Lessons Learned in the Design and Fabrication of Accelerator Magnets

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MT27

27th International Conference on Magnet Technology (MT27)

Fukuoka, Japan / 2021

Lessons are of several types

- Technology is the one we focus the most on

- But there is
  - Psychology
  - Sociology
  - Politics

How we implement the technology

Several projects have failed due to a bad mix of technology and politics

Cost/Performance requirements lead to challenges

- For colliders it is about optimizing the size of the ring and magnetic field strength
  - Highest field possible for an ensemble of industrially produced magnets – this is not clear at the beginning of a project and historically, expectations have been too ambitious.
  - Compact - in order to minimize tunnel size
- This leads to . . .
  - High engineering current density - > 1,000 A/mm^2
  - Requires active magnet protection
    - High current – low inductance
    - Minimal but adequate copper in the strand
  - Smallest possible aperture (problem for accelerator physicists and magnet builders)
  - Excellent field quality (10^{-4}) – precise location of conductors
  - Longest length that can fit on a truck (~ 15m)

First Lesson Learned:
Not everyone knows what an accelerator magnet looks like!

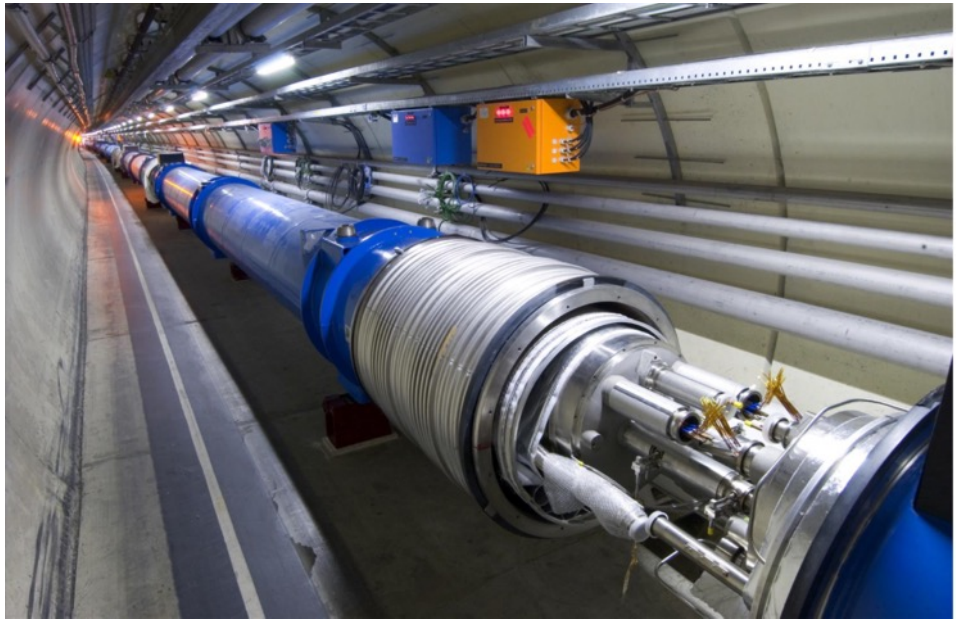
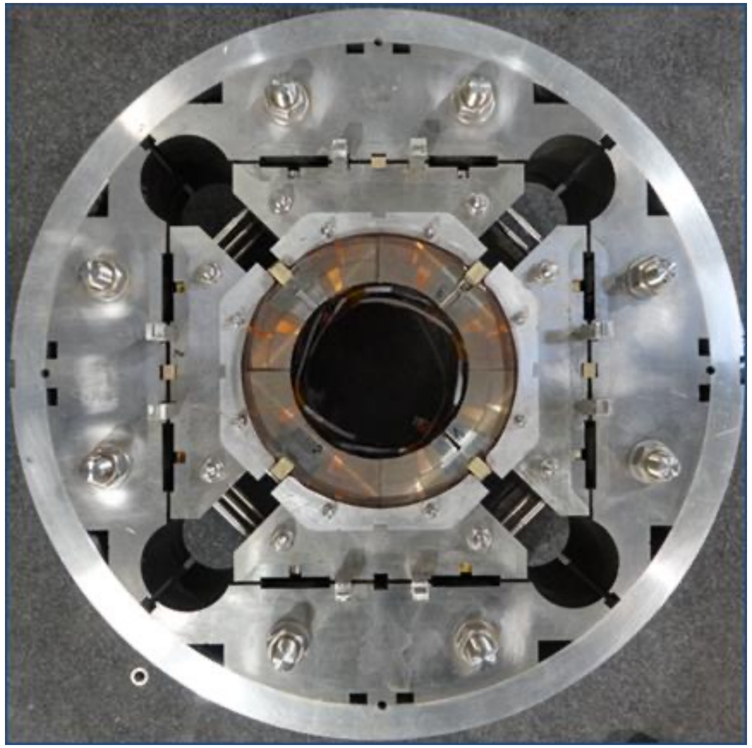
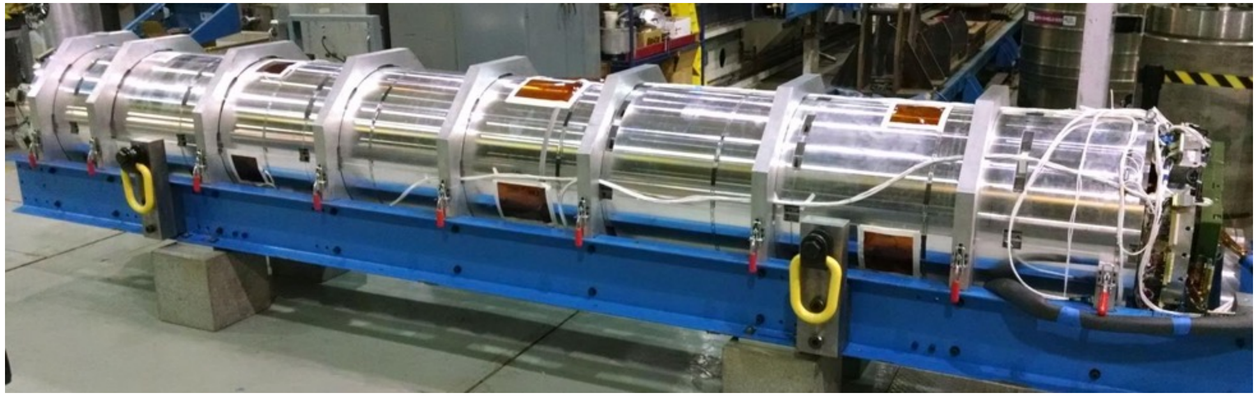


Image: CERN

LHC Dipoles





US Hi-Lumi Quadrupole

Problem highlights

- Cabling and coil winding – still a combination of art and engineering
  - Only became more difficult with Nb_3Sn and HTS
- Insulation, voltage breakdown
- Mechanical support of strain sensitive materials – everything but Nb-Ti
- Miscellaneous, ”one-off” problems
  - Magnet fell off truck
  - Shipping constraints failed during transport
  - Cut the leads off the wrong magnet
  - Quench heater trace trimmed too close to the edge leading to voltage breakdown
  - Equipment failure during fabrication

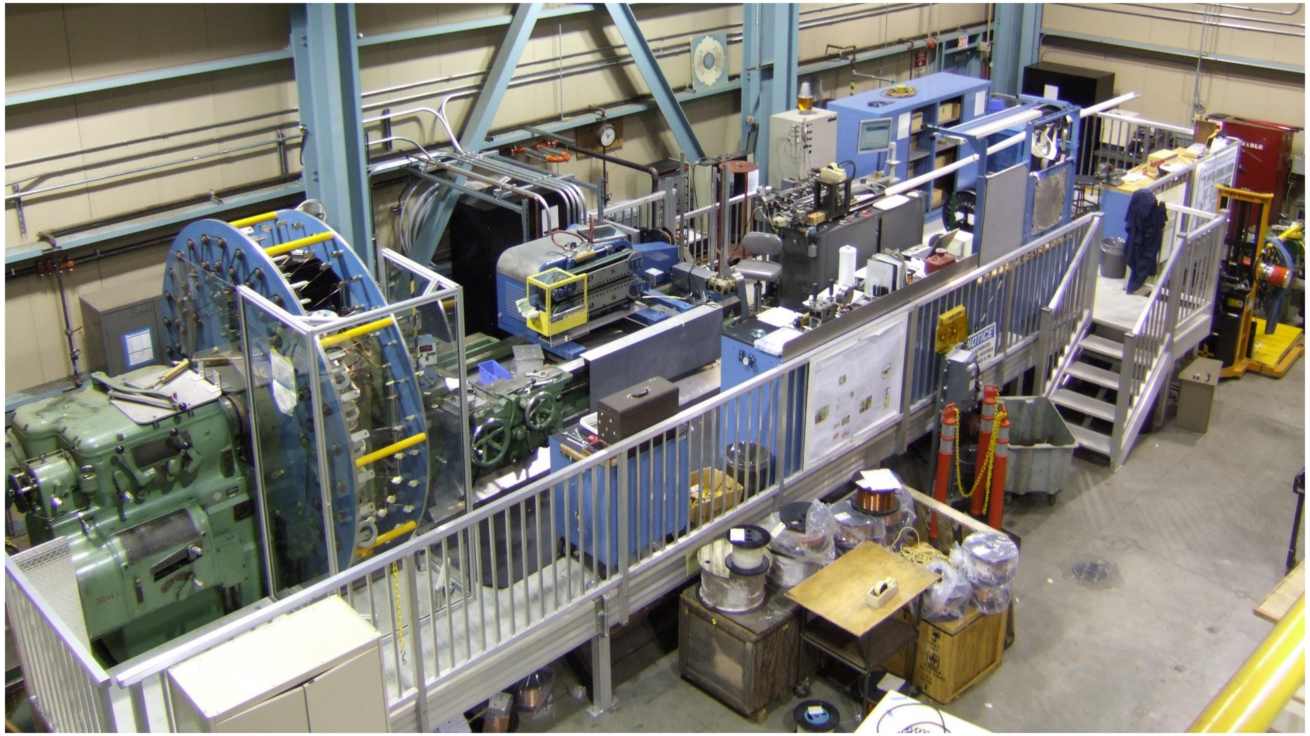
All of these events are opportunities for learning, but for some, it is just part of the process

Rutherford Cable – The “current” standard conductor

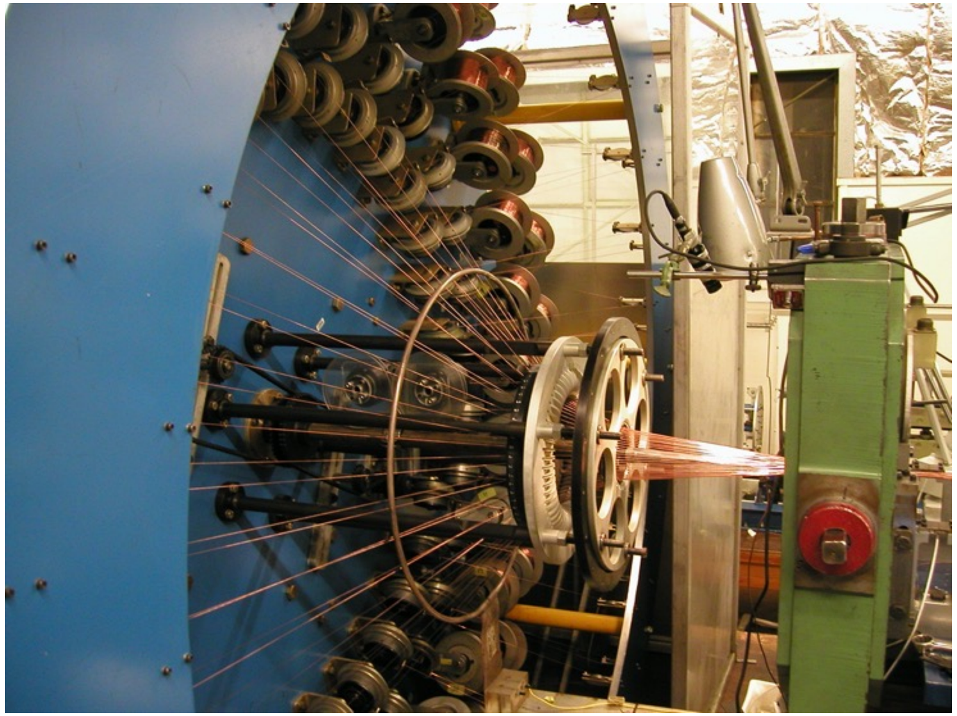
- With few exceptions all accelerator magnets use Rutherford-style cables*
  - Multi-strand – reduce strand length, fewer turns (lower inductance)
  - High current density
  - Precise dimensions – controlled conductor placement (field quality)
  - Current redistribution – stability
  - Twisting to reduce interstrand coupling currents (field quality)

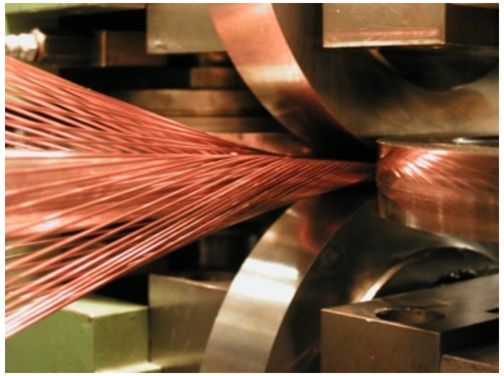
*Early mention circa. 1971

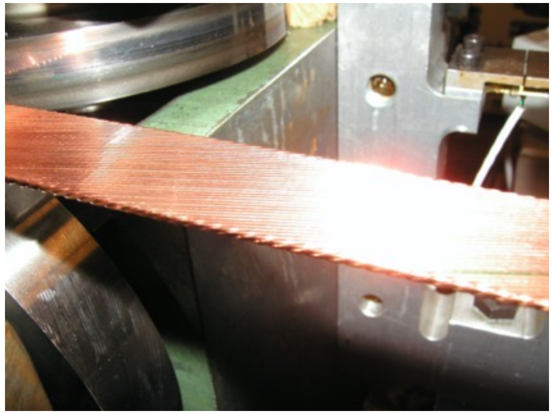
LBNL Cabling Facility

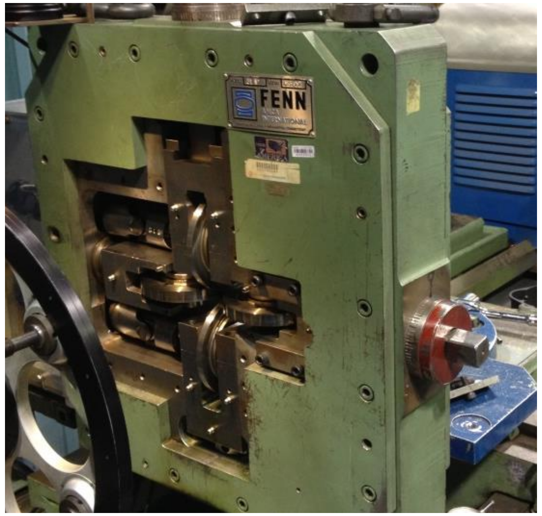


LBNL Cabling Facility





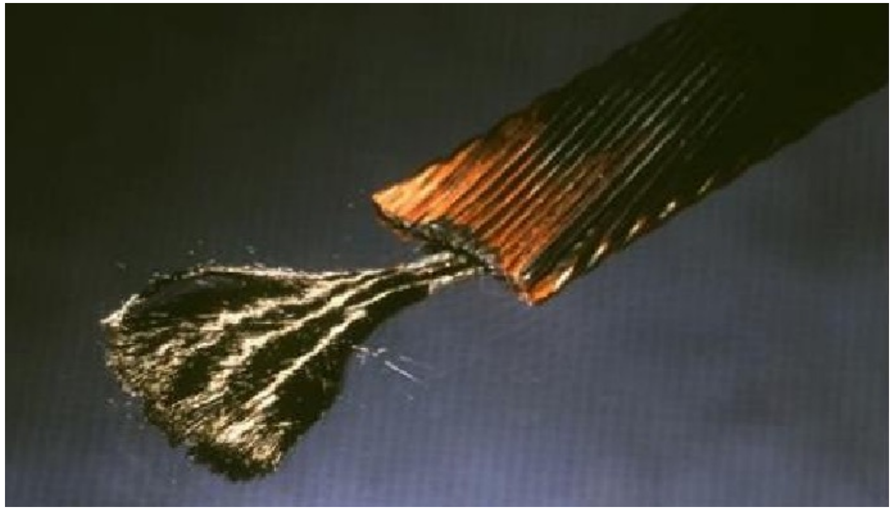




Power Turk’s Head

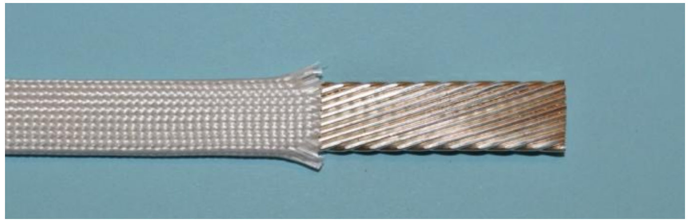
Lesson 2: Not all established processes can simply be applied to different materials

Nb-Ti cable for the FNAL
Low-Beta quadrupole upgrade



Vendor used for Tevatron produced cable with 25% degradation!

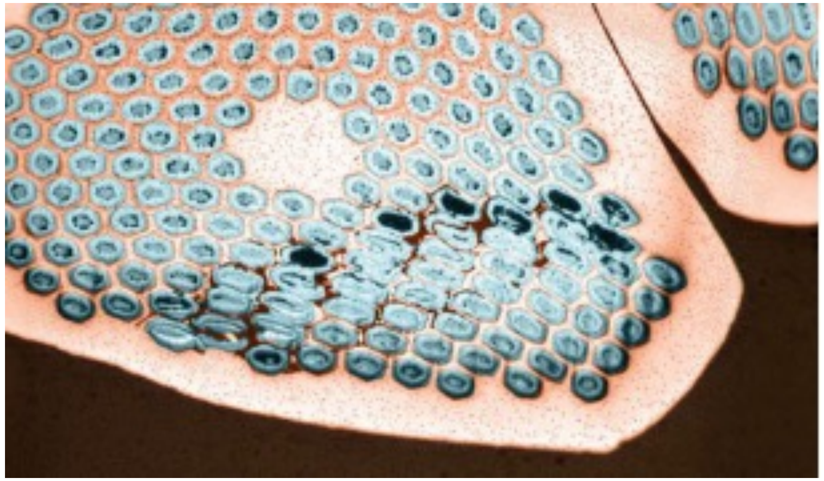
Bi-2212 cable



Traced to excess strain on small strand (0.528mm)

Designing and fabricating cable is still an iterative process between the scientists/engineers and the technicians

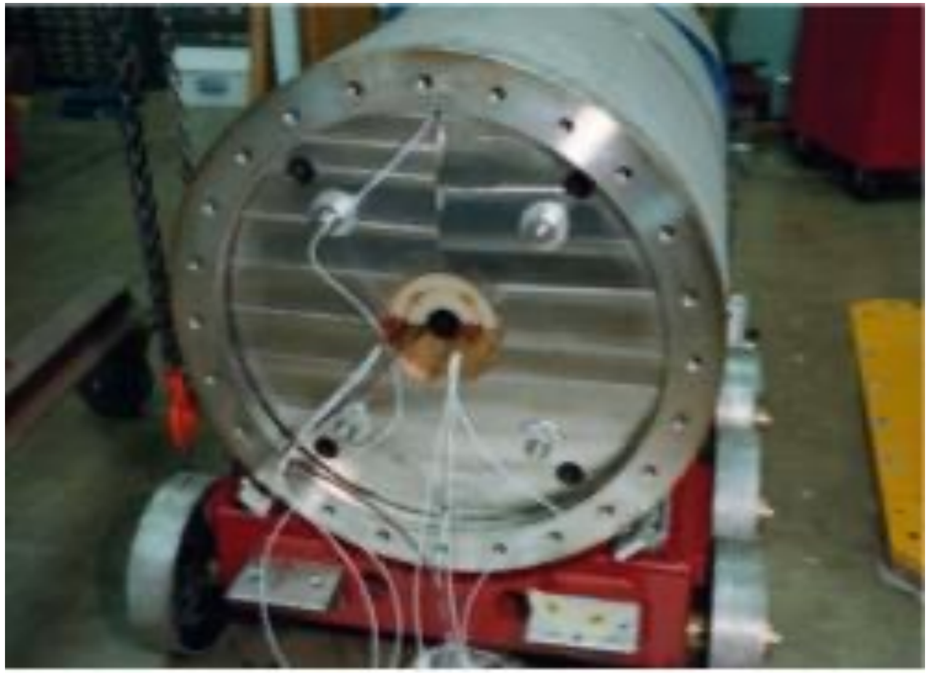
Sheared Nb_3Sn filaments



See CEC/ICMC paper by Ian Pong. “FES/HEP Cable Test Facility Nb_3Sn Dipole Superconductor - Lessons Learnt and Key Challenges”

The Life and Death Story of D20

- The LBNL magnet, D20, encountered and overcame many of the issues with Nb_3Sn that we deal with today.
- After 6 years of design and fabrication, it achieved a record dipole field of 13.5T at 1.8K. That record held for more than two decades.
- Ironically, it almost killed the program

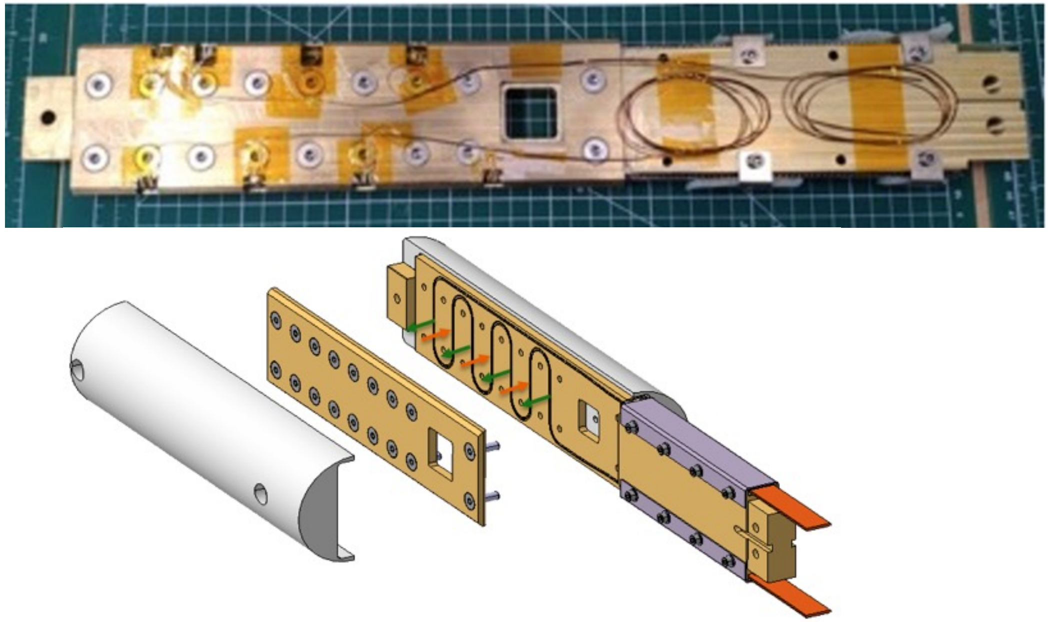


The consequence was that it caused a cultural shift in the R&D approach to accelerator magnet R&D that has spread throughout the community

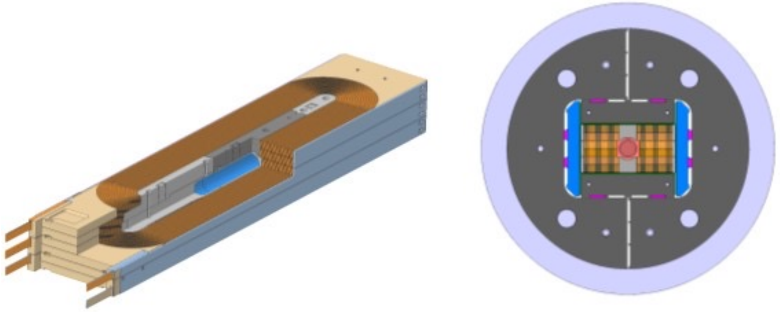
Lesson: Simpler, faster R&D approach – mistakes become learning opportunities

- “Sub-scale” magnets are being used at CERN, LBNL, BNL, FNAL, KEK, IHEP, PSI

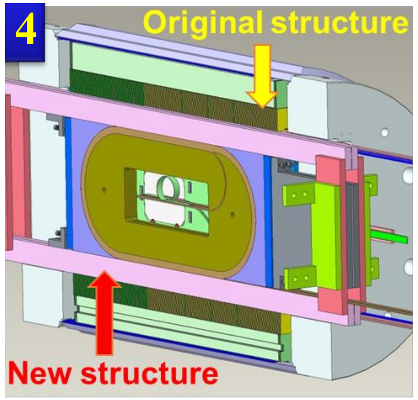
LBNL Bi-2212 coil and sub-scale magnet structure



“Box” coil. Courtesy Michael Daly et al. from CHART at PSI.



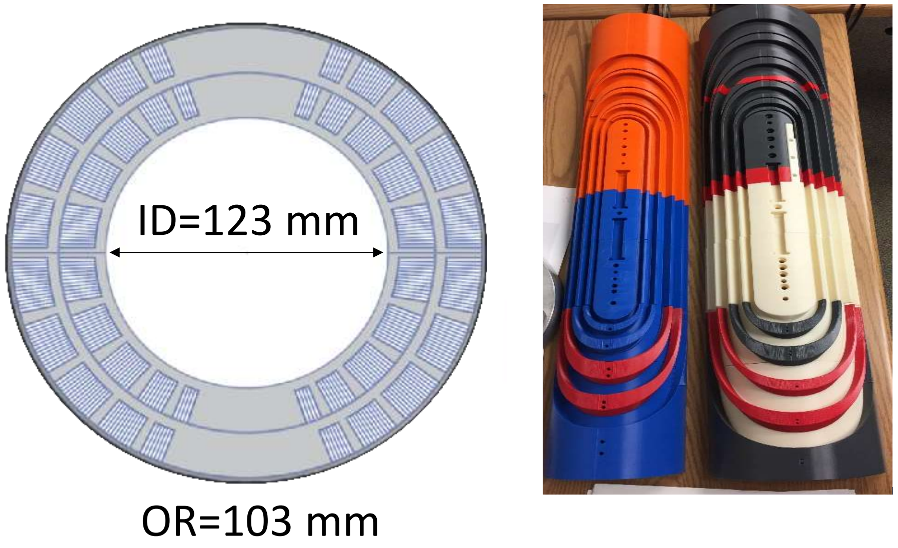
CERN Racetrack Model Coil



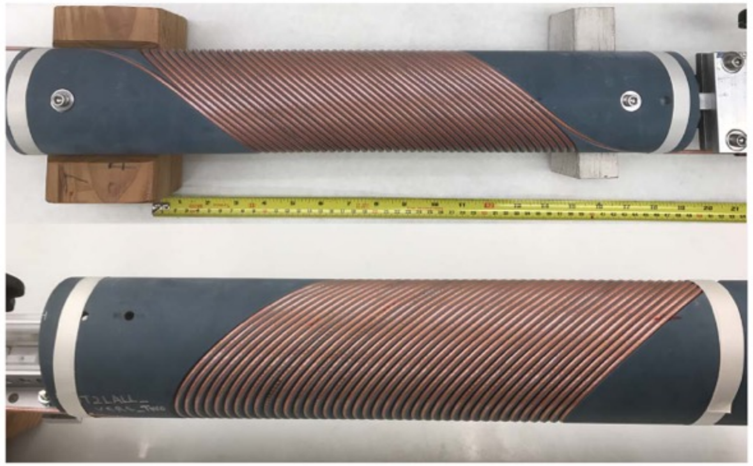
BNL cable/coil insert test facility

Additive manufacturing supports the new R&D approach

- Stress is a limiting factor for materials beyond Nb-Ti
- Use of 3D printing to develop structures, practice winding and conductor tests



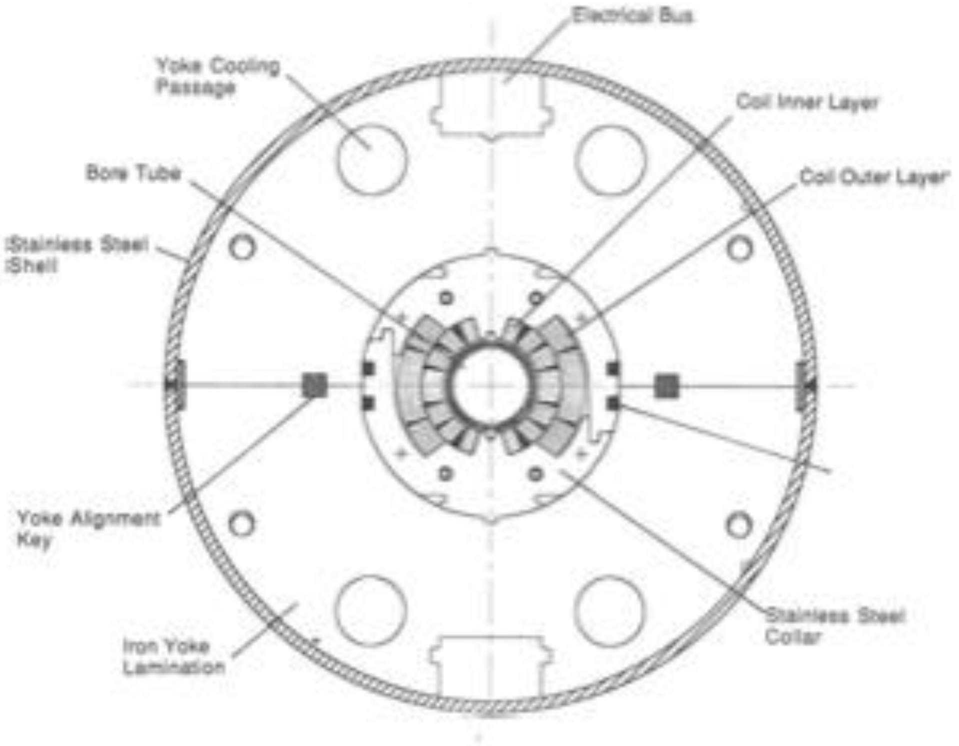
FNAL Stress-Managed Cos-Theta Magnet
(Nb_3Sn and HTS)



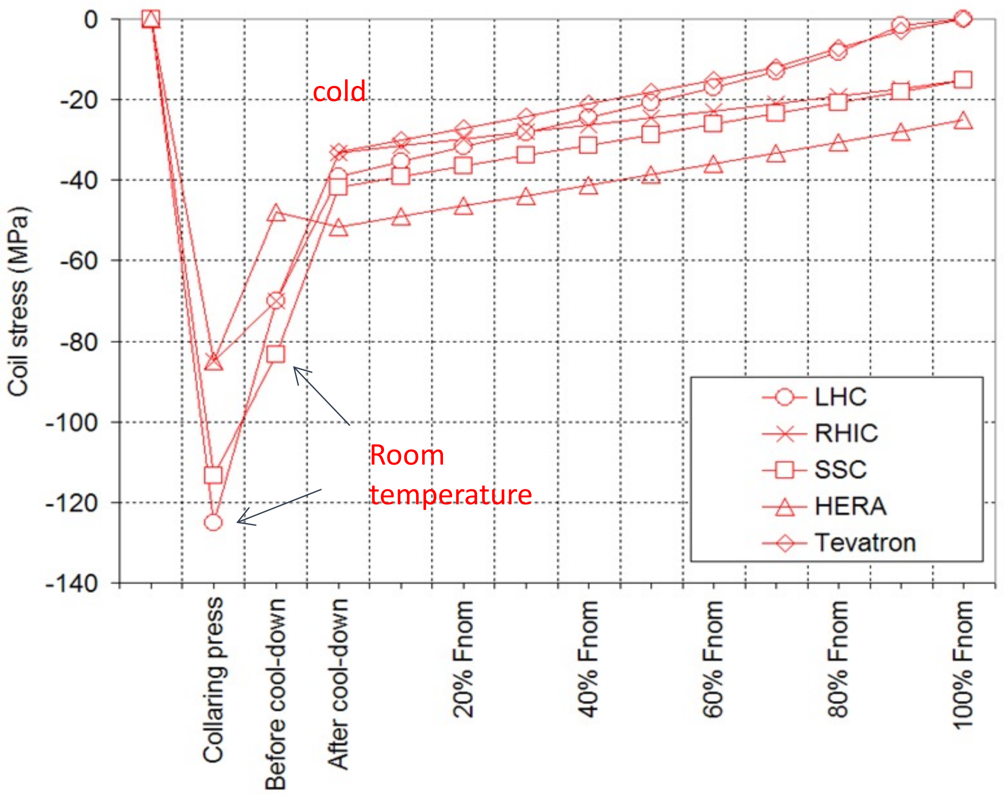
LBNL REBCO Canted-Cosine-Theta Dipole

Printed plastic Acura® Bluestone® mandrels
No impregnation

Lesson: Uncontrolled stress is your enemy



Standard collar and key structure forces high, room temperature preload that becomes a problem for high field magnets



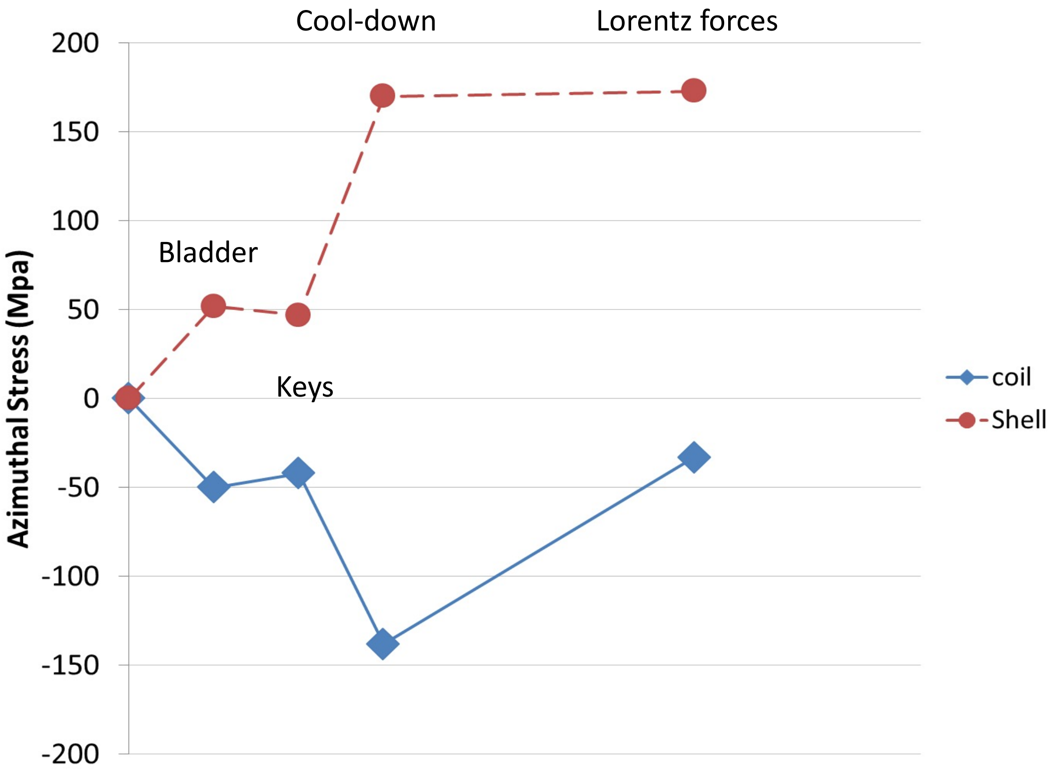
cold

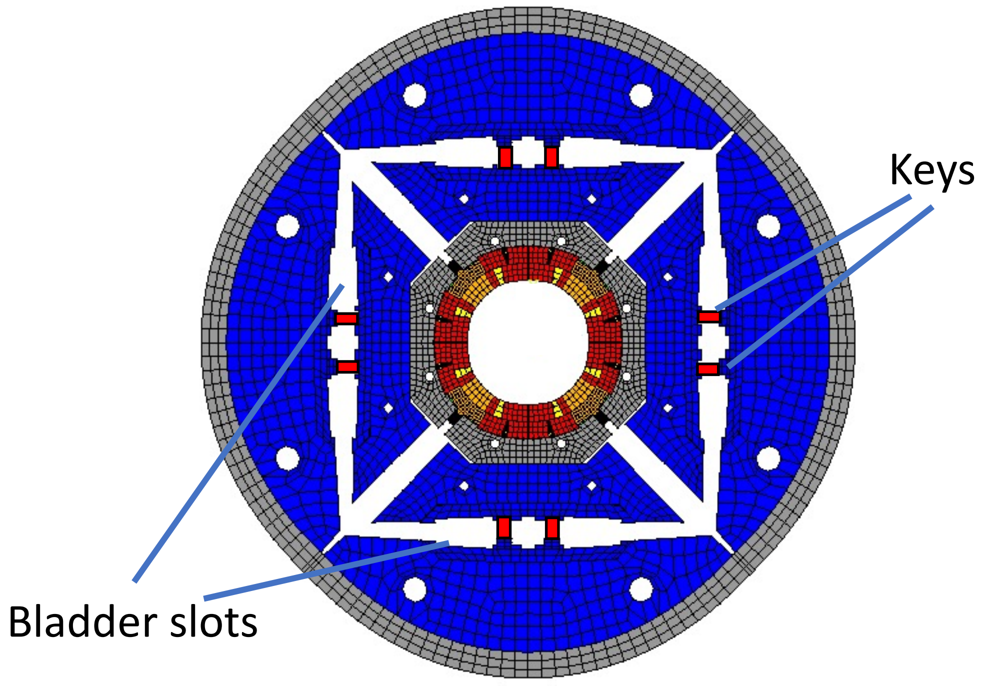
Room temperature

Collaring process- Courtesy of Paolo Ferracin

New support structure developed for strain sensitive material

Requires tighter tolerances than Nb-Ti as well



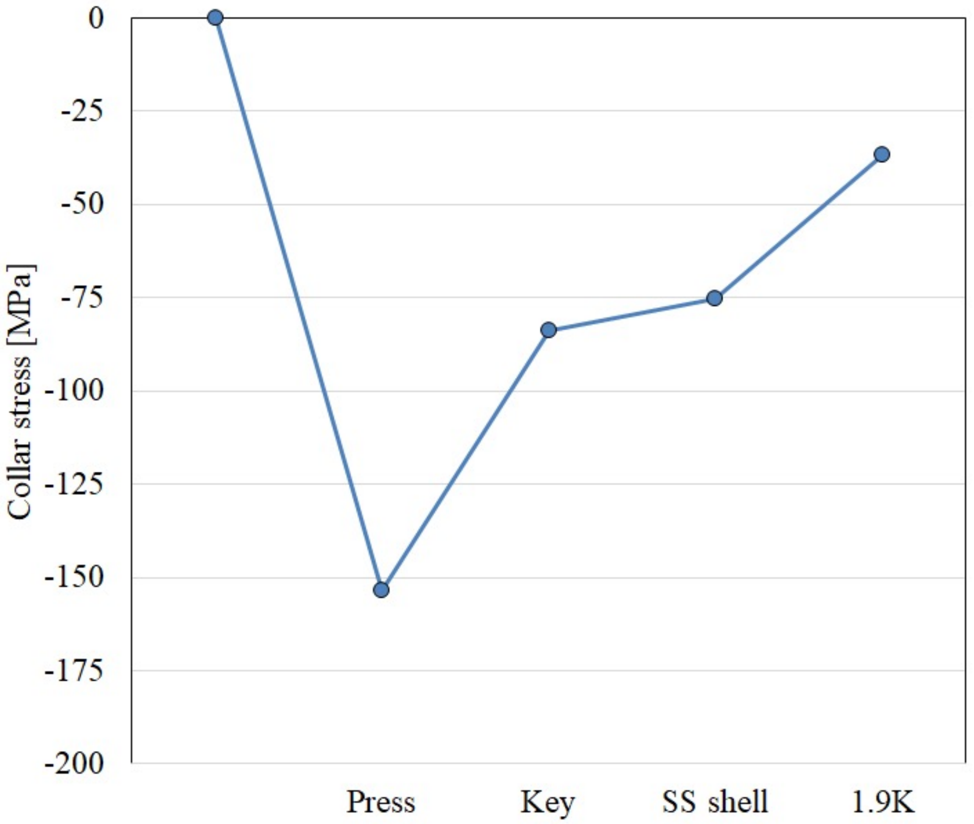


LBNL Bladder and Key

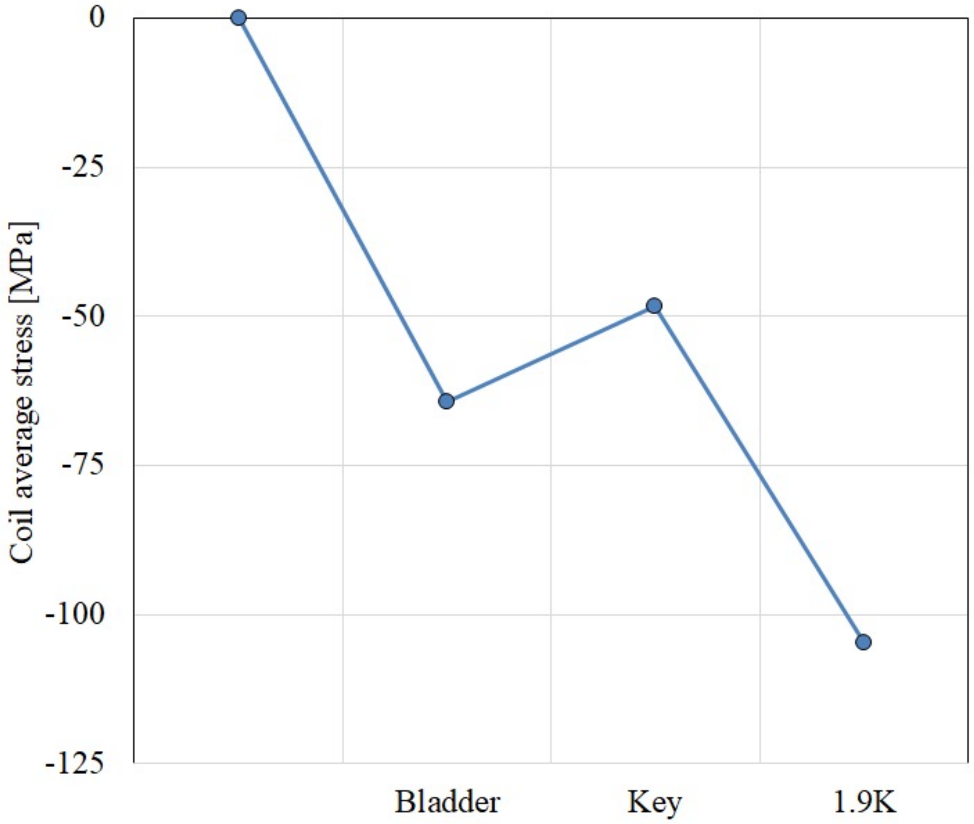
- Lower room temperature preload
- Better control
- Quicker assembly and disassembly for R&D

Courtesy Helene Felice, CERN

Coil stress evolution for the two loading schemes



Traditional Collar and Key



Bladder and Key

Courtesy Paolo Ferracin, LBNL

A new set of lessons to learn - HTS

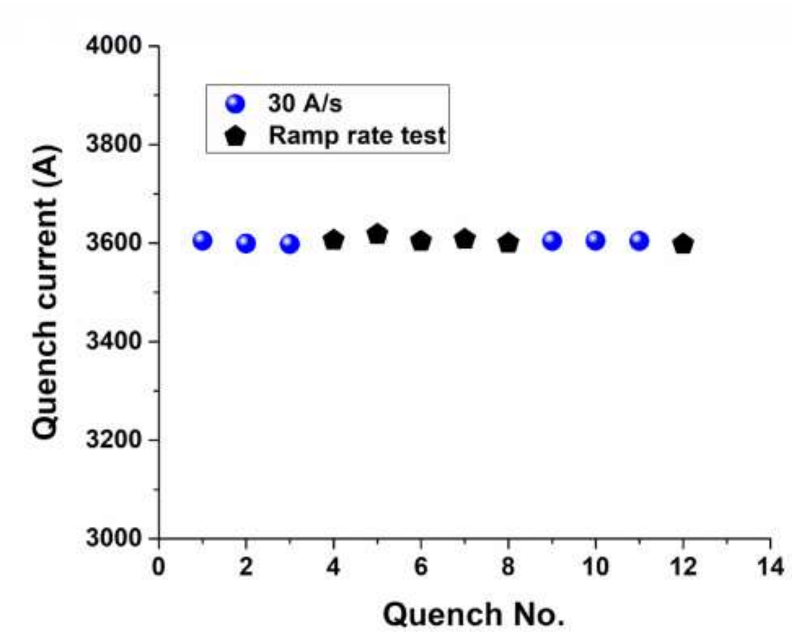
How do we realize the potential of these highly performing materials in magnets?

  - Excellent high field properties
  - No Training!
  - Strain sensitive
  - Highly stable but makes quench detection/magnet protection difficult
  - Expensive

- Bi-2212
  - Complex reaction process
- REBCO
  - Flat, anisotropic tape – field quality, winding
  - Challenging to make high current, windable cables with current sharing

Active R&D programs world-wide but still in a very early stage with respect to accelerator magnet applications

Challenges and lessons of Bi-2212



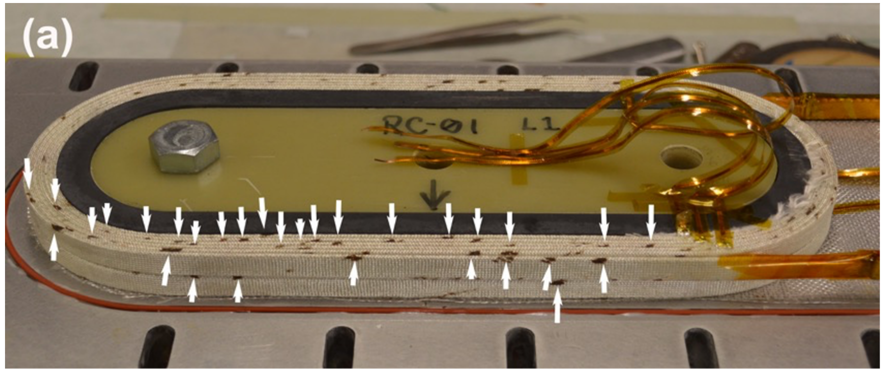
- Highly reproducible performance
  - No degradation due to quenches or thermal cycles
  - No training
  - No thermal runaway due to mechanical disturbances

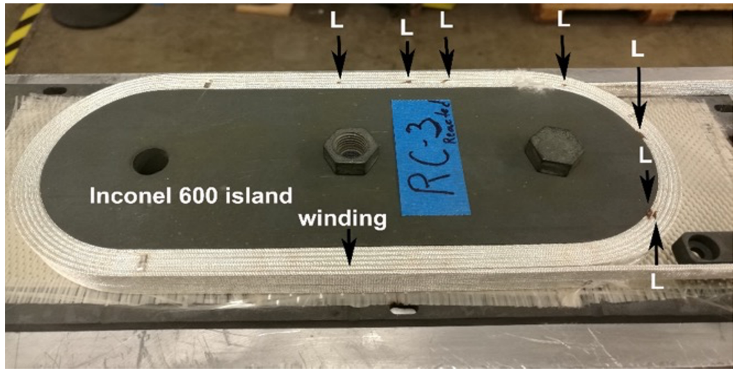
Bi-2212 leakage during reaction

(a) is mullite-only insulation

(b) Addition of TiO_2 reduces leaks

Leakage primarily at edges





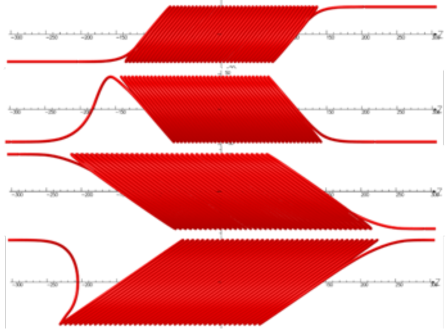
Courtesy Tengming Shen, LBNL

Challenges and lessons of REBCO

CORC® wire conductor configuration

Multi-tape cable. High current, O(10 kA), 4.2 K
Isotropic for magnetics and mechanics

- LBNL C2 REBCO Canted-Cosine-theta
  - 65 mm ID, 127 mm OD, 0.6 m long
  - 3 T designed dipole field at 4.2 K at 6.4 kA
  - Aluminum bronze machined mandrels
  - Painted Stycast after winding
  - Magnet used 100 m long 30-tape CORC® wire
    - *5 km* of 2 mm wide SuperPower tapes with 30 µm substrates
    - 30 mm minimum bending radius



- Thermal runaway observed during test
  - Led to some degradation.

Lesson Learned: With small models you can break it and do it again quickly

Courtesy Xiaorong Wang, LBNL

REBCO demands a totally different approach to accelerator magnets

- Best to avoid quenching
- Persistent currents contribute to field errors and stress but can be controlled.
- HTS magnets can be run over short sample and can be stable up to the point when heating overcomes cooling.
- Stress is concentrated where the current runs, at the edges. This is where degradation starts.

Courtesy Glyn Kirby, Jeroen van Nugteren, CERN

See https://www.researchgate.net/profile/G_Kirby

The LHC High Luminosity Upgrade – A great opportunity to learn

Nothing like a project to push development

- Nb_3Sn
  - High Temperature heat treatment
  - Epoxy impregnation
  - Strain sensitivity implies careful handling and structural loading

- Reaction requires replacing epoxy composite end parts with Al_2O_3 plasma coated stainless steel – more susceptible to shorts and it was found that hi-pot limits used in the R&D program were insufficient for the larger Hi-Lumi quads
- Aluminum shell support structure with non-conformity was used based on previous experience from R&D program – it failed
- In R&D programs and small projects there is no opportunity to get very far up the learning curve, leading to small but sometimes critical, mistakes. The only thing to do is to recover as quickly as possible.

See G. Ambrosio, et al., IEEE Transactions on Applied Superconductivity, Vol. 31, Issue 5, #4001105 (2021)

Courtesy Giorgio Ambrosio, FNAL

Some general lessons

- Simple extrapolation from what was done before doesn’t always work
  - Evaluate each new phase of a program independently
- Always seek out the experts.* They are usually very willing to help.
  - Your problem might already have been solved
- Many critical steps dictate the need for high quality, experienced technicians
  - Do not underestimate this point – (the best plumber doesn’t make the best car mechanic)
  - Trust them and include them in every aspect of the project they are involved in
  - Give them responsibility and they will accept accountability
  - Acknowledge them

*Someone who has made more mistakes than you

Acknowledgment

Many thanks to . . .

- Shlomo Caspi, Dan Dietderich, Paolo Ferracin, Ian Pong , Tengming Shen, Xiaorong Wang – Lawrence Berkeley National Laboratory
- Emanuela Barzi, Giorgio Ambrosio, Alexander Zlobin, Fermi National Accelerator Laboratory
- Bernhard Auchmann, PSI
- Helene Felice, Glyn Kirby, CERN