INTERNATIONAL SCHOOL OF FUSION REACTOR TECHNOLOGY:
Course on “SUPERCONDUCTING MAGNETS: CASE STUDIES”

Erice, Sicily

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Magnet Technology for Accelerators

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Enabling Technology: High Energy Physics

80 Years

From this . . . to this . . .

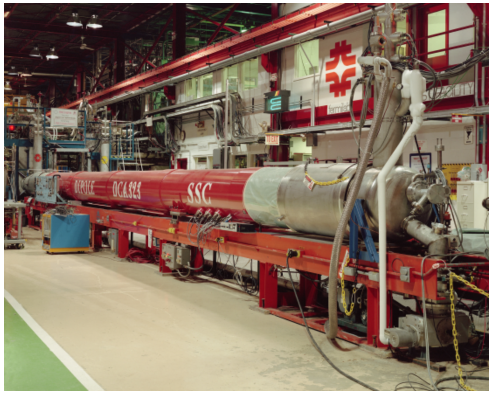
Superconducting magnets have been an enabling technology for accelerators for decades

Accelerator Magnets

Then . . .

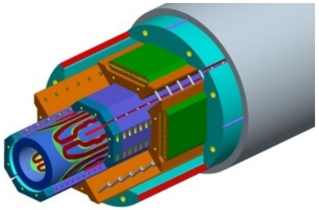
- The Tevatron (Fermilab) 1983
  - 4.4 T , NbTi, 4.2K

- HERA, SSC, UNK, RHIC



And now . . .

- LHC 2007
  - 8.3 T, NbTi, 1.9K
  - Limit of NbTi
- US LHC Upgrade
  - Nb_3Sn quadrupoles



- FAIR
  - High ramp-rate

Accelerator Magnets: Key components of particle accelerators

- **RF accelerates particles and magnets steer them in a closed orbit**

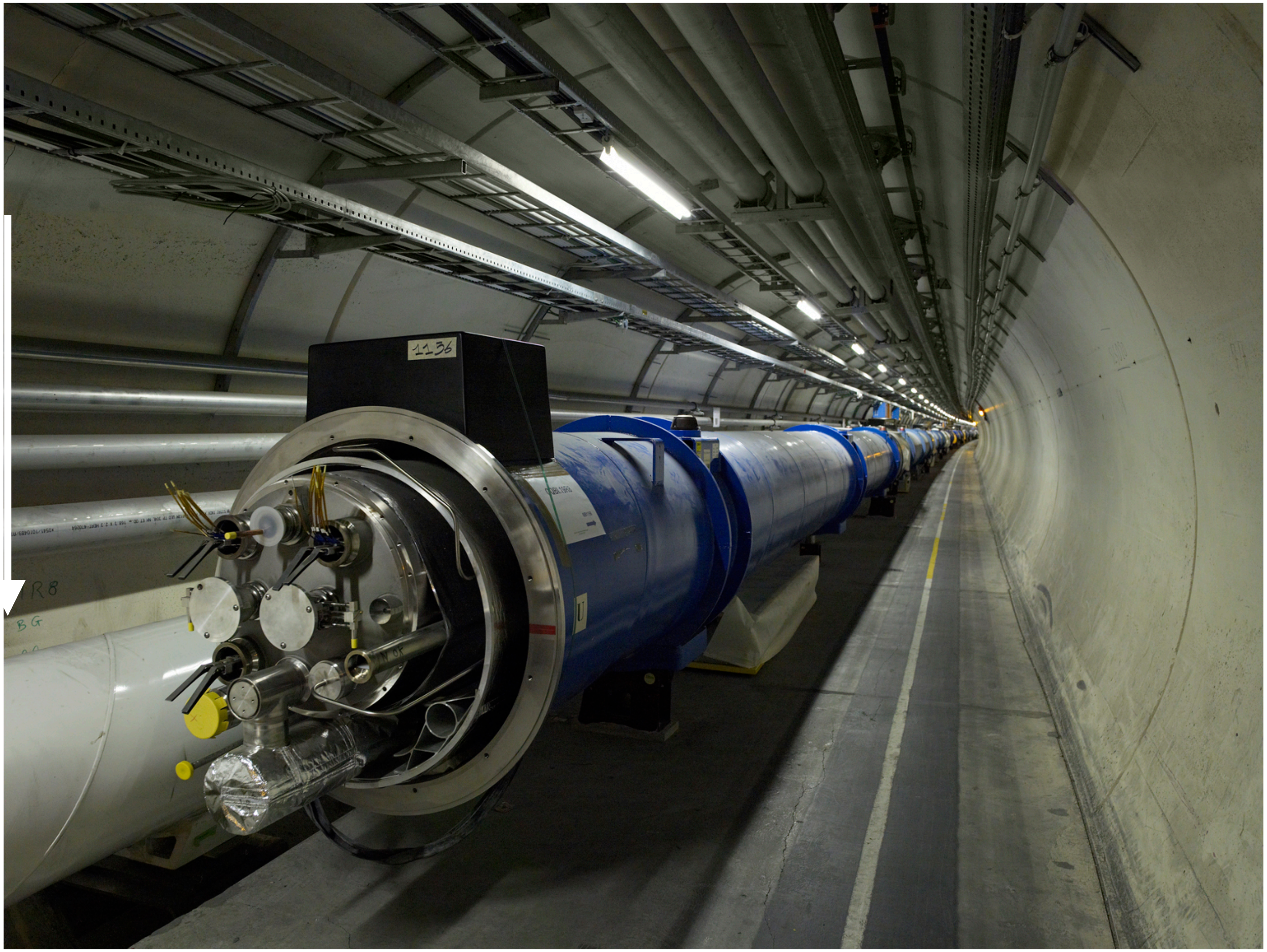
$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

  - — **Arcs – bending and focusing (dipoles and quadrupoles)**
  - — **Straight sections – focusing in Interaction Regions where collisions occur**

- **Size of accelerators (order kilometers)**
  - — **Require many magnets (order 100's – 1000's)**
    - **Means cost is a major consideration**
  - — **Variety, but many which are identical**
    - **Potential to reduce cost**

- **Function, combined with cost, determines design**

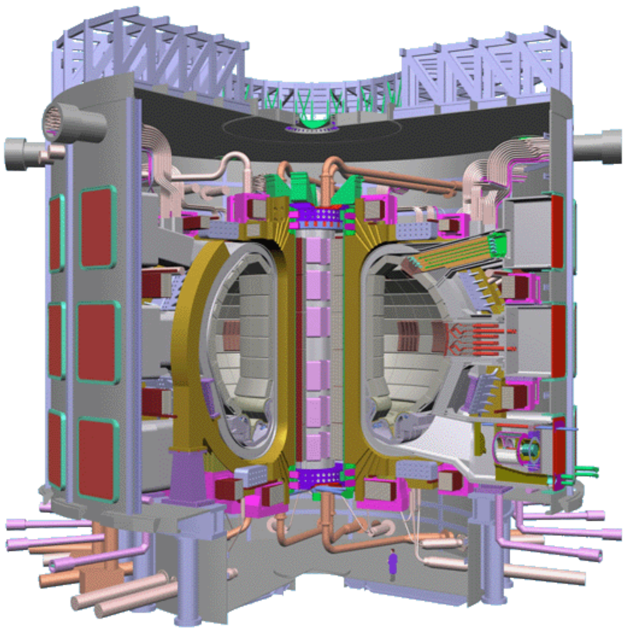
LHC Tunnel



Magnet Technology Comparison

Example of how function determines design –

Fusion Magnets vs Accelerator Magnets



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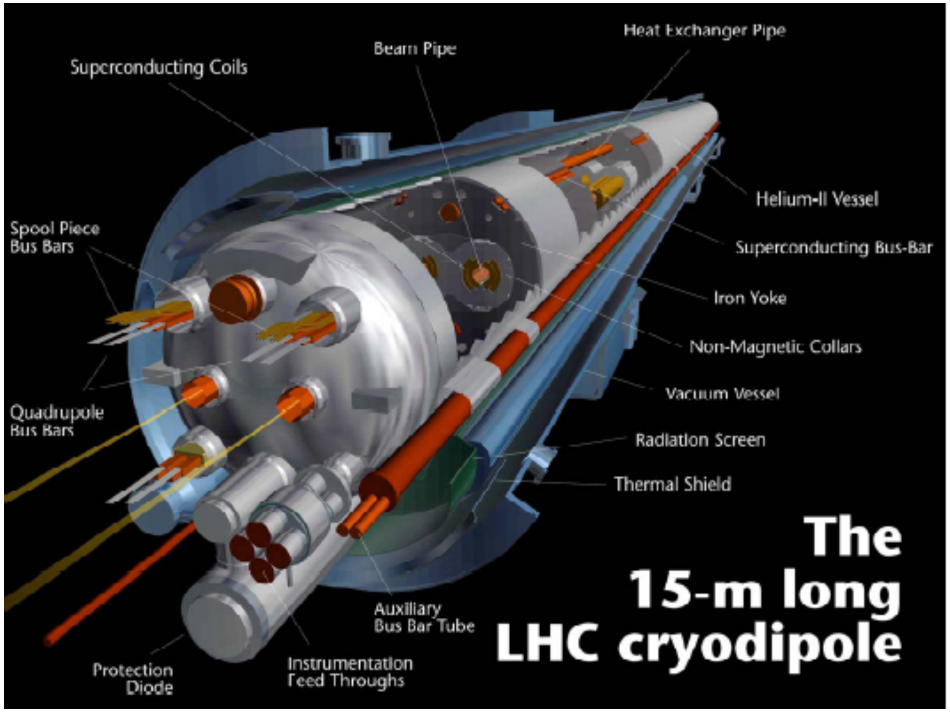

Magnet Technology Comparison

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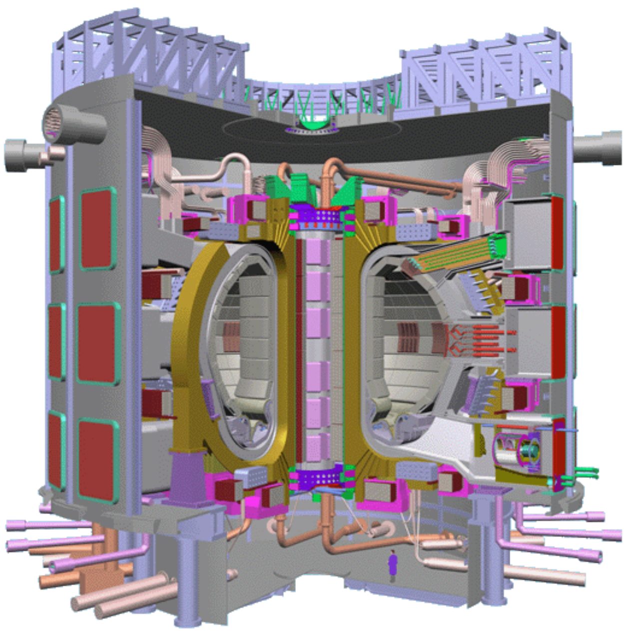

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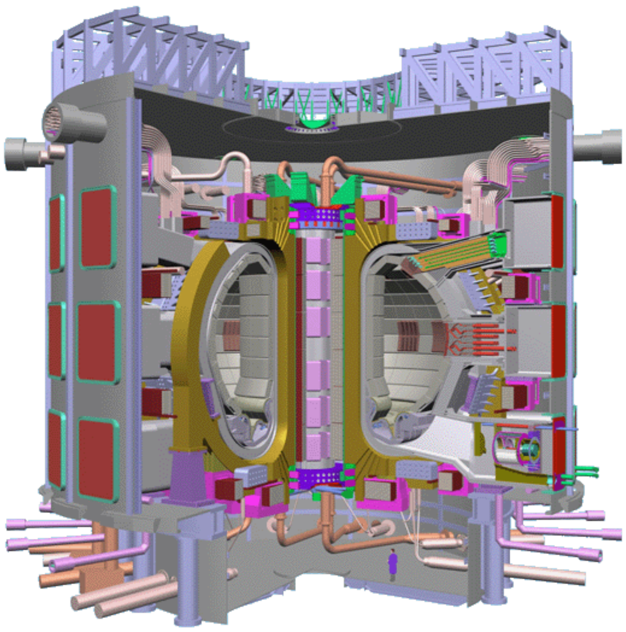
LHC Dipole

Magnet Technology Comparison

Example of how function determines design –

Fusion Magnets vs Accelerator Magnets



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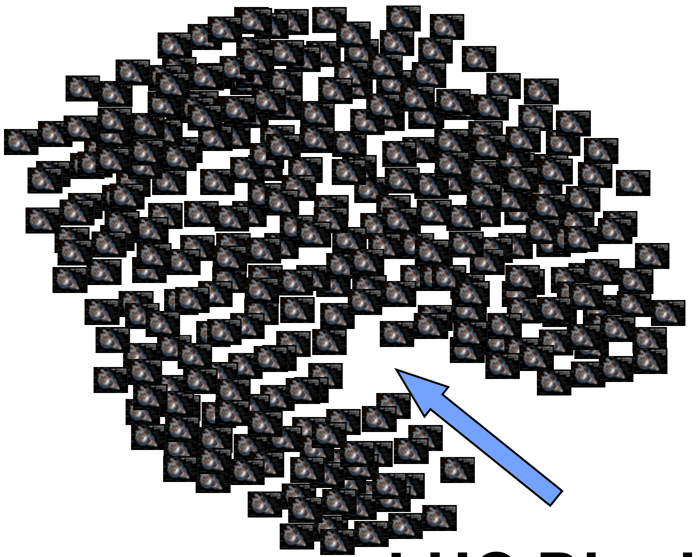


LHC Dipoles

Accelerator Magnet Design Drivers

- **Performance**
  - **Field Quality – higher order poles on order of 10^{-4} of primary field**
    - **Precise placement of conductor**
  - **Field – higher fields usually desirable in most all applications**
    - **High stress – support structures**
  - **Large number of magnets with highly reproducible characteristics**
- **Cost**
  - **Typically dominant component of facility**
  - **Magnets for SSC > 60% of total**

Leads to . . .

Magnet/System Cost

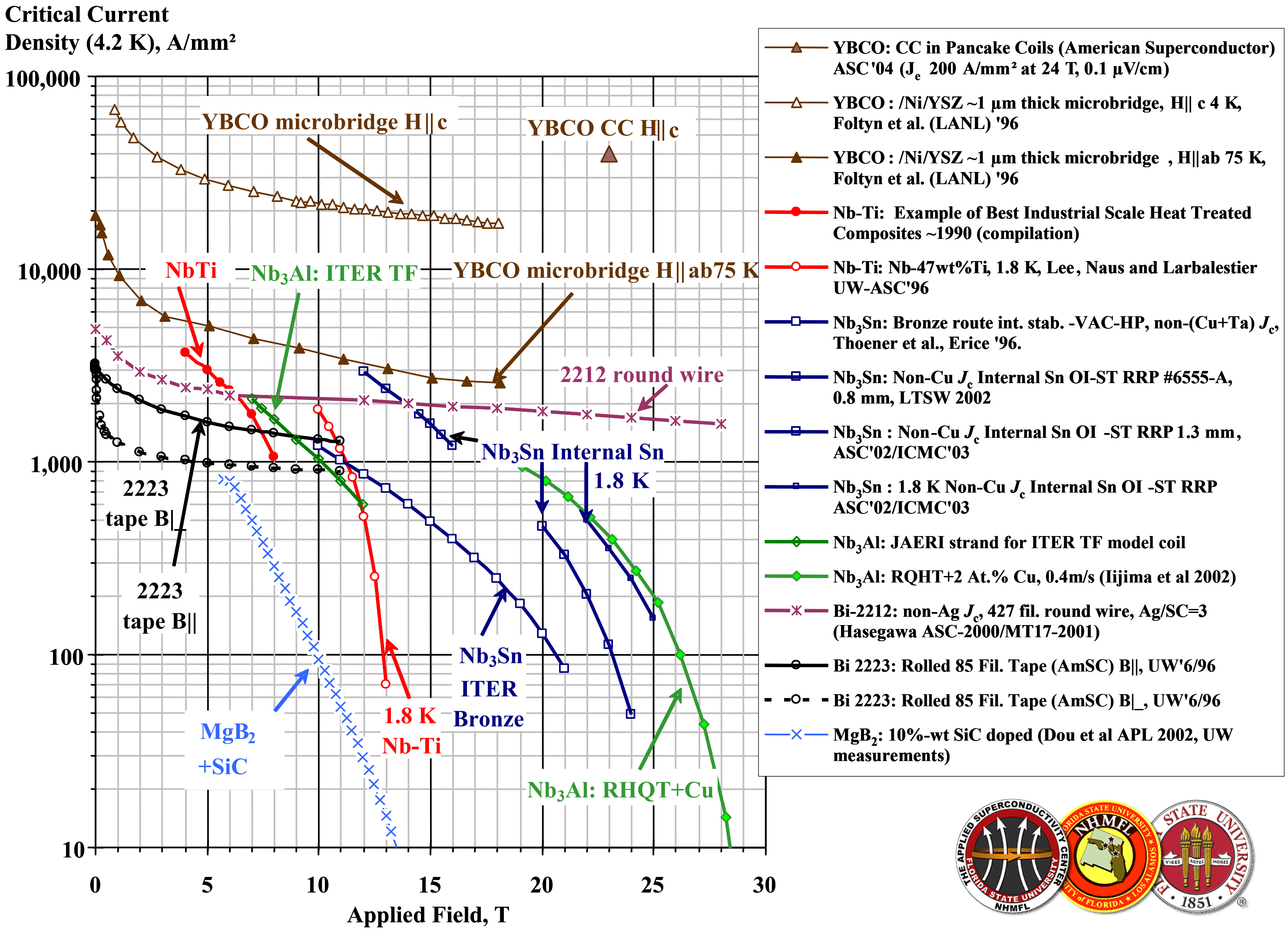
- Number of magnets (fewer, longer)
- Quantity of conductor (> 20% of cost)
  - Small Bore (compact design) order of 10's of mm
    - Very high current density
- Stored energy in MJ's, but strings of magnets raise total
  - Require active quench protection
    - Design for quench (heaters, by-pass diodes)
- Operating currents
  - 10 – 30 kA

Conductors for Accelerator Magnets

- **Conductor ultimately determines magnet performance**
  - **You can't do any better than the virgin conductor**
  - **But . . . you can do worse!**
- **With few exceptions all accelerator magnets use Rutherford-style cables**
  - **Multi-strand – reduce strand length, fewer turns (lower inductance)**
  - **High current density**
  - **Precise dimensions – controlled conductor placement (field quality)**
  - **Current redistribution – stability**
  - **Twisting to reduce interstrand coupling currents (field quality)**

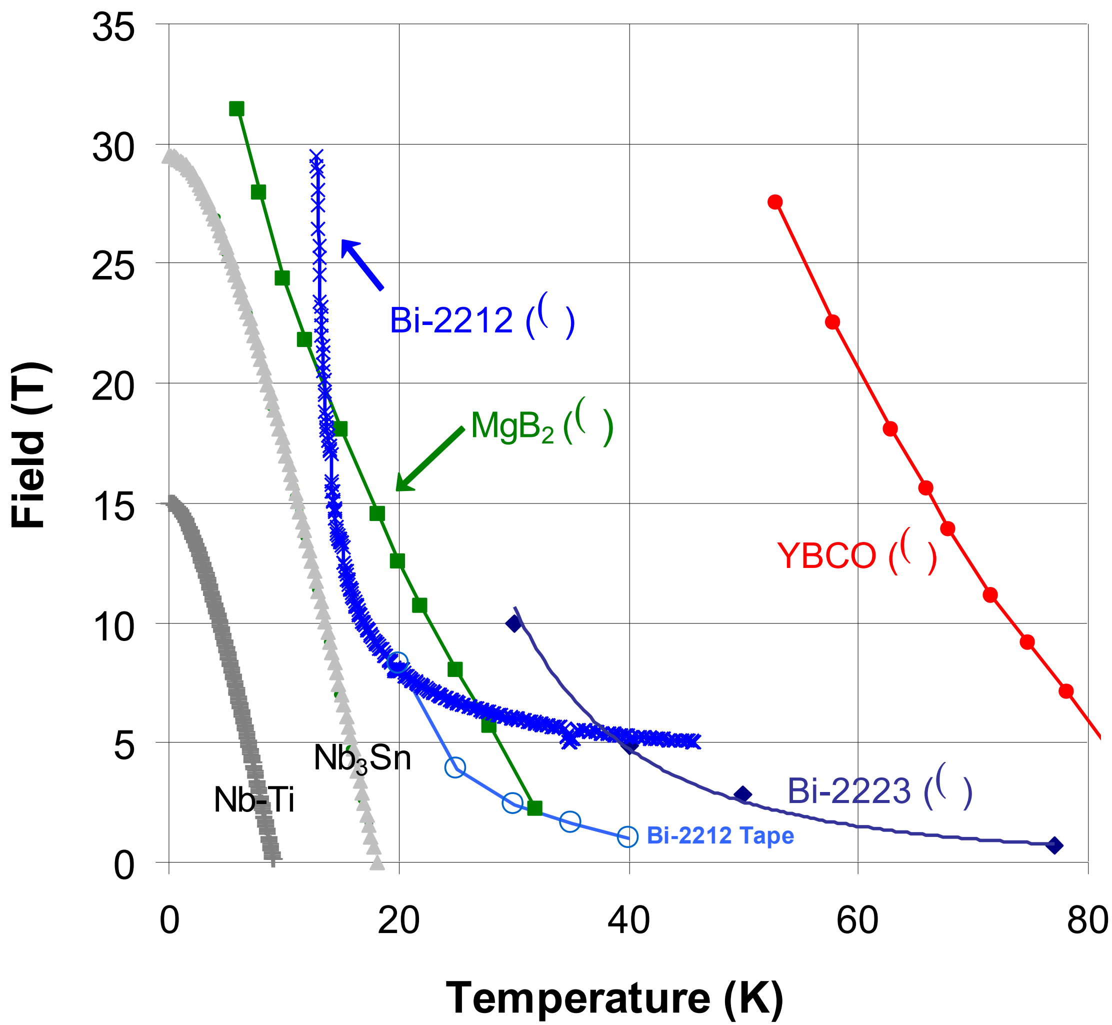
Let's start with the materials . . .

Basic Properties: Critical Current Density (J_c) vs Field



Courtesy of P.J. Lee, Applied Superconductivity Center at the National High Magnetic Field Laboratory, FSU

Field vs Temperature

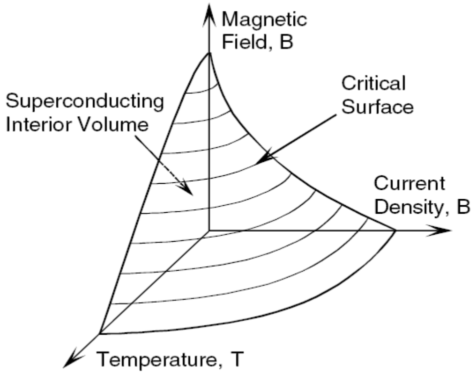


Courtesy D. Larbalestier, Applied Superconductivity Center at the National High Magnetic Field Laboratory, FSU

Materials for Accelerator Magnets

Application/performance ⟷ material properties and engineering

- **NbTi**
  - — B_{c2} (0K) ~ 14 T
  - — T_c (0K) ~ 9.5 K
    - Max practical field at 4.2 K is 7 T (9 T @ 1.8 K)
    - Excellent mechanical properties
- **Nb_3Sn**
  - — B_{c2} (4.2 K) ~ 23 – 24 T
  - — T_c (0T) ~ 18 K
    - Max practical field 17 – 18 T?
    - Brittle and strain sensitive

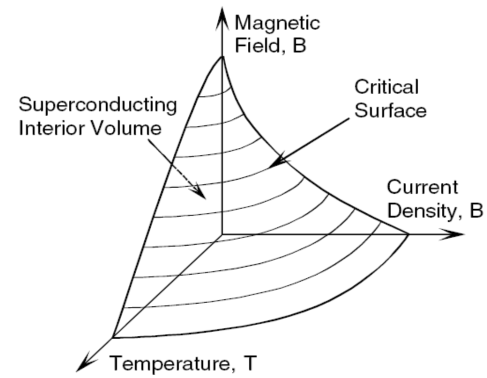


- **Nb_3Al**
  - — High J_c in magnetic field < 15 T
  - — Mechanical toughness
    - Rapid-quench process requires later addition of stabilizer
    - Actively pursued in Japan
      - – National Institute for Materials Science (NIMS)

Materials for Accelerator Magnets

Application/performance **material properties and engineering**

- **Bi-2212**
  - — Round strands in long lengths
  - — React and wind only option for large coils?
    - Strain sensitive



- **Bi-2223**
  - — Tapes in long lengths
  - — Applications for high temperature
- **YBCO**
  - — Tapes (not wires!)
  - — High critical current but length is a problem

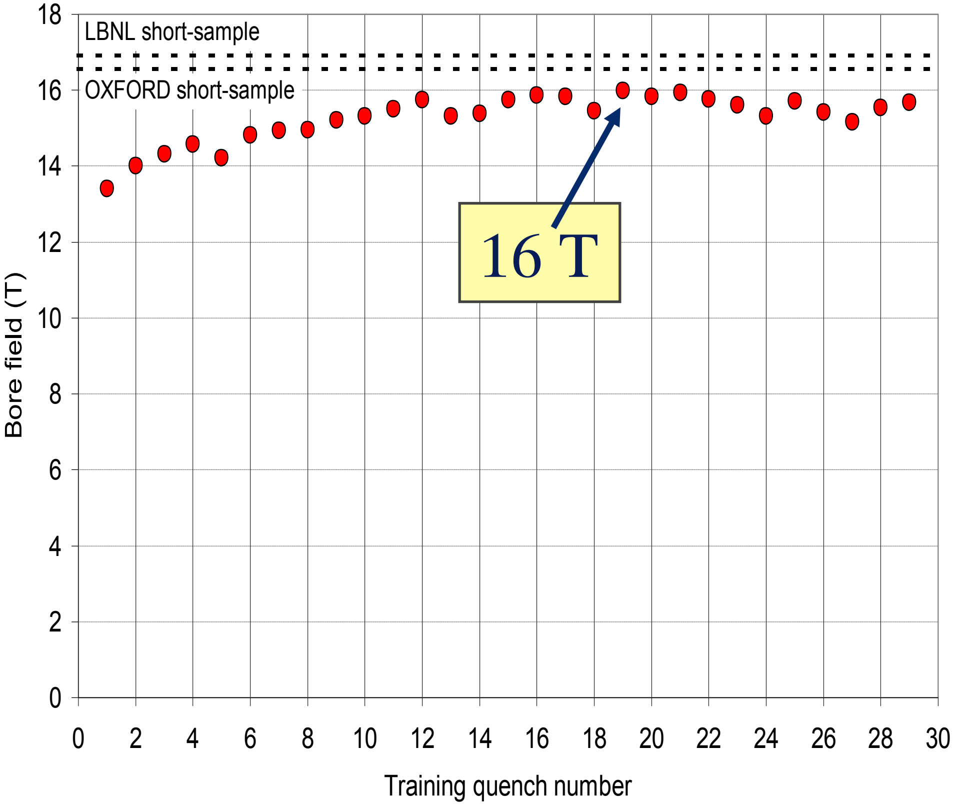
- **MgB_2 (not so HT HTS)**
  - — Better at T < 25K
  - — Anisotropic
  - — Low J_c (so far)
  - — Stabilization

But . . .

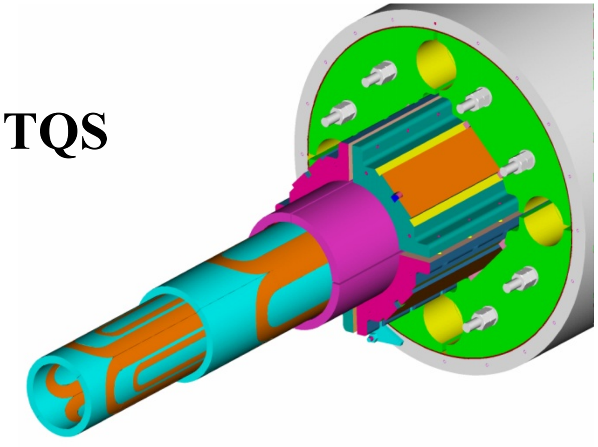
  - — Potential to exceed H_{c2} of Nb_3Sn
  - — Low cost materials

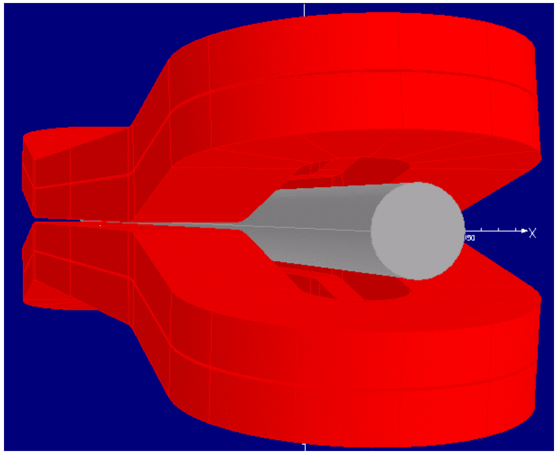
LBNL High Field Magnet Program

HD-1 16T Dipole



TQS



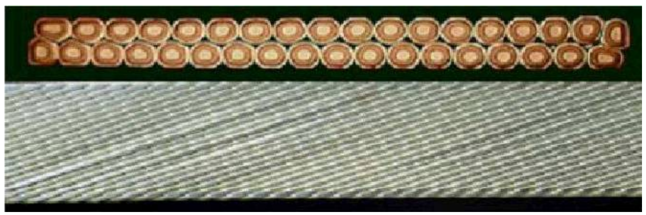


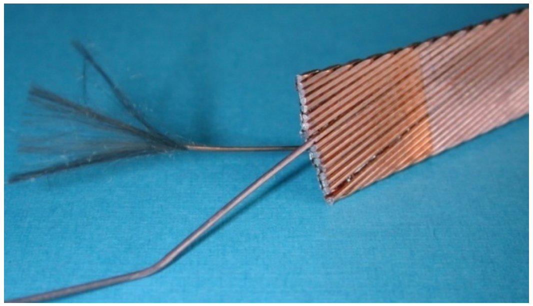
HD-2

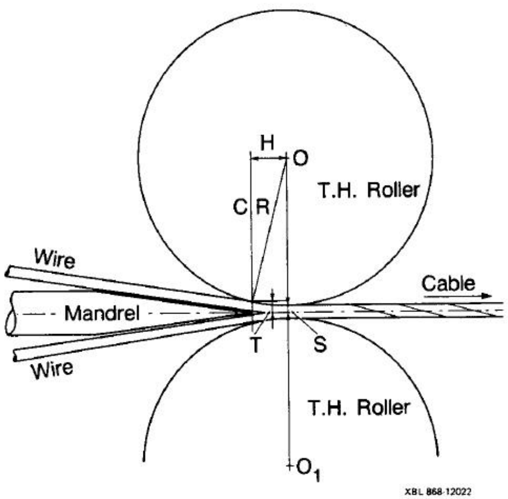
Rutherford Cables

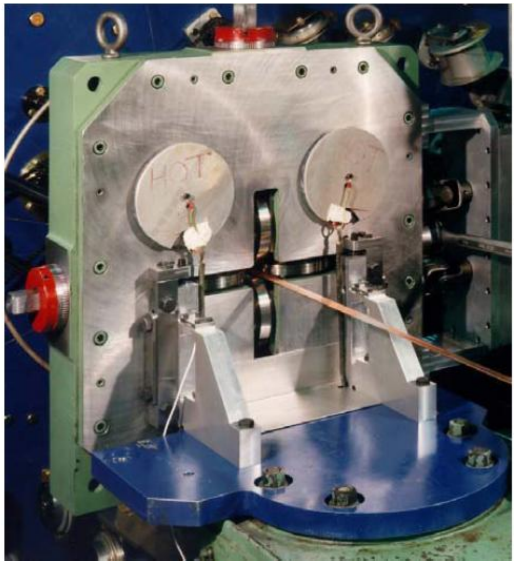
- **Cable cross-section is rectangular or trapezoidal**
- **Packing Fraction (PF) ranges from 85% - 92%**
  - **Too much compaction – damage to filaments**
  - **Too little compaction – mechanically unstable**

$$PF_{cable} = \frac{N_{wire} \pi d_{wire}^2}{4 w_{cable} t_{cable} \cos\psi_{cable}}$$

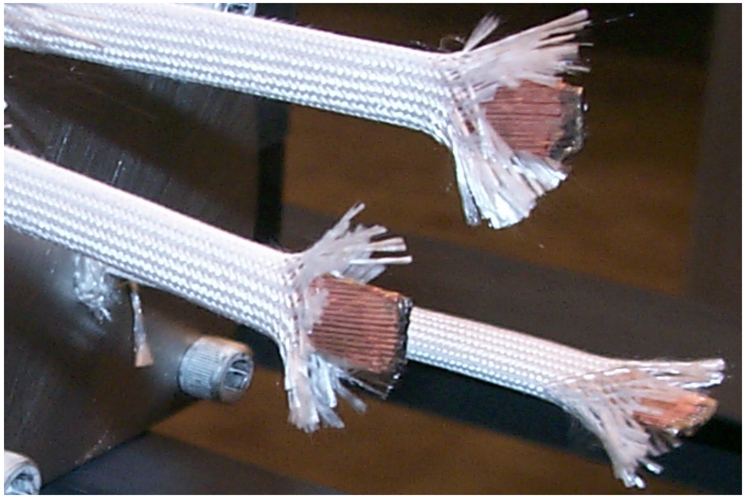






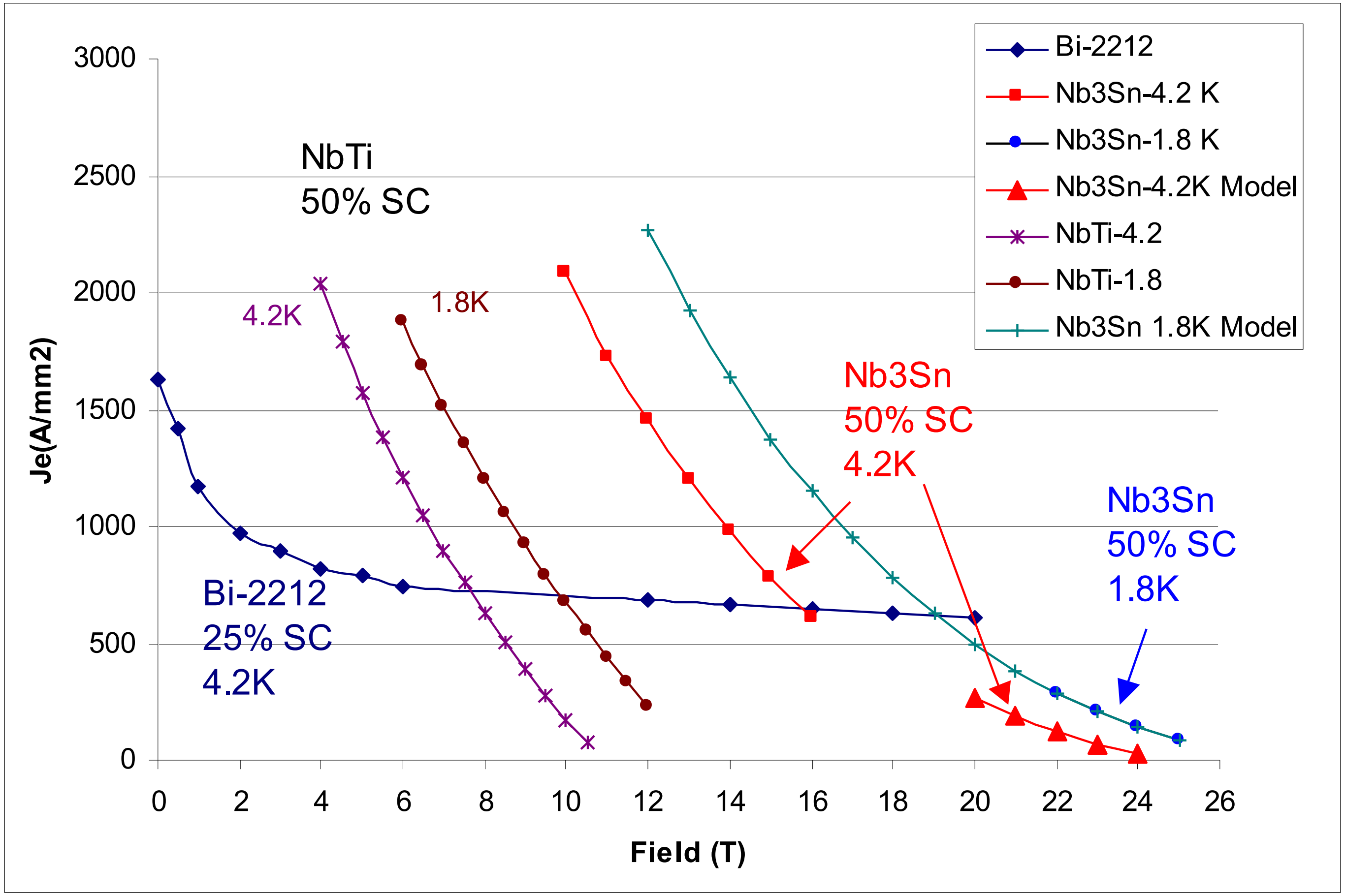


Current Density



- **Start with J_c of Superconductor**
  - — NbTi ~ 3,000 A/mm^2 @ 5T and 4.2K
  - — Nb_3Sn ~ 3,000 A/mm^2 @ 12T and 4.2K
- **Add copper/non-Superconductor**
  - — Typically ~50%
- **Cable compaction ~88%**
- **Insulation – order of 100 microns (X2) compared to ~2 mm cable thickness**
- **Filling factor = $(N_{wire}\ A_{sc})/A_{ins\_cable}$**
- **Engineering current density defined as $J_e = \kappa\ J_c$**
  - — Typically on the order of 1,000 A/mm^2

Magnet Conductor Comparison



Electromagnetic design

Accelerator Magnet Field Quality

- **Field components expressed as**

$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x + iy}{R_{ref}} \right)^{n-1}$$

EU notation

- **Coefficients (b_n and a_n) are normalized with the main field component (B_1 for dipoles, B_2 for Quadrupoles)**

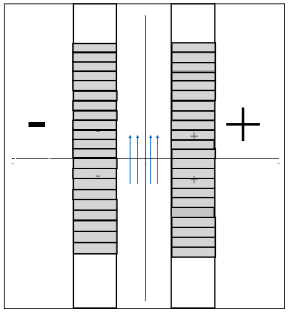
- **Dimensionless coefficients defined WRT reference radius**
  - **R_f = 2/3 of coil diameter (typically) and given in units of 10^{-4}**

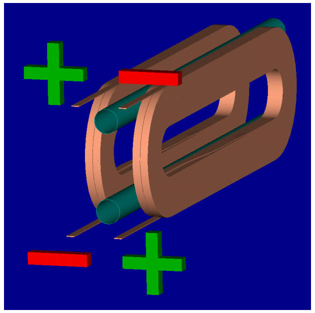
- **The coefficients b_n, a_n are called normalized multipoles**
  - **b_n are the normal, a_n are the skew components**

- **Note that unfortunately US and EU are different** $b_2^{US} = b_3^{EU}$

Start with Ideal Case for Dipole Field

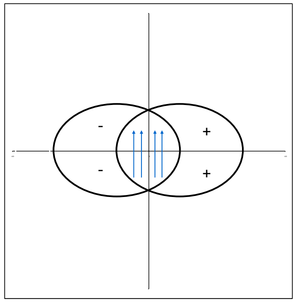
- **Uniform current walls**
  — **Easy to wind but the height is infinite**
  — **Practical implementation requires . . .**
    - **High aspect ratio**
    - **Modification of ends**





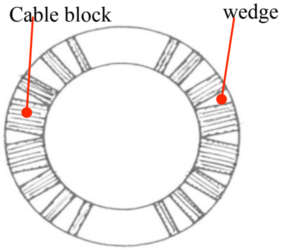
BNL "Common Coil"

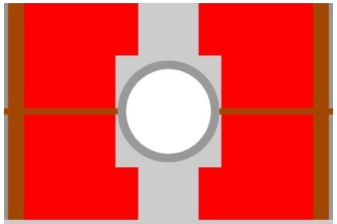
- **Intersecting Ellipses**
  — **Non-circular aperture**
  — **Requires internal support structure**



- **Cosθ current distribution**
  — **Circular aperture, self-supporting**
  — **Reasonably easy to reproduce in practical configurations**

A practical winding with one layer and wedges
[from M. N. Wilson, pg. 33]



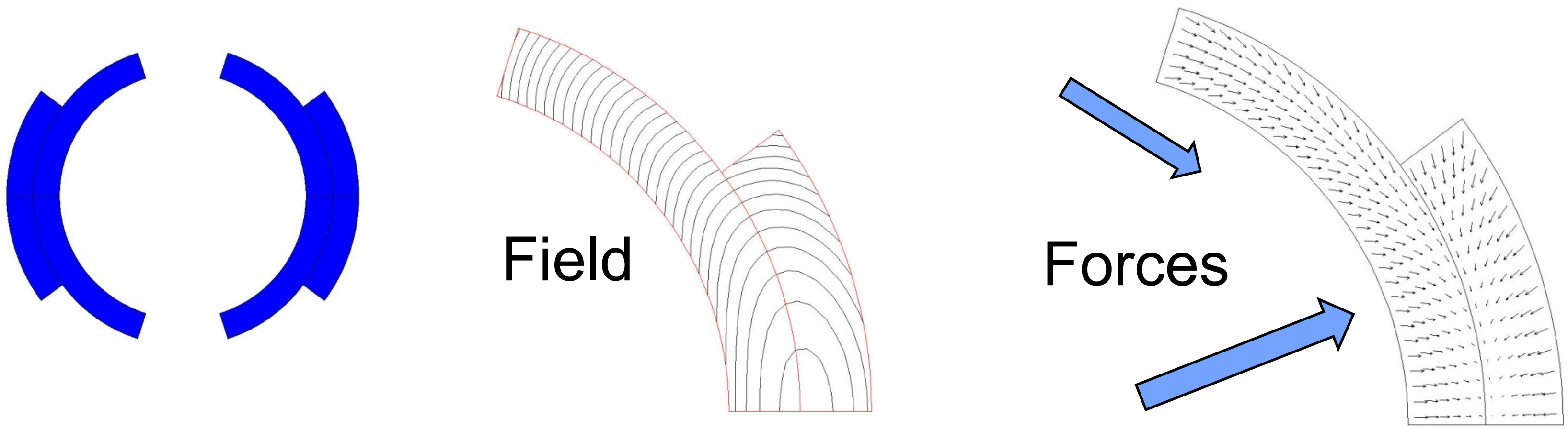


Block Coil Implementation
LBNL "HD-2"

Forces, Stresses and Structures

Lorentz Forces in Dipoles

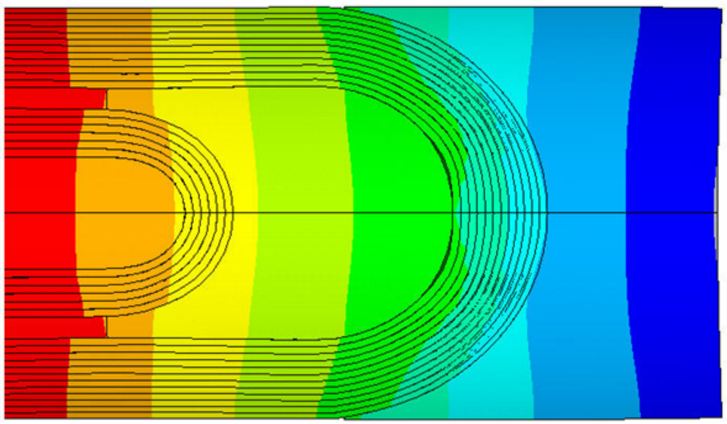
- **Coils are subjected to large forces due to high current densities and high fields**
  - **Must prevent coil motion/deformation**
    - **Field quality good to ~ 1 part in 10^4 (conductor positioning to 25 microns)**
    - **Restrict motion to prevent conductor going normal ("Quench")**



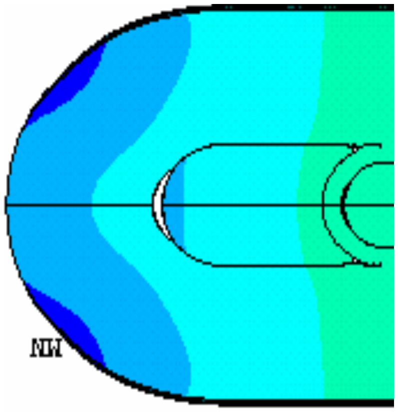
- **Forces are outward in radial direction and towards the mid plane in the azimuthal direction**

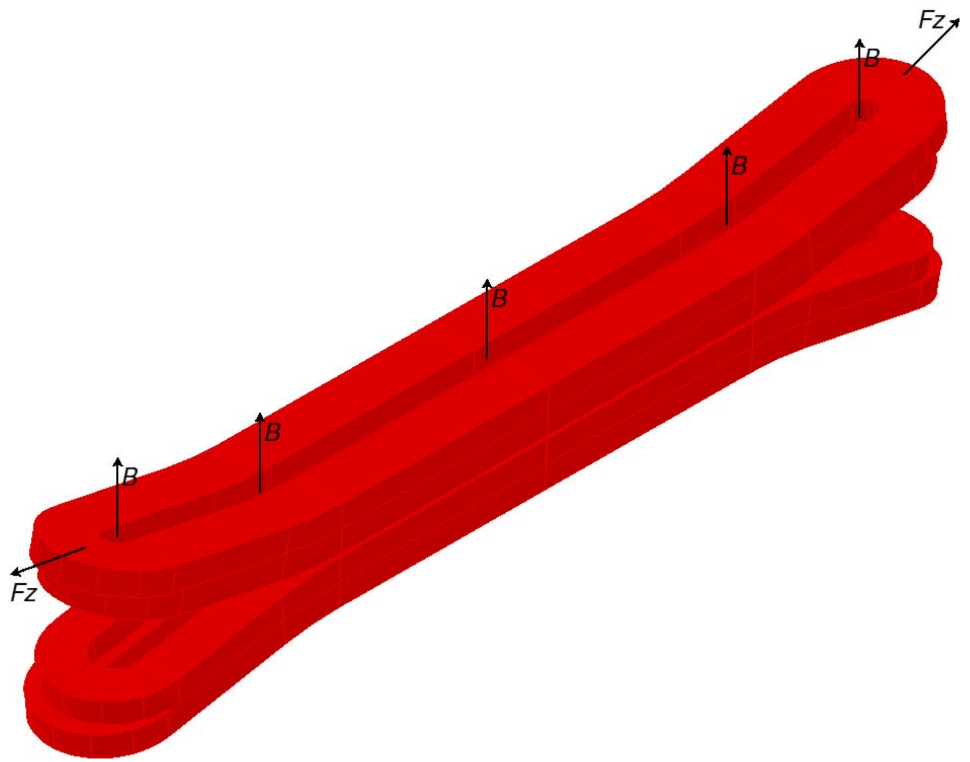
Ends

- **Lorentz forces creates an axial tension, pushing the coil ends outward (not unlike a solenoid)**



Source of many design decisions and challenges





Forces

- The magnetic pressure, p_m acting on the winding surface element is given by

$$p_m = \frac{B_0^2}{2\mu_0}$$

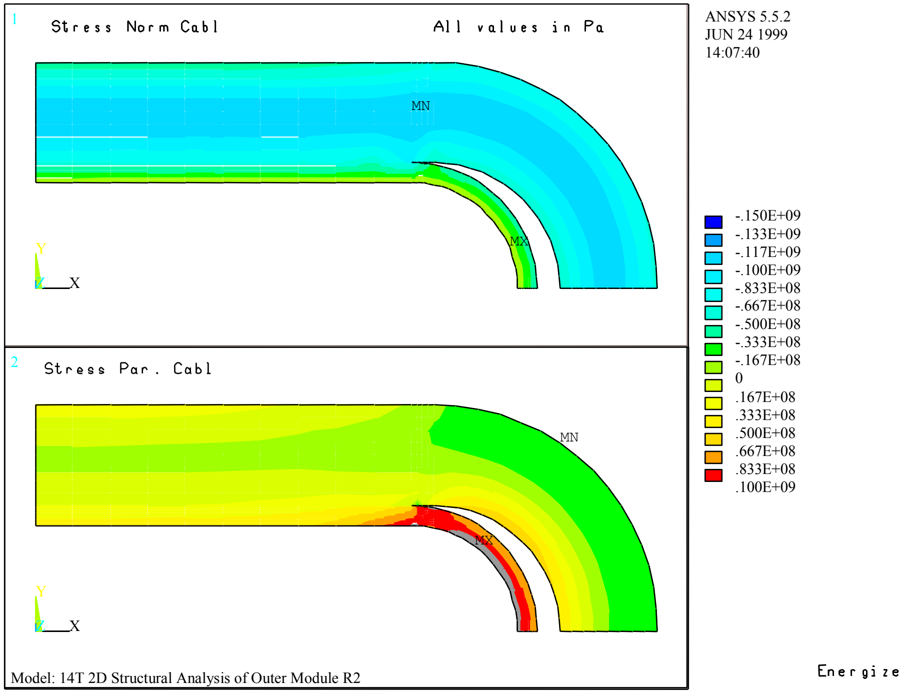
similar to the pressure of a gas acting on its container

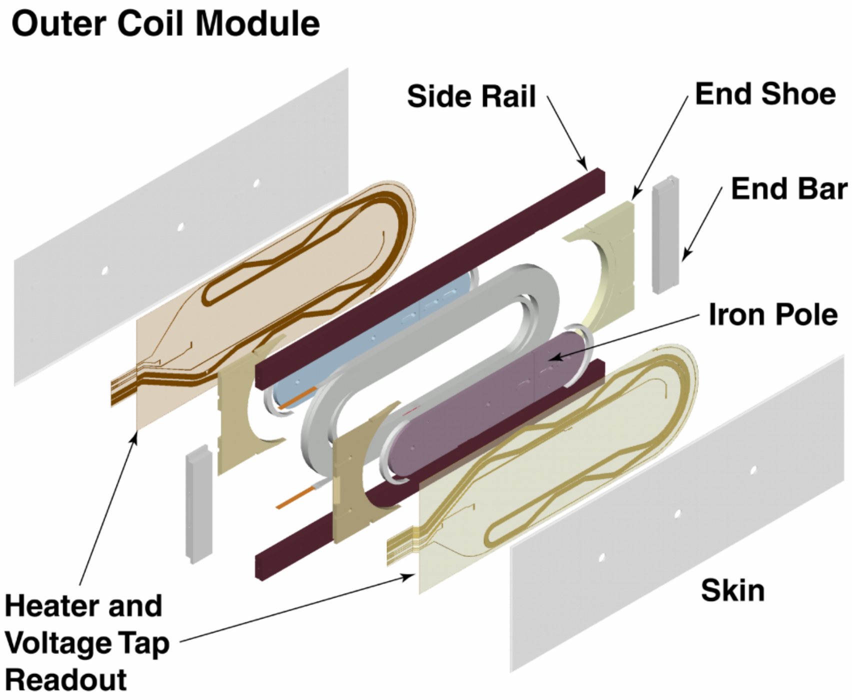
- In the example to follow we have 12 T

so . . . $p_m = (12^2)/(2 \cdot 4\,\pi \times 10^{-7}) = 5.7 \times 10^7$ Pa = 555 atm

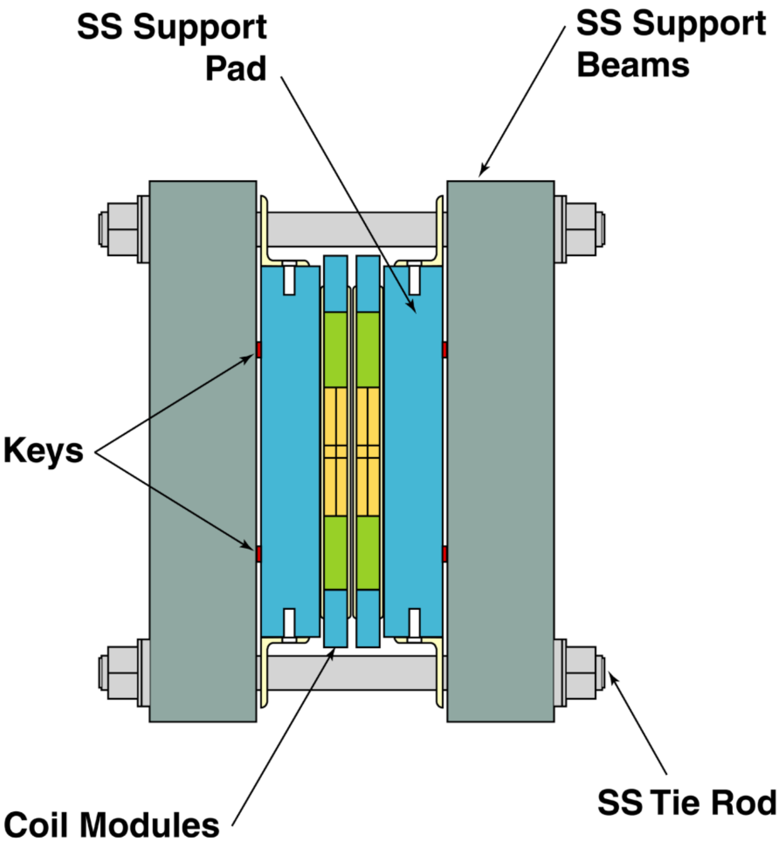
Racetrack Coil Test (RT-1)

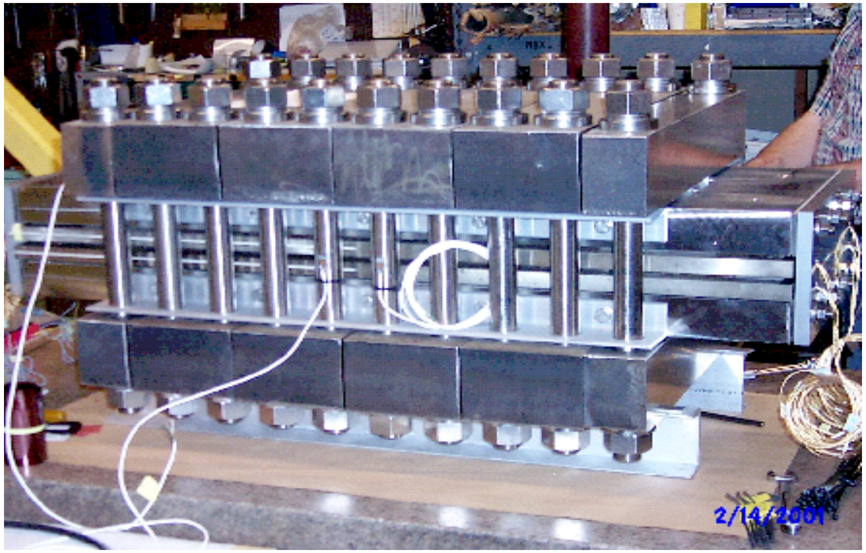
- **Two simple racetrack coils**
  - 50 cm long
  - 12 Tesla



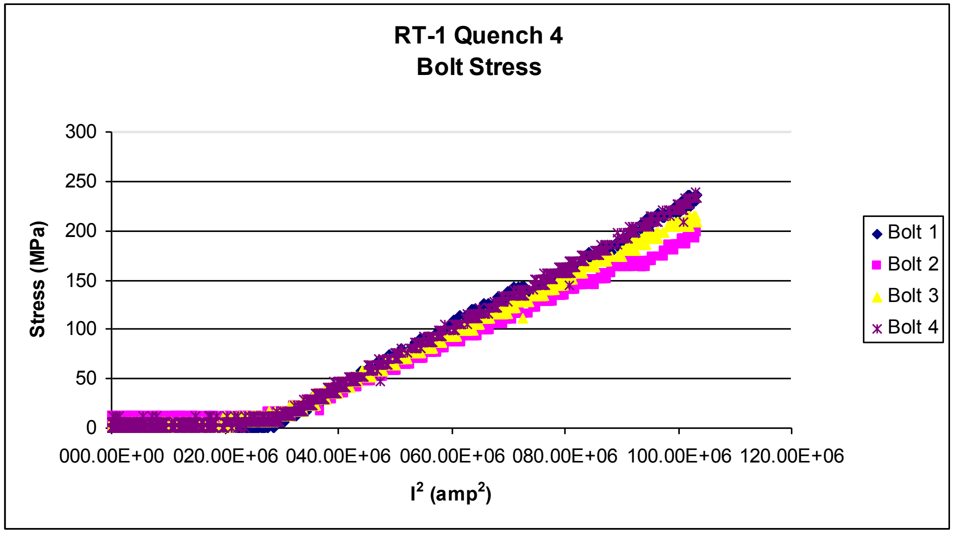


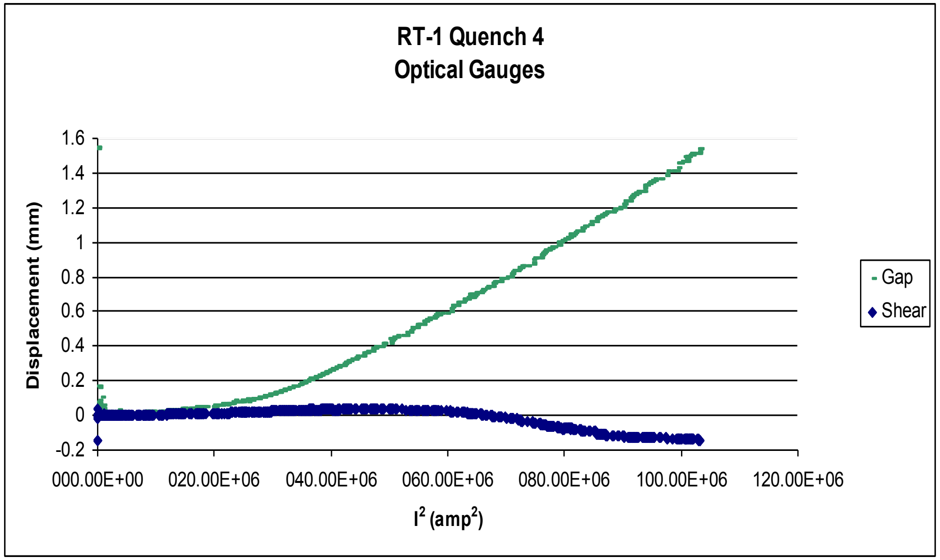
Support Structure

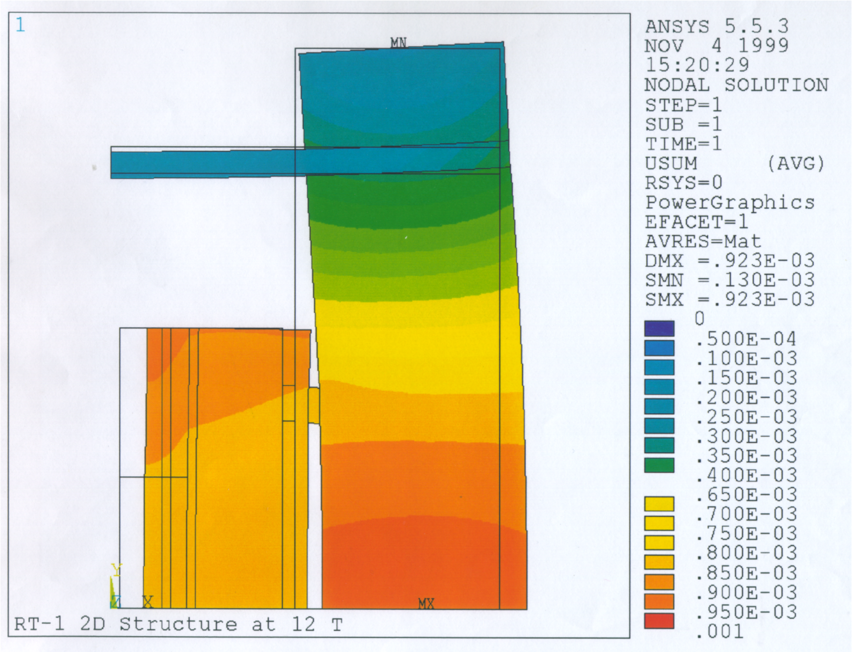




Test Results



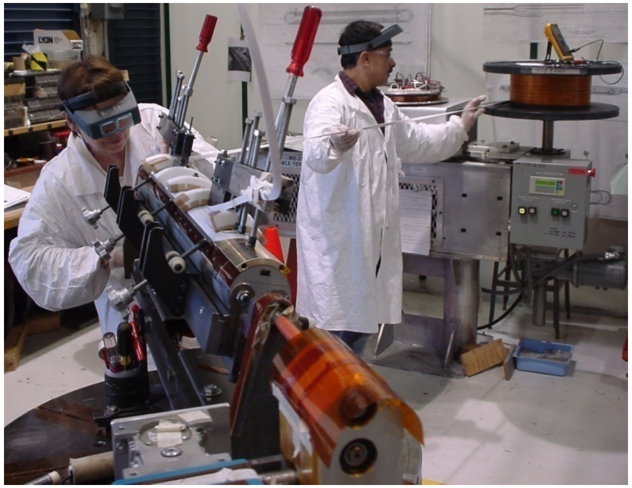


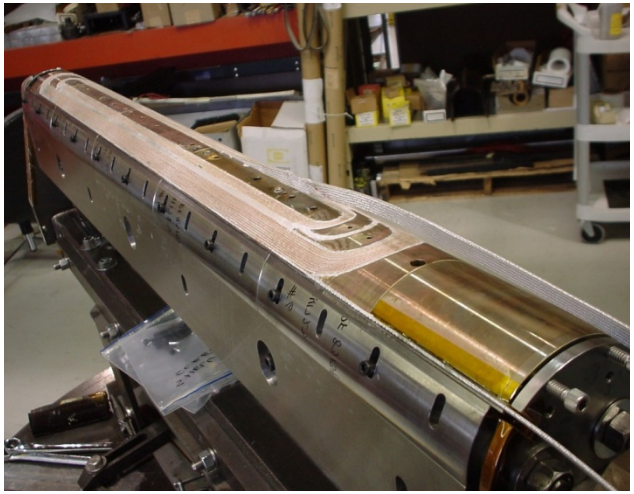


Coil Fabrication

Consider NbTi (dominates use now) and Nb_3Sn (coming up)

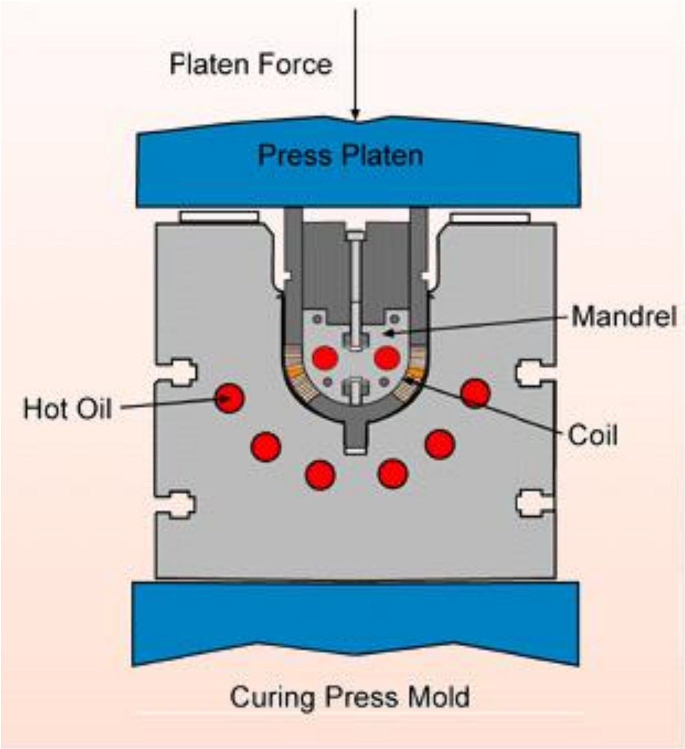
- Winding
  - — Virtually the same process for both materials
  - — Start with insulated cable
    - NbTi – 1 or 2 layers of polyimide wrap
    - Nb_3Sn – S-2 glass "sock" – really not insulator but matrix for later epoxy impregnation

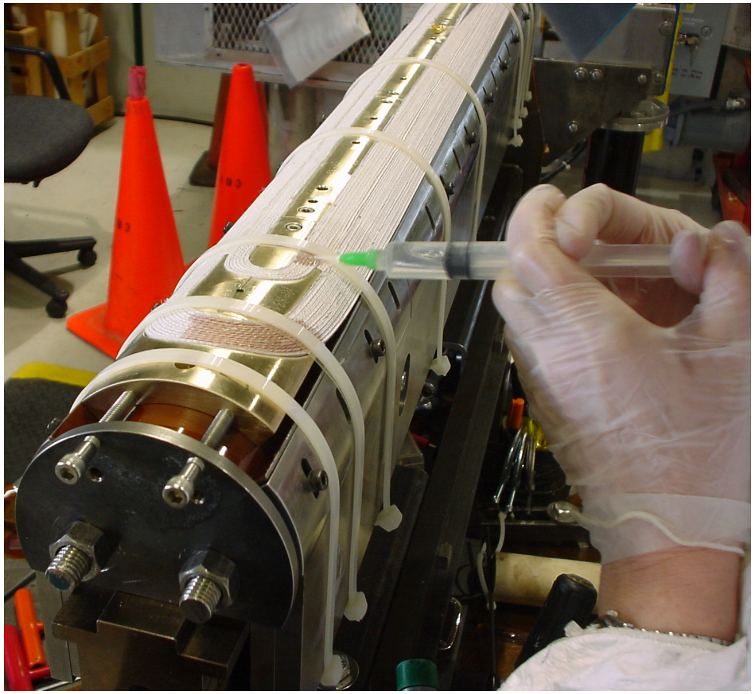




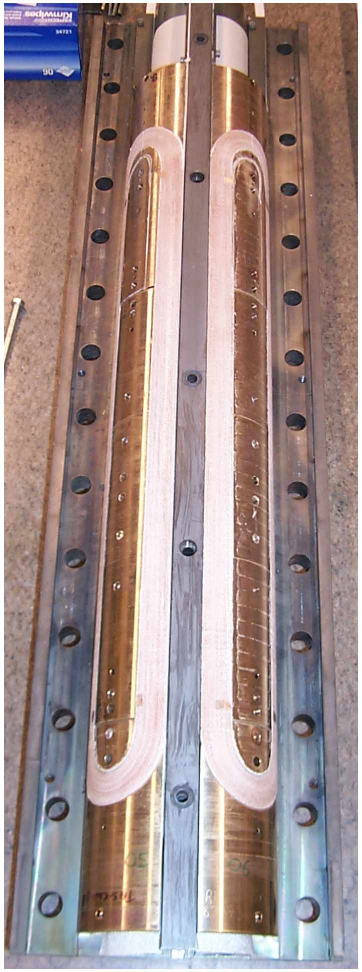
Coil Fabrication

- **Curing/Reaction**
  - — NbTi coils "cured" in fixture to set dimension and aid handling
  - — Nb_3Sn coils "cured" with ceramic binder and reacted (650 – 700 ^{0}C)



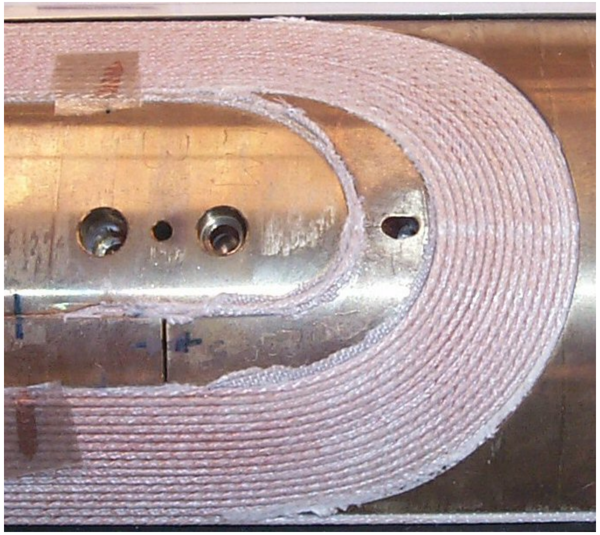


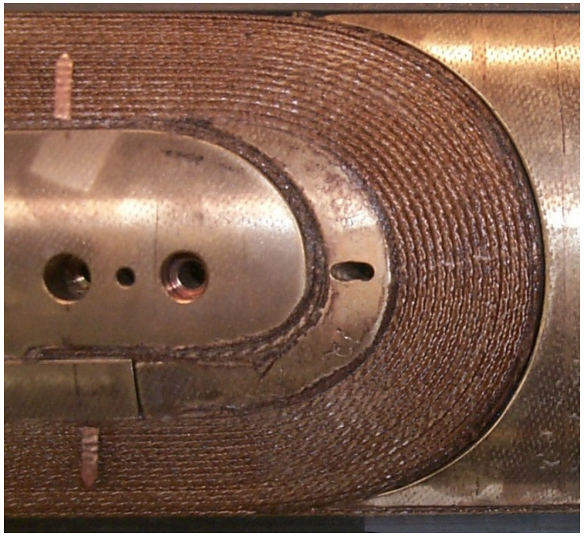
Reaction Fixture for Nb_3Sn Coils

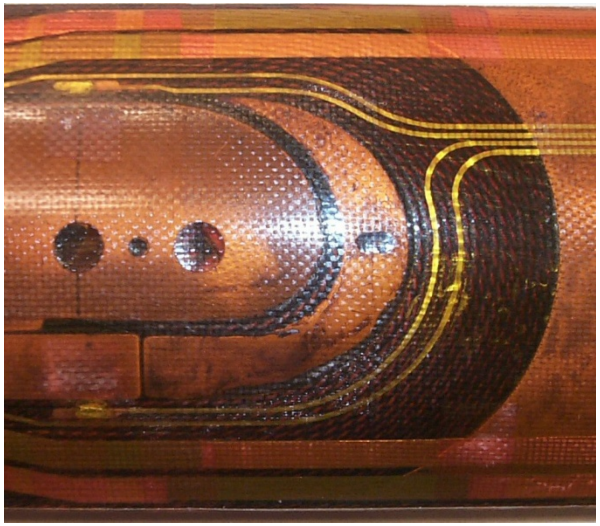


Coil Fabrication

- **Epoxy impregnation of Nb_3Sn Coils**
  - — **In US CTD-101 is used for impregnation (looking at cyanate esters)**
  - — **Two-fold purpose -**
    - **Provide insulation**
    - **Distribute load between strands to reduce stress points**

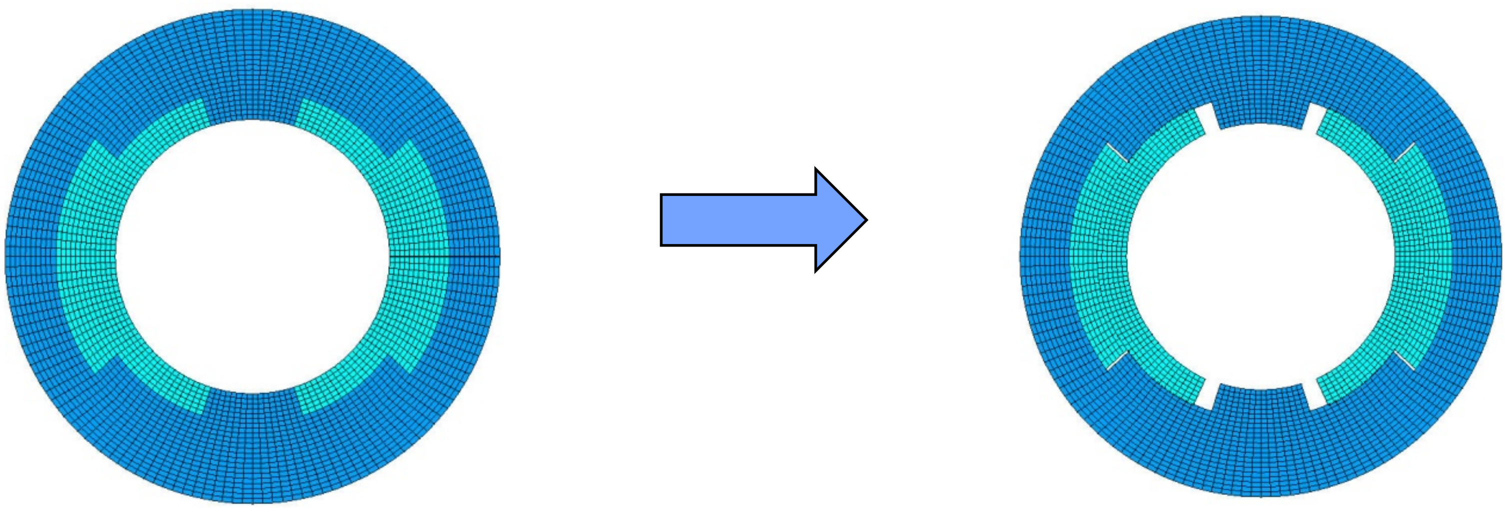






Structures and Pre-Stress

- Due to character of Lorentz forces, a simple rigid structure is not sufficient.
- "Pre-stress" is required to prevent conductor from losing contact with the structure



- Due to uncertainties, some margin is allowed, ~ 20 MPa

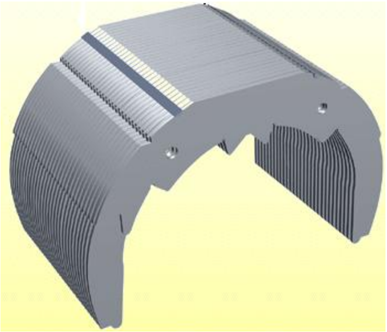
Support Structure

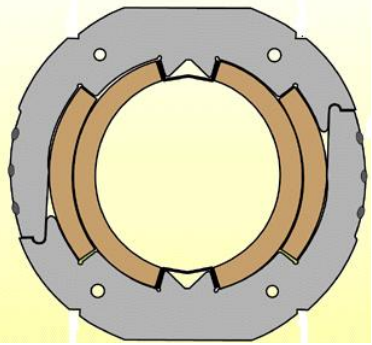
- Provides
  - Precise positioning and alignment
    - Prevents changes in coil shape that could affect field quality
  - Pre-stress and prevents movement under Lorentz loading
    - Conductor displacement that could release frictional energy

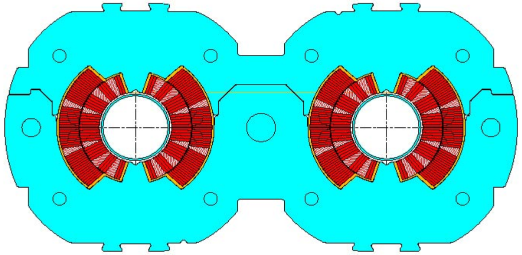
- But must prevent over-stressing the coil
  - Insulation damage at about 150-200 MPa
  - Possible conductor degradation of Nb_3Sn magnets at 150 – 200 MPa.
  - Yielding of structural components

Collars

- **First introduced in the Tevatron**
  - **Since used in most accelerator magnets**





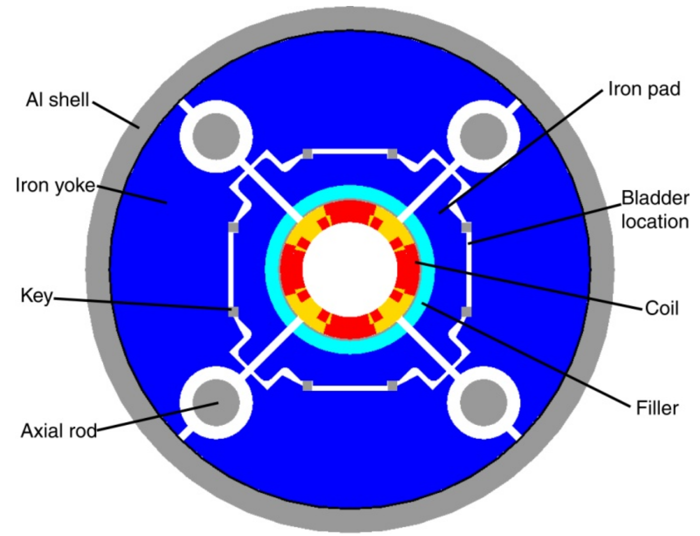


LHC

  - **Provide some or all of the pre-stress**
  - **Precise cavity (~ 20 microns)**
  - **Composed of Al or stainless steel laminations**

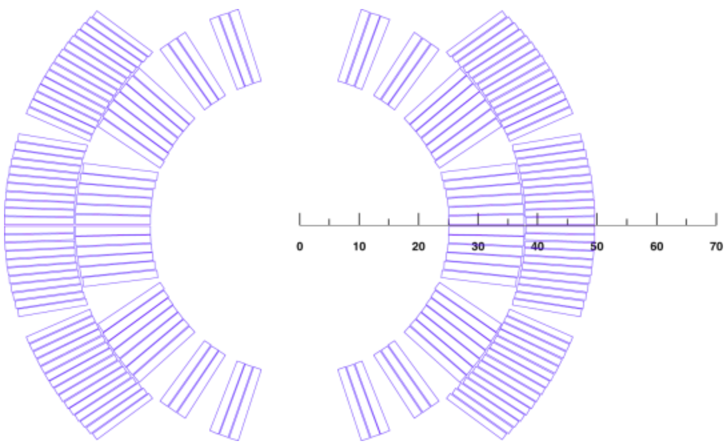
Final Assembly

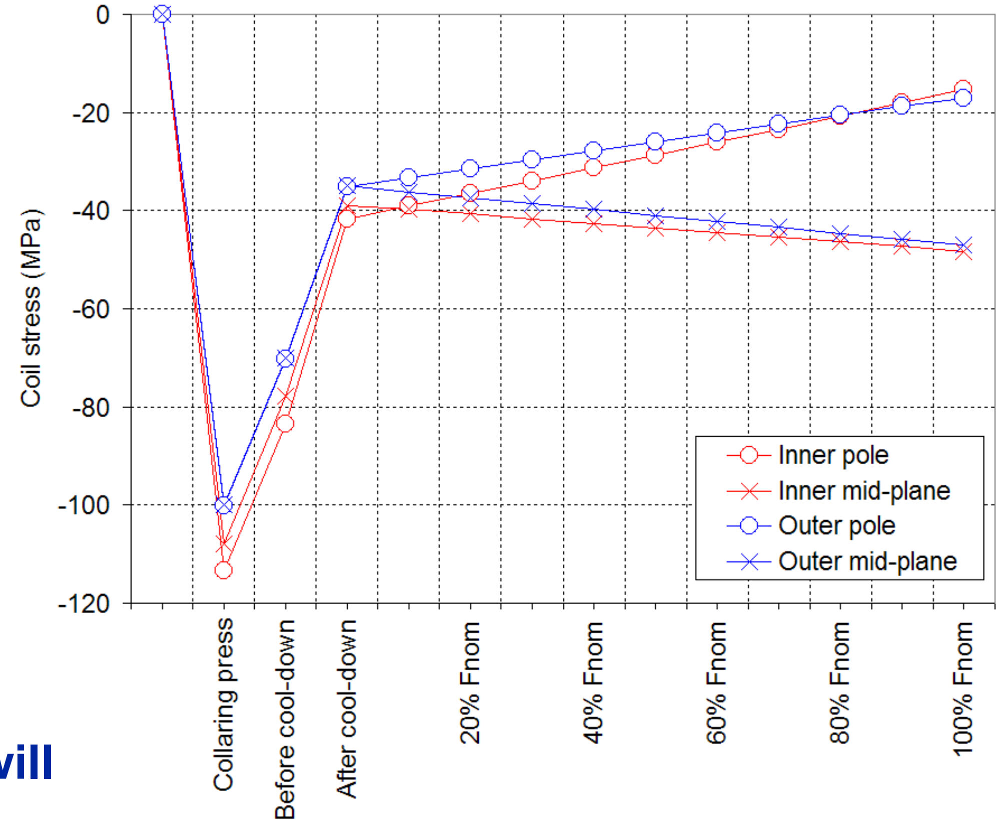
- Iron yoke
  - Shields and enhances field
  - In some cases provides additional preload
- "Skin" or shell
  - Yoke is contained within two welded half-shells of stainless steel (the "skin") or a shrinking cylinder of aluminum
    - Outer shell contributes to coil rigidity and provides helium containment
- End support or loading
  - Thick plates provide axial support



Classic Example (SSC Dipole)

- **Goal**
  - **Load but don't overload the coil with enough pre-stress to keep coil in contact with structure at full field**

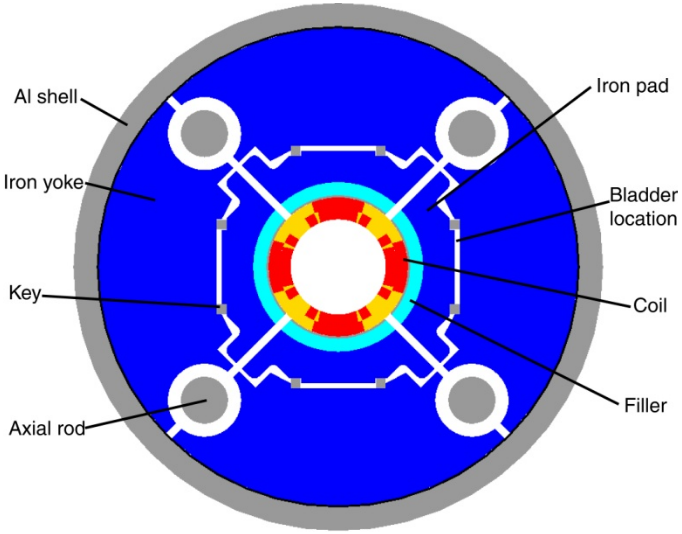


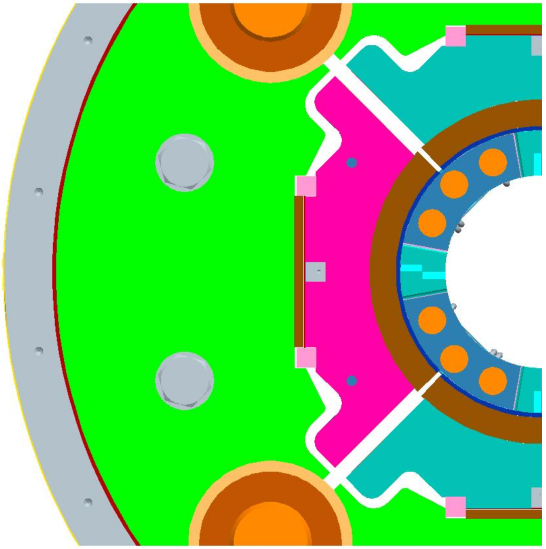


  - **What if you need more?**
  - **And high field magnets will need a lot more . . .**

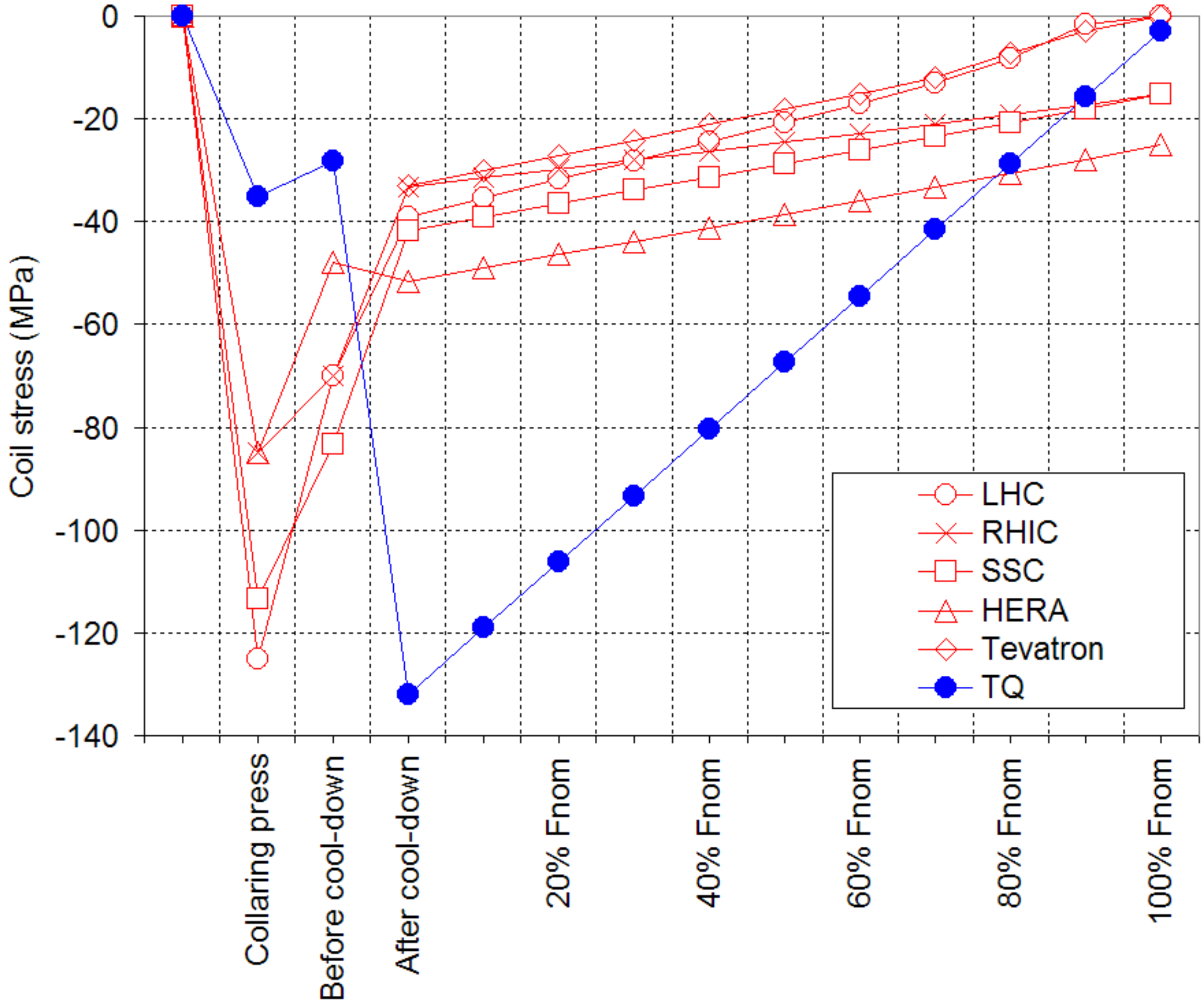
Key and Bladder (LARP/LBNL TQS Quad)

- Four pads or collars transfer load to coils
- Yoke is contained by aluminum shell
- Preload provided by inflating bladders and held via keys
- Coil pre-stress increases during cooldown due to the high thermal contraction of the aluminum shell.



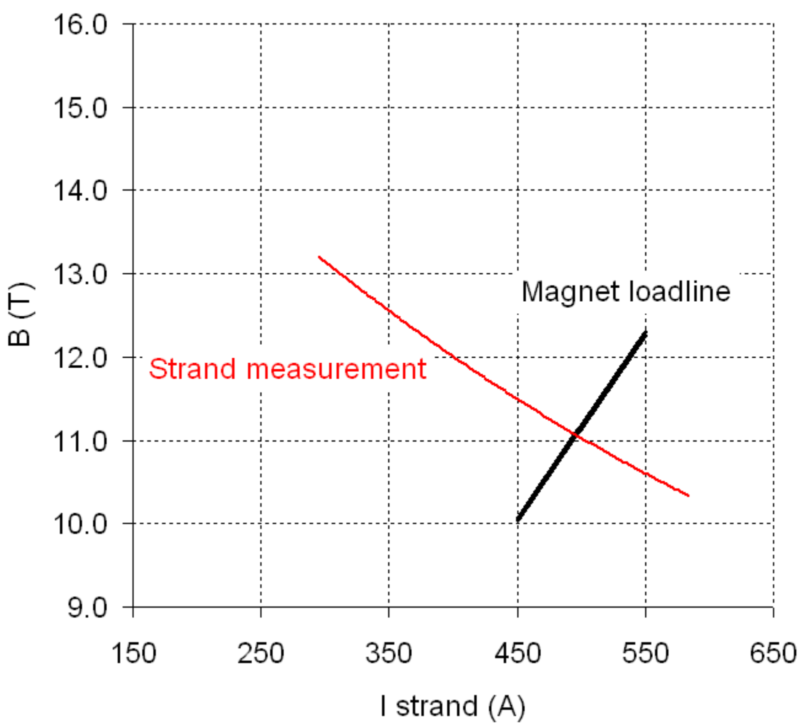


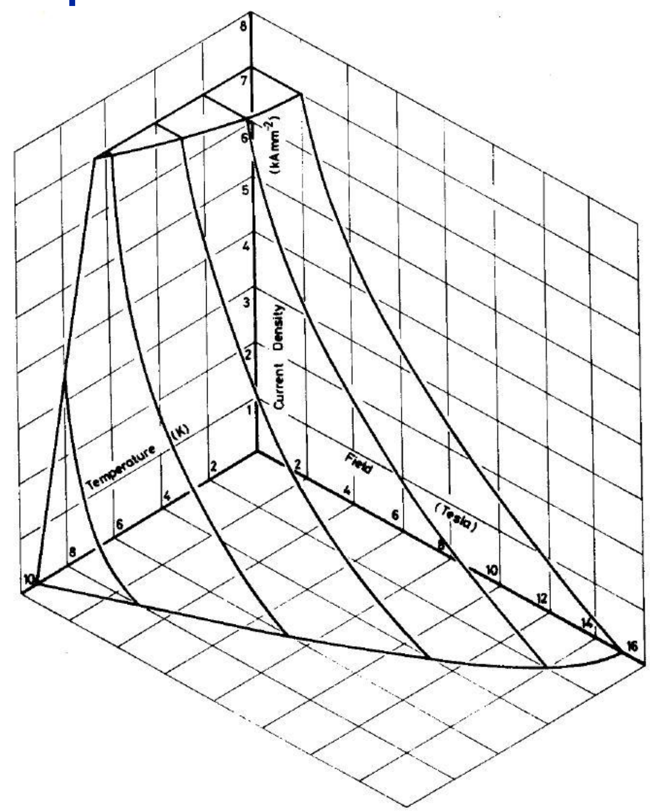
Comparison


Coil stress (MPa)
0
-20
-40
-60
-80
-100
-120
-140
Collaring press
Before cool-down
After cool-down
20% Fnom
40% Fnom
60% Fnom
80% Fnom
100% Fnom
LHC
RHIC
SSC
HERA
Tevatron
TQ

Quench and Training

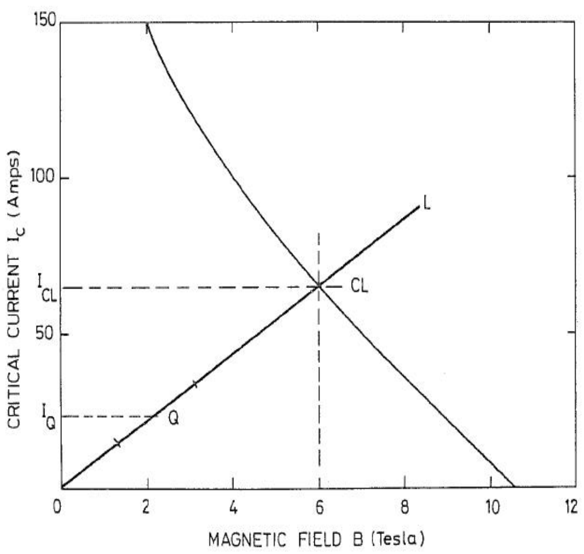
- **Magnet operates below the critical surface**
  - **Continued increase of the current will eventually create a "normal" zone at some location in the magnet**
  - **Propagation of the normal zone is called a "quench"**

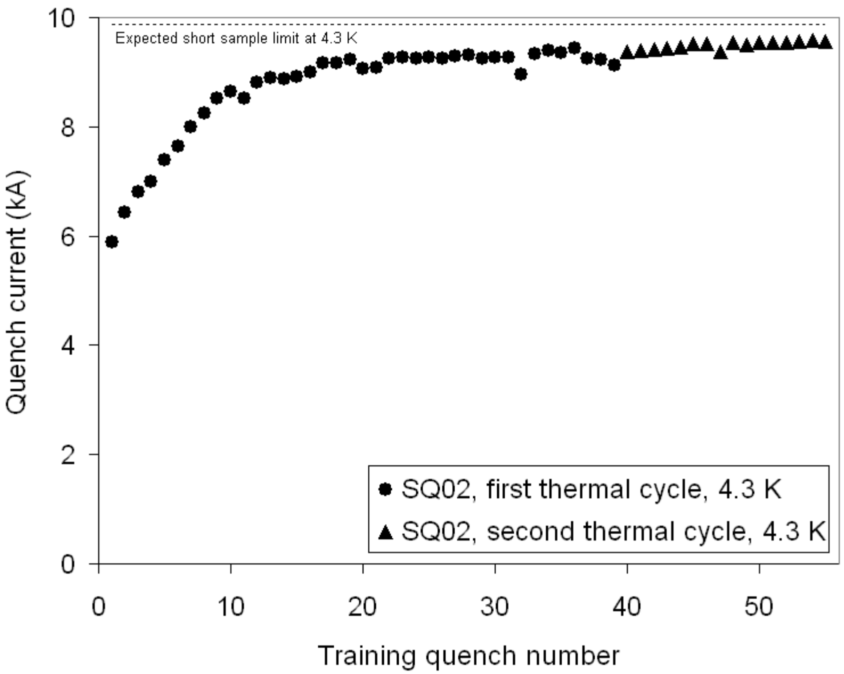




Quench and Training

- **Two categories of quench**
  - — Conductor limited $I_{max} = I_c$ (short sample limit)
    - Increase of I and B
  - — or $I_{max} < I_c$ (energy deposited quench)
    - Increase of temperature
  - — Successive, increasing quench current is called "training"

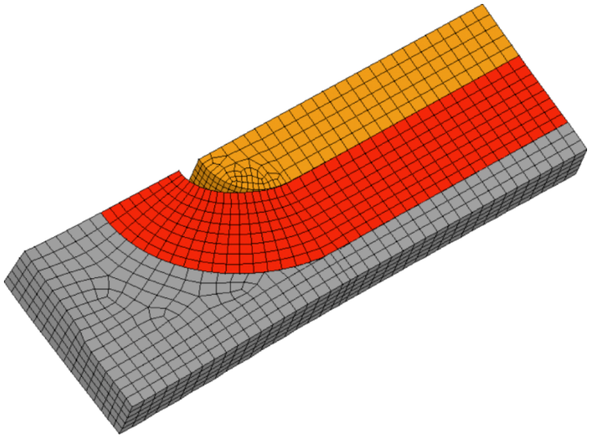


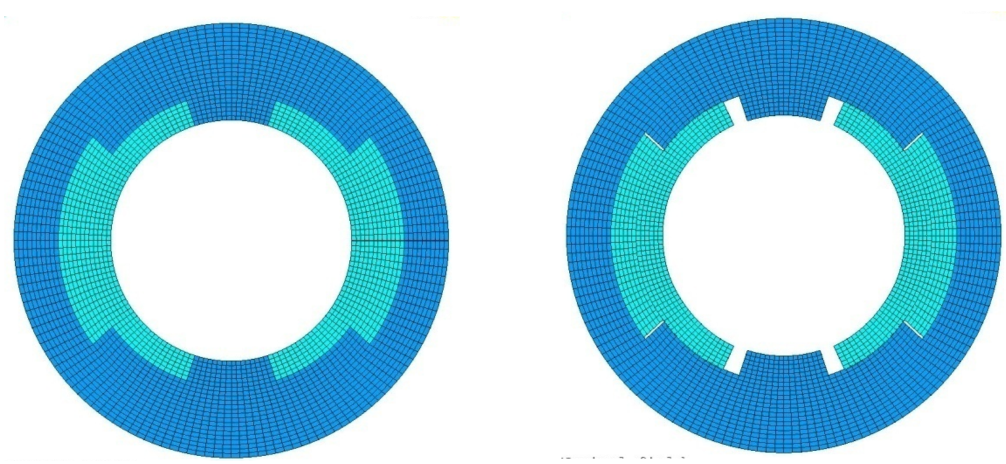


Causes of Training

- **Frictional motion of a superconductor**
  - **Azimuthal, radial and axial motion between collar and coil**

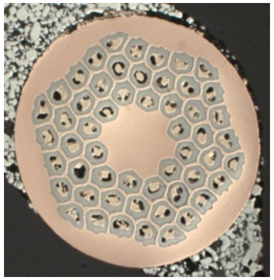
- **Epoxy failure (Nb_3Sn magnets)**

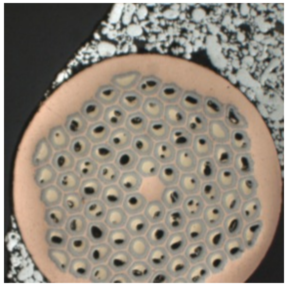


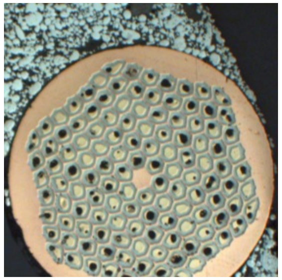


Next Steps for Materials

- Nb_3Sn
  - — Maintain high J_c and reduce filament diameter
  - — No permanent strain degradation up to 150 MPa (depends on environment)
    - Track influence of microstructure on strain sensitivity
- Radiation hard insulation
- Start simple experiments to develop HTS
- Reduce cost
  - — Scale-up







OST

54/61 90/91 126/127

Future Accelerator Applications

LHC Upgrades

- Interaction Region (IR) Quadrupoles
  - LHC Luminosity Upgrade
- LHC Energy Upgrade (high field dipoles)

Wigglers and Undulators

- Light source upgrades
- Superconducting technology substantially increases performance

Rapid Cycling Magnets

- Challenging
  - Field quality degradation
  - Cryogenic losses
    - Hysteresis
    - Eddy currents

Despite this, there is a need . . .

- Nuclotron dipole at JINR, Dubna
- Two new examples
  - GSI – Facility for Antiproton and Ion Research (FAIR)
  - SPS upgrade at CERN

References

- Martin N. Wilson, "Superconducting Magnets", 1983.
- US Particle Accelerator School Lectures prepared by

  S. Prestemon, P. Ferracin and E. Todesco

- For those interested in accelerator magnet design I suggest you attend the next available class

- Contact me at sagourlay@lbl.gov to get on the mailing list for notification of the next class

Next Steps in Magnet R&D

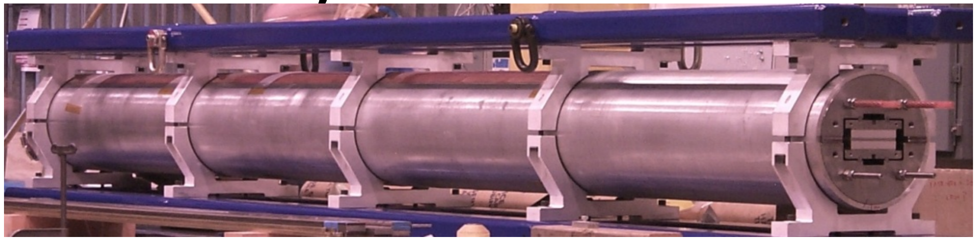
Steve Gourlay
LBNL

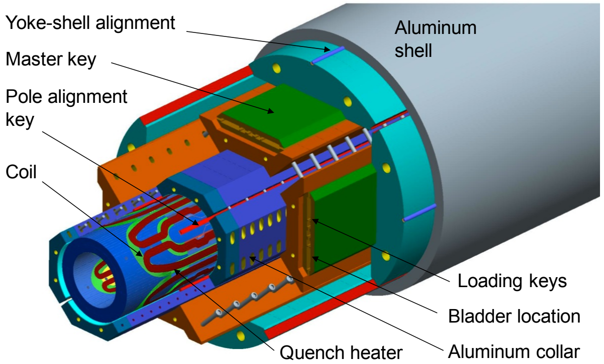
EuCARD Workshop on a High Energy LHC

Malta
October 14, 2010

Current Status

- **Phase 1 of LARP magnet program close to completion**
  - **TQ – technology development and reproducibility**
    - ***surpassed LARP target gradient***
  - **LQ –handling, fab, protection of long magnets (~ 4m)**

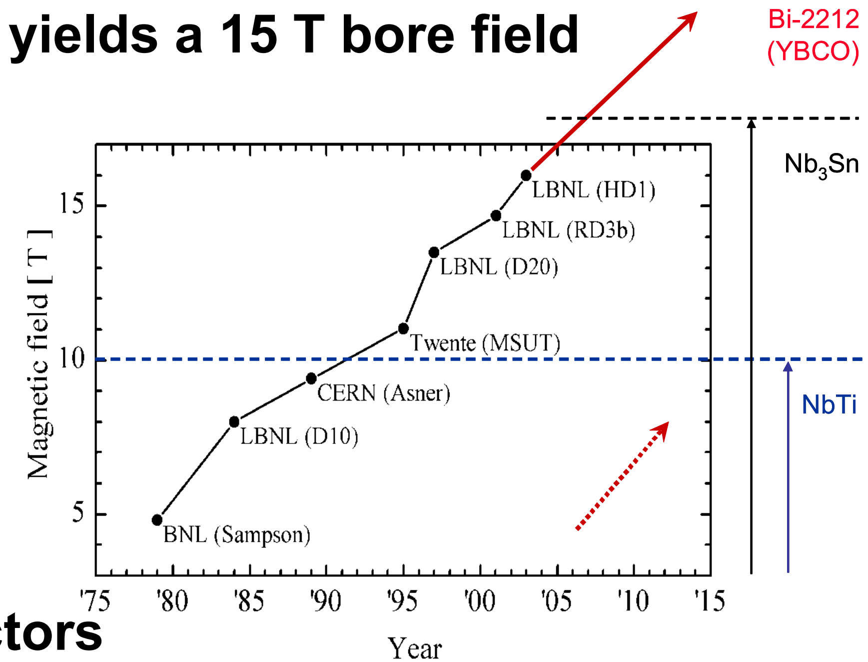




Excellent progress so far

Next Phase – Two separate regimes

- **Regime 1**
  - — **Up to 17 T**
    - **Nb_3Sn – optimistically yields a 15 T bore field**



- **Regime 2**
  - — **Above 17 T**
    - **Introduce HTS conductors**
    - **A quantum leap in technology**

Technological Readiness

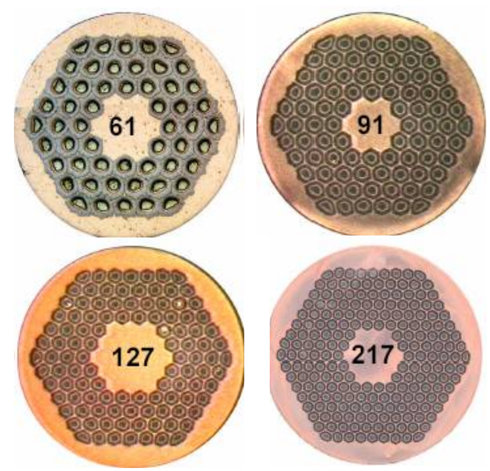
- Ready to go or minor development still required
- Not yet demonstrated
- Need completely new idea/technique
- Major risk

Regime 1 – maximizing Nb_3Sn

- **Conductor**
  - — J_c
    - Nearly fully optimized
      - – 3,400 A/mm^2 has been achieved. Practical limit is 4,000 A/mm^2
    - Some non-Cu area fraction is still not used for current transport (the Sn source area), but optimizing this would require a presently not available/known conductor fabrication method
  - — Increase density of pinning sites
    - A factor 10 can increase the critical current around 12 T by a factor of 3.5 to 4, as demonstrated theoretically
    - Don't know how to do this in wires
  - — D_{eff}
    - Still important, but more so for medium field magnets (<10 T)

Regime 1 – maximizing Nb_3Sn

- **Conductor – cont' d**
  - **Strain dependence**
    - **Poorly understood – need continued R&D**
    - **Not a show-stopper**



- **Bottom-line**
  - **Nearly ready to go**

Should we spend much more effort to raise J_c?

Regime 1 – maximizing Nb_3Sn

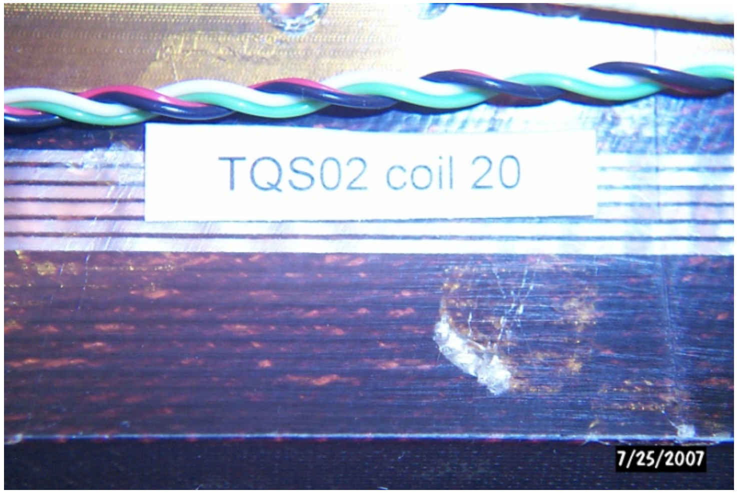
- **Preparing for high radiation environment**
  - — Current filler matrix contains Boron
    - Need to transition to ceramic
  - — CTD-101 not rad hard
    - Outgassing – catastrophic expansion of matrix
  - — Cyanate Ester (or blend)
    - Need to understand required properties
    - Start with ITER work
  - — Polyimide

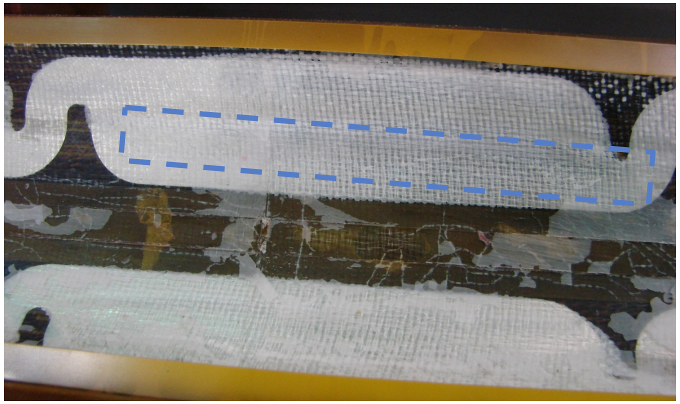
Regime 1 – maximizing Nb_3Sn

- **Quench Protection**
  - — At 4 m, 14 T peak field, LQ is already a limit of stored energy. Now we want to go to 10 m and 20 T!
  - — Heaters now at 400V/2m. May not want to go higher. What happens if we go to 6, 10, . . .?
  - — Need more detailed quench calculations/tests
    - Include quench back
  - — Mechanical issues
    - Still see some heater deformation @ 4.2K. Cycling tests are OK. Thermal cycles seem to be a pr

Heater Delamination

- **Delamination on coil Inner Diameter**
- **Different from “TQ-style” bubbles**
  - **larger => only underneath the large sections of the heater**
  - **No conductor exposed**
  - **Not clear if bubble underneath stainless steel or only glass sheet => impact on heater performance ?**
- **Possible causes:**
  - **Superfluid helium + quench (only 2 quenches) <=> TQ**
  - **Heat from heaters on ID <=> LQ**





Coil 6 (showing epoxy “peeling” related to double impregnation, already observed before test)

Regime 1 – maximizing Nb_3Sn

- **Structure**
  - Field quality – know how to do this
  - Dynamic range? Assuming higher energy injection
  - 2-in-1 configuration
    - **Need to see if this is a viable option for tin magnets**

Regime 2 – 17 T and above

- **Conductor**
  - **Bi-2212**
    - J_e is presently in (almost) leak free wires around 200-250 A/mm^2 at 4.2 K, ~12 T, a factor of 3 less than NbTi and Nb_3Sn
    - A factor 3-4 increase in 2212 J_e is needed to become competitive with Nb_3Sn. Without increase, 2212 is a dead end
    - **Strain dependence**
      - The reduction of Jc with strain is irreversible in 2212
      - the intrinsic strain dependence is possibly reversible, brittle web of interconnected filaments needs to be supported in order to reduce stress concentrations
      - Potential show-stopper
    - **Other technical issues:**
      - leakage, materials compatibility, the reaction of larger coils with sufficient T and O_2 homogeneity, etc. need more R&D

Regime 2 – 17 T and above

- **Conductor (con' t)**
  - **YBCO**
    - Very high current density but only 1% of the cross-section is YBCO, => $J_e \sim 250\ \mathrm{A/mm^2}$ comparable with 2212 and available tape insulation methods reduce this by another factor of two
    - Expensive and only available in tape form
    - Lack of filament structure
      - Can we learn how to use this?
  - **Bi-2223**
    - **J_e' s comparable to 2212 and YBCO**
      - Still a tape but has filament structure
      - Perhaps it deserves a look
  - **Development of HTS conductors in industry is orthogonal to needs of HEP. How do we encourage/fund development?**

[redacted]

Regime 2 – 17 T and above

- **High Radiation environment**
  - Is HTS less or more rad hard than Nb_3Sn?
  - Same issues as for Regime 1
- **Quench Protection**
  - Stored energy goes even higher
  - Hybrid designs - Can we operate in series (and protect) or do we need separate power supplies?
- **Structure**
  - Integration of coils with different materials (maintain small tolerance)
    - Completely different processing for each conductor type
  - Bring together in low stress configuration (especially 2212)
  - Size – accept large stray field? Active shielding?

Summary

- Accelerator magnets with peak fields less than 17 T are challenging but clearly feasible
  - It will require a coordinated community development program
- Above 17 T requires significant conductor development and engineering
  - Much R&D to do

Acknowledgements

- **Thanks to . . .**
  - **Paolo Ferracin**
  - **Helene Felice**
  - **Arno Godeke**
  - **Dan Dietderich**
  - **Shlomo Caspi**

. . . for information and valuable discussions