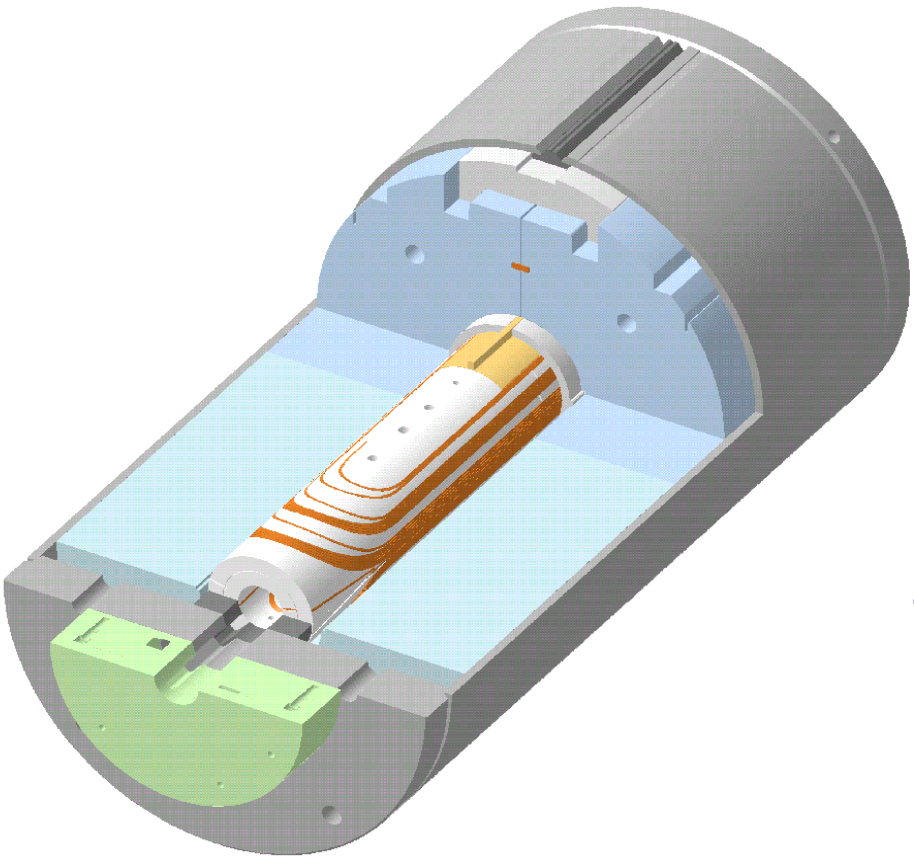
Status of Nb_3Sn Cos(θ) Dipole Model Program

Deepak Chichili

Outline

- Magnet Design and Technology Overview
- Discussion on the first three Dipole Models
  - Observations
  - Post-mortem Analysis
  - Design & Tooling Modifications
- Current Model, HFDA-04
  - Fabrication Status
- Future Plans

Mechanical Support Structure



DESIGN FEATURES:

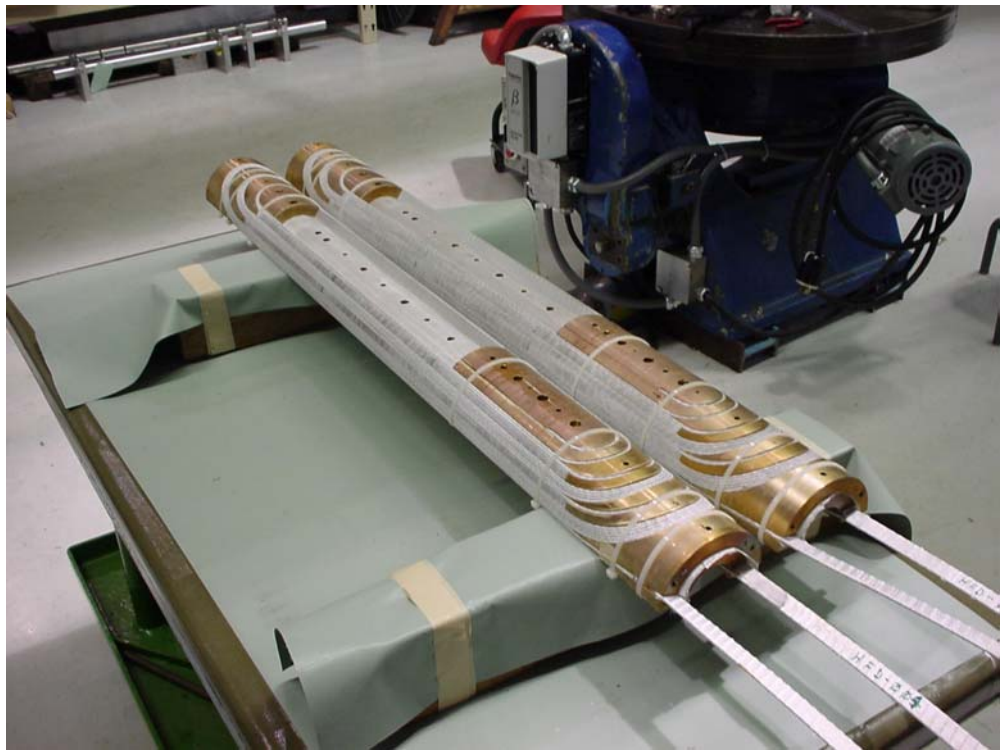
- **Nb_3Sn Conductor with Wind and React approach**
- **Ceramic Insulation with Ceramic Binder**
- **No Interlayer Splice**
- **Spacers instead of Collars**
- **Vertical Gap between the two iron yoke halves remain open**
- **Coil prestress provided by both aluminum clamps and Skin**

Magnet Technology Overview

- **Fabrication Steps**
  - **Cable Insulation**
  - **Coil Winding and Curing**
  - **Coil Reaction**
  - **Splice Joints**
  - **Coil Impregnation**
  - **Yoking and Skinning**

Cured Half Coils

Two half coils ready to be reacted…

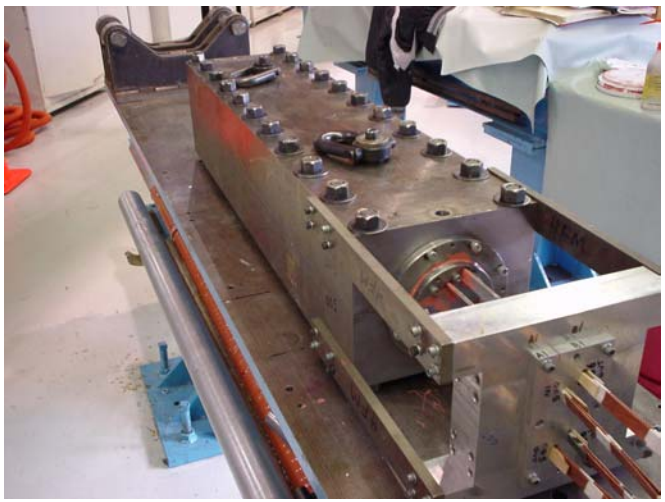


Reacted Coil

- Good bonding between the turns even after reaction

- Easy to handle

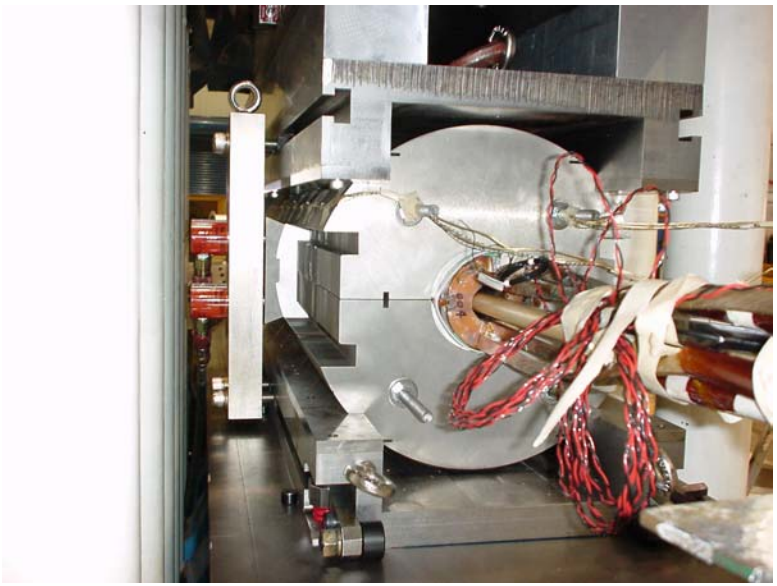
Epoxy Impregnation



Impregnated Coil

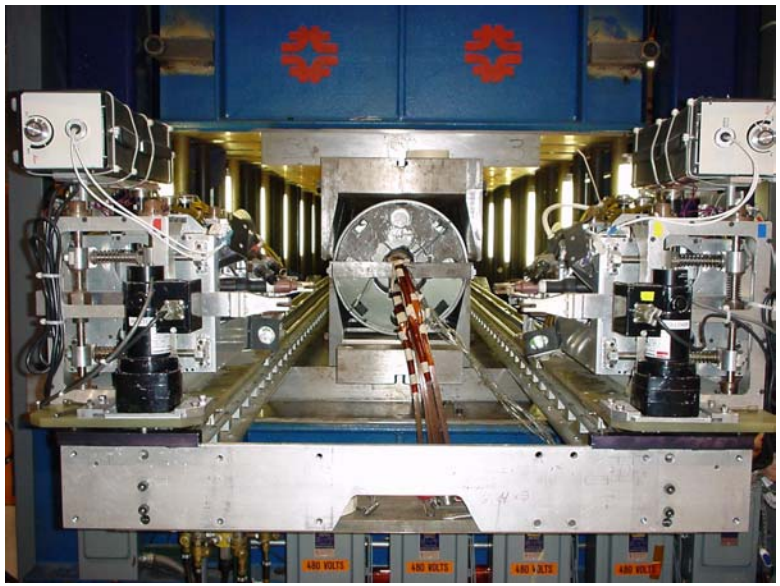
High Field Magnet Program

Yoking

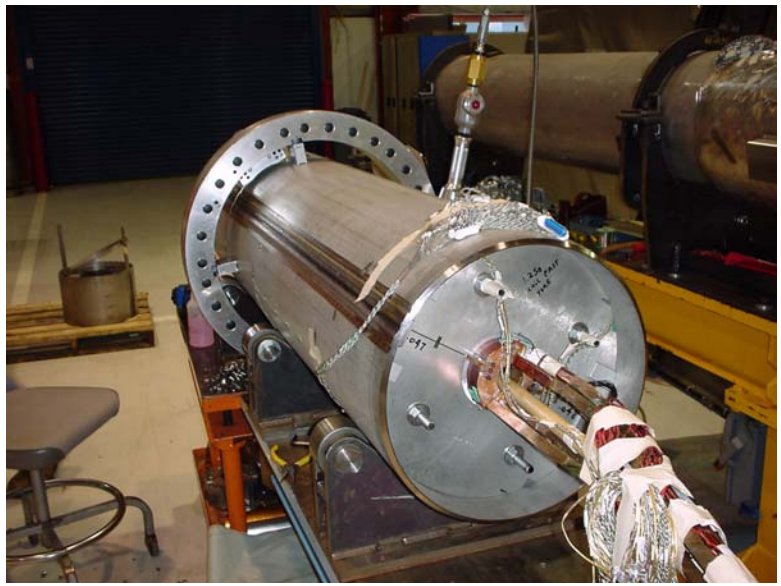


- Aluminum spacers were first installed around the impregnated coil
- The whole assembly is then placed into the bottom yoke packs after which the top yoke halves are installed
- Assembly-press is used to compress the two yoke halves and then to insert aluminum clamps into the slots.

Skinning



Magnet inside the welding press



Magnet after welding skin

HFDA-01

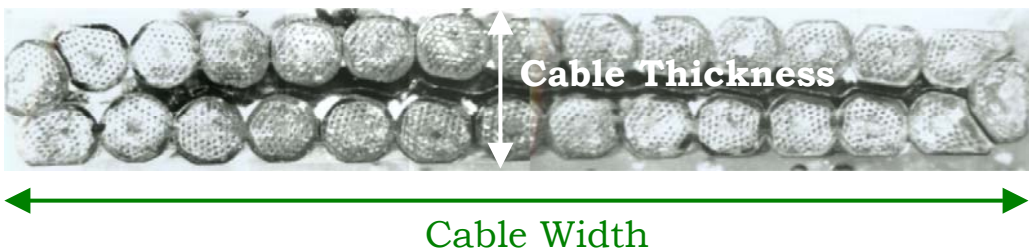
- Magnet fabrication was stopped after coil reaction due to tin-leakage in the conductor
- Possible reasons for this behavior –
  - High compaction of coils during reaction due to the formation of the Nb_3Sn Phase. The formation of this new phase increases the overall size of the coil
  - Removal of low temperature, 200 ^oC step from the reaction cycle
  - The conductor itself was week to handle the cabling process. Later tests on some of the free cable samples also showed tin-leakage
- Cable volume expansion during hear-treatment and effect of heat-treatment cycle were investigated

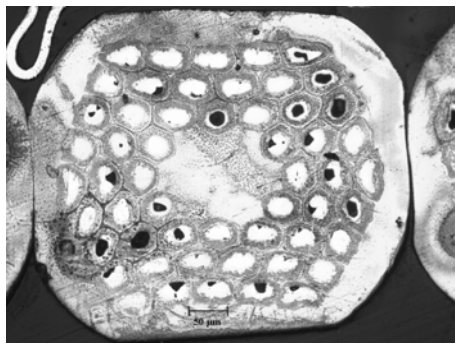
R&D Test Results

❖ Volume expansion of the cable

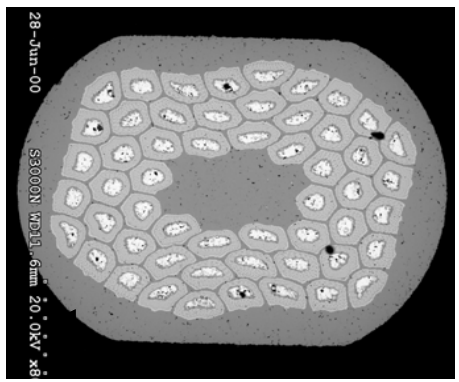
- **Anisotropic volume expansion in the cable compared to isotropic expansion in a virgin strands. Plastic deformation induced during cabling is responsible for the observed behavior**

Manufacturing Technology	Thickness Expansion, μm	Width Expansion, μm
MJR	55	13
PIT	49	12
IT	85	--
ITER	25	4





Strand in a Rutherford cable



Compressed strand

Changes Introduced Based on HFDA-01

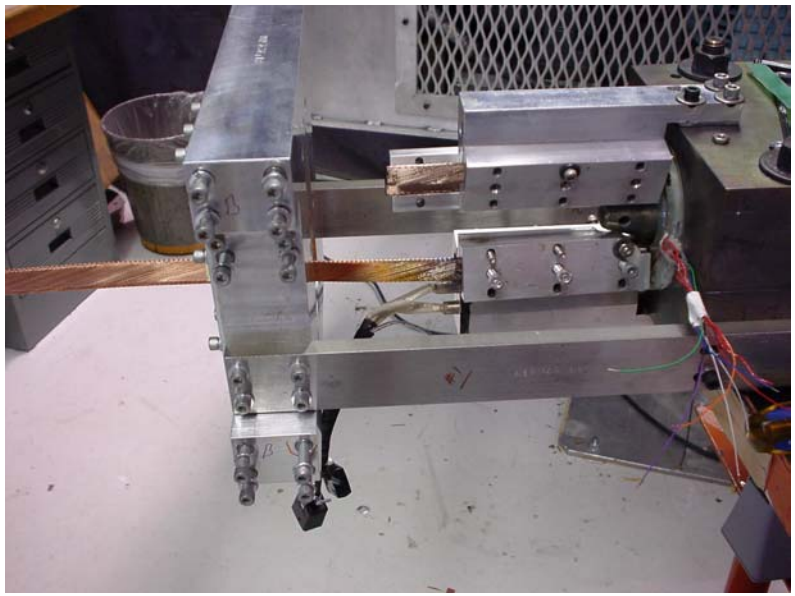
- **The azimuthal coil size after curing was optimized such that the coil is at the nominal size after reaction. This will eliminate the excessive pressure on the conductor during reaction**
  - **The coil azimuthal size before reaction was reduced by about 1.0 mm by decreasing the amount of overlap of the insulation tape from 50% to 40%**

- **The reaction cycle was modified to have a low temperature step in the beginning to allow tin to diffuse in solid phase.**
  - **Several cable samples were reacted using various heat-treatment cycles to study the issue of tin-leakage**

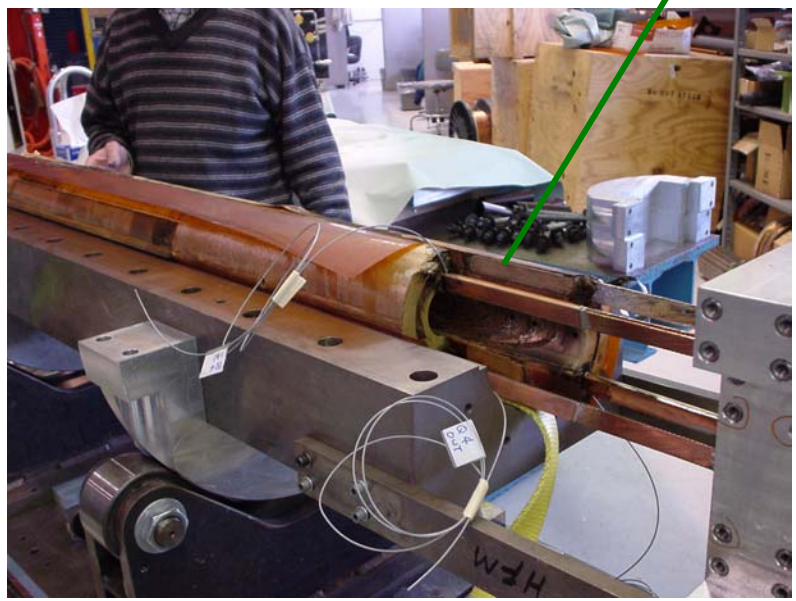
HFDA-02

- The outer layer lead cable was broken during the splicing operation. It was repaired by moving the splice joint into the end-saddle area.

Repaired Splice Joint



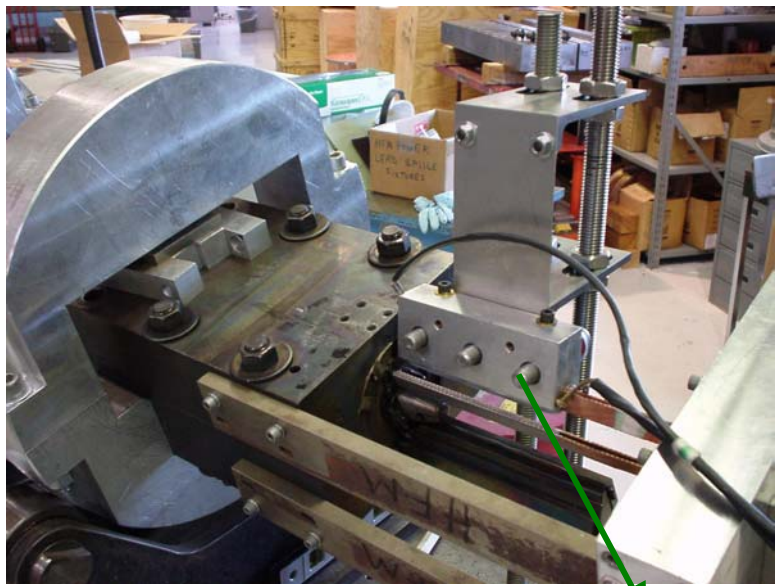
Splice Tooling



Finished splice Joints

Changes Introduced in Splice Tooling

- Each Nb_3Sn lead was spliced individually to avoid damage due to misalignment during assembly
- The tooling was made flexible to account for any motion during the heating process



HFDA-03 Splice Joints

Spring loaded

HFDA – 03

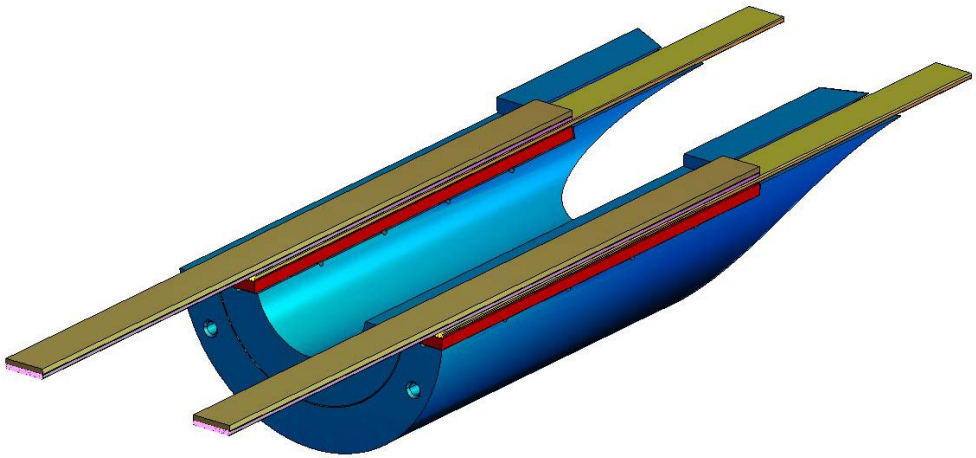
- The fabrication of HFDA – 03 went smoothly without any set-backs. However both HFDA – 02 and HFDA – 03 had very similar quench performance.

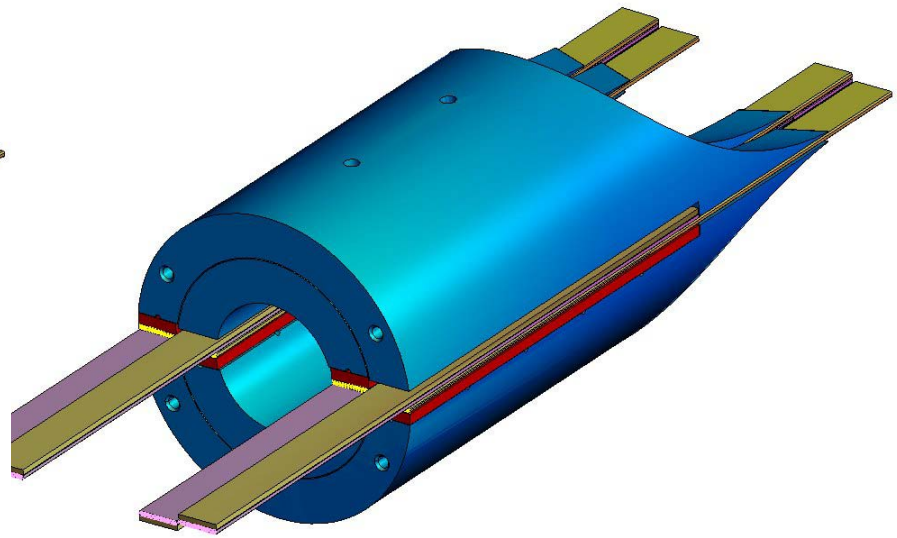
- Based on the voltage tap data, it was concluded that the quench location was close to the splice joint in both the magnets

- This showed us that the tooling and the fabrication changes introduced in HFDA – 03 did not fix the problem.

Changes Introduced Based on HFDA-03

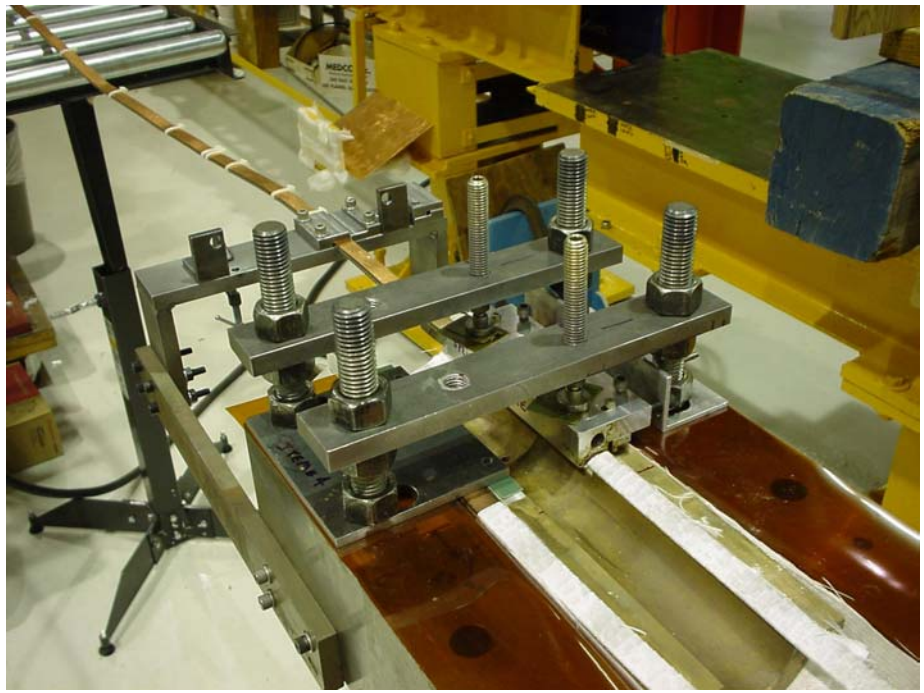
- **Design changes for Splice Joints-**





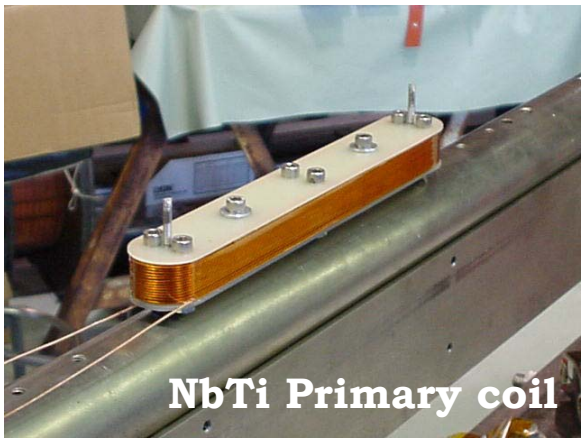
Changes Introduced Based on HFDA-03

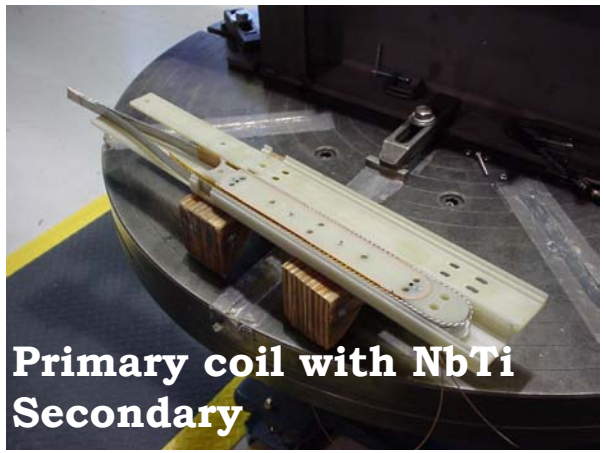
- **Splicing Procedure**
  - **Each half coil will be spliced separately.**

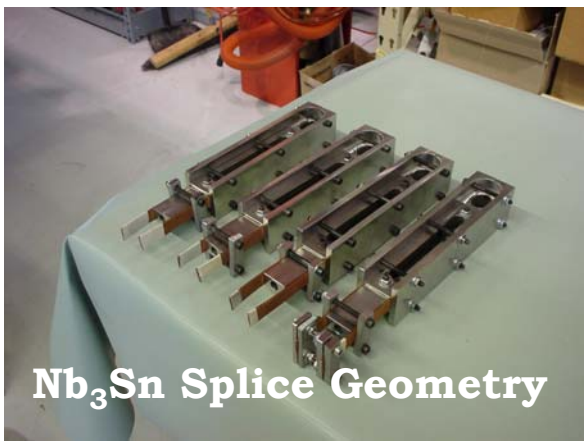


Verification

❖ Splice Testing: Transformer Design & Fabrication


NbTi Primary coil


Primary coil with NbTi Secondary


Nb_3Sn Splice Geometry

Transformer Assembly

Verification

❖ Splice Test Results:

Sample #	Splice Resistance nano-ohms	Current kA	Comments
1	6 (1 + 5)	13	Quenched. The reason is the mechanical strain induced in Nb_3Sn cable due to relaxation of NbTi cable.
2	2.5 (1.5 + 1)	16	Quenched. The cable might have displaced during splicing. Acceptable splice resistance
3	5 (2 + 3)	19	No quench. Splice Tooling was modified. However, low pressure was applied during splicing operation which resulted in high splice resistance.
4	2.5	22.5	No quench. Good quality of splices with acceptable splice resistance. Pressure during splicing operation was increased.

Verification

❖ Splice Test Results:

Effect of Pressure

Pressure MPa	Splice Thickness Deviation mm	Splice Resistance nano-ohms	Current* kA
2	0.625	2.2	16.5
5	0.500	1.7	18.6
9	0.375	1.4	20.5
23	0.250	1.2	21.5
38	N/A	1.1	21.8

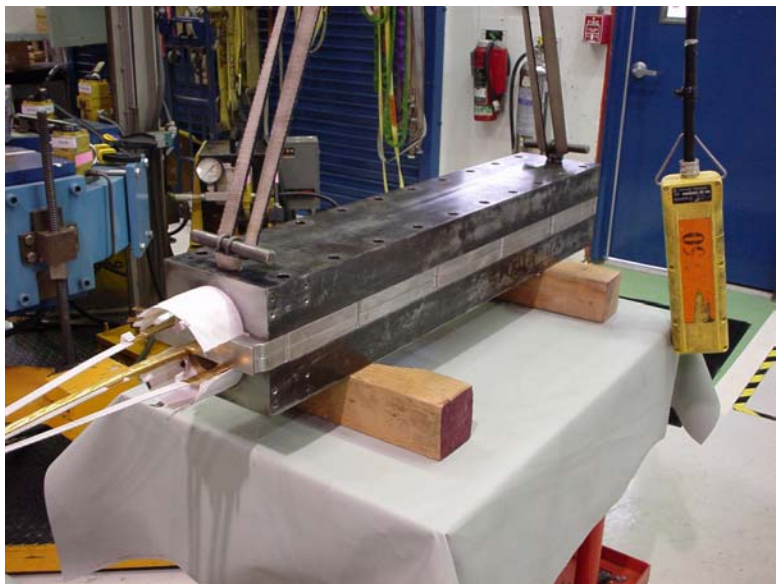
***No quenches were observed**

Effect of conductor displacement

Splice Tip Displacement, mm	Displacement @ 7 mm from Clamp, mm	Current* kA	Splice Resistance nano-ohms
17 (out of cable plane)	0.250	19.5	1.6
4 (in the cable plane)	0.200	17.6	2.1

Current Magnet: HFDA-04

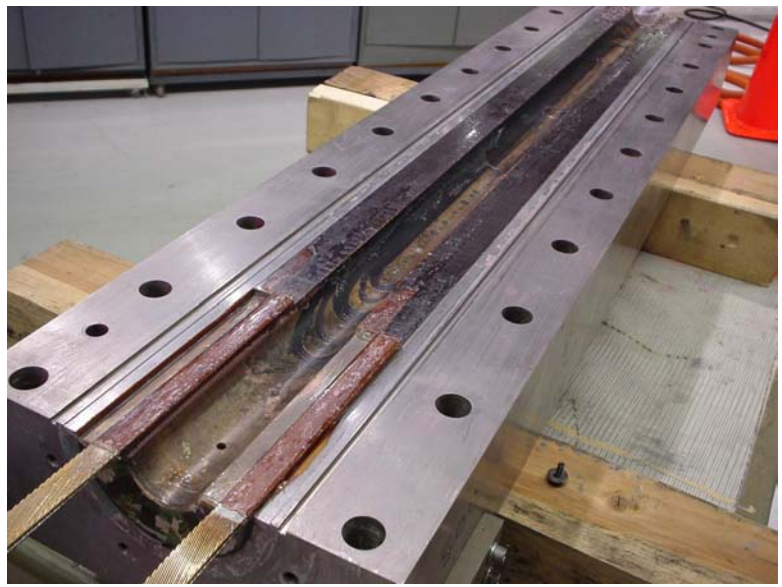
- **Reaction Fixture**
  - **In order to better support the lead cables and to have the option of splicing each half-coil separately, the reaction fixture was modified**



HFDA-04

- **First Half Coil: Splice Joints and Impregnation**

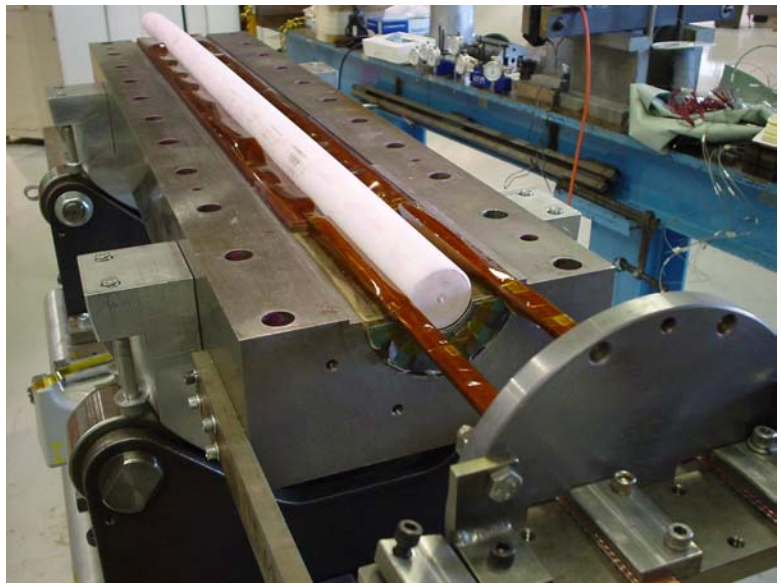
Splice Joints before Impregnation



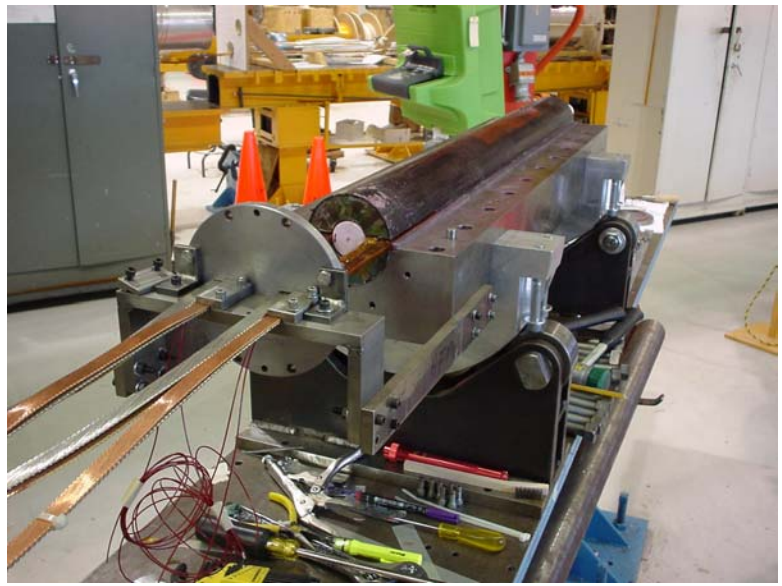
Half Coil 07 after Impregnation

HFDA-04

❖ Second Half Coil: Splicing and Impregnation



Splice Joints before Impregnation



Second half coil was impregnated along with the first half coil which has already been impregnated once.

High Field Magnet Program

Plan for the rest of the Fiscal Year

- **Complete the Fabrication of HFDA – 04 by the middle of May**
- **Complete HFDA – 05 Fabrication by the end of this fiscal year**
- **The start date of HFDA-05 will depend on the results of HFDA – 04**
- **Start the Mechanical Model of 2-in-1 warm iron yoke design**

Summary / Current Status

- Design of Splice Joints have been changed to better support the Nb_3Sn conductor
- A transformer has been designed, fabricated and used to test the splice joints in the same configuration as will be used in the current magnet
- HFDA-04 is under production. The coils have been impregnated and ready to be yoked
- Expected to finish HFDA-04 by the middle of May