SC Magnet Development at LBNL

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Superconducting Magnet Program

ILC Small-angle IR Workshop
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Program Objectives

1. ***Push the limits of accelerator magnet technology***

High Field Magnets ⇔

- **Materials**: superconductors, insulation, structural
- **Coil designs**: efficient, simple & cost-effective
- **Structures** to handle large forces and stresses
- **Design, analysis and diagnostics** tools

2. ***Apply our expertise towards the goals of the HEP community***

Main Arc Dipoles ⇒

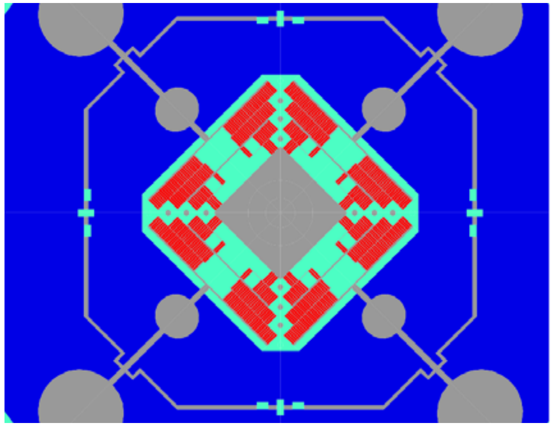
- **Key enabling technology** for the highest energy colliders
- Maximum potential for **new discoveries** in HEP

IR Quads & Dipoles ⇒

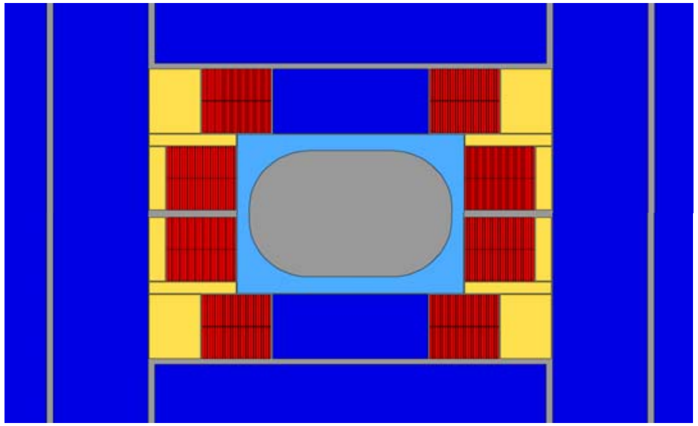
- **LHC** luminosity upgrade: **"absolutely central"** (HEPAP)
- High field magnet technology is also **relevant to ILC**

Operating Field Requirements

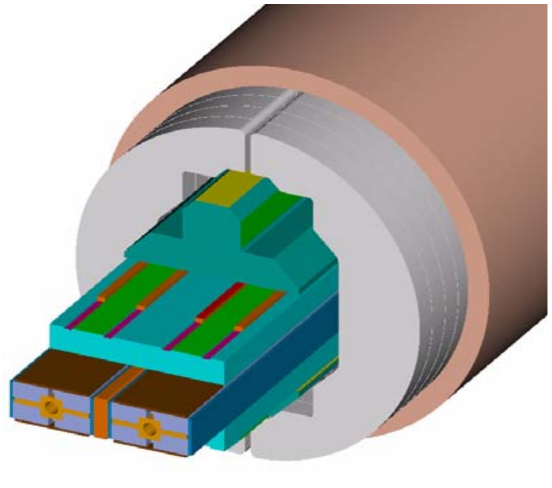
LHC IR Quads: >12 T



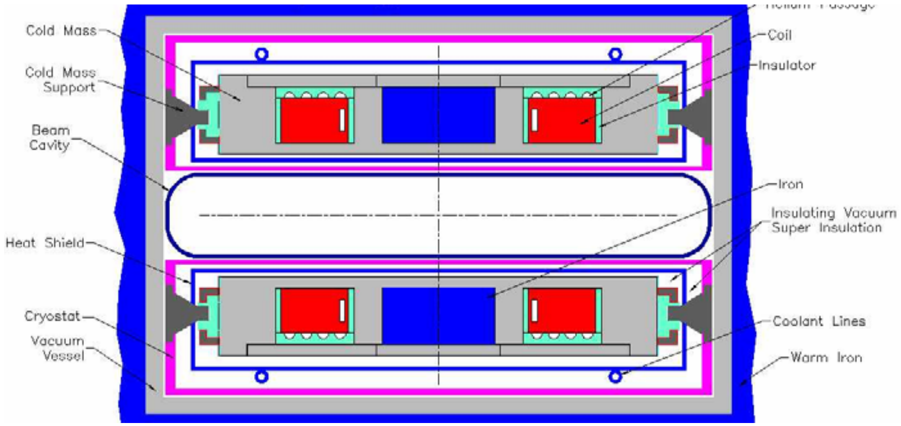
LHC IR Dipoles: > 13 T



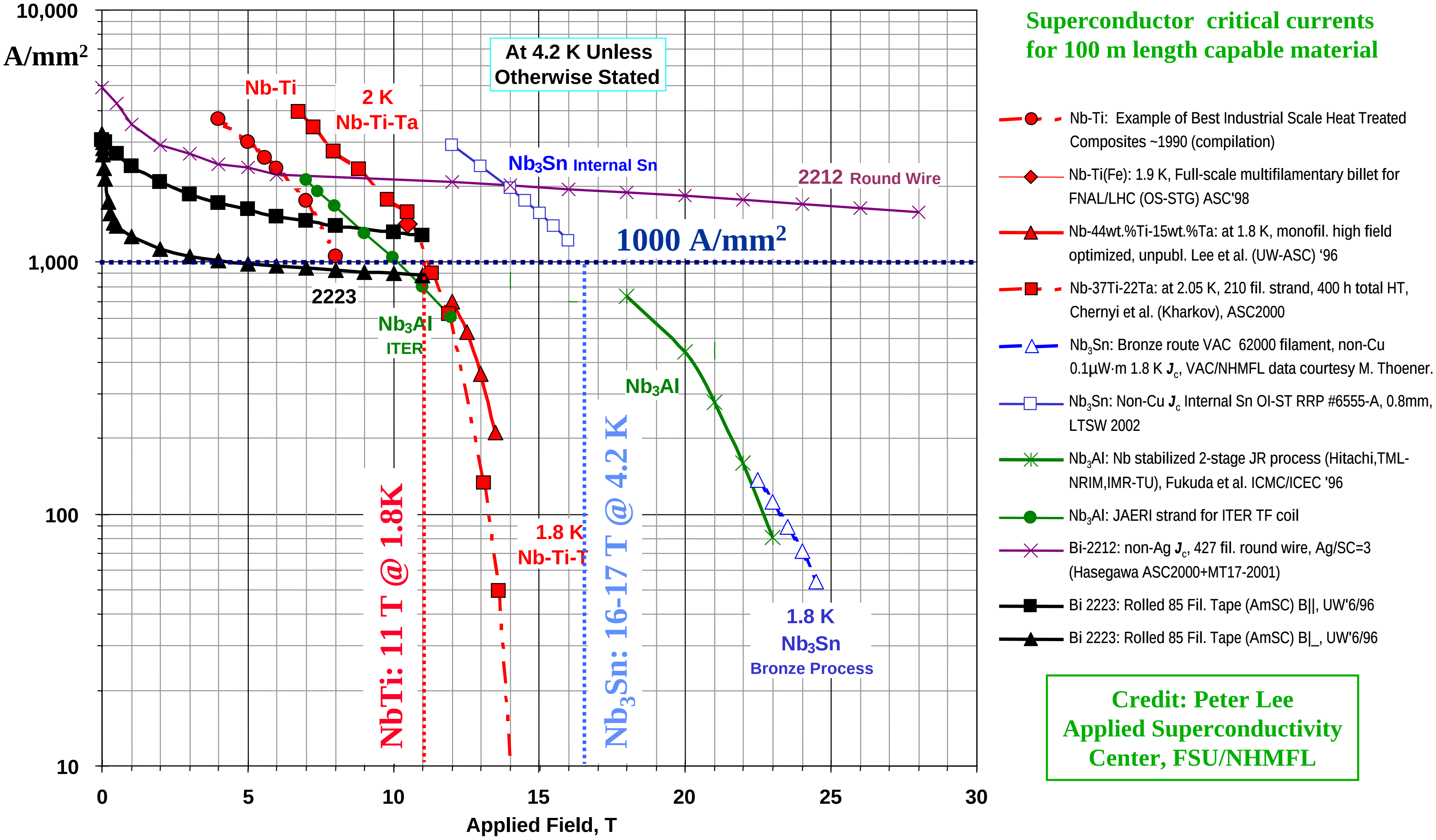
LHC Energy Upgrade: >15 T



Muon Collider Dipoles: >12 T (coil)



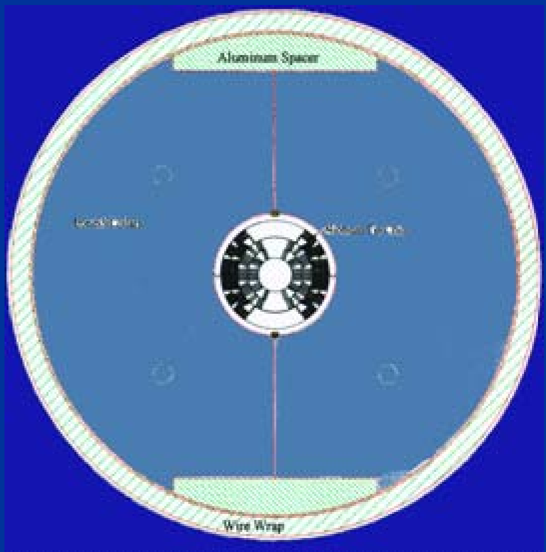
Conductor Options



LBNL High Field Nb_3Sn Dipoles

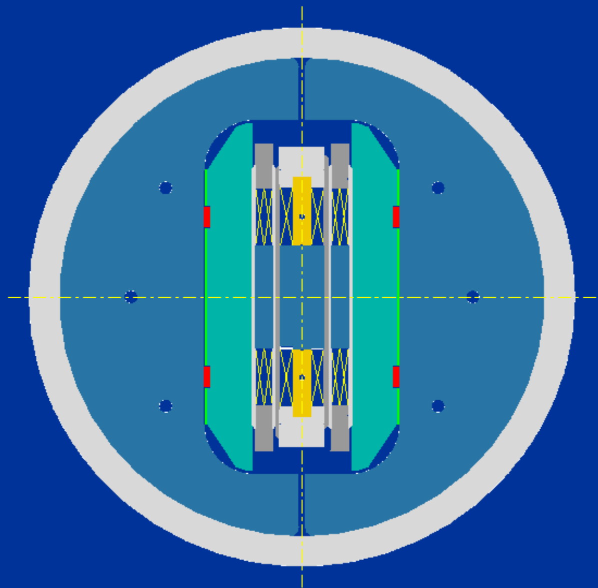
- *Exploring coil and structure design options while pushing the field limits*
- *Technology foundation for the LHC luminosity (and energy) upgrades*

D20 (13.5 T)



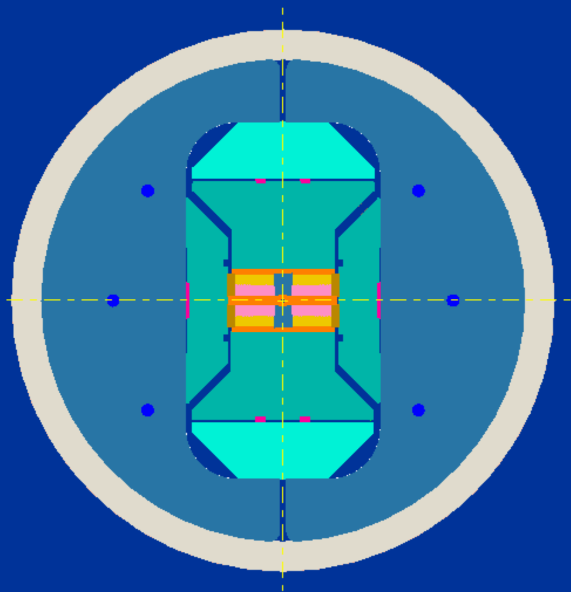
Cos θ

RD3b (14.5 T)



Common Coil

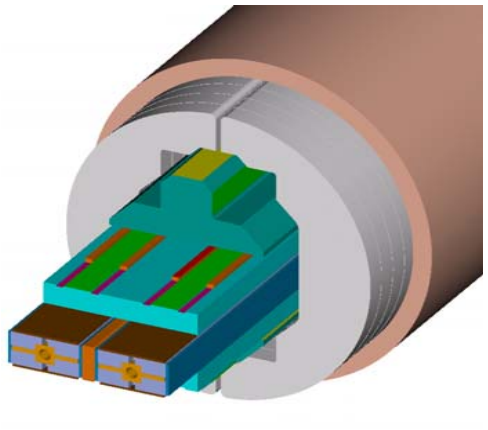
HD-1 (16 T)



Block

Next High Field Dipole: HD2

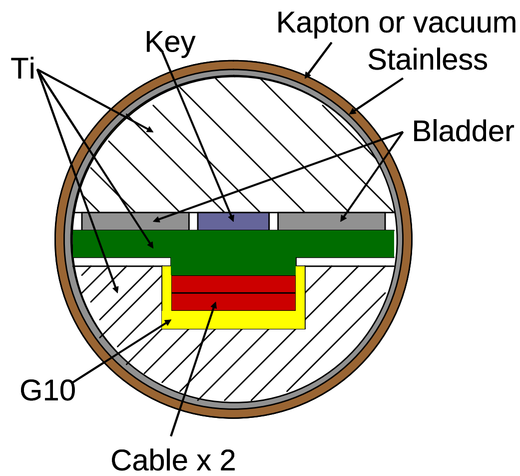
LHC Energy Upgrade

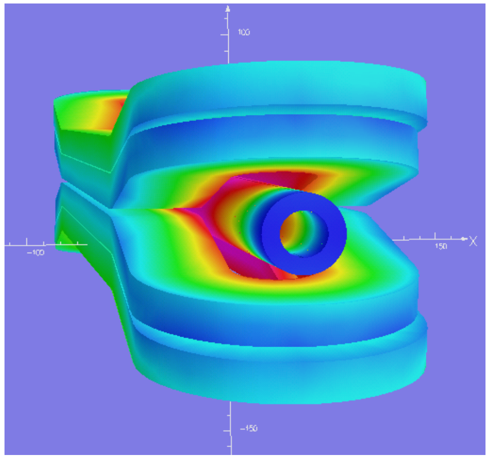


Design Features & Applications

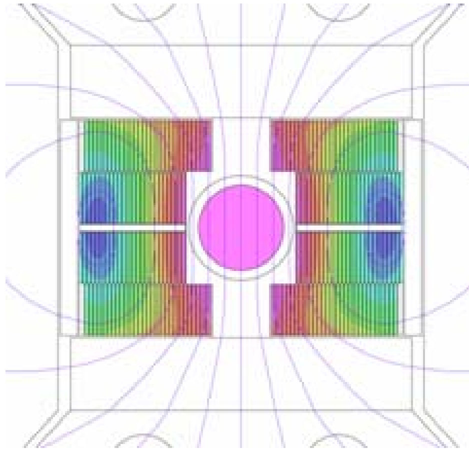
- Target field above 15 Tesla
- Clear bore 35 mm
- Simple coil configuration
- Geometric harmonics: 10^{-5}
- Suitable for HF cable testing
- Compatible with HTS inserts

High-field cable testing

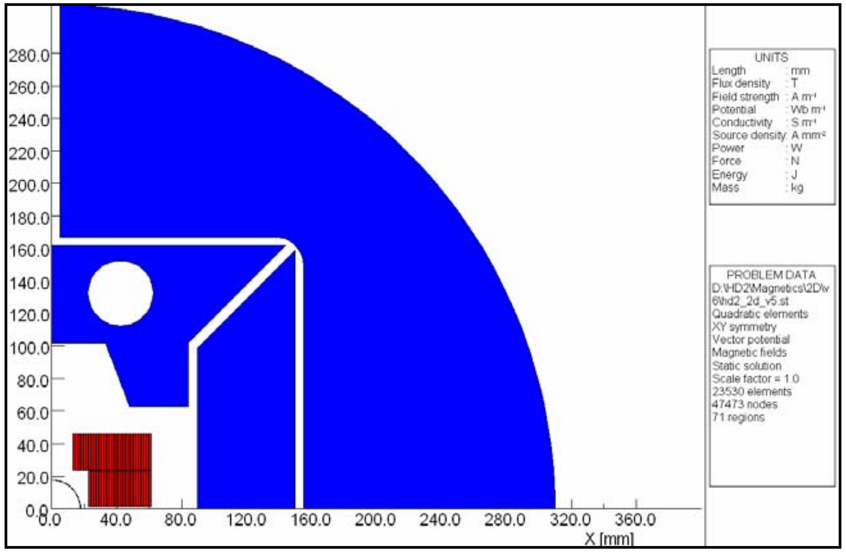


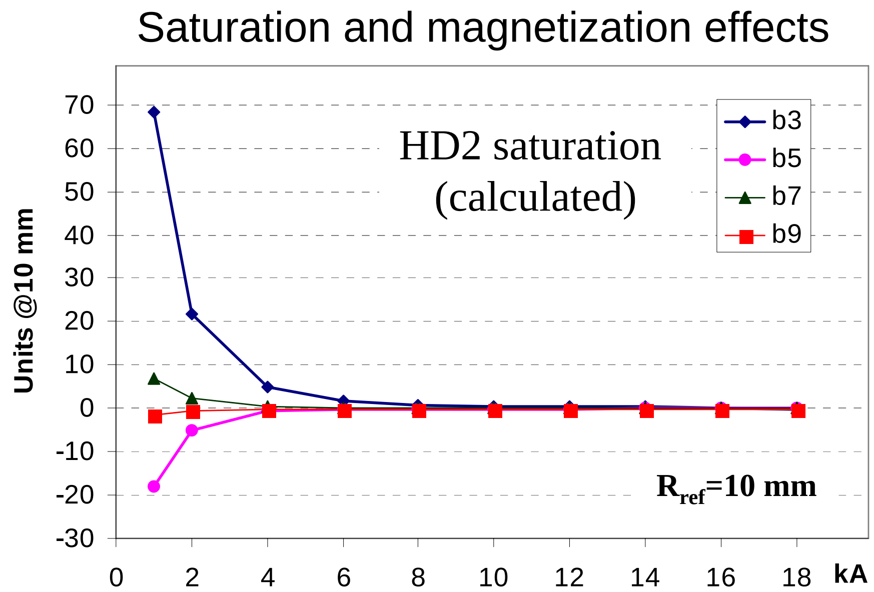


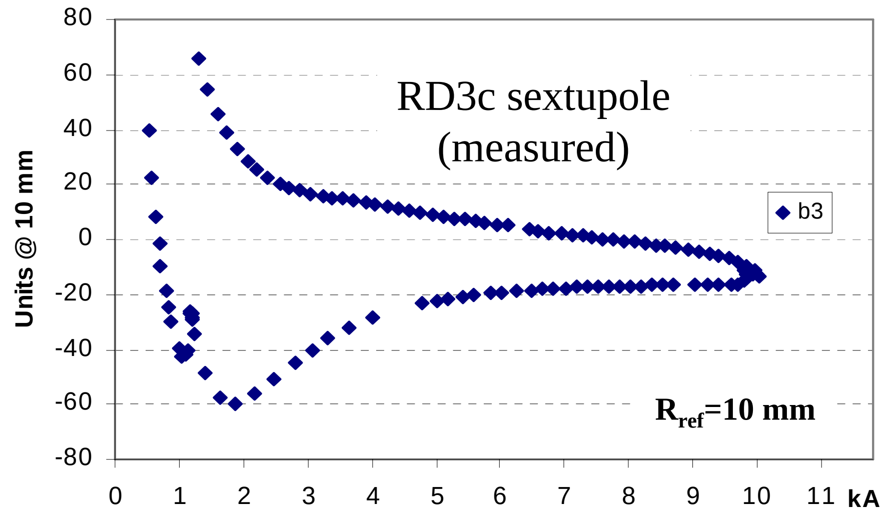
Parameter	Unit	HD1	HD2
Clear bore	mm	8	35
Coil field	Tesla	16.1	16.1
Bore field	Tesla	16.7	15.3
Max current	kA	11.4	15.2
Stored Energy	MJ/m	0.66	0.89
F_x (quadrant, 1ap)	MN/m	4.7	5.9
F_y (quadrant, 1ap)	MN/m	-1.5	-2.7
Ave. stress (h)	MPa	150	140



HD2 Field Optimization (2D)







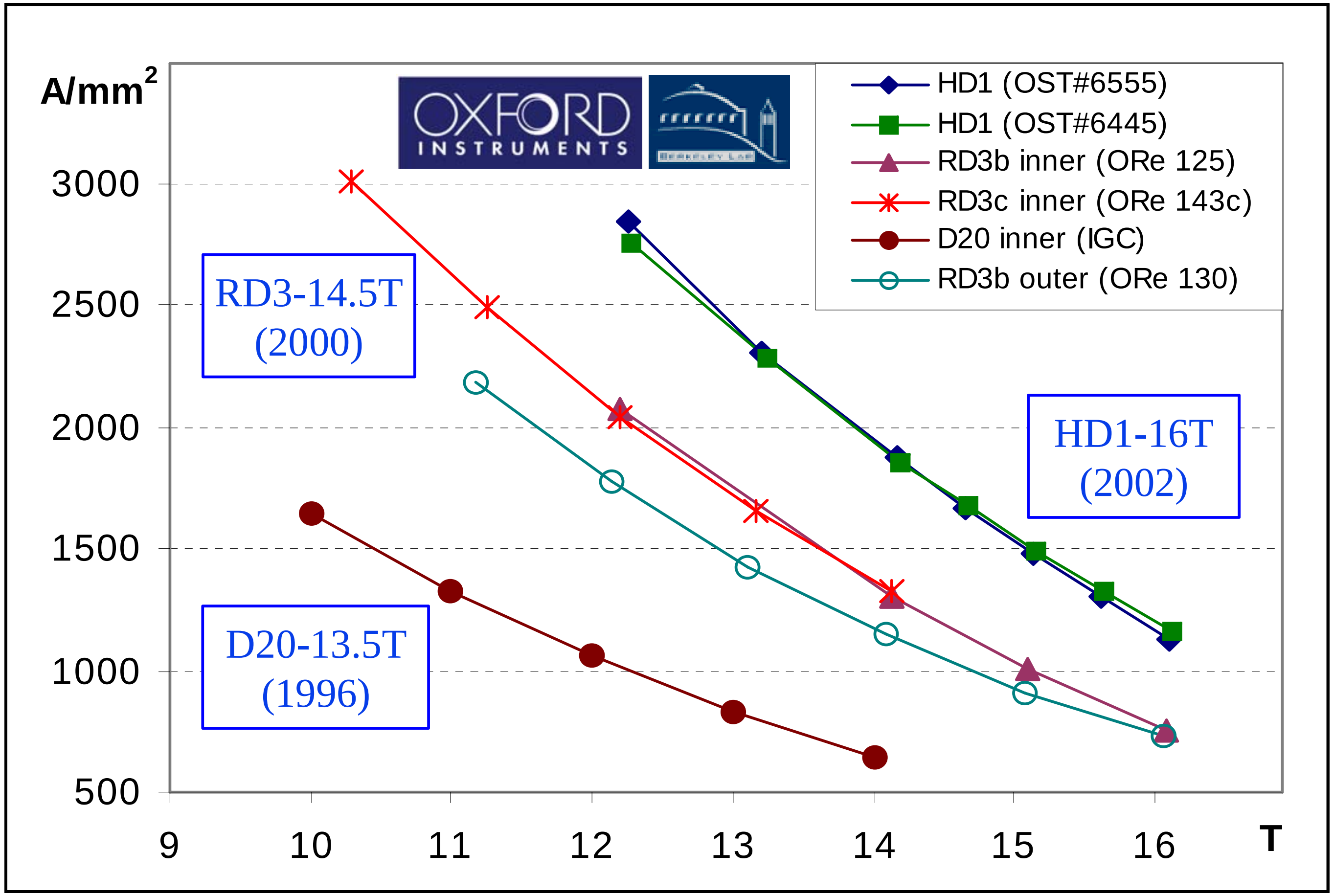
- Coil can be optimized for very small geometric harmonics (<0.1 units)
- Yoke cross-section and iron insert optimized to compensate persistent current harmonics
- Goal: all measured high field harmonics at 10^{-4} or lower (R_{ref} = 10 mm)

High Field Magnet R&D

Advance towards higher field ⇔ Push all technological limits:

- Engineering properties of wires
- Cabling of advanced wires
- Nb_3Sn coil technology
- Bi-2212 coil technology
- Improved modeling capabilities
- New mechanical structures
- New assembly procedures
- Coil/magnet instrumentation
- Diagnostics & data analysis

Conductor for Dipole Protoypes



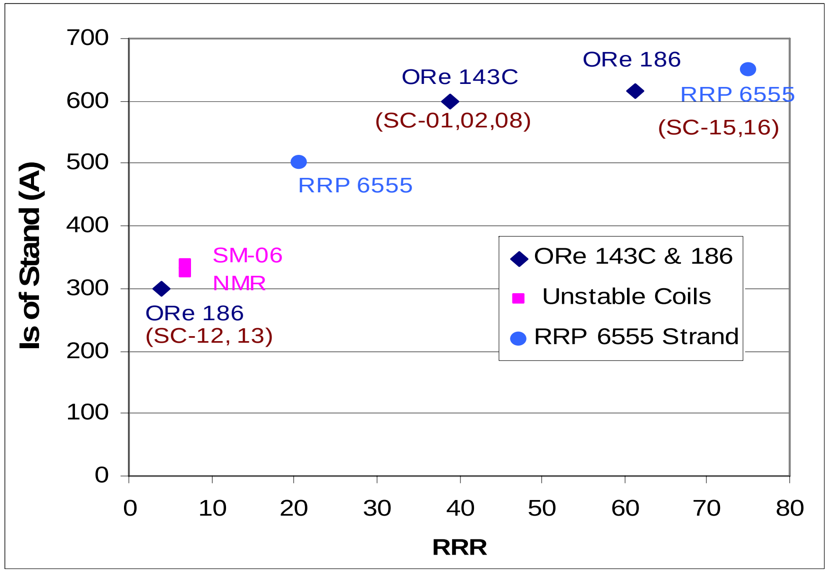
Critical current densities in Nb_3Sn wires for LBNL high-field dipoles

Materials R&D

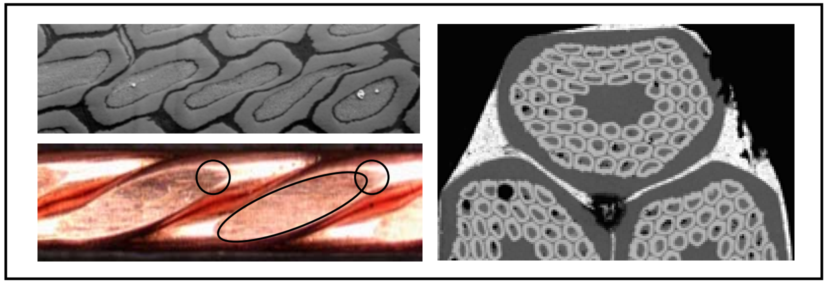
<u>Recent Highlights:</u>

- New reference J_c: 3 kA/mm^2 at 12 T, 4.2K
- Strand heat-treat optimization studies to achieve high RRR and improve stability thresholds
- CDP: new strands designs are less sensitive to HT schedule, while retaining high critical currents
- CDP: development of wires with smaller D_{eff}
    - *increased number of sub-elements*
    - *Use of NbTi rods to split sub-elements*
- Cable optimization studies to minimize edge damage while retaining mechanical stability
- Successful completion of production-scale HTS cabling runs for Showa

Strand Optimization

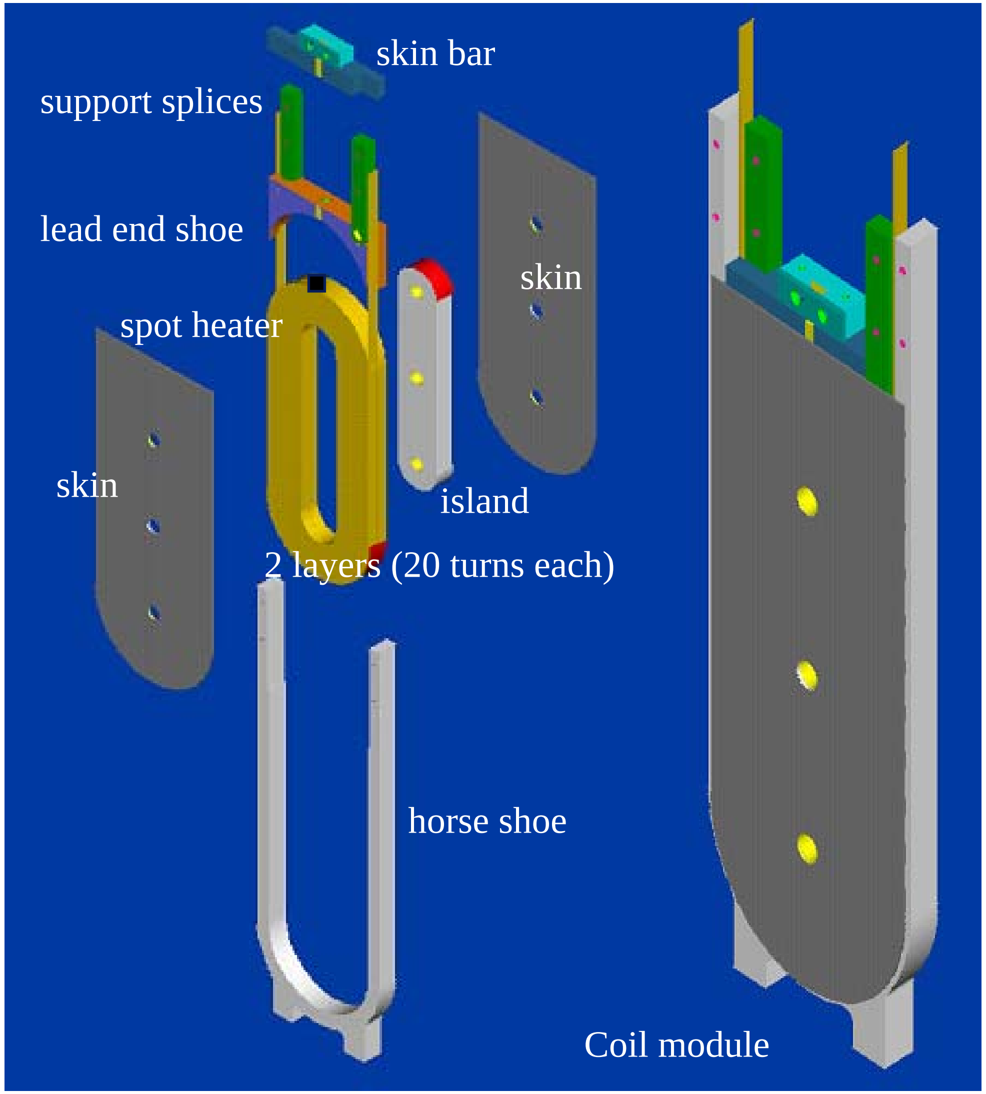


Cable Optimization



Technology R&D with sub-scale coils

- Two-layer racetrack coils
- Field range of 9-12 Tesla
- Fully instrumented
- Cost-effective, rapid turn-around
- Testing in small dewars
- R&D topics:
    - *conductor & cable*
    - *coil heat treatment*
    - *new insulation schemes*
    - *instrumentation development*
    - *modeling & analysis*
    - *mechanical structures*
    - *fabrication procedures*
    - *parametric studies*
    - *quench limits*
    - ...



Bi-2212 Coil Technology Development

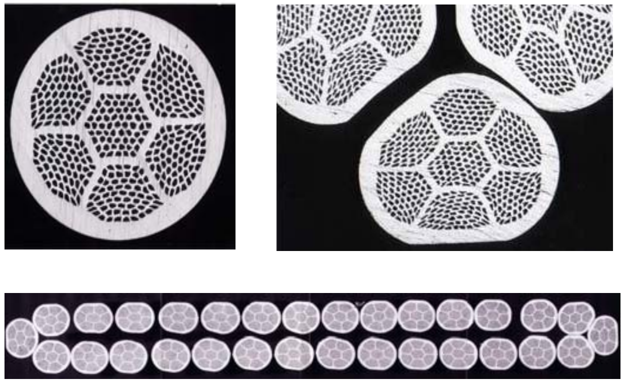
HD1 & HD2 operate close to the limits of Nb_3Sn

R&D plan to approach a 20 T dipole field:

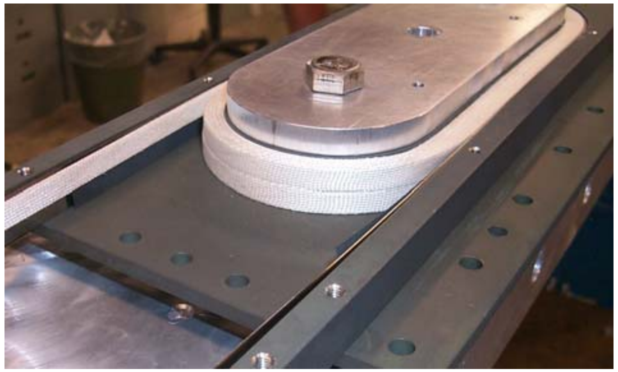
- Fine-tune Nb_3Sn performance to its full potential
- Introduce design features for high-field coil inserts
- Develop Bi-2212 W&R coil technologies:
  - *Cabling parameters and winding procedures*
  - *Heat treatment of large thermal mass at*
  - *Optimization of oxygen flow during HT*
  - *Chemical compatibility (insulation, structure)*

First steps are planned for 2007:

- HTS wind-and-react coil fabrication
- High field cable testing in HD2

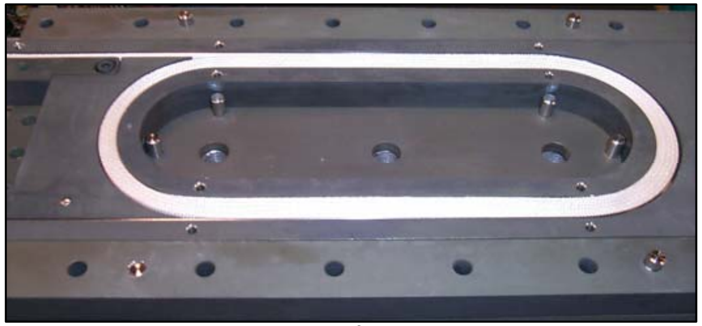


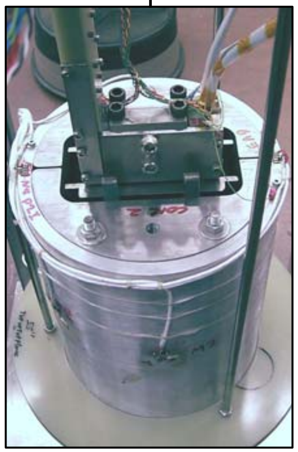
Cable fabrication



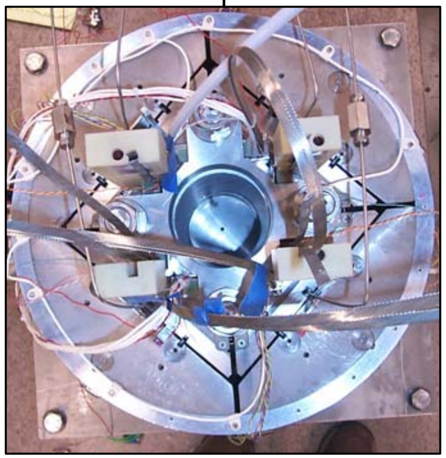
Dummy coil for HT studies

Sub-scale magnet tests

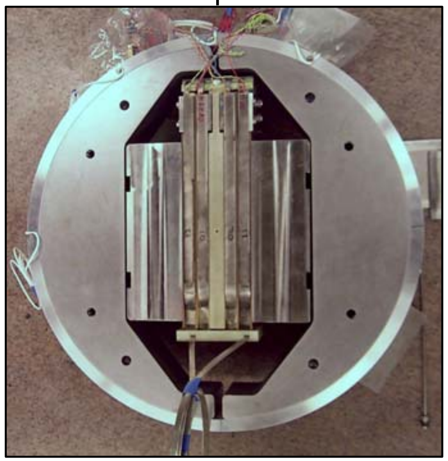




SM
Low field
Low stress



SQ
High stored energy
High Axial forces



NMR
4-coil layout
High field

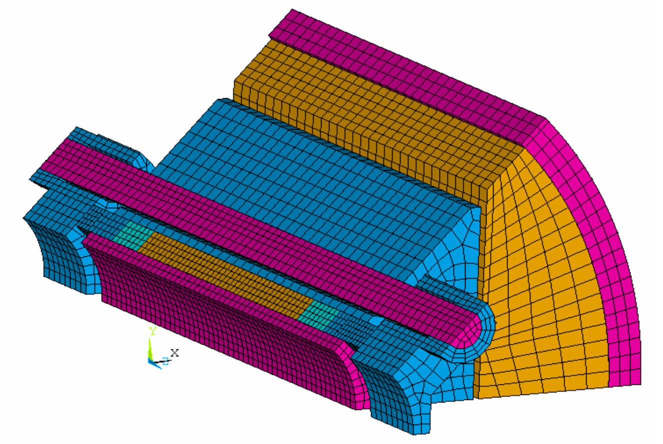
SD
High field
High stress

Modeling & Analysis

- Full integration of CAD & analysis tools
- Coupled magnetic, mechanical, and thermal analysis across different platforms
- Modeling of the mechanical behavior of the 3D structure from assembly to excitation: coil end displacements and gaps
- 3D quench propagation modeling, computation of the thermal stress

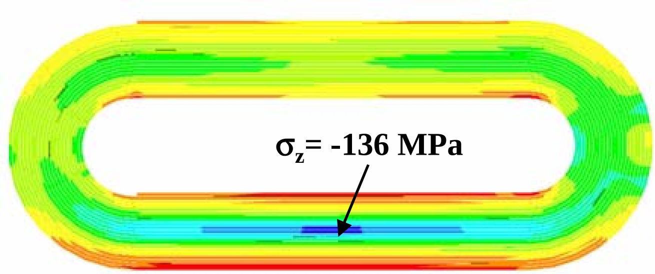
<ins>In progress:</ins>

- Analysis of the interfaces between structural components (friction, frictionless, bonded)
- Analysis of irreversible coil displacements during excitation cycles (ratcheting)
- Evaluation of frictional energy dissipation during excitation cycles



3D structural analysis

Thermo-mechanical transients

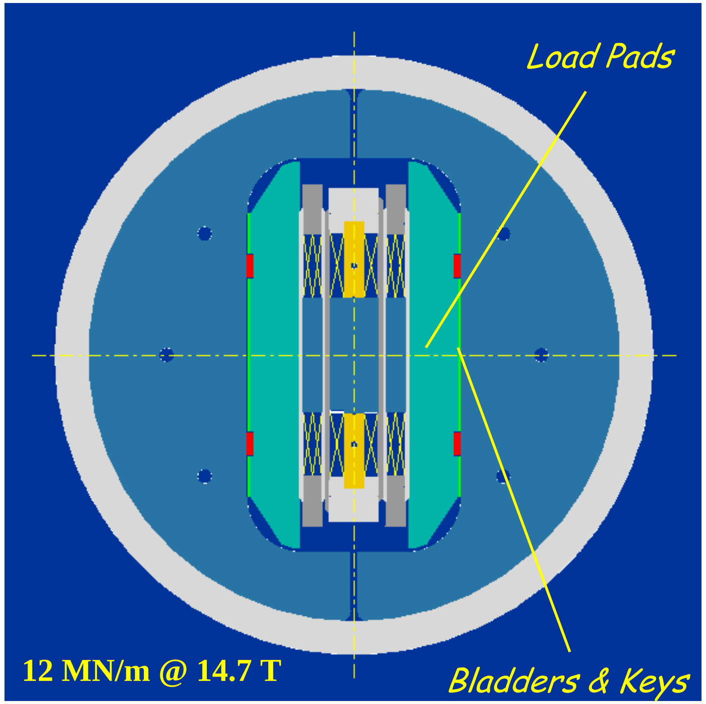


Axial & turn to turn velocity;Temp. & voltage

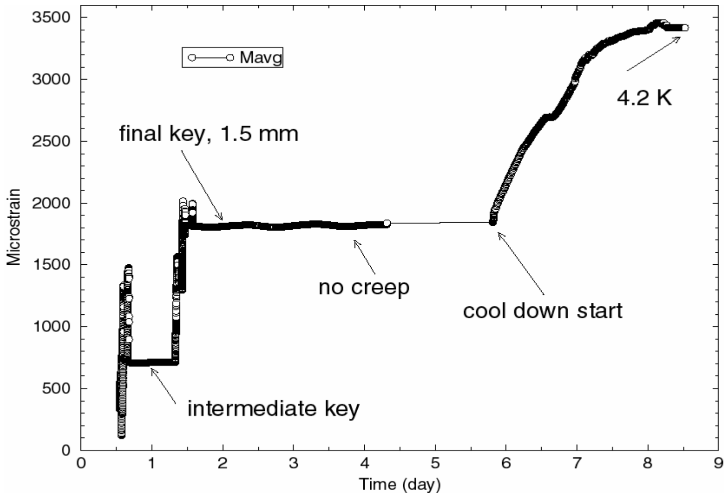
Mechanical Structures & Assembly

Aluminum shell over iron yoke for large stress increase at cool-down

RD3b Common Coil Magnet



Magnet Assembly and Cool-down

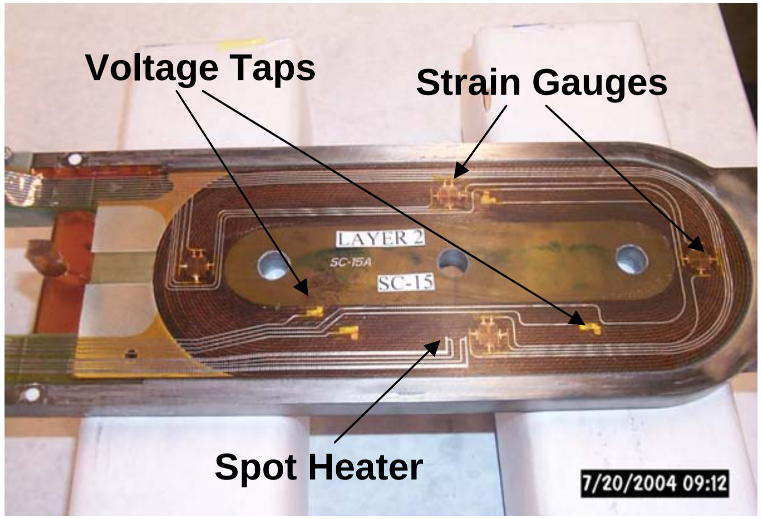


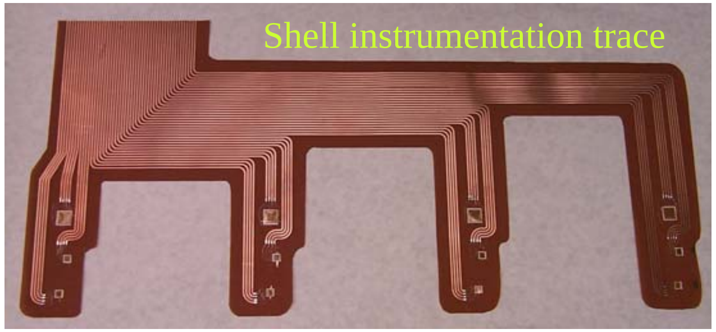
- Water-pressurized bladders for accurate pre-load control & easy assembly/disassembly
- Sub-scale program played a critical role in the development of this concept

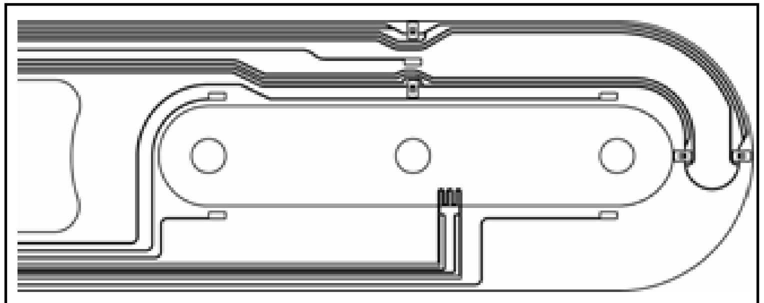
Coil and Structure Instrumentation

- Traces are modeled on CAD: accurate documentation, including strain gauge orientation
- CAD plot provides full-size artwork for photo-etching the copper-on-kapton trace medium
- Traces are also used on the shell to facilitate installation of multiple gages and route signals to connector locations.

SC coil instrumentation





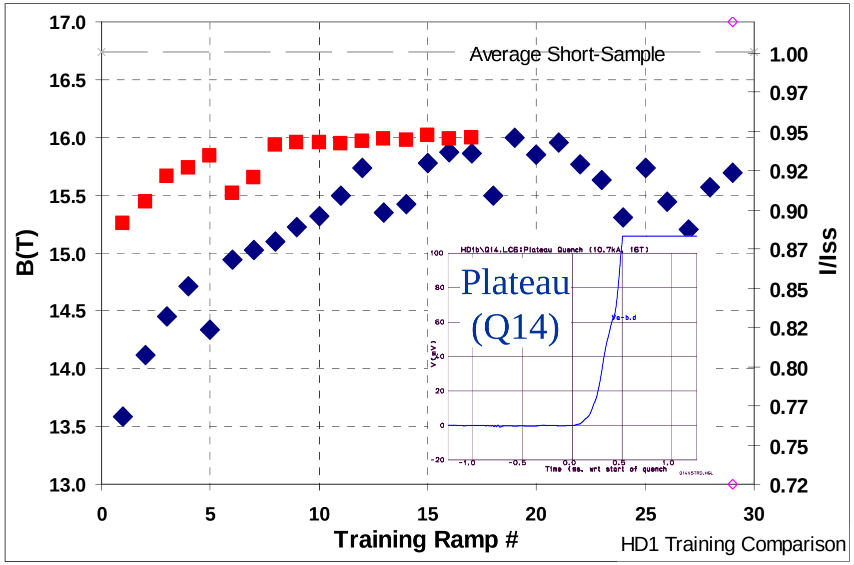


SC coil instrumentation trace

Quench Diagnostics

- Fast-flux diagnostics helps understand magnet performance
- Improvements due to lower noise levels
- Adding capability to identify locations

HD1 & HD1b Quench Performance

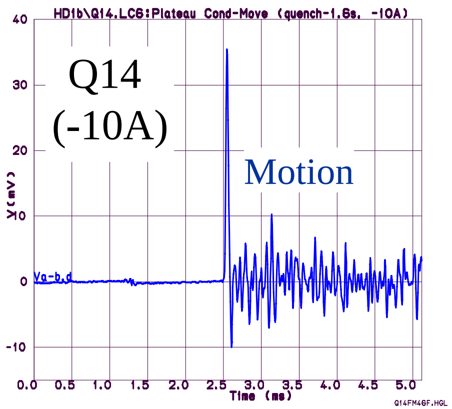


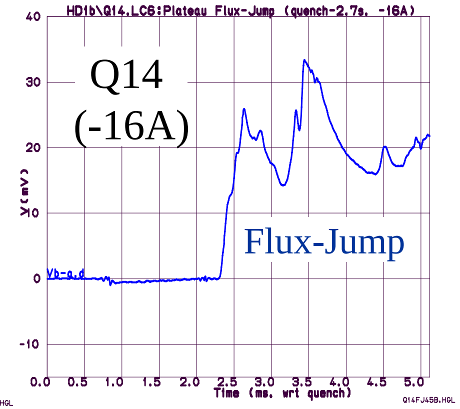
Type of events:

Flux Jump:
- “Slow” (10 ms)
- Low current
- No training
- Repeat at down ramp

Stick-slip:
- “Fast” (0.1 ms)
- High current
- Some training
- Not at down ramp

No precursor:
- exhausted margin
- plateau quenches





Accelerator Quality Magnets

- Achieving the required field is the first step for successful magnet development
- Pushing the field limits requires technological advances in many areas
- Design simplifications may be appropriate to focus R&D on fundamental issues
- However, design approaches need to be extendable to accelerator quality magnets
- Accelerator quality features need to be included and experimentally demonstrated

Fundamental requirements:

- Deliver required aperture
- Meet field quality specs
- Lifetime under radiation load
- Fabrication in long length

Efficiency/cost issues:

- Operate close to critical surface
- Minimize displacements and training
- Minimize conductor & structural needs
- "Simple", reliable fabrication procedures

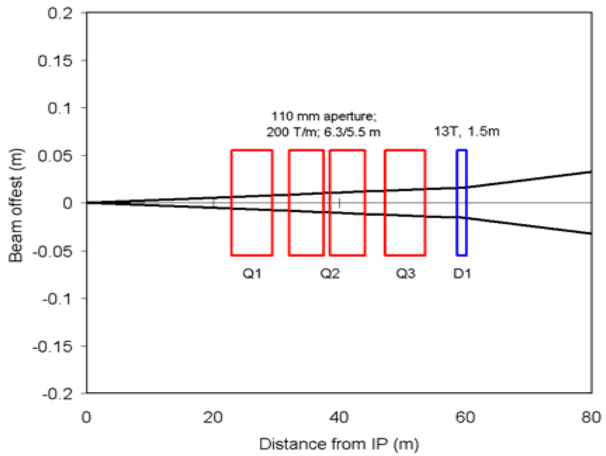
Accelerator quality development *underway under both core program and LARP*
Core program: *high field block-dipoles*; LARP: *high-gradient shell-type Quads*

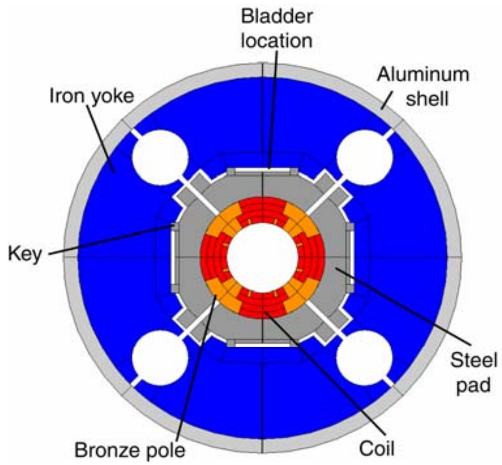
LHC Luminosity Upgrade Magnets

Quad first optics

⇒ IR Quads

- Large aperture
- High gradient
- IR radiation
- Collision FQ

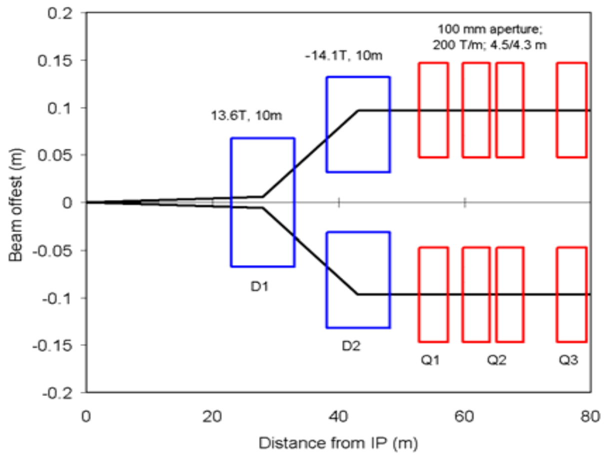


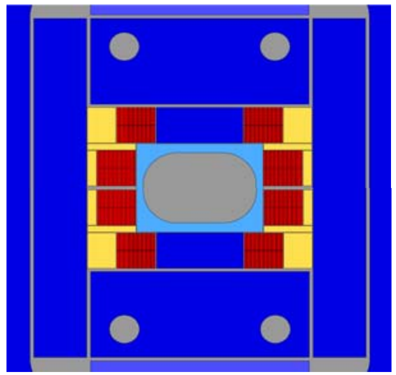


Dipole first optics

⇒ IR Dipoles

- IR radiation
- Coil stress
- Large aperture
- High field





The LHC Accelerator Research Program (LARP) coordinates the US-DOE effort

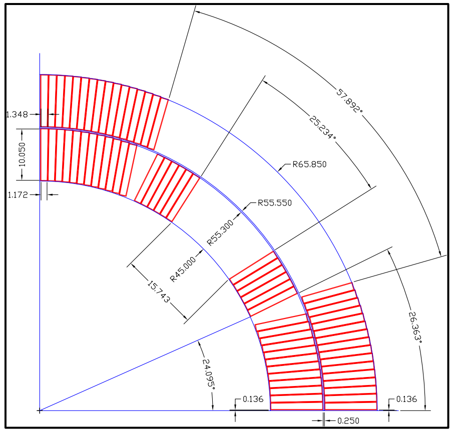
Technology Quadrupoles

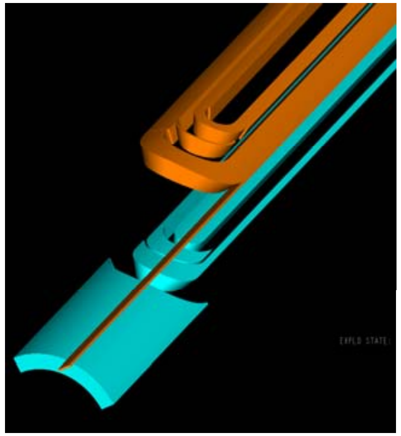
- Main Parameters: aperture = 90 mm, L = 1 m, Gradient > 200 T/m
- Nb_3Sn is required for high gradient and temperature margin
- Two series of models suing the same coils and different structures
- LBNL is focusing on a shell-type structure (TQS series)

TQ Coil Design and Fabrication

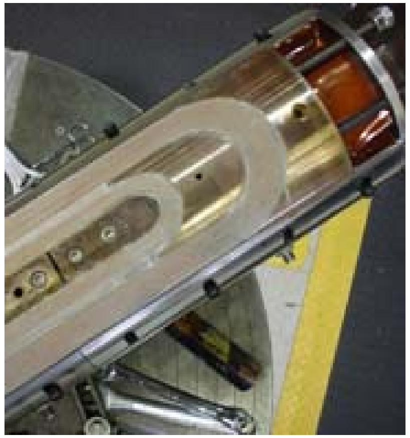
Design features:

- Double-layer, shell-type
- One wedge/octant (inner layer)
- TQ01: OST-MJR strand, 0.7 mm
- TQ02: OST-RRP strand, 0.7 mm
- 27-strand, 10.05 mm width
- Insulation: S-2 glass sleeve





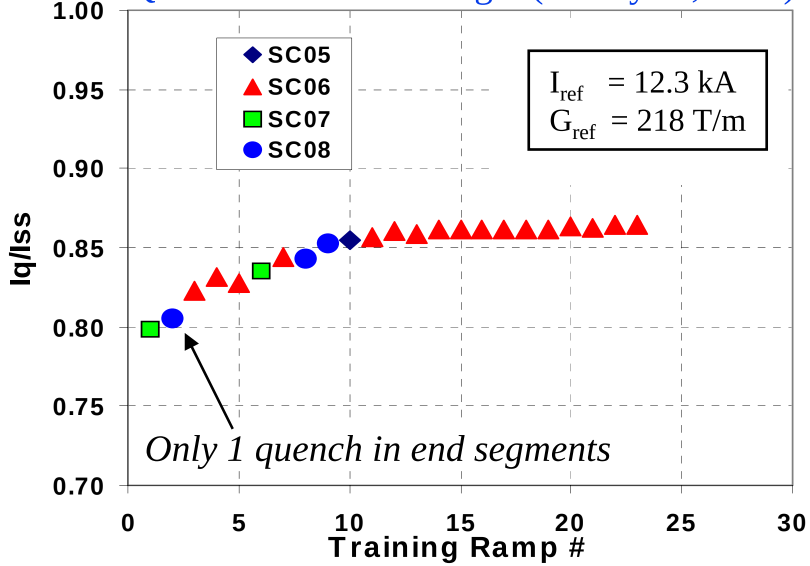
Winding & curing (FNAL - all coils)



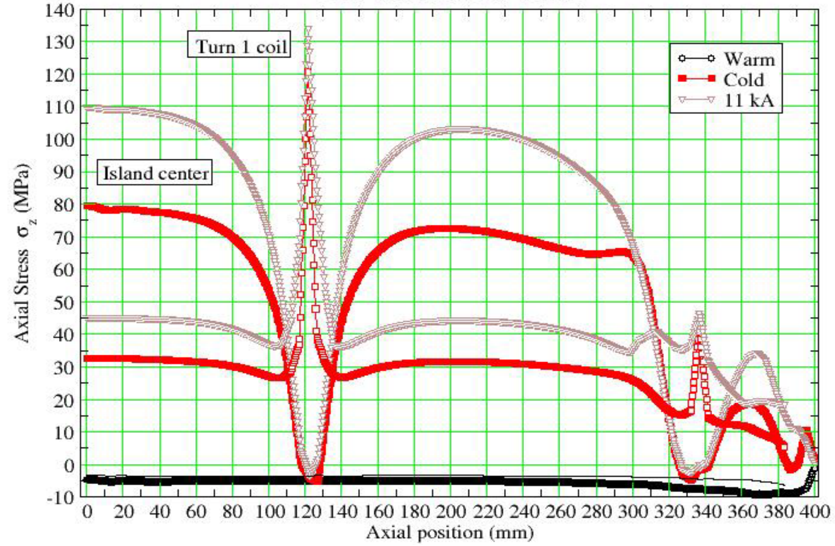
Reaction & potting (LBNL - all coils)

TQS01 Performance Analysis

Quench current and origin (first cycle, 4.5K)



Calculated axial stress at pole gap (3D FEA)

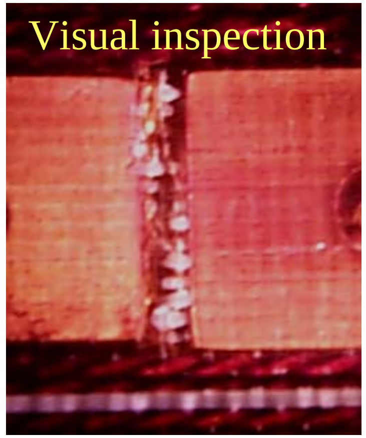


Analysis findings:

- Performance limit in the "pole-gap" area of coil 6
- FEA results: coil axial tension spike in gap area
- Post-test inspection shows epoxy tearing (all coils)

Corrective actions:

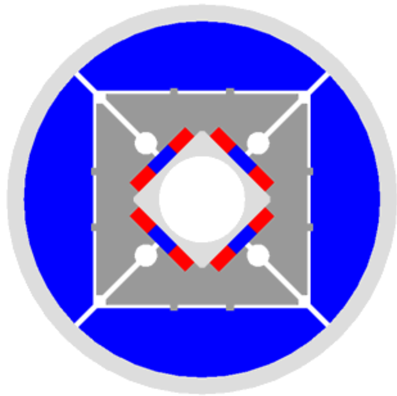
- TQS01b: replace coils & decrease coil/pad friction
- TQC02: eliminate co-planar gaps in the two layers
- TQS02: low thermal contraction material in pole

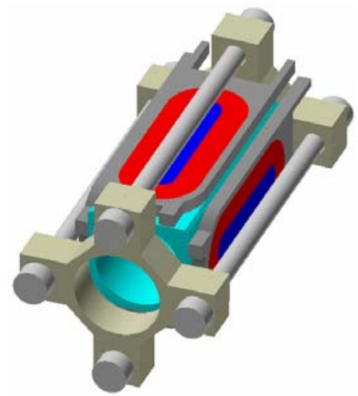


Supporting R&D with sub-scale Quads

Design:

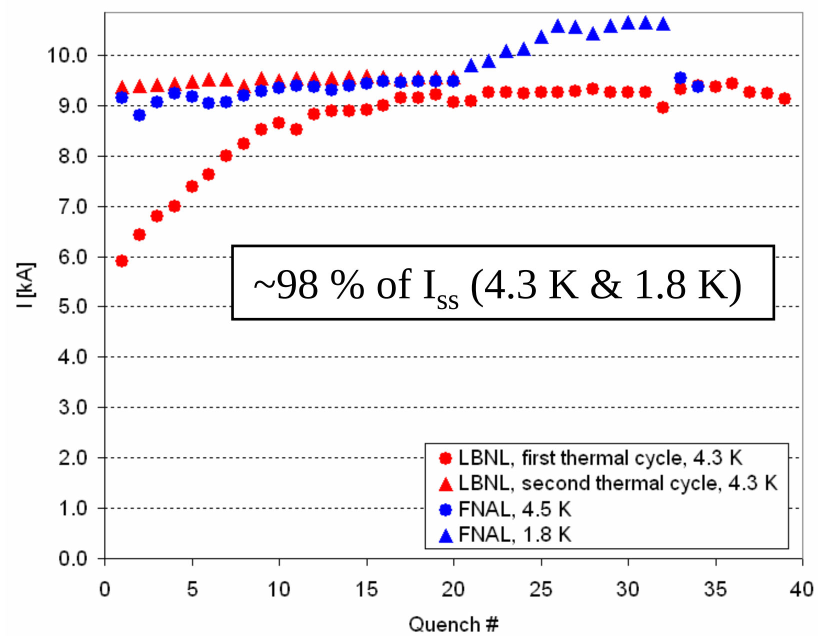
- 4 racetrack coils in square configuration
- Coil aperture 130 mm (clear bore 110 mm)
- Shell-based structure w/axial load (TQS)
- Similar load line as TQ (11.3 T @460 A)
- Similar coil stress as TQ (100-130 MPa)
- Similar axial force as TQ (350 kN @ Iss)





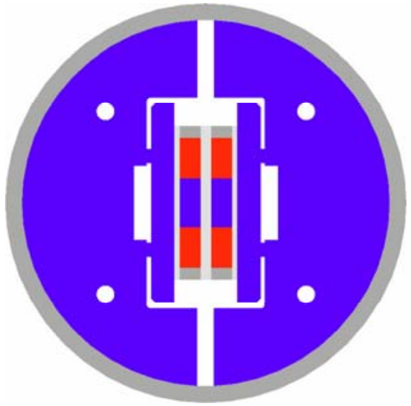
Results:

- 2 magnets, 2 tests each (LBNL/FNAL)
- Cable and conductor evaluation
- Verification of heat treatment for TQ
- Verification of conductor stability
- Evaluation of stress degradation
- Analysis of quench initiation and training
- Study of the effect of axial load
- Improved assembly procedure

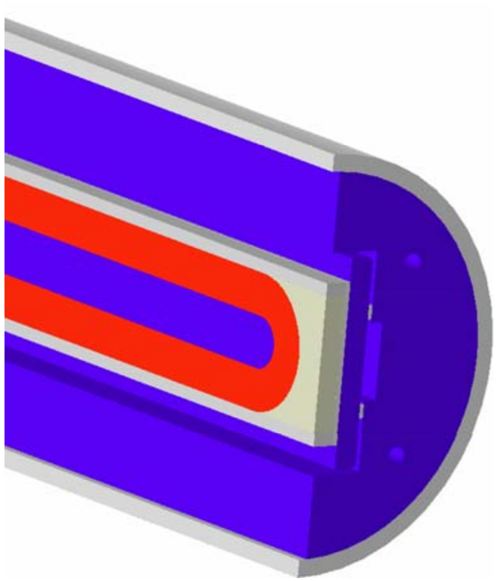


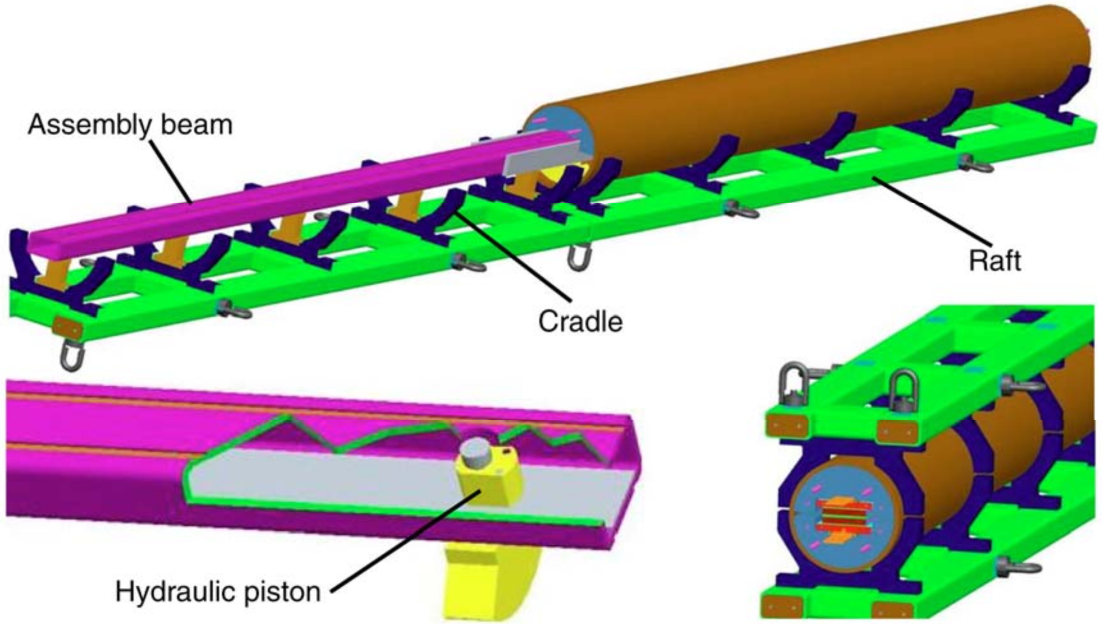
Nb_3Sn Magnet Length Scale-up

<u>*First step: supporting R&D with Long Racetrack dipole (LR):*</u>



- simple coil design → focus on length dependent issues
- well understood baseline (SC/SM subscale program)
- common coil dipole – lower forces, energy, pre-stress
- coil fabrication/assembly at BNL, structure from LBNL
- opportunity for scale-up of shell-based structure (TQS)





Summary

Progress:

- Established a **technology foundation for fields up to 16 T**
- Expanding the **accelerator magnet design toolbox**
- Improved **analysis of magnet behavior**

Challenges: accelerator quality and fields beyond 16 T

- **Materials**: superconductors, insulation, structural
- **Coil design:** field quality, efficiency, simplicity
- **Coil fabrication technologies**
- **Mechanical structures** and stress limits
- **Scale-up** to long coils and structures