ACADEMIC TRAINING

Technology and applications of high field accelerator magnets

G. Ambrosio

Fermilab – Technical Division

Lesson 3:

- Nb_3Sn coil fabrication technology
- Magnet assembly - I

CERN June 2-6, 2008

Outline

- Coil fabrication technology
  - All steps of Nb_3Sn coil fabrication
  - Case studies: LARP TQ, LQ, LR coils
- Magnet assembly - I
  - Case study: LARP TQC magnet assembly
    - Technological quadrupoles with collars

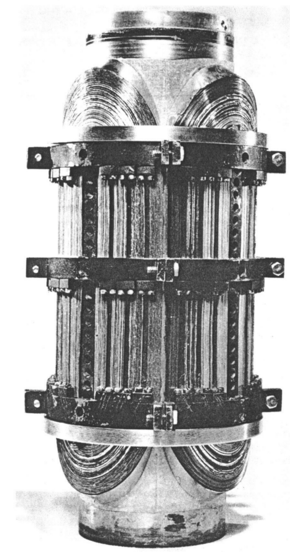
  - Plan for next lessons

Closer look at Nb_3Sn

- **Better performance (~50%) at 4.2 K than NbTi at 1.8 K**
- **Larger temperature margin**
- **Development of Nb_3Sn magnets started in the 60's†**

BNL 76 mm aperture Quad from Nb_3Sn Tape

W. B. Sampson, MT-2 1967



†Nb_3Sn accelerator magnet development around the world
M. J. Lamm; *Applied Superconductivity, IEEE Transactions on*
Volume 13, Issue 2, Part 2, June 2003 Page(s):1278 - 1283

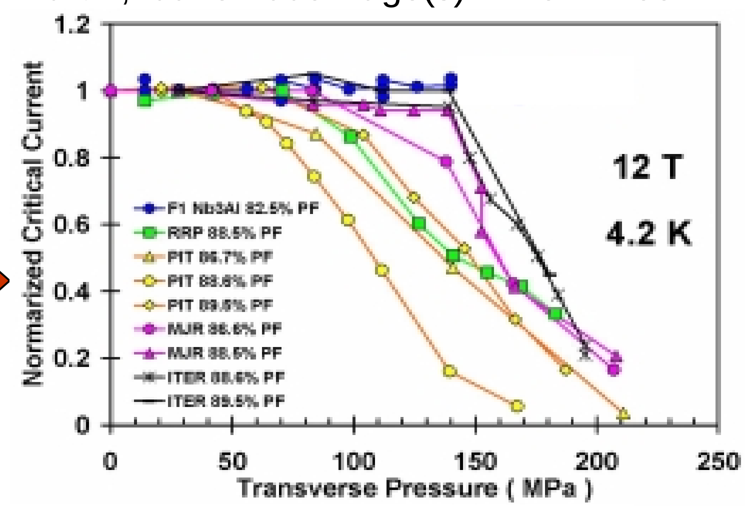
Why not yet?

"Why there are no Nb_3Sn magnets in any HE accelerator?"

Because Nb_3Sn is a <u>brittle material</u>

➔ **Large degradation at longit. strain > 0.4%**

➔ **Degradation at transv. pressure > 150 MPa**



E. Barzi

LARP baseline strand

"Baseline Strand"- Specs.

- **LARP Magnets will use OST production Wire**
- **R**od **R**e-Stack **P**rocess, RRP 54/61 Design
  - 0.7mm diameter
  - Sub-element (Filament) Diameter ~ 70 μm
  - $J_c > 2400 A/mm^2$ at 12T
  - $I_c > 500$ A at 12T
  - Copper Fraction 47%
  - RRR of stabilizer Cu > 100
  - Stability current $I_s \sim 1000$ A
- Magnet Operating Current ~ 500 A (~ 12T)

Heat treatment optimization to balance critical current and stability

For the strand $I_s > 2 \times I_{op}$

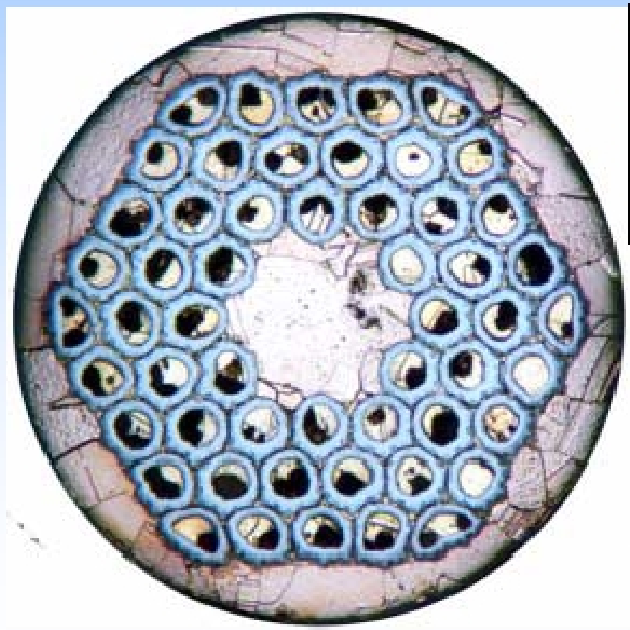
LARP DOE Review June 12-14, 2006 Materials – Conductor Support - A. Ghosh 4

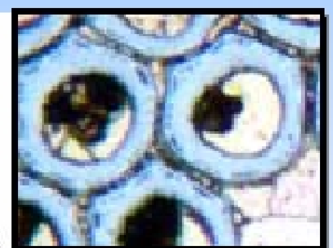
Effective filament size

Key issue for high Jc-Nb_3Sn Strand

Lack of "Adiabatic" stability in currently available strands (RRP 54/61 design)

After reaction strand is essentially a 54-filament conductor with filament diameter d_{eff} ~ sub-element diameter

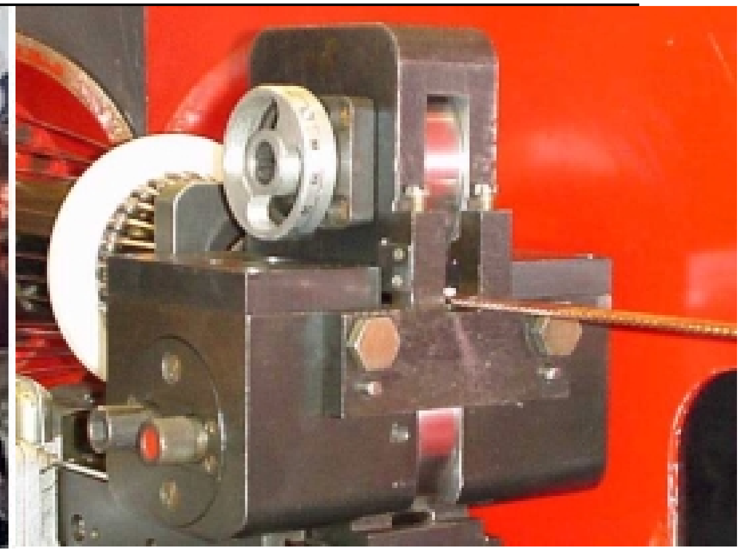




LARP DOE Review June 12-14, 2006 Materials – Conductor Support - A. Ghosh 5

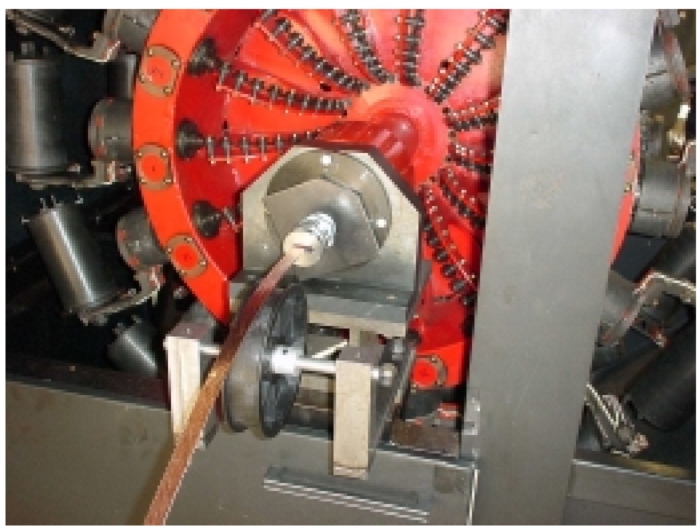
Rutherford Cable Fabrication

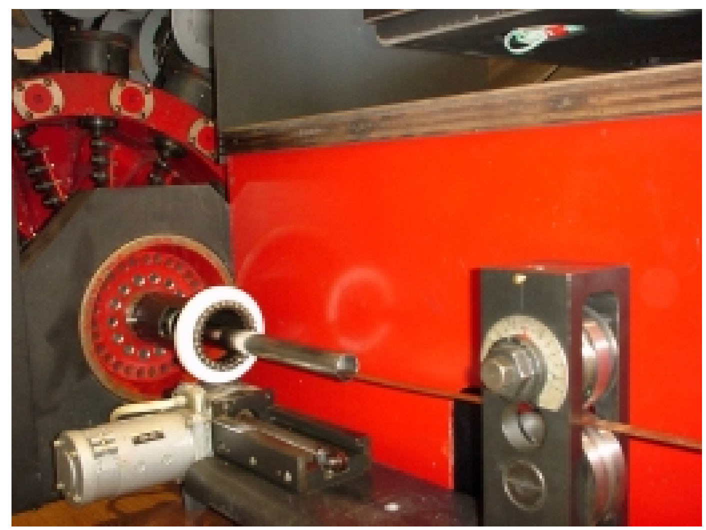
First pass:
Rectangular cable



Annealing:
To remove cabling tension

Second pass:
Keystoned (trapezoidal) cable





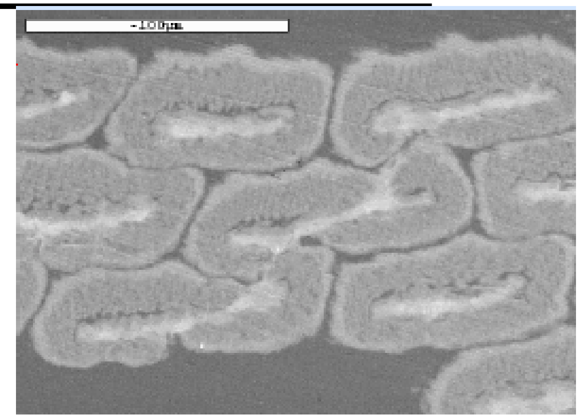
Cabling optimization

Need to find a balance between compaction

➔ mechanical stability, higher eng. current density

and strand deformation

➔ degradation of critical current and stability threshold

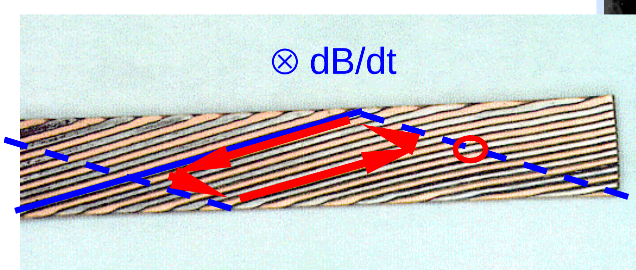


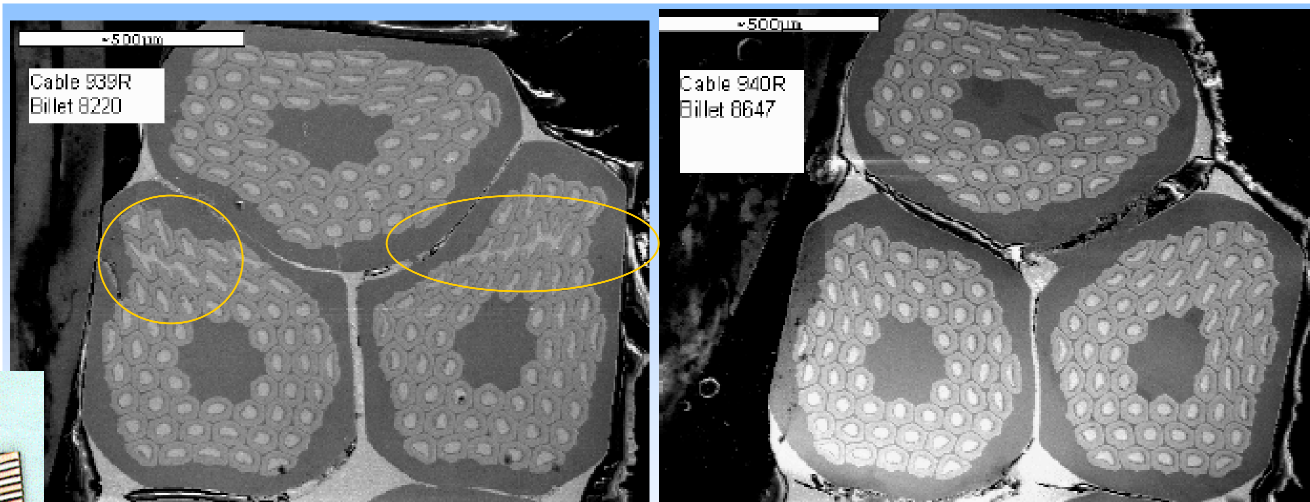
Need to increase inter-strand resistance

R_c is too low

Large dynamic effects

➔ Add ss core

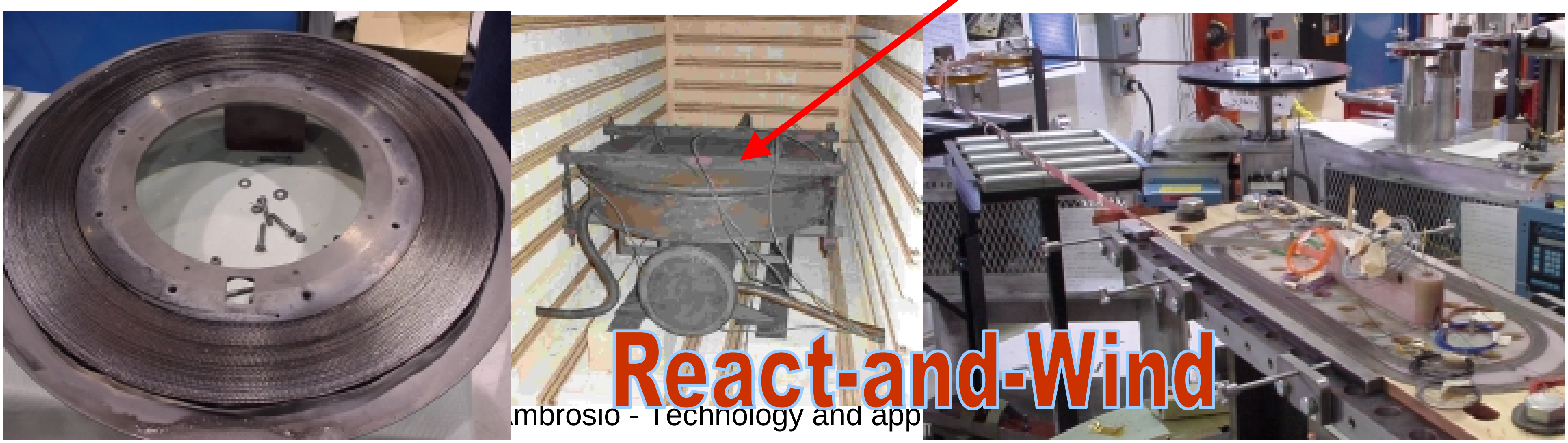




- Cable 939 over-compacted during the re-roll operation leading to significant barrier damage.
  - Cabling procedures being modified to avoid this problem.

Fabrication Technologies

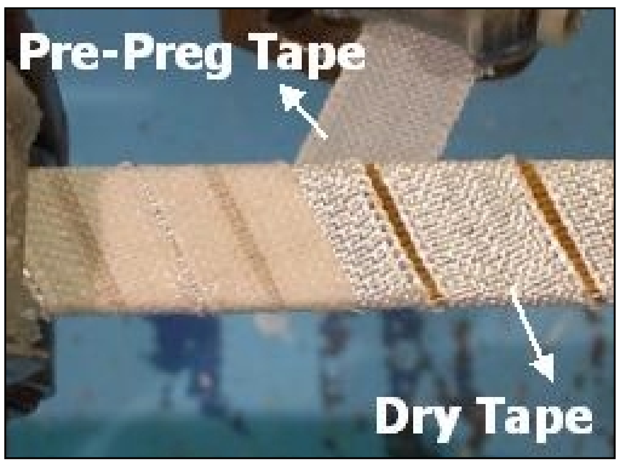
(Nb + Sn) in Cu matrix ➔ Nb_3Sn during heat treatment at 630-700 ^oC

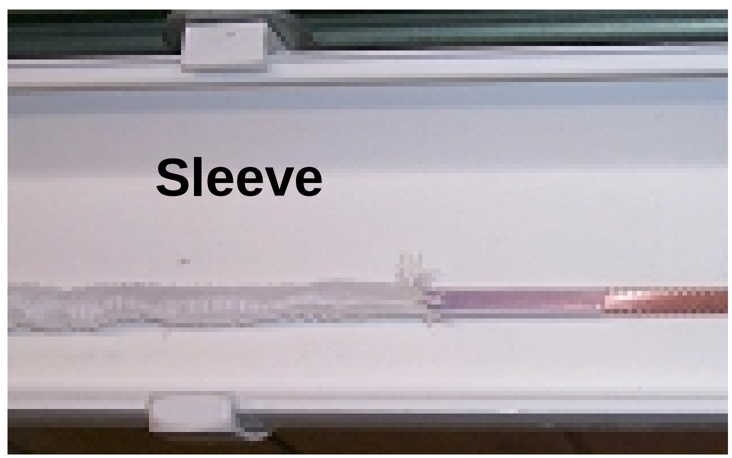


Insulation

glass or ceramic with non-organic binder

- Requirements:
  - No organic materials
  - Strong enough to withstand mechanical stresses
  - Should withstand heat-treatment temperature up to 700º C under pressure (Wind-and-React only)
  - Should be compatible with vacuum impregnation
- Options:





Sleeve braided on the cable

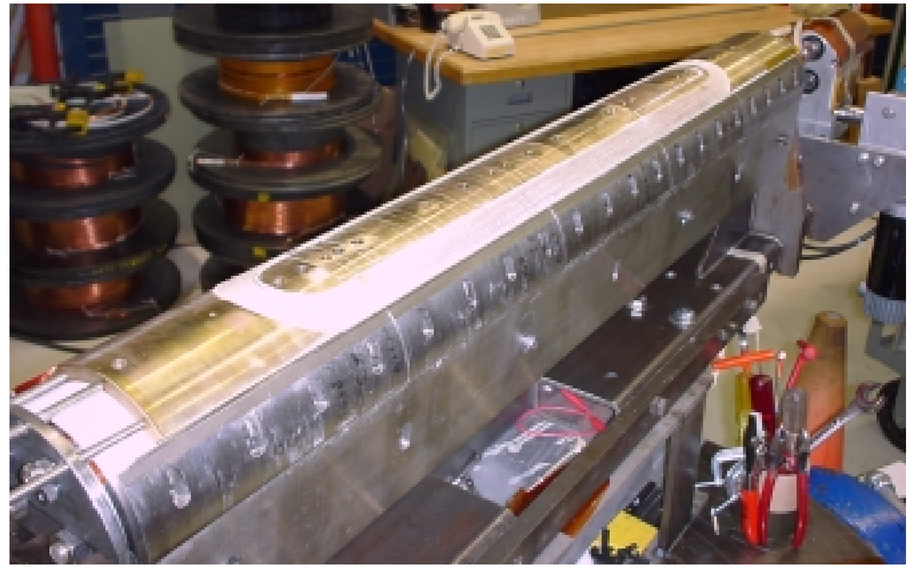
+ No length limit
- needs overlap

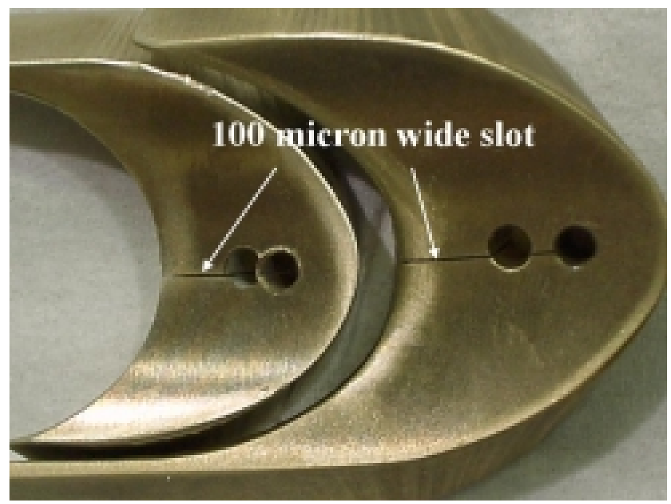
+ No overlap
- limited max cable length

+ No overlap
+ No length limit

Winding

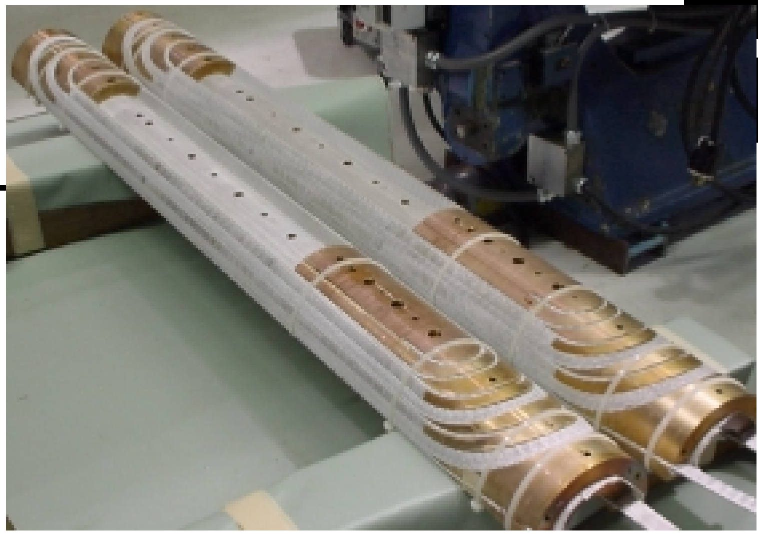
- Fixtures and tooling are similar to NbTi coil winding
  - Rotating table (short coils)
  - Winding machine (long coils)
- All coil parts should withstand the heat treatment
  - Metal or ceramic
    - Not for React-and-Wind
  - LARP TQ: Al-bronze, Ti-Al-V
- The insulation is less strong than Kapton
  - Slots in end parts to give flexibility



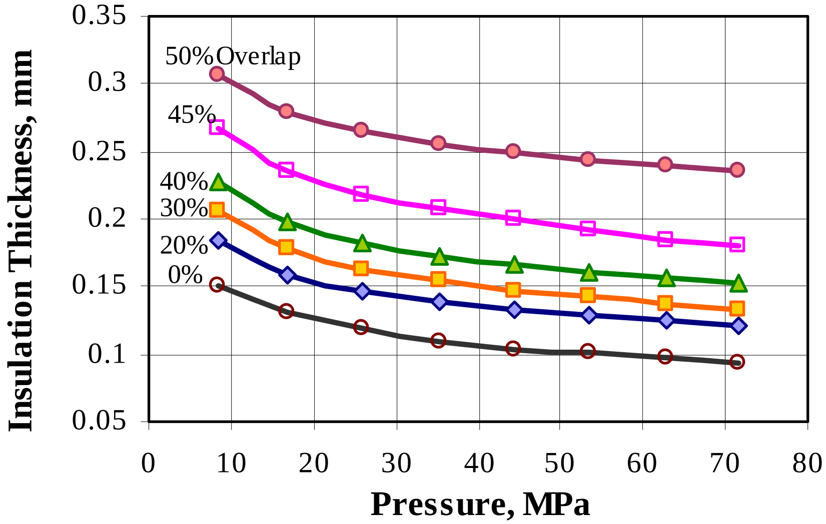


Curing

- Fermilab has introduced the use of a ceramic binder* that becomes a glue after curing at 150º C for 30 min under pressure
  - Easy handling of coils
  - Possibility of measurements and inspection



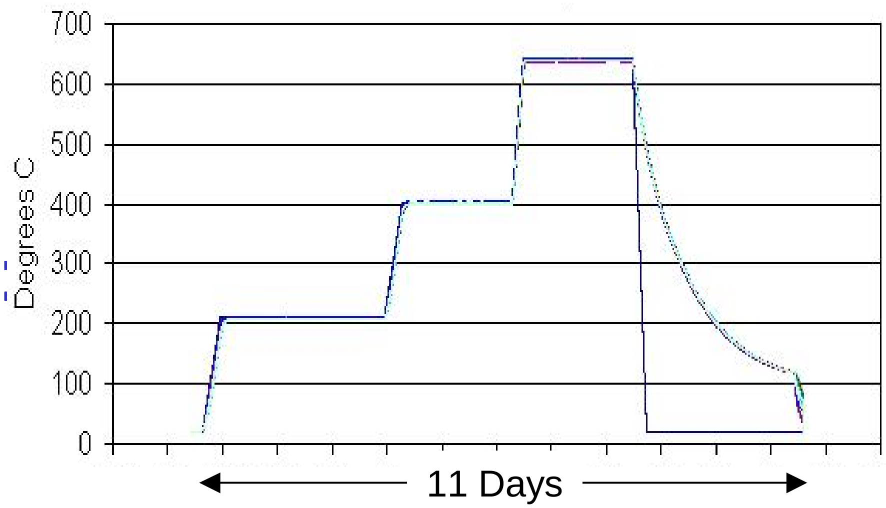
Optimization of tape overlap in order to achieve the nominal insulation thickness under pressure



Developed by Composite Technology Development: http://www.ctd-materials.com/*
D.R. Chichili, et al*., "Investigation of cable insulation and thermo-mechanical properties of epoxy impregnated Nb_3Sn composite"* IEEE Trans. Appl. Superc.Vo 10, No 1, March 2000 Pag: 1317 - 1320

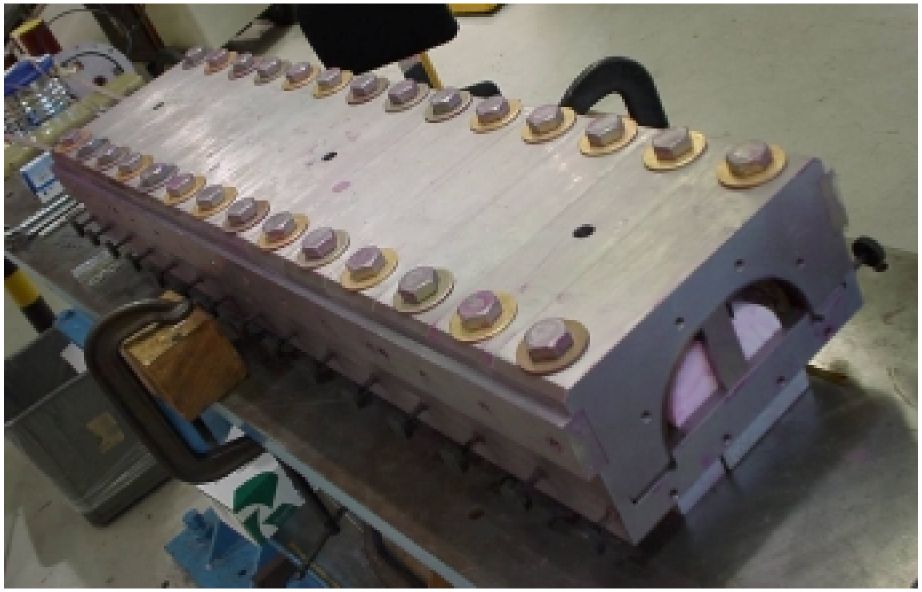
Heat treatment - I

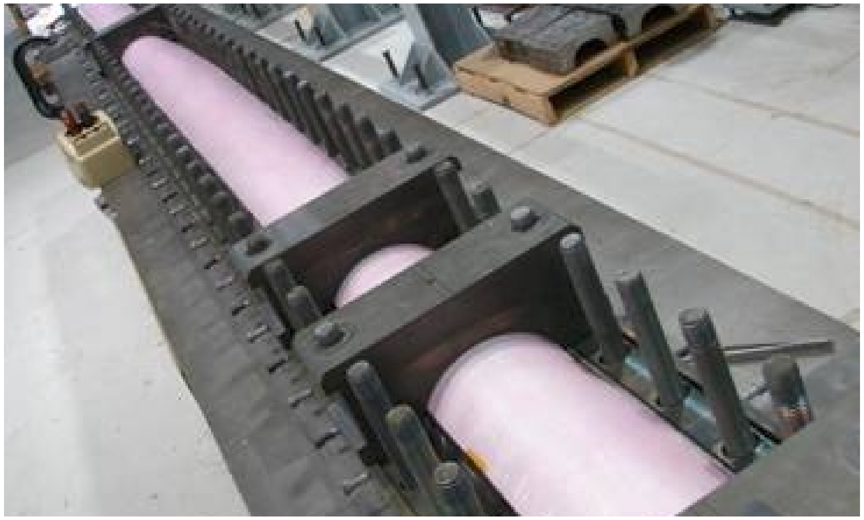
- This is a very critical step!
  - Temperature control and uniformity
    - Steps at ~210º C, 400-450º C, and 630-670º C
  - No oxygen (argon or vacuum)
- Reaction fixture should accommodate:
  - Coil volume increase
    - Due to Nb_3Sn formation
  - Different thermal expansions
- Reaction fixt. should provide:
  - Nominal coil geometry
  - Easy extraction of reacted coil
    - Most critical handling



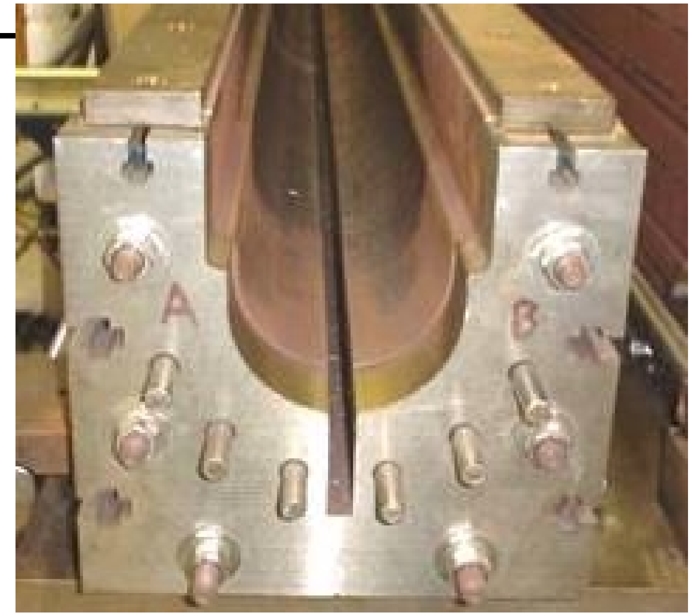
Heat treatment - II

- Segmented tooling with base and top plates
  - ➔ Very high accuracy of coil cavity size for any length
- The fixture can be assembled / disassembled around the coil
  - ➔ Minimize coil handling

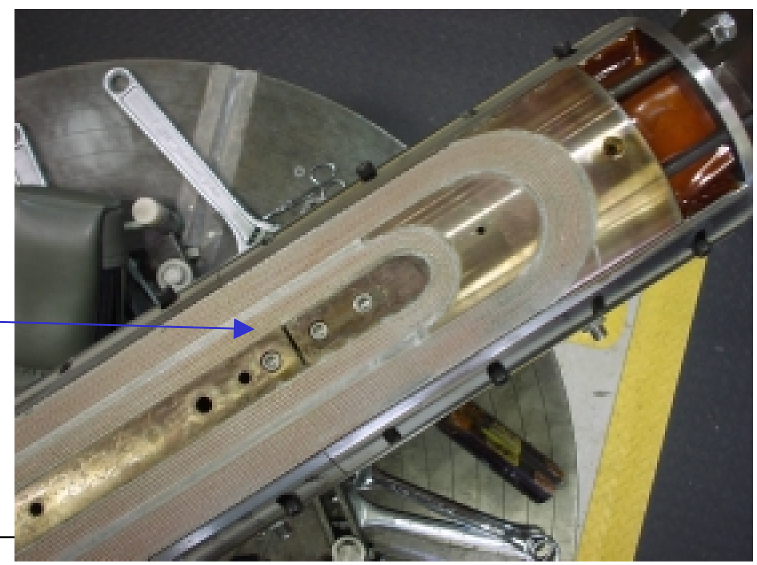




Heat treatment - III



- Coil azimuthal size:
  - Size of curing mold is slightly smaller than nominal dimension
  - Size of reaction fixture is equal to nominal dimensions
  - ➔ coil growths during HT, and fills the reaction cavity with small pressure
- Coil longitudinal behavior:
  - The coil CTE changes during the HT
  - Al-bronze pole matches the coil CTE after HT but leaves gaps at pole tips
  - ➔ gaps between pole parts
  - Ti (Ti-Al-V) has smaller CTE and doesn't leave gaps at pole tips

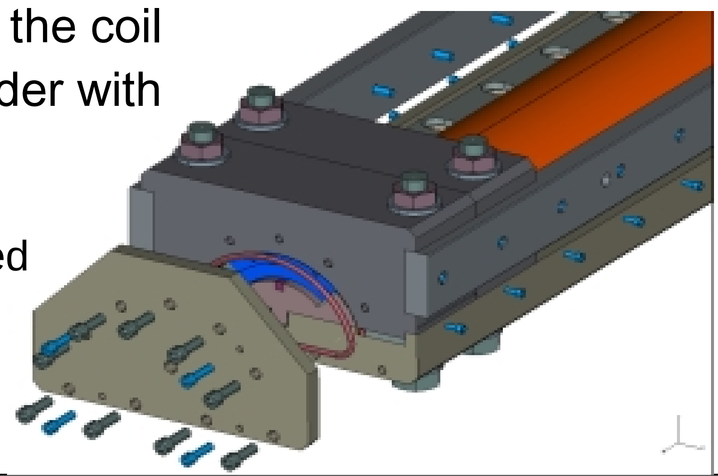


Impregnation

- **Goals:**
  - Fill all voids inside the coil in order to avoid stress concentration on the conductor
  - The coil becomes a solid object for easy and well controlled magnet assembly

- **LARP Solution:** CTD-101 K:
- long pot life
- very good penetration inside the coil
- Compatible with ceramic binder with good mechanical properties

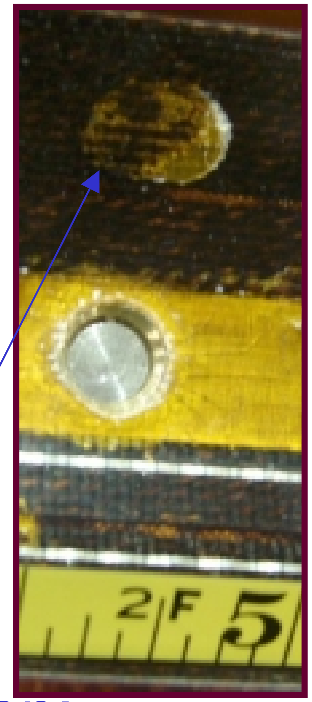
The reaction fixture can be sealed by using a shell and O-rings
➔ Impregnation fixture



Instrumentation

Needs:

- **Voltage taps** during R&D for:
  - Quench start localization
  - Quench propagation
- **Strain gauges** during R&D for:
  - Monitoring stresses during assembly, cooldown and operation
- **Spot heaters** during R&D for:
  - Initiating a “planned” quench
- **Protection heater** R&D and production:
  - Distribute energy on the whole magnet



LARP Solution: “Trace”

- Kapton foil with photo-etched ss traces for protection heaters and wiring for voltage taps/ strain gauges/ spot heaters
- May cause/contribute to “bubbles” when quenching at 2K

Short Coils - Results

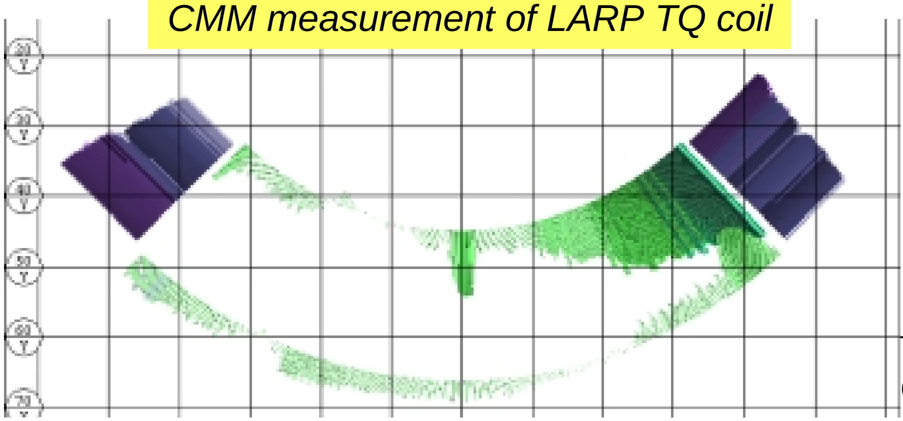
Technological Quadrupoles (1-m coils):

Quench performance 70-90% of SSL

- Some degradation due to coil fabrication?
  - Other magnets using similar coil fabrication technology reached SSL (BNL, FNAL, LBNL)
  - Ti-Al-V is used for the first time, but coils with Al-bronze didn't show better performance
  - The 2-in-1 reaction & impregnation fixture causes some systematic deviations from nominal size

Or magnet assembly and operation, or conductor …

CMM measurement of LARP TQ coil

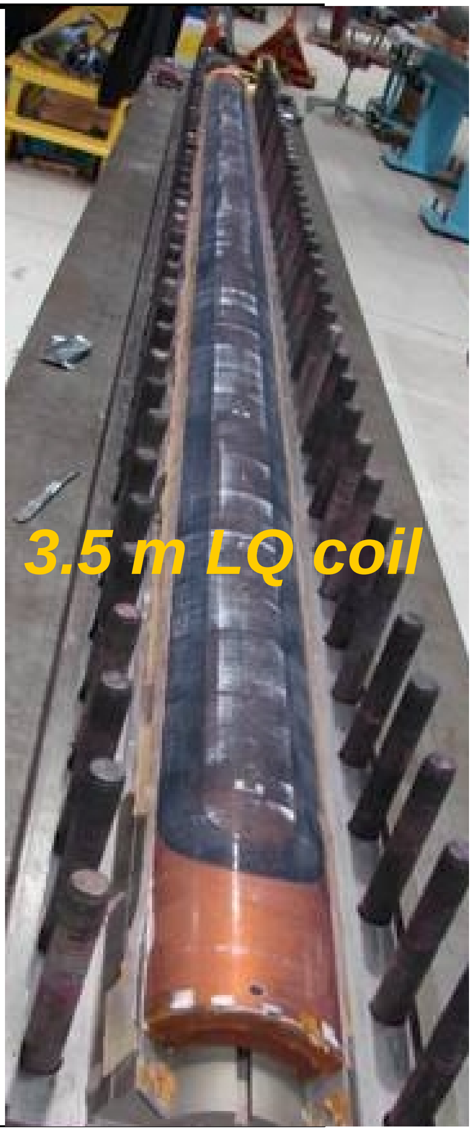


➔TQs: Matching coils during magnet assembly

➔Next LARP magnets: Single coil fixtures

What about long coils?

- Conductor:
  - Need km-size strand piece length, and long cabling runs (250 m for 4m long quad coils)
- Insulation:
  - Need technique for long coils
- Reaction:
  - Long oven
  - The displacements due to differential expansions scale with length
  - Total friction force scales with length
- Impregnation:
  - Impregnation time increases with length
- Handling:
  - LARP set criteria for Max strain: -0.15%< ε <0.05%



LQ coil fabrication

- Scale-up issues:
  - Coil bowing because of winding tension
    - Keep always under load
  - Coil bowing after reaction
    - Pre-heat treat the fixture
    - Symmetric fixture (2 plates)
    - Reduce friction (mica)

Long Coils - Results

- Best Long Racetrack (4m coils): 96% of SSL
  - So we can successfully make long Nb_3Sn coils!
    - But the LR had flat coils without ceramic binder, and coils were not heat treated in a closed cavity under pressure
  - We have to demonstrate long accelerator-quality Nb_3Sn coils
- 1st Long Mirror (2m coil): ~ SSL
  - ~ Accelerator quality coil using PIT conductor
    - Cos-theta coil w wedges, end spacers
- 2nd Long Mirror (4m coil): 87% SSL
  - ~ Accel. quality coil using RRP 114/128
    - Performance improved by heating the outer layer ➔ instability

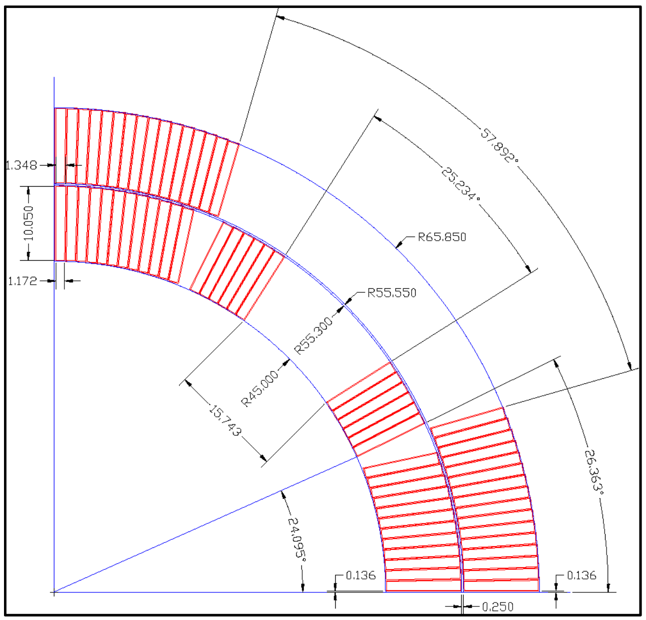
98% SSL taking into account simulated temperature increase

Front view of mirror magnet

Magnet Assembly

Case study:
LARP TQs
"Technological Quadrupoles"

TQ Magnetic Design



Coil layout:

- 2 layers
- 10 mm wide cable
- 1° keystone angle
- 27 strands 0.7 mm diam.

Parameter	Unit	**Collars**	**Shell**
N of layers	-	2	
N of turns	-	136	
Coil area (Cu + nonCu)	cm^2	29.33	
4.2 K temperature			
Quench gradient	T/m	**221**	**233**
Quench current	kA	13.3	13.4
Peak field in the body at quench	T	11.5	11.9
Peak field in the end at quench	T	11.9	11.4
Inductance at quench	mH/m	4.6	4.9
Stored energy at quench	kJ/m	406	439
1.9 K temperature			
Quench gradient	T/m	**238**	**251**
Quench current	kA	14.4	14.5
Peak field in the body at quench	T	12.4	12.9
Peak field in the end at quench	T	12.9	12.4
Stored energy at quench	kJ/m	472	512

J_c = 2400 A/mm^2 at 12T, 4.2K

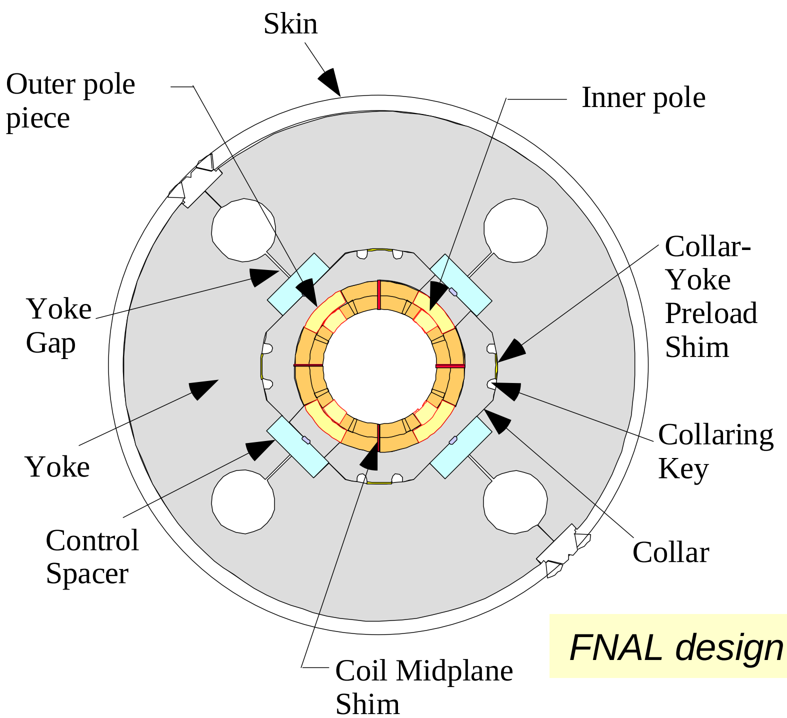
TQ Mechanical Designs

Two mechanical designs have been developed

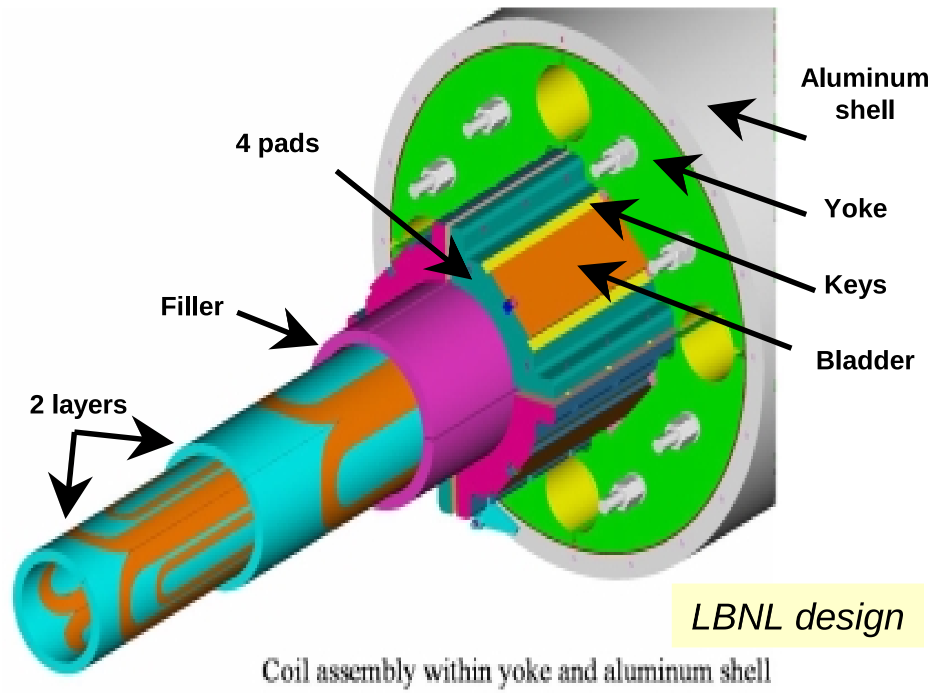
Same coils & Aperture (= 90 mm) & Gradient (> 200 T/m)

TQC: using collars
Collar laminations from LHC-IR quads
1st time applied to Nb_3Sn coils

TQS: using Al-shell
Pre-loaded by bladders and keys
1st time applied to shell-type coils



FNAL design

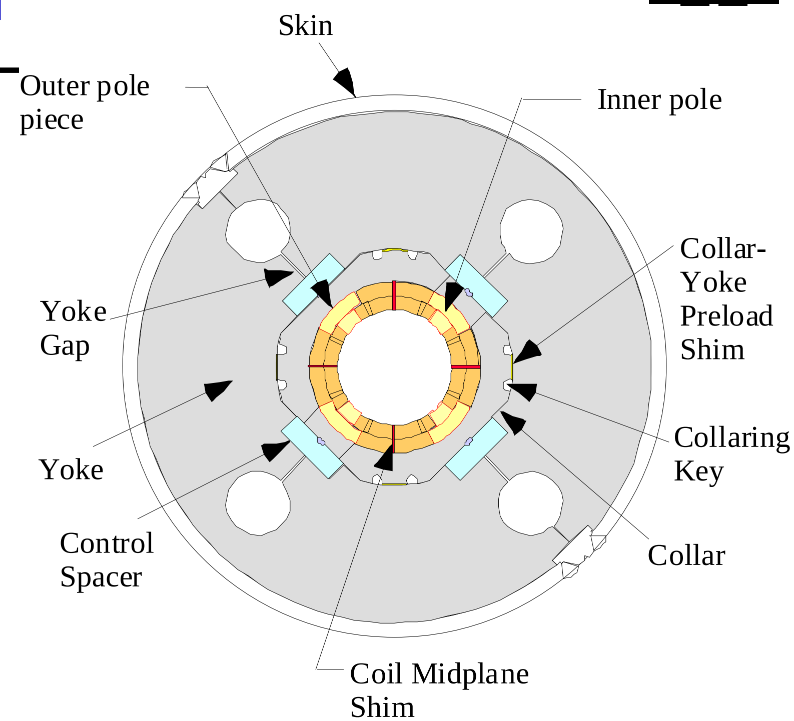


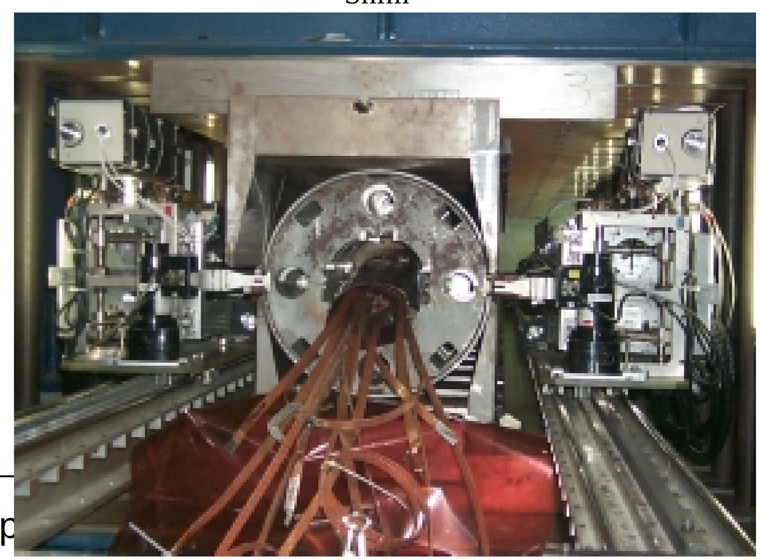
LBNL design

Coil assembly within yoke and aluminum shell

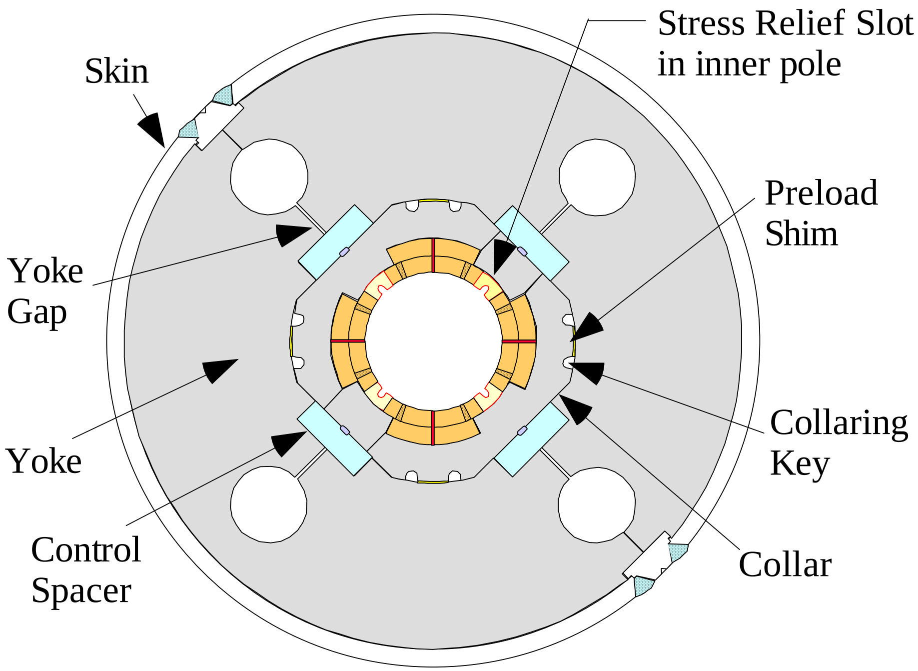
TQC Concept

- Concept:
  - Support by SS collars + yoke&skin
  - Assembly under a press
    - Collaring & skin welding
- Advantages:
  - Proven for accelerator-quality:
    - Coil alignment
    - Cooling & heat removal
  - Proven for scale-up
- R&D issues:
  - Provide support and prestress (higher forces than NbTi) within Nb_3Sn limits
    - stress and strain





TQC Mechanical Structure



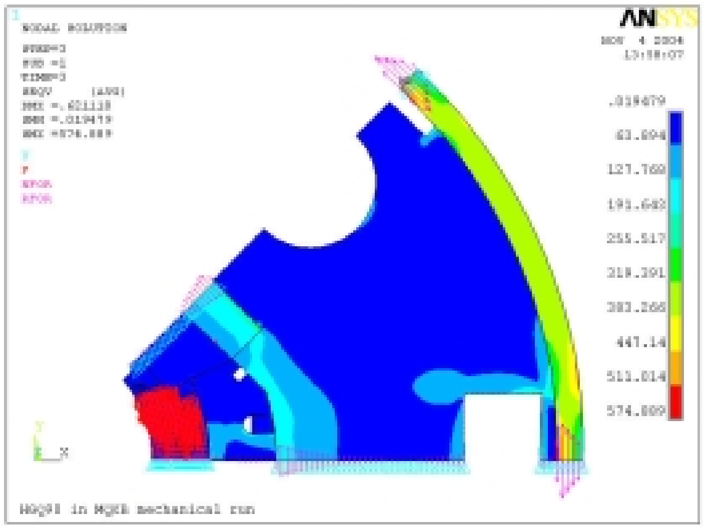
- Control spacers
  - for collared coil alignment and yoke motion control.
- Shims between collar and yoke at each midplane
  - to allow preload to be shared between skin and collars and control collar-yoke interference.
- A radial cut is made in each yoke quadrant
  - to provide symmetrical loading to the collars.
- Mechanical structure and coil pre-stress is studied and optimized using FEM and mechanical models.

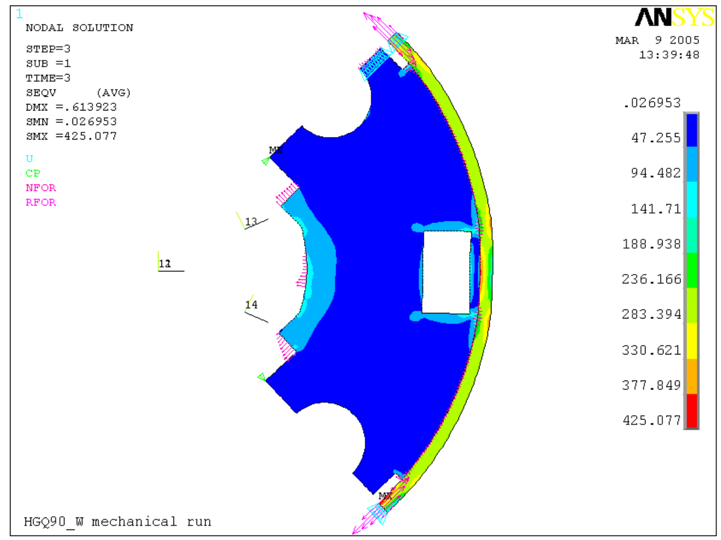
Collars for:
← TQC 1st generation

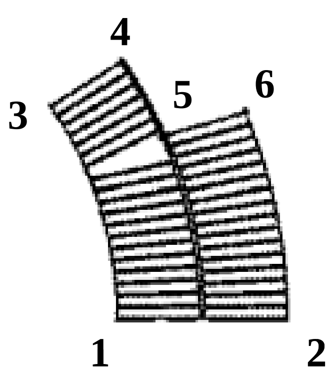
2nd generation had slot instead of tip

← LHC-IR quads

TQC Mechanical Analysis







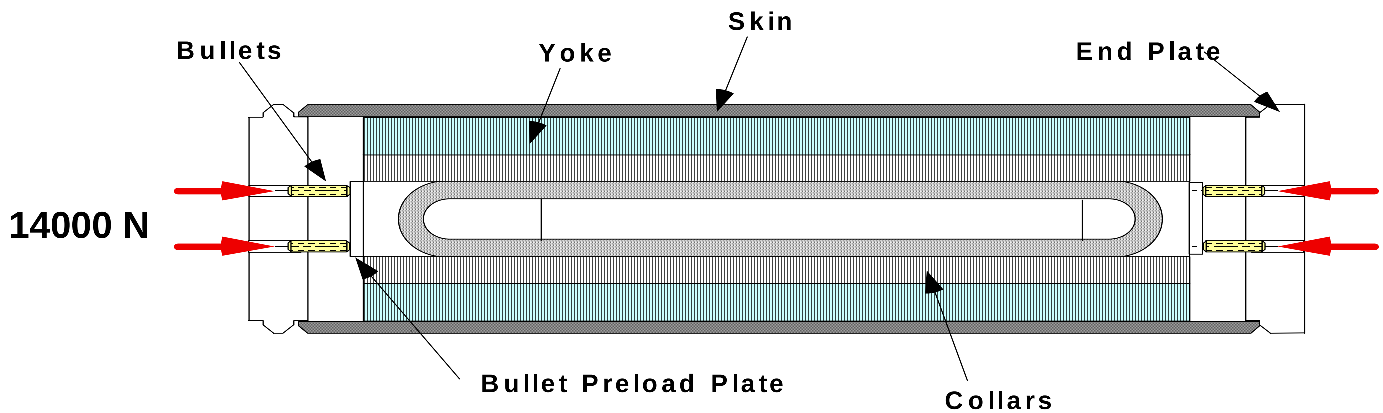
	Max/Min Coil Stress	At Coil Pos. No.	Pole Insert	Control Spacer	Collar	Yoke	Skin 8mm	Skin 12mm
300K	140/65	3/1&2	250	50	420	170	230	150
4.3K	150/80	3/1&2	230	150	470	270	400	270
Bmax	145/20	2/3	50	50	460	280	450	300

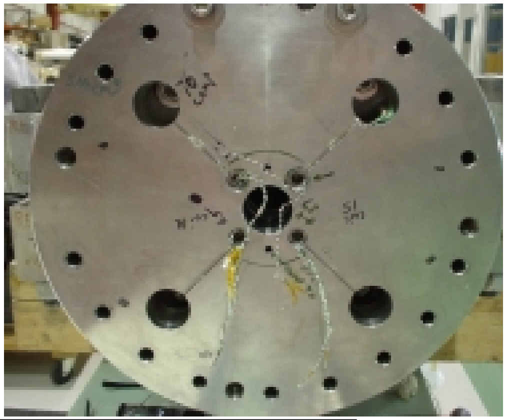
Stresses in the coils during collaring < 70 MPa

TQC ends

- 3D FEA (LBNL and FNAL) of coil ends:
  - separation between the pole tip and the first turn of the coil of 20 - 200 um when the magnet is powered
    - **depending on input parameters and end loading,**
  - effect of this separation on training behavior is not clear
    - **LBNL racetracks at LBNL showed correlation between gaps and training**
    - **FNAL Nb_3Sn and NbTi magnets, with minimal and no end loading, have not exhibited excessive training quenches in the ends**

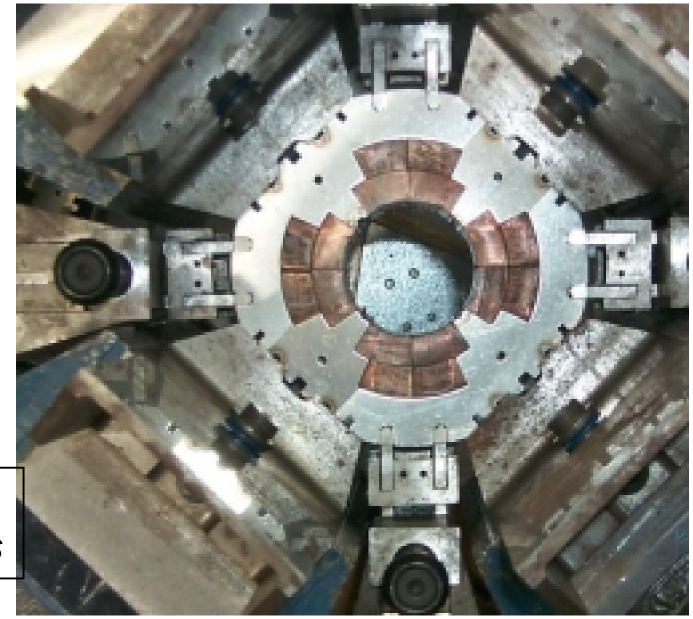
➔ TQC magnets test the “minimal” axial end loading system: 14000 N
  - **End force applied by 4 preloaded screws (“bullets”) through 50-mm thick stainless steel end plates**



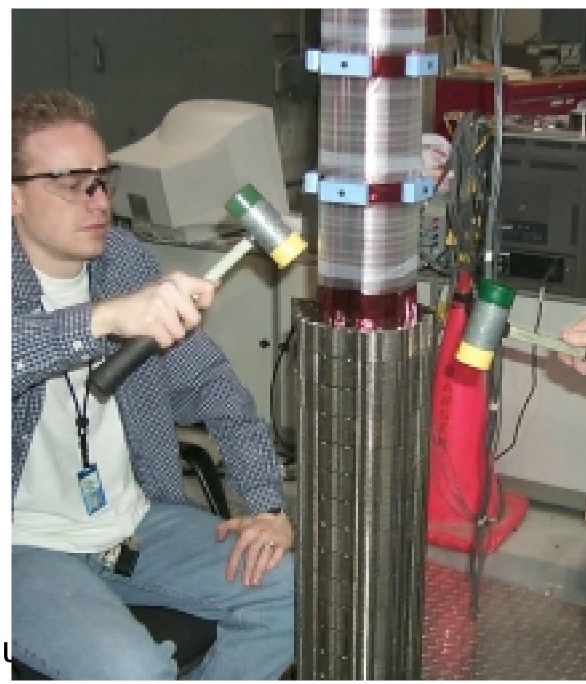


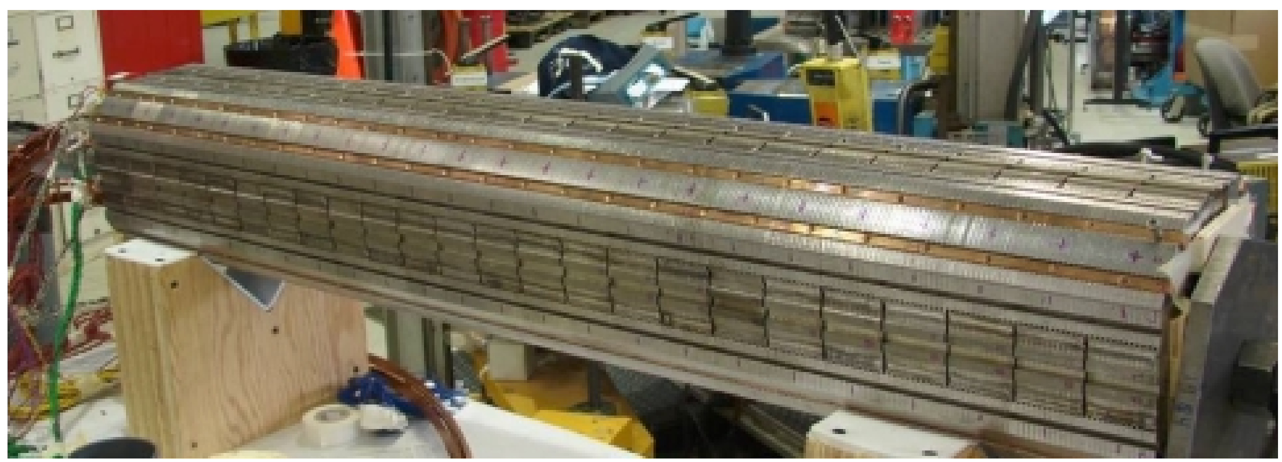
TQC Collaring

- Impregnated coils are assembled and surrounded by layers of Kapton for ground insulation
- Collar packs are placed over the coils
- Assembly is hung vertically over collaring press, and keys are inserted over several steps while pressure is applied



Collaring of a mechanical model with LHC-IR collars

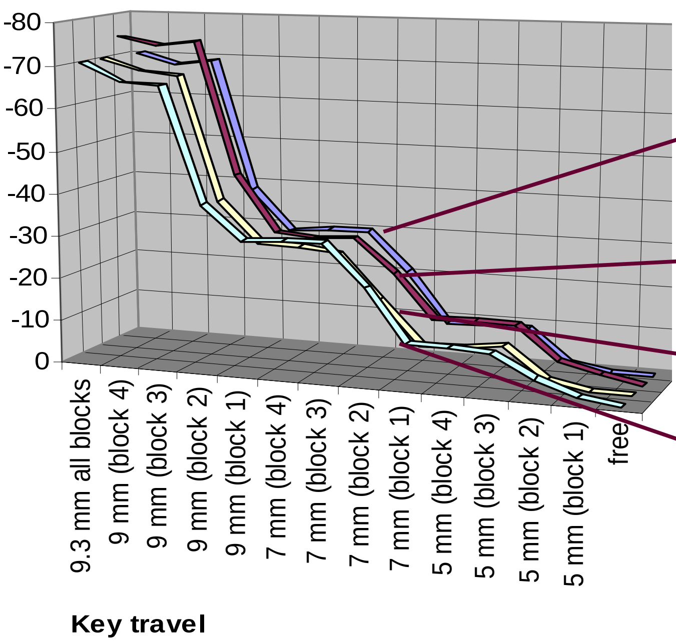


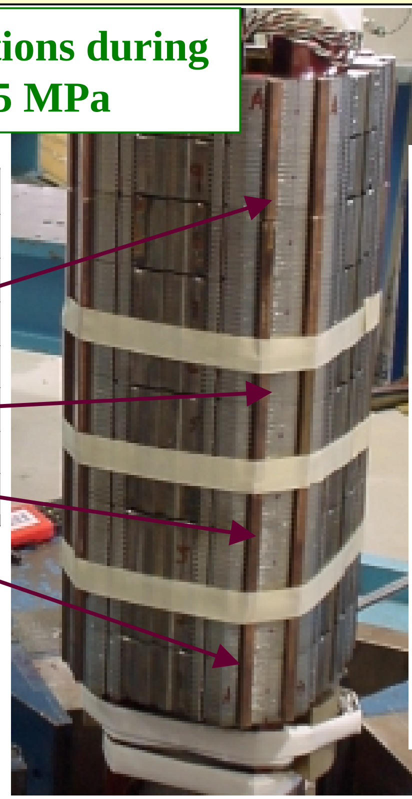


TQC Collaring Development

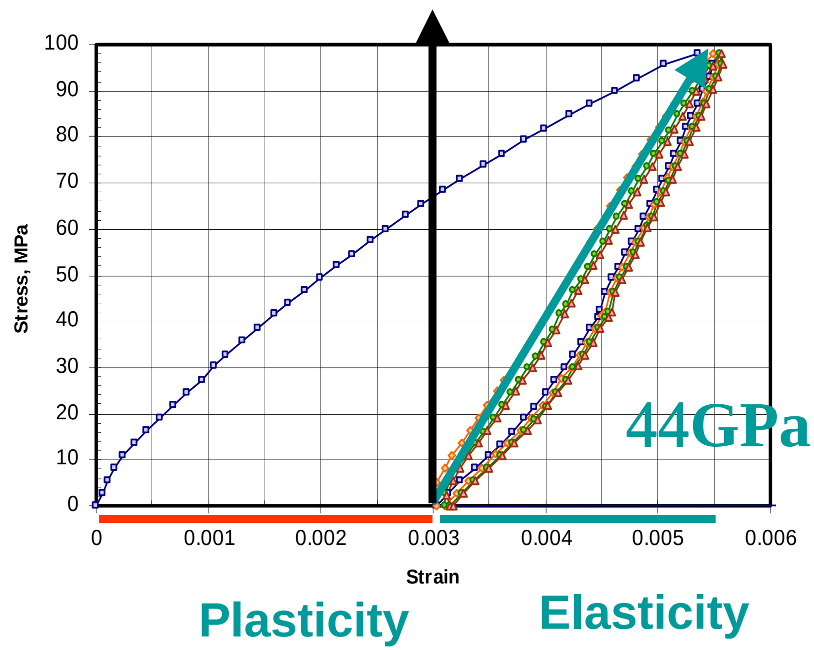
- Four mechanical models have been assembled and tested in order to develop collaring procedure for Nb_3Sn coils
- FEM analysis with Nb_3Sn coil plasticity

Stress in different longitudinal sections during keys insertion: uniform within +/- 5 MPa



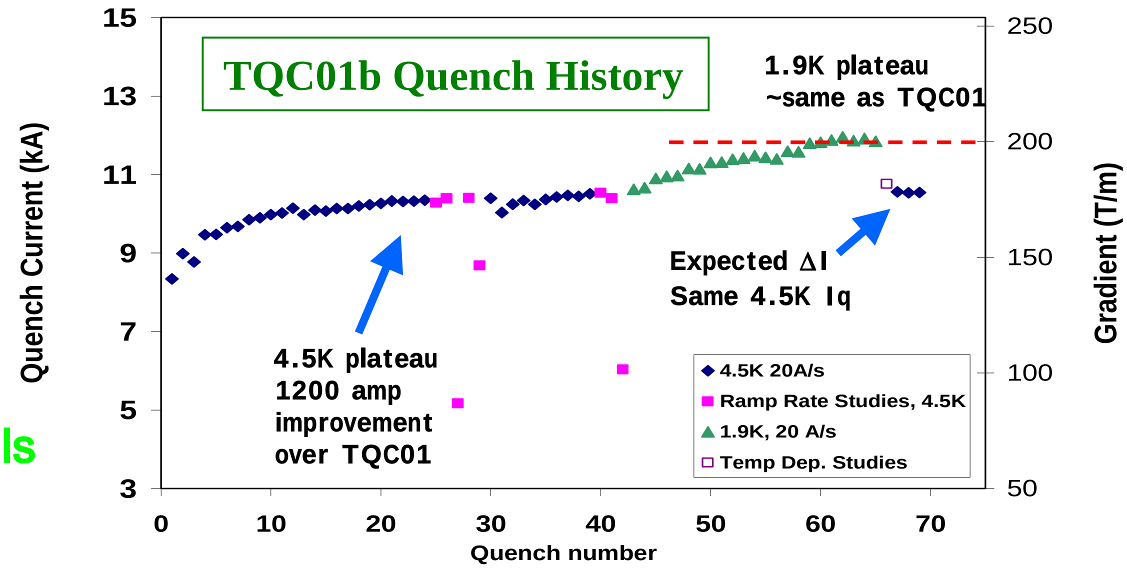


Stress strain plot showing plastic-elastic behavior of coil samples



TQC Results

- TQC01 (MJR)
  - 72% SSL at 4.5K
  - 87% = 202 T/m at 1.9K
  - Damage during test
    - Too low pre-stress
- TQC01b (MJR)
  - 88% at 4.5K
  - 90% = 202 T/m at 1.9K
    - Reassembly w 2 TQS coils
- TQC02e (RRP 54/61)
  - 88% = 203 T/m at 4.5K
  - 80% = 200 T/m at 1.9K
    - No improvement at 1.9K
- TQC02a (RRP 54/61)
  - 69% at 4.5K
  - 68% at 1.9K
    - Likely damaged during collaring (higher than previous magnets)



Magnet assembly:

- *Collaring + Yoke&skin can provide prestress and support for these forces*
- *These collaring technique cannot provide full prestress*

Outline of the lessons

D1
- Introduction
- Conductors

D2
- Magnetic design
- Mechanical design

D3
- Coil fabrication technology

D4
- Magnet assembly
  - Long magnets

D5
- Quench protection design
- Cryogenic design
- Magnet test and analysis
- Lifetime issues
- Next steps

Acknowledgement

Fermilab

N. Andreev, E. Barzi, R. Bossert, G. Chlachidize

V.V. Kashikhin, F. Nobrega, I. Novitsky, A.V. Zlobin

BNL

M. Anerella, A. Ghosh, J. Schmalzle, P. Wanderer

LBNL

S. Caspi, D. Dietderich, P. Ferracin, H. Felice,

A. Lietzke, G.L. Sabbi,

Texas A&M University

A. McInturff , P. McIntyre

CERN

L. Rossi, E. Todesco