U.S. MAGNET DEVELOPMENT PROGRAM

CCT Magnet Development: Results and Next Steps

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Outline

- Short review of the original MDP plans related to the Canted Cos-Theta concept
- Review of main CCT design features
- Overview of CCTs tested to-date
- Design details and test results of CCT4
- Lessons-learned and design modifications of CCT5
- Test results of CCT5
- Lessons-learned and development of subscale CCTs
- HTS developments
- Summary

The program has been structured to align with the primary goals

Magnets	Lead
Cosine-theta 4-layer	Sasha Zlobin
Canted Cosine theta	Diego Arbelaez
Bi2212 dipoles	Tengming Shen
REBCO dipoles	Xiaorong Wang

Area I

Area II

Technology area	LBNL lead	FNAL lead
Modeling & Simulation	Diego Arbelaez	Vadim Kashikhin
Training and diagnostics	Maxim Martchevsky	Stoyan Stoynev
Instrumentation and quench protection	Maxim Martchevsky	Thomas Strauss
Material studies – superconductor and structural materials properties	Ian Pong	Steve Krave

Area III

Cond Proc and R&D	Lance Cooley

Area IV

US Magnet Development Program (MDP) Goals:

GOAL 1:

Explore the performance limits of Nb_3Sn accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

GOAL 2:

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

GOAL 3:

Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

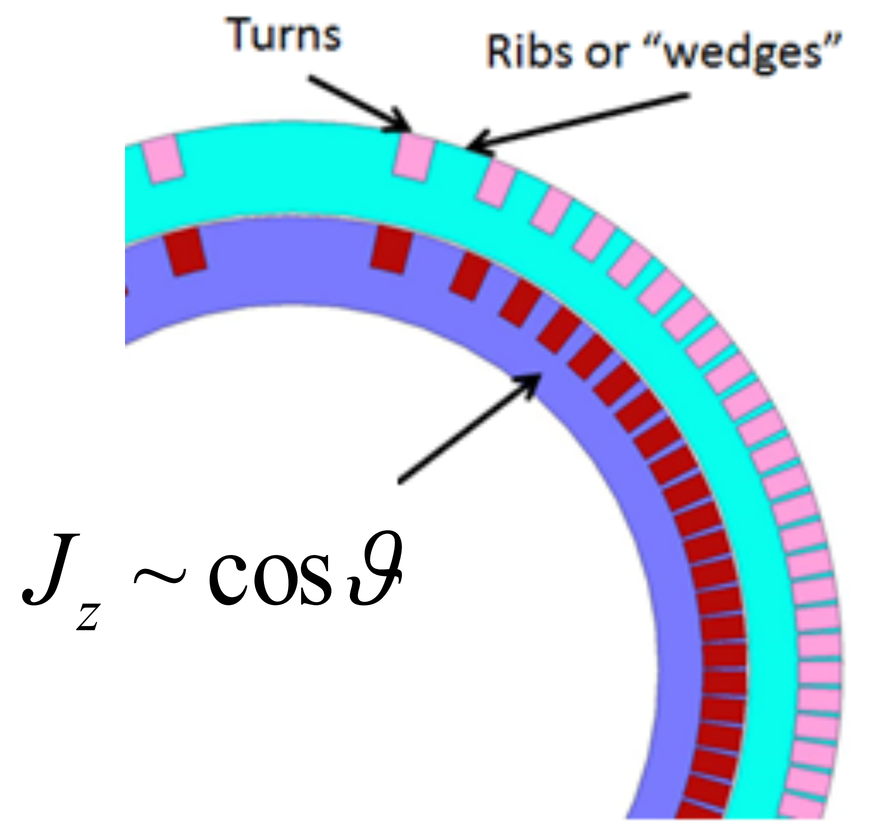
GOAL 4:

Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

Recap of the "CCT concept" and motivation for its investigation

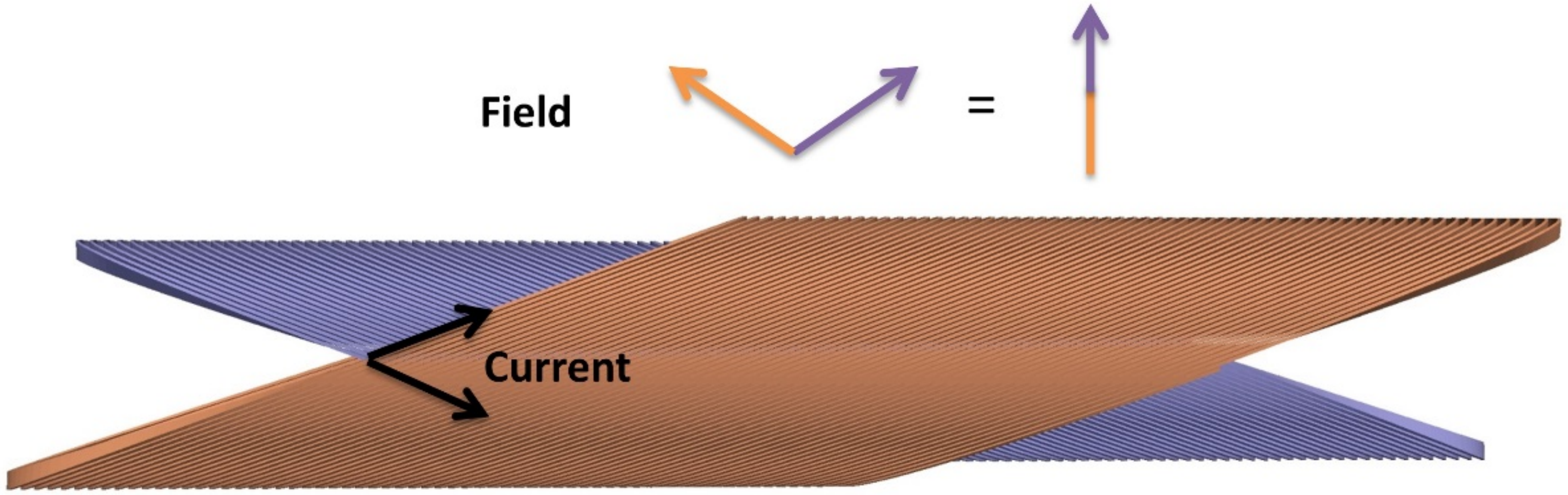
- "Canted" windings in opposing directions produce dipole field (excellent field quality)
  - Solenoidal field components cancel (cost efficiency)
- Windings are placed in a mandrel with grooves - Ribs in mandrel intercept Lorentz force leading to substantially reduced azimuthal stress –limiting case of "stress management"
- Ease of fabrication and minimal tooling can lead to reduced cost
- Fabrication methods and modularity of approach leads to natural extension for HTS materials

Ribs Intercept Lorentz Force



Transverse current density with cos-theta distribution approaches a perfect dipole current density distribution

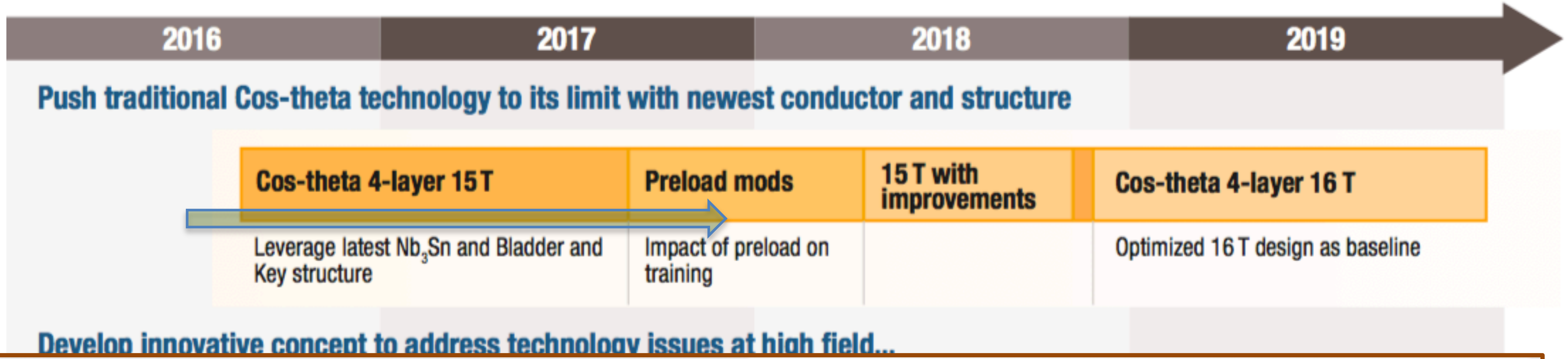
Winding Geometry

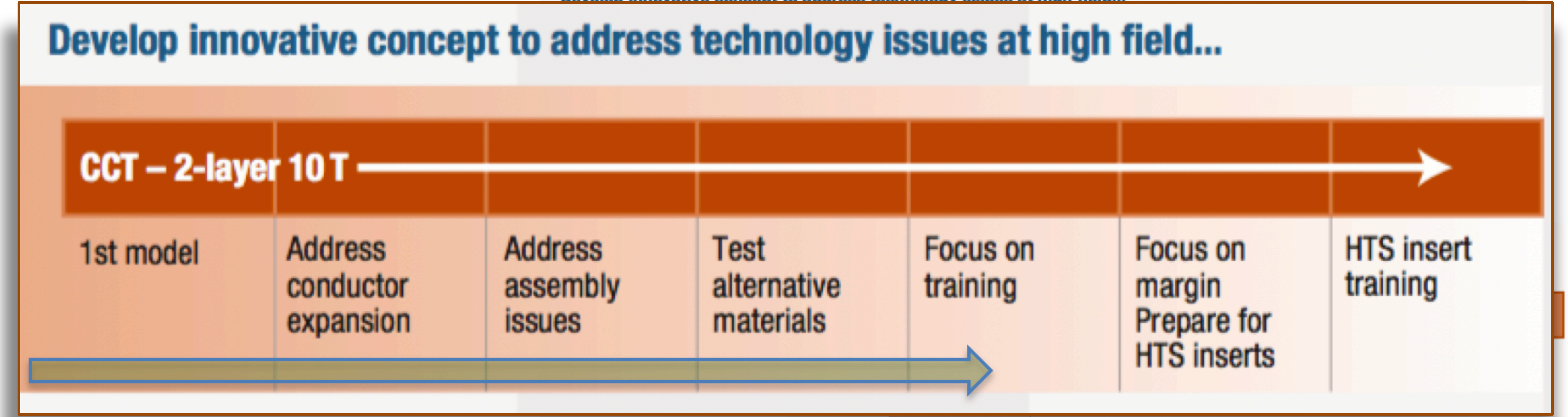


The MDP Nb3Sn magnet efforts had a two-pronged approach, based on ongoing efforts at the time and limited funding of the program

Area I: Nb_3Sn magnets

- Our focus has been on:
  - The Cos-t demonstrator
  - Investigation of the CCT concept



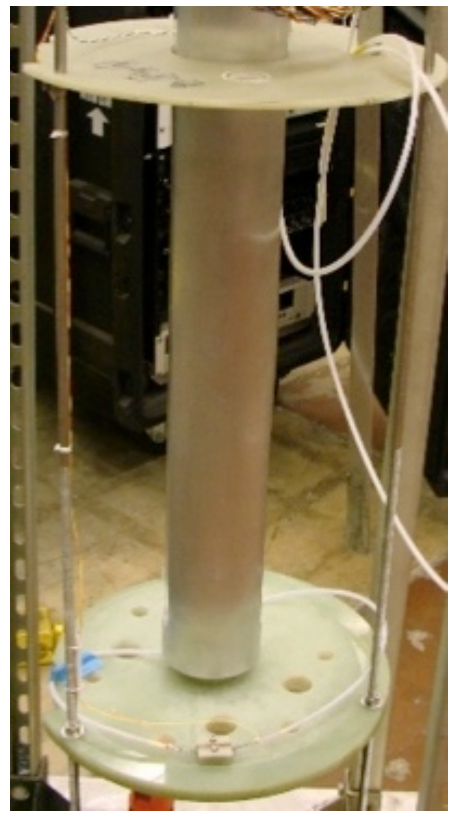


A systematic process was undertaken to develop the CCT technology

CCT1

- 2.5 T short-sample dipole
- 50 mm clear bore
- 8 strd. NbTi cable
- not impregnated
- 11/2013: ***tested up to 2.5 T***

CCT1

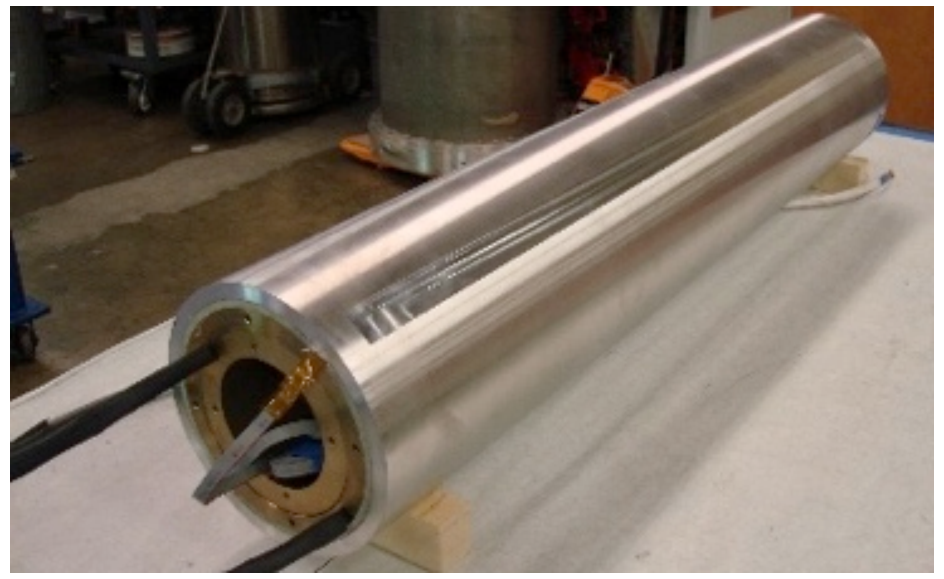


NbTi

CCT2

- 5.3 T short-sample dipole
- 90 mm clear bore
- 23 strd. NbTi cable   (0.8 mm SSC Inner)
- epoxy impregnated
- 5/2015: **tested up to 4.7 T**

CCT2



CCT3/4

- 10.5 T bore field at round wire short-sample (RRP 54/61)
- 90 mm clear bore
- CCT3 03/2016: **reached bore field=7.4 T (conductor damage)**
- CCT4 08/2017: **reached bore field=9.1 T (substantial training)**

CCT3/4

Nb_3Sn

CCT5

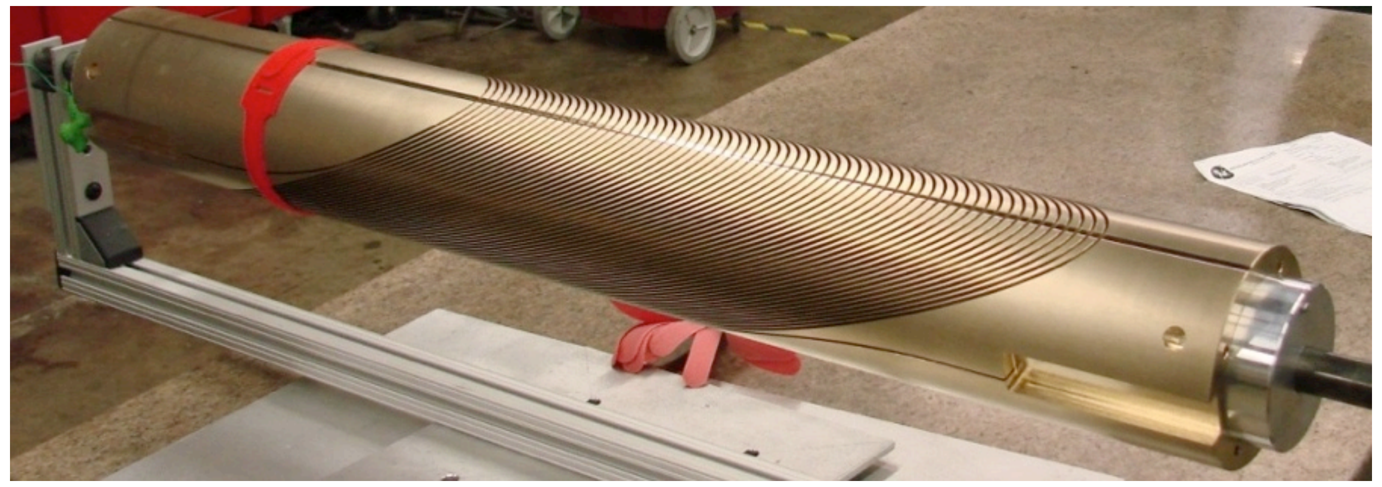
9.7 T bore field at round wire short-sample (RRP 108/127)

- 90 mm clear bore
- 10/2018: Achieved 8.51T (87.7% short-sample)
- Still substantial training, but improved from CCT4

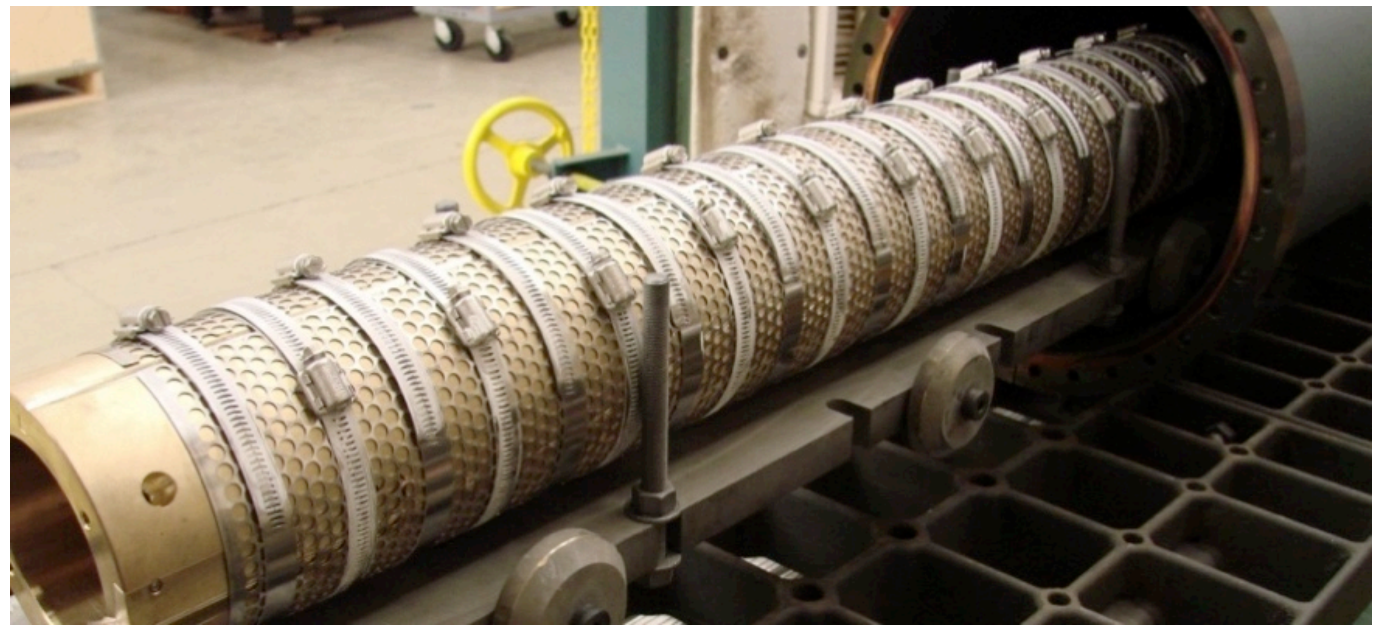
CCT4 further developed Nb_3Sn CCT techniques and tooling

- Aluminum Bronze mandrels incorporate features for stress management and cable positioning
- Minimal tooling is required for heat treatment and epoxy impregnation

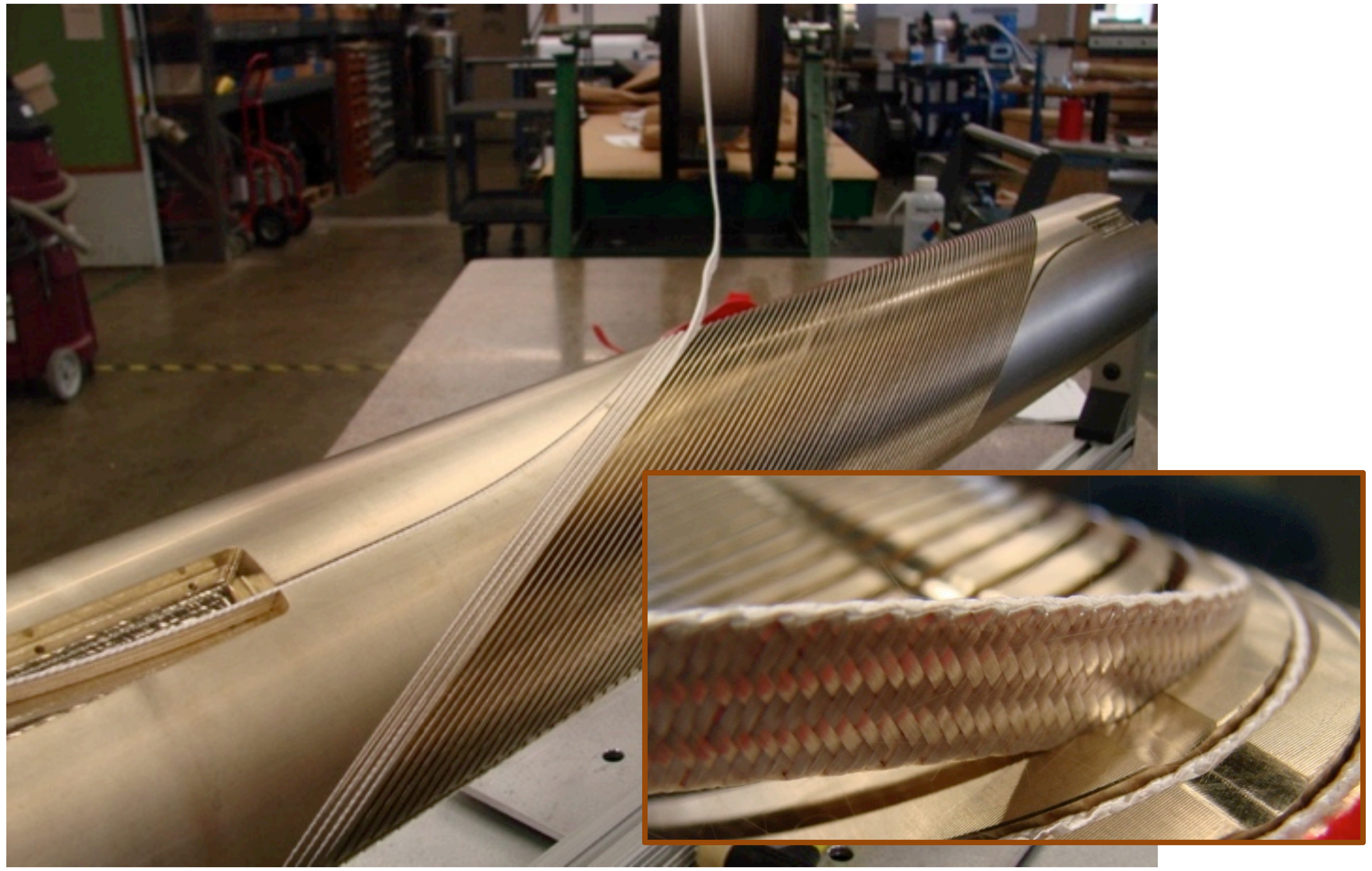
Machined Mandrel



Heat Treatment with SS Sheet and Clamps



Coil Winding

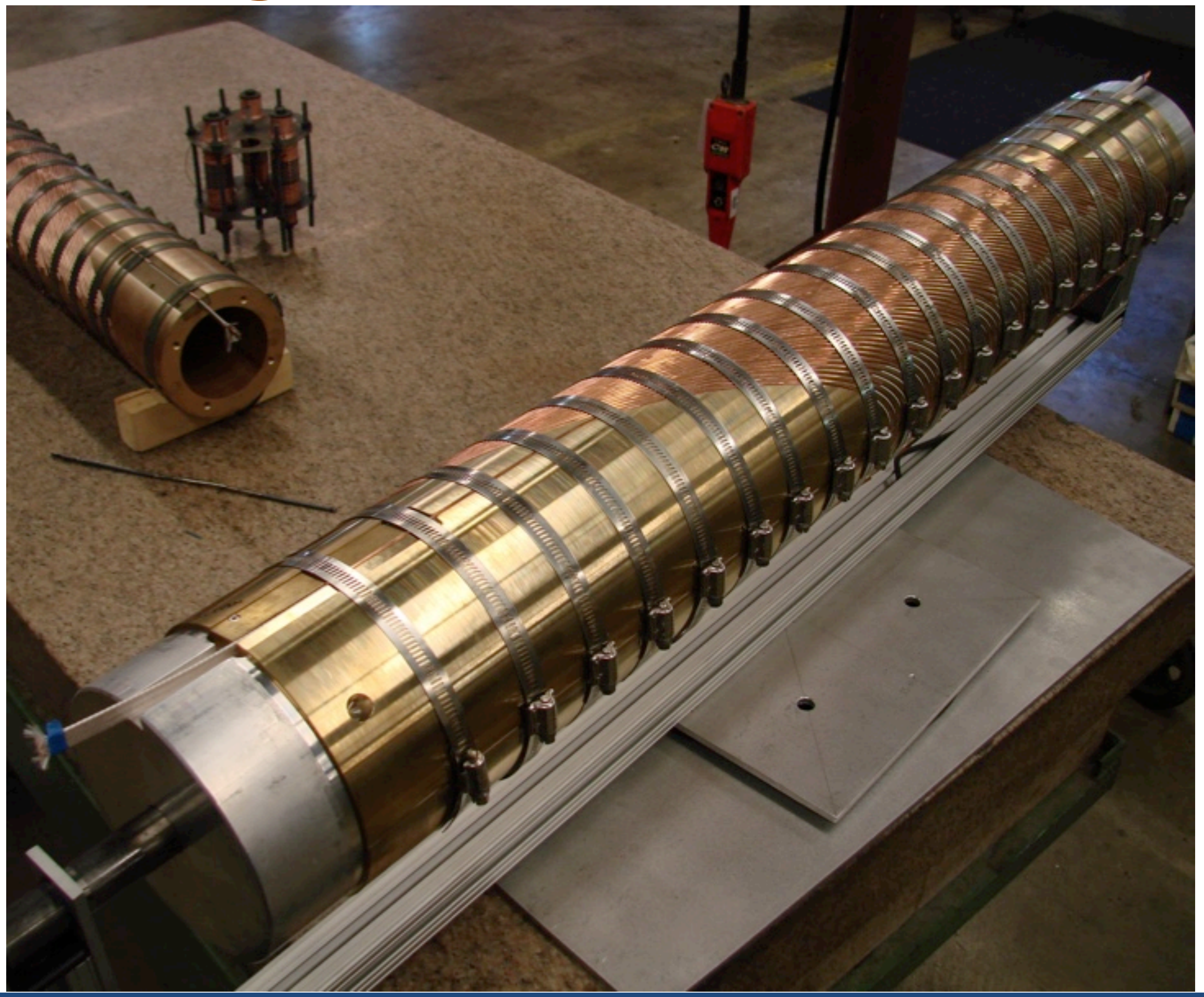


Coil Impregnation

CCT4 – Heat Treatment and Assembly

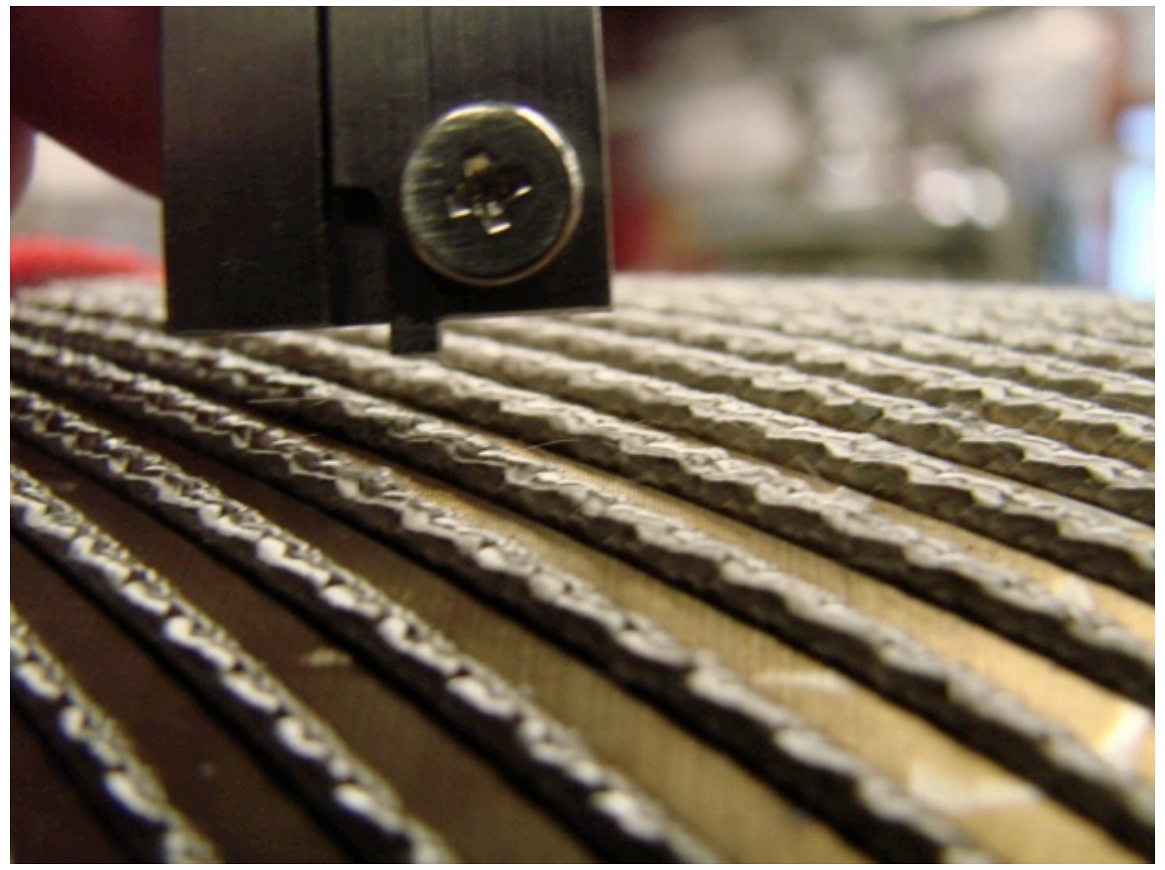
- Copper wire is used to force the cable to the bottom of the channel
- Mandrel is secured with hose clamps
- Cable is below mandrel surface after heat treatment
- Layers are wrapped with G10 sheets and inserted into the outer layer and shell

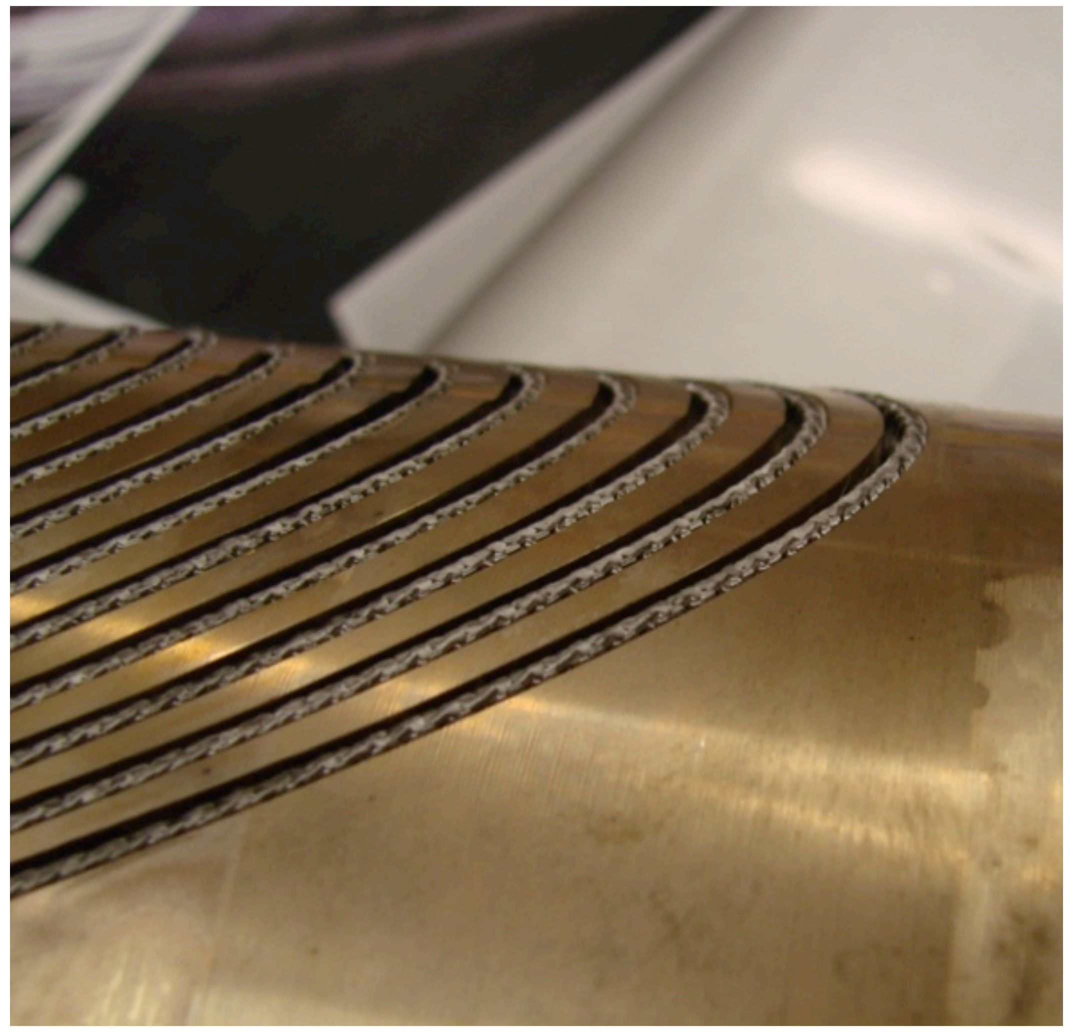
CCT4 Heat Treatment Configuration



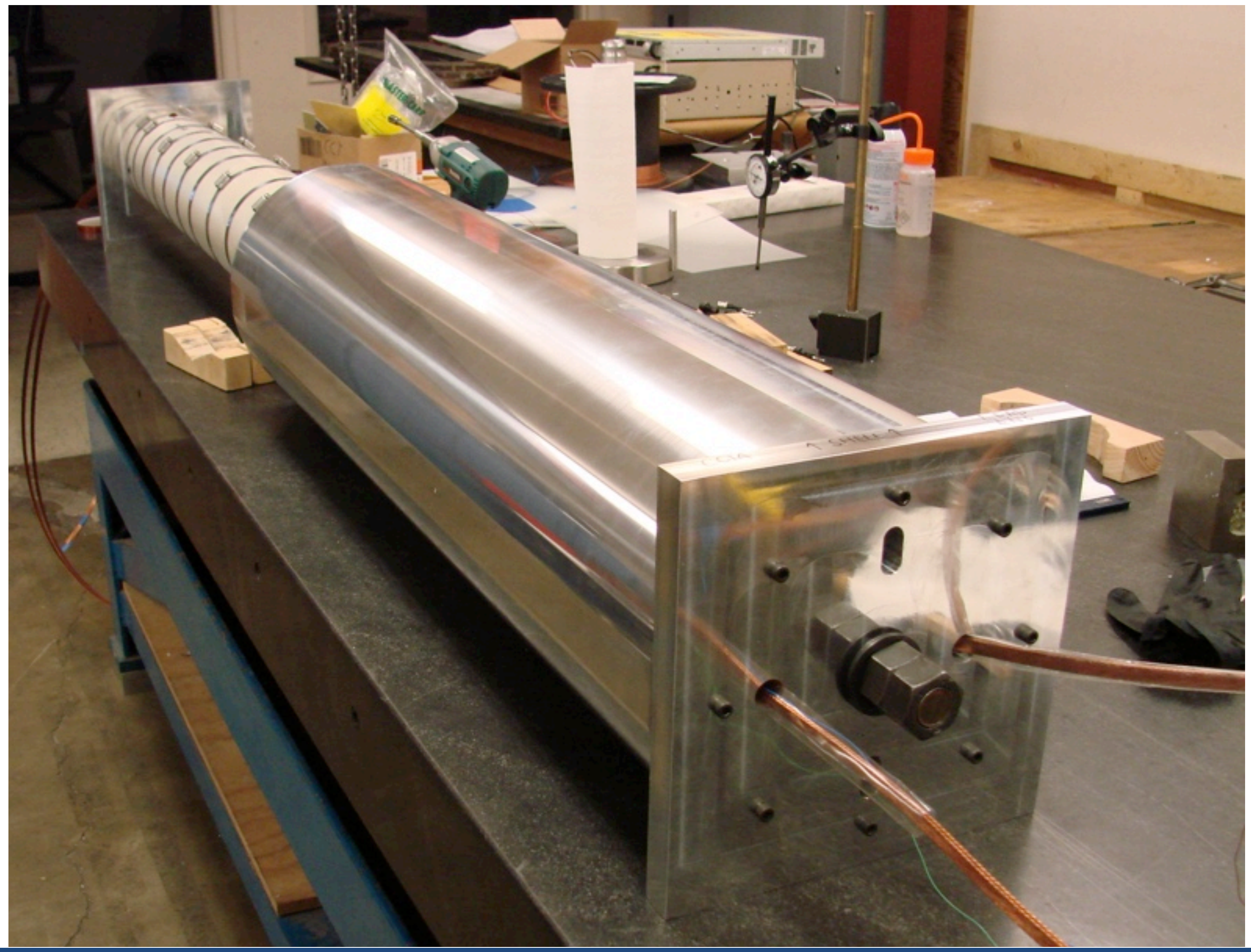
Cable Position After Heat Treatment

CCT3 → **CCT4**





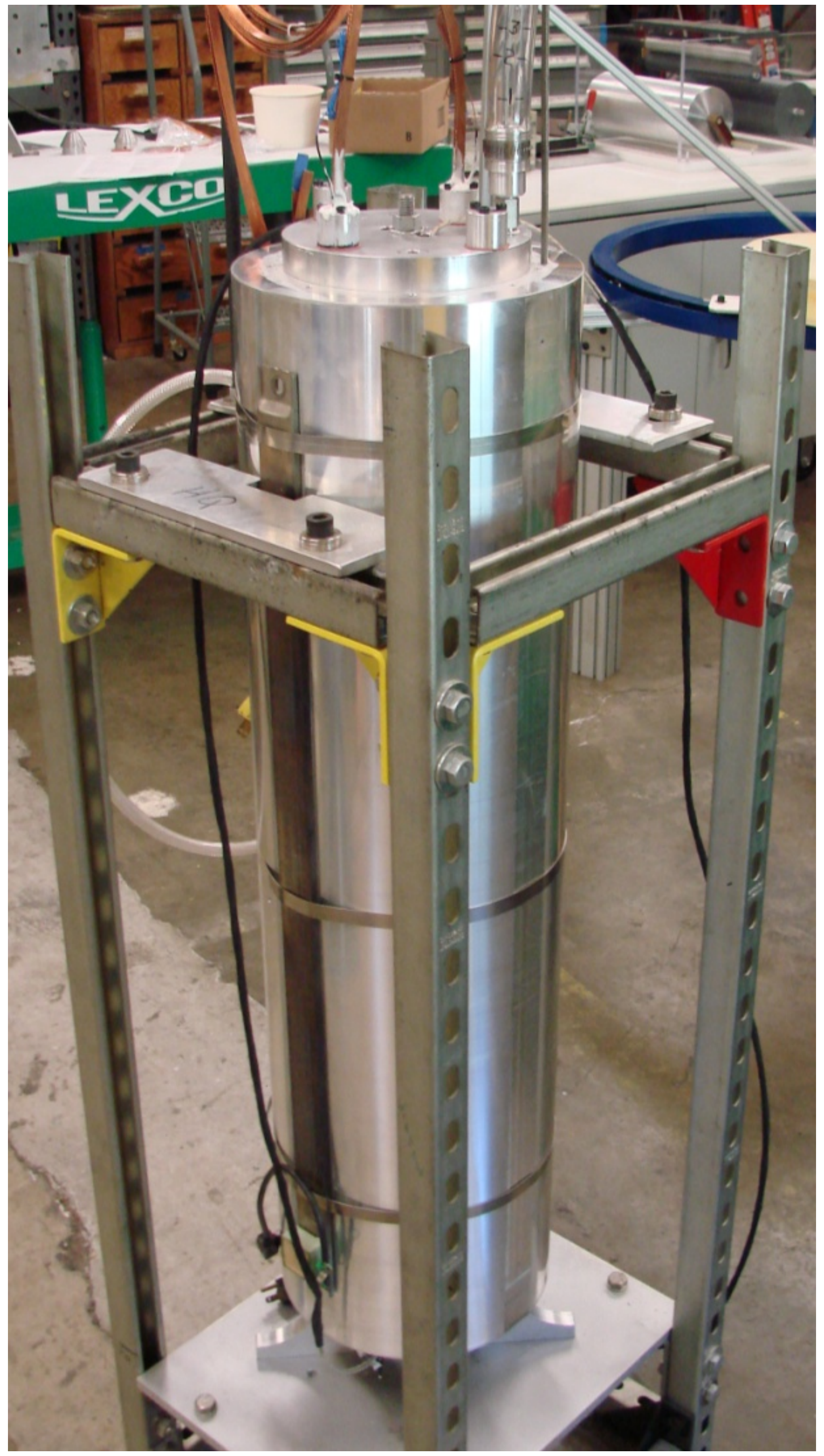
CCT4 Assembly



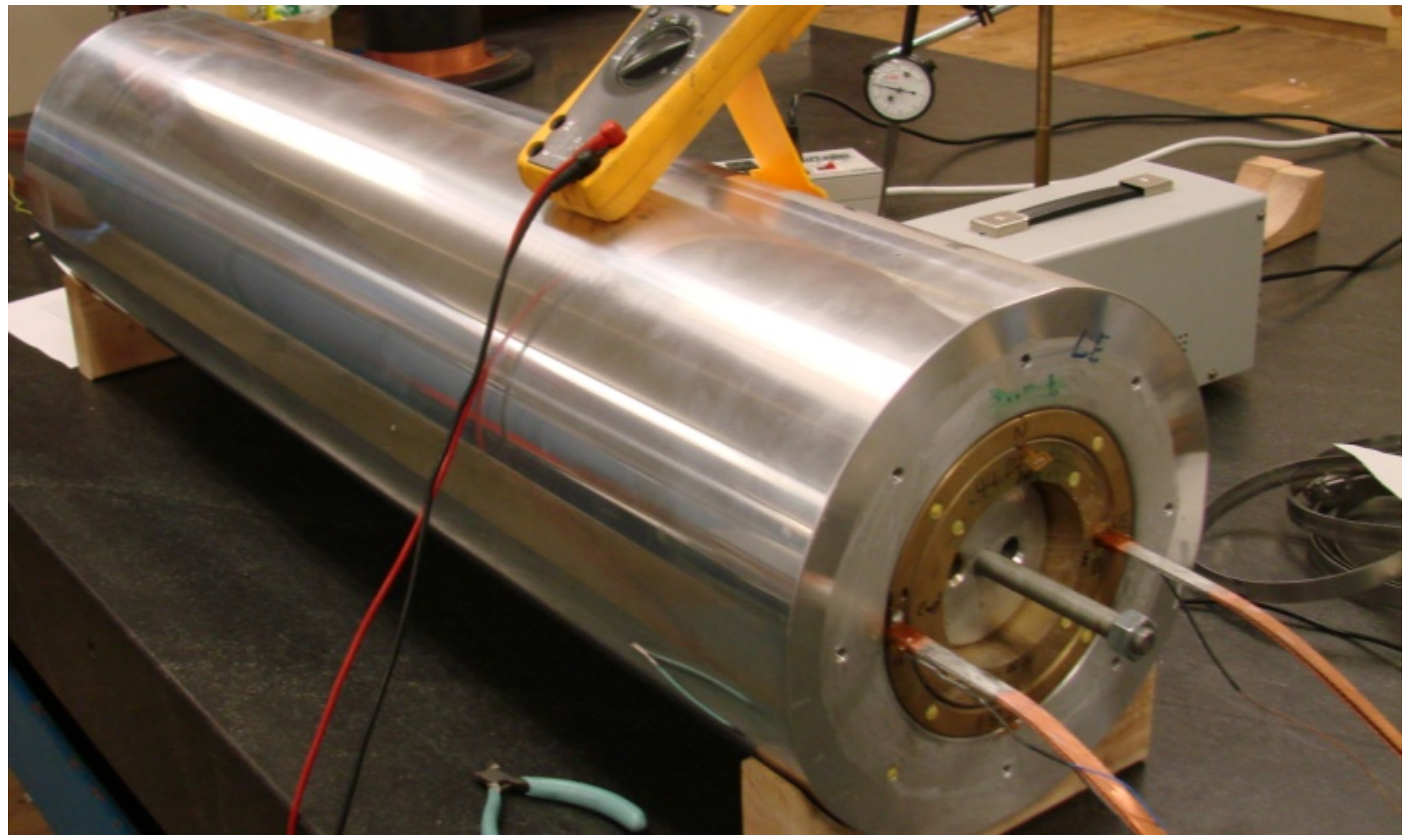
CCT4 Magnet Impregnation with simple tooling

- Coils and shell assembly is impregnated with epoxy
- Simple tooling is used to create a seal from the bore to the ends of the shell
- Inside of outer layer and shell were mold-released to avoid energy release from delamination at the interfaces
- Next Step: Development of individual layer potting and assembly is under way

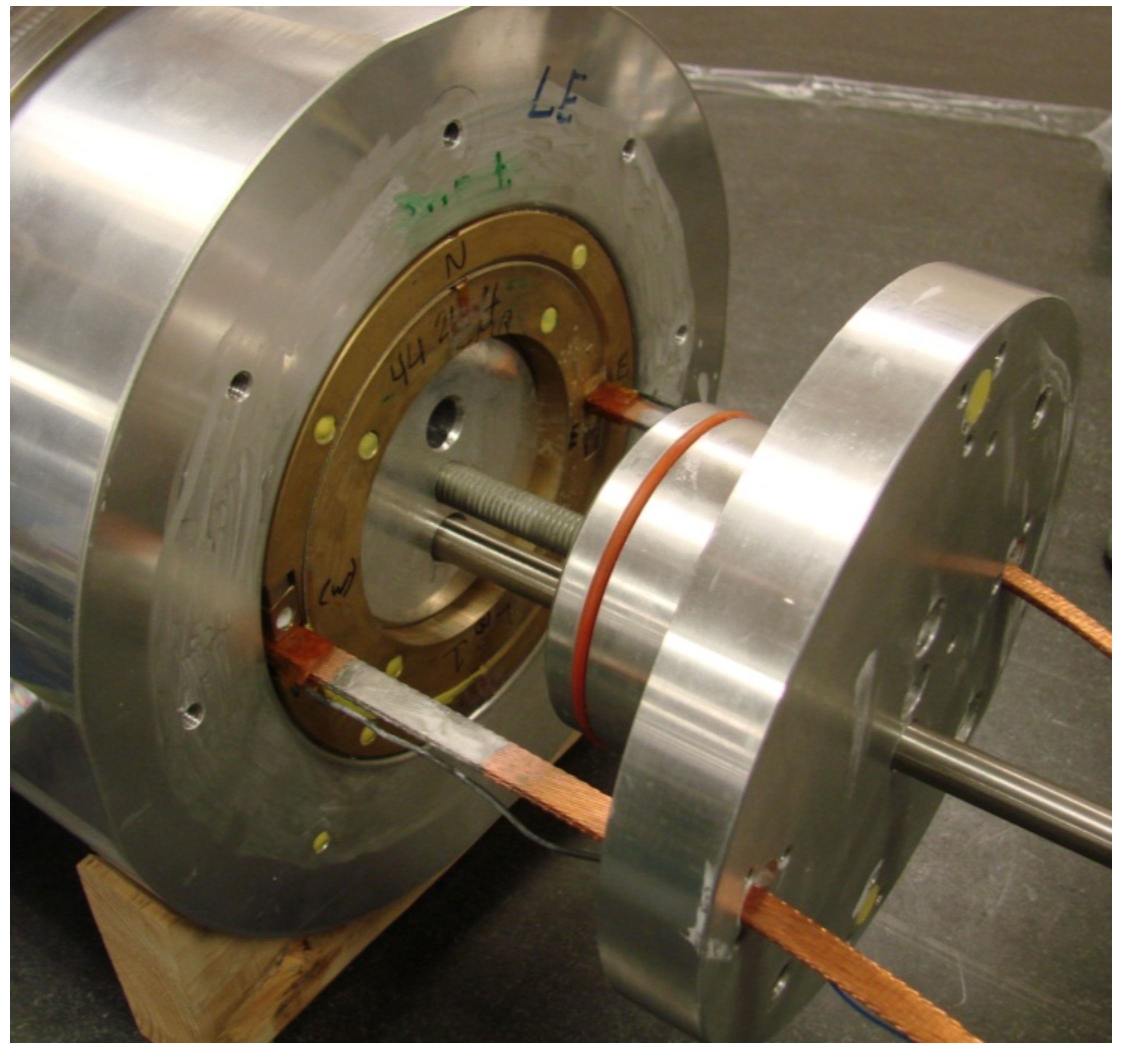
Potting Assembly



CCT4 Coil Assembly



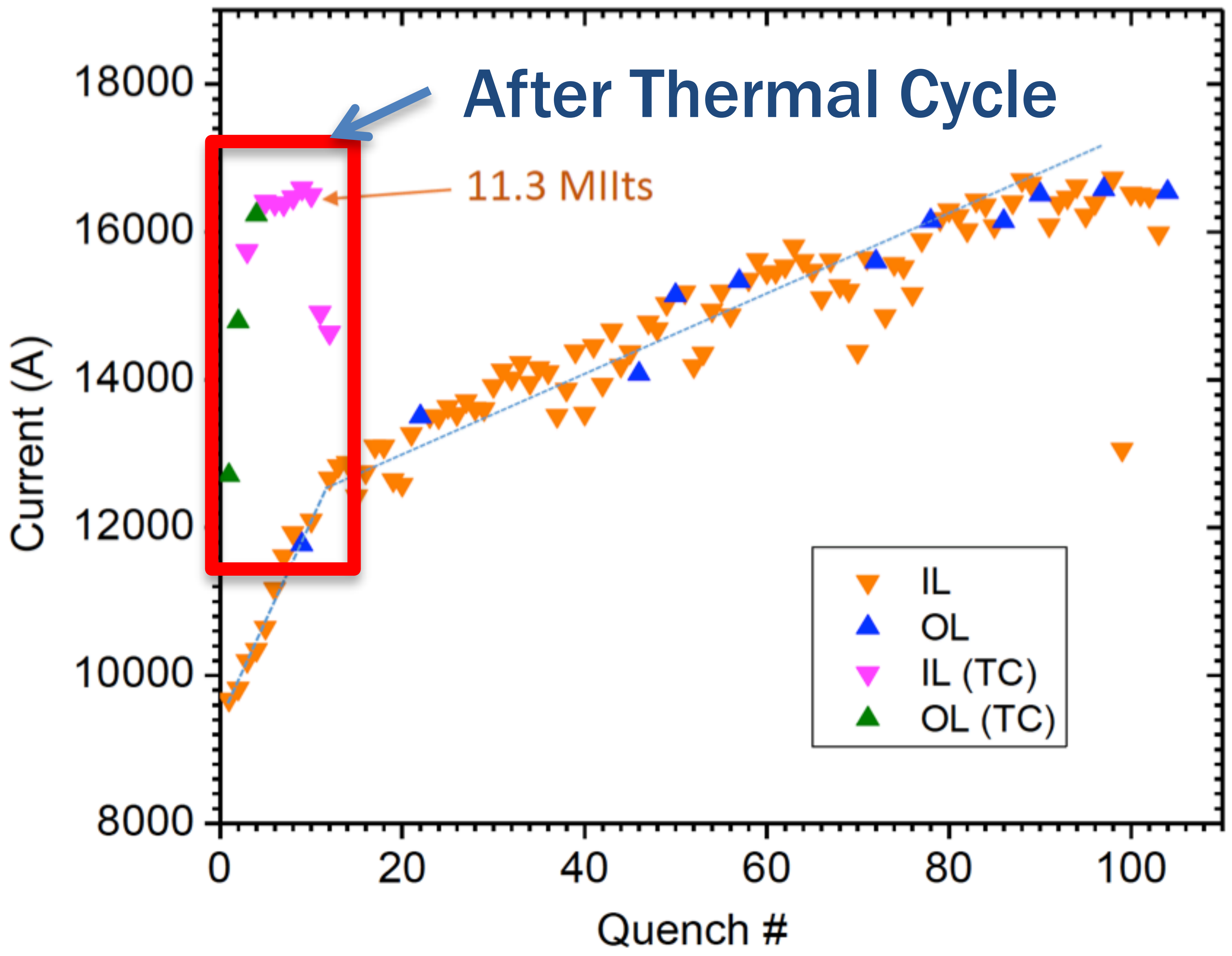
Sealing End Caps

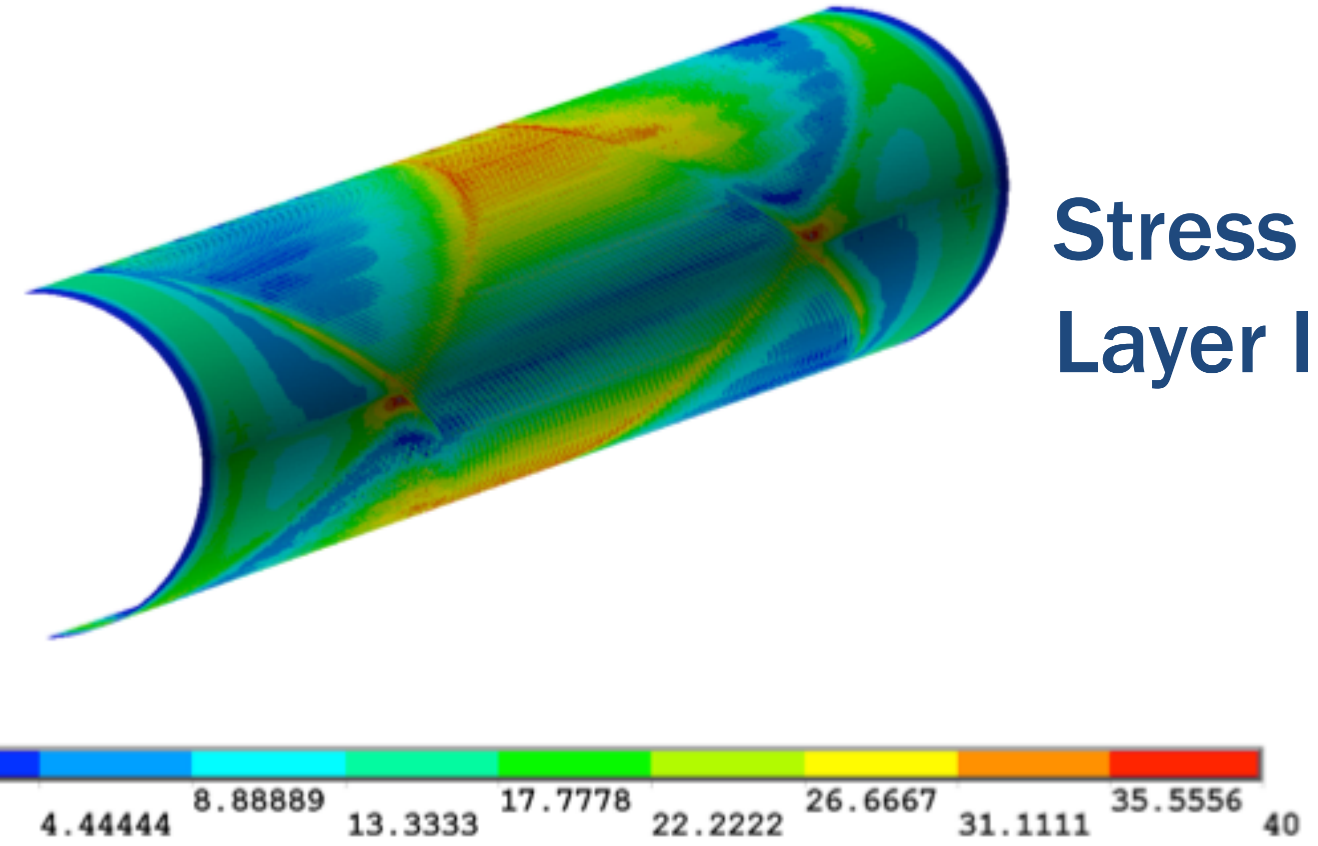


CCT4 Results Lead to Focus on Training Reduction for CCT5

- Reached 86% of round wire short sample after 85 quenches
- Maximum current is 16.7 kA
- Maximum bore field is 9.14 T (90 mm aperture)
- Magnet exhibits long training but good memory after thermal cycle

CCT4 Training Behavior





Stress at Layer-to-Layer Interface

Lessons-learned

- Two “regimes” of training, and acoustic signal analysis, suggest epoxy micro-cracking may be source of early quenches
- Interface between layers, and between outer layer and shell, complicate assembly and inhibit disassembly/reassembly

CCT5 design incorporates a number of modifications based on lessons—learned from CCT4

CCT3=>CCT4

- Modifications focused on mitigating conductor damage

CCT4=>CCT5

- Modifications focused on addressing training, assembly improvements

	CCT3	CCT4	CCT5
Bore size [mm]	90	90	90
Groove design	constant width	1.25 mm gap at pole	1.65 mm gap at pole
Conductor	RRP 54/61 Ta doped	RRP 54/61 Ta doped	RRP 108/127 Ti doped
HT Temp [C]	650	660	665
Potting configuration	full magnet	full magnet	individual layers
Epoxy	CTD-101K	CTD-101K	FSU Mix 61
Layer-to-layer interface	bonded	mold released	bend & shim

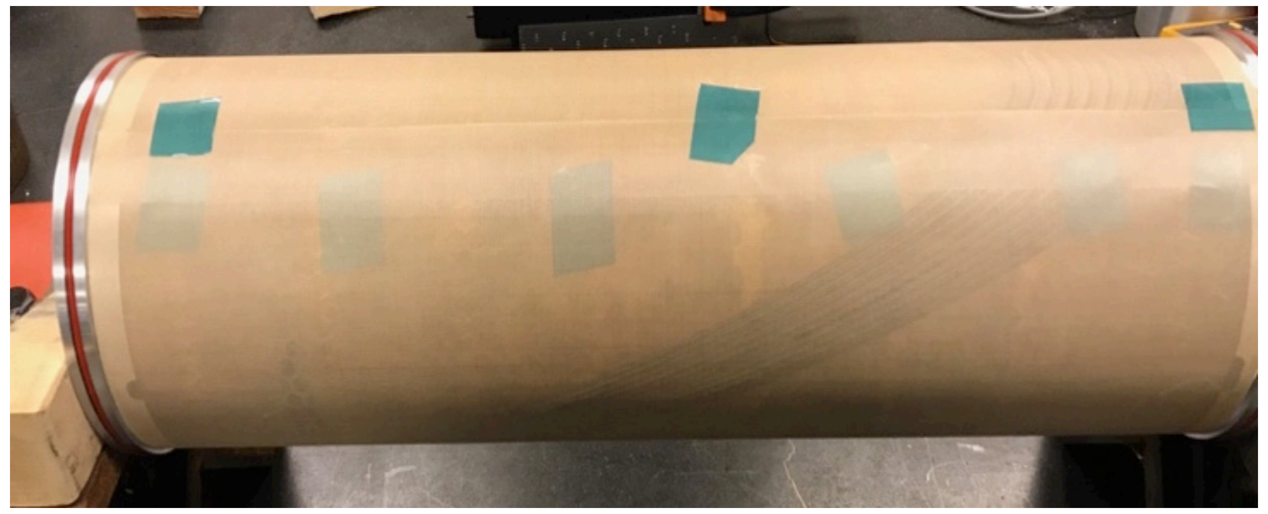
- Conductor damage
- Field quality
- Cost and scalability
- Training

Potting of Individual Layers opens up design space

- **Motivation**
  - **Individual potting of layers is desirable since magnet can be assembled and disassembled after testing**
  - **Faster turnaround for R&D if only one layer needs to be fabricated**
  - **Damaged or problematic layer can be replaced**
  - **Layers can be reused for a four or more layer magnet**

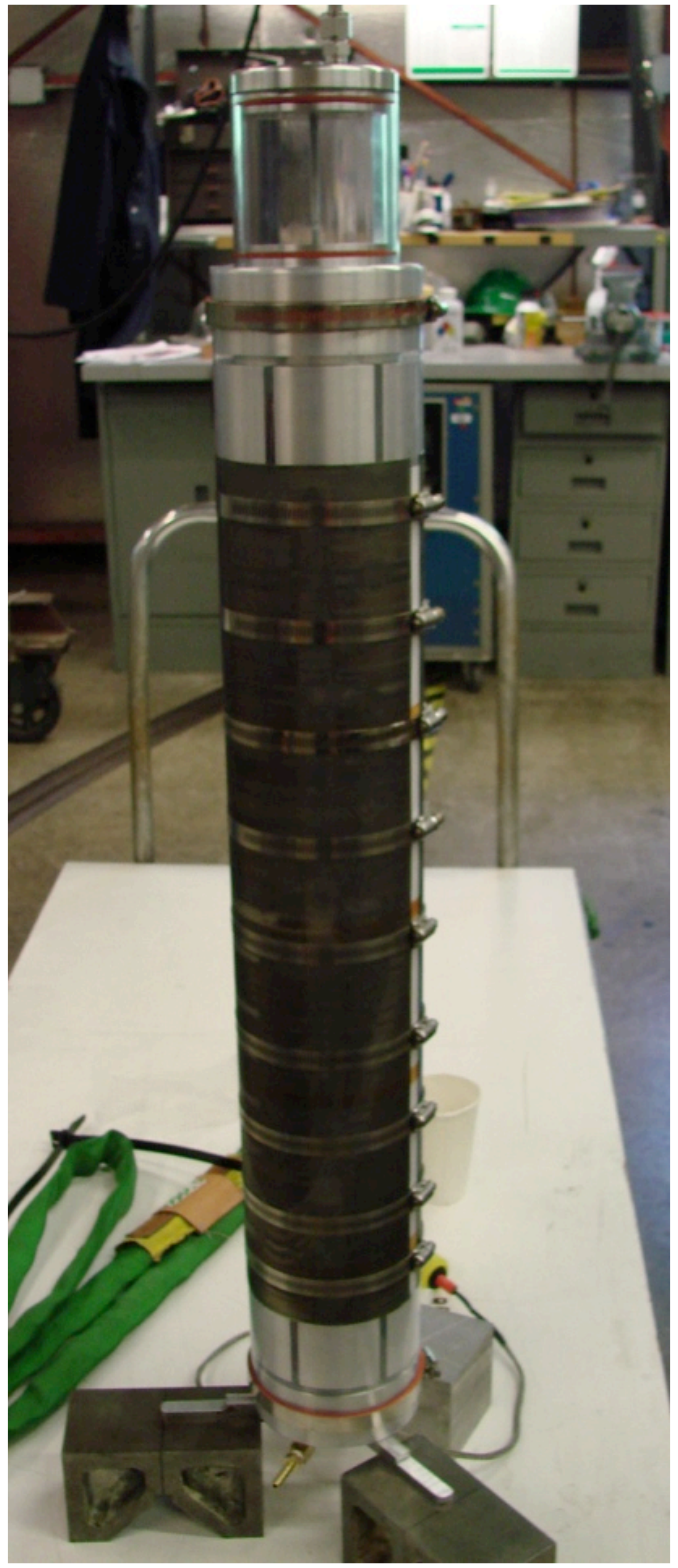
Sealing end Caps are the only non-consumable component

Release Film Leaves Clean Surface



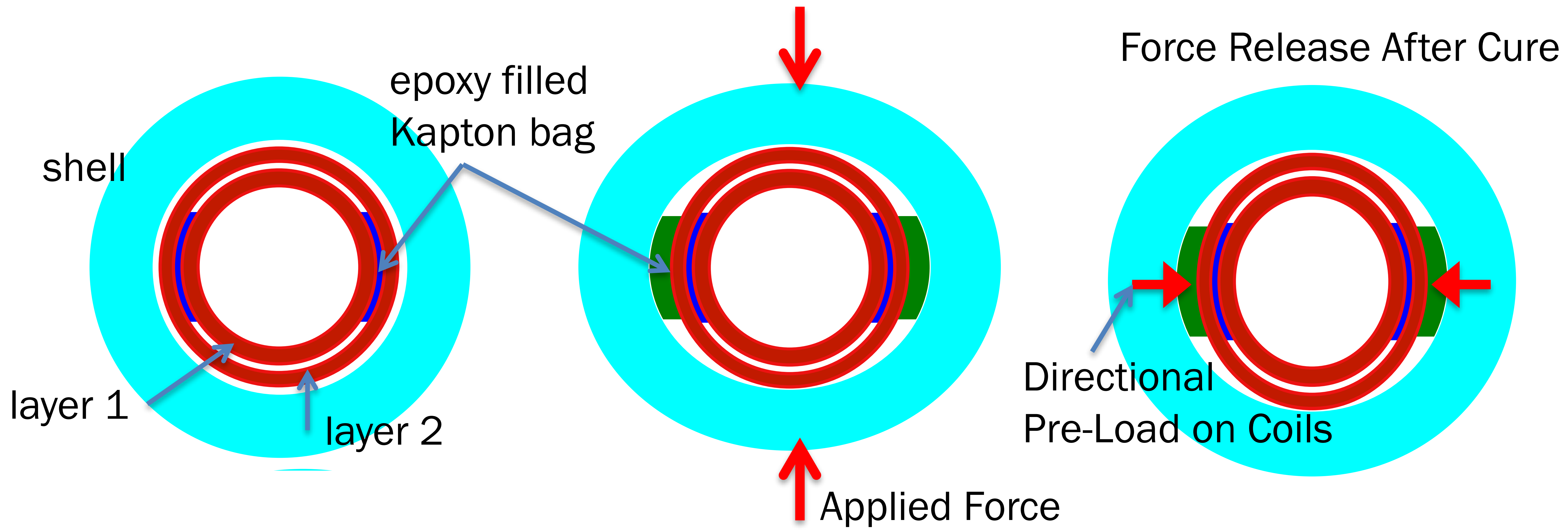
Porous Flow Media for Epoxy Flow

Shrink Tube Method

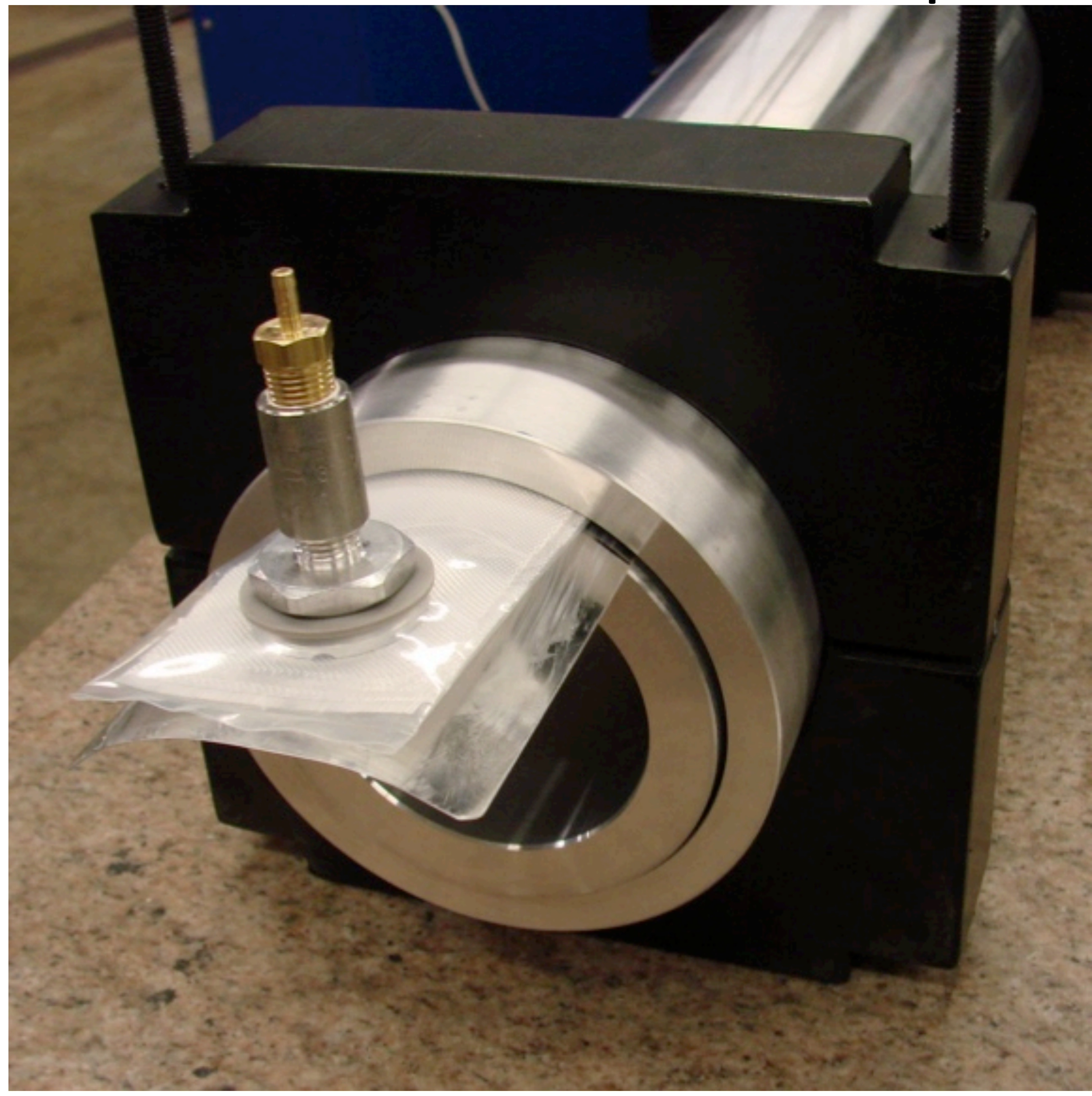


Separately-potted layers enables/requires mechanical coupling of system: “Bend and Shim” Method for Coupling Layers

- Contact location between layers is controlled by using shims and Kapton bags that are filled with glass and epoxy
  - Allows for control of contact location
  - Fracture in interface epoxy does not propagate to the coil
  - Improved cooling at the pole regions from direct contact with LHe
- Directional preload to reduce energized stress can be applied by bending layers or shell, filling and curing epoxy in bent state, releasing bending pressure



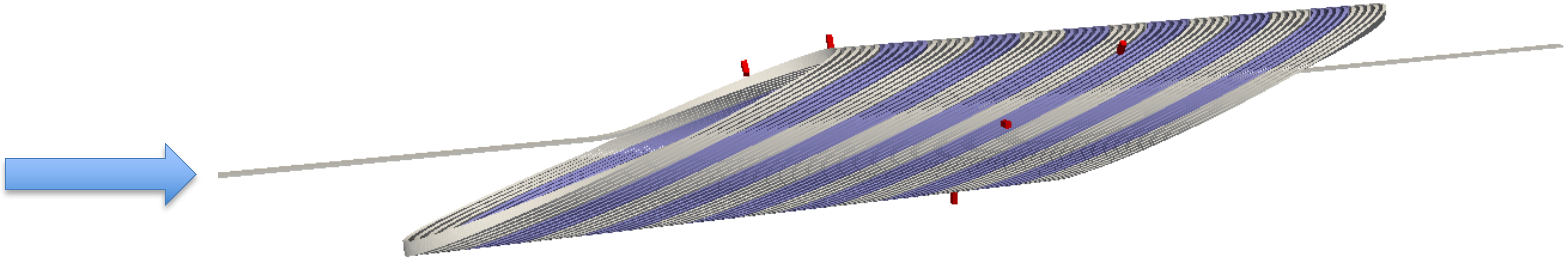
“Conformable” shim developed



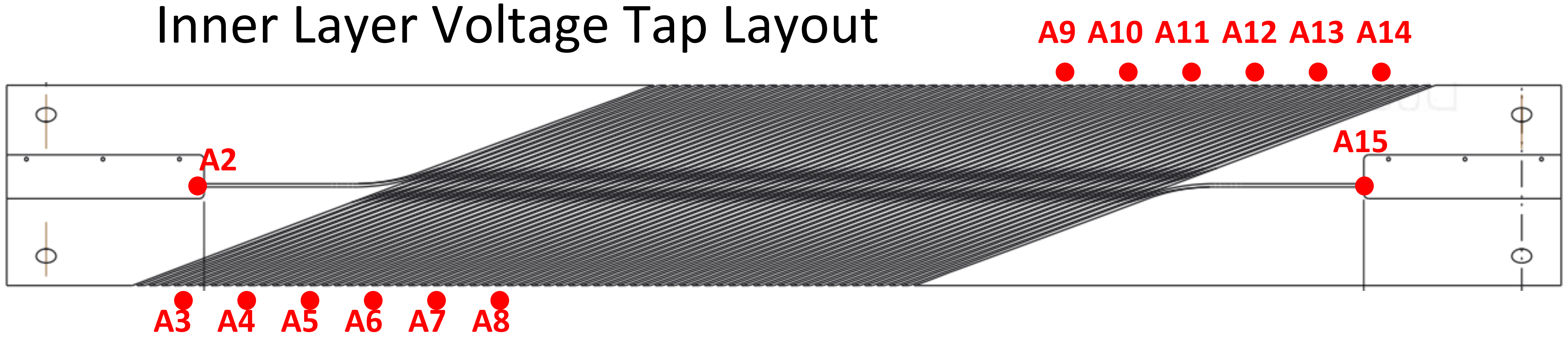
CCT5 Instrumentation includes mix of “old” and “new” diagnostics

•Voltage taps at every 5th turn in inner layer (sparse on outer layer)
•Acoustic sensors at coil ends and inside of the bore (new development)
•Strain gages on shell
•Spot heater with associated voltage taps and thermometer in groove

Quench Localization With Acoustic Sensors

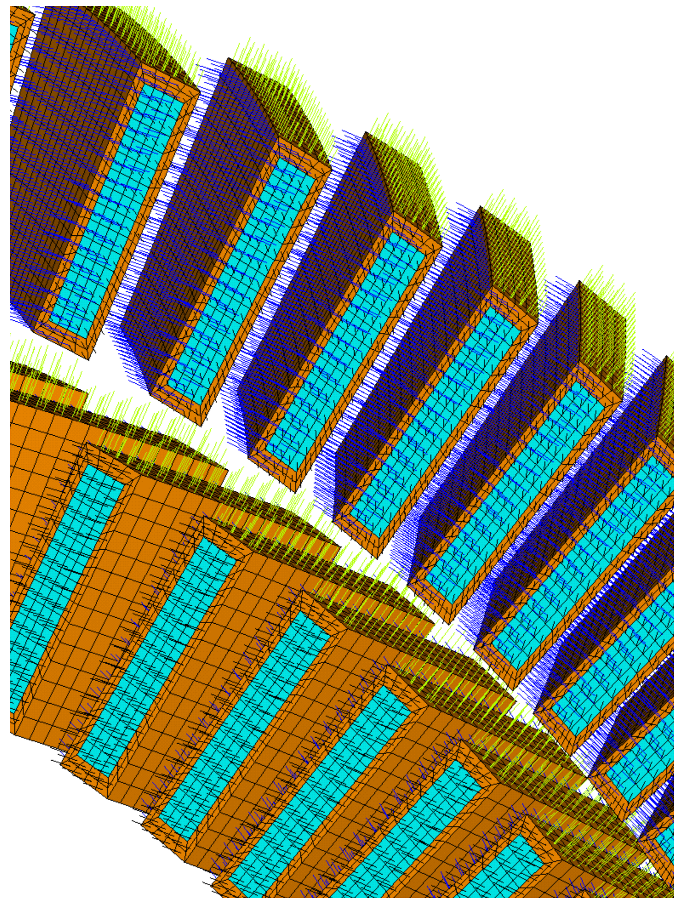


Inner Layer Voltage Tap Layout

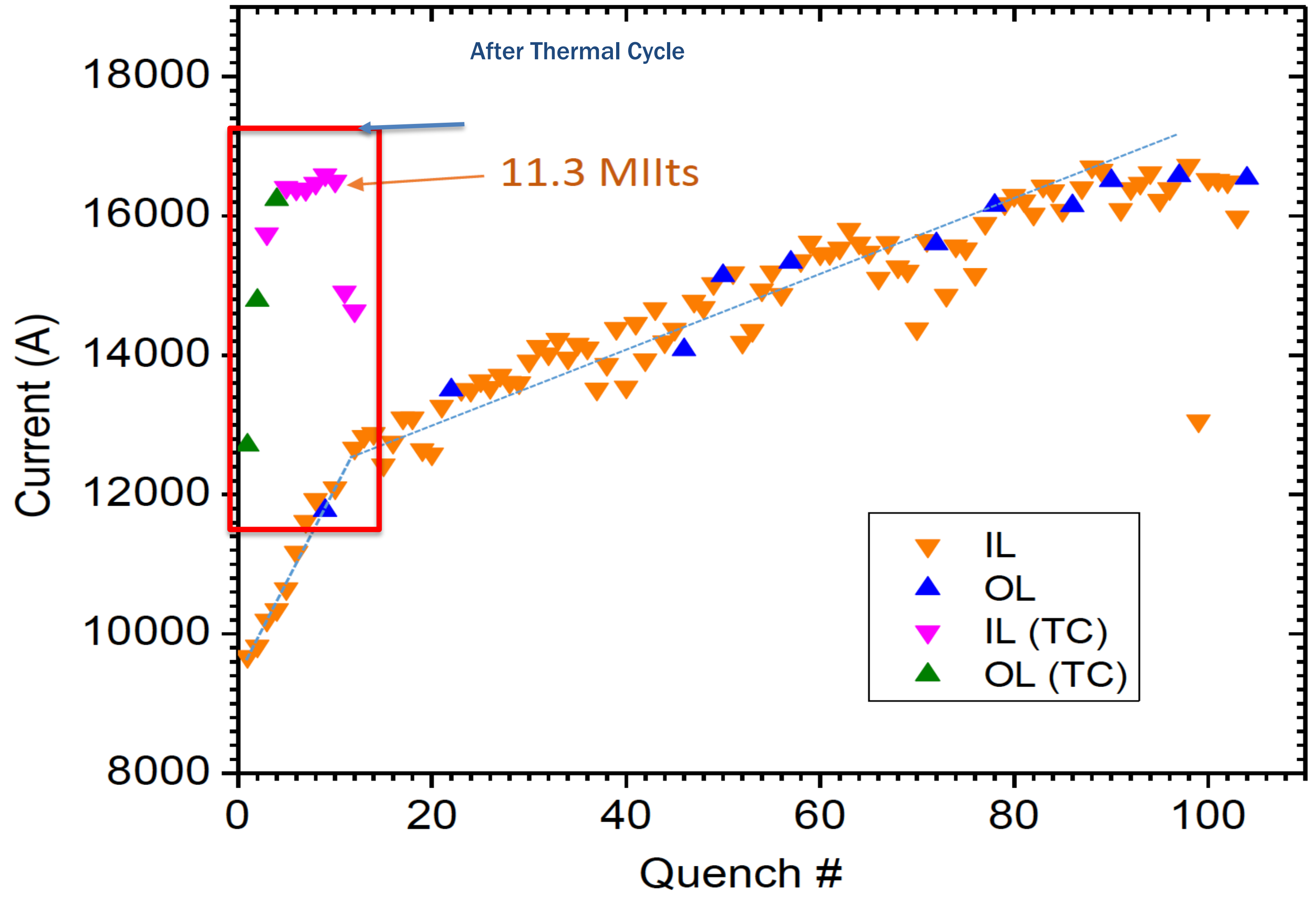


CCT5 Shows Initial Improvement in Training Followed by Similar Behavior to CCT4

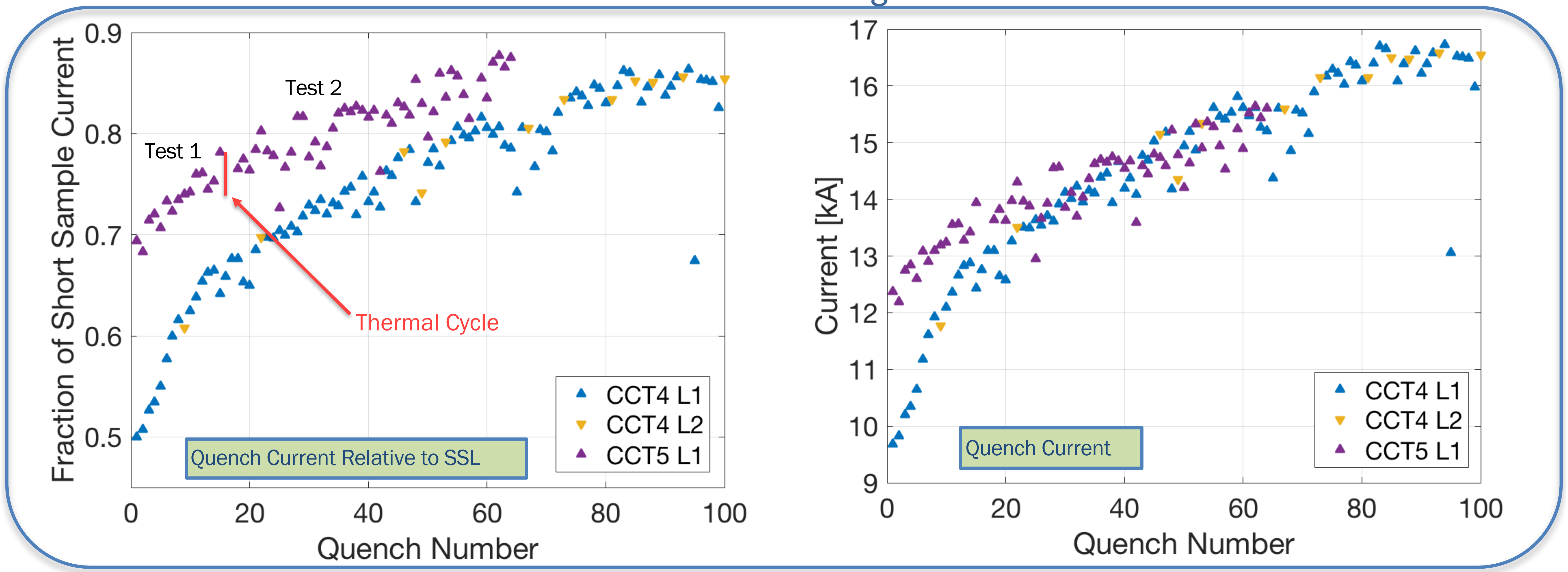
- CCT4 conductor has higher Ic (CCT4: 54/61 RRP, CCT5: 108/127 RRP)
- First quench at 69% of short sample, magnet reached 88% of short sample after 59 training quenches
- After initial improvement training rate is similar to CCT4
- After approx. quench #20 there are many detraining quenches with large drops in quench current (similar to CCT4 after approx. quench #30)



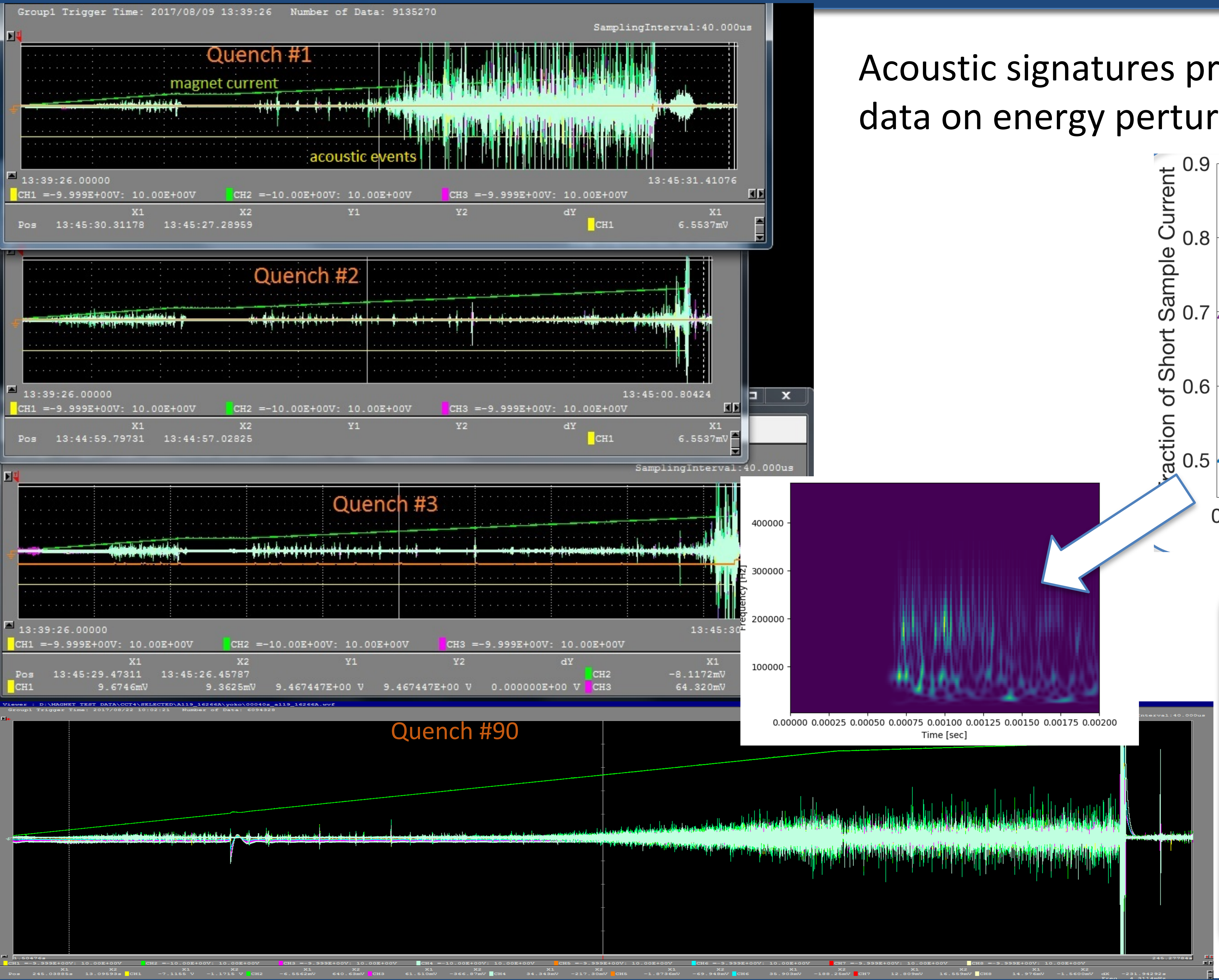
CCT4 Training Behavior



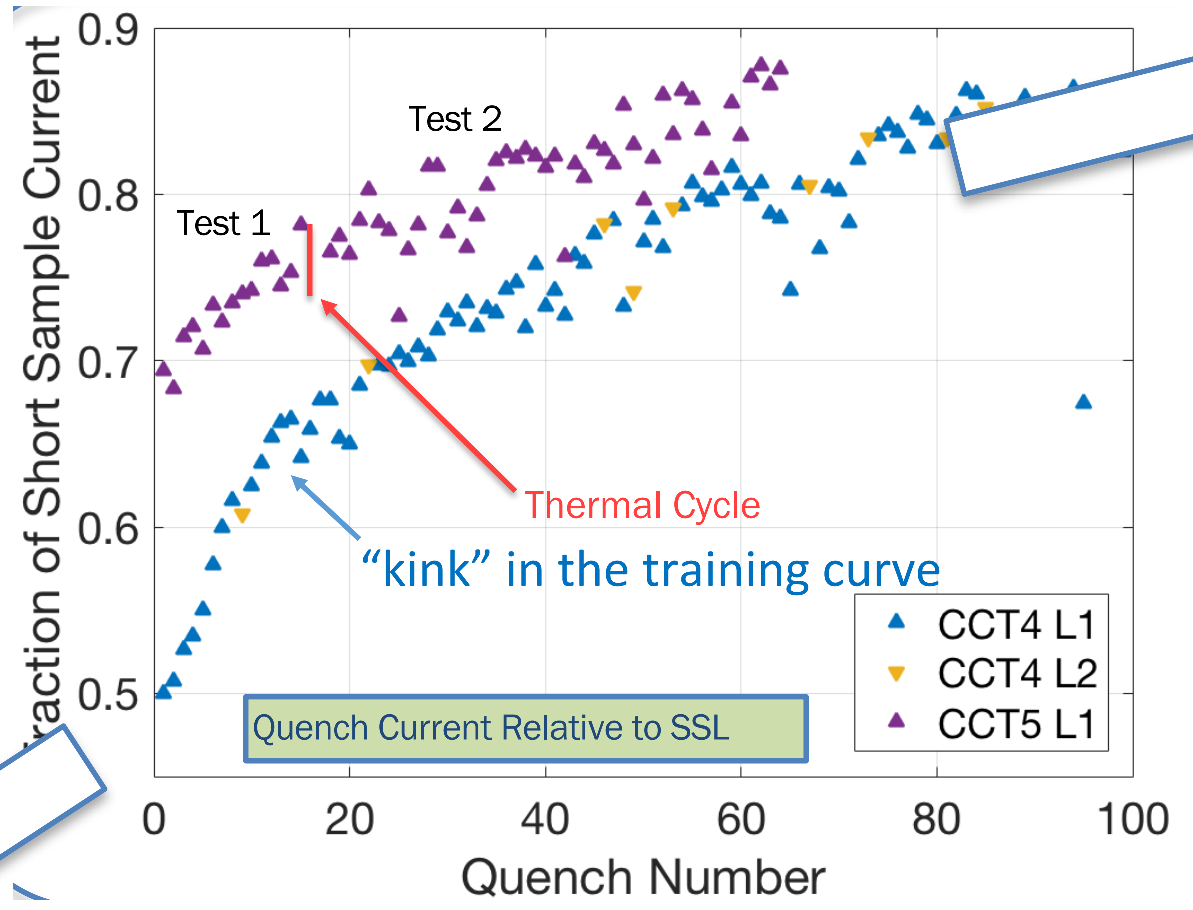
CCT5 Training Behavior

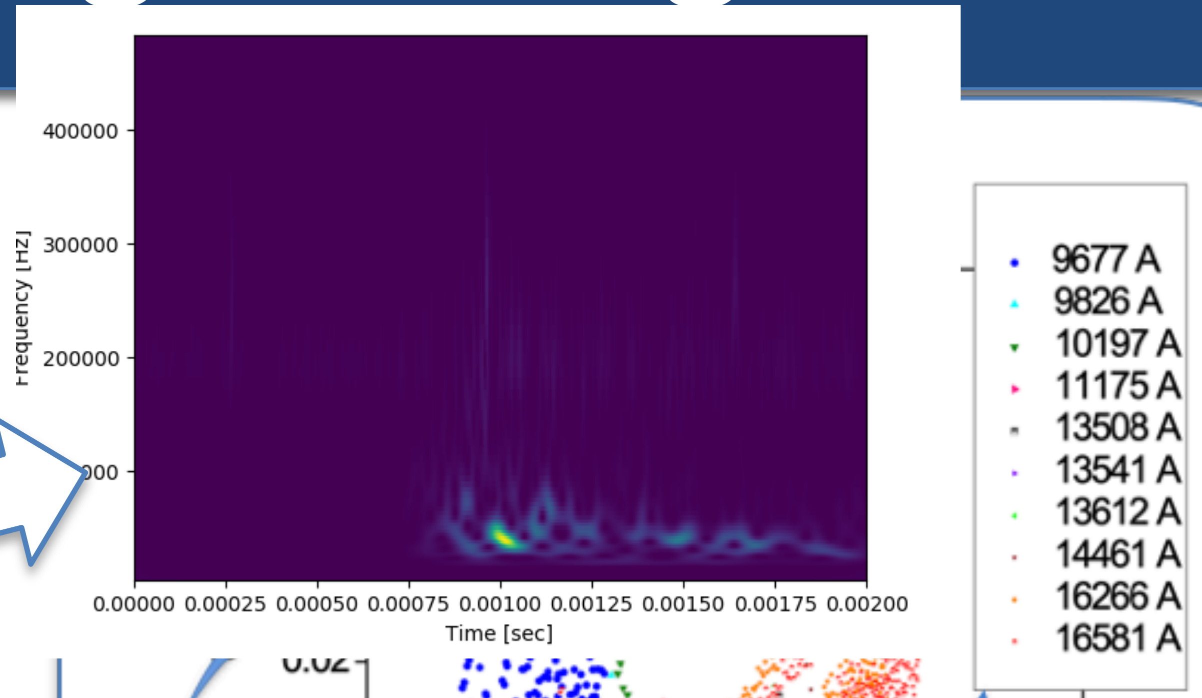


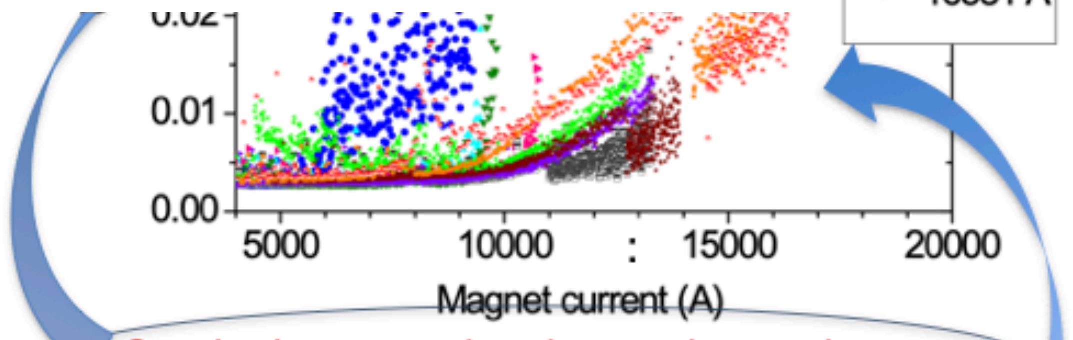
Diagnostics are critical for understanding of magnet performance and to provide feedback to magnet design



Acoustic signatures provide a wealth of data on energy perturbations in magnets



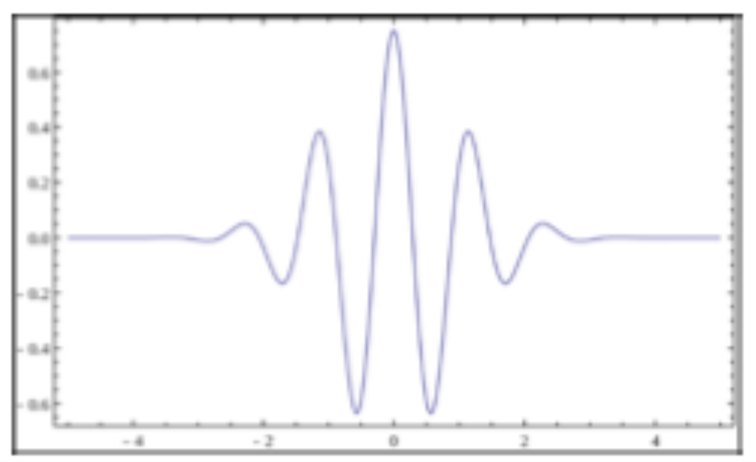


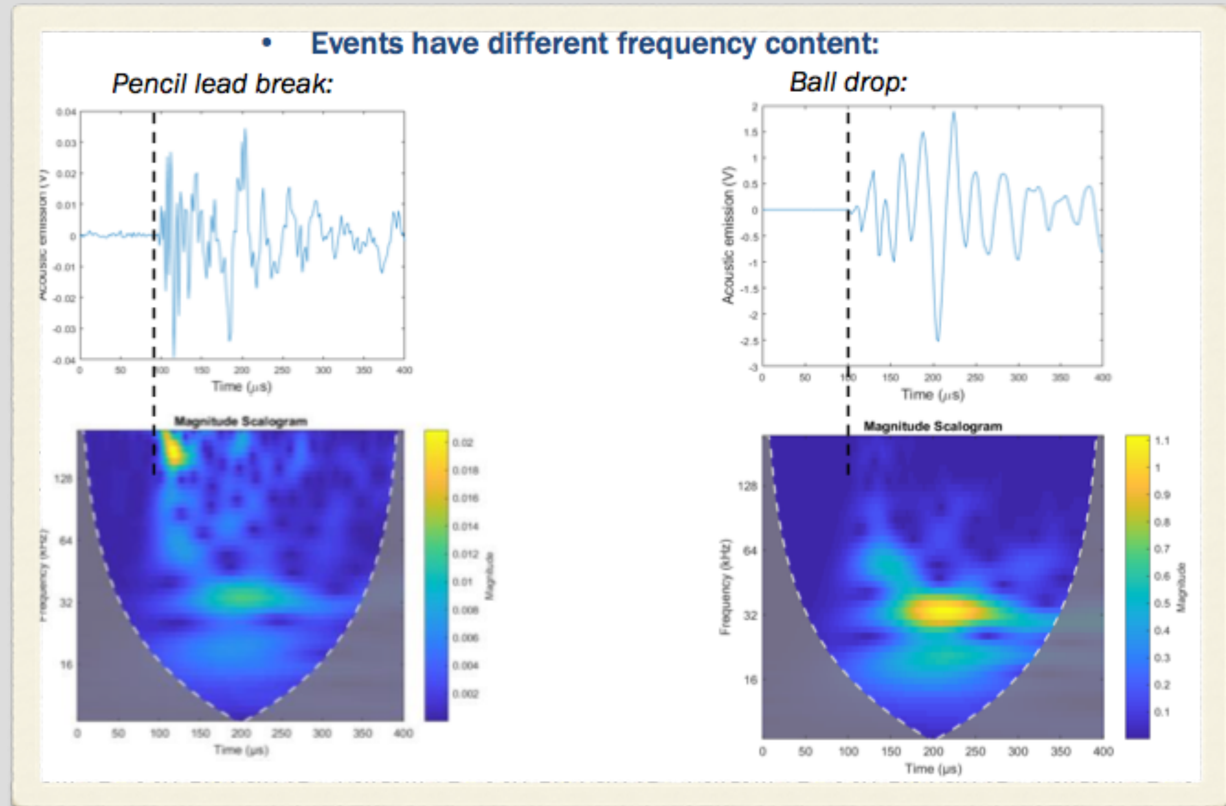


Cracks in epoxy develop and percolate

=> slip-stick between grains and parts

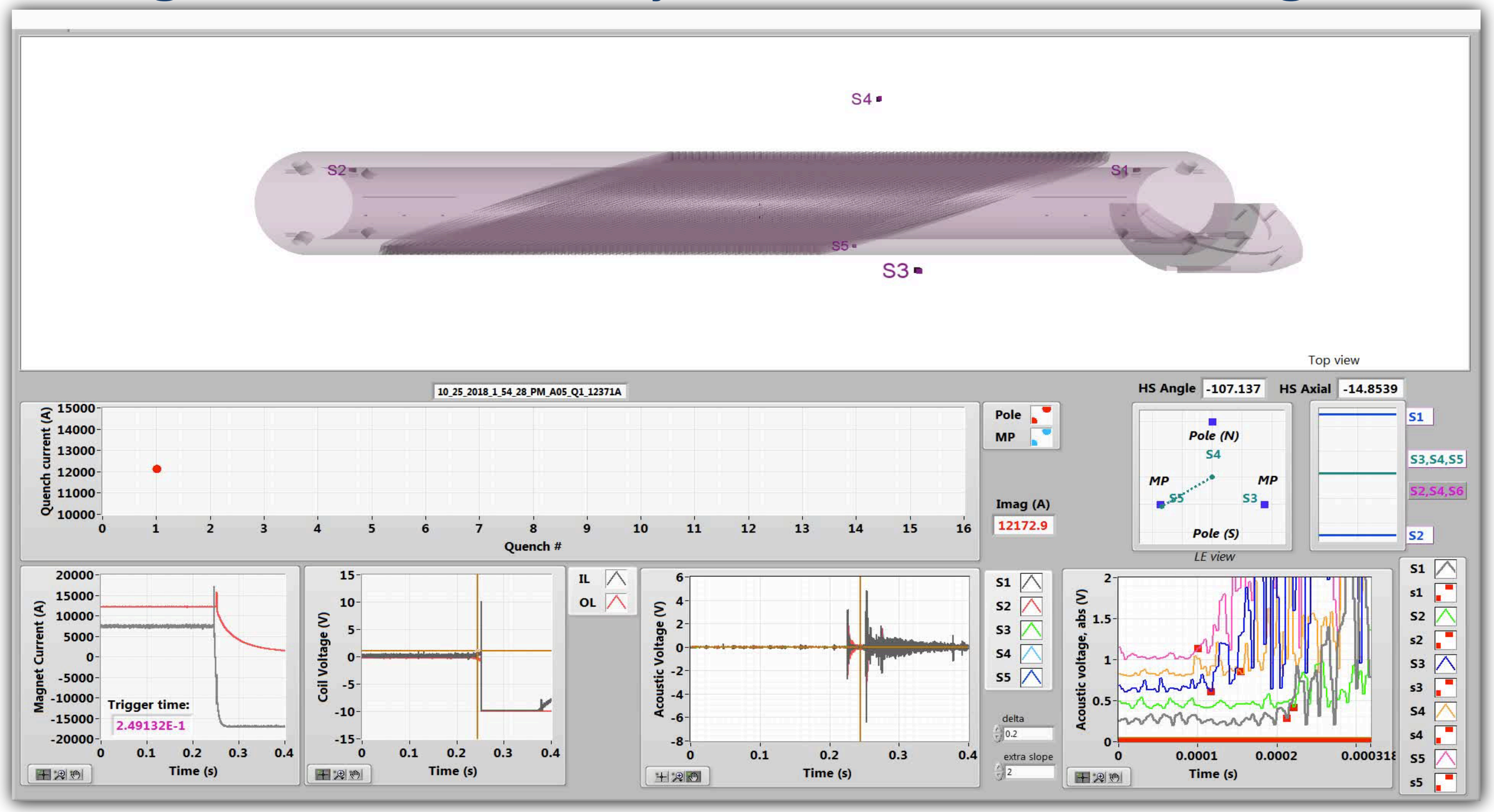
Wavelet analysis provides robust mathematics platform for transient signal analysis

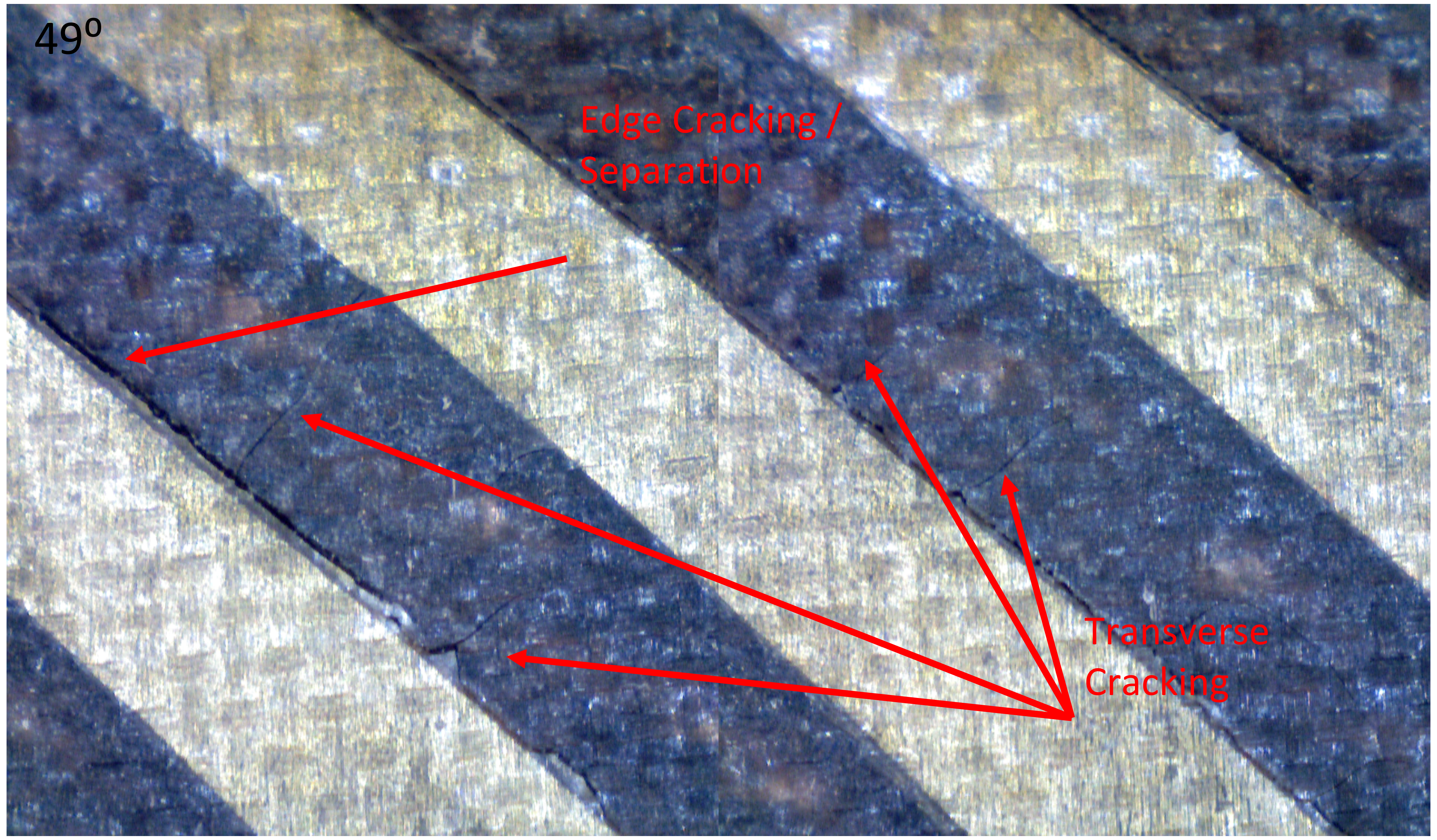




CCT5 Test Observations and Conclusions

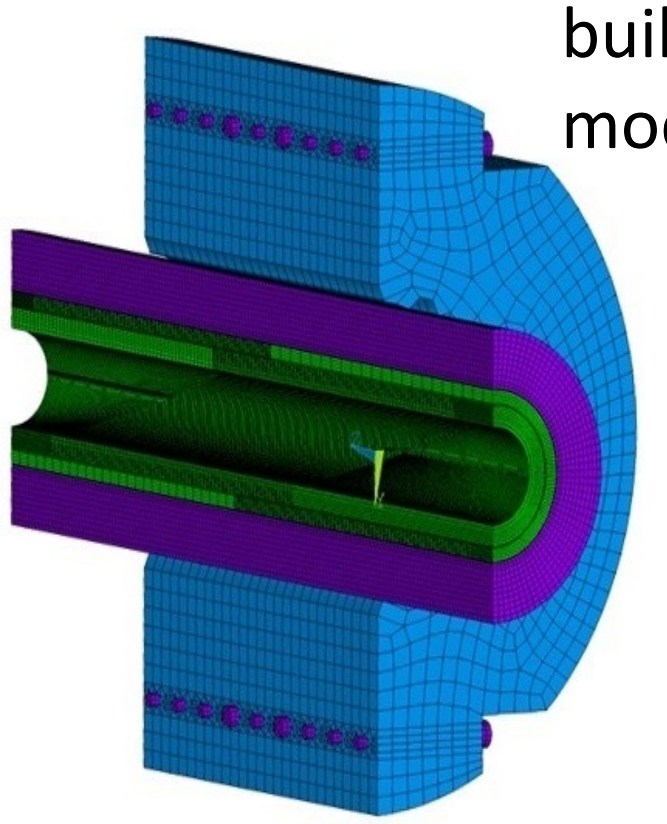
- Improvement in early training (e.g. first quench current), but similar training after initial section
- Initial improvement likely due to change of epoxy and interface condition between layers
- All quenches in layer 1
- Significant changes to epoxy and interface between layers, yet similar training after initial improvement
  - This suggests that we focus on stress in cable and cable/groove interface (plan for subscale magnet testing)
  - Surface quality for bonding is known to be poor due to residue deposit on the mandrel surface after heat treatment
- Magnet was successfully disassemble after testing



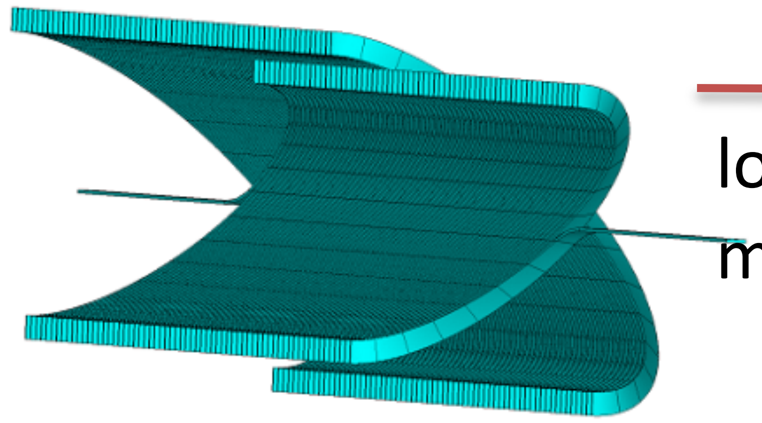


Ongoing work – look at ”local margin” and acoustic energy deposition

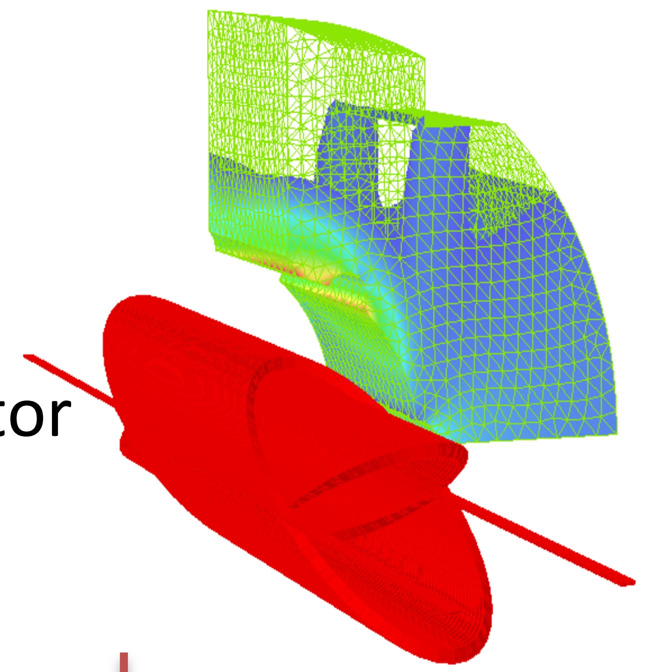
ANSYS, Opera, and strain scaling fit are combined to calculate Ic(ε,T,B) at every conductor mesh node



build and mesh ANSYS mechanical model of CCT4



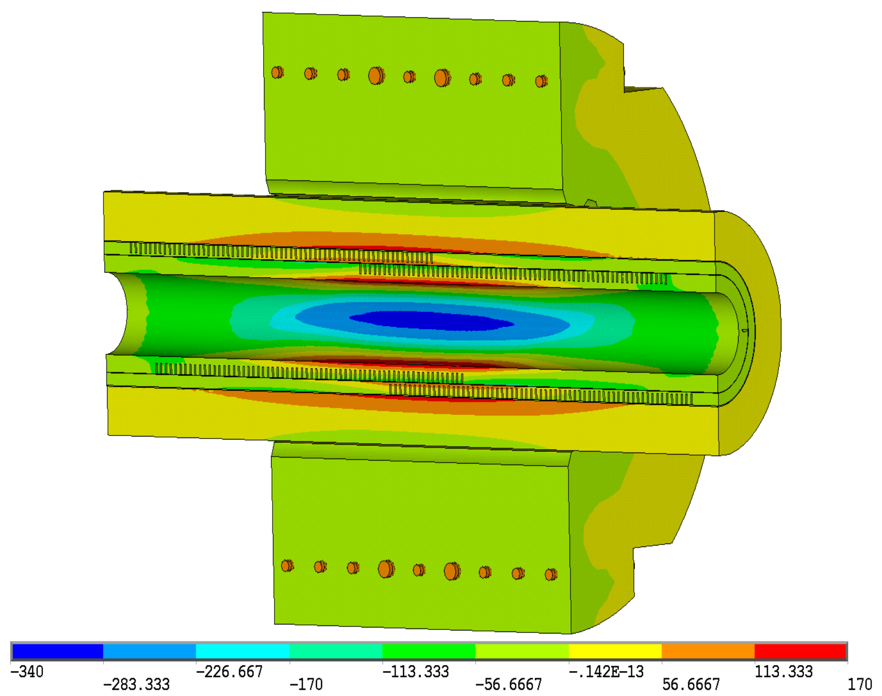
location of conductor mesh nodes

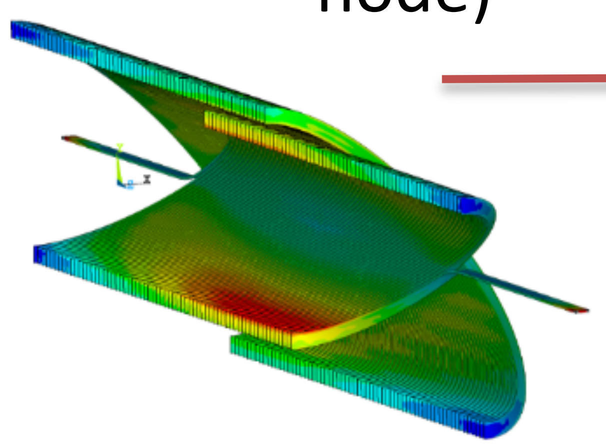


opera

field at conductor (by node)

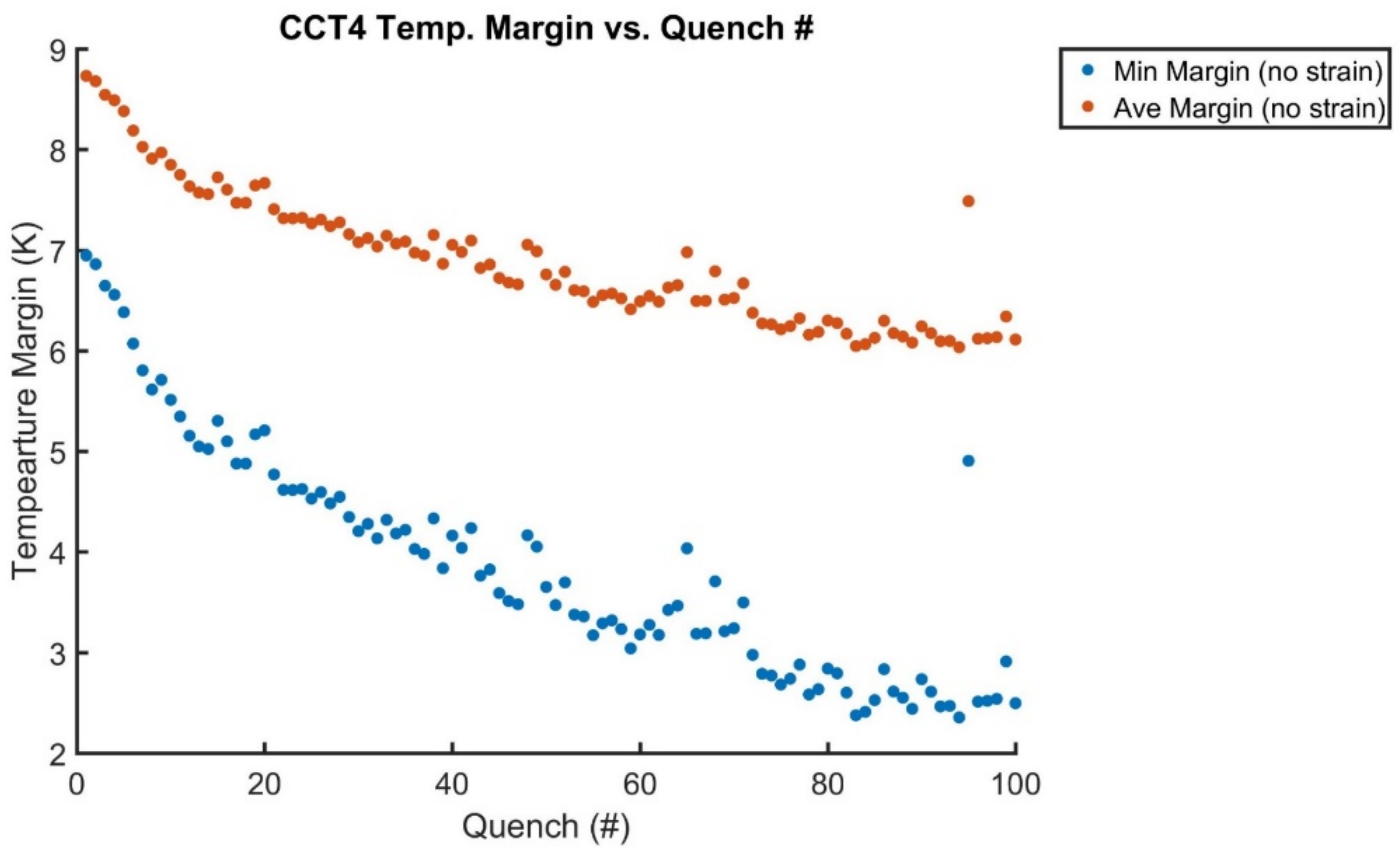
solve mechanical model in ANSYS

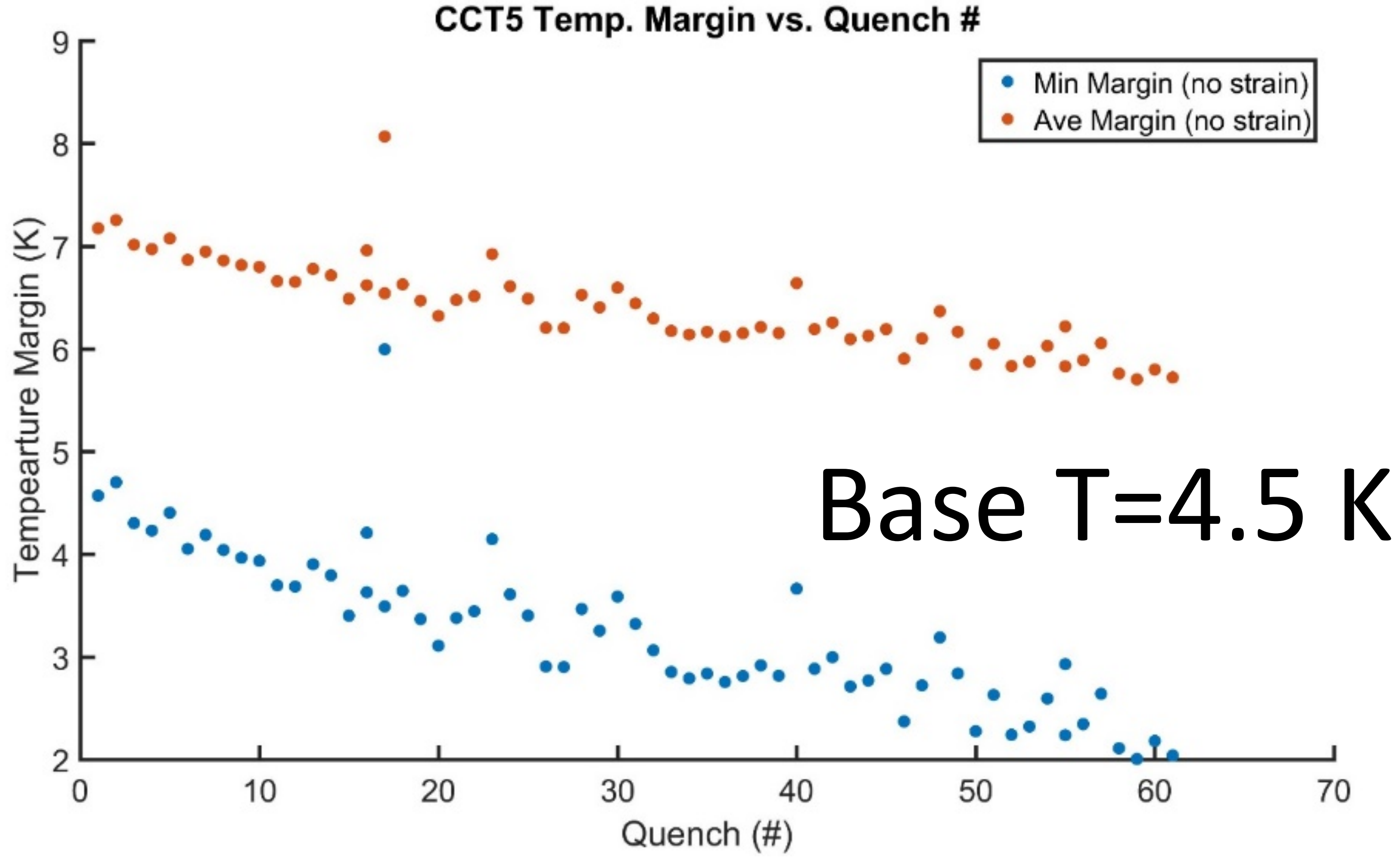




principal strain (by node)

Assume fixed temperature of 4.5 K and calculate Ic at every node Ic(ε,T,B) in Matlab



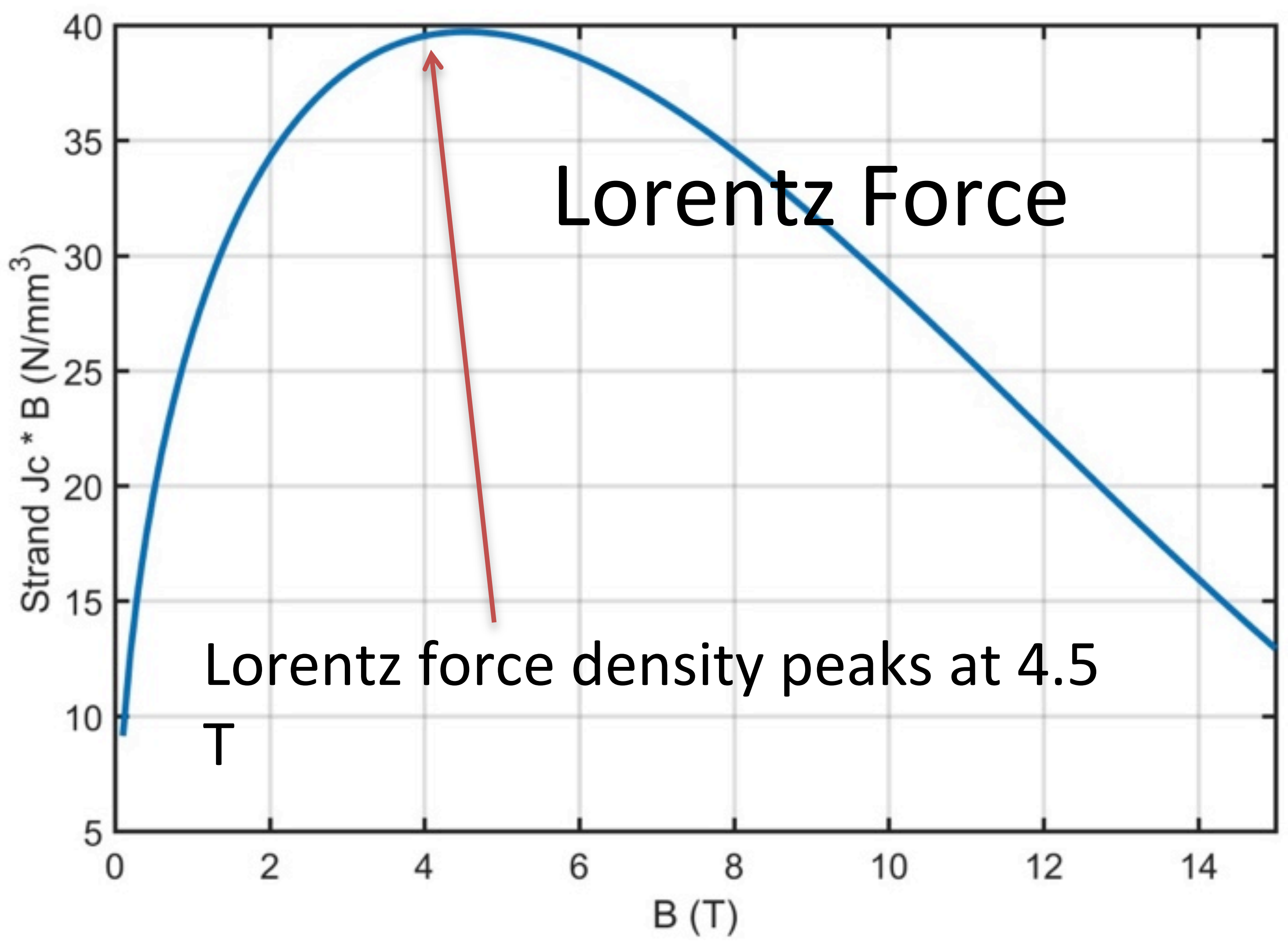


Next steps: a subscale program for CCT is underway to rapidly investigate technical understanding

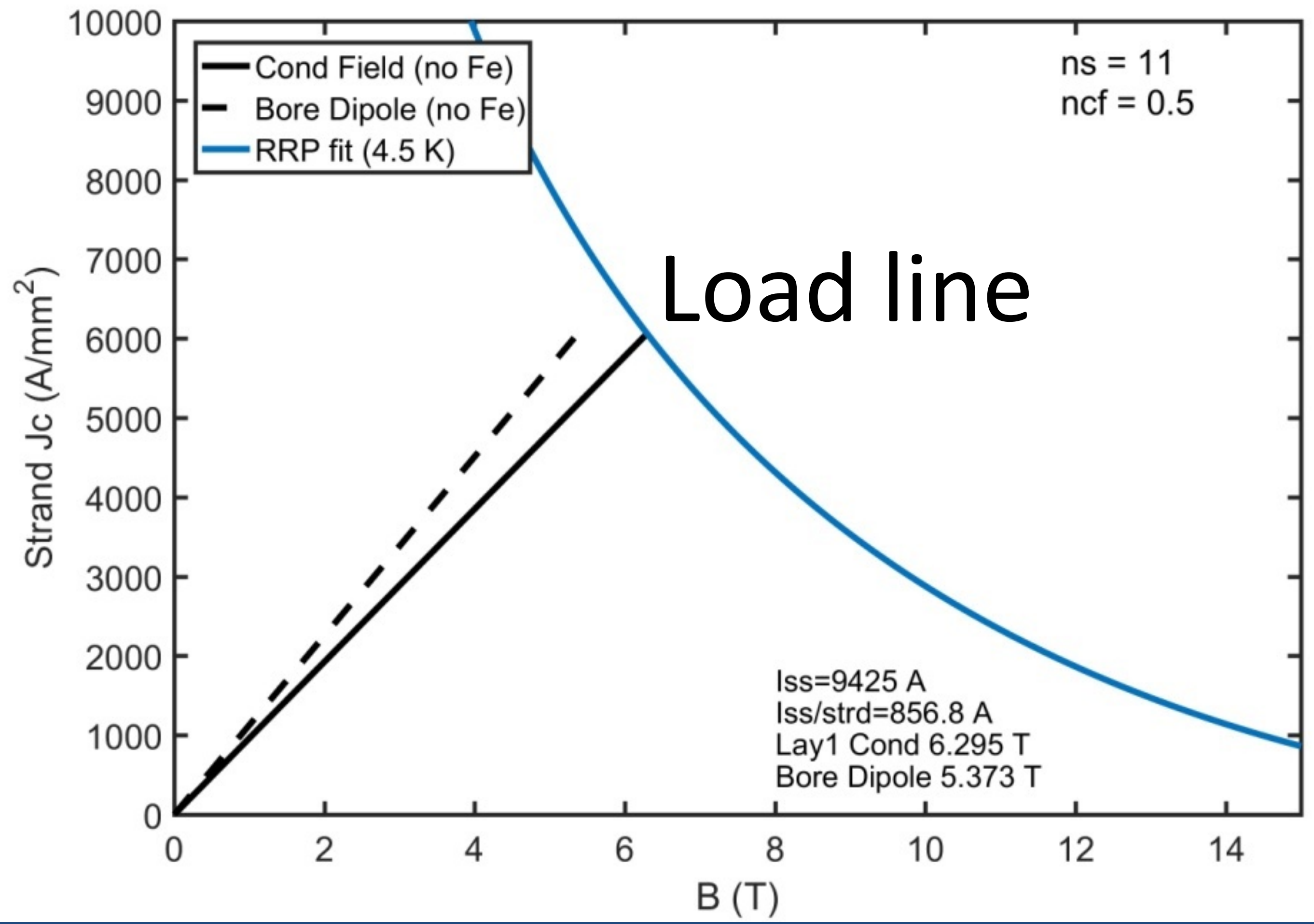
- **Motivation**
  - Allows for faster turn-around to understand CCT behavior
  - Can be tested in small cryostat

- **Design**
  - 5.2 T bore field and small mandrels and cables
  - Operate at higher Lorentz force on the conductor
  - Normal stress is comparable to that for full size two layer models
  - Shear Stress is about half of the full size model
  - Stresses are substantially above level where training starts in full size 2-layer models

- **Better understanding of CCT magnets**
  - Testing of epoxies and interfaces
  - Mandrel deformation during heat treatment
  - Test of assembly methods
  - Test of new instrumentation methods

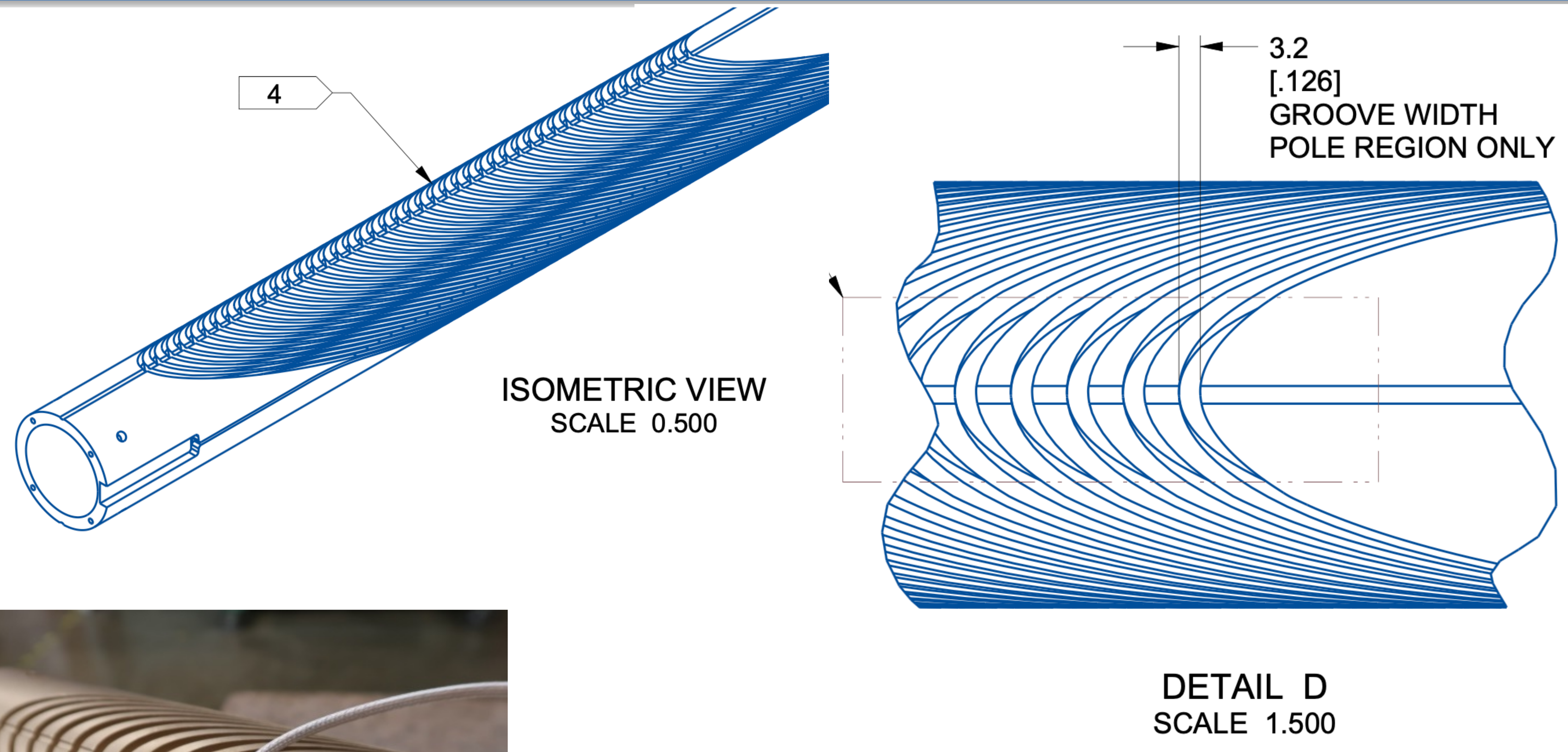


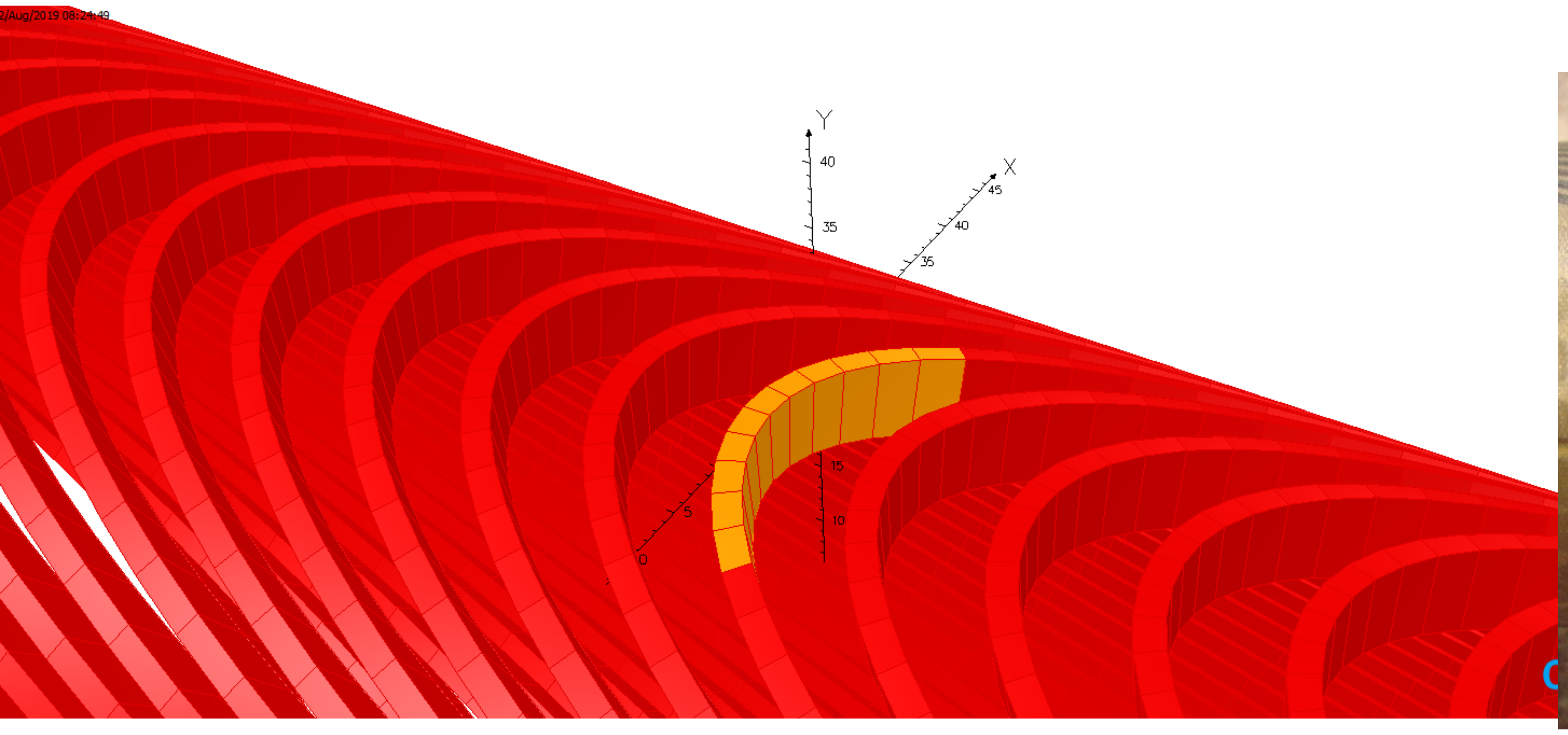
CCT Subscale Load Line

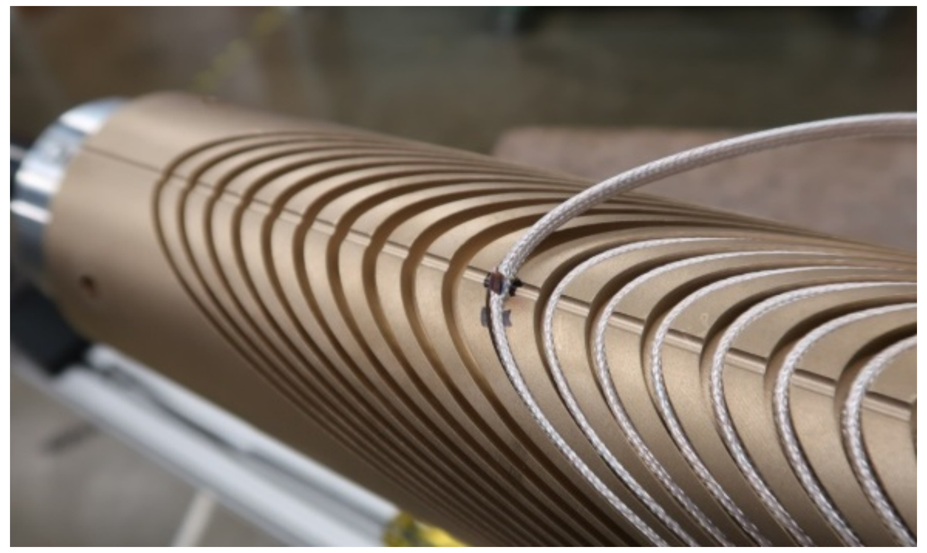


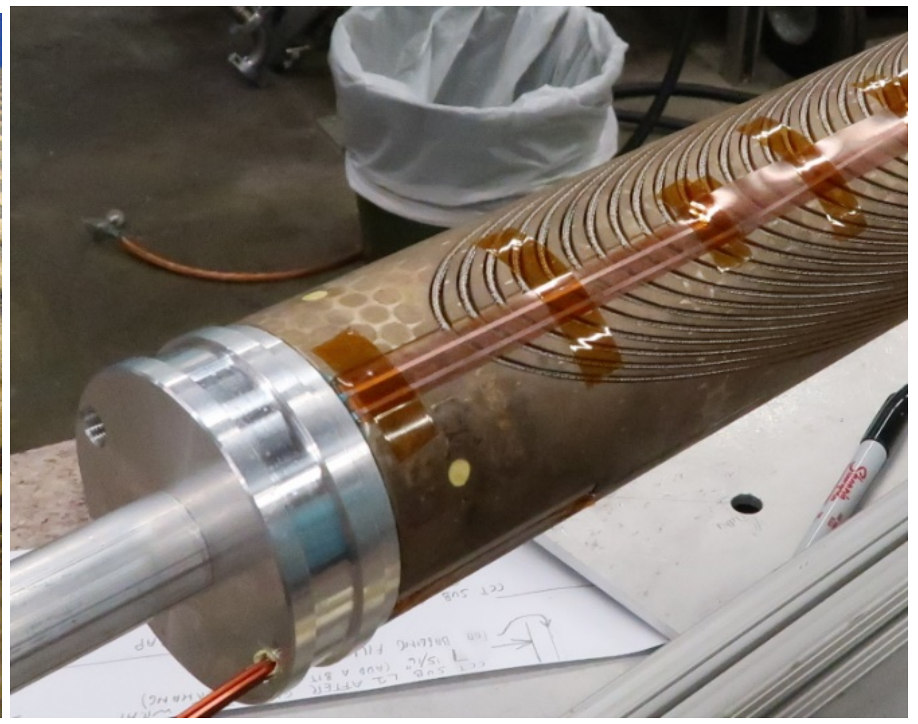
Multiple “coils” are currently in production – operations can be done in parallel to speed up development and testing

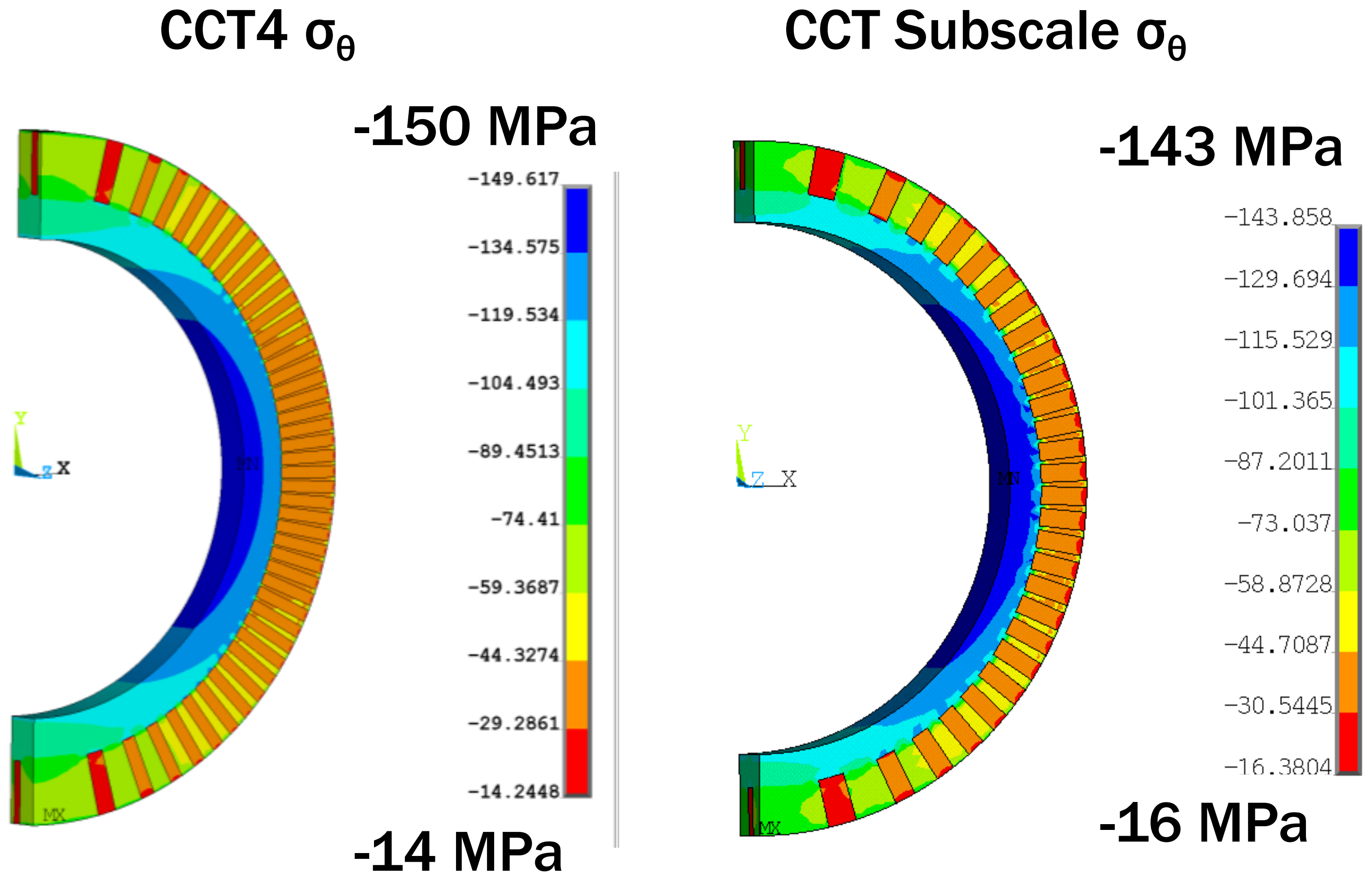
- Mandrels fabricated by in-house CNC machine
- Spar thickness is a free parameter to impact shear vs normal stress
- Multiple ”coils” can be reacted together
- Individual coil impregnation allows investigation of different epoxies
- Resulting magnets can be tested in ”small” cryostats with faster turn-around









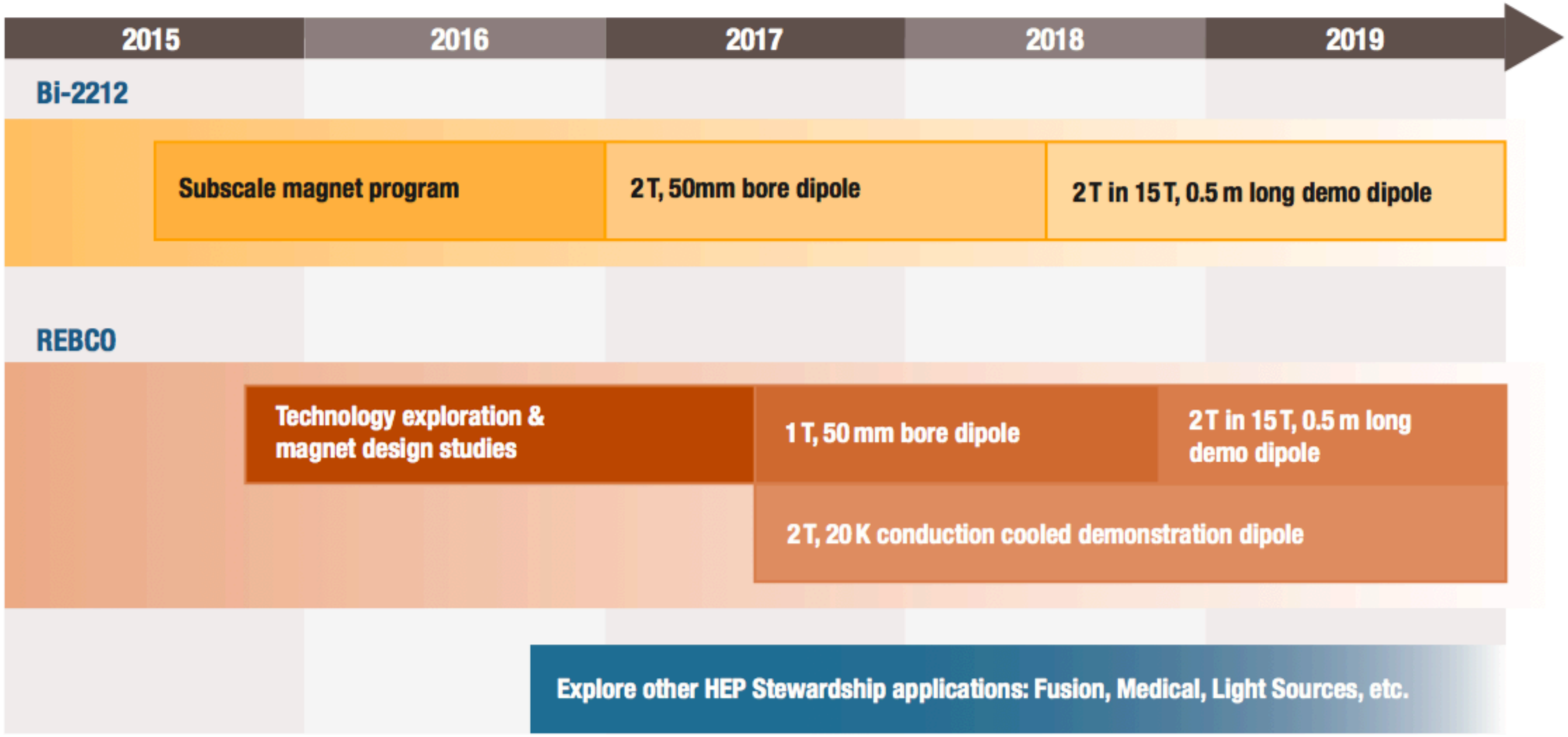


** Spar thickness can be modified to probe different stress states*

The US MDP has been pursuing HTS accelerator magnet technology through close collaboration with University and Industry collaborators

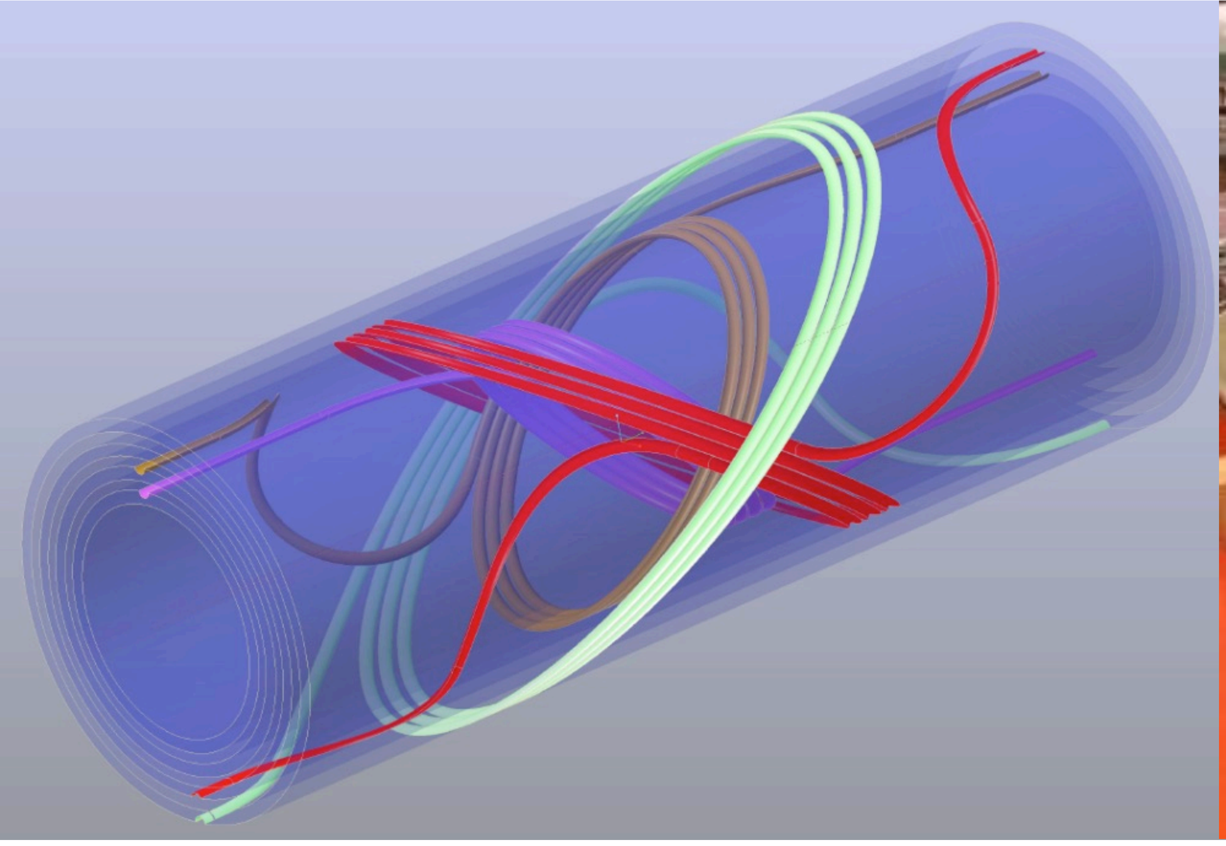
- The MDP HTS accelerator magnet technology program has worked to tailor superconductor, cable, and magnet technology for HEP applications

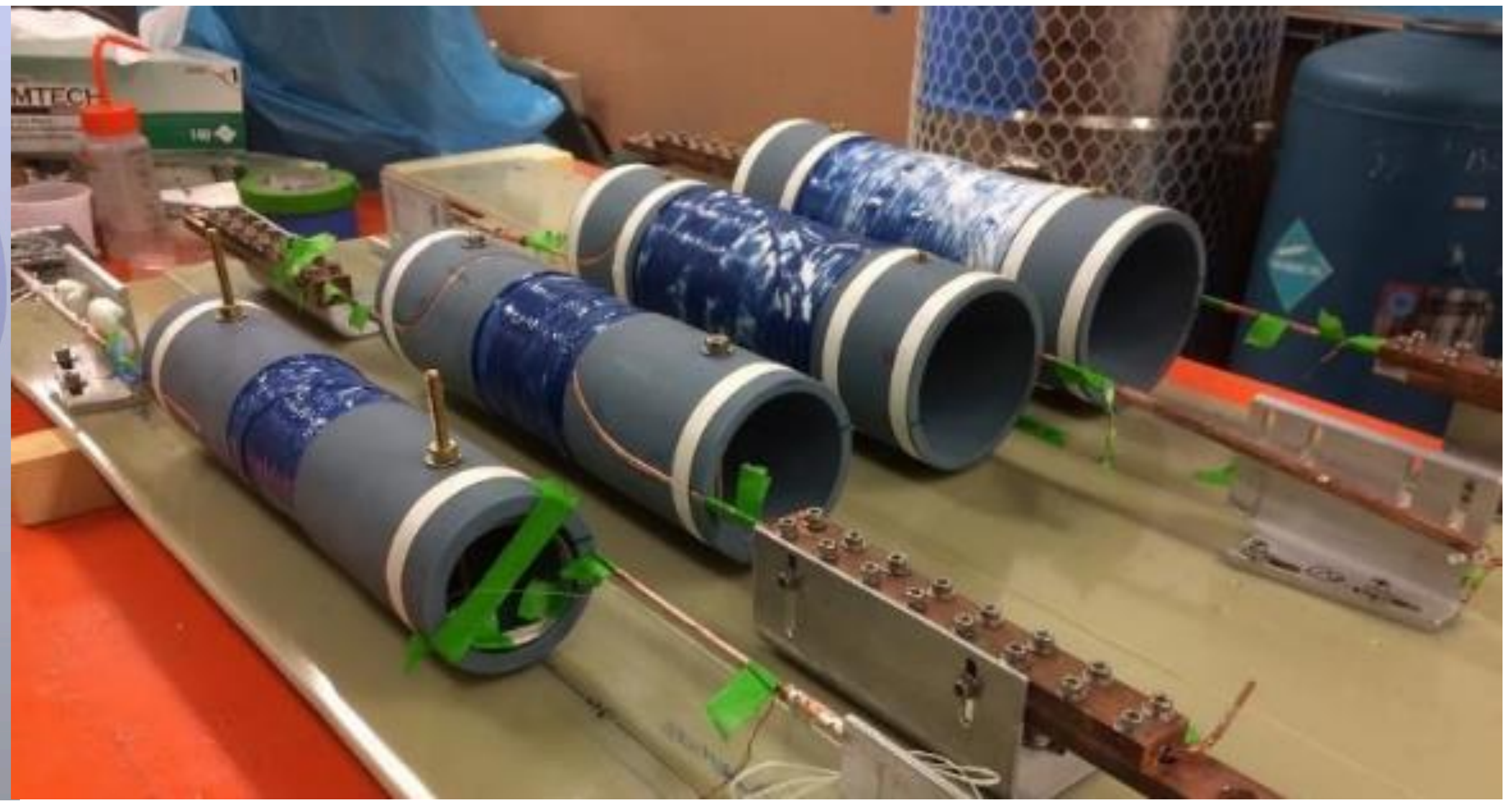
- Focus to-date has been on core technology development
  - Conductor and cable characterization
  - Fabrication techniques and processes
  - Test behavior: V-I transition, performance reproducibility, etc.

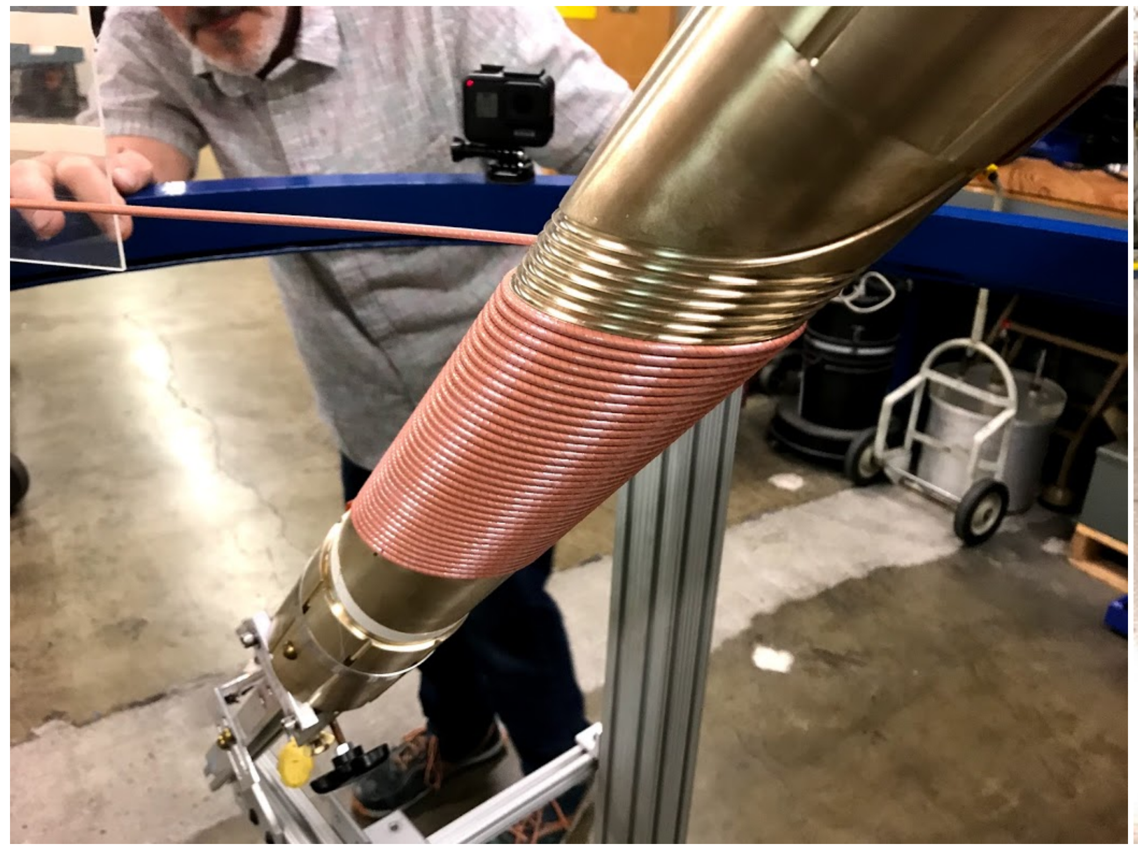


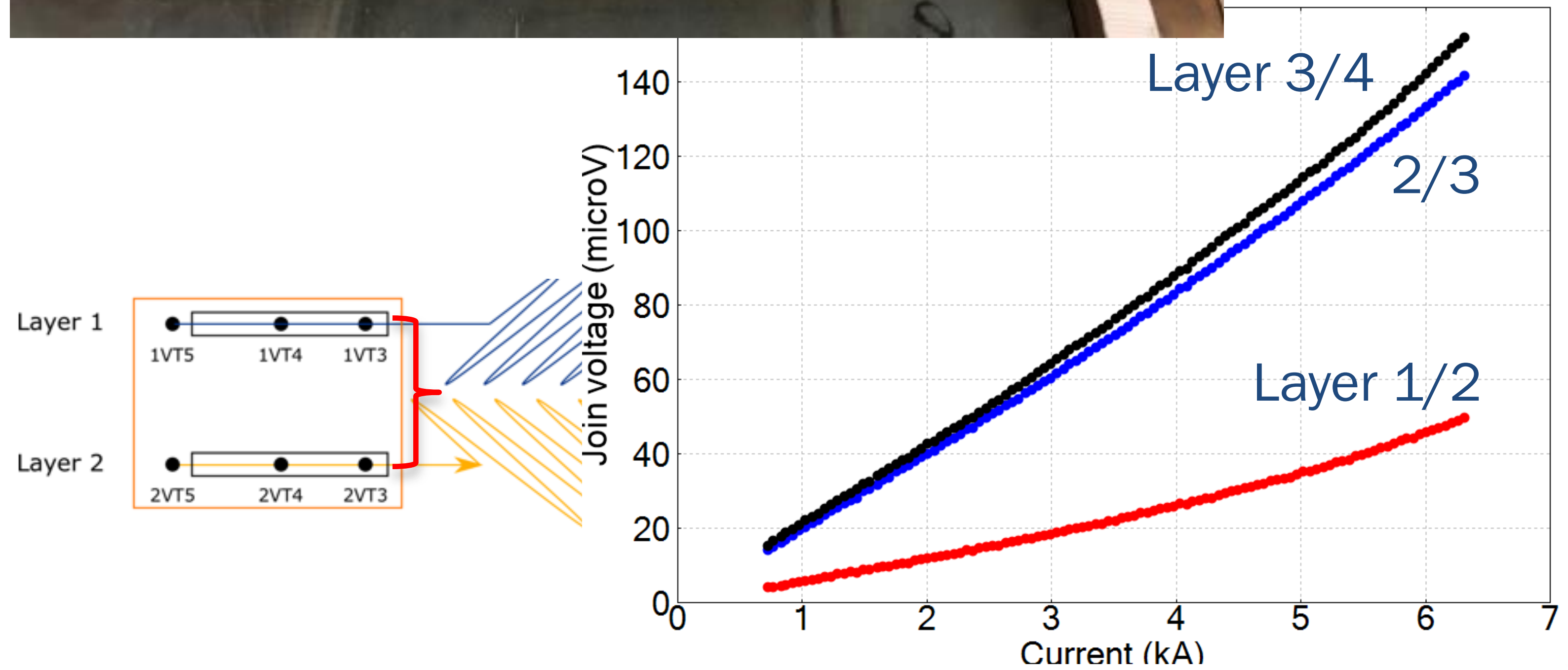
The "stress management" nature of the CCT concept has advantages for HTS inserts as well – REBCO example

Concept/technology development → Prototype fabrication and test









- Develop dipole magnets with increasing fields and complexities
  - C1, 1.2 T (2017) Concept demonstration
  - C2, 2.9 T (2019) Metal mandrel, 4 layer
  - C3, target 5 T in 2020. Demonstrate magnet technology towards higher fields
  - Roadmaps beyond 5 T formulated

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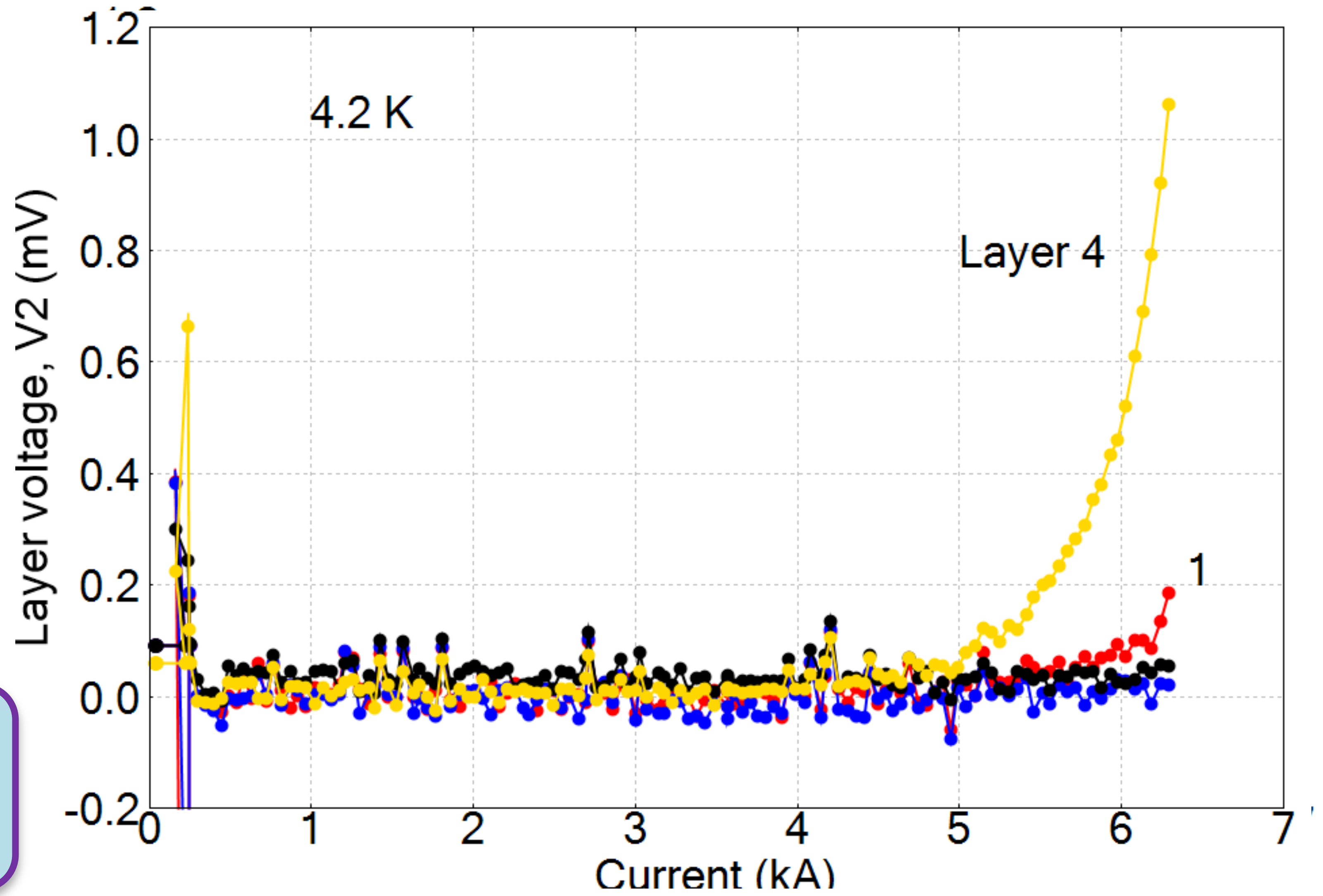
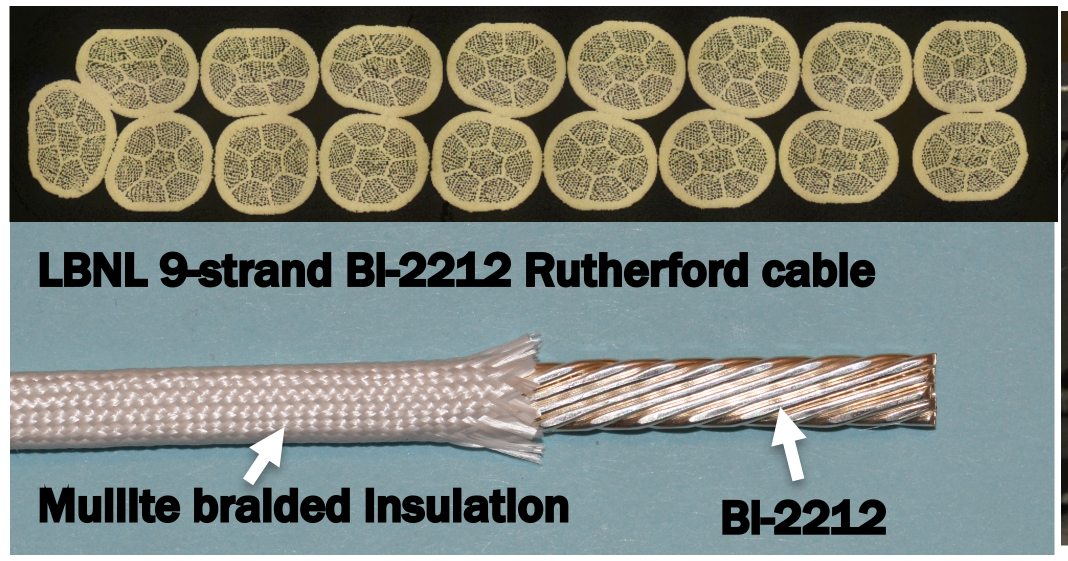
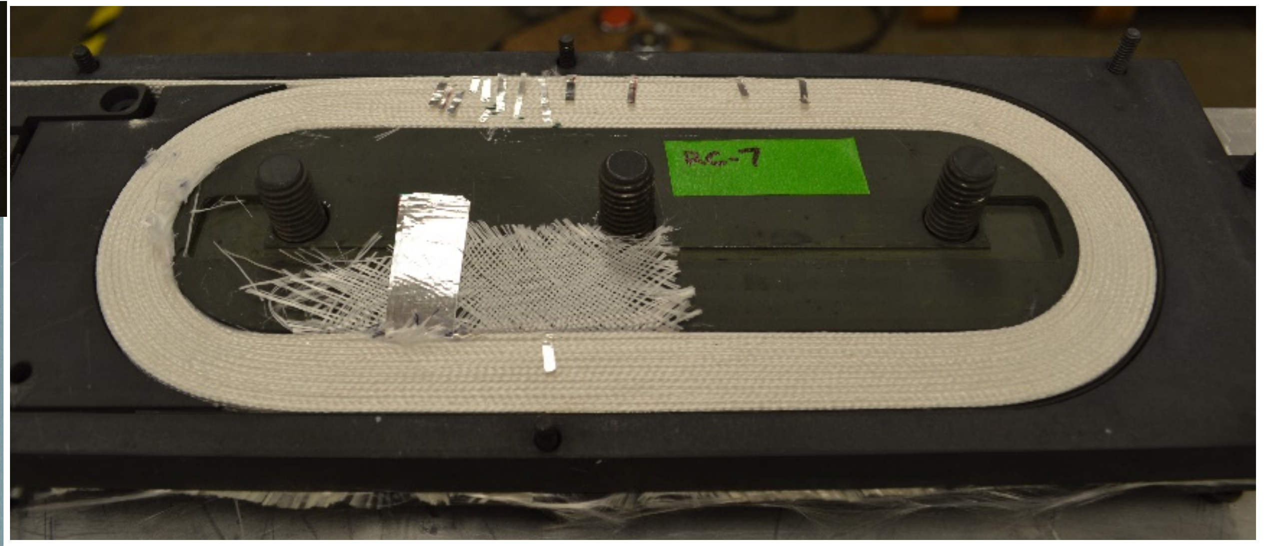
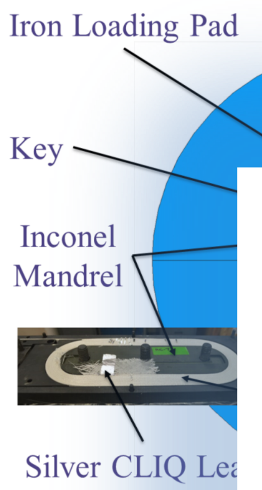


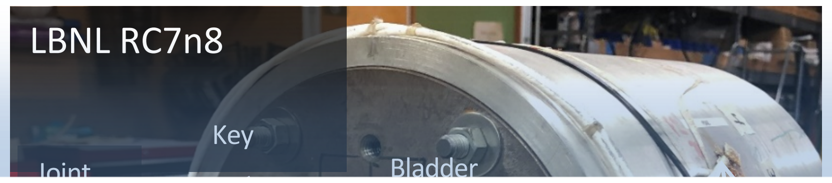
The Bi2212 magnet effort was developed using racetrack technology, and is now transitioning to CCT for higher field

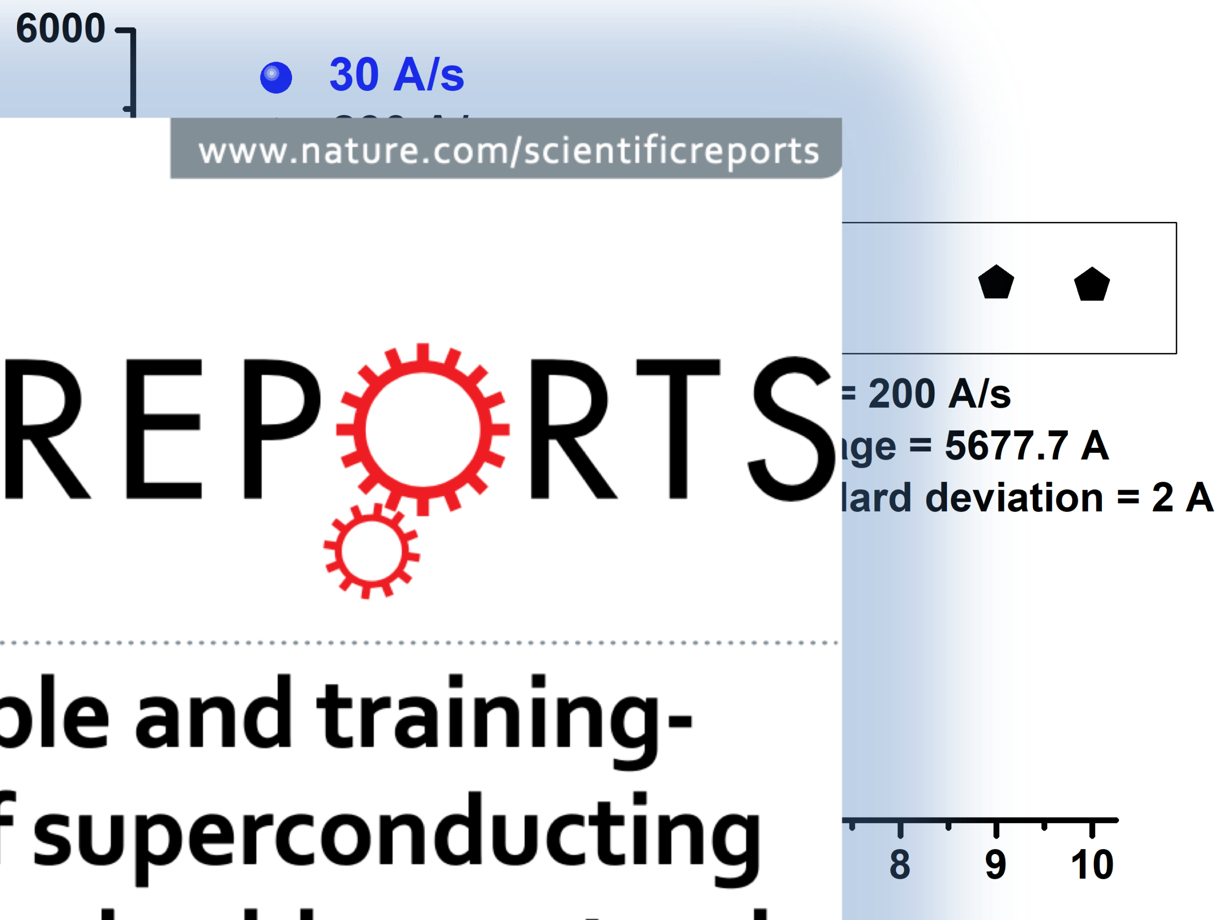




Concept/technology development







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Stable, predictable and training-free operation of superconducting Bi-2212 Rutherford cable racetrack coils at the wire current density of 1000 A/mm²

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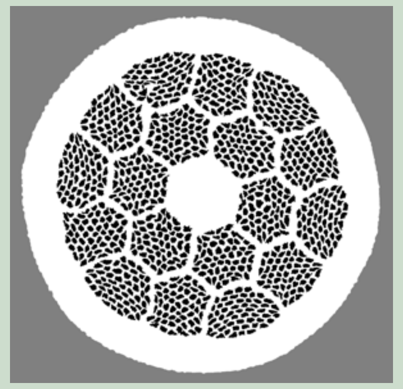

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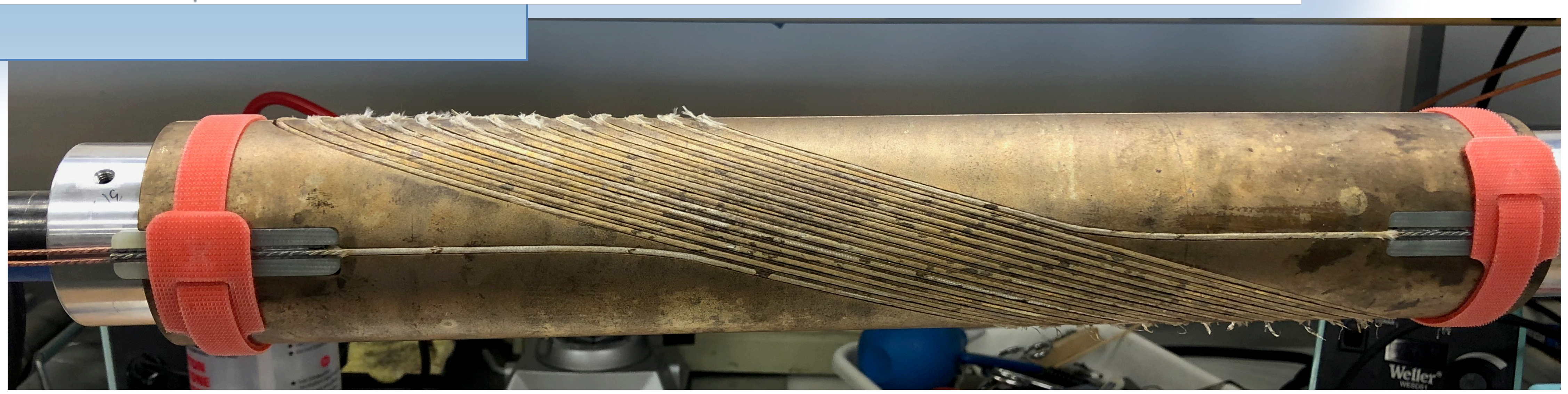
ASC
BRUKER
BERKELEY LAB

Successful test of CCT BIN5aOL on Oct. 1, 2019

- first CCT-based on Bi2212 Rutherford cable t
- Achieved about 4250 A (9-strand Rutherford
- Dipole field of 0.75 T (the field on conductor
- No quench training

Tengming Shen: *"Potential to yield a new high-field, likely quench-training free, easy-to-fabricate magnet technology"*



Summary statements

- The CCT concept has matured significantly – first Nb_3Sn 2-layer magnets have yielded >8.5T in a 90mm bore, and >85% of short-sample limit
  - Significant training (similar to HD-series of the 2000's)
  - Inroads are being made to reduce training via a strong diagnostics and modeling push
  - The subscale program promises cost-effective, rapid investigation into training reduction

- The HTS accelerator magnet technology development is leveraging the stress-managed nature of the CCT concept
  - Steady progress on the REBCO front – the next planned magnet should achieve 5T stand-alone
  - The very promising and productive racetrack development of Bi2212 is now being transferred to CCT for future insert testing

- The CCT concept serves as a "limiting case" of stress management; lesson's-learned and modeling and diagnostics tools developed for the CCT program will apply to other stress management concepts that are planned in the updated roadmaps