Accelerator Magnet Fabrication as Related to Strand and Cable Properties

Stephen A. Gourlay

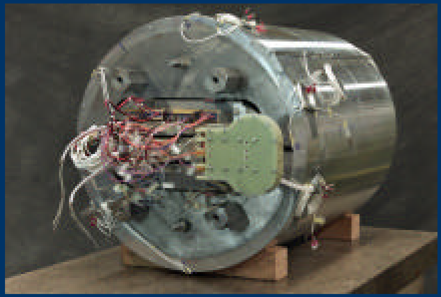
Lawrence Berkeley National Laboratory

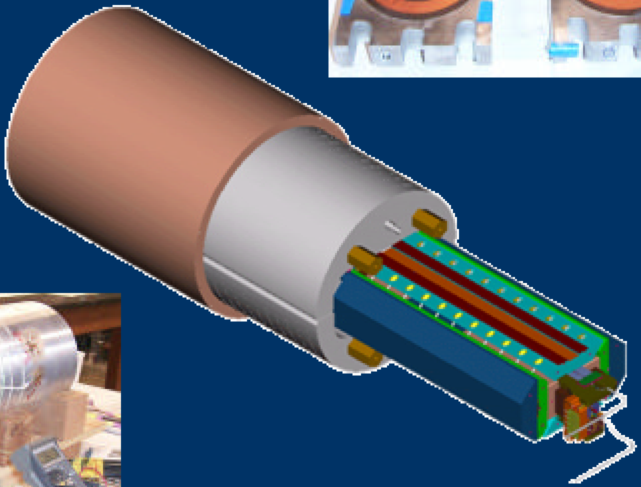
WAMS, Archamps

March 24, 2004

Outline

- Nb_3Sn for Magnet Builders
  - – Potential
  - – Challenges
- Implications for Design and Fabrication
  - – Some Primary Examples using HD-1
    - Wind and React
      - – Cables and Winding
      - – Reaction
    - Design and Analysis
  - – Some words on R&W vs W&R





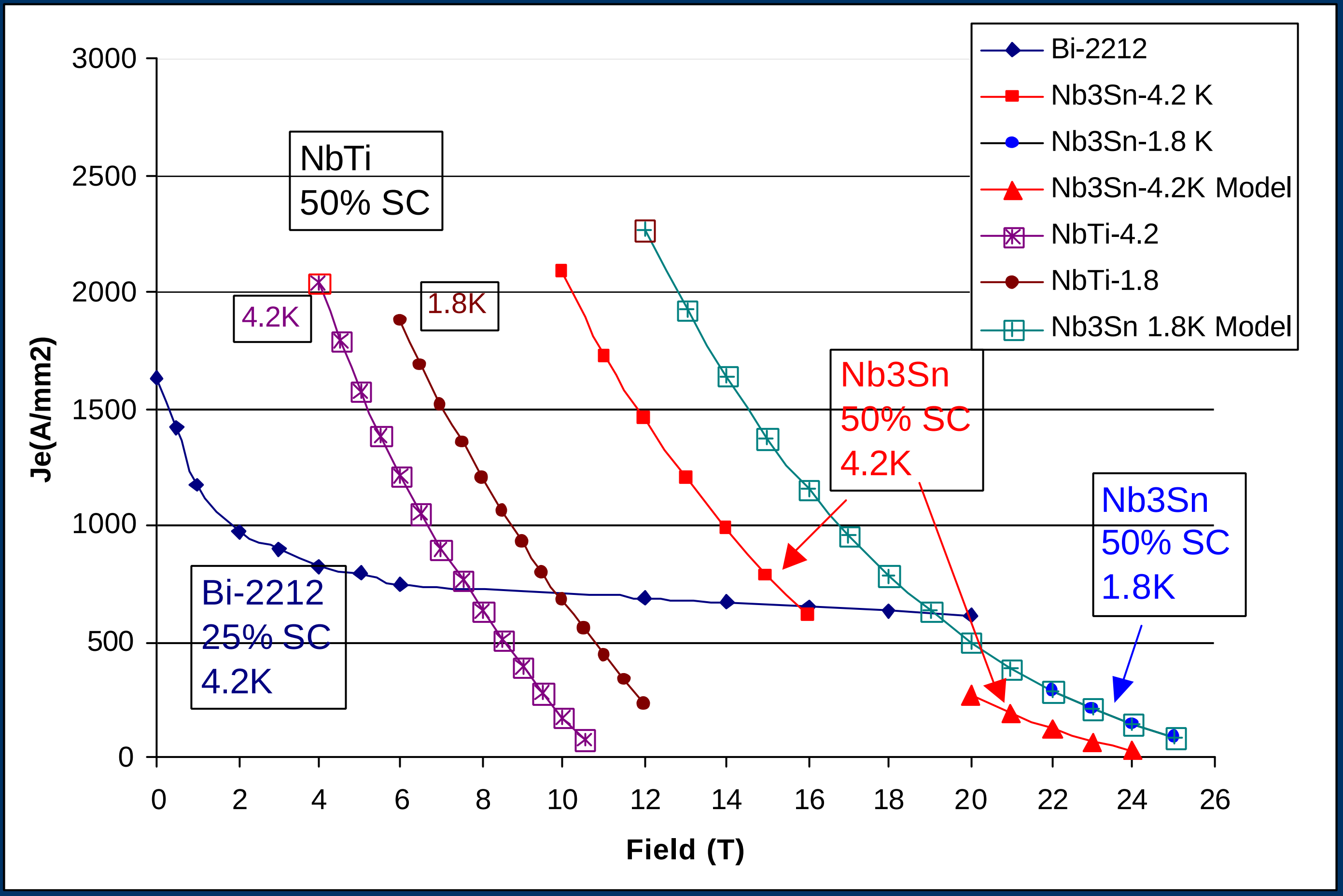

Process Derived from Conductor and Cable Properties

Conductor/
Cable

Design and
Analysis

Fabrication
Techniques

Conductor Performance Comparison

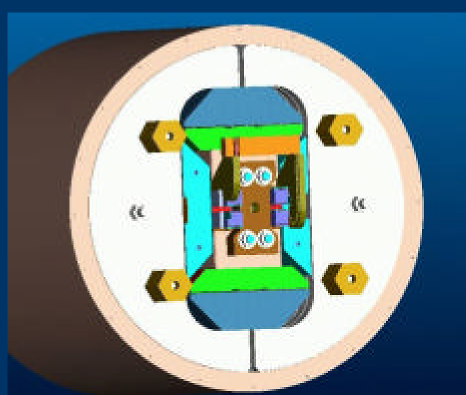


S. Gourlay, LBNL

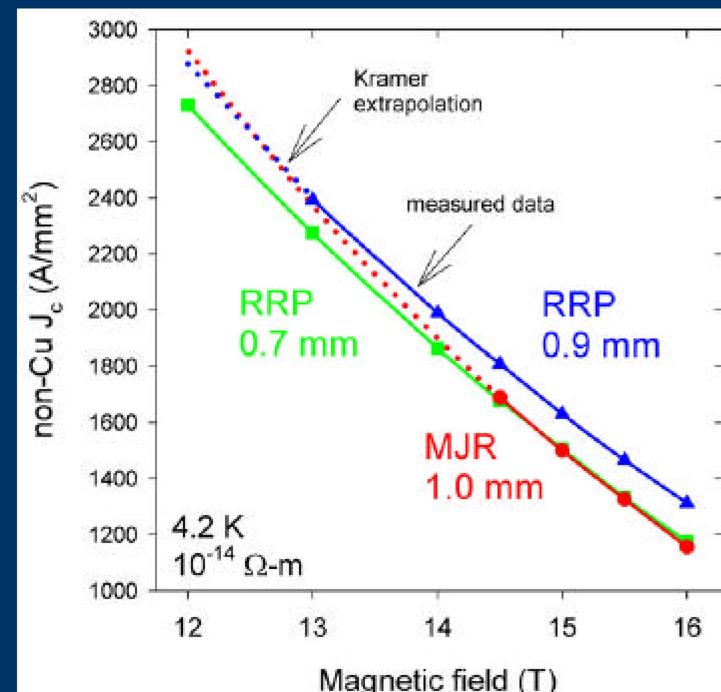
World record J_c values for Nb_3Sn

Oxford Superconducting Technology

Exceeds 3,000 A/mm^2 at 12 Tesla



LBNL
HD-1 16 Tesla



The Potential . . .

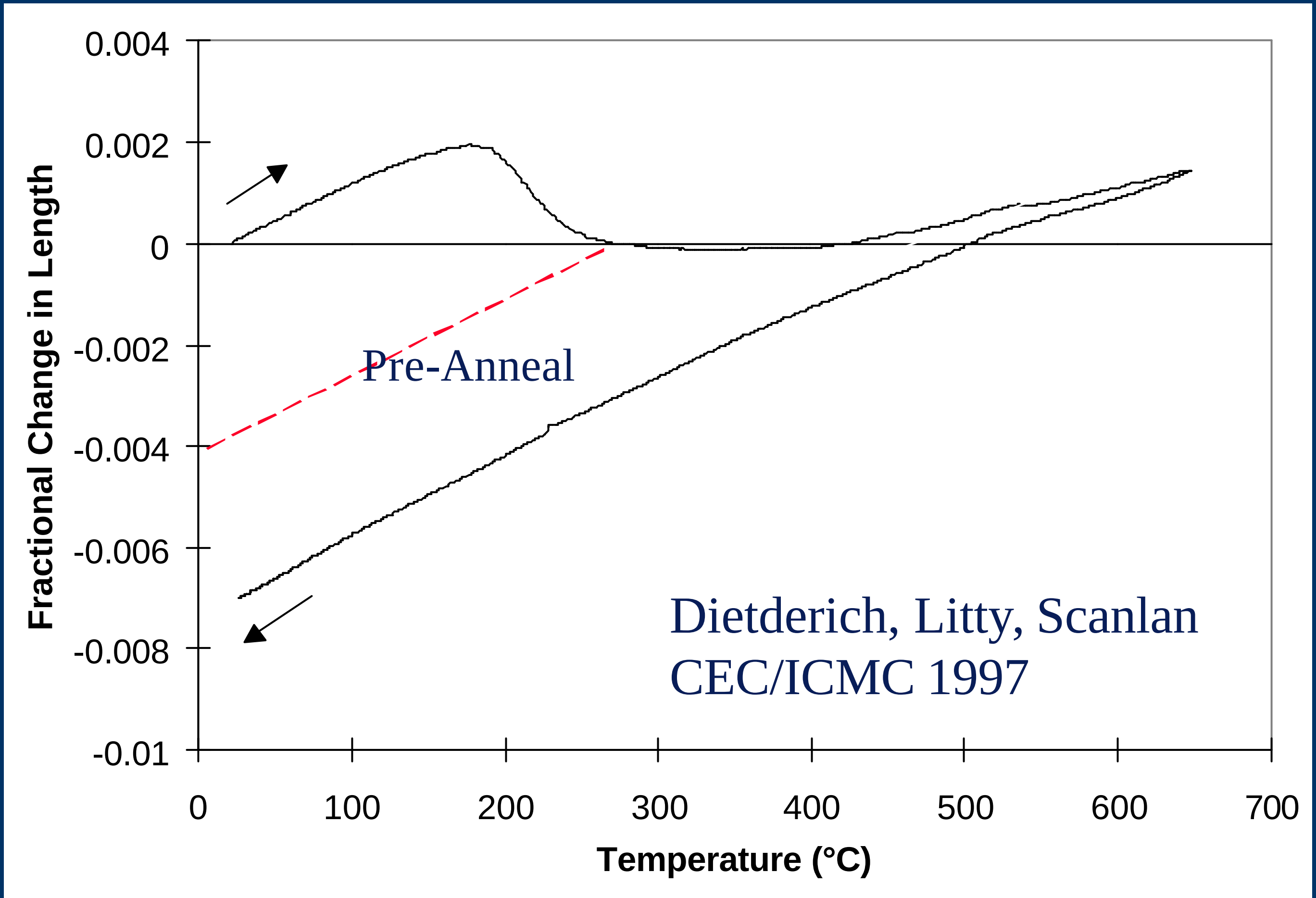
- Nb_3Sn has some excellent properties for magnets
  - High current density at high field
  - Much higher thermal margin than NbTi
- This potential has been demonstrated up to 16 T (so far)
  - Major mechanical shortcomings have been overcome
    - What are ultimate limits?

The Challenges . . .

- Higher sensitivity to cabling degradation
  - Effects are more detrimental to magnet performance
  - Don't know the limits on keystone angle yet
- Brittle and strain sensitive
  - Large temperature range (1000 K – 4 K)
  - Issue for long magnets?
- Field quality
  - Insulation thickness
  - Coil size control/uniformity
  - Magnetization

Still need to study length-related issues

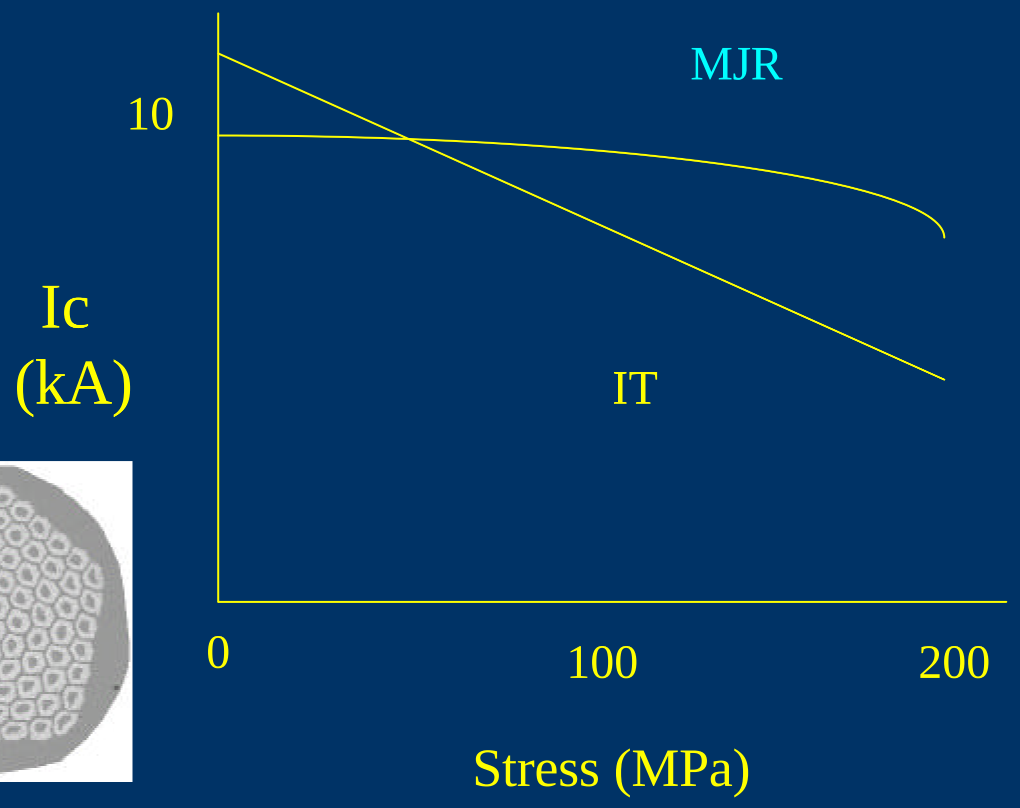
Fractional Length Change in Nb_3Sn

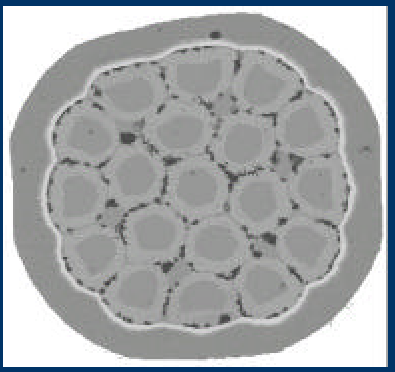


The Stress/Strain Issue

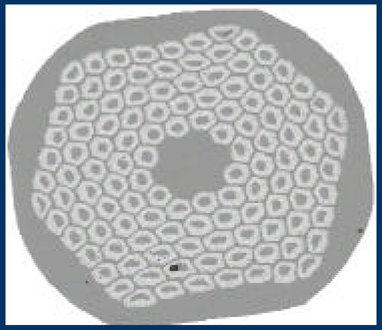
- Nb_3Sn is known to be strain sensitive
  - Depends on field (consider this in design choices)
- What we can say
  - Compressive stress up to 150 MPa is OK (HD-1)
    - Avoid non-uniform compression
    - Avoid tension
  - Measured cable samples show variations depending on sub-structure
    - Reversible degradation up to 200 MPa

More work needs to be done to understand limits for magnets





Internal Tin



MJR

D. Dietderich
ASC 98

Design, Analysis and Fabrication

- In order to use conductor at it's full potential we need . . .
- Designs that mitigate constraints and maximize performance
- Analysis and fabrication techniques to implement the designs

Fabrication Methods

- Nb_3Sn requires . . .
  - approximately 100 hour heat treatment at 650 ^{0}C
  - epoxy impregnation to support brittle cable and provide insulation
  - limiting stress to < 150 MPa (a little higher may be OK)

Two Approaches

Wind and React

Cable
Wind coil
React

→

Impregnation
Assembly

←

React and Wind

Cable
React
Wind coil

Wind and React

HD-1 as an example

Cable Considerations

Large cable with small bend radius

- increase winding tension
- need stable cable
- higher compaction
- greater possibility of degradation

Degradation vs
Mechanical Stability

Nb_3Sn is more susceptible to degradation

and

consequences are more severe

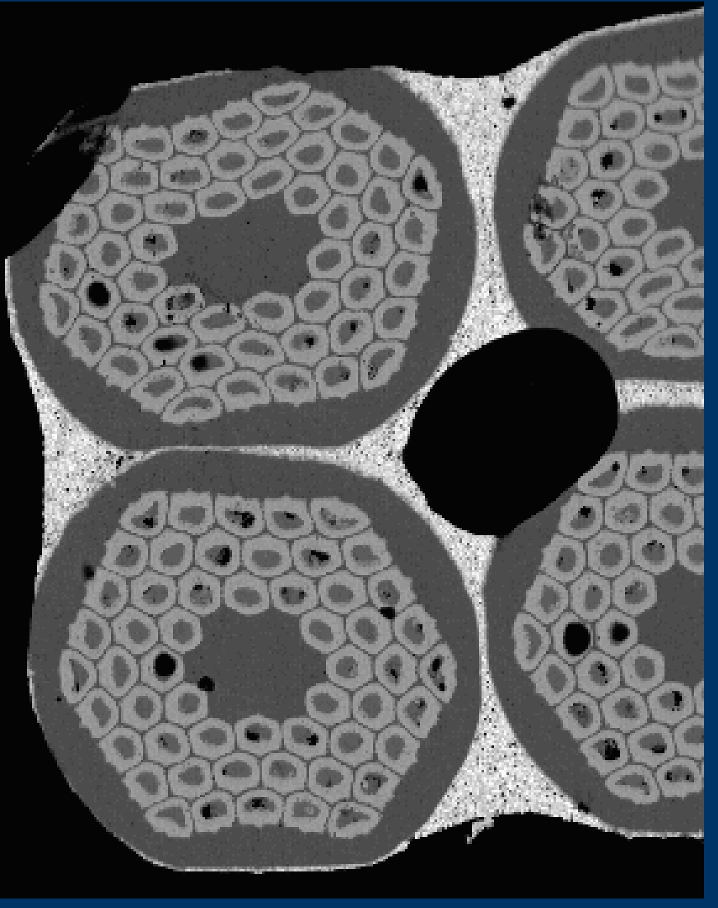
Filament coalescing

RRR

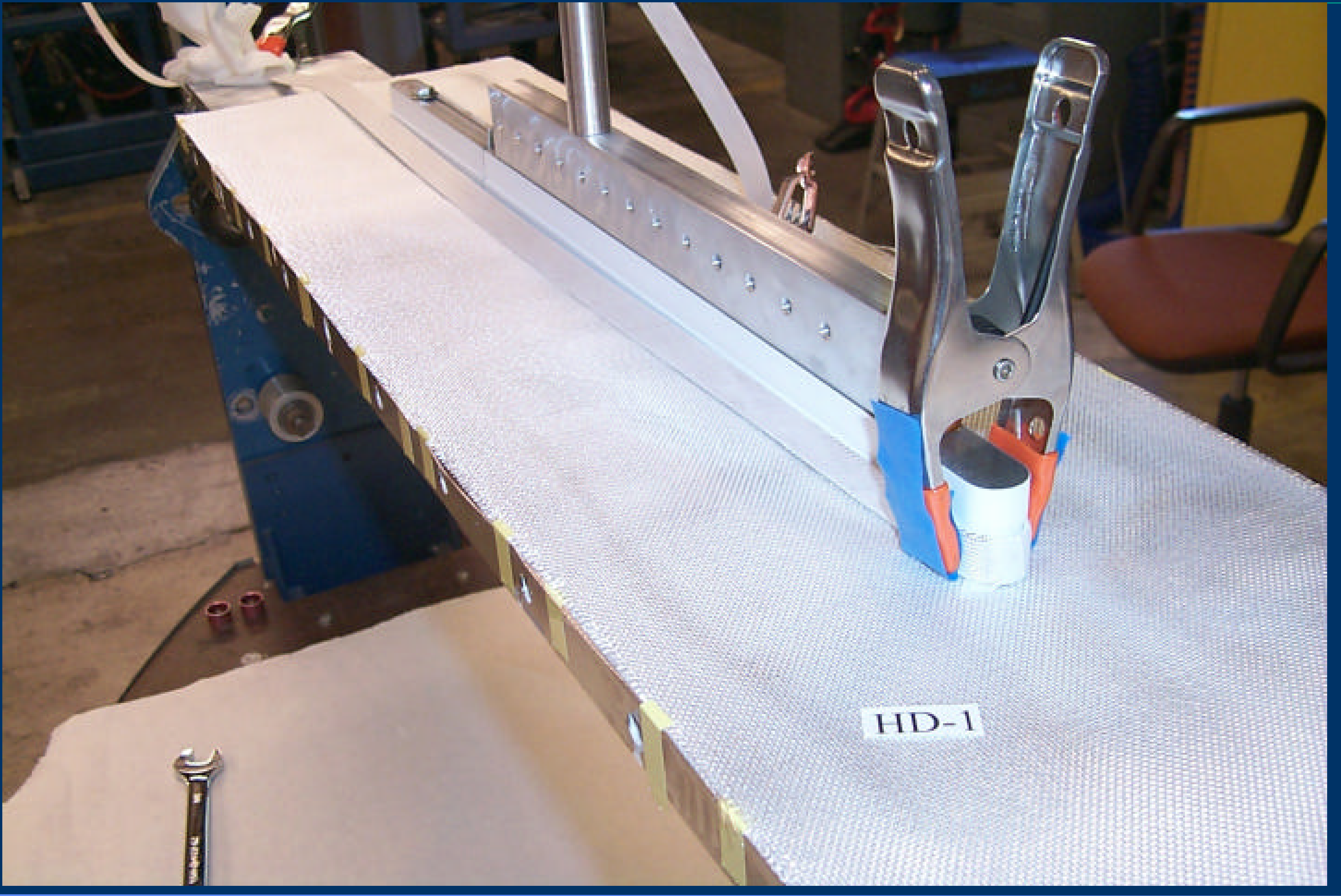
Instability?

HD-1 Cable and Coil

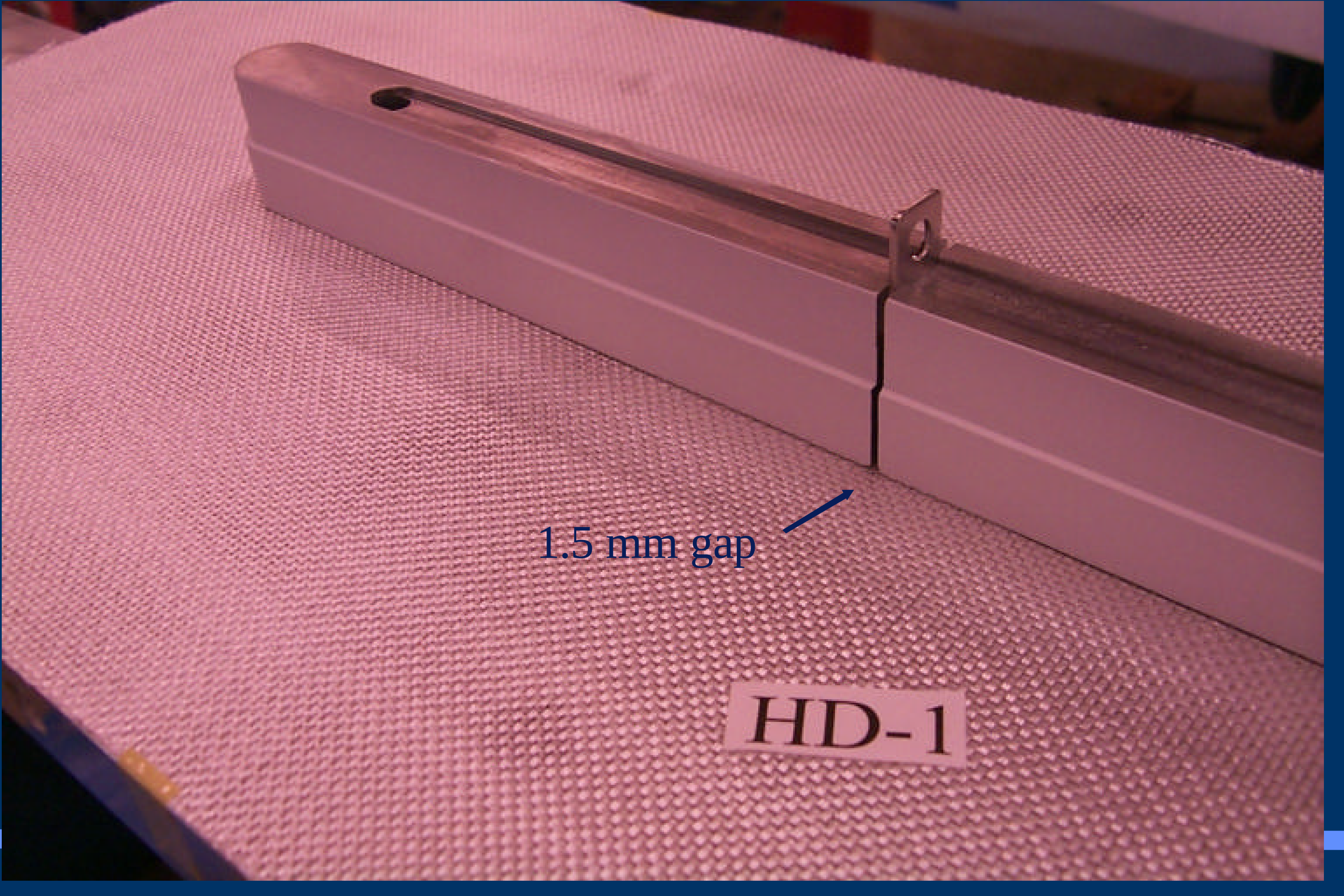
- 36 strands, 0.8 mm diameter
- 1.36 X 15.7 mm (rectangular)
  - Initial thickness = 1.41 mm
  - Annealed
  - Re-rolled to 1.36 mm
- 18 kg winding tension
- 10 mm bend radius (minimum for this cable)
- No microscopically observable damage
- Insulation
  - S-2 glass (0.107 mm @ 14 MPa)



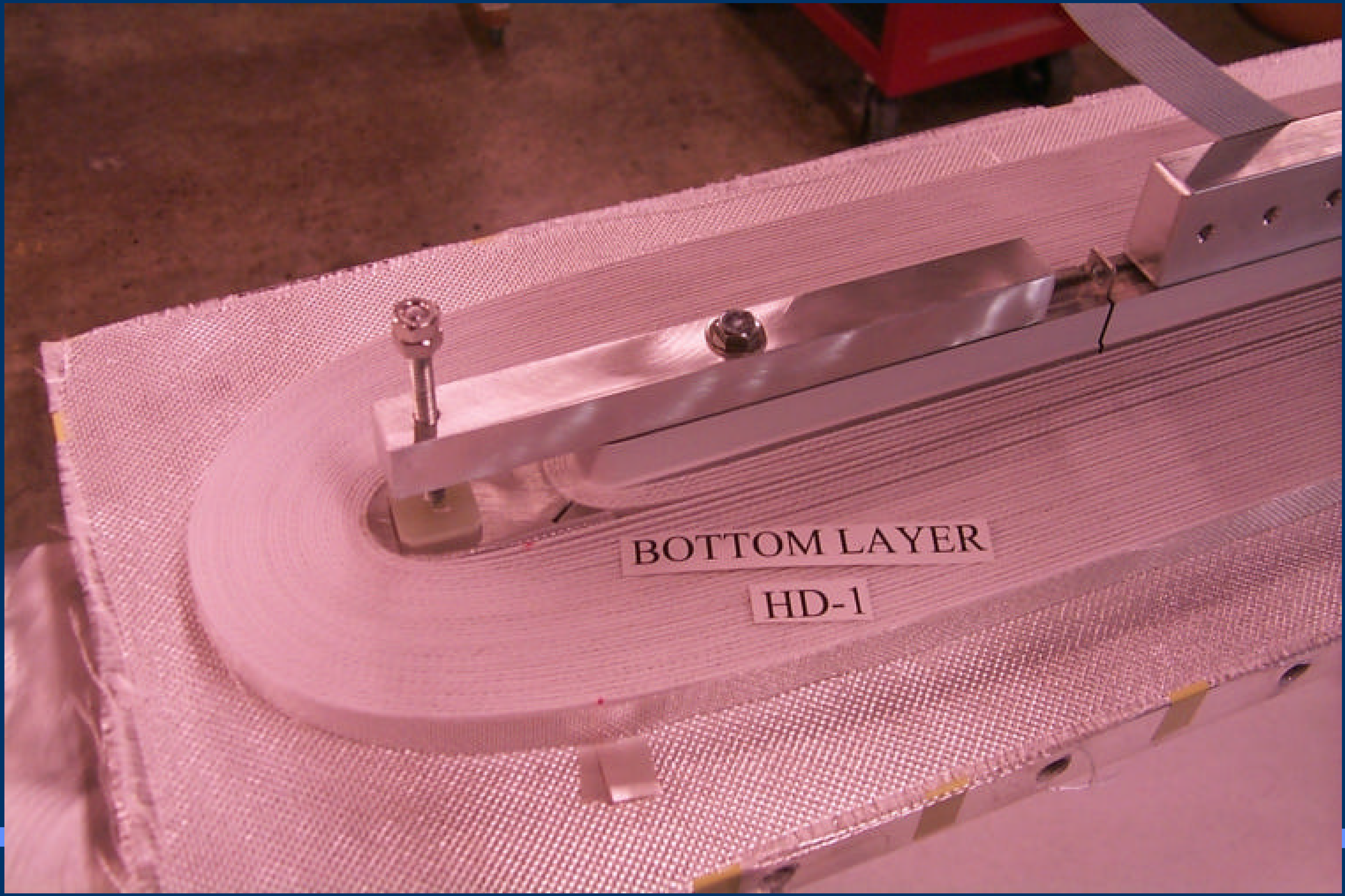
1st Turn



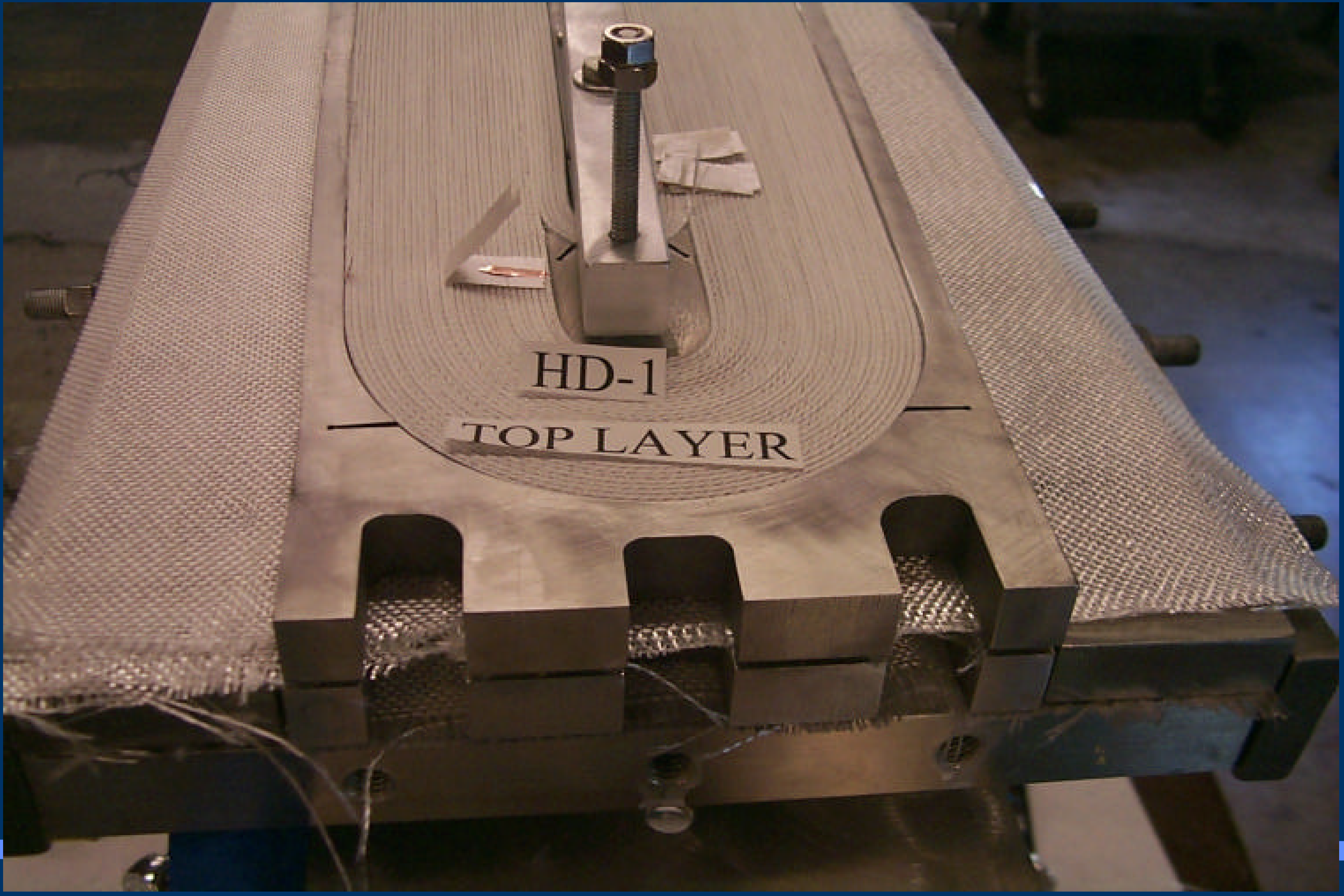
Pole Gap



Layer-1 with End Spacer



Horseshoe and Voltage Taps



Evaluation of Cable Parameters

- Determine the deformation limits of different strands
- Cables with a mixture of Cu and superconducting stands
- Cables with Cu-Stainless Steel cores
- Keystoned cables with a core
- Cable handling and winding characteristics database
- Relate cable parameters
  - Type of strand, width & thickness, with and without a core, etc.

  to winding mechanics
  - Popped strands, bending hard way and easy way

Reaction Prep

- Coil is constrained in all dimensions
  - Gap in island to accommodate dimension change
  - 14 MPa normal to conductor face
  - Moderate compression axially and “vertically”

Wind/React – React/Wind?

- Wind and React
  - Small bending radii
  - Strand coupling
    - Cores?
  - Insulation
  - Length issues
    - Reaction
      - Strain/dimension control
    - Handling

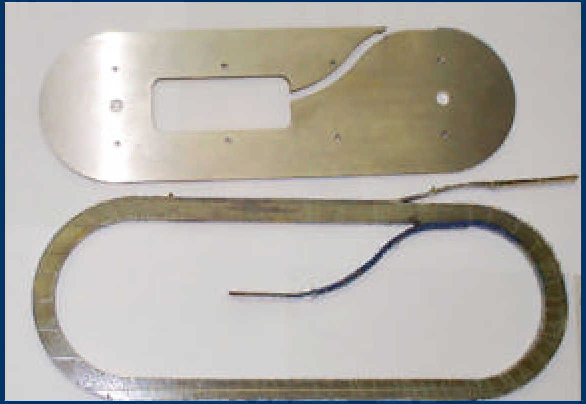
- React and Wind
  - Large bending radii required
  - Some problem in sizing coil?
  - Handling and winding
    - QC challenge
  - Only option for HTS

Need to investigate this ASAP

BNL

Long History with Nb_3Sn

- Current effort is on react and wind ("10-turn coils")
  - Nb_3Sn
  - HTS (Bi-2212)



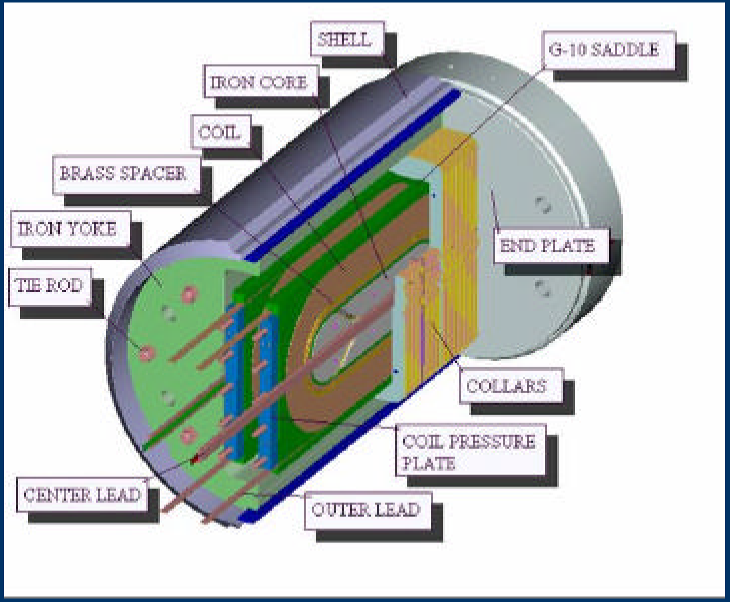
- To Date:
  - Nb_3Sn
    - Early tests with ITER were very successful
    - Results with high performance strand have shown significant degradation

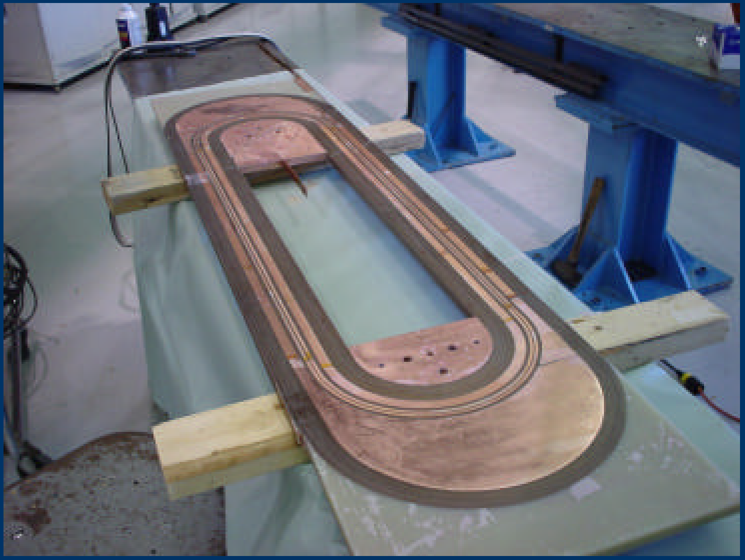
But, still on learning curve

  - HTS
    - Results are encouraging . . .

BNL Plans

High Field R&D: Nb_3Sn and HTS flat coil fabrication and testing.





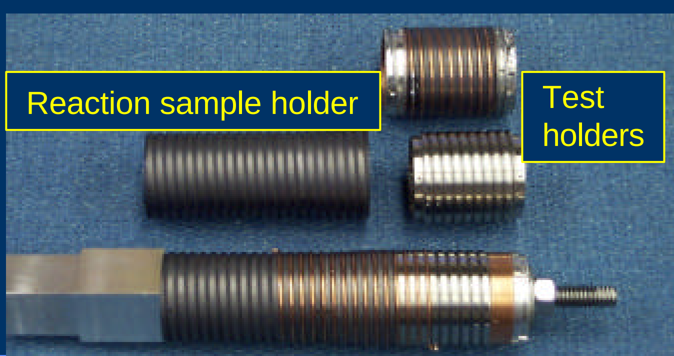
- Goal of 12 T react and wind magnet next year
- Background magnet for cable testing

Plan for React & Wind development - I

SC Magnets at Fermilab

Find the best conductor for the next steps of the R&D:

- Verify stability of conductor (MJR) used in FNAL and BNL racetracks fabricated with R&W tech.
- Study bending degradation of PIT and RRP strands
- Auxiliary studies:
  - Measurement of pre-strain at 4.2K (NIST)
  - Check for cracks under large bending (Univ. of WM)

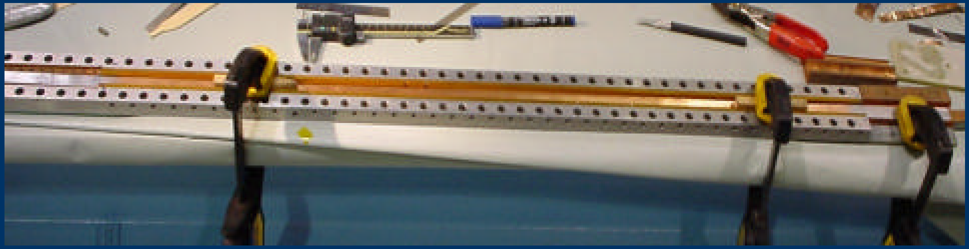


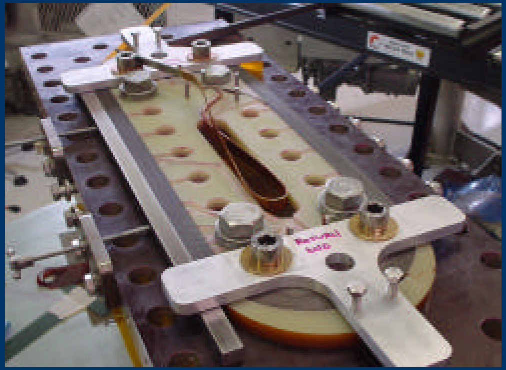
Plan for React & Wind development - II

SC Magnets at Fermilab

Cable and coil R&D

- Measure Ic of cables bent after HT
  - Synthetic oil or plating/coating to prevent sintering during HT
- Measure inter-strand resistance in cable and coil samples
  - Develop techniques to remove residues of oil after HT
- Fabricate and test small magnets to assess technology



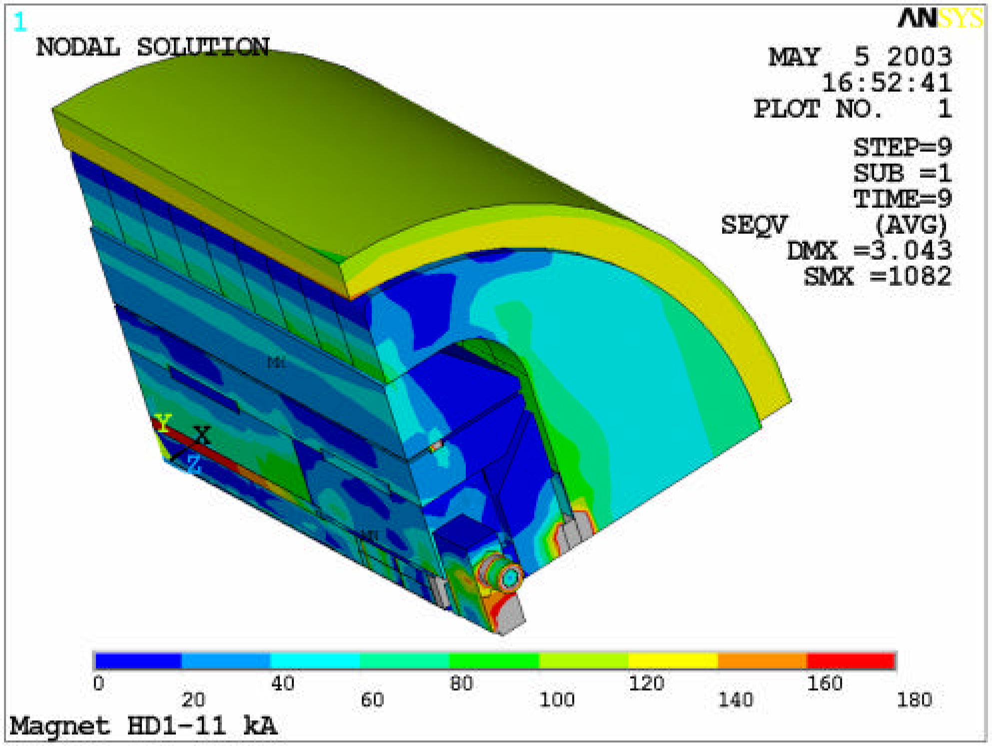


Application of Design Tools

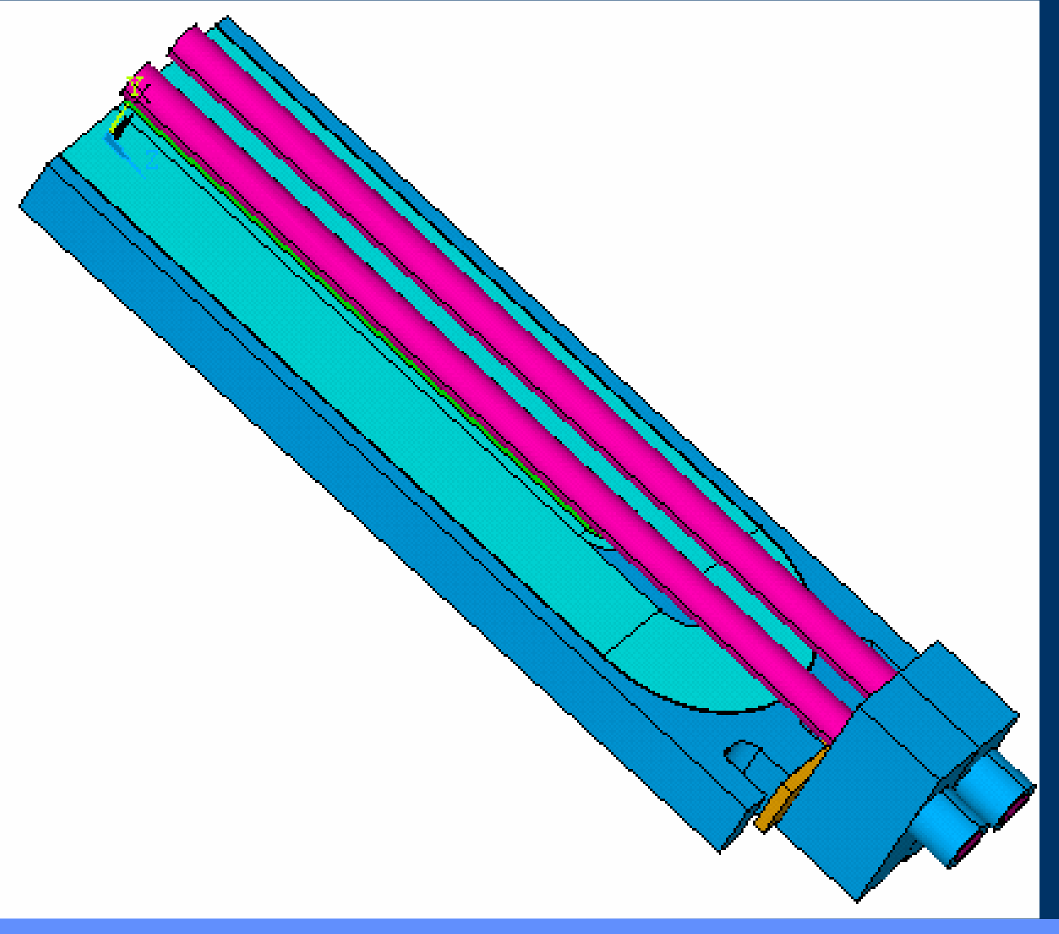
- Integrated design

Cross section – generate coil – CAD – FEA

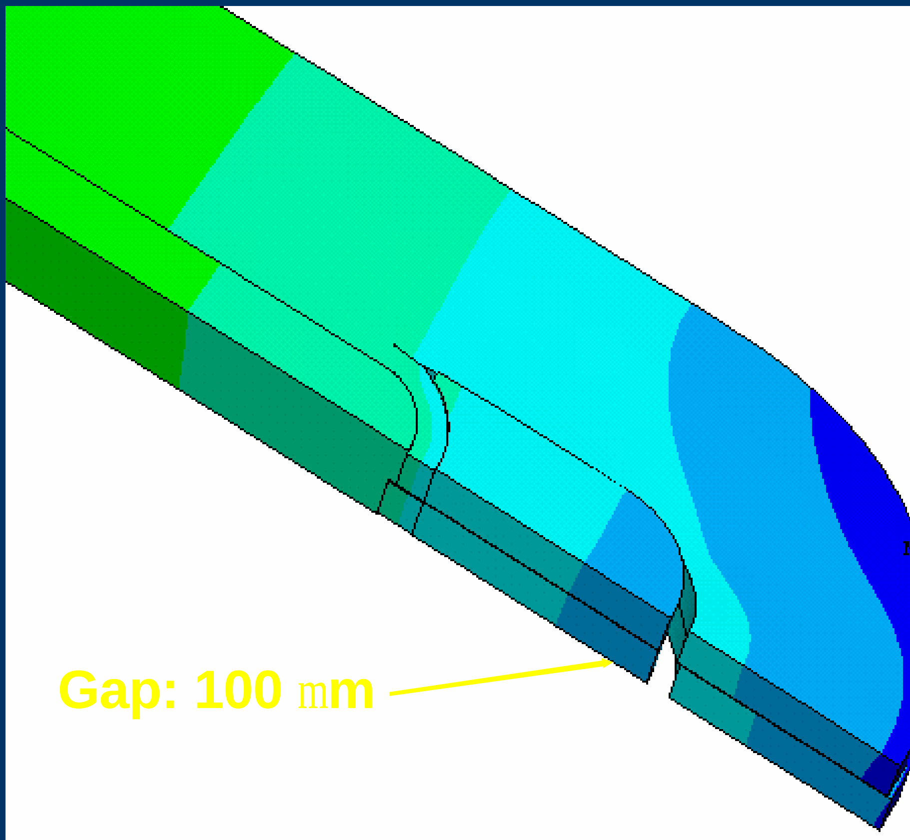
- 3-D analysis is standard
  - Control/limit maximum stress on conductor



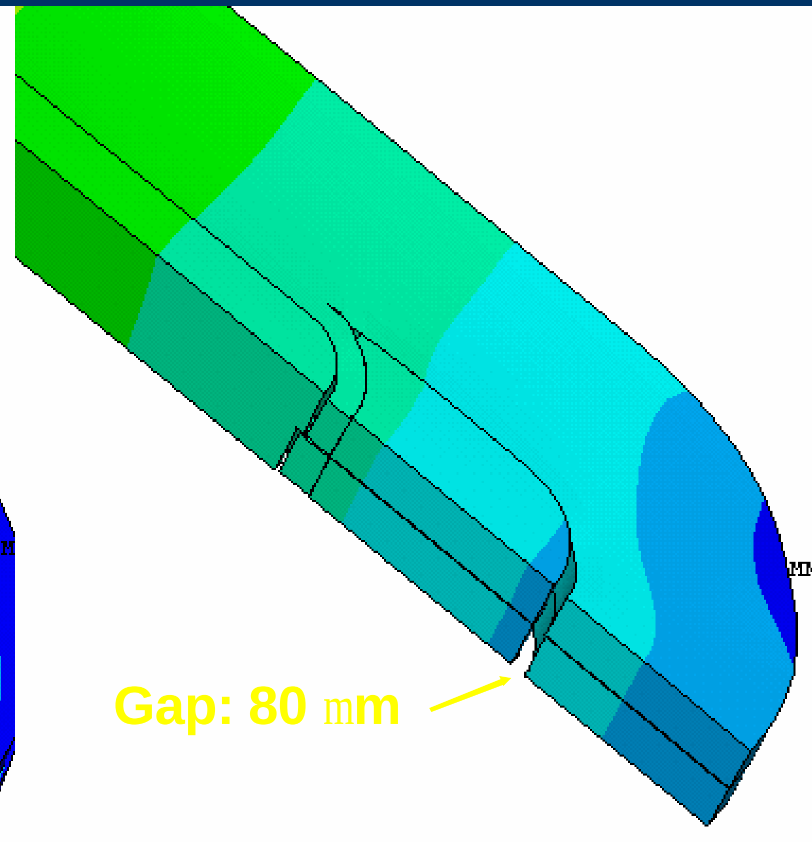
Axial support



Gaps in the end region at 16 T

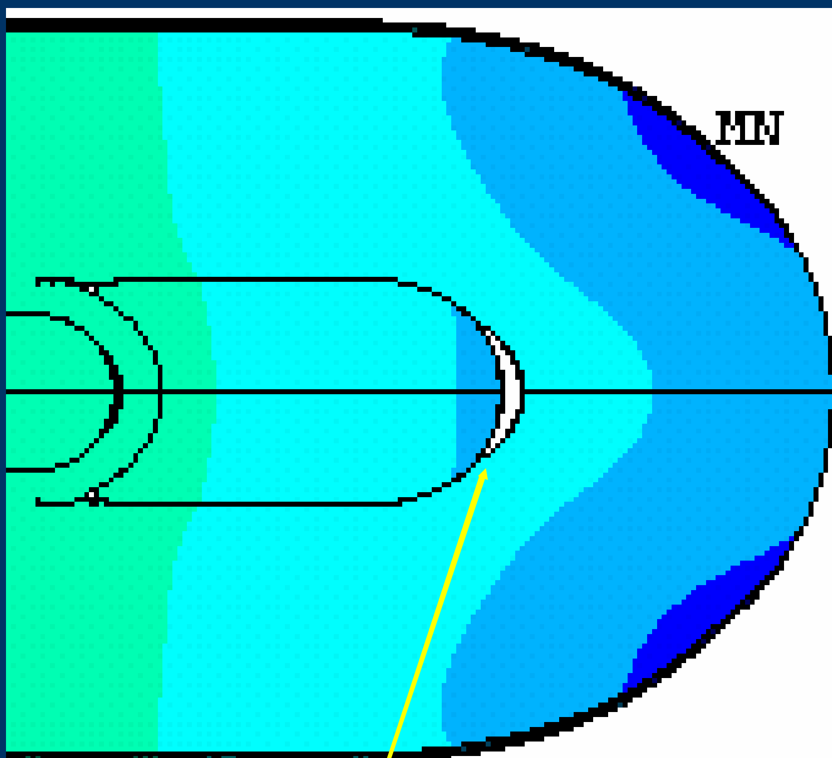


Frictionless model

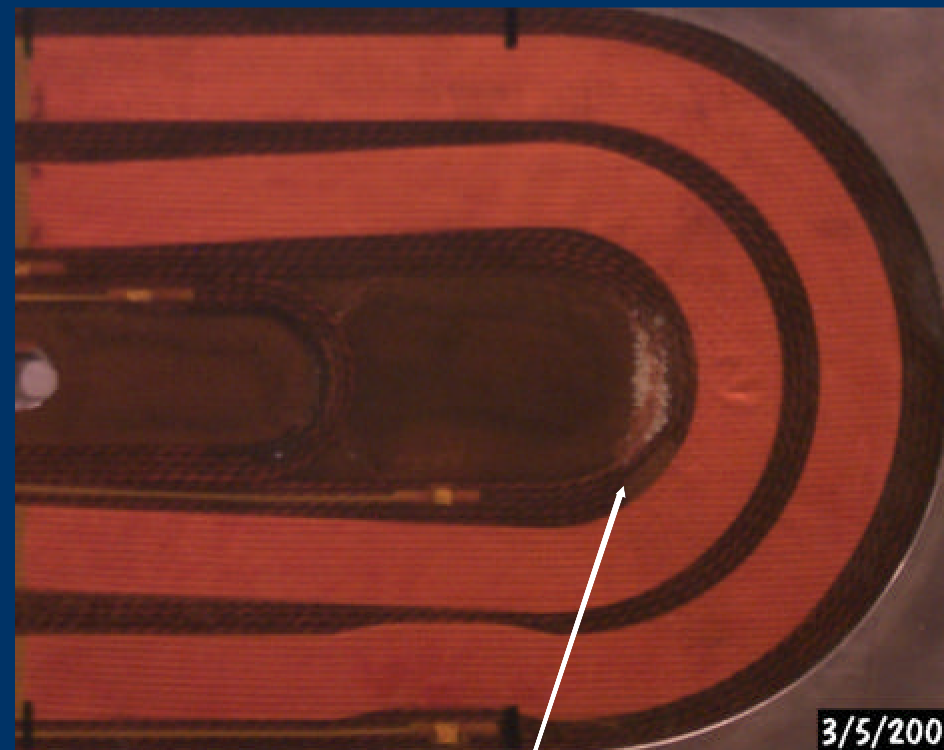


Friction model

Visual inspection

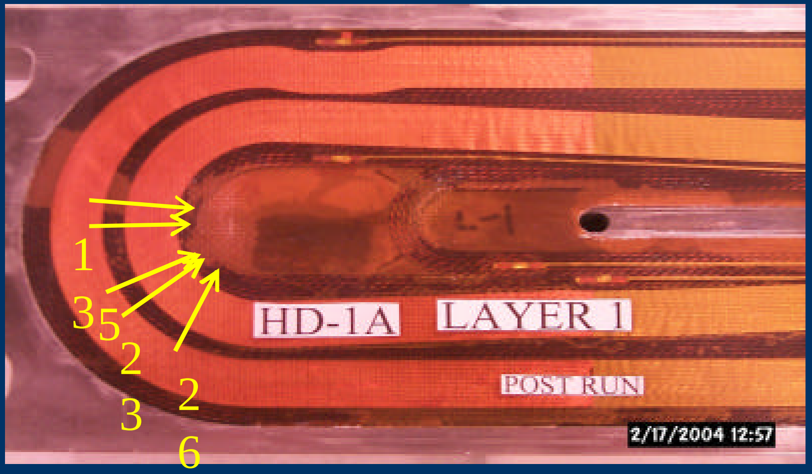


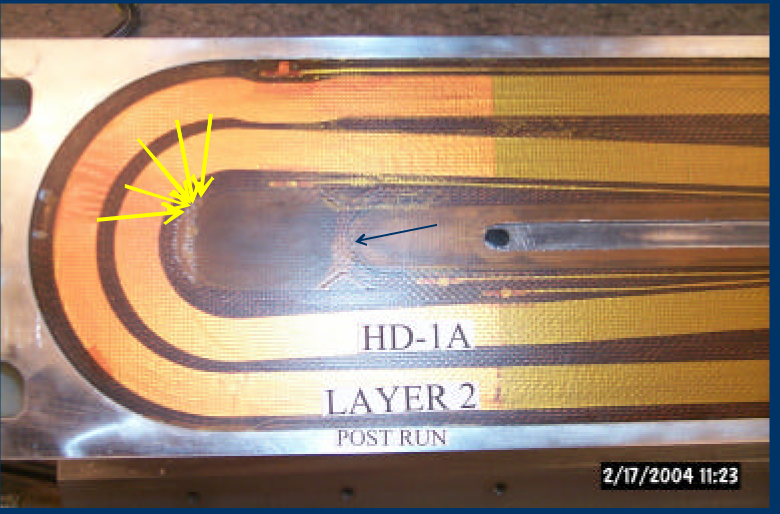
Gap: 80 mm

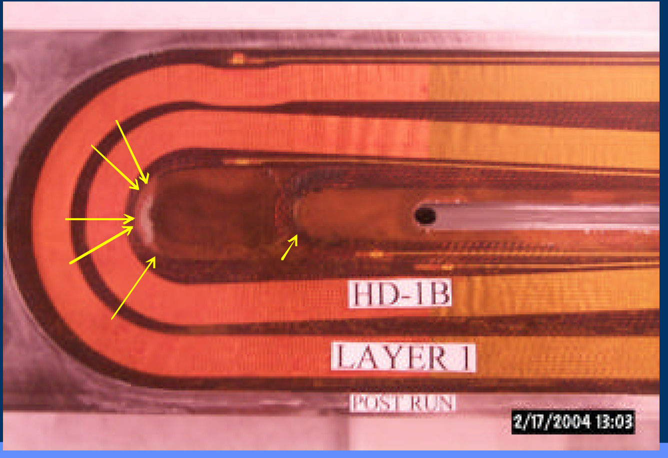


Epoxy discoloration

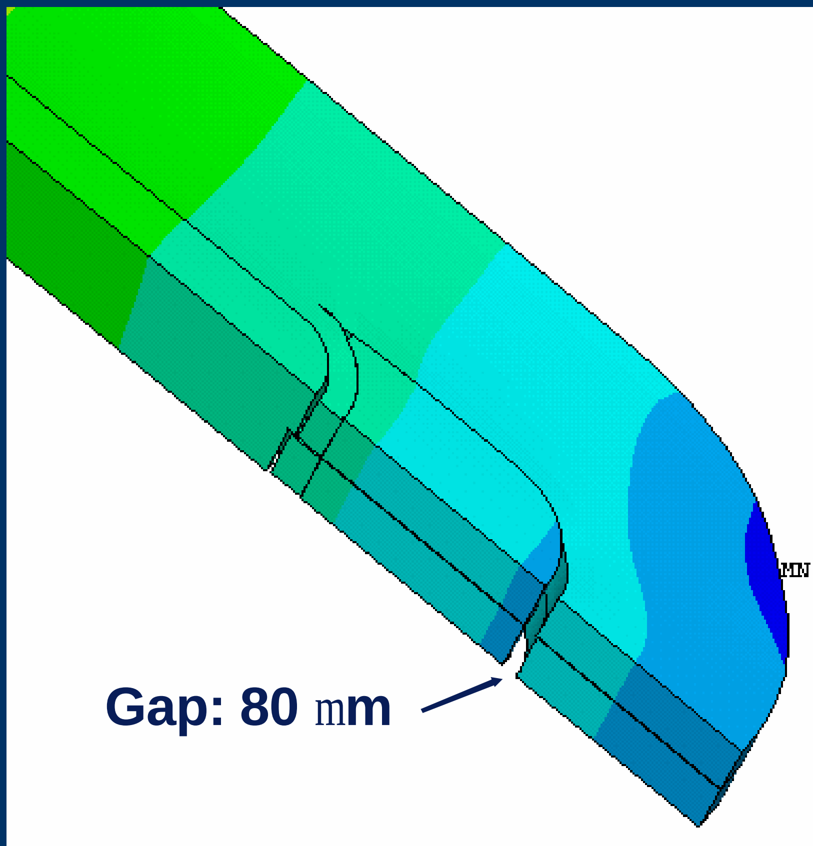
Measured Quench Locations



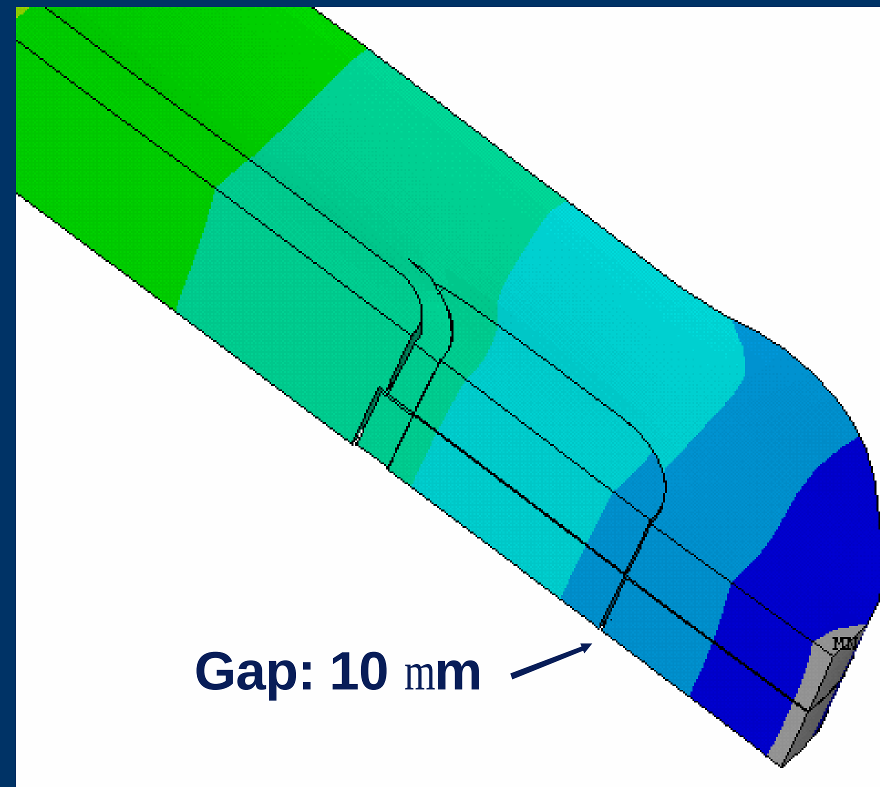




Modified Design to Reduce Conductor Movement in the Ends



Original design

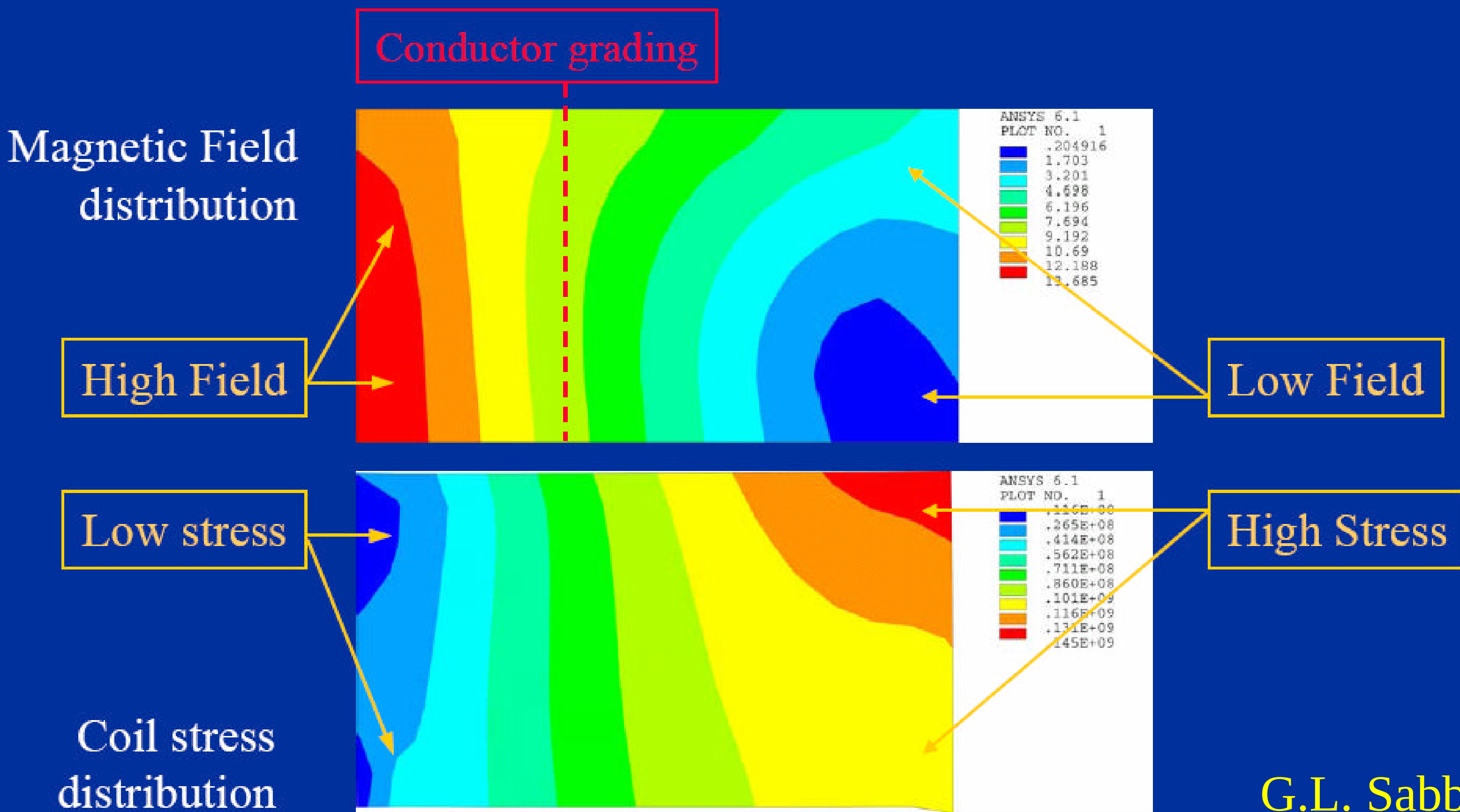


Modified design

Design Choice Example

BERKELEY LAB

Block Coil Advantages



G.L. Sabbi

Summary

- We have a point in parameter space that we are comfortable with
- How far can constraints or parameters be pushed for accelerator magnet applications?

Thanks to

Shlomo Caspi, Dan Dietderich, Paolo Ferracin, Hugh Higley, Roy Hannaford, Ron Scanlan. LBNL

Arup Ghosh, Ramesh Gupta, BNL

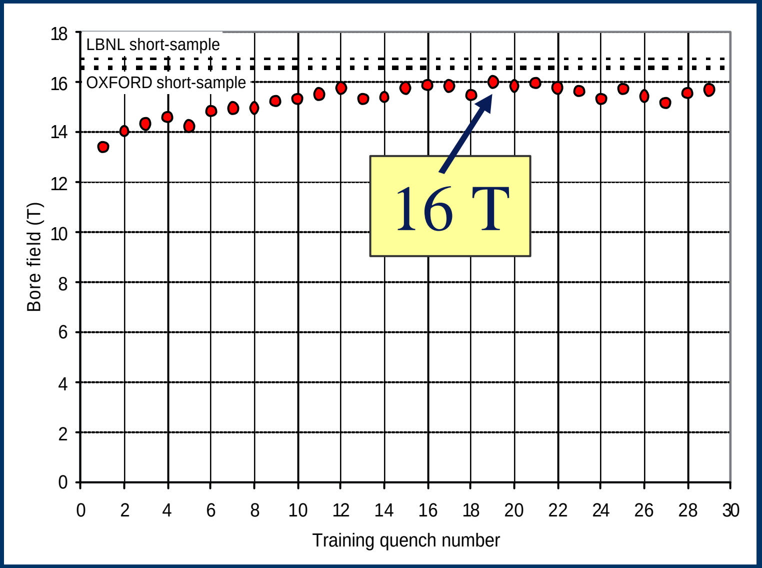
Giorgio Ambrosio, FNAL

Ancillary Slides

HD-1 Demonstrates the Viability of a New Technological Tool

HD-1 Objectives

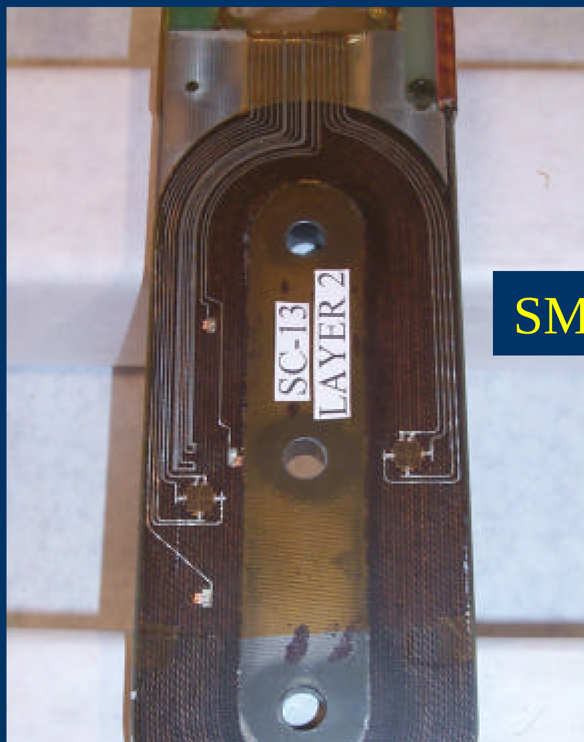
- Push limit on dipole fields and stresses
- Study the properties of block-coil designs
  - Suitable for very high field accelerator dipoles
  - Efficient technology R&D
- Success based on
  - Improved conductor
  - Integrated design approach
  - Fabrication techniques



16 Tesla max field is 4.5 Tesla higher than closest competitor

Test at 1.8 K could exceed 17 Tesla

Training Tests and Studies



Sub-scale coil with
surface-mounted strain gauges

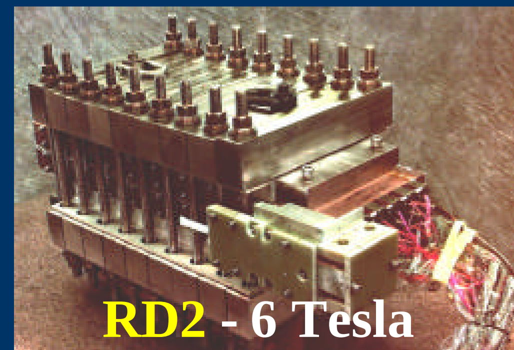
SM-06

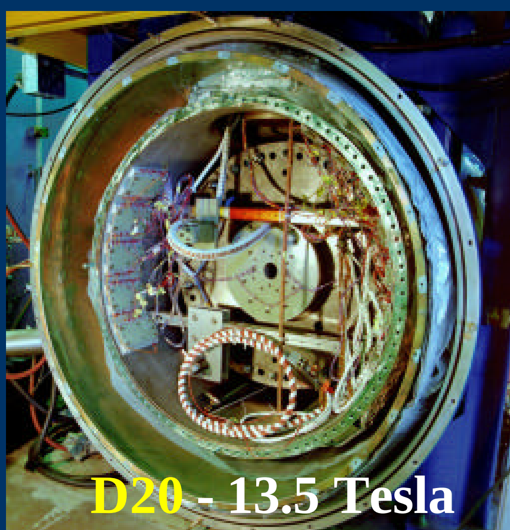
Scaled version of main magnet

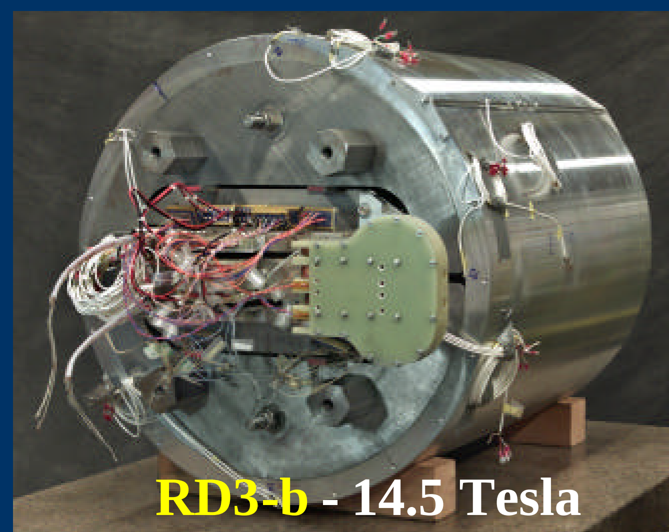
Simple fabrication, simple testing

Field range of 9 – 12 Tesla

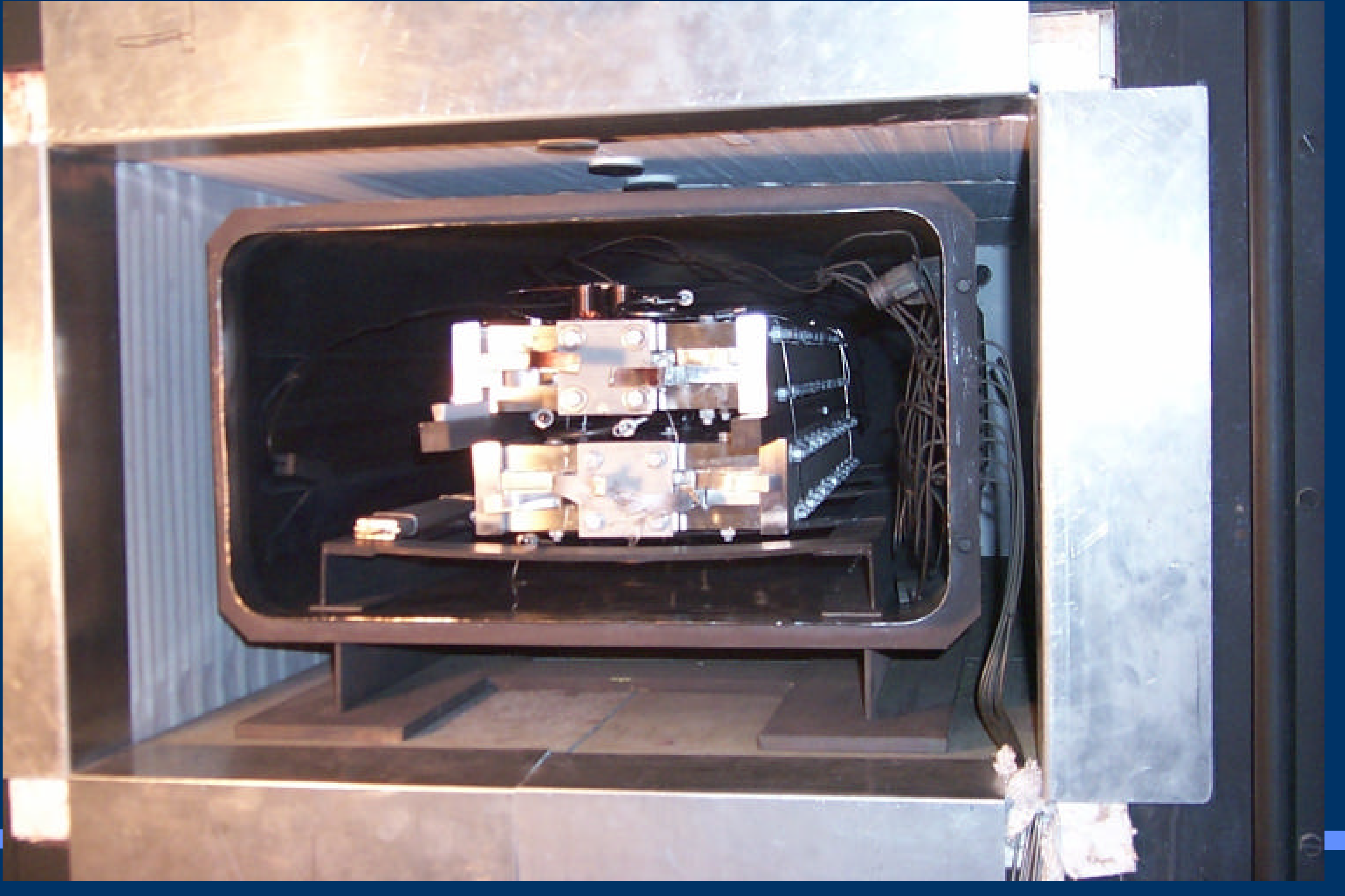
LBNL Prototype Highlights



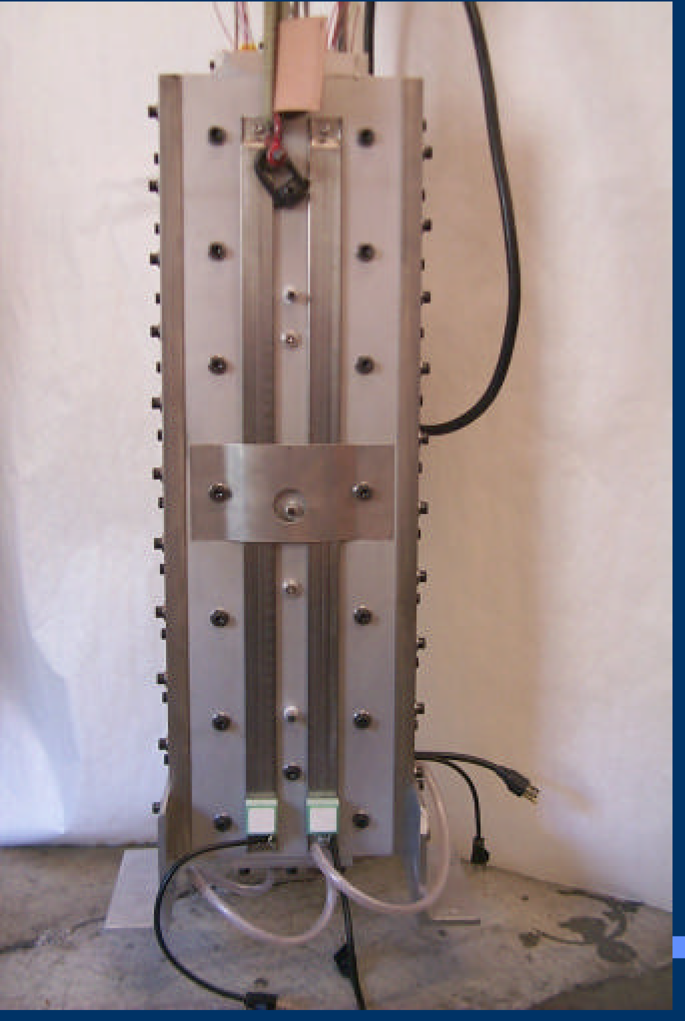




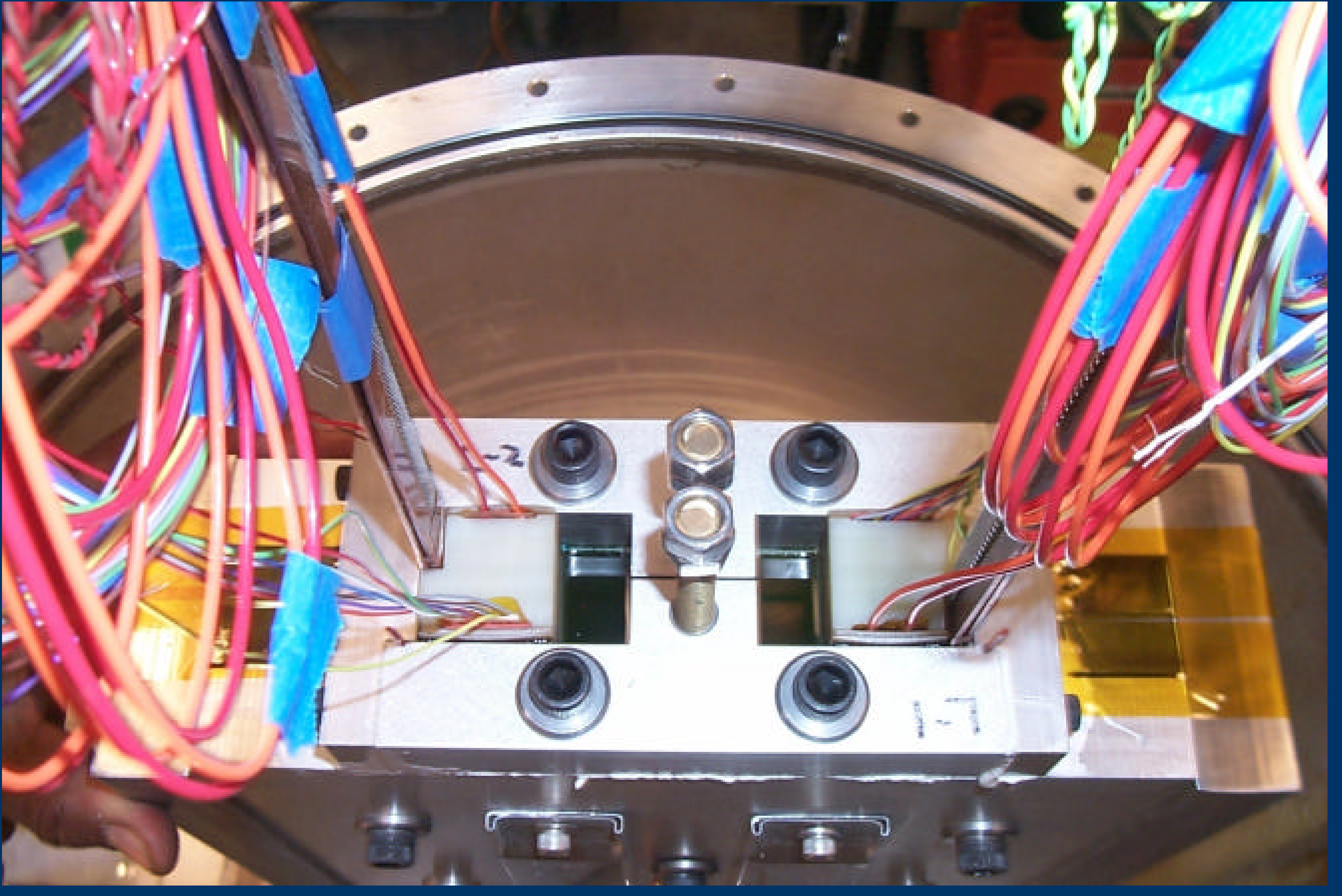
Coils in Reaction Oven



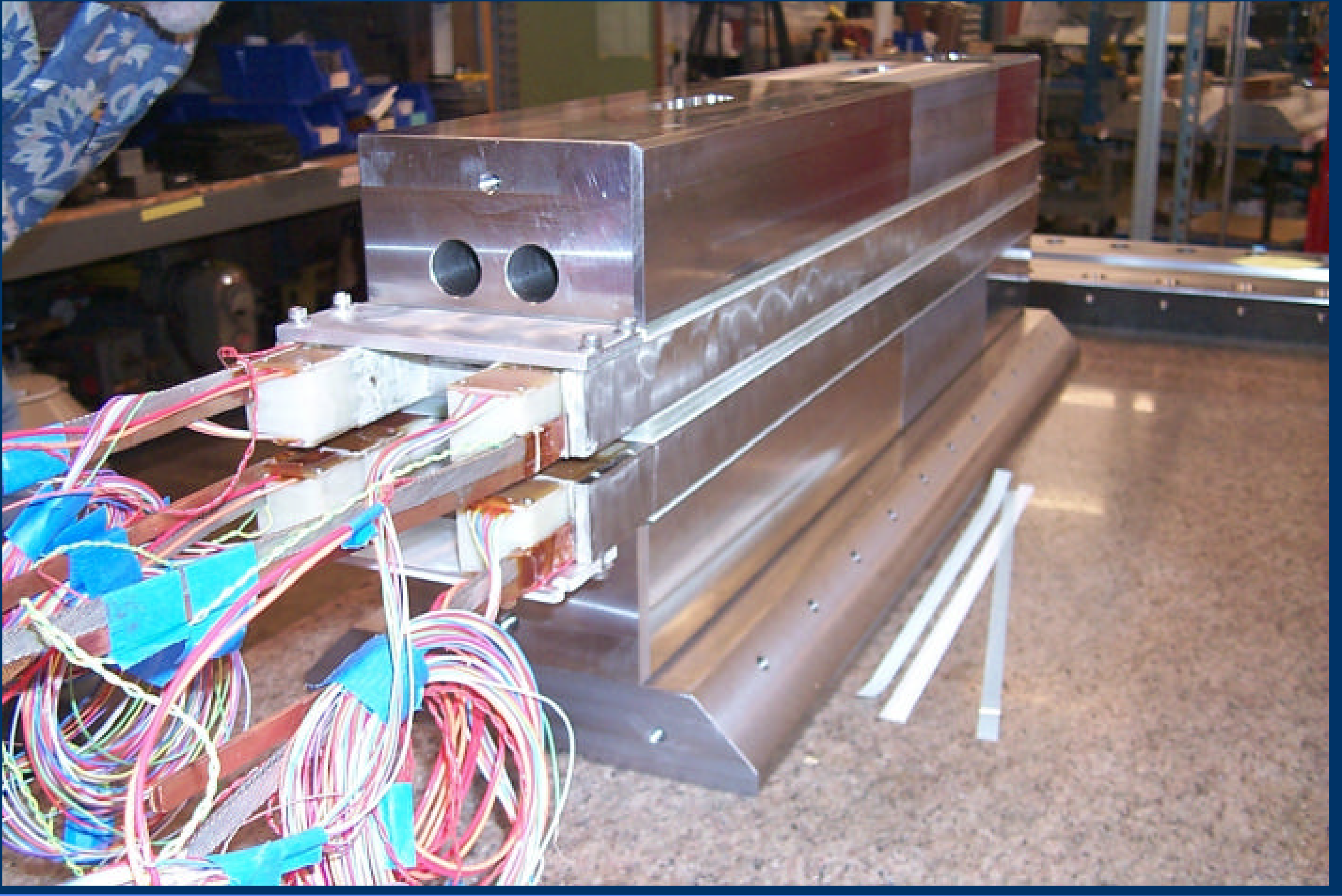
Potting Fixture



Impregnation



Begin core stack



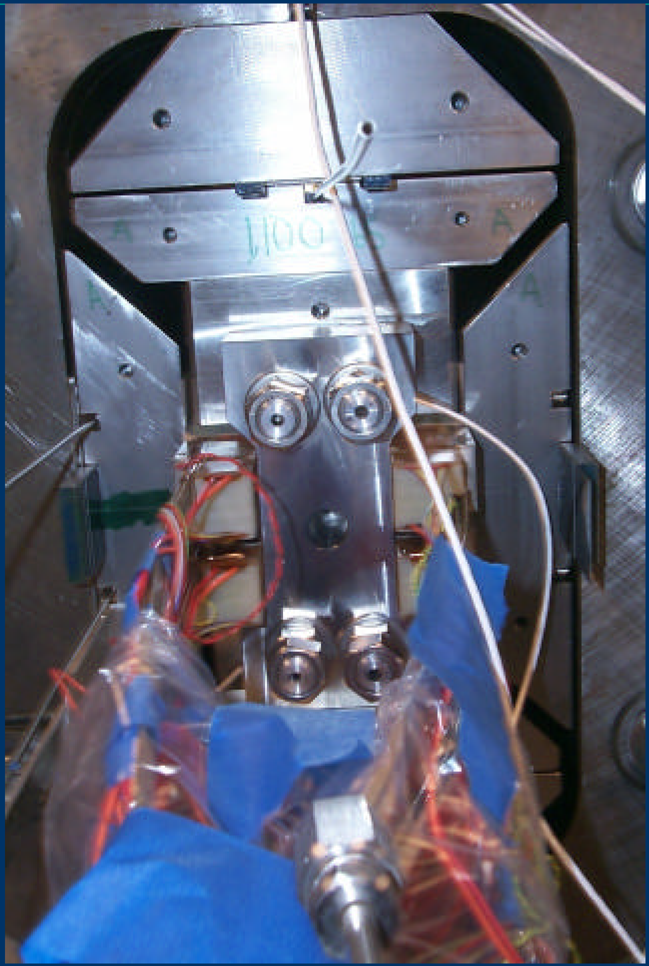
Completed core module

S. Gourlay, LBNL

Yoke and shell

S. Gourlay, LBNL

Bladders in (lead end)



Rod Loading