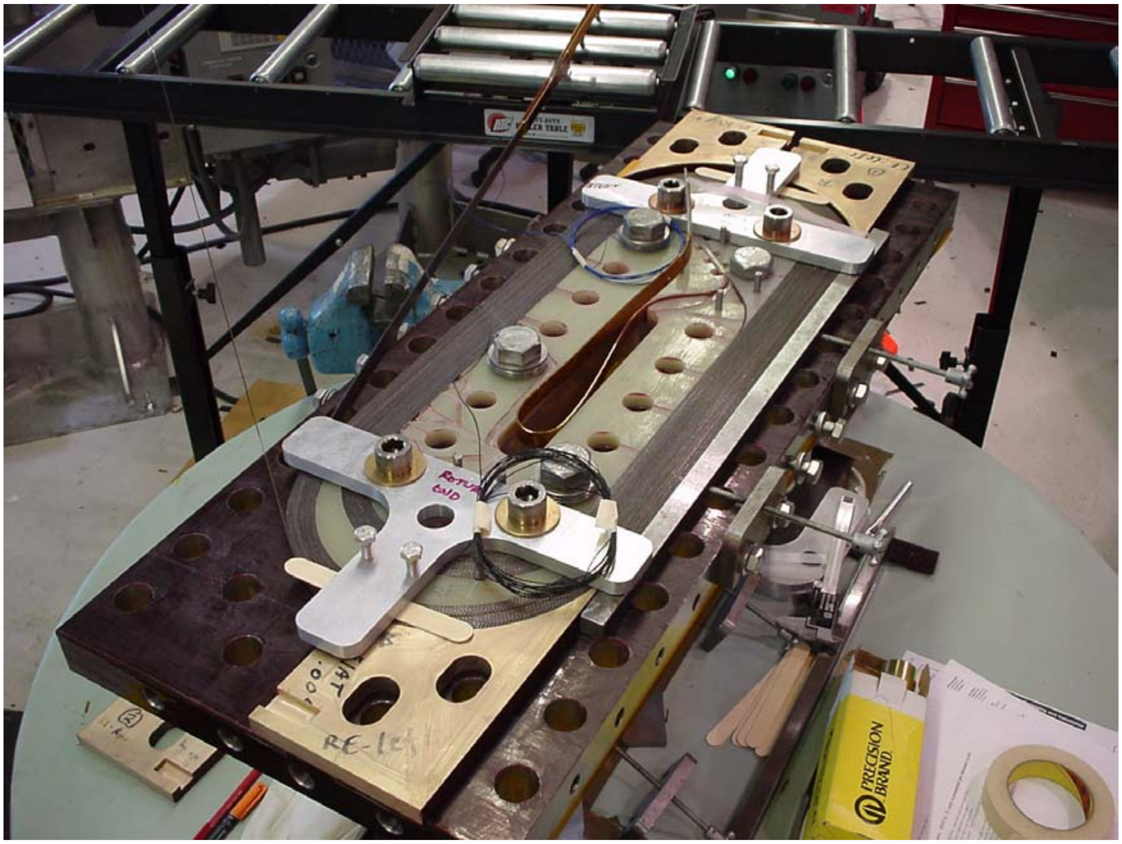


Figure 5: bottom coil after winding and before lead splice

Figure 6: bottom coil – splice to NbTi leads and copper radiators

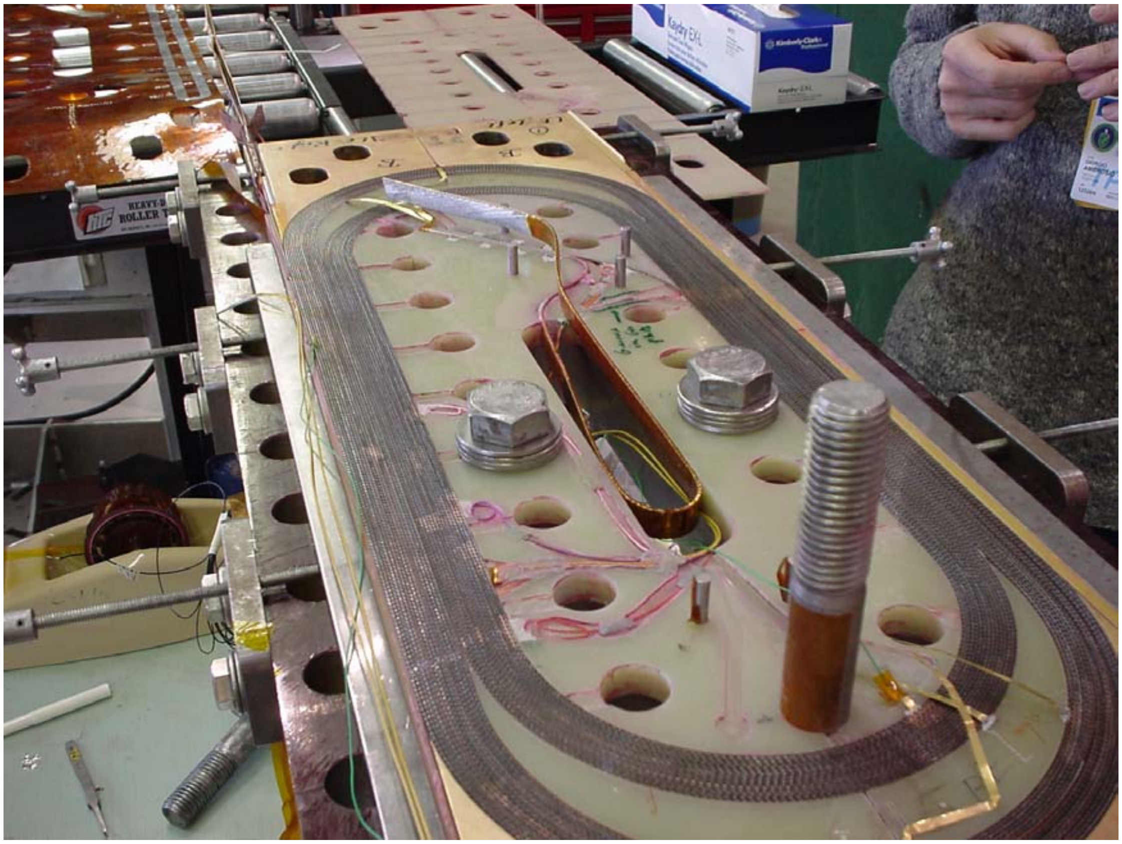


Figure 7: Instrumentation of the bottom coil

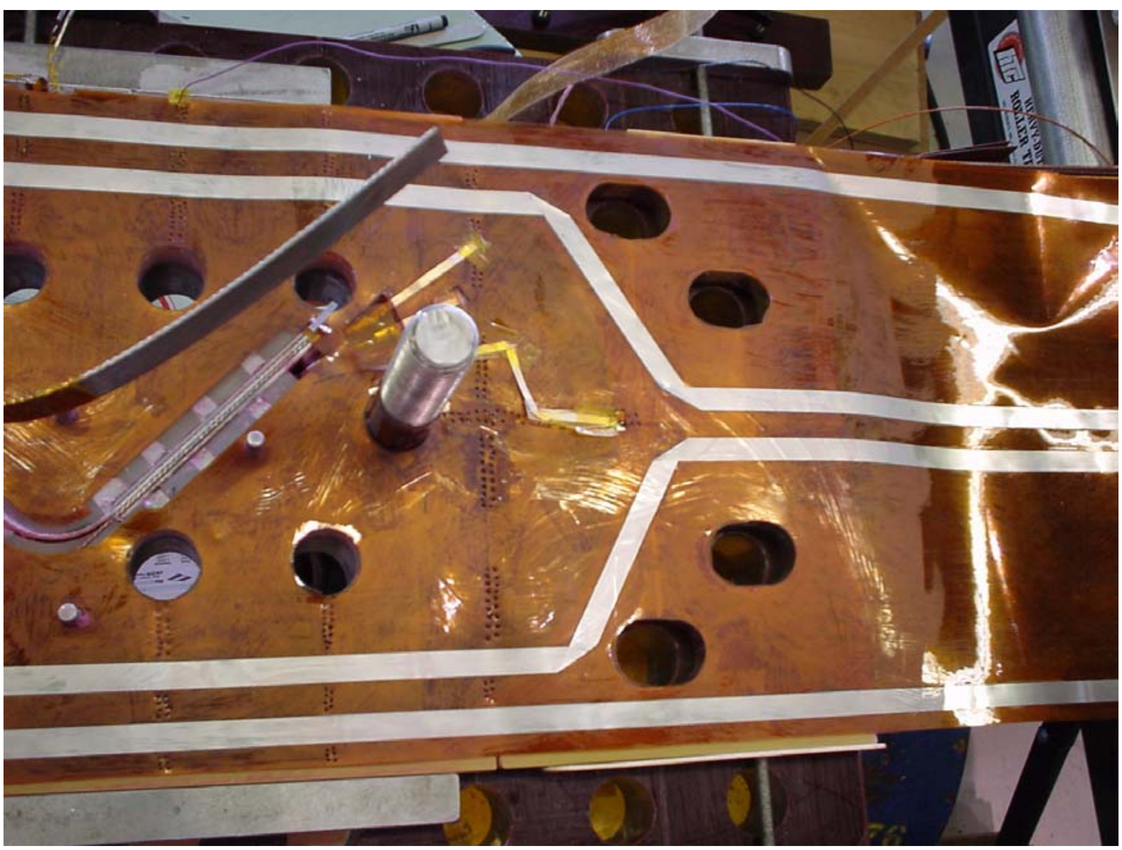


Figure 8: Quench heater installed on the bottom coil

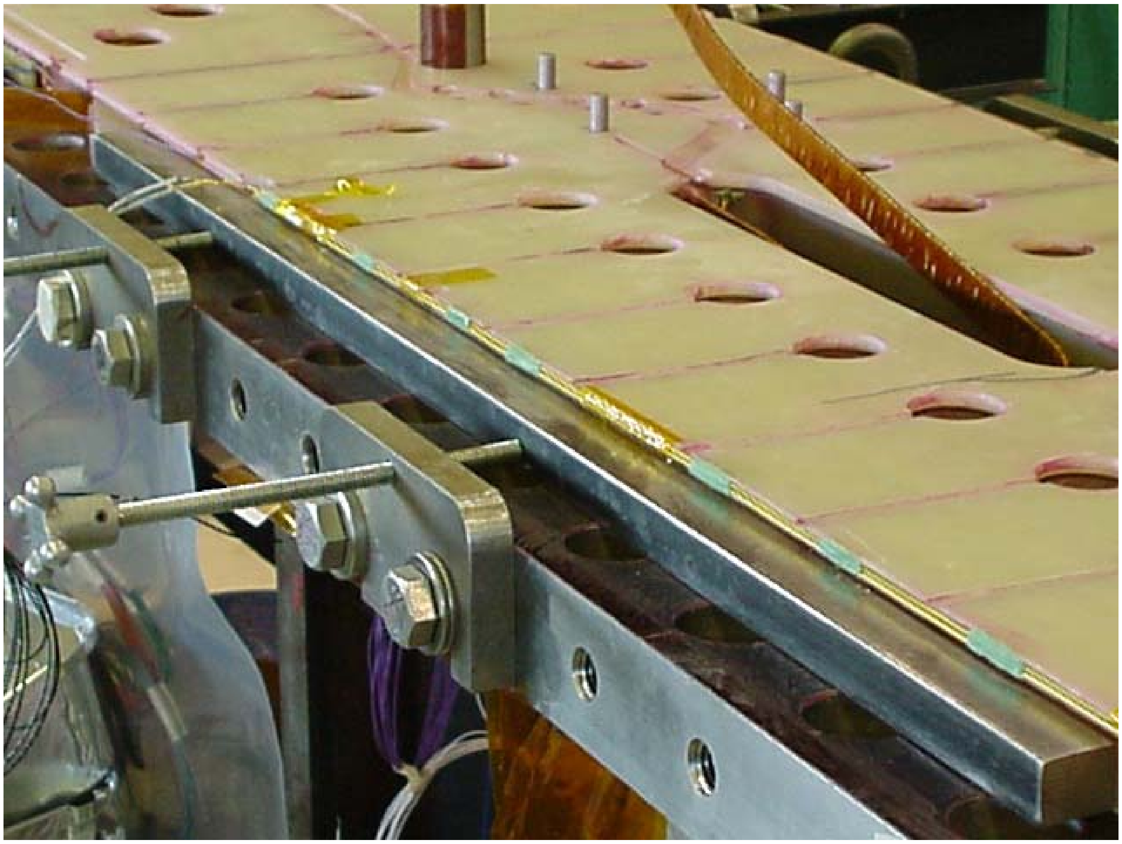


Figure 9: G10 plate installed on the top of the bottom coil. On its edge the wires for the spot heater.

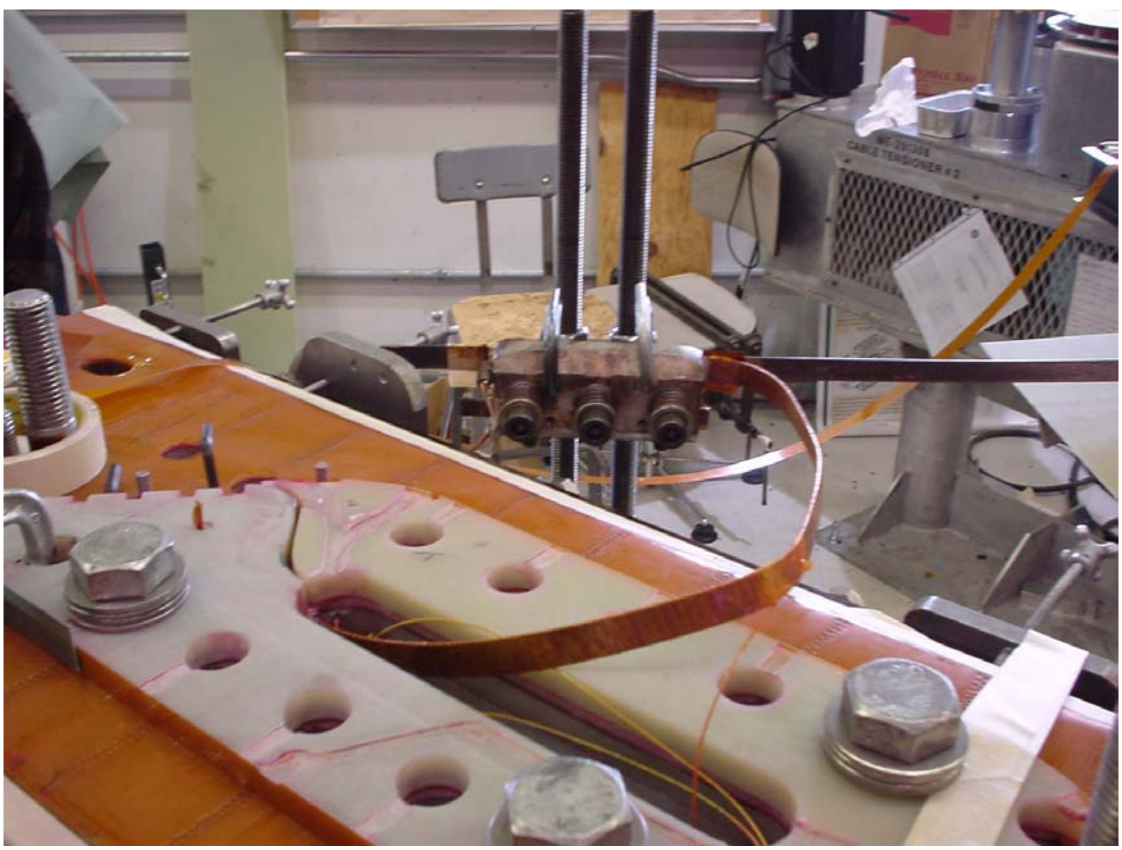


Figure 10: Inner splice of the top coil

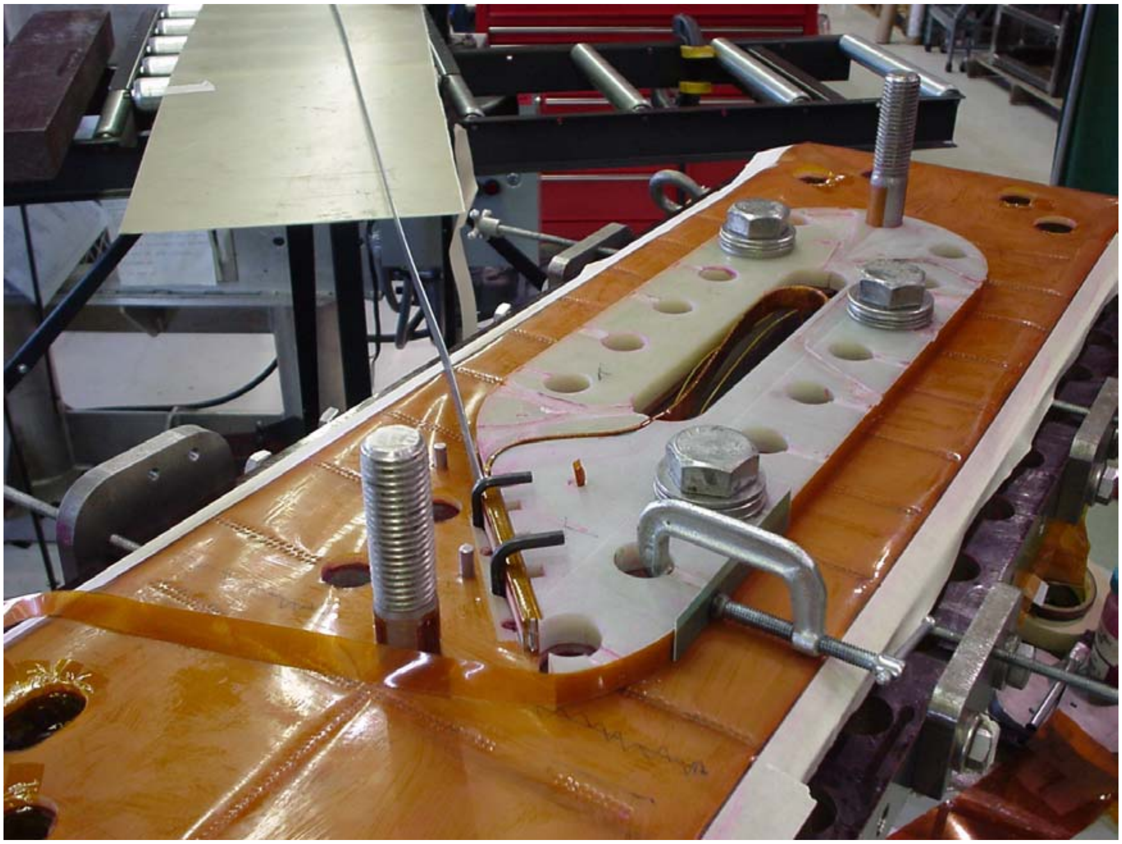


Figure 11: inner splice of the top coil set in place

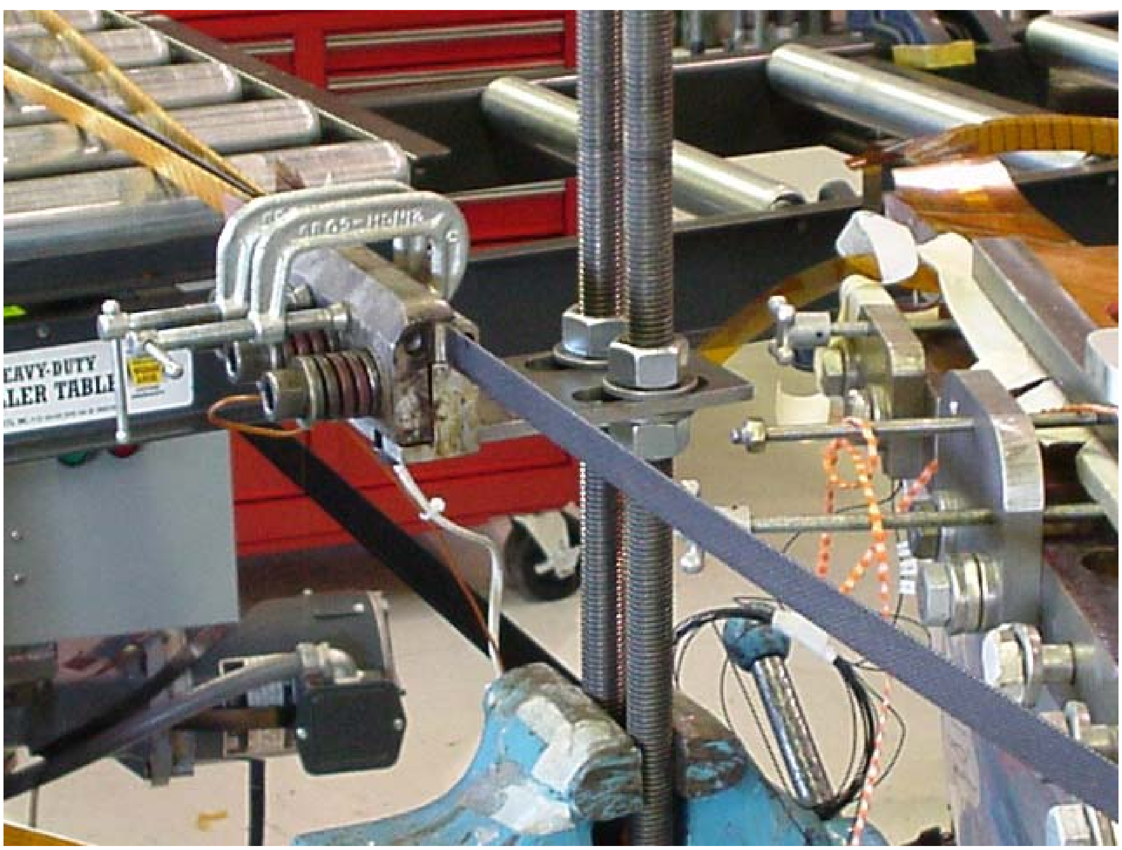


Figure 12: Splice to the leads of the top coil

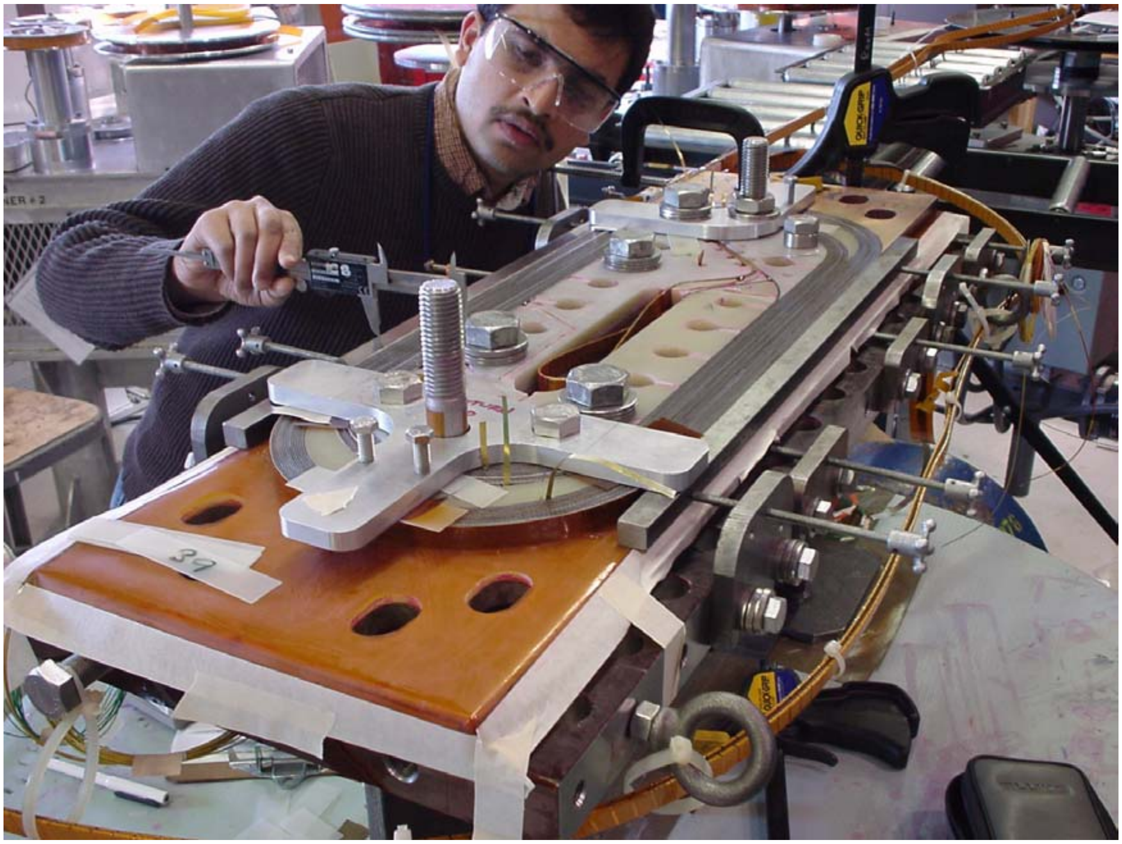


Figure 13: Top coil after winding and splice

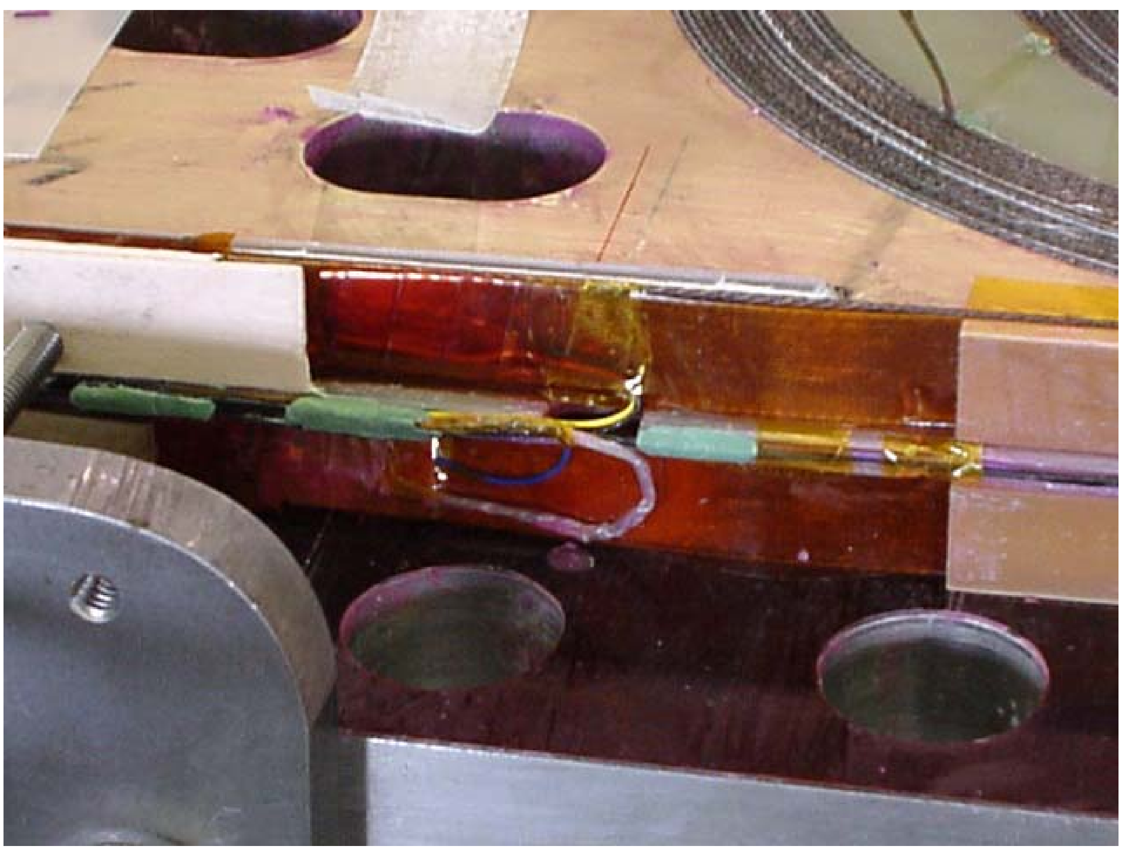


Figure 14: Detail of the lead splices of both coils. The end of the G10 shims is visible on the right.

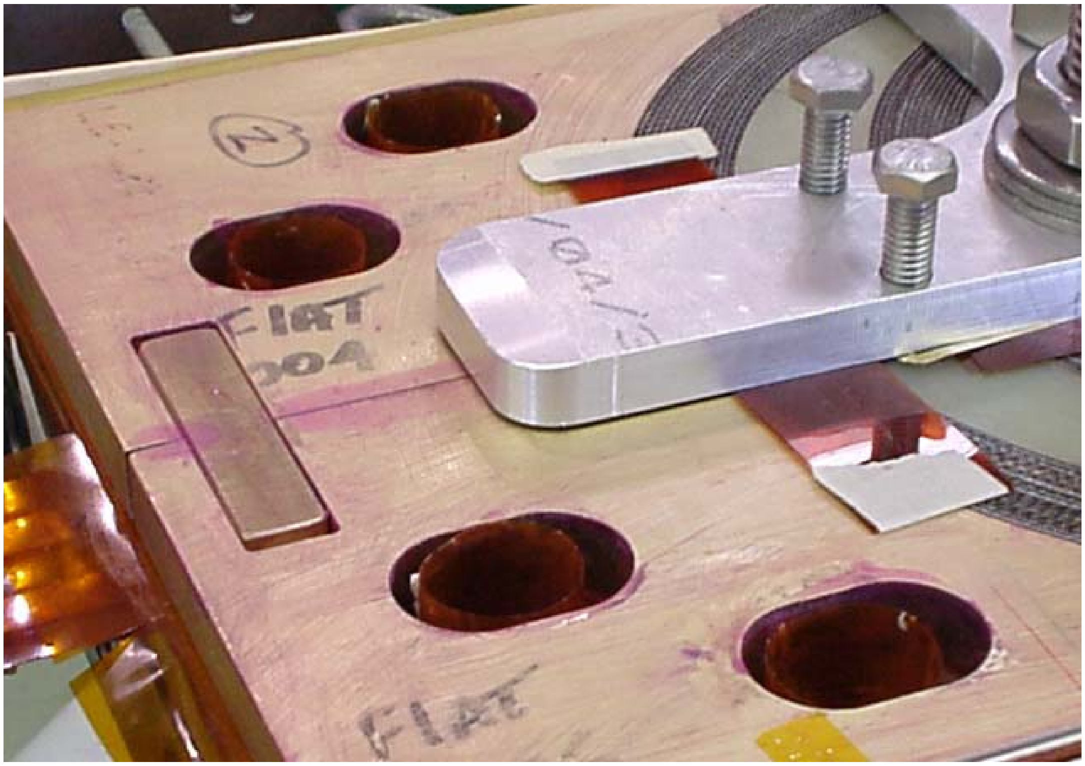


Figure 15: End-shoes in the lead end of the top coil. The locking key is clearly visible

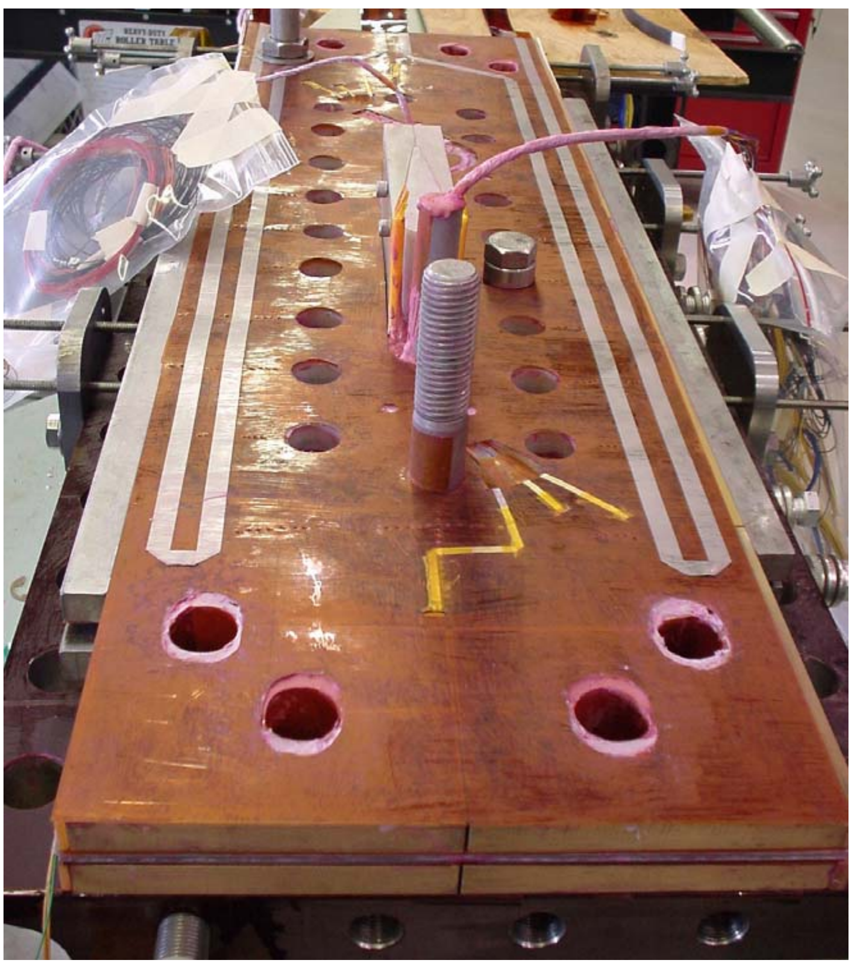


Figure 16: Quench heater on the top coil, note the brass strips used for the voltage taps in the ends

Figure 17: Preparation for impregnation.

Figure 18:Cleaning after impregnation. Lead end plate have been just removed

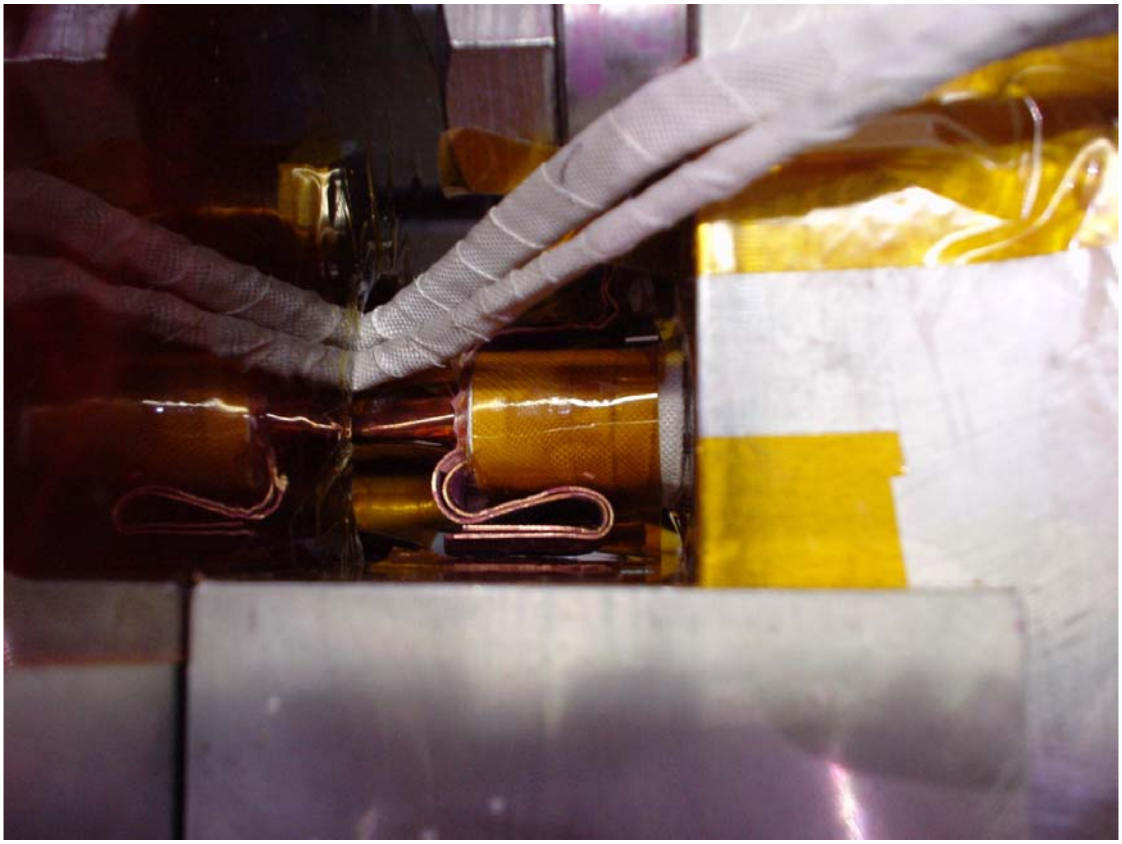


Figure 19: detail of the copper radiators used to cool the lead splice

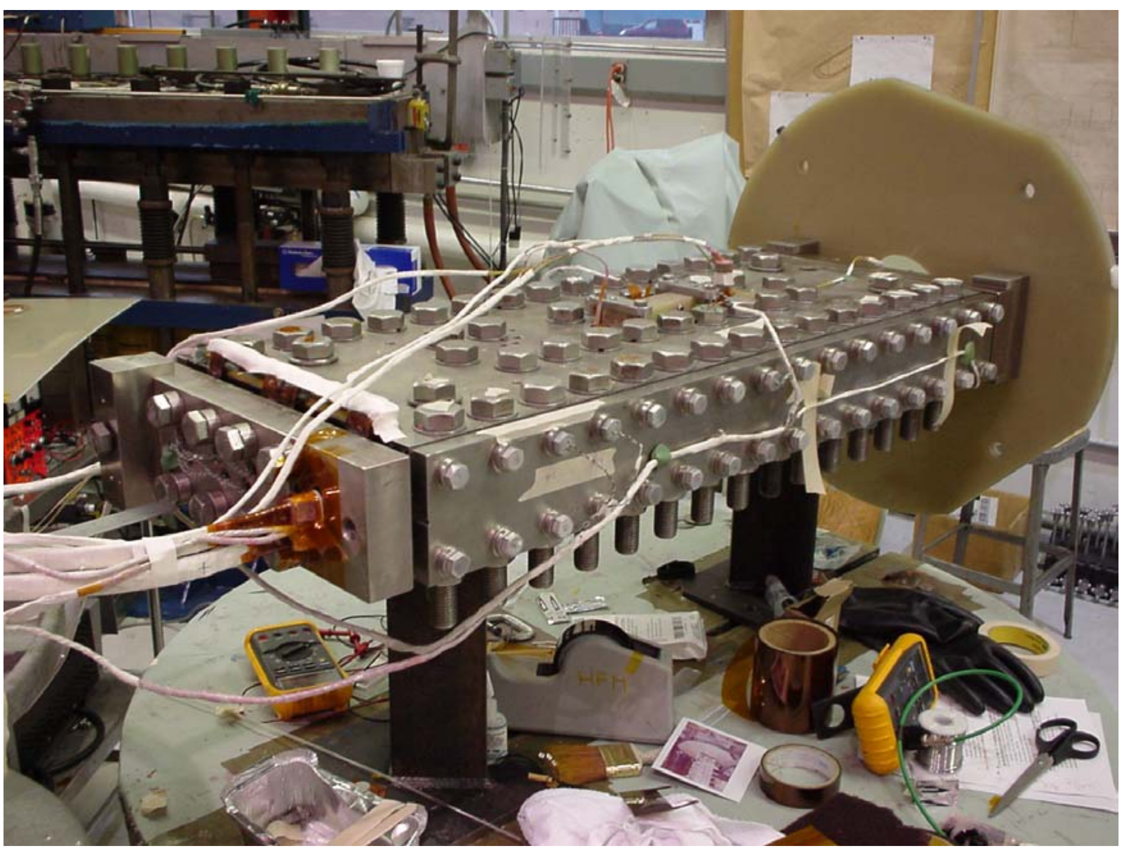


Figure 20: Preparation for delivery to VMTF