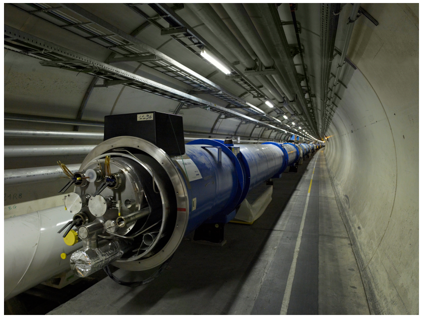
High Field Magnet Development and Prospects for an Energy Upgrade of the LHC



S. Gourlay

Accelerator and Fusion Research Division

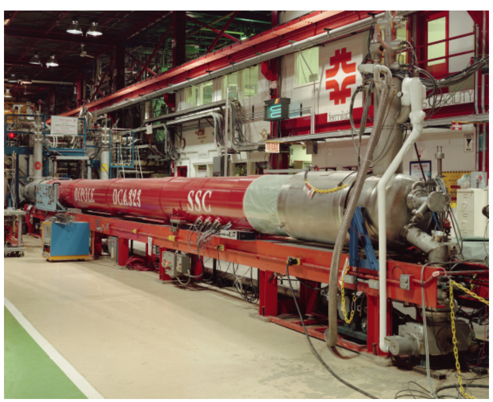
Accelerator Magnets

BERKELEY LAB

Then . . .

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

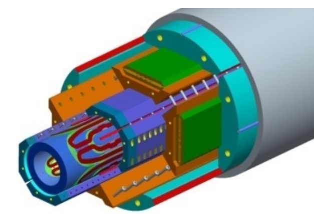
- HERA, SSC, UNK, RHIC



And now . . .

- LHC 2007
  - 8.3 T, NbTi, 1.9K
  - Limit of NbTi

- US LHC Upgrade
  - Nb_3Sn quadrupoles



- FAIR
  - High ramp-rate

CERN Accelerator Strategy

- CERN is the energy frontier laboratory

- We have (almost)
  - LHC at 7 TeV/beam; the highest energy collider on the planet for the foreseeable future
  - HL-LHC; proposed luminosity upgrade for installation 2020-2021 and operating until around 2030 (includeing the upgrade of the LHC Injectors)

High-priority large-scale scientific activities (2)

Roy Aleksan
CERN
Feb. 22, 2013

Recommendation #2

d) To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. *CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron-positron high-energy frontier machines. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide.*

So, what's new?

- LHC Energy Upgrade is now a topic of considerable discussion

EuCARD Workshop on a High Energy LHC
Malta
October 14, 2010

Joint Snowmass-EuCARD/AccNet-HiLumi LHC Workshop
CERN
February 21-22, 2013

Contributing to the interest . . .

LBNL Magnet R&D Program in High Field Magnets

LHC Accelerator R&D Program (LARP)

The super-exploitation of the CERN complex: Injectors, LEP/LHC tunnel, infrastructures

	1980	1985	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035
LEP	Construct.		Physics		Upgr							
LHC		Design, R&D		Proto	Construct.		Physics					
HL-LHC					Design, R&D			Construct.	Physics			
HE-LHC							Design, R&D	Proto	Construct.		Physics	

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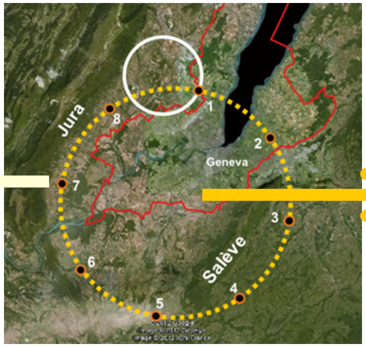
Either using existing LEP/LHC tunnel to reach 26-32 TeV collisions



Or build (or reuse) an 80km tunnel to reach 80-100 TeV collisions
➪ more detailed study of such a tunnel needed

In both cases, SC challenge to develop 16-20 Tesla magnets!
Magnets for HL_LHC is an indispensible first step

HE-LHC Parameters

	nominal LHC	HE-LHC	
beam energy [TeV]	7	16.5	
dipole field [T]	8.33	20	
dipole coil aperture [mm]	56	40	
beam half aperture [cm]	2.2 (x), 1.8 (y)	1.3	
injection energy [TeV]	0.45	>1.0	
#bunches	2808	1404	
bunch population [10^{11}]	1.15	1.29	1.30
initial transverse normalized emittance	3.75	3.75 (x), 1.84 (y)	2.59 (x & y)
initial longitudinal emittance [eVs]	2.5	4.0	
number of IPs contributing to tune shift	3	2	
initial total beam-beam tune shift	0.01	0.01 (x & y)	
maximum total beam-beam tune shift	0.01	0.01	
beam circulating current [A]	0.584	0.328	
RF voltage [MV]	16	32	
rms bunch length [cm]	7.55	6.5	
rms momentum spread [10^{-4}]	1.13	0.9	
IP beta function [m]	0.55	1 (x), 0.43 (y)	0.6 (x & y)
initial rms IP spot size [μm]	16.7	14.6 (x), 6.3 (y)	9.4 (x & y)
full crossing angle [μrad]	285 (9.5 $\sigma_{x,y}$)	175 (12 σ_{x0})	188.1 (12
Piwinski angle	0.65	0.39	0.65
geometric luminosity loss from crossing	0.84	0.93	0.84
stored beam energy [MJ]	362	478.5	480.7
SR power per ring [kW]	3.6	65.7	66.0
arc SR heat load dW/ds [W/m/aperture]	0.17	2.8	2.8
energy loss per turn [keV]	6.7	201.3	
critical photon energy [eV]	44	575	
photon flux [10^{17}/m/s]	1.0	1.3	
longitudinal SR emittance damping time [h]	12.9	0.98	
horizontal SR emittance damping time [h]	25.8	1.97	
initial longitudinal IBS emittance rise time	61	64	~68
initial horizontal IBS emittance rise time [h]	80	~80	~60
initial vertical IBS emittance rise time [h]	~400	~400	~300
events per crossing	19	76	
initial luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0	
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	2.0	
beam lifetime due to *p* consumption [h]	46	12.6	
optimum run time t_r [h]	15.2	10.4	
integrated luminosity after t_r [fb^{-1}]	0.41	0.50	0.51
opt. av. int. luminosity per day [fb^{-1}]	0.47	0.78	0.79

Consider:

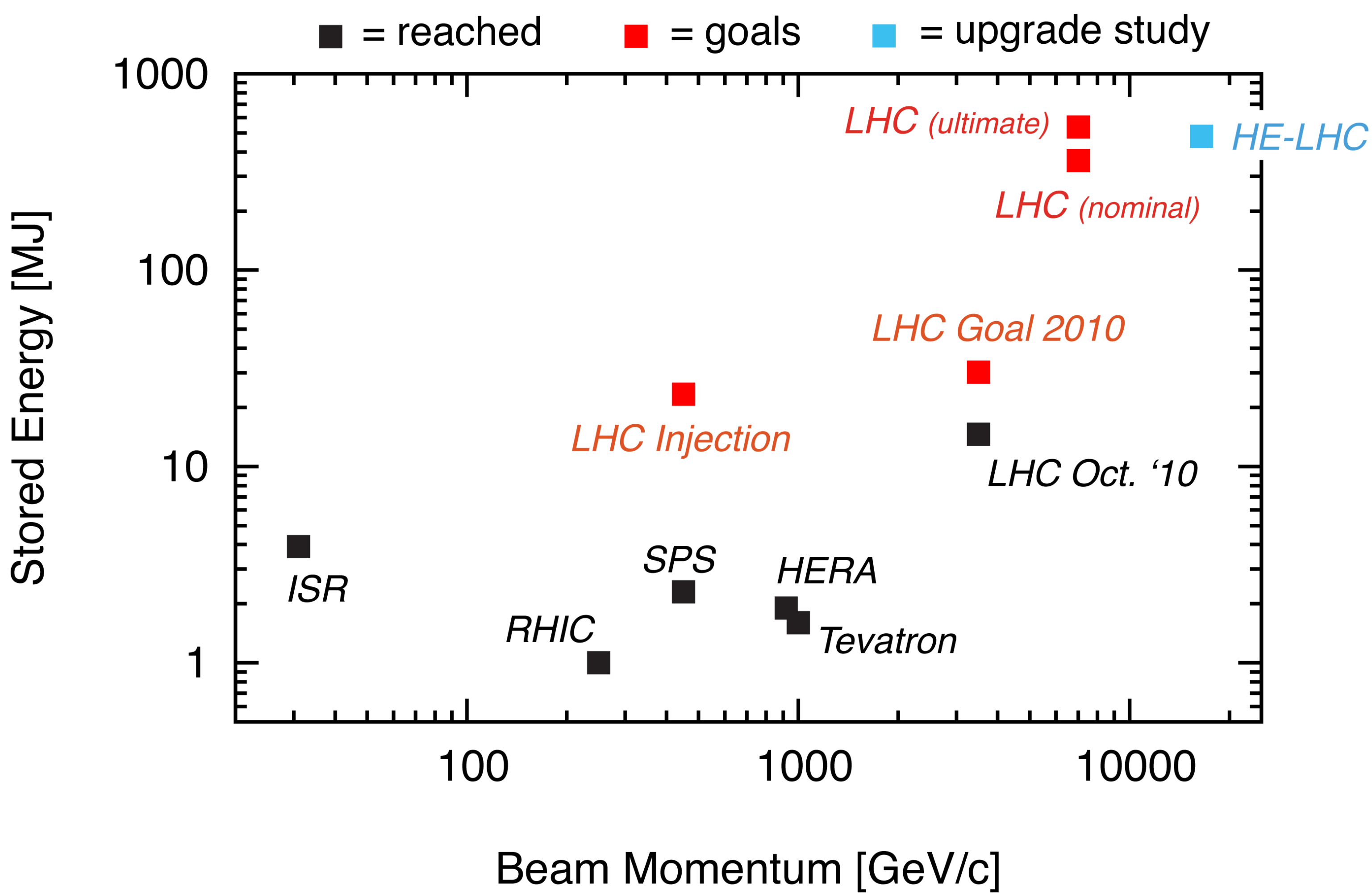
Round case
Compare to nominal LHC
Typical collimator location β = 80m

Main issues:

	Nominal	Upgrade
E	7.0 TeV	16.5 TeV
γ	7461	17587
ε	0.5 nm	**0.15 nm**
E_{stored} (tot)	362 MJ	482 MJ
ρ_e (tot)	2.9 GJ/mm^2	15.4 GJ/mm^2
E_{stored} (1b)	128 kJ	242 kJ
ρ_e (1b)	1.0 MJ/mm^2	**7.7 MJ/mm^2**

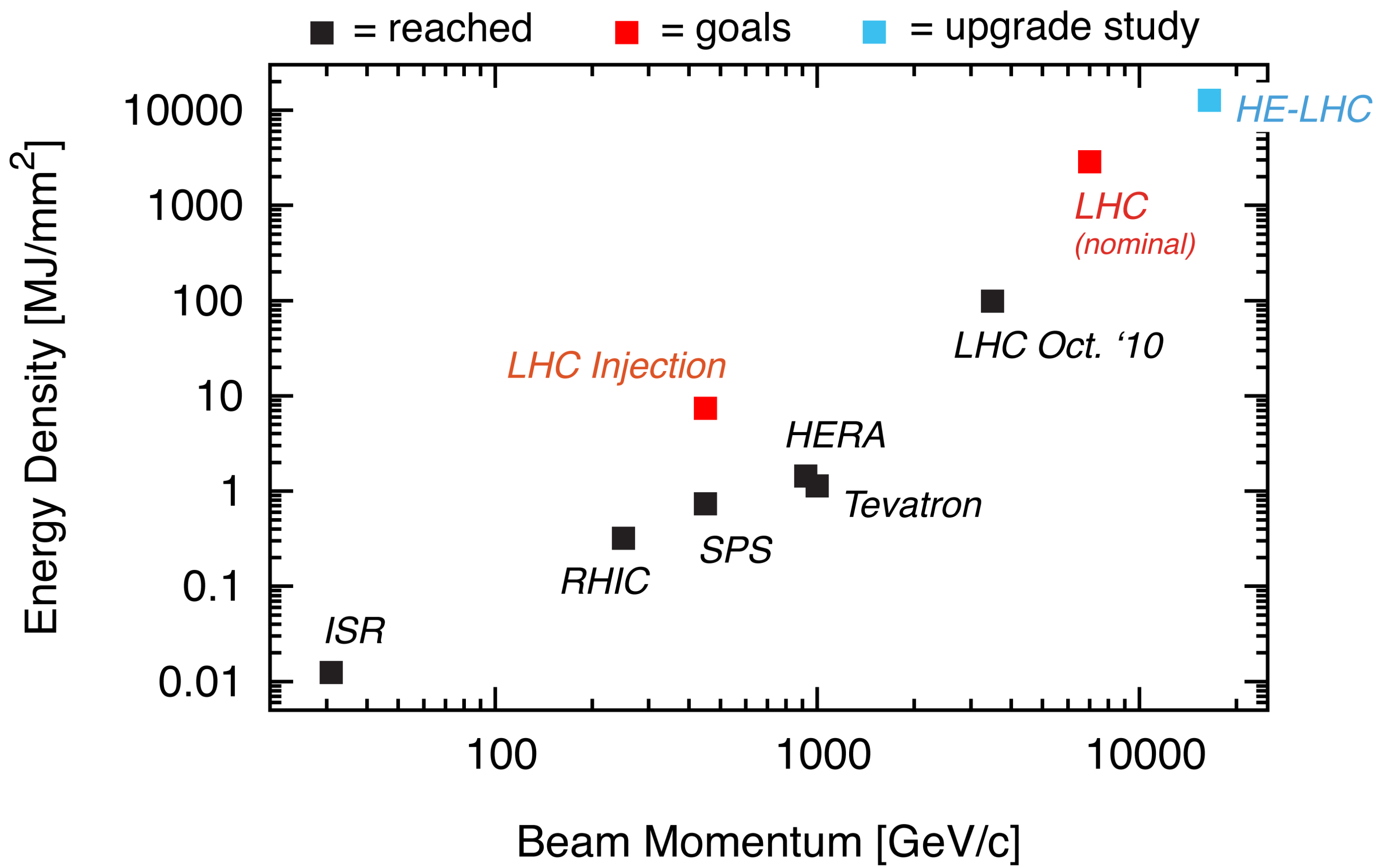
R. Assmann, Malta

Stored Energy



R. Assmann, Malta

Energy Density



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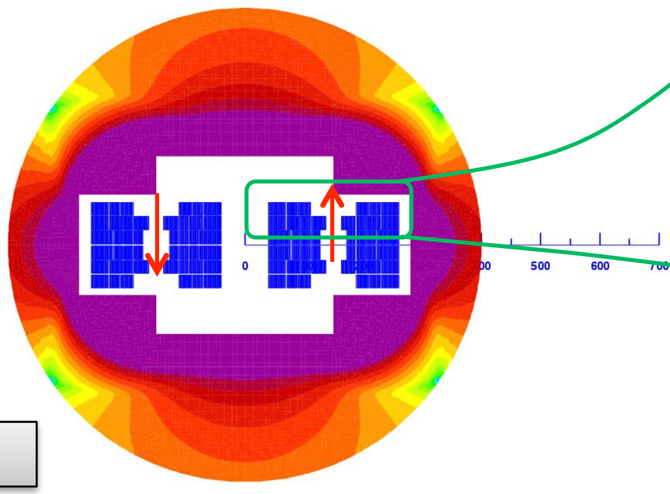
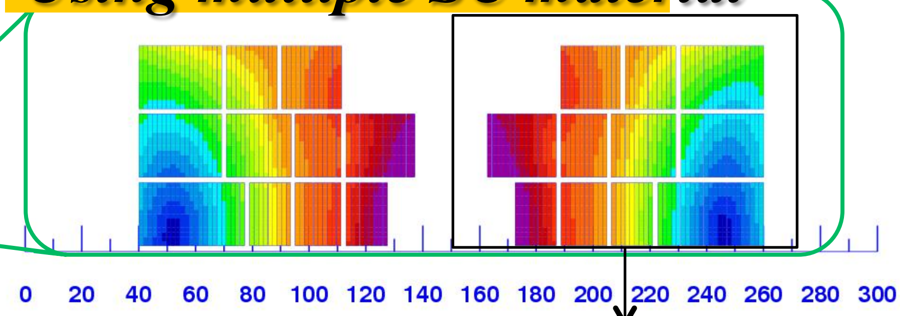
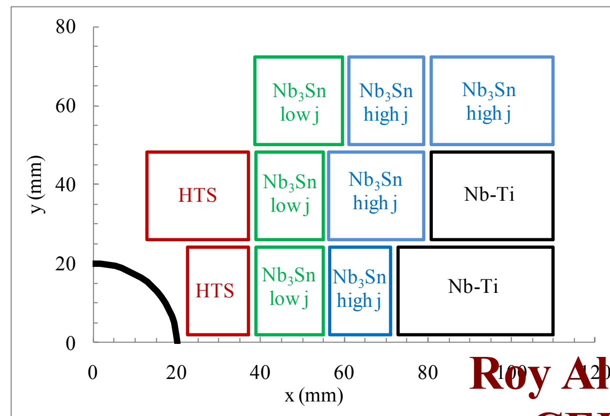
First consistent conceptual design

Using multiple SC material







L.Rossi

Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380
Nb3Sn (high Jc)	55	37%	13	380
Nb3Sn (Low Jc)	30	20%	15	190
HTS	24	16%	20.5	380

20 T field!

Roy Aleksan
CERN
Feb. 22, 2013

Magnet design: 40 mm bore (depends on injection energy: > 1 Tev)
Approximately 2.5 times more SC than LHC: 3000 tonnes! (~4000 long magnets)
Multiple powering in the same magnet for FQ (and more sectioning for energy)
Only a first attempt: cosϑ and other shapes needs to be also investigated

Some Magnet Background to Establish a Baseline

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**
    - **Especially for LHC Energy Upgrade (Fixed tunnel circumference)**
    - **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 . . .

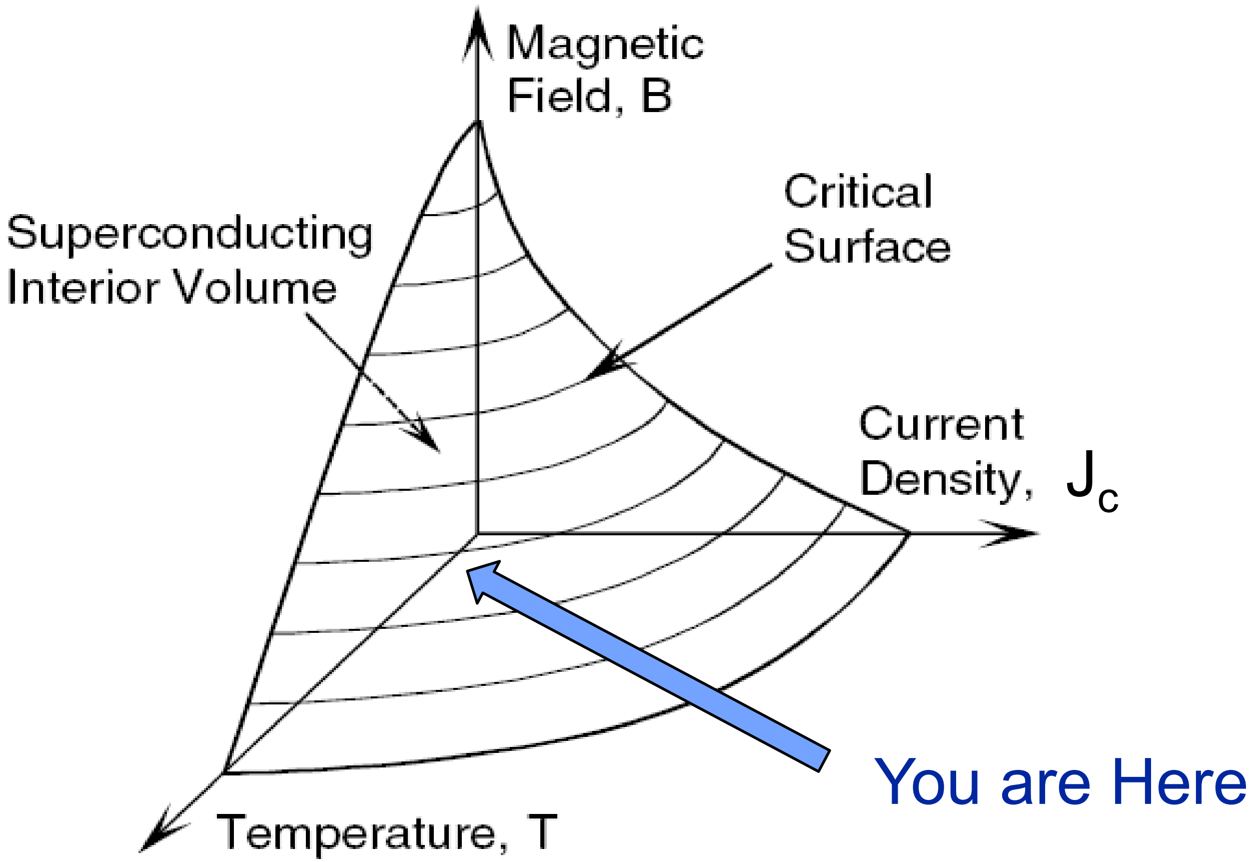
Magnet/System Cost

- **Number of magnets (fewer, longer)**
- **Quantity of conductor (> 30% of cost)** Keep an eye on this!
  - **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**

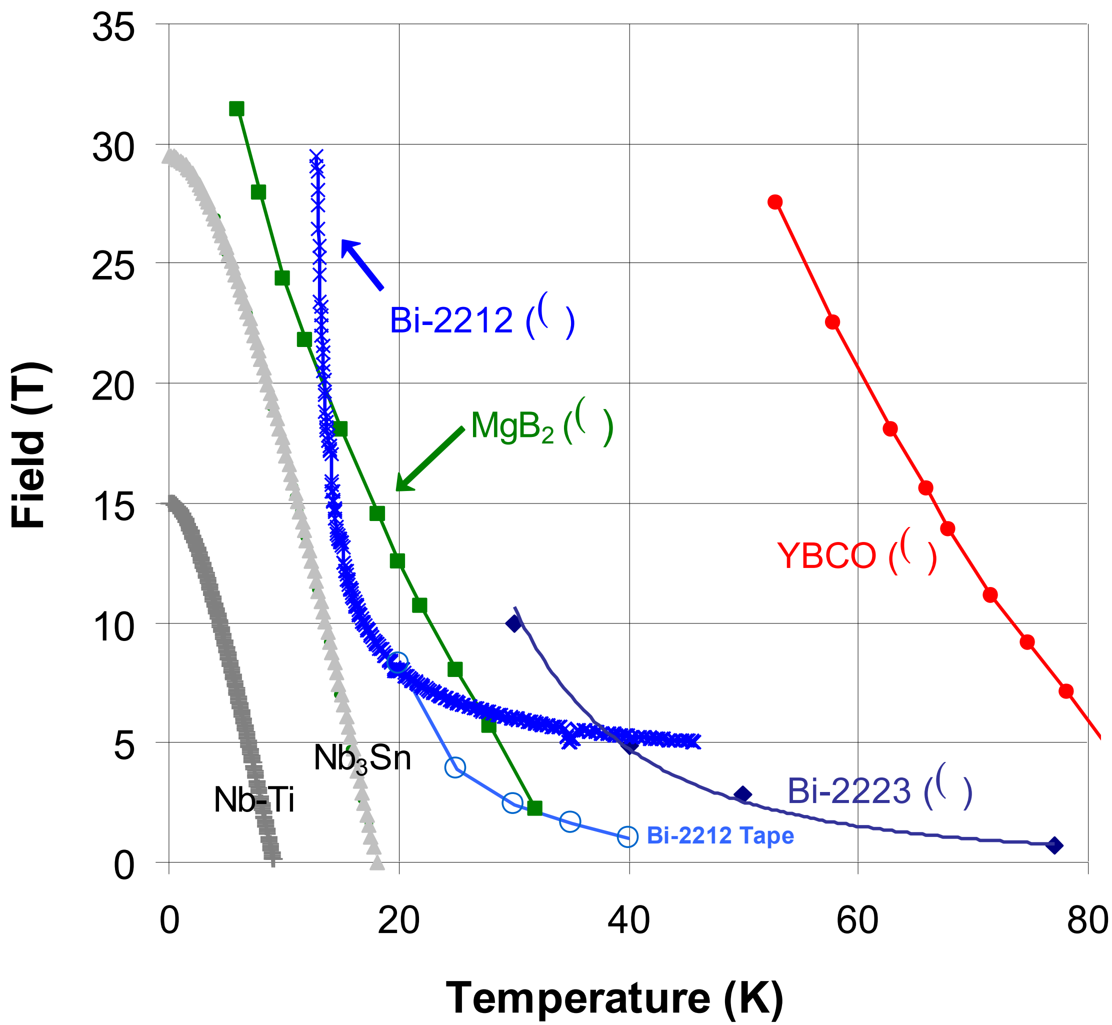
Conductors for Accelerator Magnets

- **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 . . .

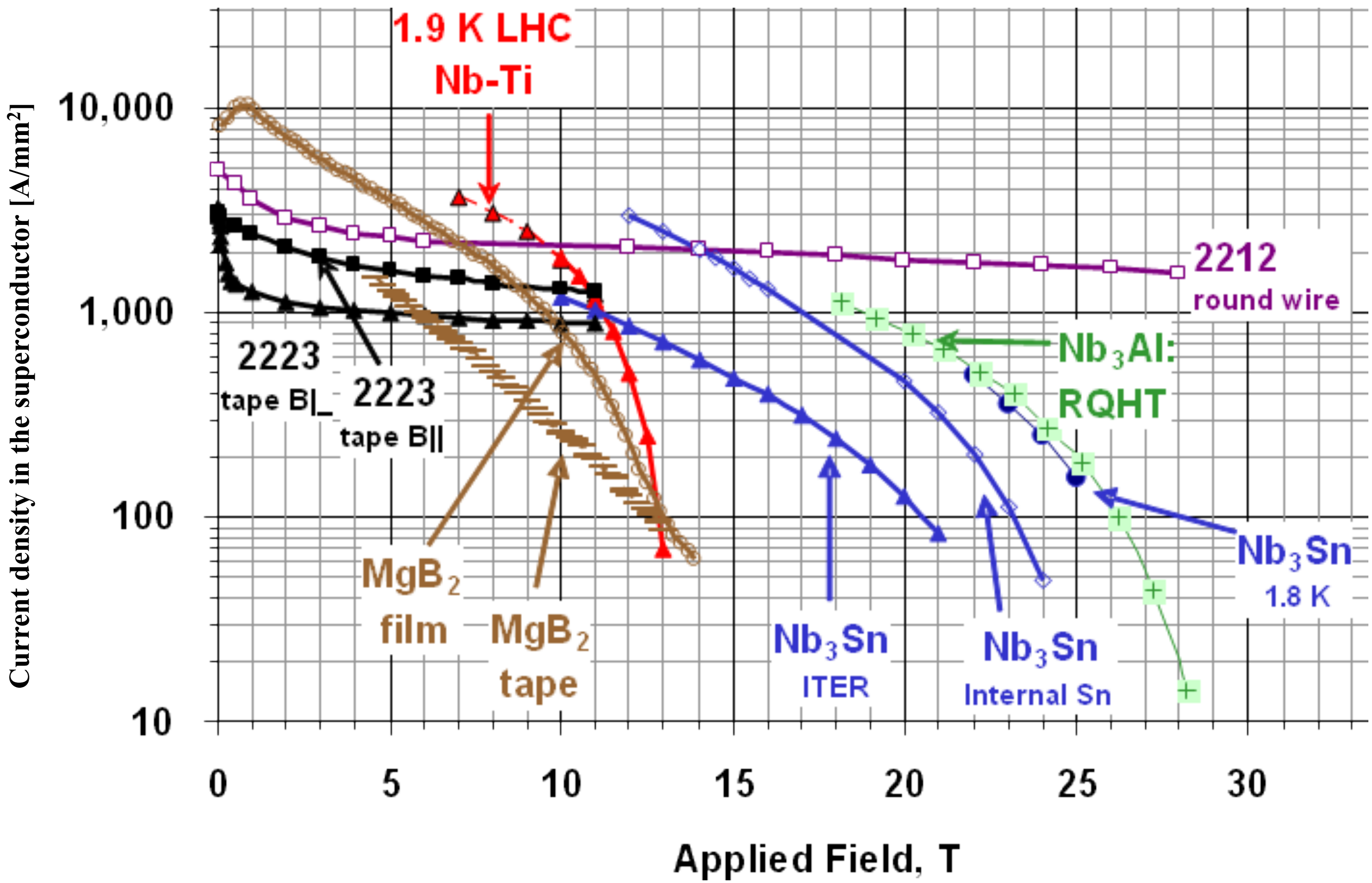

Magnetic
Field, B
Critical
Surface
Superconducting
Interior Volume
Current
Density, J_c
You are Here
Temperature, T

Field vs Temperature



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

Critical Current Density (J_c) vs Field



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

Options for Fields above 18T

YBCO: Looks great on paper but . . .

Tape only, low engineering current density,

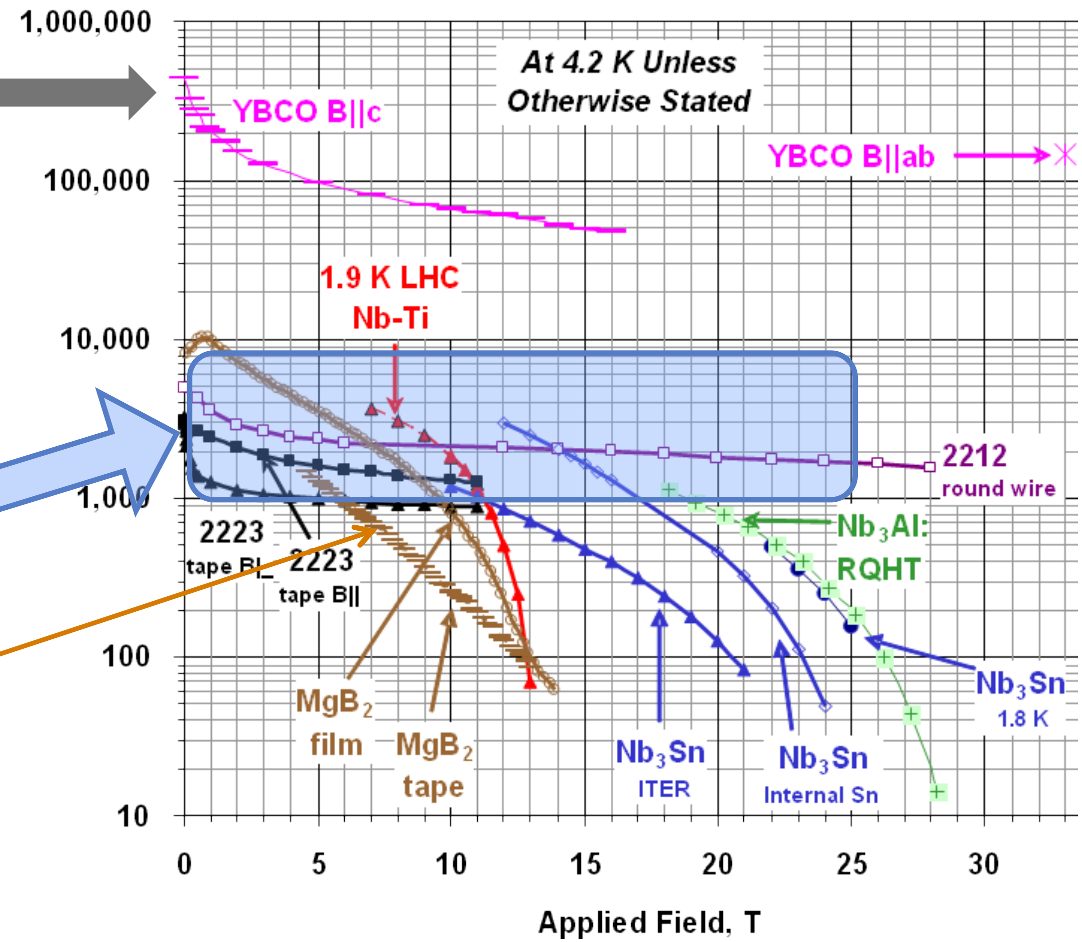
really, really expensive

Maybe in the next talk

Region of interest is where $J_c > 1000$ A/mm^2

Forget MgB_2 (for 3-5 years)

Best candidate is Bi-2212



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
  - — Actively pursued in Japan
    - — National Institute for Materials Science (NIMS)
    - Rapid-quench process requires later addition of stabilizer

Materials for Accelerator Magnets

Application/performance ⟷ material properties and engineering

- **Bi-2212**
  - — Round strands in long lengths
  - — Requires 900 ^{0}C heat treatment
  - — Strain sensitive
- **Bi-2223**
  - — Tapes in long lengths
  - — Applications for high temperature
- **YBCO**
  - — High critical current but length is a problem
  - — Tapes (not wires!)
  - — Lousy engineering current density
  - — Really Expensive

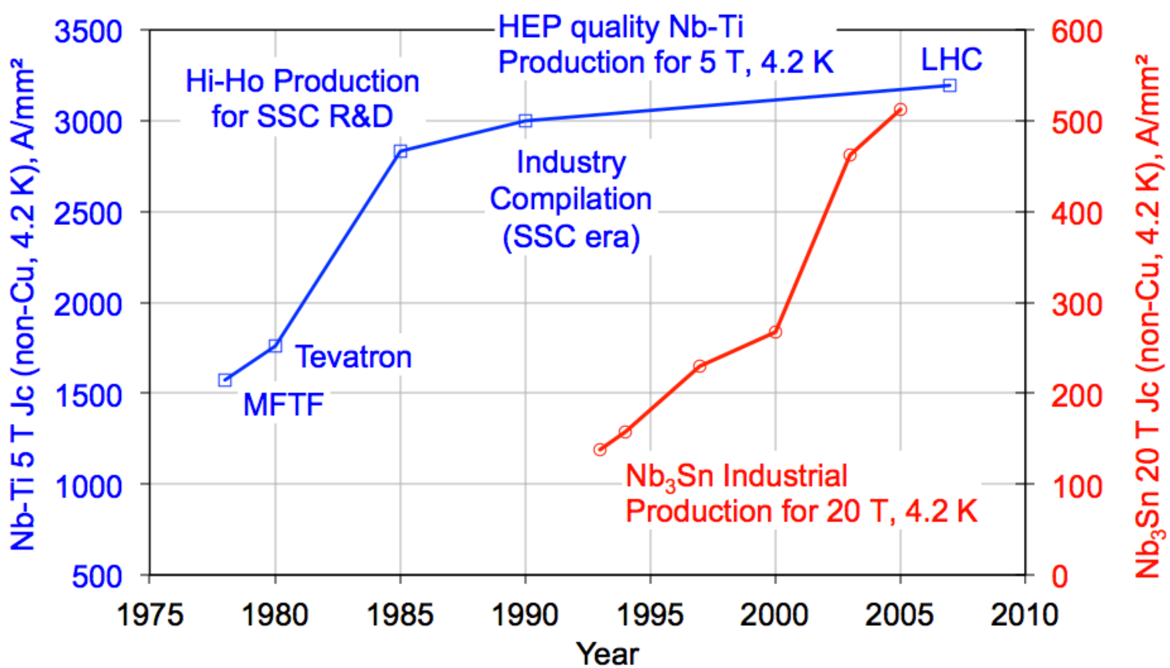
- **MgB_2 (not so HT HTS)**
  - — Better at T < 25K
  - — Anisotropic
  - — Low J_c (so far)
  - — Stabilization

But . . .

  - — Potential to exceed H_{c2} of Nb_3Sn
  - — Low cost materials
  - — Leading candidate for LHC Lumi upgrade (SC cables)

Where are we with NB_3Sn?

- Nb_3Sn performance has greatly improved (doubled in ten years)
- Can we expect more?

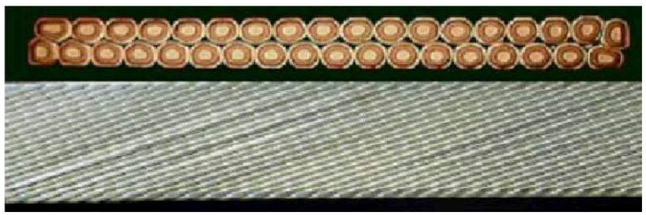


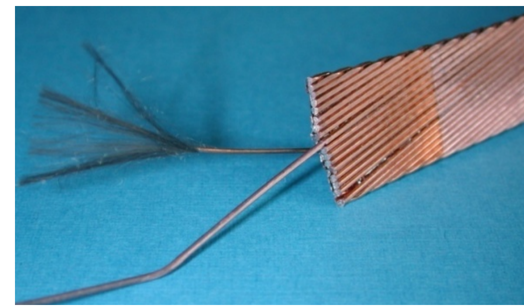
An historical view on the improvement of Nb-Ti and Nb_3Sn performance [L. Bottura, ASC 2012]

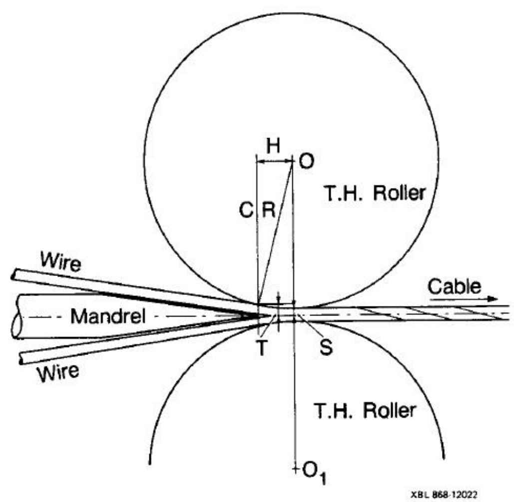
Rutherford Cables

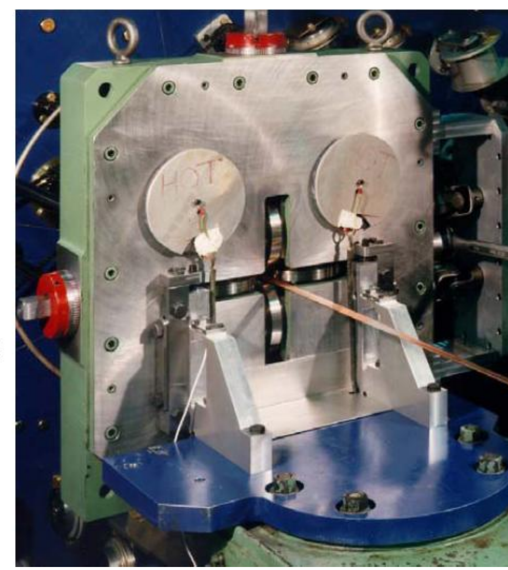
- **Cable cross-section is rectangular or trapezoidal**
- **Packing Fraction (PF) ranges from 85% - 92%**
  - **Too much compaction – damage to filaments**
  - **Too little compaction – mechanically unstable**

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



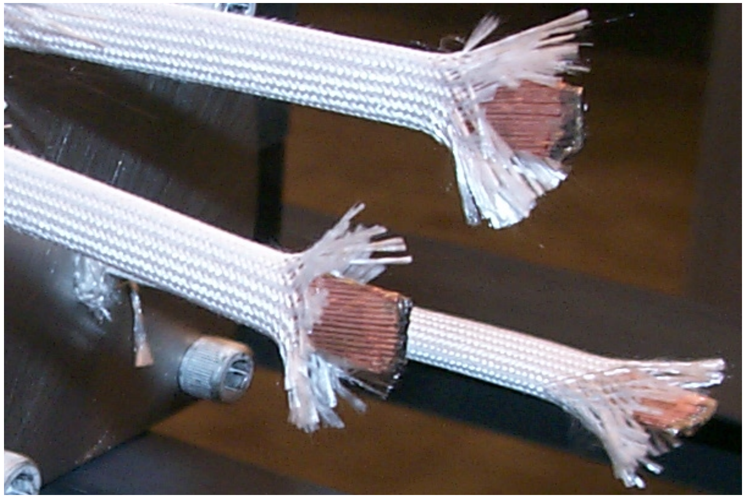






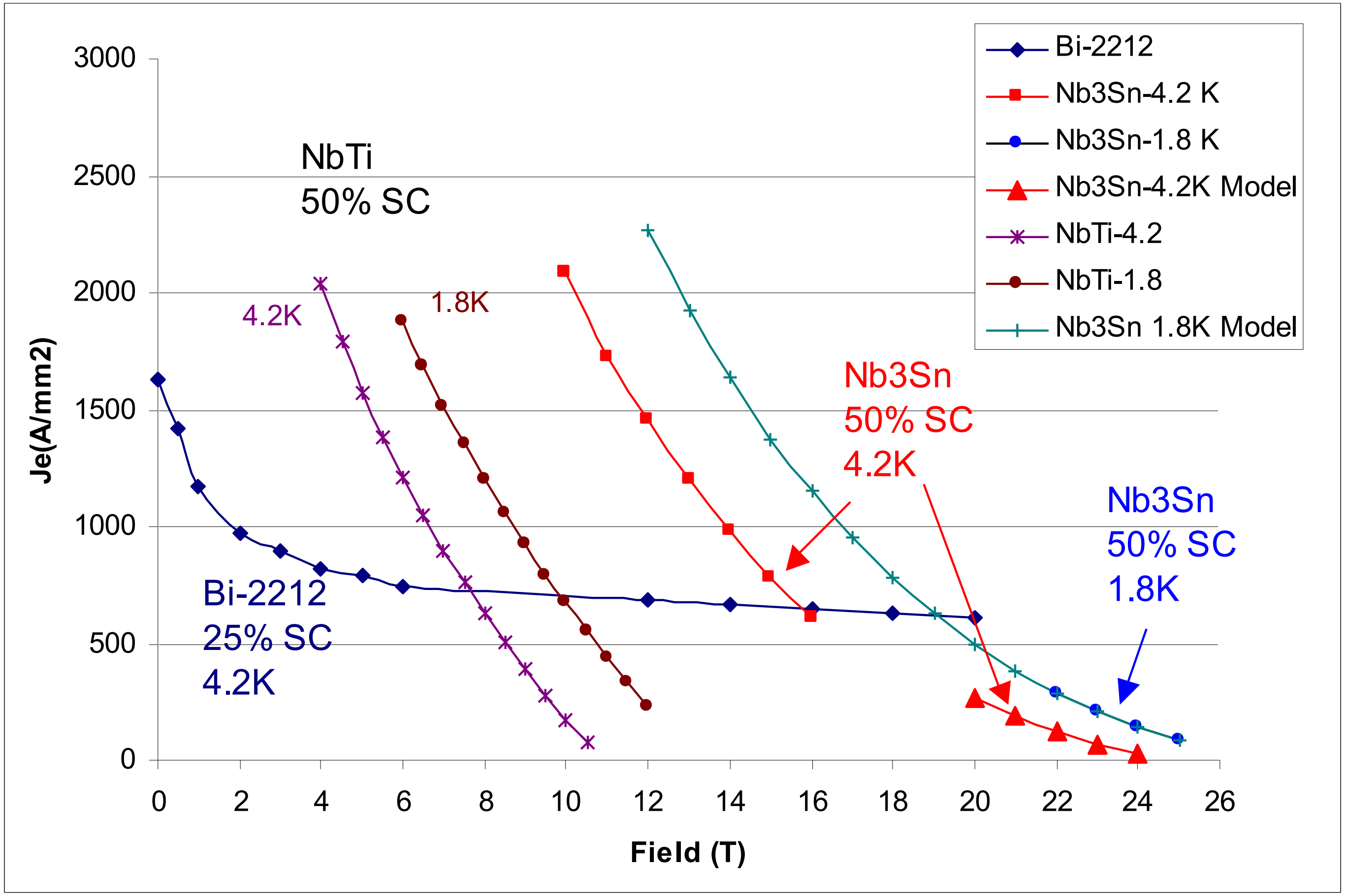
Engineering Current Density

- **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 (κ) = $(N_{wire} A_{sc})/A_{ins\_cable}$**
- **Engineering current density defined as $J_e = \kappa J_c$**
  - — Typically on the order of 1,000 A/mm^2

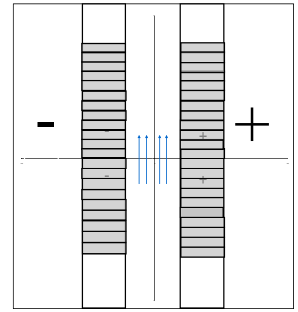
Magnet Conductor Comparison
J_e is what counts

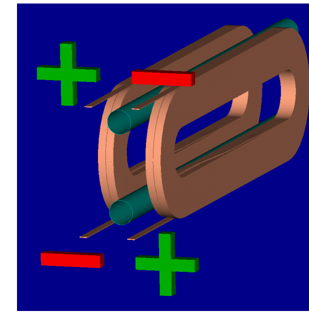


Electromagnetic design

Start with Ideal Case for Dipole Field

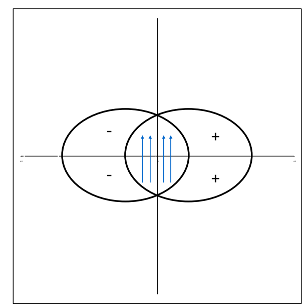
- **Uniform current walls**
  - **Easy to wind but the height is infinite**
  - **Practical implementation requires . . .**
    - **High aspect ratio**
    - **Modification of ends**





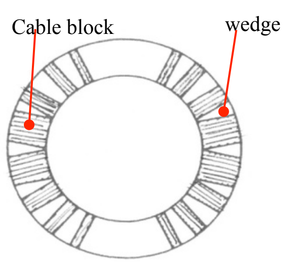
BNL "Common Coil"

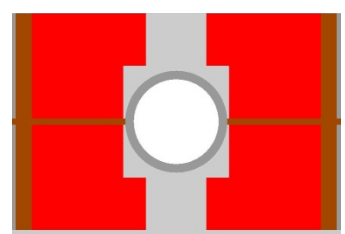
- **Intersecting Ellipses**
  - **Non-circular aperture**
  - **Requires internal support structure**



- **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]



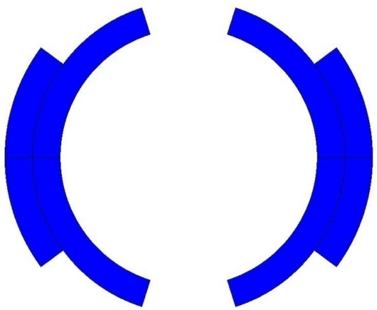


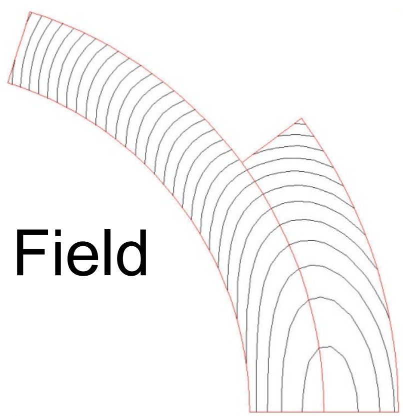
Block Coil Implementation
LBNL "HD-2"

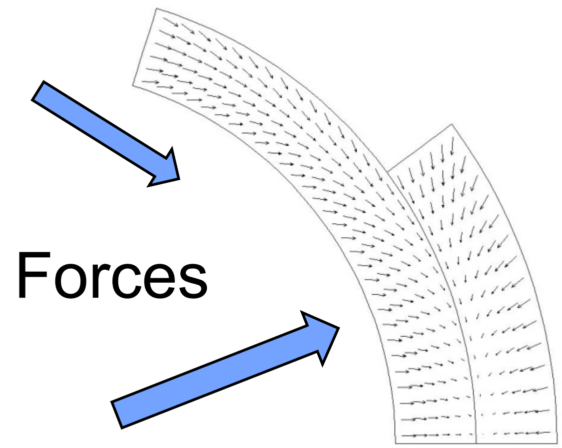
Forces, Stresses and Structures

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")**



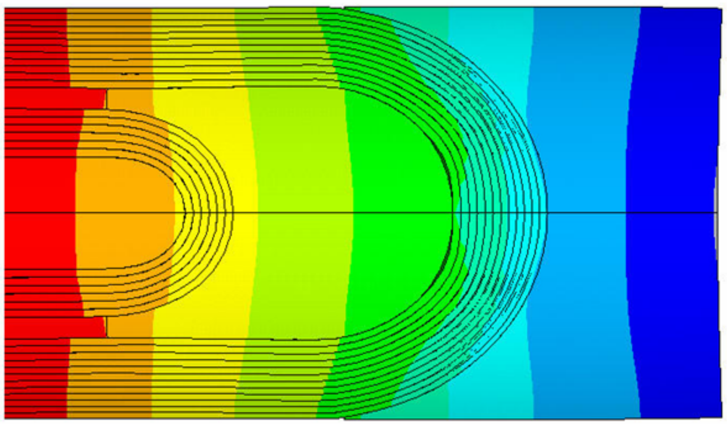




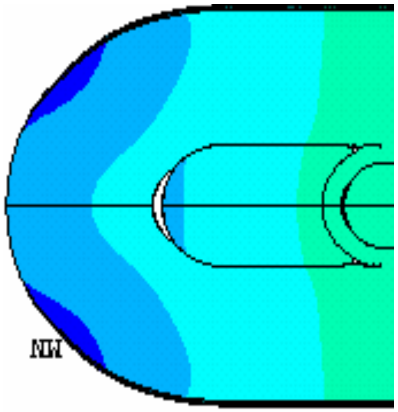
- **Forces are outward in radial direction and towards the mid plane in the azimuthal direction**

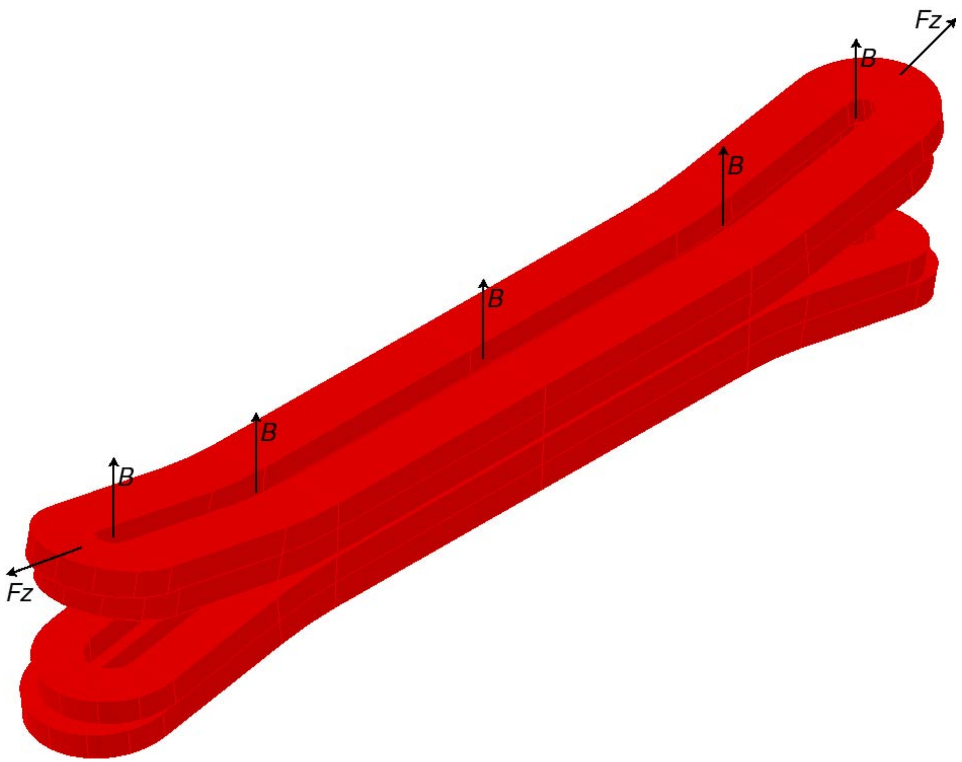
Ends

- **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**

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

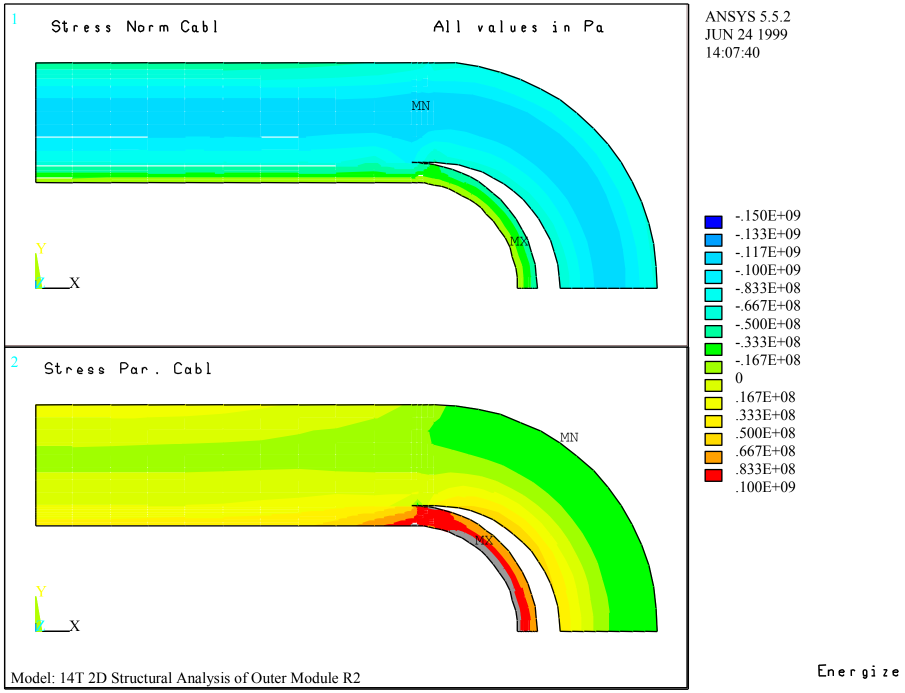
similar to the pressure of a gas acting on its container

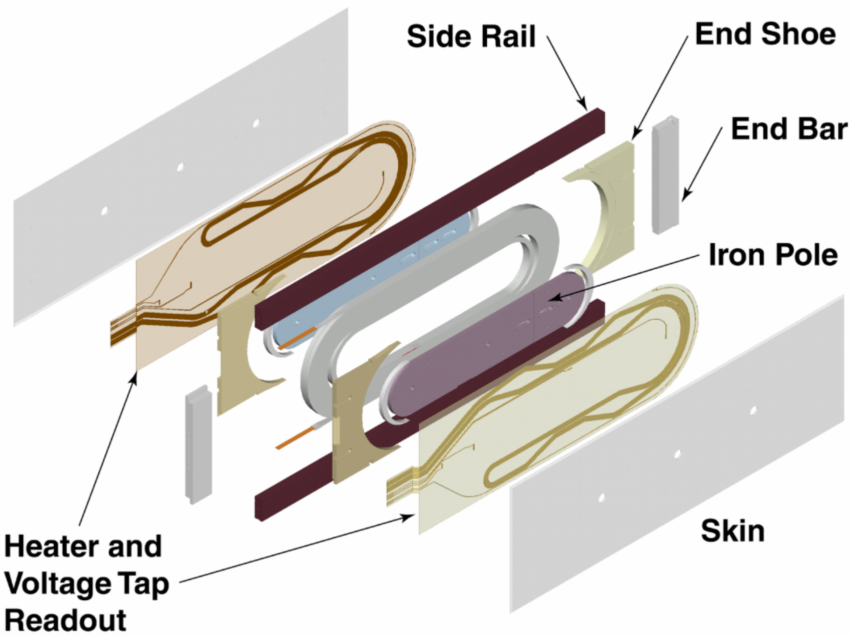
- **In the example to follow we have 12 T**

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

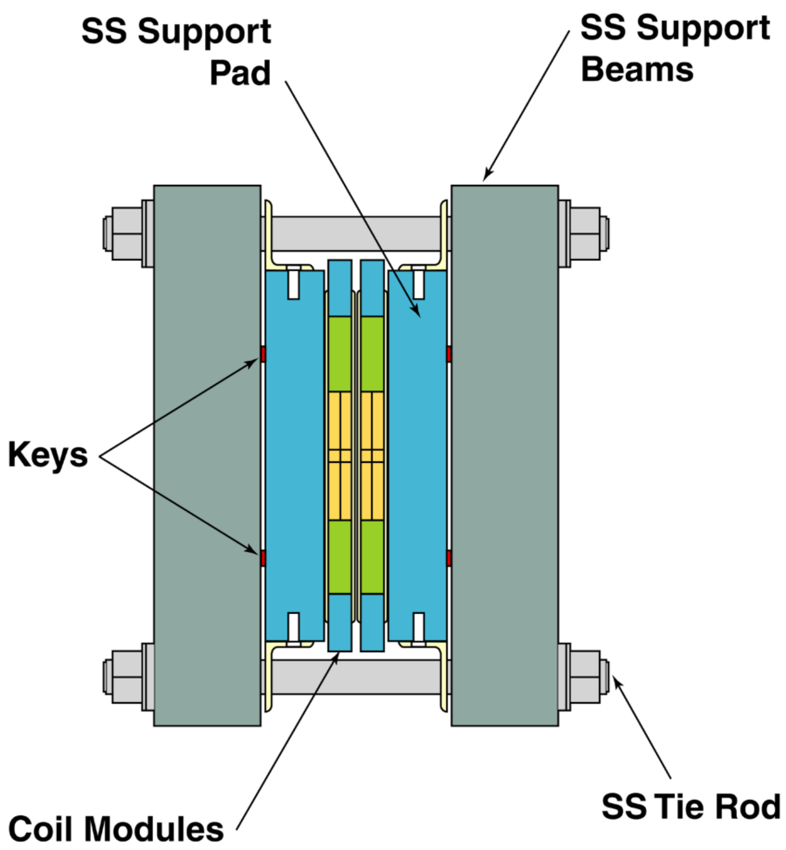
General example of forces – at 5 T the force trying to separate the two coil halves is 100 Tons/m

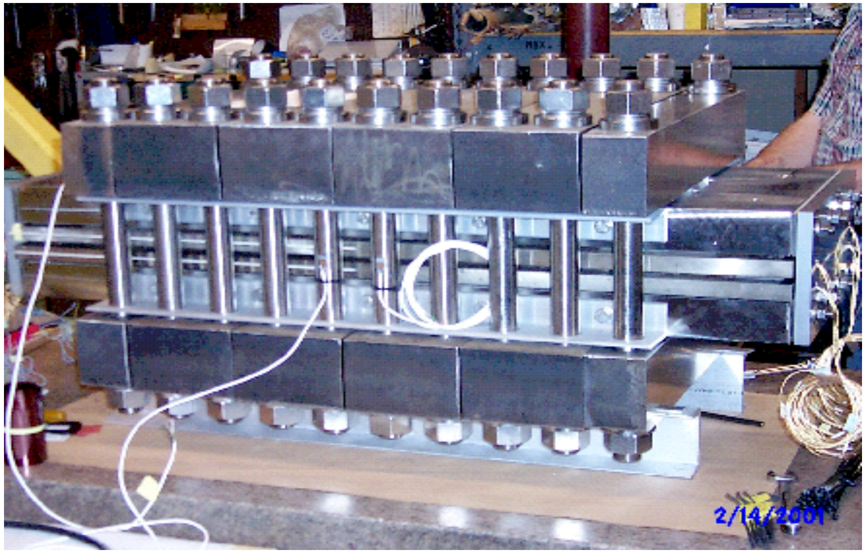
- **Two simple racetrack coils**
  - 50 cm long
  - 12 Tesla



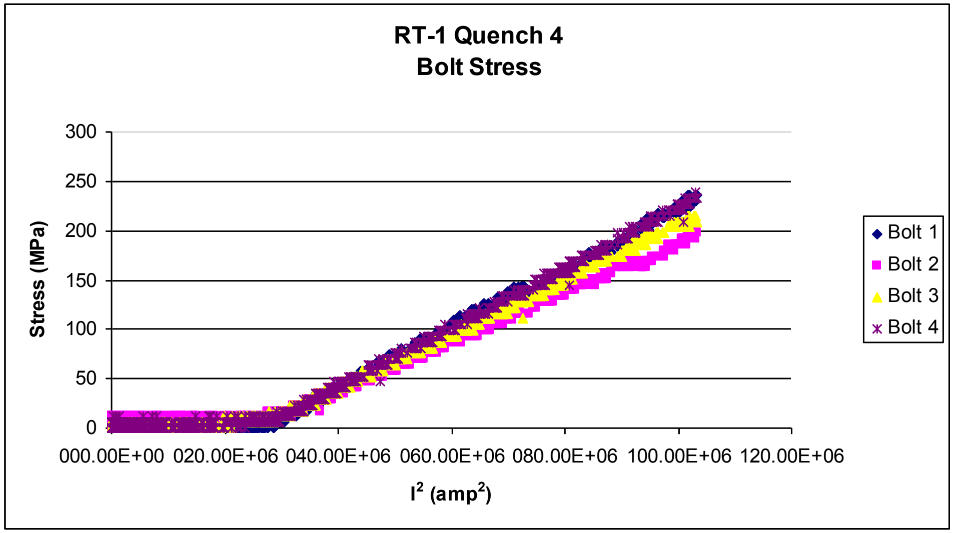


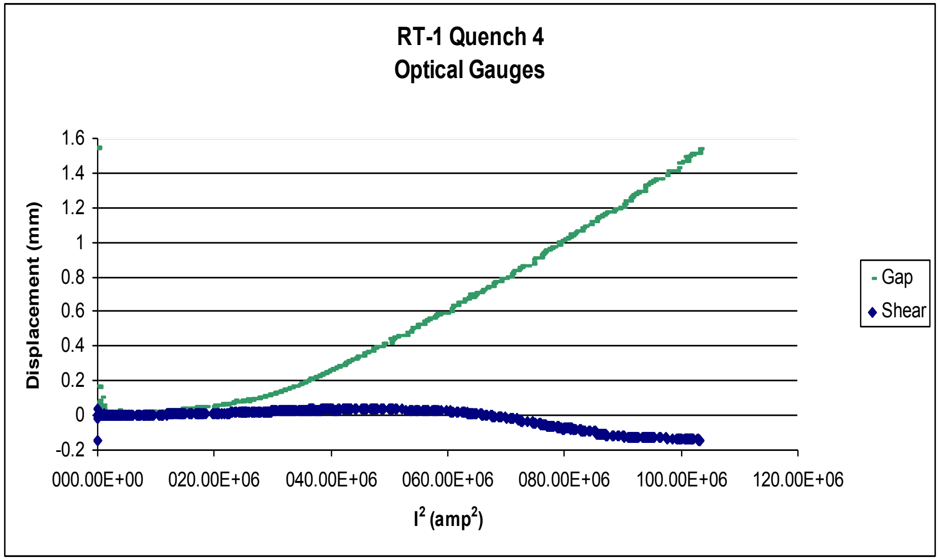
Support Structure

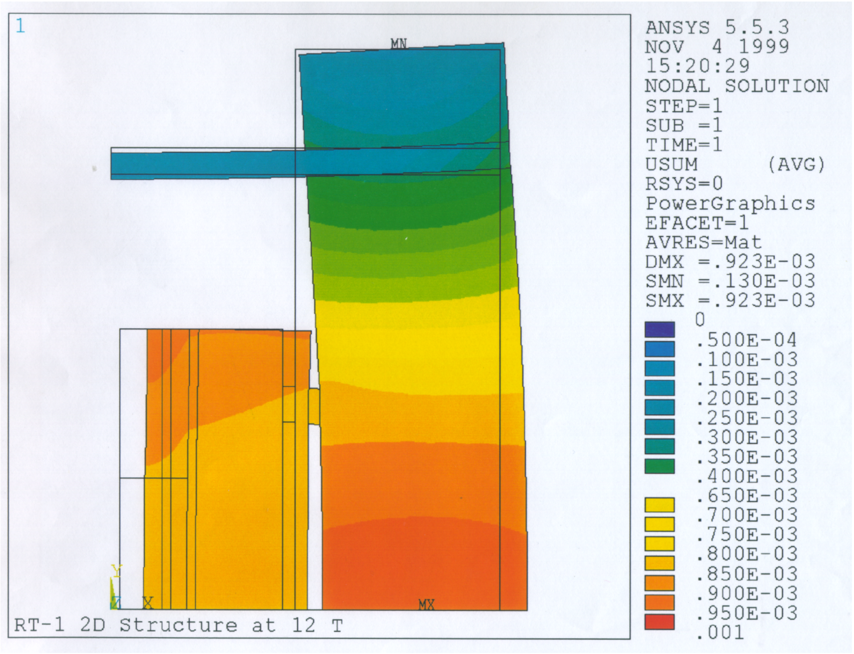




Test Results





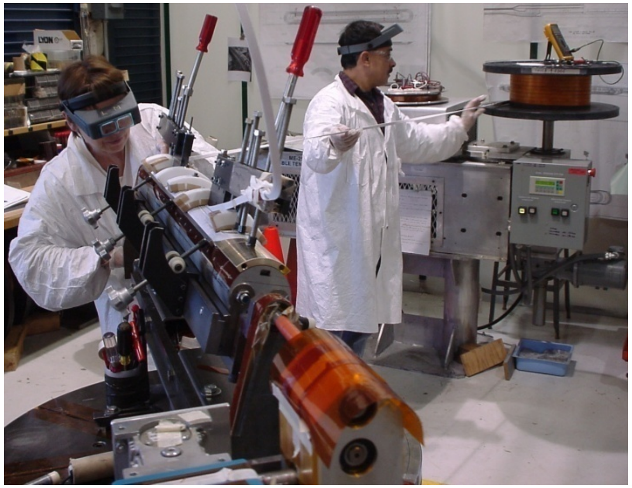


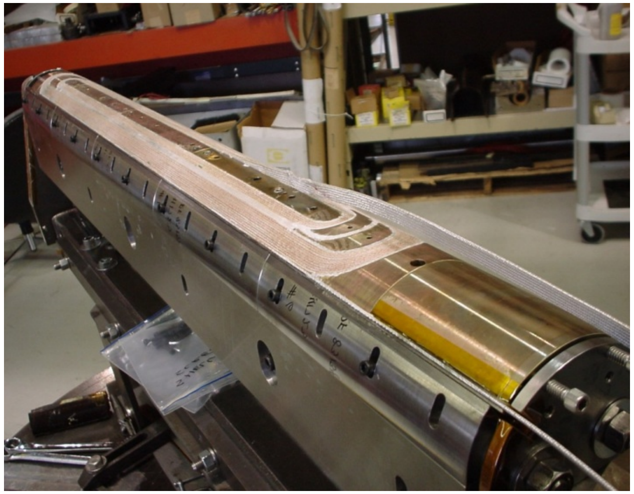
Coil Fabrication

BERKELEY LAB

Consider NbTi (dominates use now) and Nb_3Sn

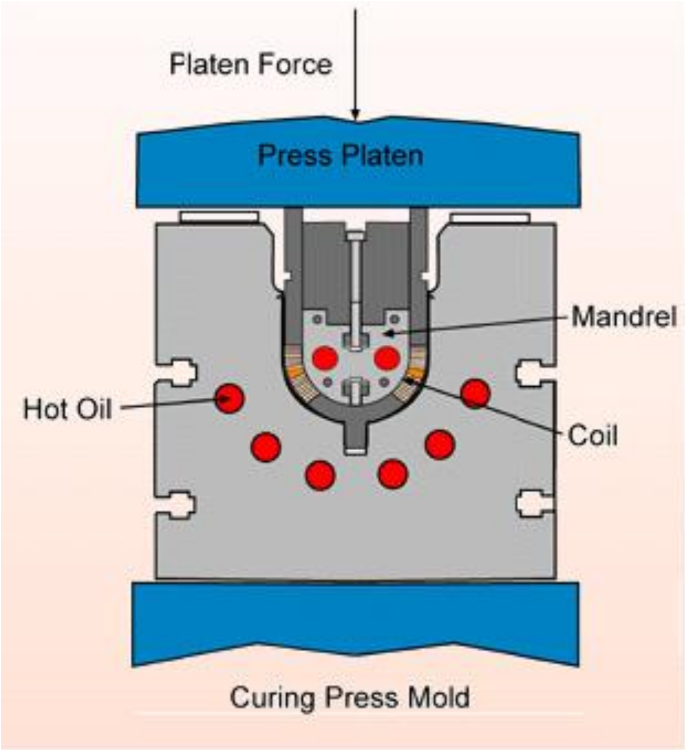
- **Winding**
  - — **Virtually the same process for both materials**
  - — **Start with insulated cable**
    - **NbTi – 1 or 2 layers of polyimide wrap**
    - **Nb_3Sn – S-2 glass "sock" – really not insulator but matrix for later epoxy impregnation**

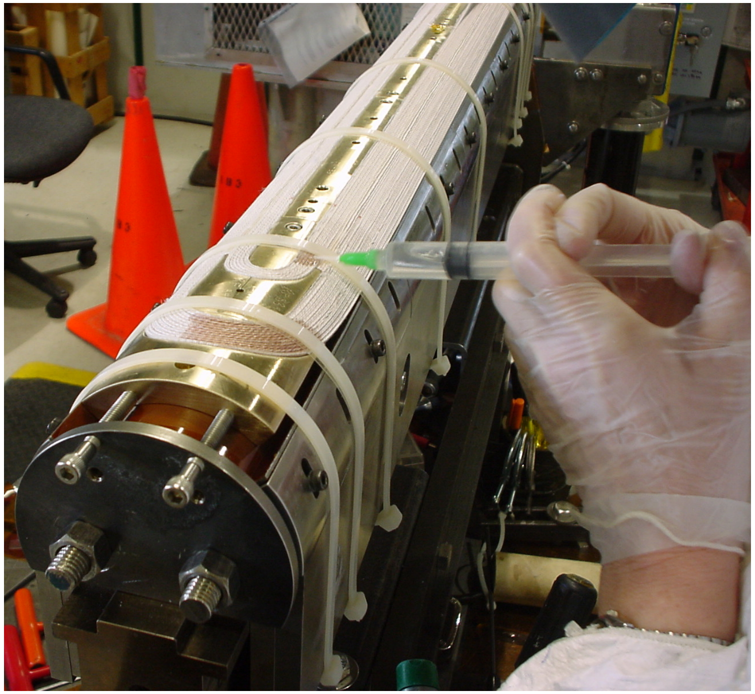




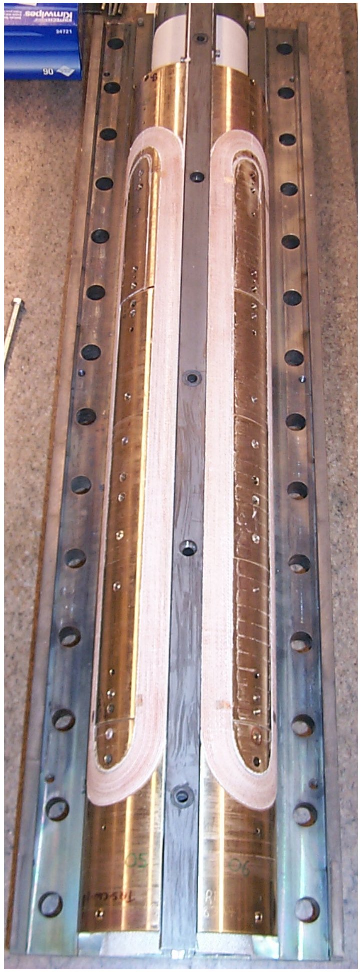
Coil Fabrication

- **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)**



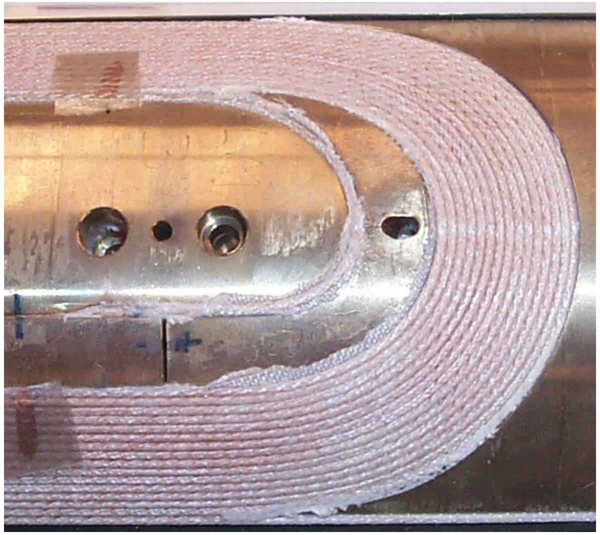


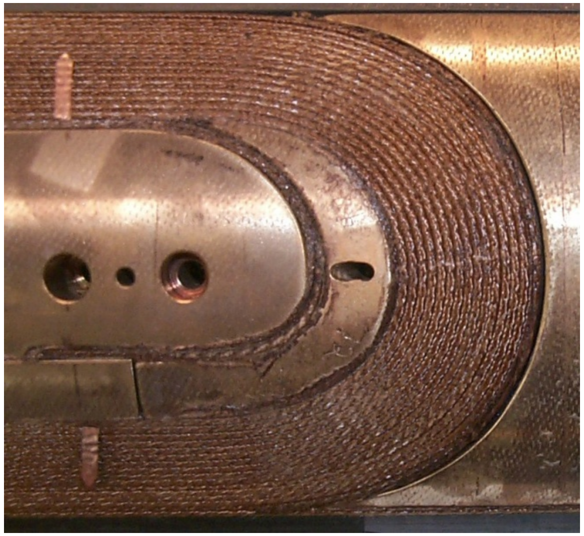
Reaction Fixture for Nb_3Sn Coils

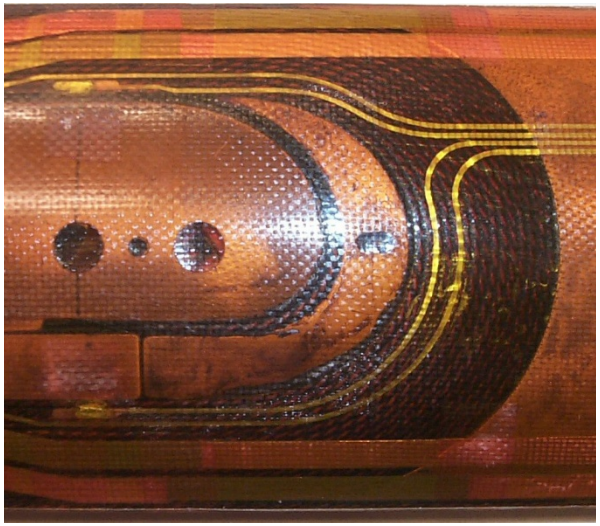


Coil Fabrication

- **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**

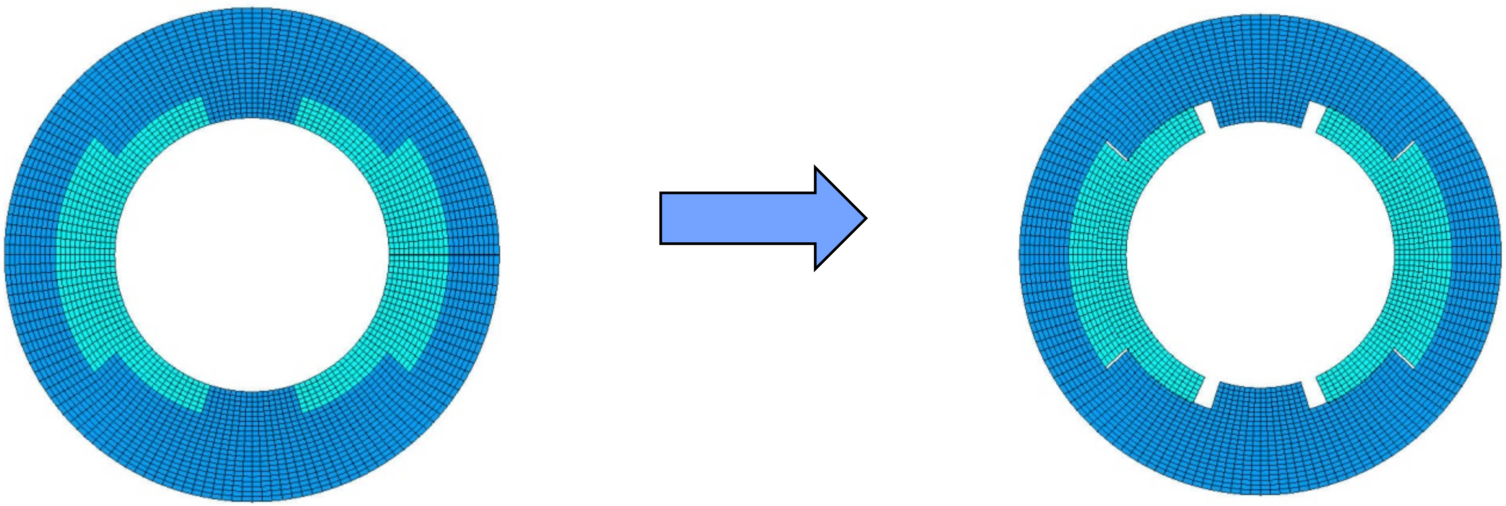






Structures and Pre-Stress

- **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**

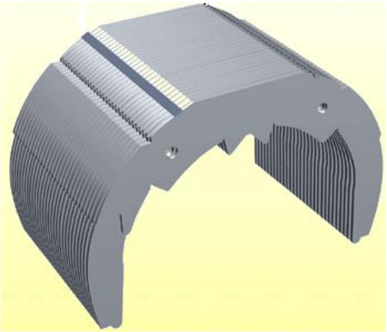
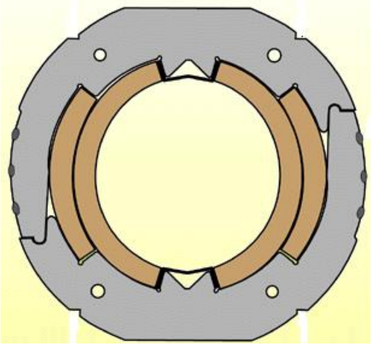
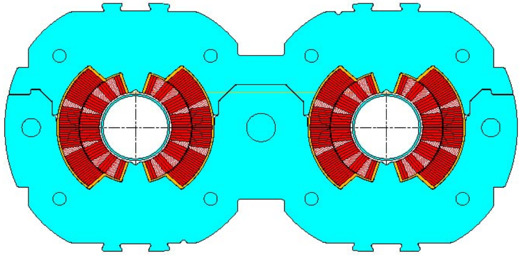
Support Structure

- **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**

Remember this!

Collars

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

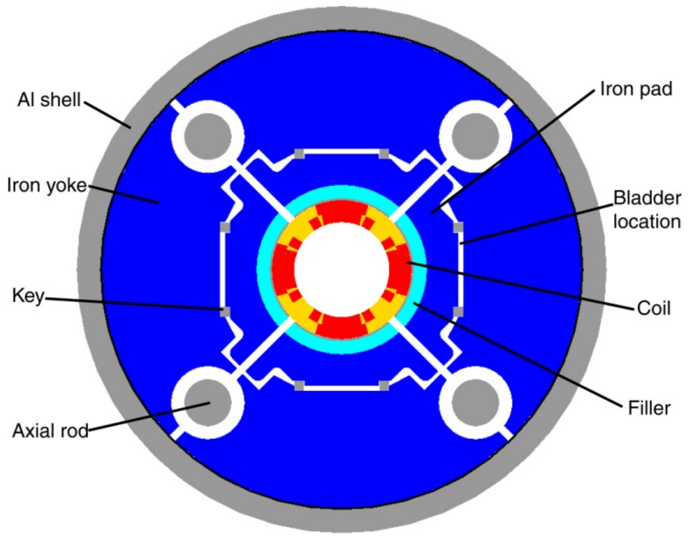




LHC

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

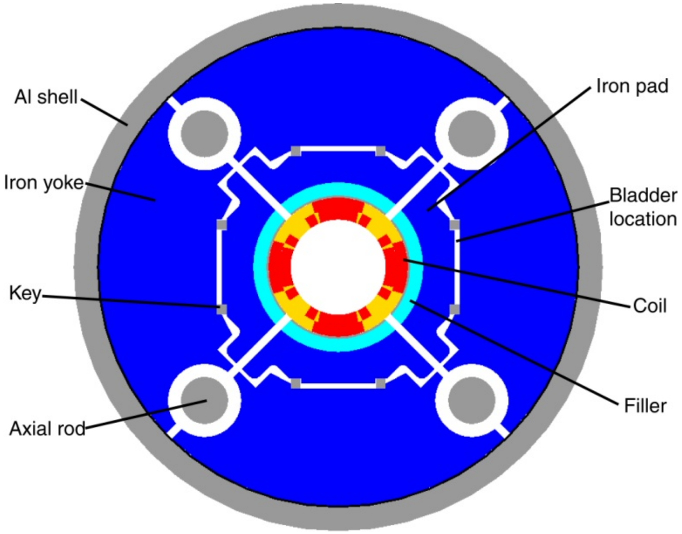
Final Assembly

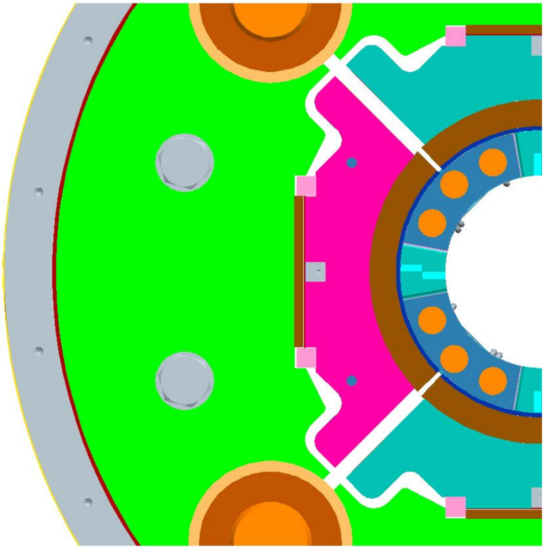
- **Iron yoke**
  - — **Shields and enhances field**
  - — **In some cases provides additional preload**
- **“Skin” or shell**
  - — **Yoke is contained within two welded half-shells of stainless steel (the “skin”) or a shrinking cylinder of aluminum**
    - **Outer shell contributes to coil rigidity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



Key and Bladder (LARP/LBNL TQS Quad)

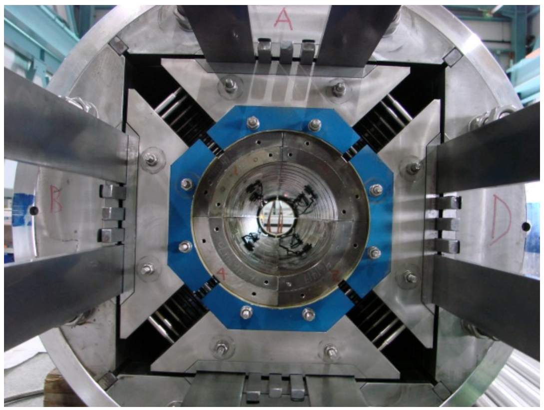
- Four pads or collars transfer load to coils
- Yoke is contained by aluminum shell
- Preload provided by inflating bladders and held via keys
- Coil pre-stress increases during cooldown due to the high thermal contraction of the aluminum shell.

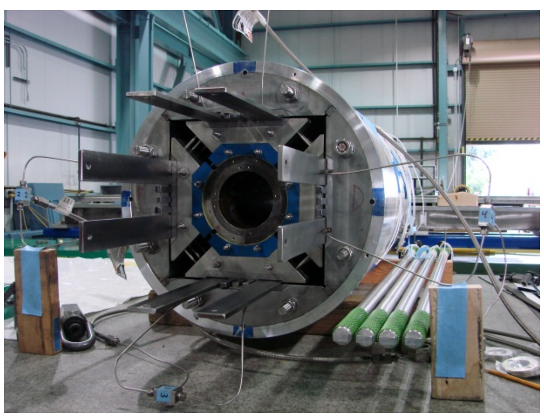


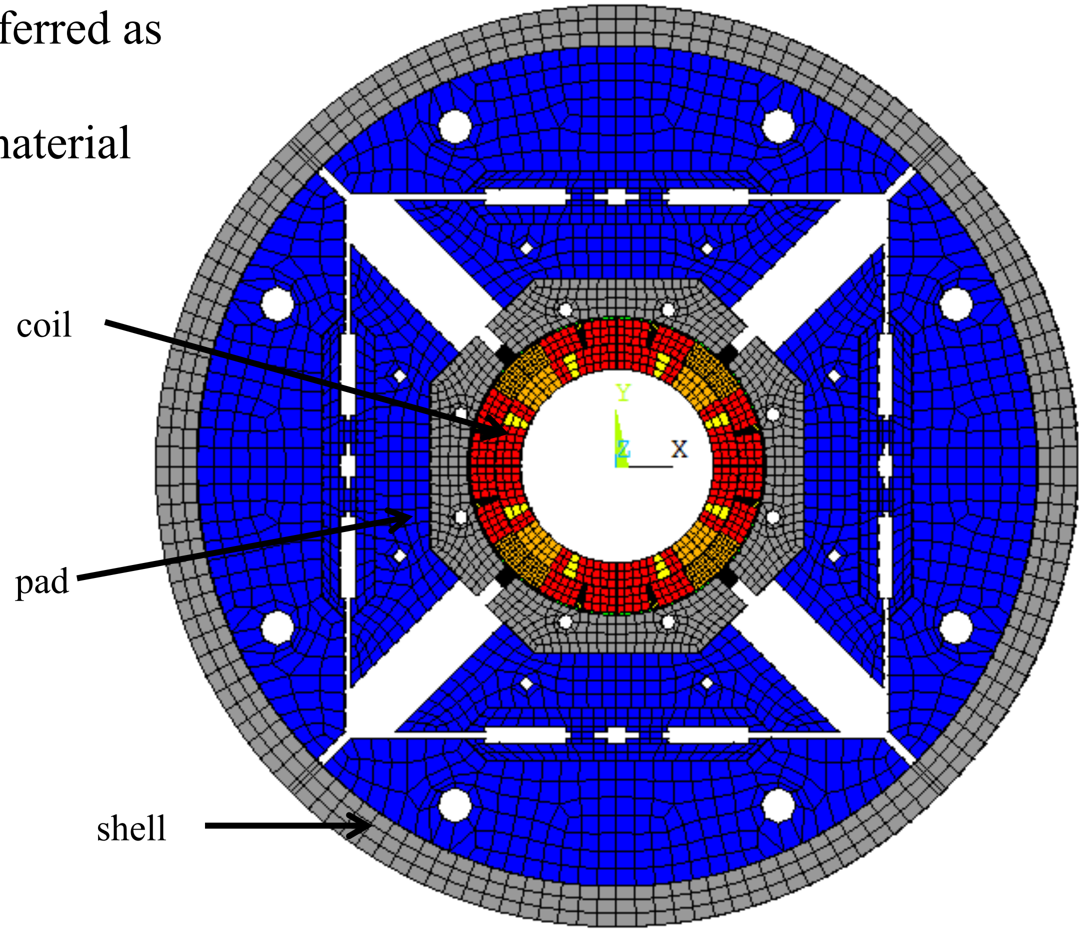


Magnet Design Support Structure

- Shell-based support structure often referred as "bladder and keys" structure
developed at LBNL for strain sensitive material







Courtesy Helene Felice

Magnet Design Support Structure

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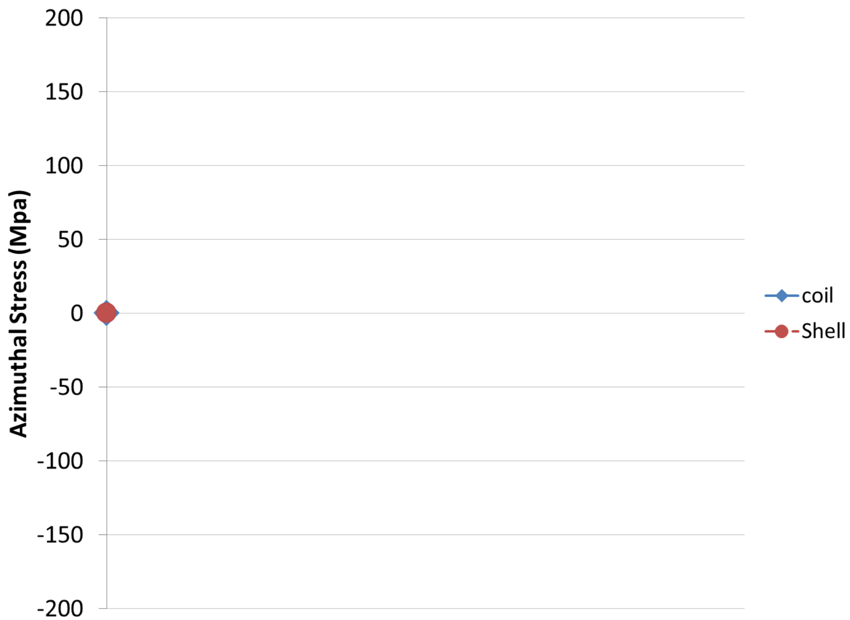

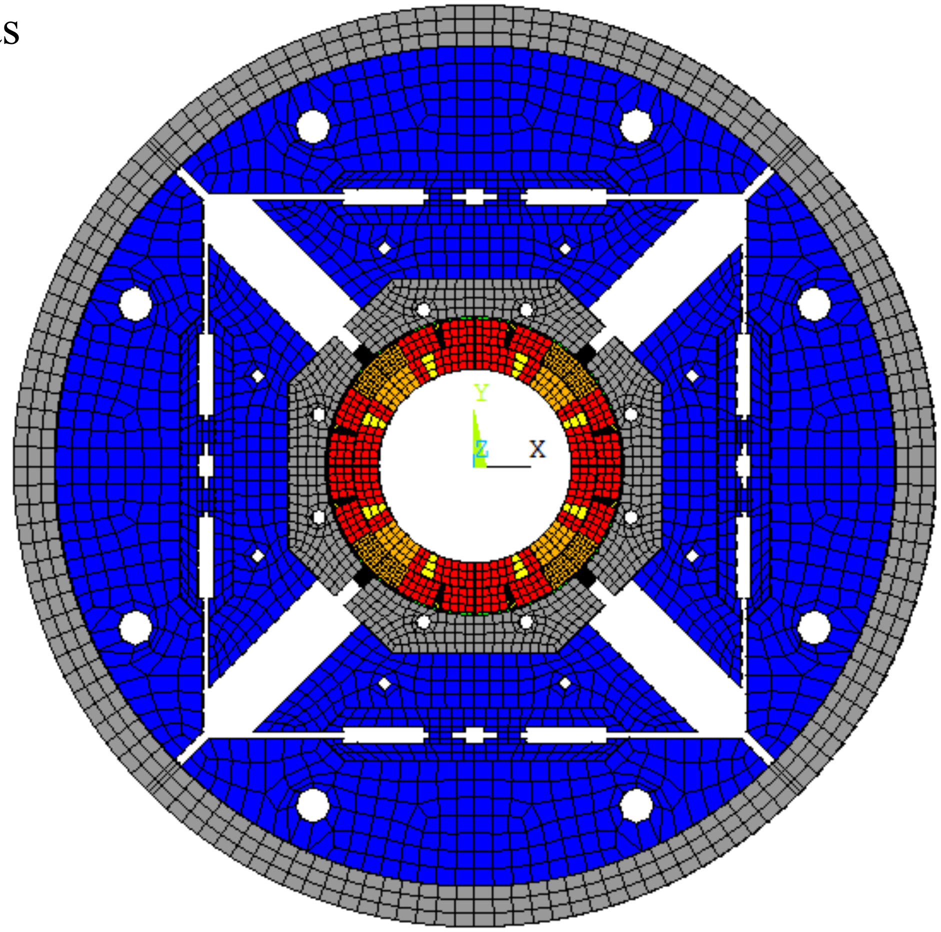

Courtesy Helene Felice

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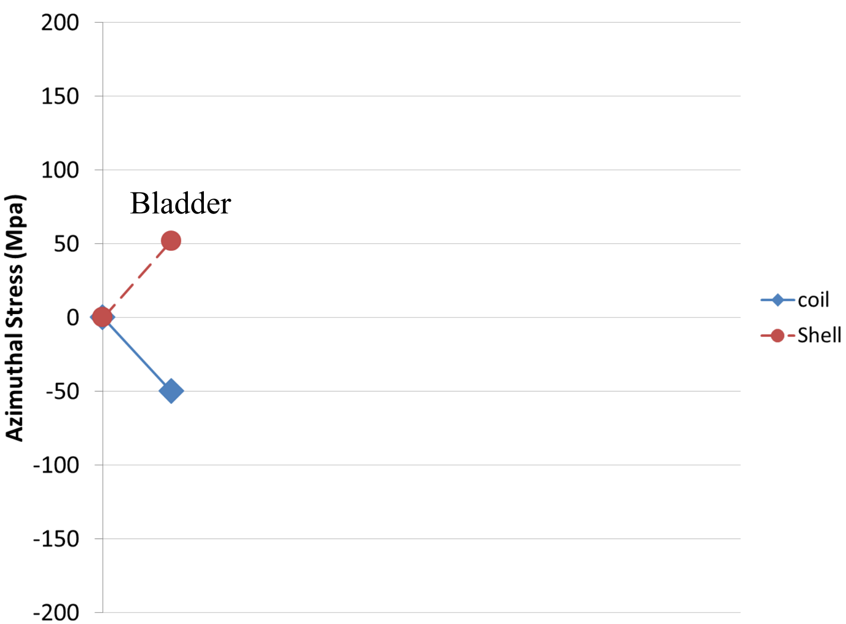
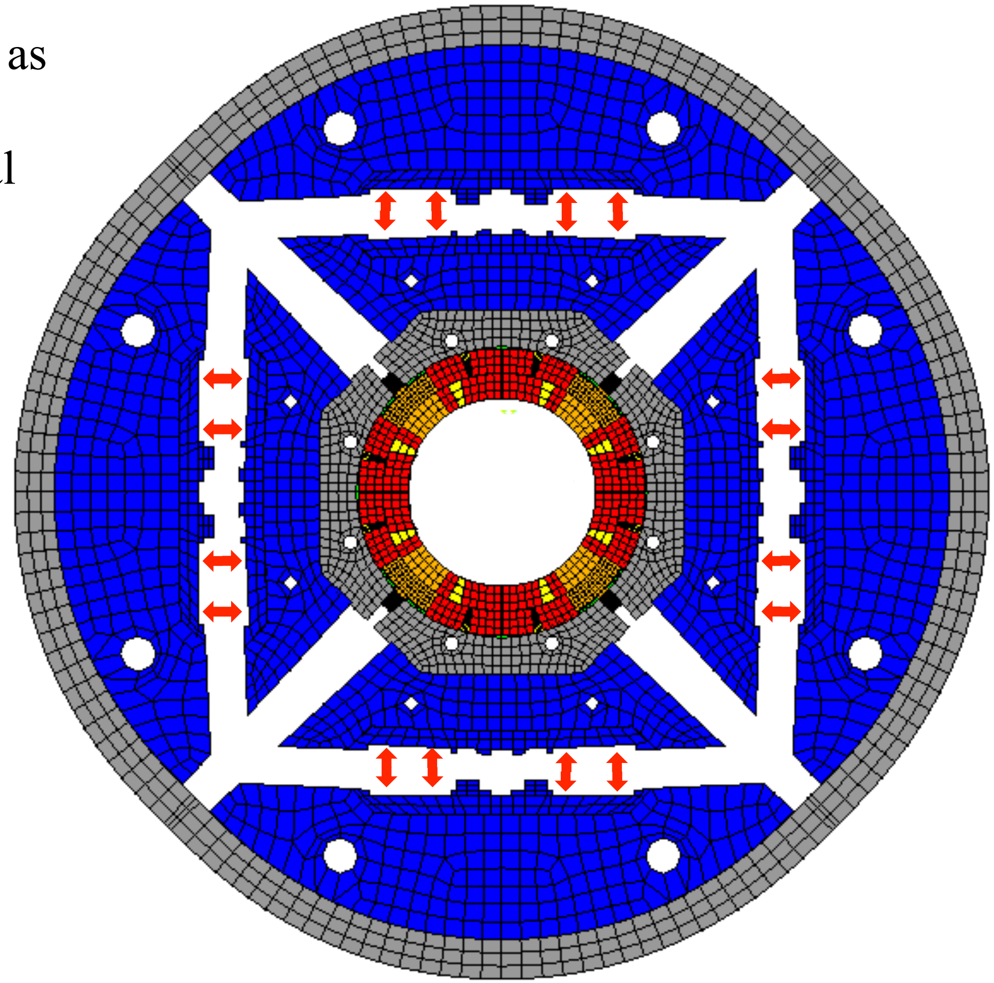


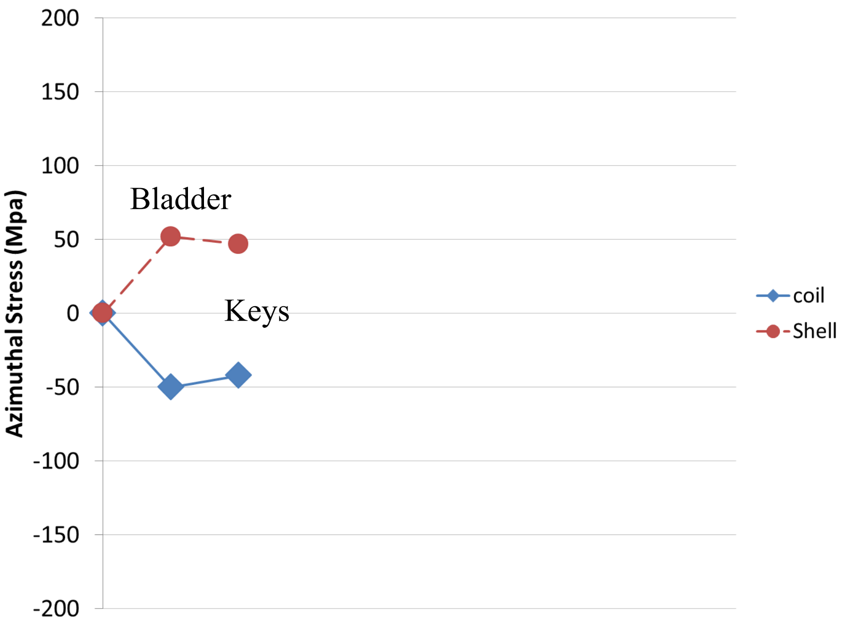


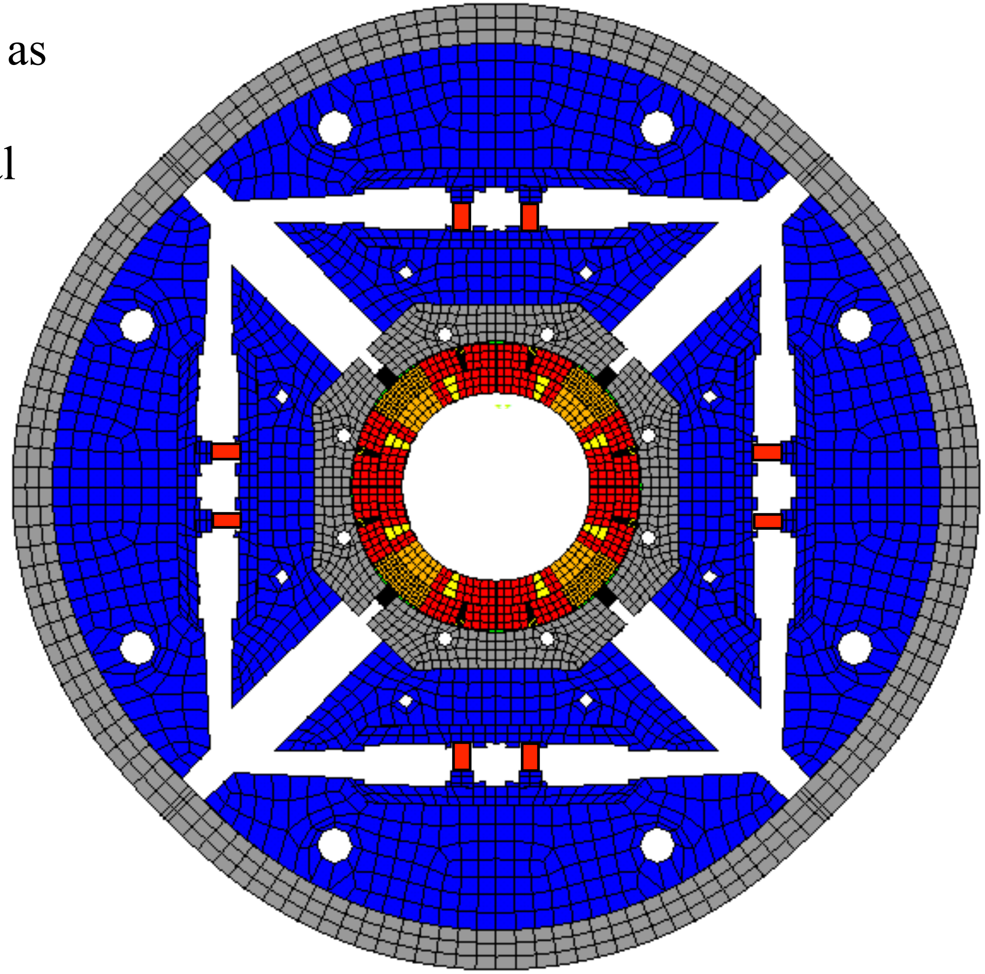
Courtesy Helene Felice

Magnet Design Support Structure

Shimming of the load leys

- Shell-based support structure often referred as "bladder and keys" structure developed at LBNL for strain sensitive material





Courtesy Helene Felice

Displacement scaling 30

Magnet Design Support Structure

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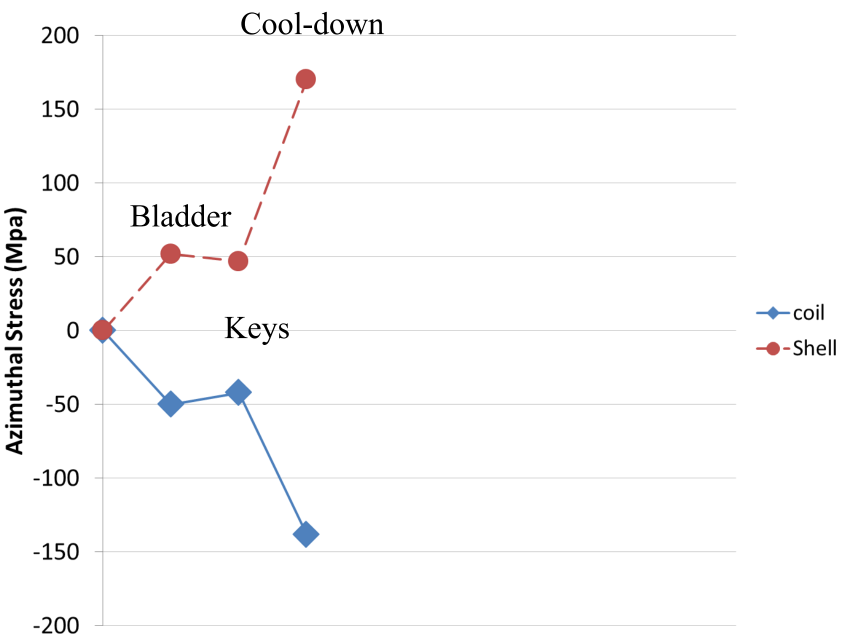
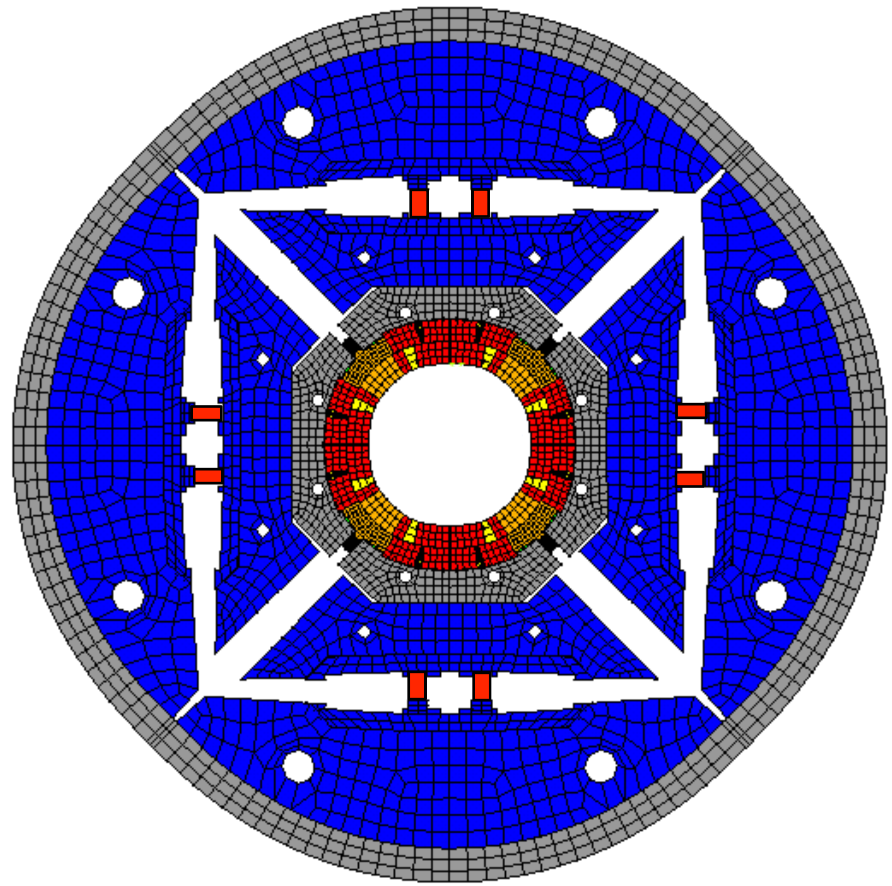


Cool-down



Courtesy Helene Felice

Magnet Design Support Structure

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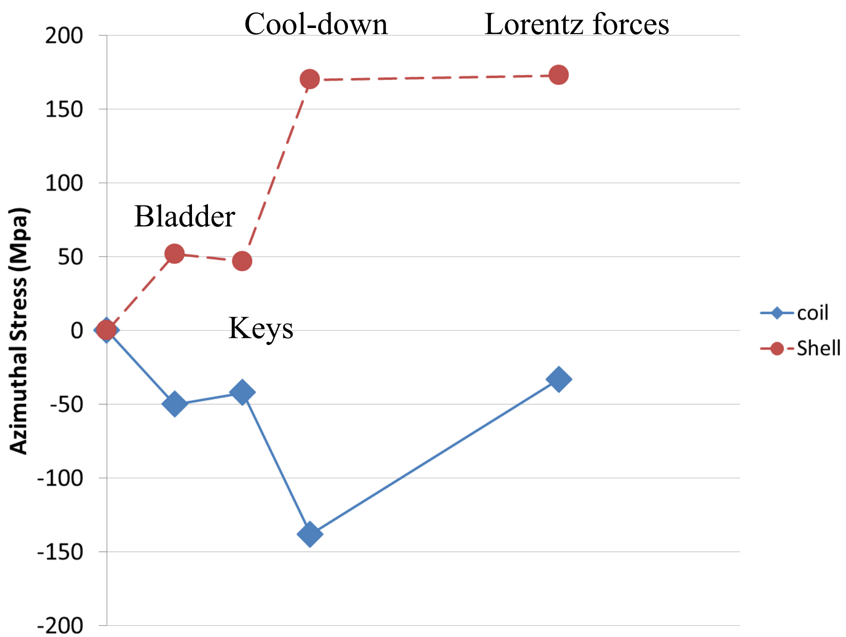
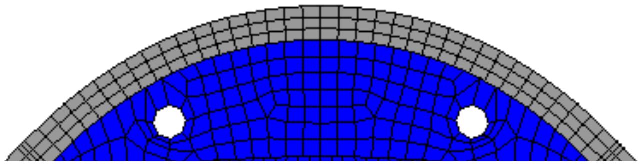
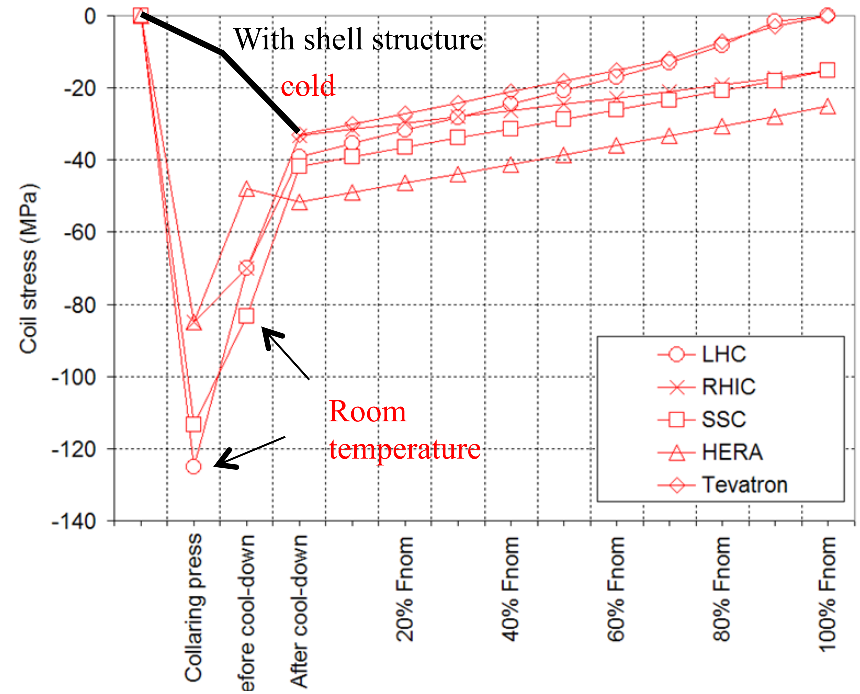


Courtesy Helene Felice

Energized





Collaring process- Courtesy of Paolo Ferracin

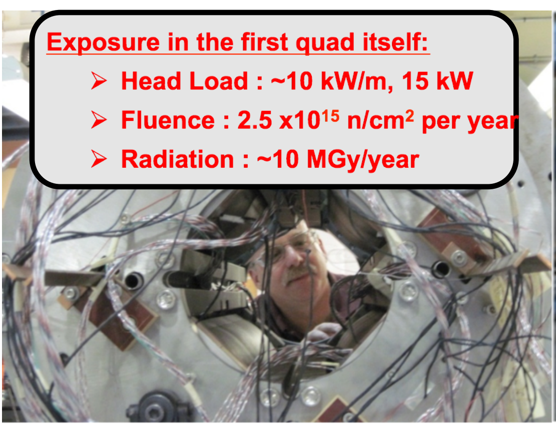
Displacement scaling 30

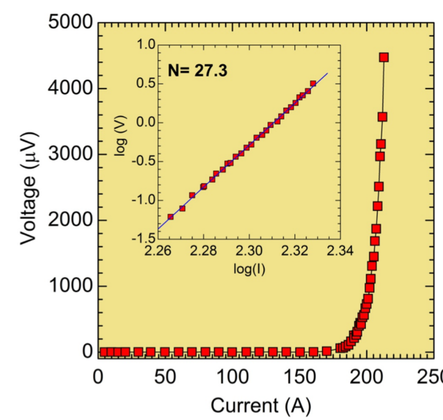
US Magnet Programs

BNL Magnet Program

- Accelerator dipole and quadrupole magnet programs
  - — HTS magnet is now part of the baseline design of a major proposed facility – Facility for Rare Isotope Beams (FRIB)
    - This is a significant 1st – perhaps a major milestone
  - — High field magnets in a hybrid design for LHC upgrade
- High field solenoid programs
  - — For Muon Collider and Energy Storage

Courtesy Ramesh Gupta





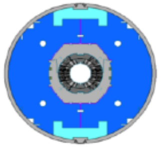
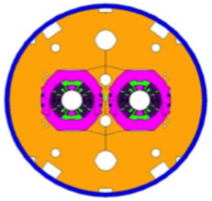
FNAL High-Field Magnet Program

- ***The mission*** of the High Field Magnet Program at Fermilab is the development of advanced superconducting ***accelerator*** magnets and baseline technologies for present and future particle accelerators.
- ***At the present time the focus*** is on the development of high-field accelerator magnets with operating fields up to 15 T based on Nb_3Sn superconductor.
- ***In the longer term*** the program will support the development of accelerator magnets with operating fields above 20 T.

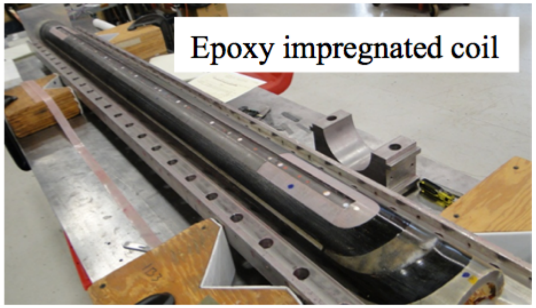
Courtesy Sasha Zlobin

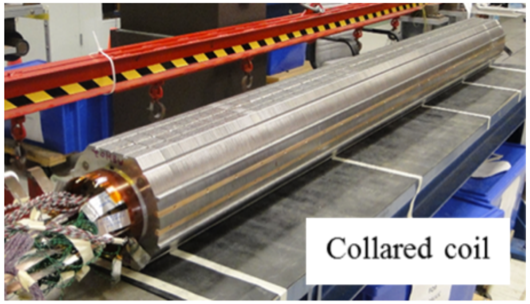
FNAL: Twin-aperture 11 T Nb_3Sn Dipole

- **Collaboration with CERN for possible use in LHC**
  - **2012: 2-m long single-aperture demonstrator**
    - Magnet assembled and tested, B_{max}=10.4 T at 1.9K
  - **2013: 1-m long twin-aperture model**
    - First aperture assembled and being tested
    - Fabrication of the second aperture has started
  - **2014: 2-m long twin-aperture demonstrator**
  - **2015: 5.5-m long prototype**

Parameter	Single-aperture 	Twin-aperture 
Aperture	60 mm	
Yoke outer diameter	400 mm	550 mm
Nominal bore field @11.85 kA	10.86 T	11.25 T
Short-sample bore field at 1.9 K	13.6 T	13.9 T
Margin B_{nom}/B_{max} at 1.9 K	0.80	0.81
Stored energy at 11.85 kA	473 kJ/m	969 kJ/m
F_x per quadrant at 11.85 kA	2.89 MN/m	3.16 MN/m
F_y per quadrant at 11.85 kA	-1.57 MN/m	-1.59 MN/m

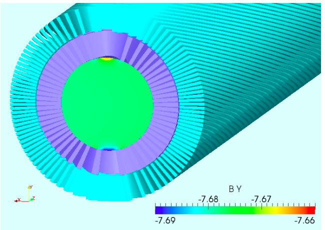
40-strand keystoned cable

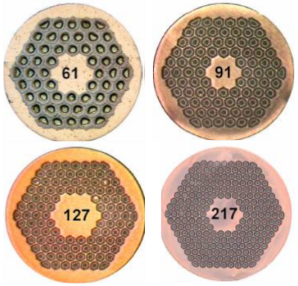


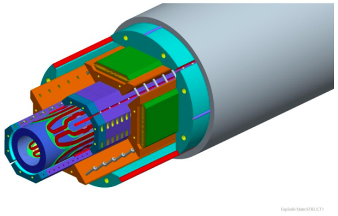


LBNL Superconducting Magnet Program

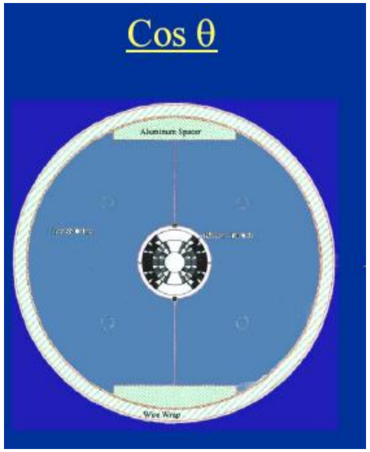
- **World-leading R&D program in high field accelerator magnets beyond 11T**
- **Integrated program from material, through analysis, fabrication and test**
  - — **Hierarchal modeling: micro to macro**
- **Strategy**
  - — **Innovative ideas to push the limits of high field accelerator magnets**
    - **Next breakthrough: 20 T**
      - – Combine materials development with innovative structures
  - — **Strong support of ongoing and future HEP programs/projects**
    - **LARP, MAP (MICE)**
  - — **Our technology is a key component of the Stewardship Program**



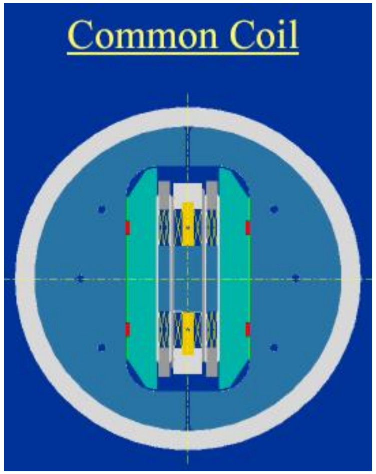




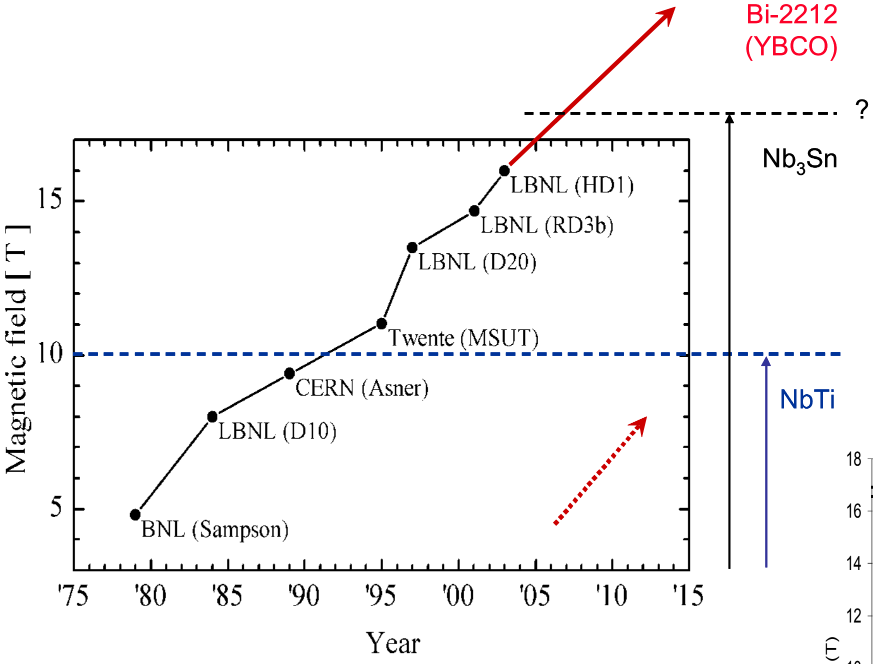
High field superconducting dipoles ….

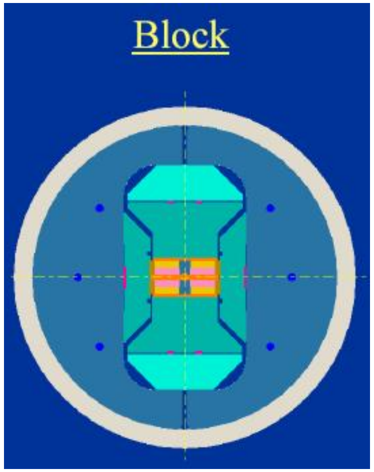


D20

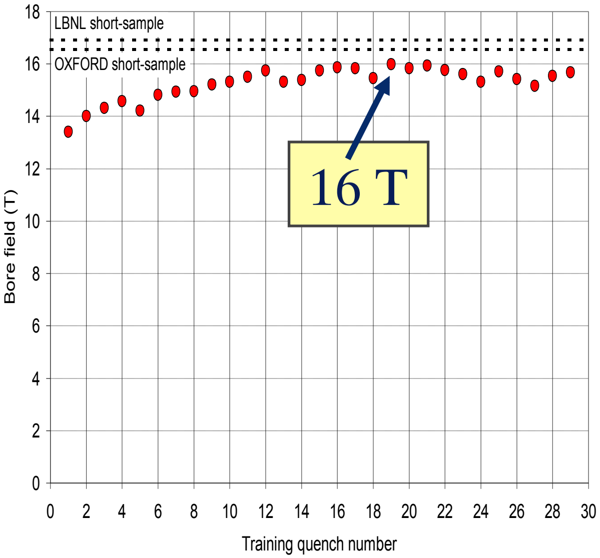


RD



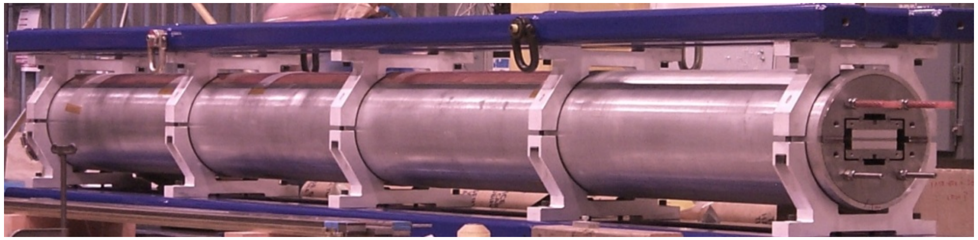


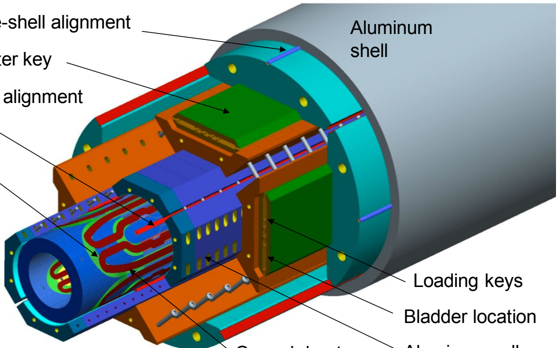
HD



LBNL has a major role in the LHC Accelerator Research Program (LARP)

- Phase 1 of LARP magnet program completed
  - — TQ – technology development and reproducibility
    - *surpassed LARP target gradient*
  - — LQ –handling, fab, protection of long magnets (~ 4m)
    - *achieved 220 T/m*





CERN Program on High Field Magnets

- Technology development (dipoles and quads) for LHC upgrades and future accelerators
- Fairly new to Nb_3Sn technology – Process, structures
- Initial focus on conductor development (Nb_3Sn PIT and YBCO)

First step (2004 – 2012):

- Conductor technology : NED 1.25 mm, Fresca2 1 mm (2010), 11 T 0.7 mm (2011)
- Magnet technology : Short Model Coil (2011)
- Personnel training on existing technologies : test TQ & HQ @ CERN (2009)

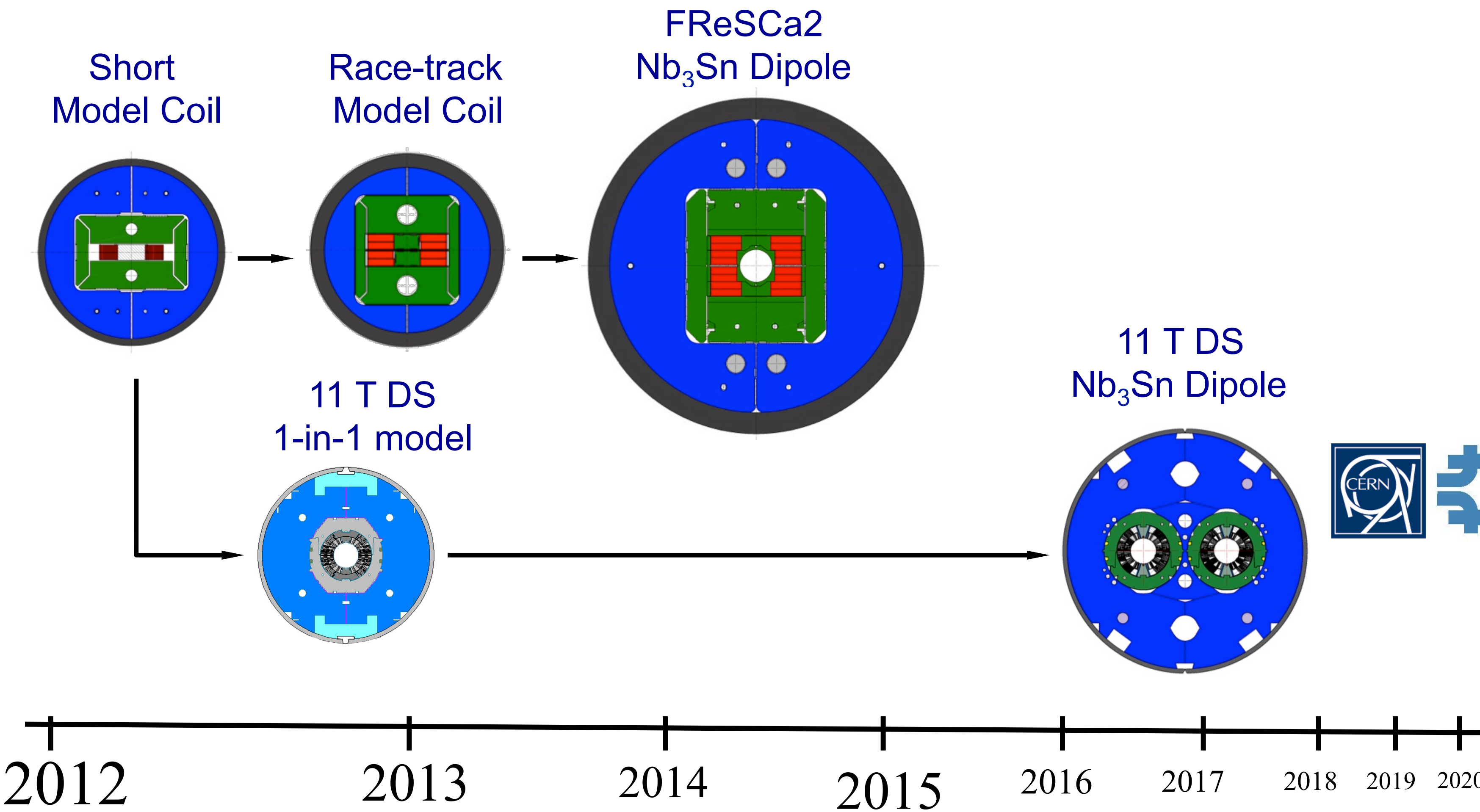
Second step (2009 – 2014):

- Magnet models : Fresca2 (2013), IR quad model (2013), 11 T dipole model (2013)
- Conductor test facilities upgrade to 15 T test station (2014-2015)
- Radiation hardness studies for Nb_3Sn and coil insulation (2010-2014)
- Magnet concepts from 15 T to 20 T : EuCARD 6 T insert (2013), EuCARD2 (2016)

Third step (2014 – 2016):

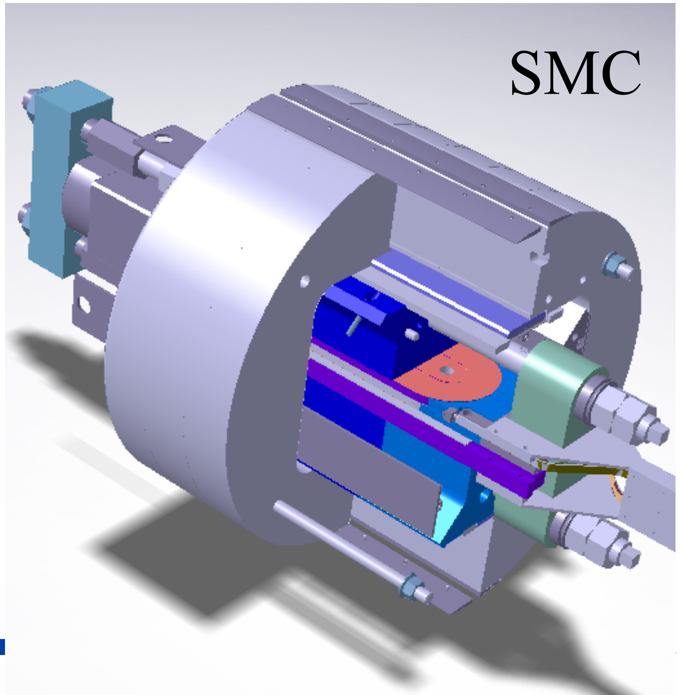
- LHC Dispersion Suppressor dipole prototype (2015)
- LHC Inner triplet quadrupole prototype (2016)

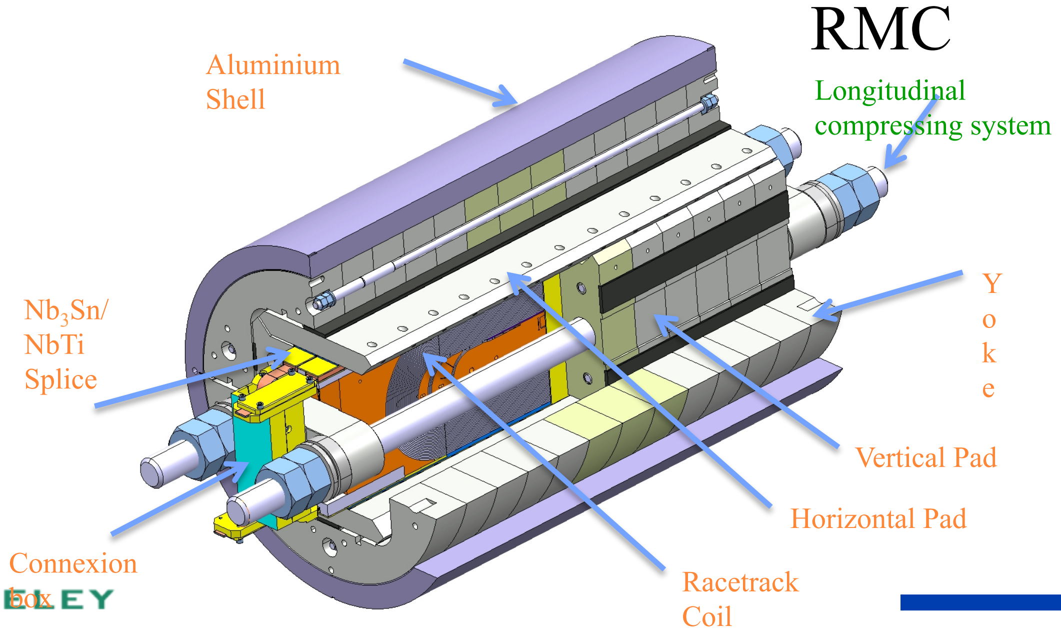
High Field Magnet R&D



Short Model Coil and Racetrack Model Coil

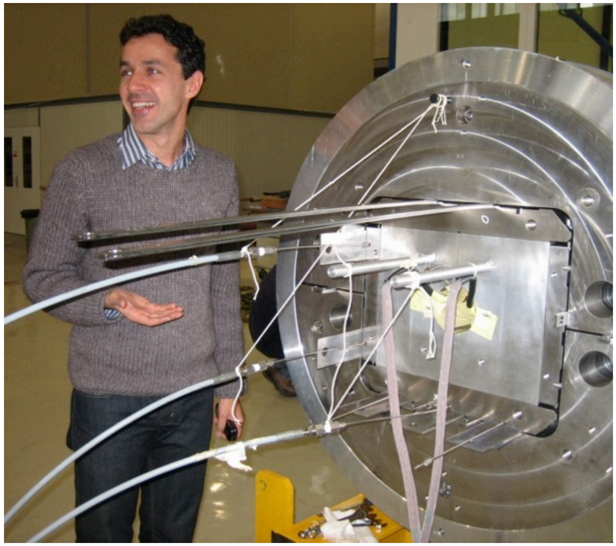
- SMC : test Nb_3Sn conductor and coil technology with a small 10 mm cable
    - 1 coil set tested
    - 2nd coil set reacted: to be tested in spring 2013
- RMC: test the Fresca2 conductor and coil technology with the 21 mm Fresca2 cable
    - 1st coil set being manufactured: to be tested end spring 2013

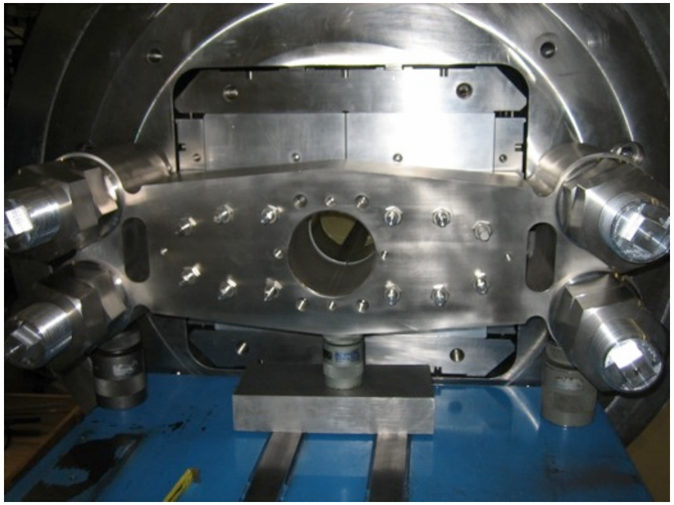




Fresca2 structure, mounting with dummy Al coil blocks

- Mounting Last week,
- LN2 test end of March to study mechanical behaviour





Design Considerations for an LHC Upgrade

- Start with field
  - — LHC will (hopefully) operate at 8.33 T (7 TeV) with about a 20% margin
  - — A factor of 2 gives us ~ 17 T (operating)
    - Same situation as above implies > 21 T
    - Given current status of conductors, this means HTS is required
- Other factors
  - — Must fit in the tunnel
    - 570 mm diameter for the cold mass in the LHC
    - We assume 800 mm diameter for the HE-LHC
    - Coil must be reasonably compact
  - — Cost
    - Magnet has to rely on Nb_3Sn and on HTS
    - Cost of Nb_3Sn: 4 times Nb-Ti
    - Cost of HTS: 4 times Nb_3Sn

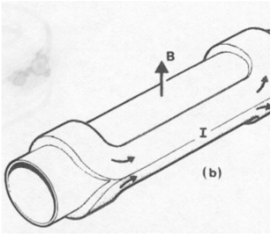
    → grading of material is necessary

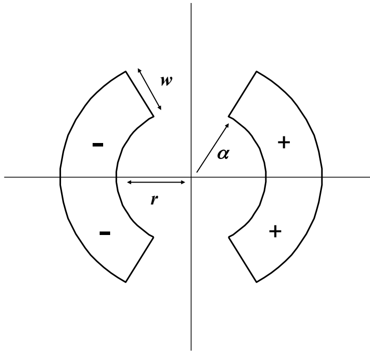
Getting to High Fields

- Field is proportional to current density and coil thickness

B [T] ~ *0.0007* × *coil width* [mm] × *current density* [A/mm^2]

LHC: 8 [T]~ 0.0007 × 30 × 380



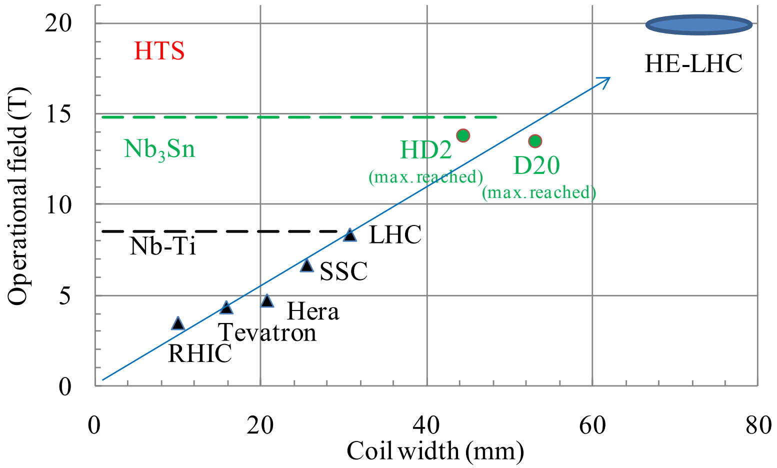


— Accelerators use current density of the order of 350-400 A/mm^2

- This provides ~2.5 T for 10 mm thickness
- 80 mm needed for reaching 20 T

— Grading the material:

- 30 mm of Nb-Ti to get 7.5 T
- 30 mm of Nb_3Sn to get another 7.5 T
- 20 mm of HTS to get the last 5 T



Operational field versus coil width in accelerator magnets

High field magnets – status and challenge

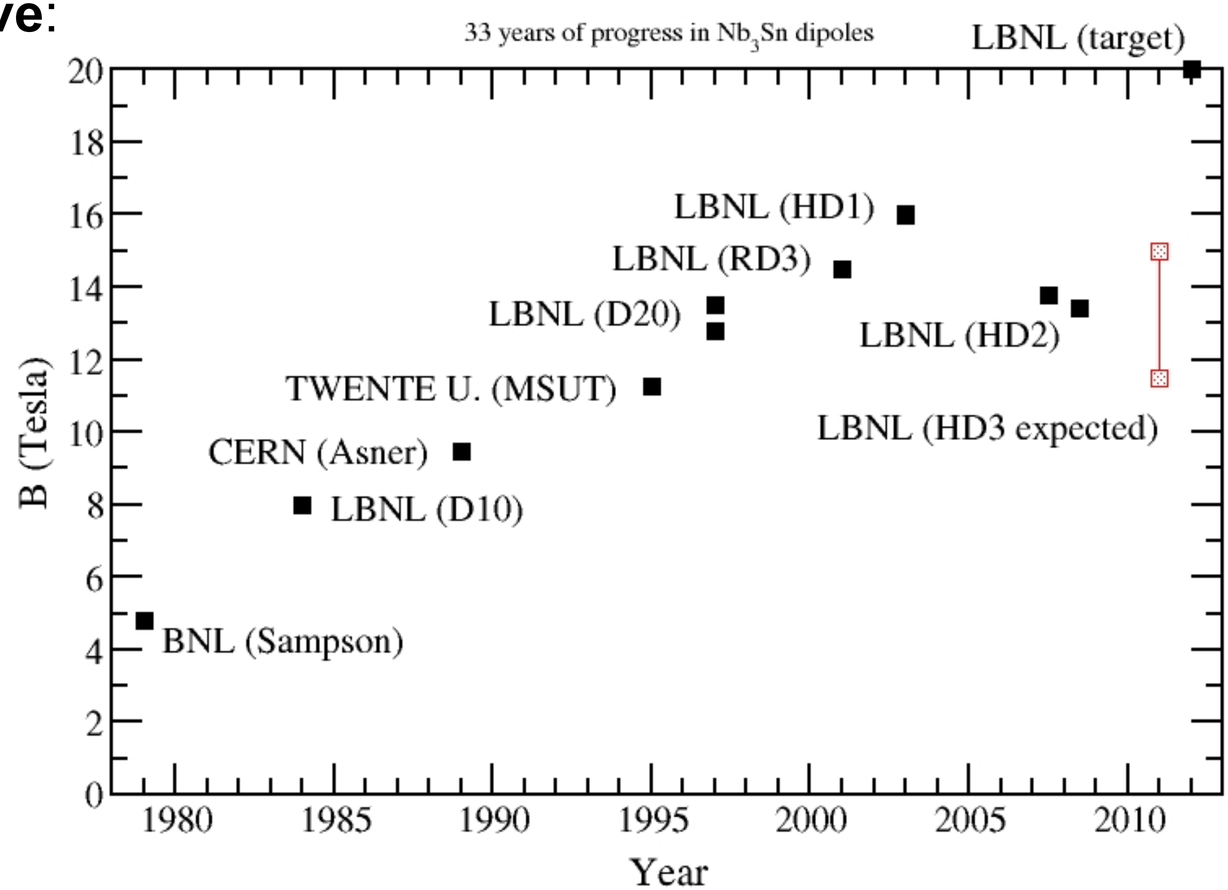
An historical perspective:

1979-2012

<u>**20T -** Nb$_3$Sn</u>

- Brittle coils
- Magnet and bore size
- Coil stress > 200 Mpa
- Structure ~20 MN/m
- Delicate assembly
- Protection

- **Next –**
  - new design?
  - revised design ?



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New Application of an Old Idea

Published paper by D.I. Meyer and R. Flasck in 1970

(D.I. Meyer, and R. Flasck "A new configuration for a dipole magnet for use in high energy physics application", Nucl. Instr.and Methods 80, pp. 339-341, 1970.)

A NEW CONFIGURATION FOR A DIPOLE MAGNET FOR USE IN HIGH ENERGY PHYSICS APPLICATIONS*

D. I. MEYER and R. FLASCK

Physics Department, University of Michigan, Ann Arbor, Michigan 48104, U.S.A.

Received 16 December 1969

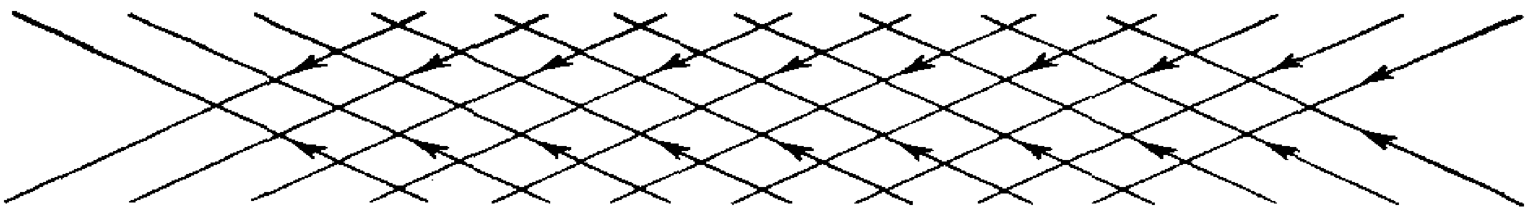

Fig. 2. Two superimposed coils with opposite skew.

Renewed interest during the past decade

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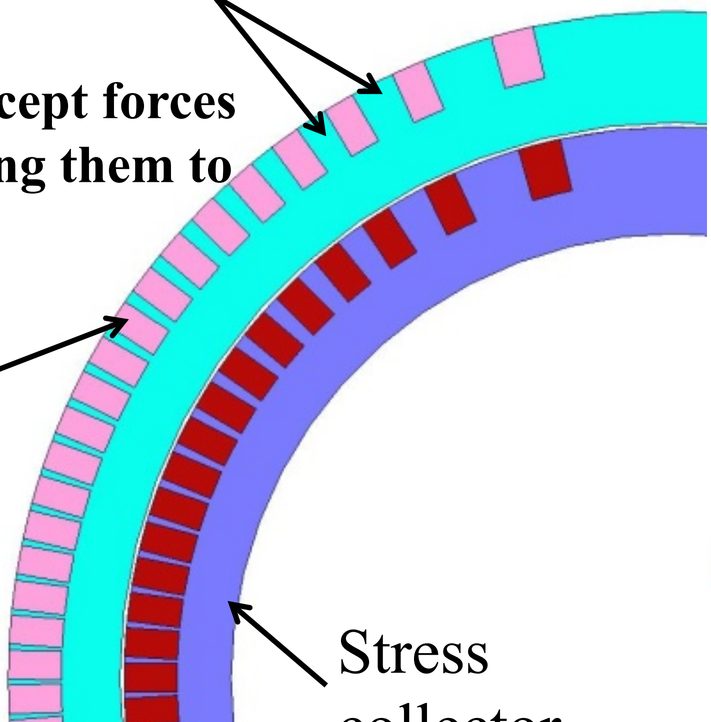
The Canted Cosine-Theta-Magnet (CCT)

Individual turns are separated by **Ribs**

Ribs intercept forces transferring them to the spar

Individual turn

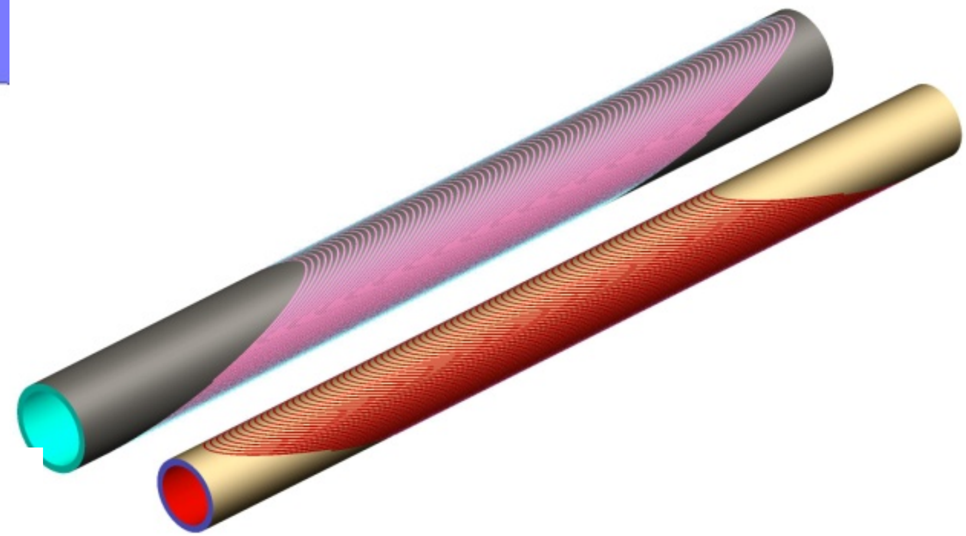


Stress collector **(Spar)**

Unique turns distribution

$$J_z \sim \cos\vartheta$$

Canted right:
Field - up dipole + right solenoid



Canted left:
Field - up dipole + left solenoid

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The CCT Basics

Geometry

- Single turns are placed into machined channels.
- Layers are nested "pipes" (no assembly, no collars)

Magnetics

- Field quality over cross-section without optimization
- Field quality over "ends" without optimization
- ~20% more conductor, some recovery through grading

Structural

- Transverse Lorentz forces intercepted (accumulated in the spar)
    - Applicable to High fields
    - Applicable to Large bores
    - No experience

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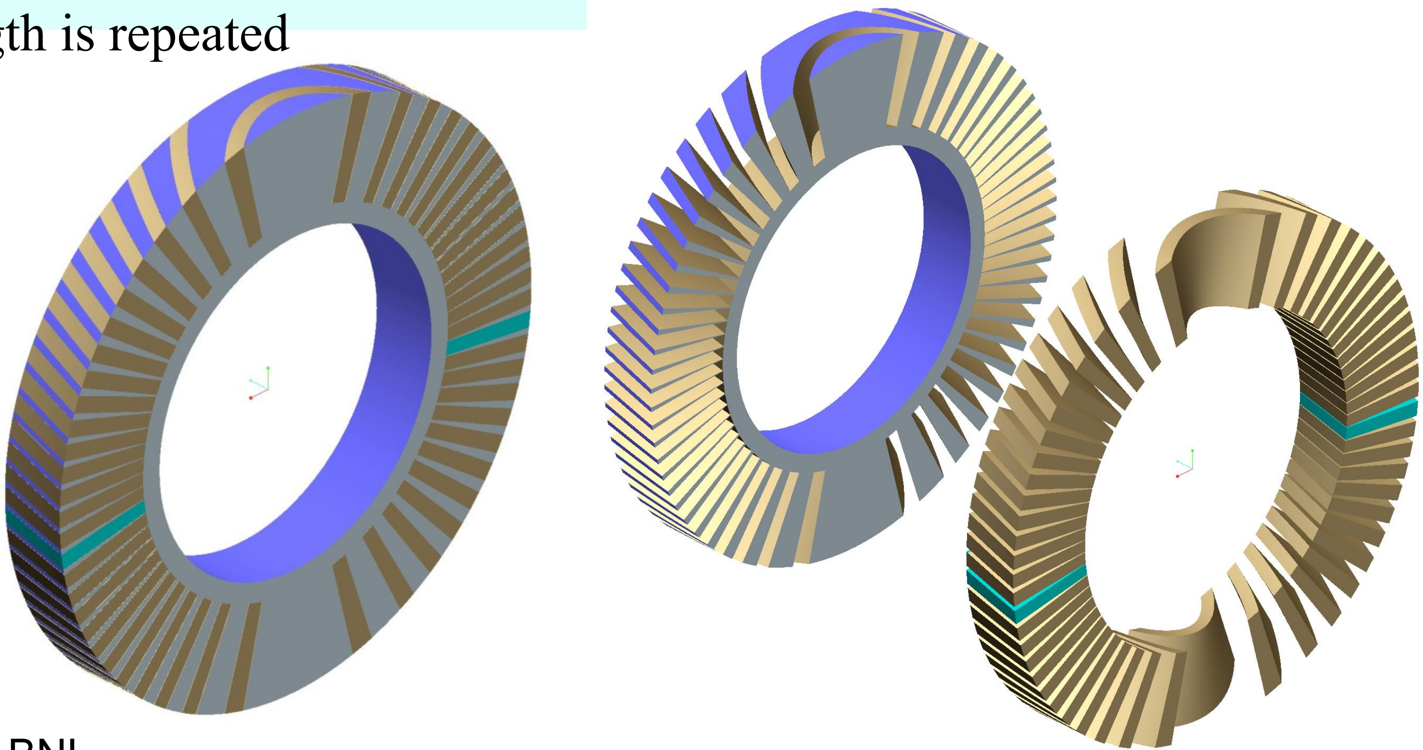
Repeated Lamination - 10.05 mm thick

A slice of a pitch-length is repeated



<u>Impacts:</u>
Construction
Computation

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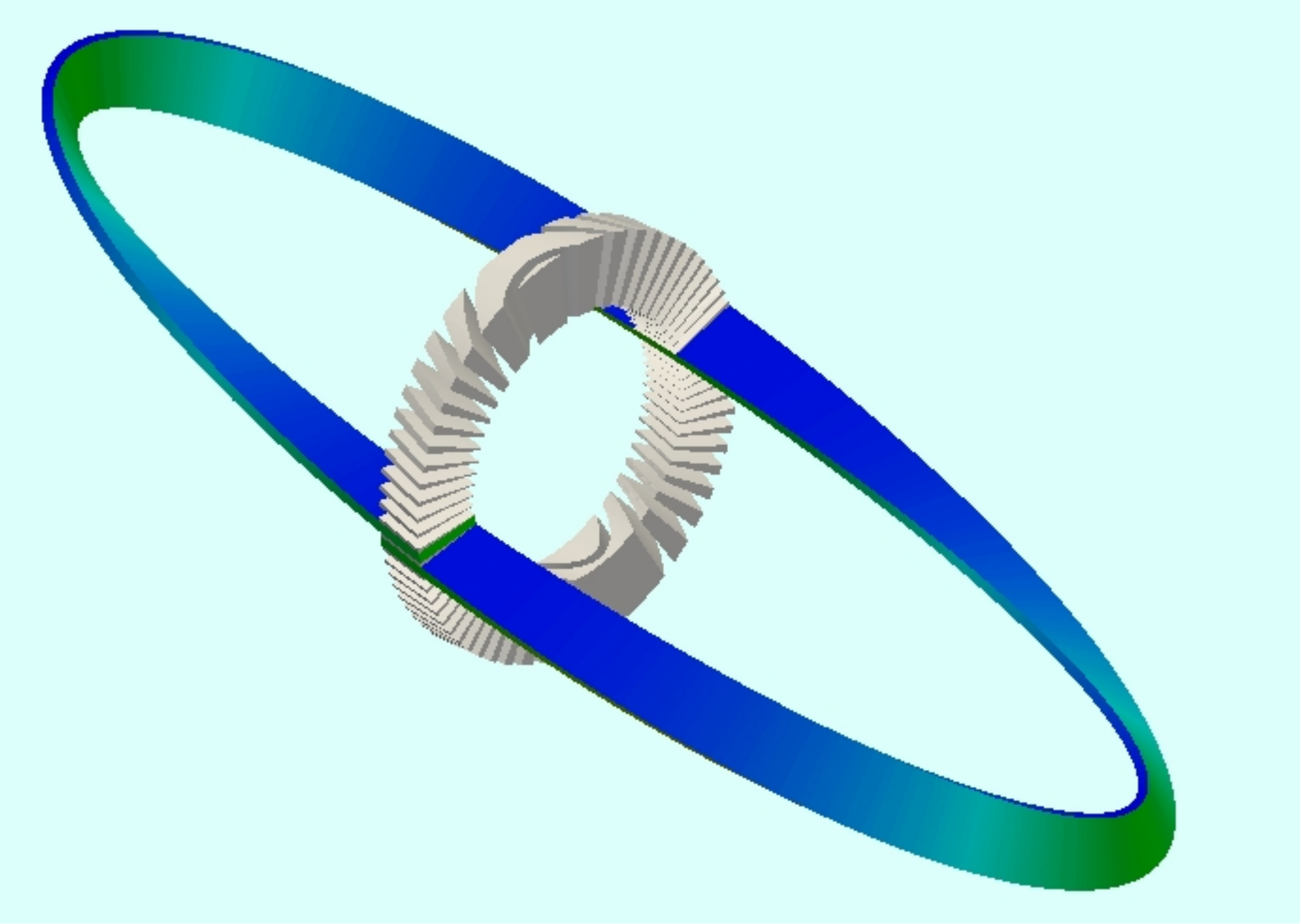
A complete turn is a Lamination



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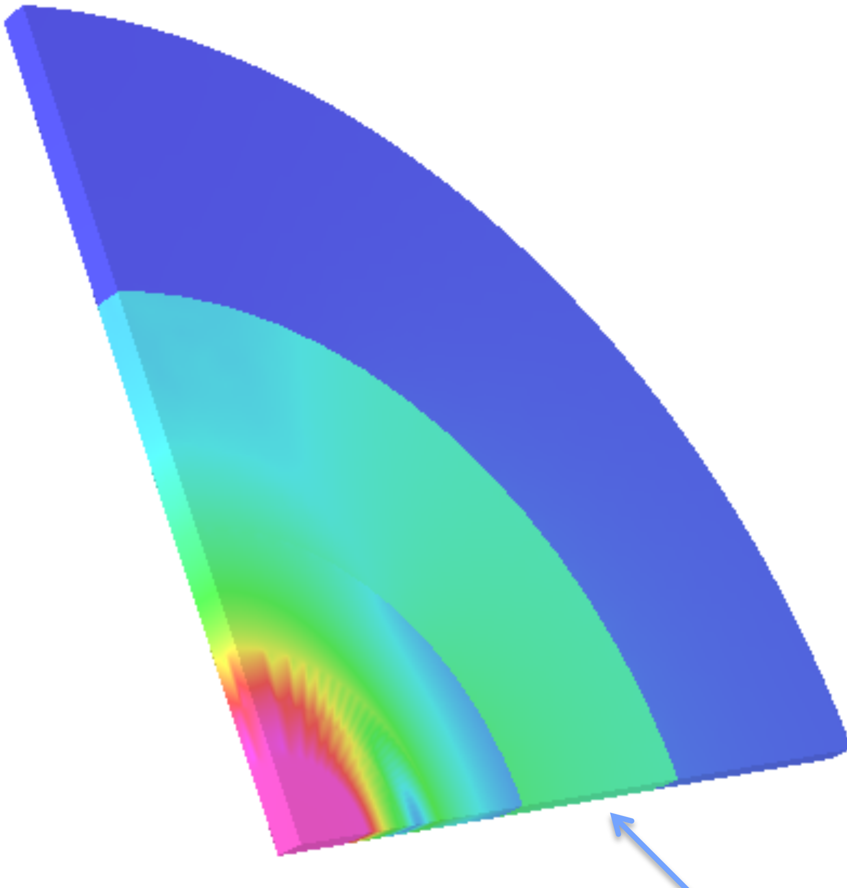
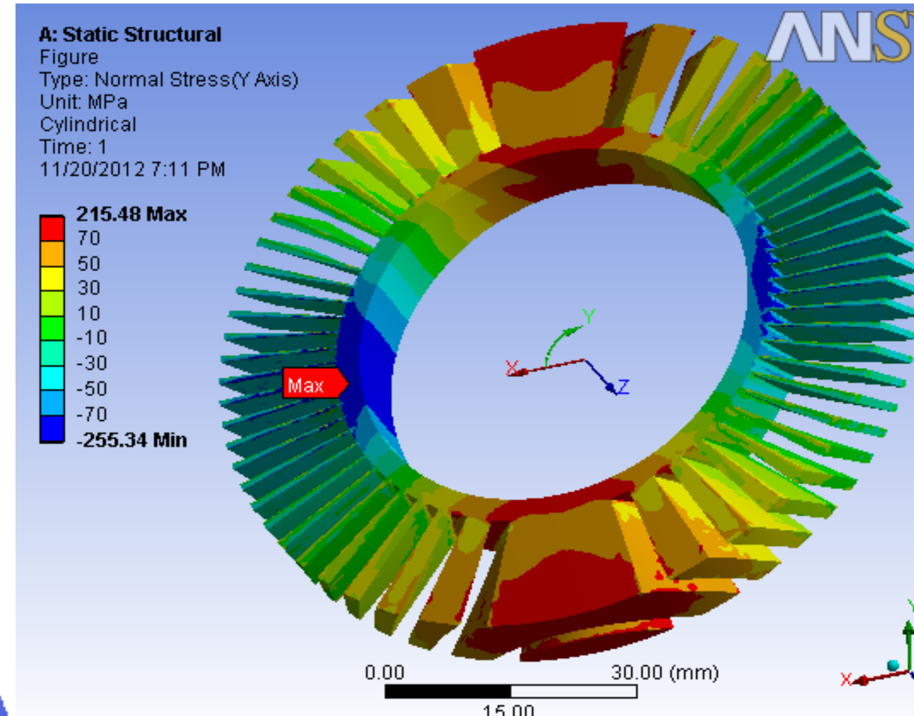
Simplify "2D" Analysis



Magnetic – TOSCA



Structural - ANSYS

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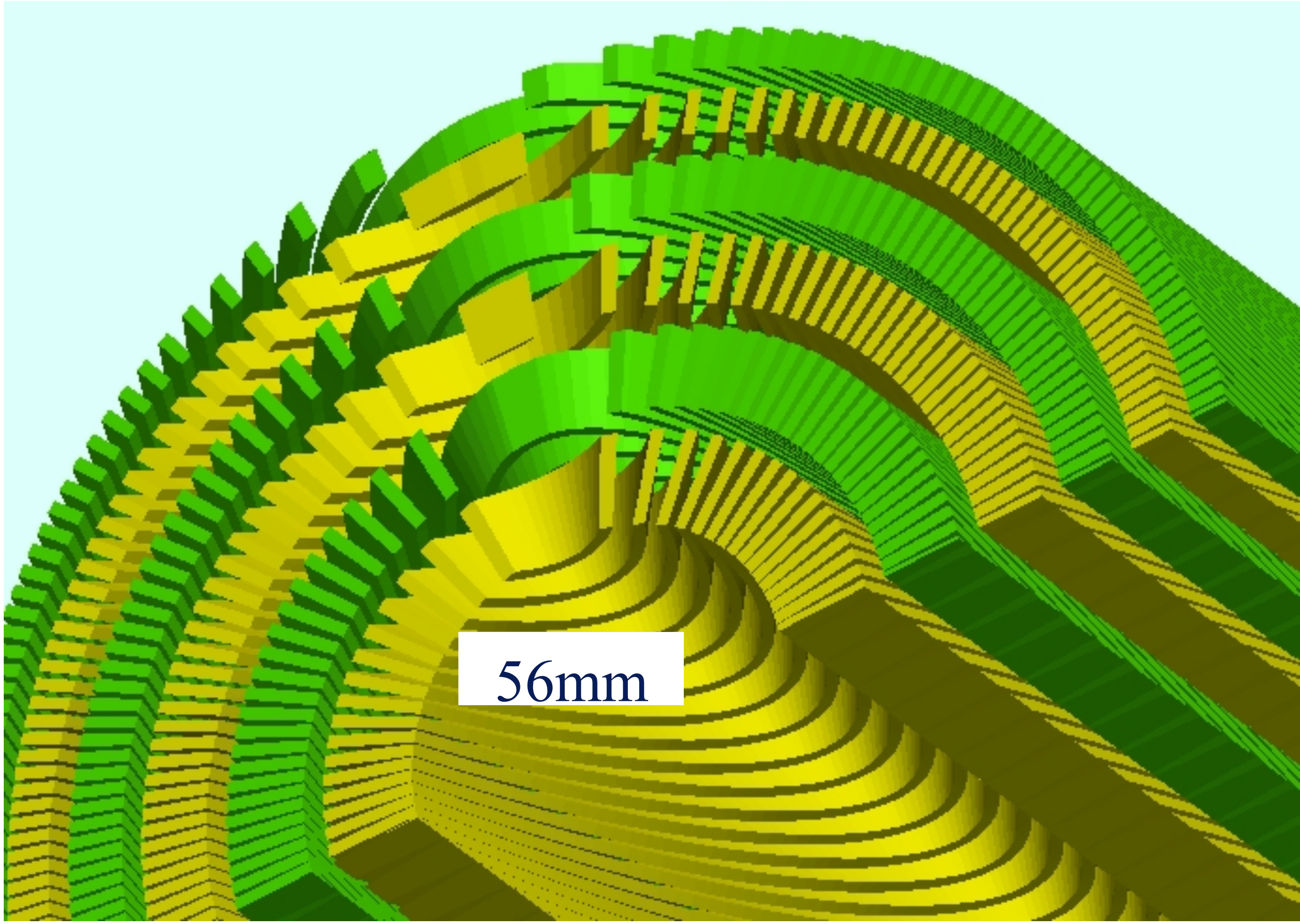
Example – 18T dipole with a 56mm bore

Layer 1, 30 strands
Layer 2, 26 strands
Layer 3, 22 strands
Layer 4, 18 strands
Layer 5, 14 strands
Layer 6, 12 strands



- 6 layers, graded
- Conductor 60mm thick
- Current 10.5 kA
- 10.5 kA 18 T at 1.9K
- Intercepted stress

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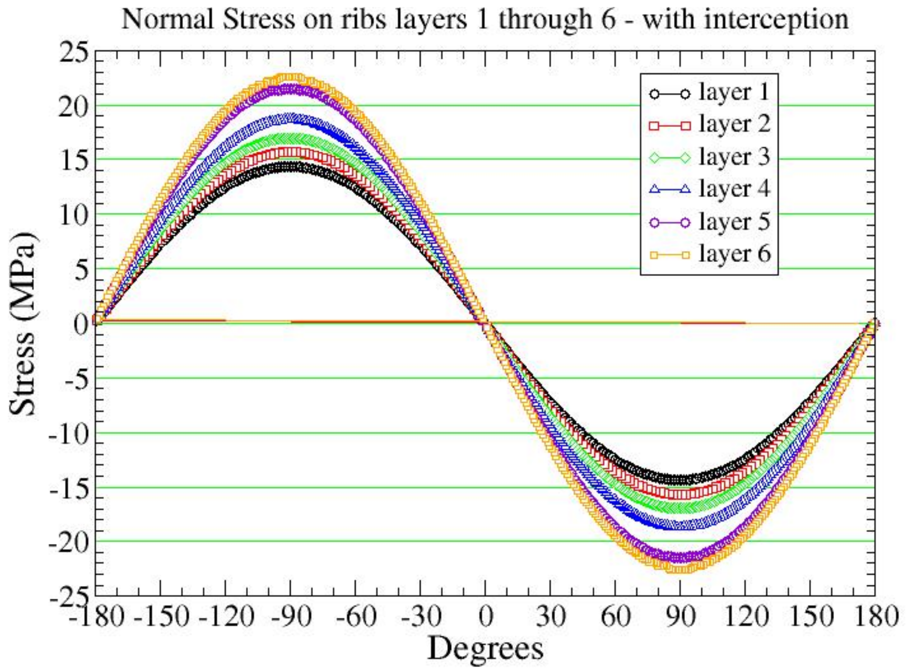
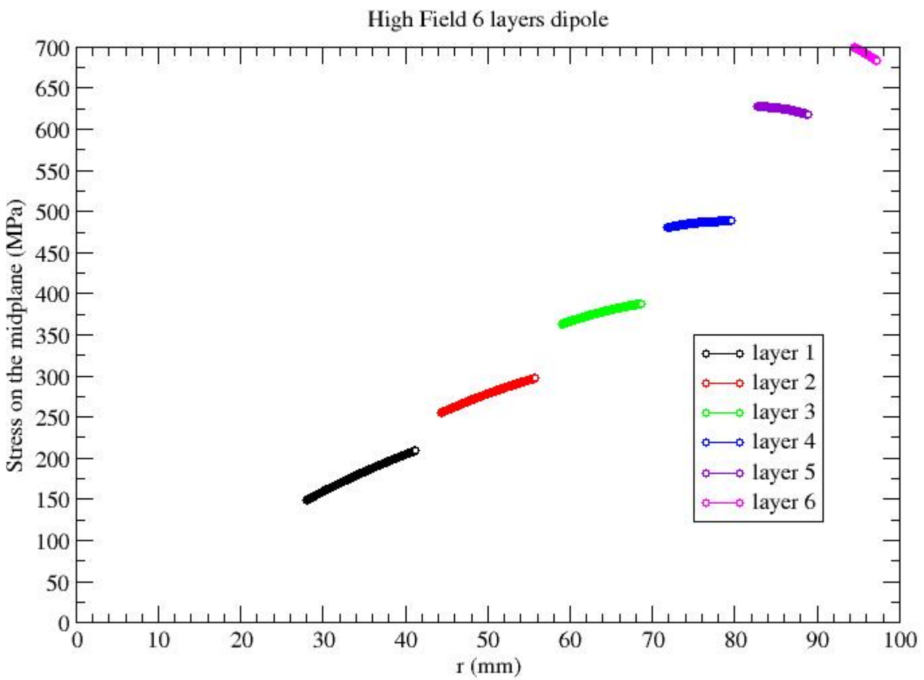
Conductor Stress – with/without interception

With stress interception the Lorentz stress in conductor < 25MPa

Without stress interception the Lorentz mid-plane stress in conductor 200-700MPa





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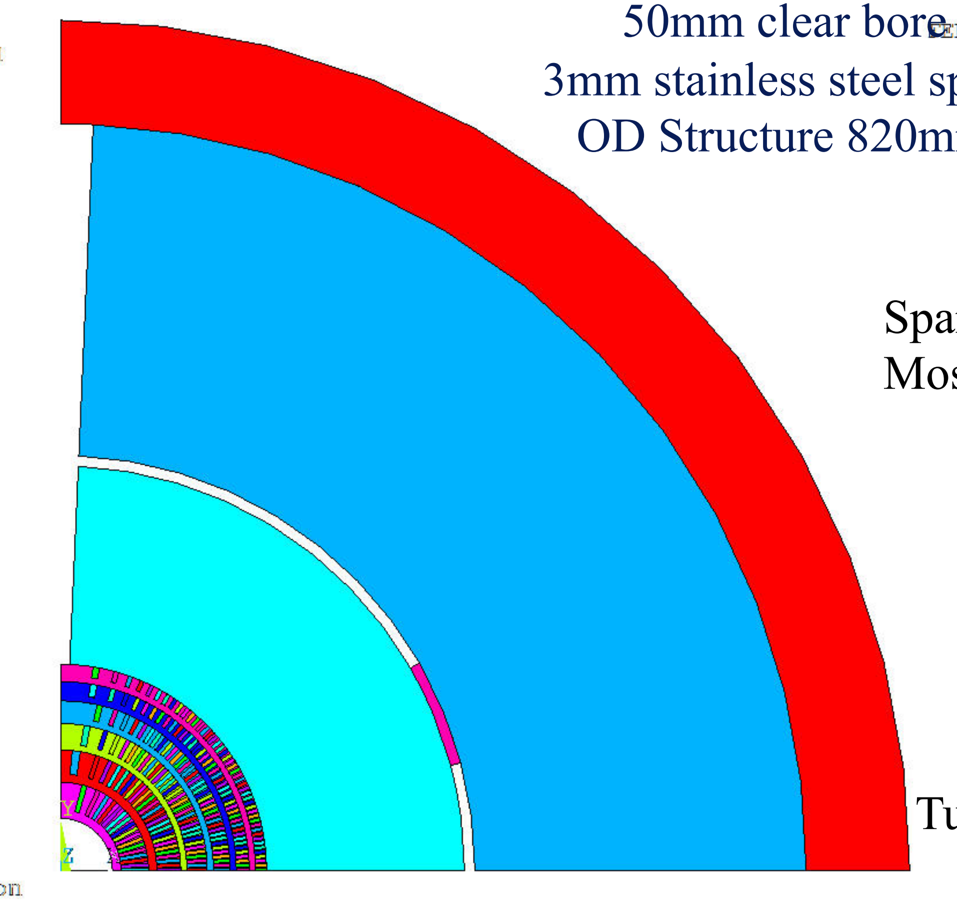
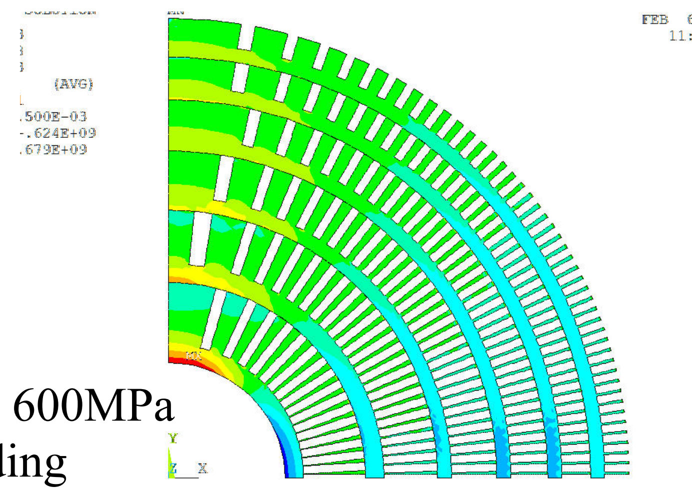
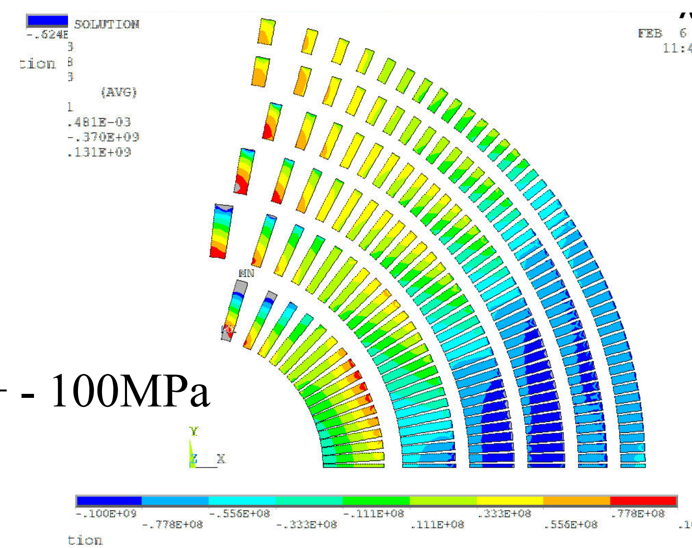
Structure - 2D ANSYS

6 layers, graded 10.5kA, 19.4T
50mm clear bore
3mm stainless steel spars
OD Structure 820mm





Spars at 20T + - 600MPa
Mostly do to bending



Turns at 20T + - 100MPa

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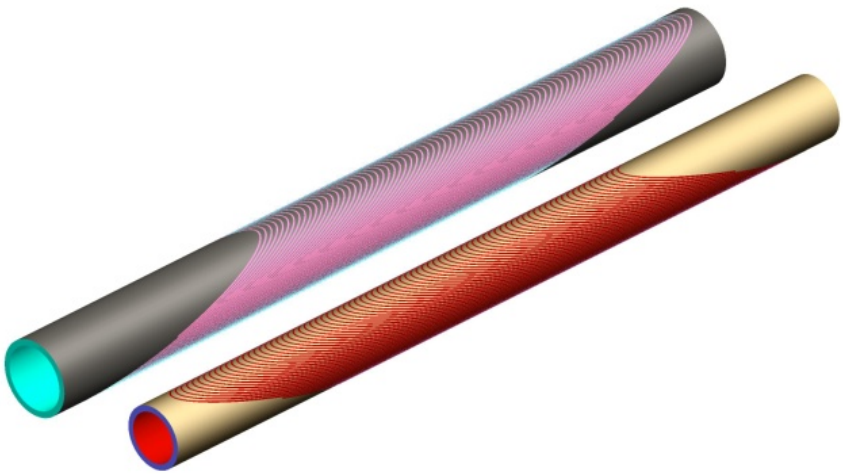
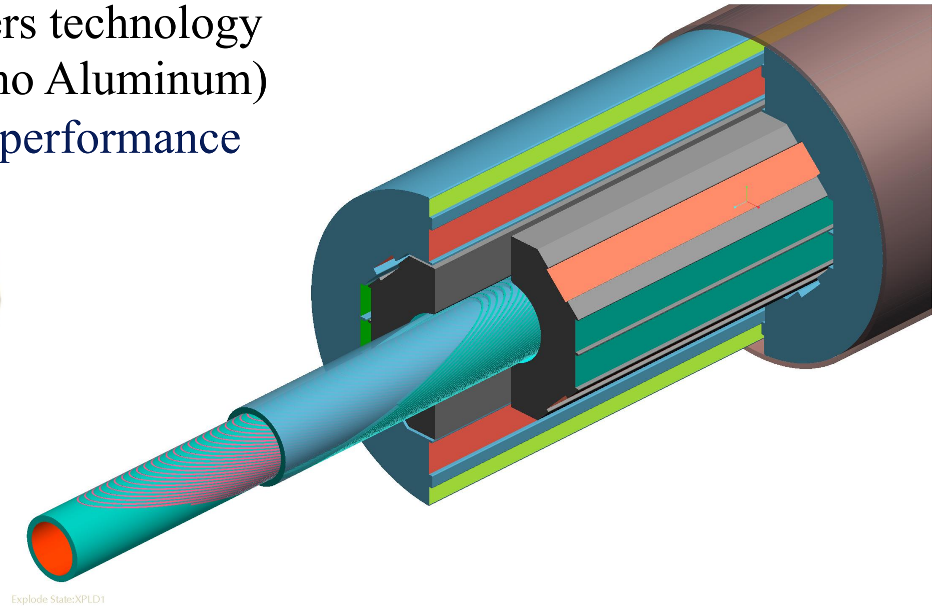
Future Plans

1. Wind and test a 2 layer NbTi dipole – 50mm clear bore, 3T - CCT1
   - Pads and yoke using key and bladders technology
   - Stainless steel spars and outer shell (no Aluminum)
   - Evaluate manufacturing, test magnet performance





2. Wind and test a 2 layer Nb_3Sn dipole – 50mm clear bore, 10T
3. Modular multi-layer Nb_3Sn dipole - 50mm clear bore, 15T-20T
4. Explore a HTS insert >20T

Courtesy S. Caspi, LBNL

Summary

- Doubling the energy of the LHC is feasible
  - Another 10 years of R&D is required unless funding increases dramatically
    - Improve J_c of Nb_3Sn and reduce cost (scale-up)
    - Demonstrate viability of Canted Cosine-Theta concept or something equally acceptable
    - Quench protection
    - Need rad hard materials for impregnation
    - I'm not betting on HTS
- Machine issues are at least as challenging (but feasible)
  - Machine protection
  - Vacuum
  - Injection (X2 in energy but same real estate)