U.S. MAGNET DEVELOPMENT PROGRAM

Status update from LBNL
MDP - FCC - EuroCirCol Meeting
03/12/2018

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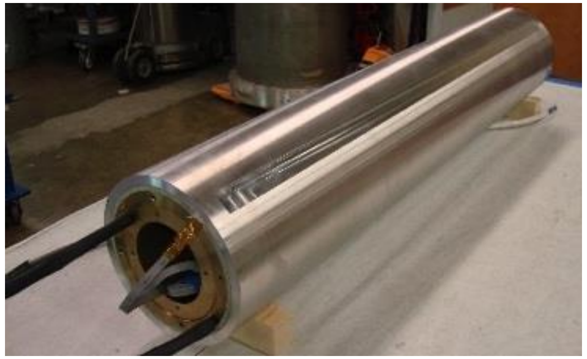
for the (LBNL) MDP team

History of CCT Dipole Tests at LBNL

CCT1
- 2.5 T short-sample dipole
- 50 mm clear bore
- 8 strd. NbTi cable (0.65 mm SSC Outer)
- not impregnated
- 11/2013*: **tested up to 2.5 T***

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
- 90 mm clear bore
- CCT3 03/2016: **reached bore field of 7.4 T (conductor damage)**
- CCT4 08/2017: **reached bore field of 9.1 T (substantial training)**

CCT3 / CCT4

CCT Design Requires Minimal Amount of Tooling and Parts When Compared to Traditional Dipole Magnets

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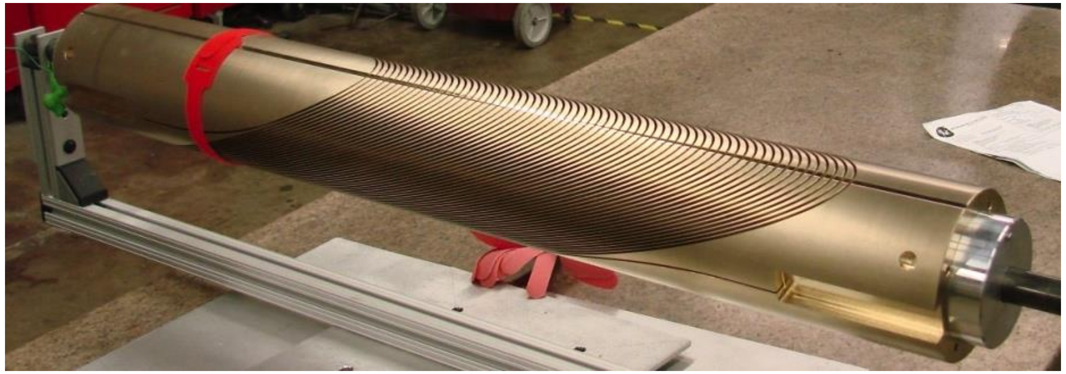
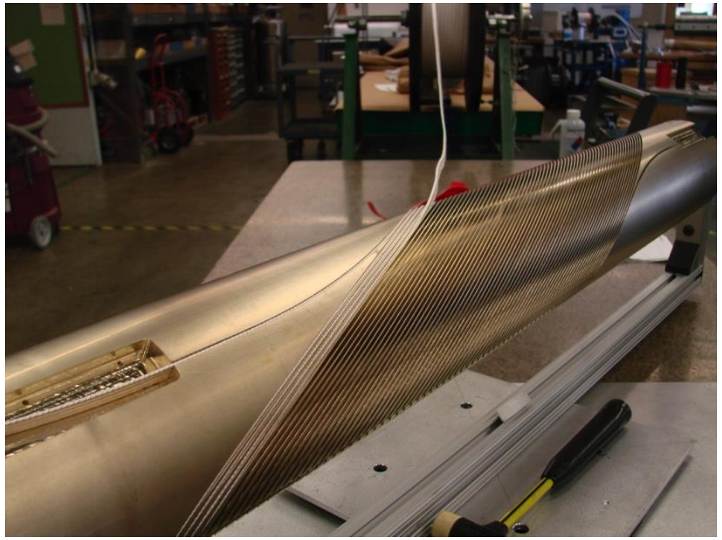
- **Aluminum Bronze mandrels incorporate features for stress management and cable positioning**
- **Minimal tooling is required for heat treatment and epoxy impregnation**

Machined Mandrel



Heat Treatment with SST Sheet and Clamps

Coil Winding



Coil Impregnation

Main Technology Issues Are Being Addressed With CCT 2-Layer Magnet Series

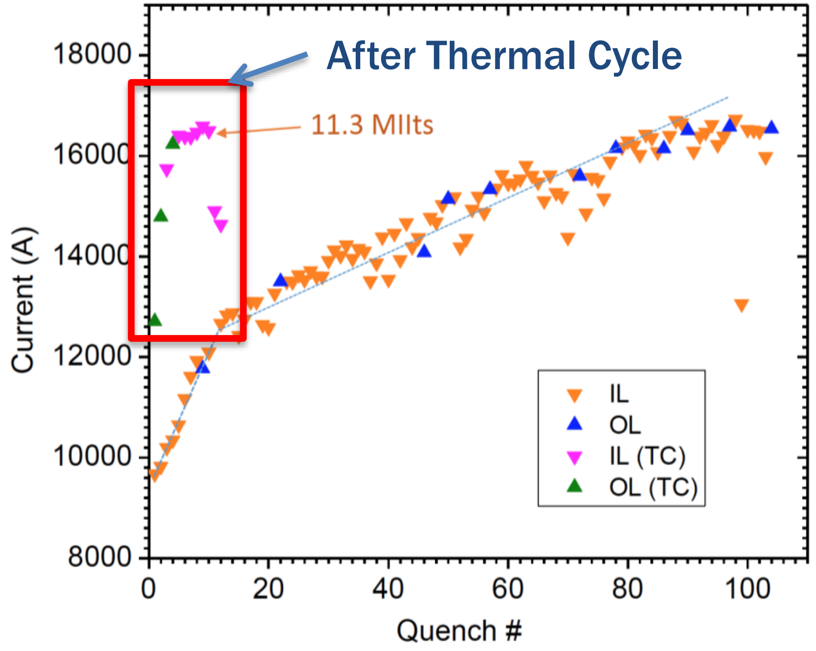
	CCT3	CCT4	CCT5
Bore size [mm]	90	90	90
Groove design	constant width	1.25 mm gap at pole	1.65 mm gap at pole
Conductor	RRP 54/61 Ta doped	RRP 54/61 Ta doped	RRP 108/127 Ti doped
HT Temp [C]	650	660	675
Potting configuration	full magnet	full magnet	individual layers
Epoxy	CTD-101K	CTD-101K	FSU Mix 61
Layer-to-layer interface	bonded	mold released	bend and shim process
Short Sample Current	19.3 kA	19.3 kA	17.8 kA

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

Conductor Damage Problems Were Resolved for CCT4 and Results Lead to Focus on Training Reduction for CCT5

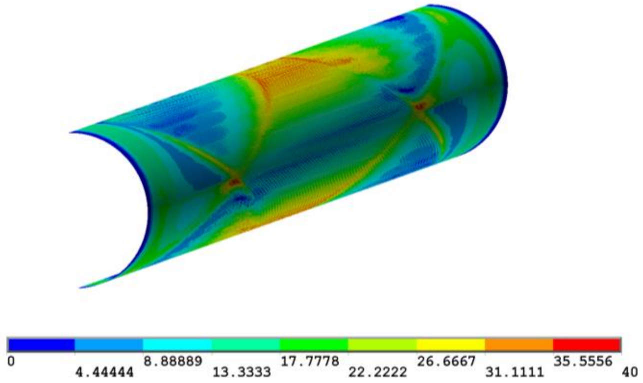
- Reached 86% of round wire short sample after 85 quenches
- Maximum current is 16.7 kA
- Maximum bore field is 9.14 T (90 mm aperture)
- Magnet exhibits long training but good memory after thermal cycle

CCT4 Training Behavior

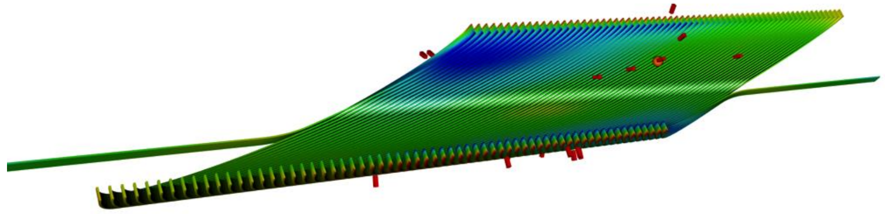


- Reduction in training is the main focus for CCT5
  - Impregnation material (CCT5 uses tougher epoxy)
  - Frictional interfaces (CCT5 uses shim interface)

Stress at Layer-to-Layer Interface



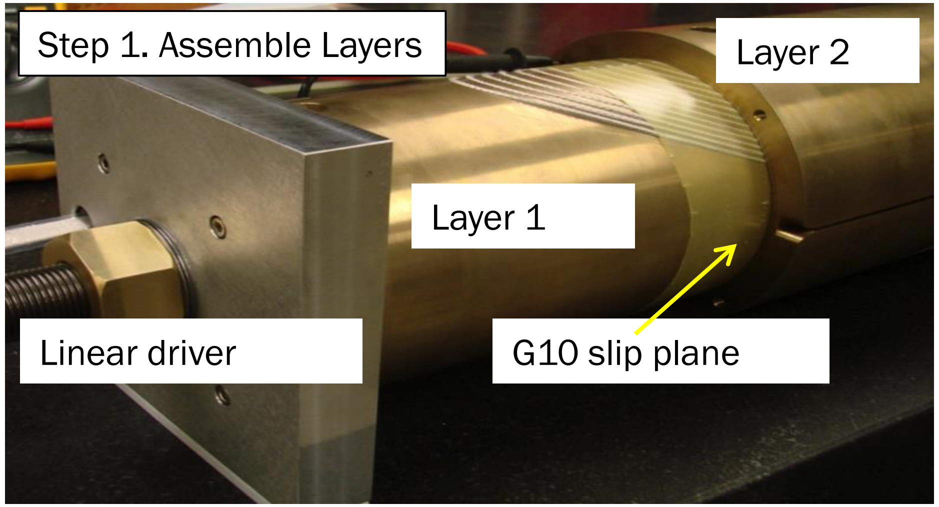
Localization of Quenches from Acoustic Signals

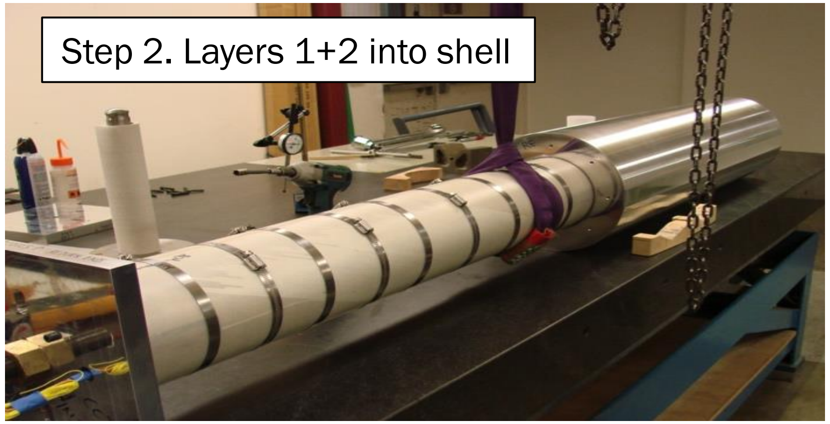


See talk by M. Martchevskii

Reminder: CCT3/CCT4 Layers Were Assembled Into The Shell And Impregnated As One Unit

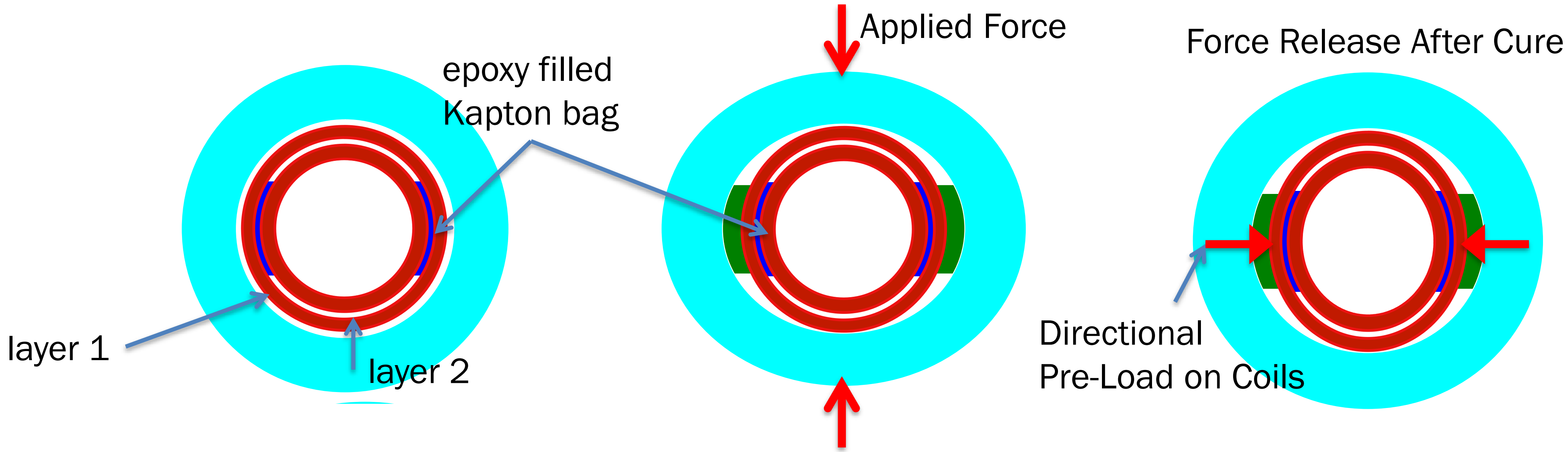
- Reacted coils are assembled together with G10 shim between layers
- Coils are inserted into the Aluminum shell and the entire assembly is vacuum impregnated with epoxy
- Areas of unfilled epoxy remain between the layers
  - G10 shim has to be substantially thinner than gap between layers due to distortion of the mandrels during heat treatment





CCT5: New Method Developed for Coupling of Individually Potted Layers (Bend-and-Shim)

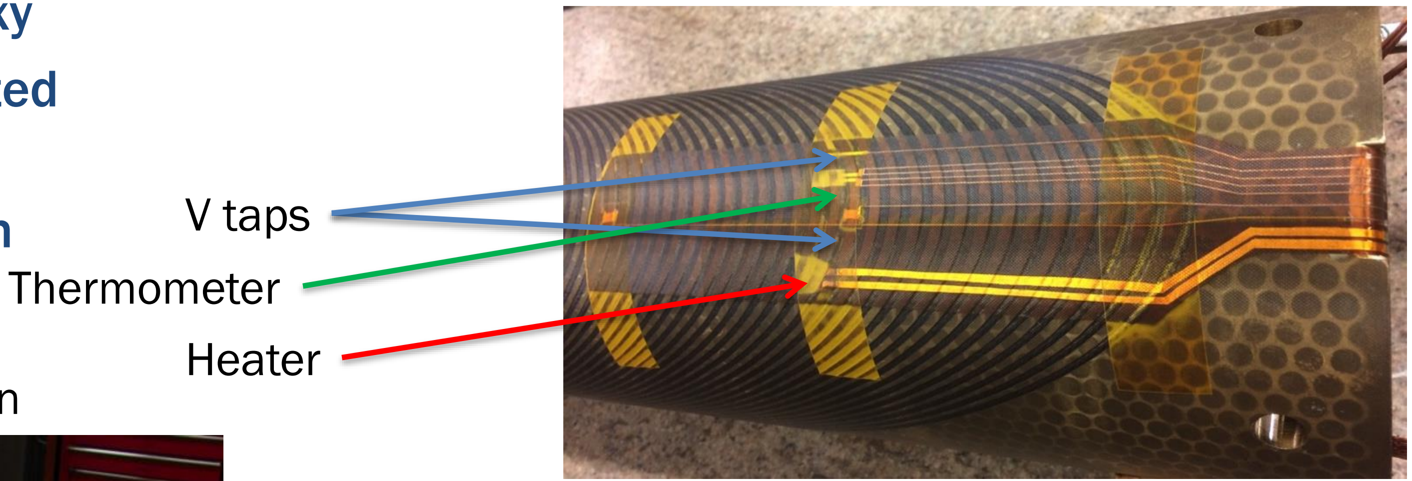
- Contact location between layers is controlled by using shims and Kapton bags that are filled with glass and epoxy
  - Allows for control of contact location
  - Fracture in interface epoxy does not propagate to the coil
  - Improved cooling at the pole regions from direct contact with LHe
- Directional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



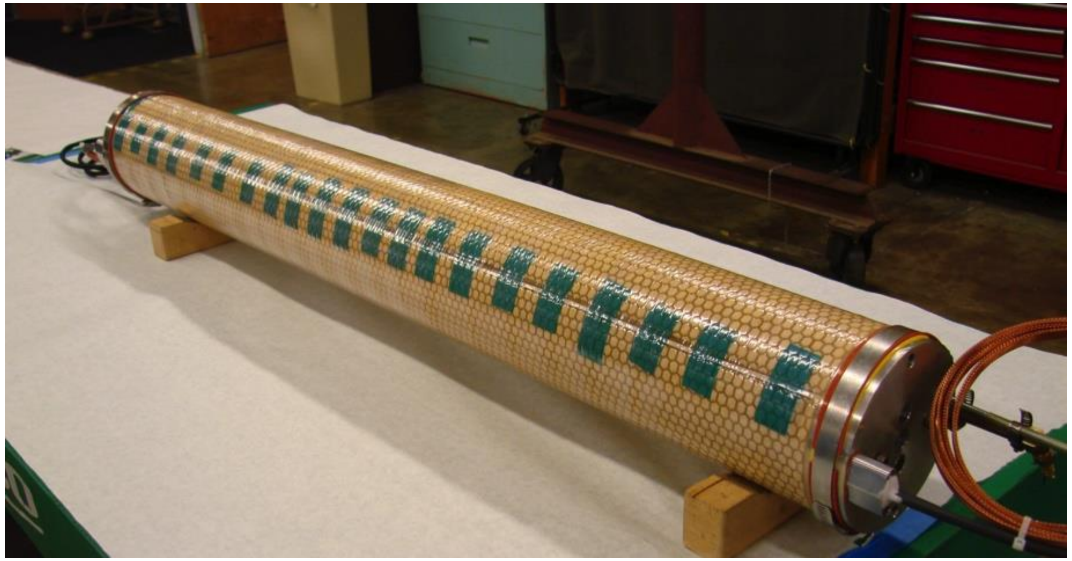
Vacuum Impregnation of CCT5 1 Meter Coils using New Process Was Successful

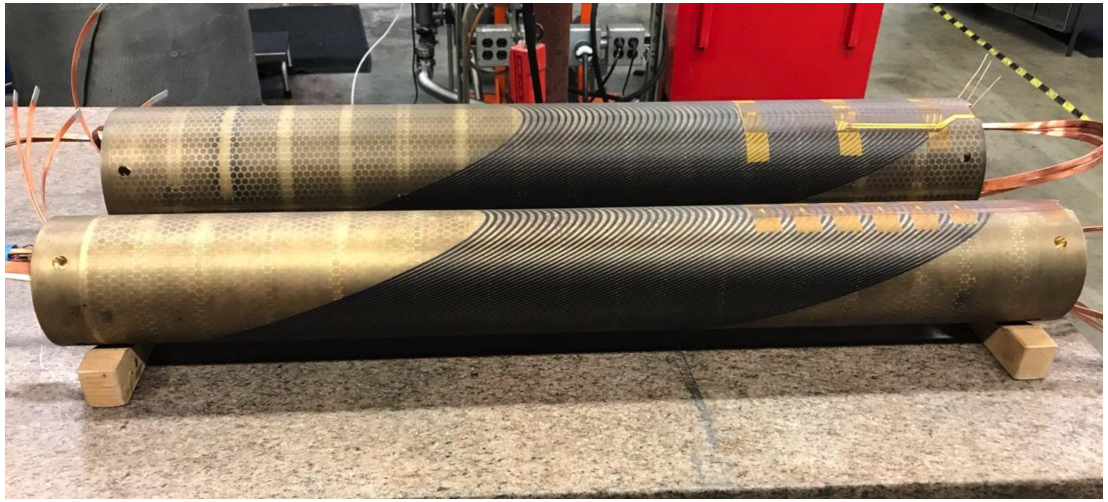
- Coils are impregnated with mix 61 epoxy
- CCT5 coils were successfully impregnated with new process
- Instrumentation traces were included in the impregnation

Instrumentation Trace After Potting



Wrapped Coil After Impregnation





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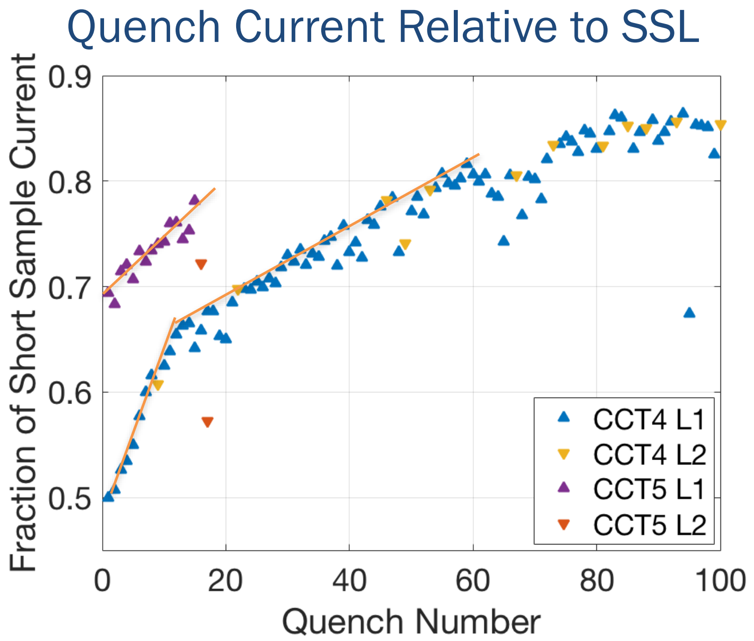
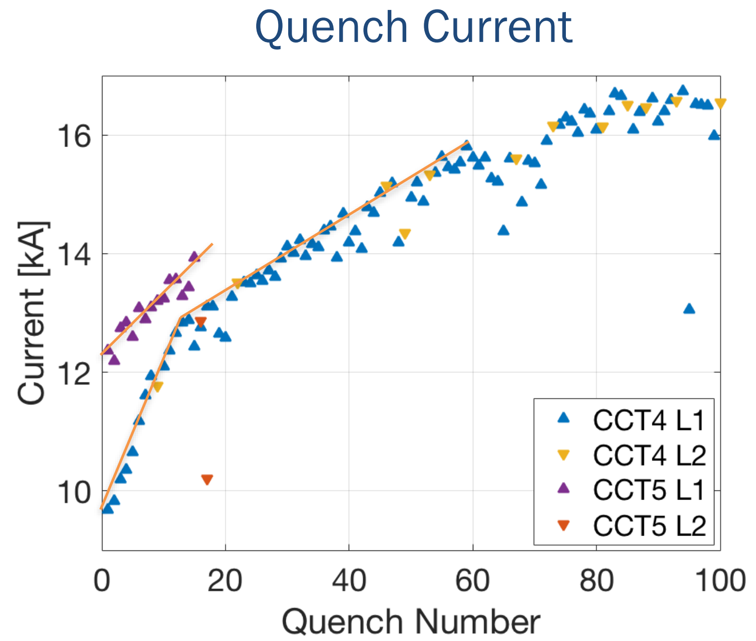
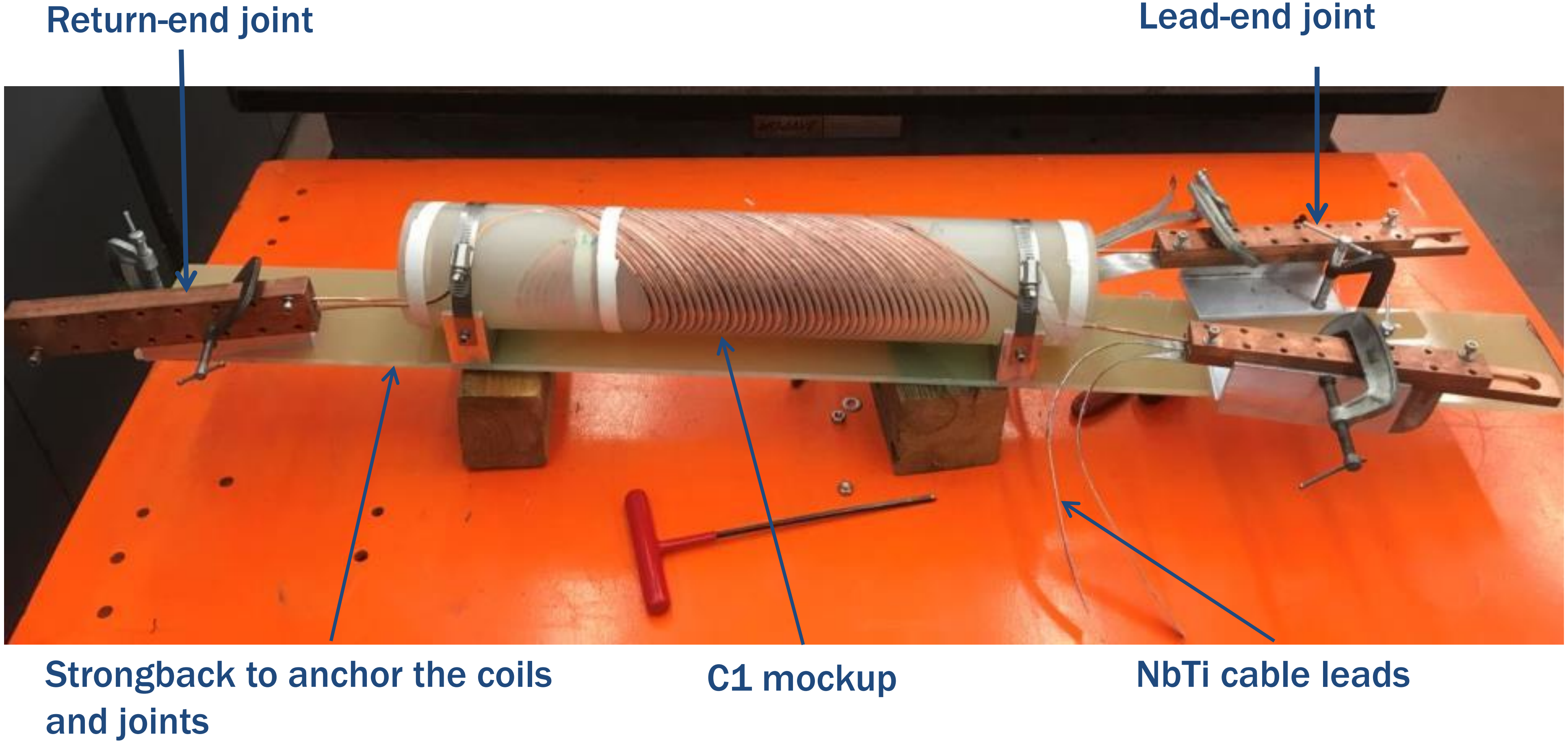
First Quench Training Results

- First quench at 69% of short sample
- Magnet reached 78% of short sample after 15 training quenches
- Outer layer (L2) quench current drops substantially after highest current quench
    - Quench was initiated in the inner layer (L1)
    - Irregular voltage develops during extraction
- Improvement in early training (e.g. first quench current) and training rate possibly improved, but not dramatically

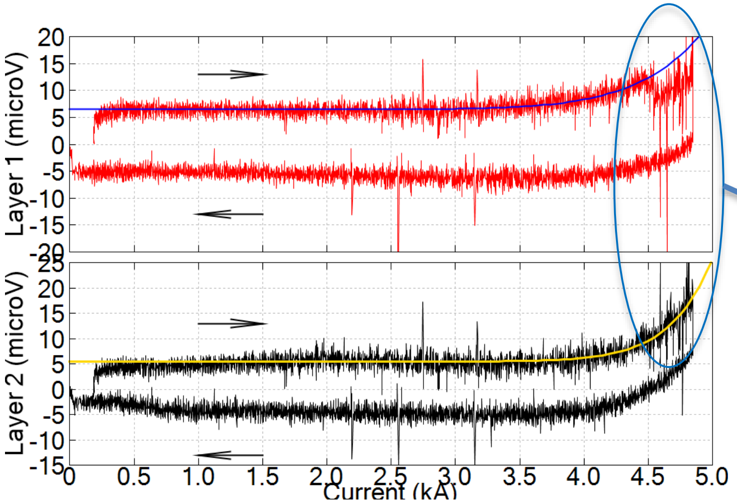


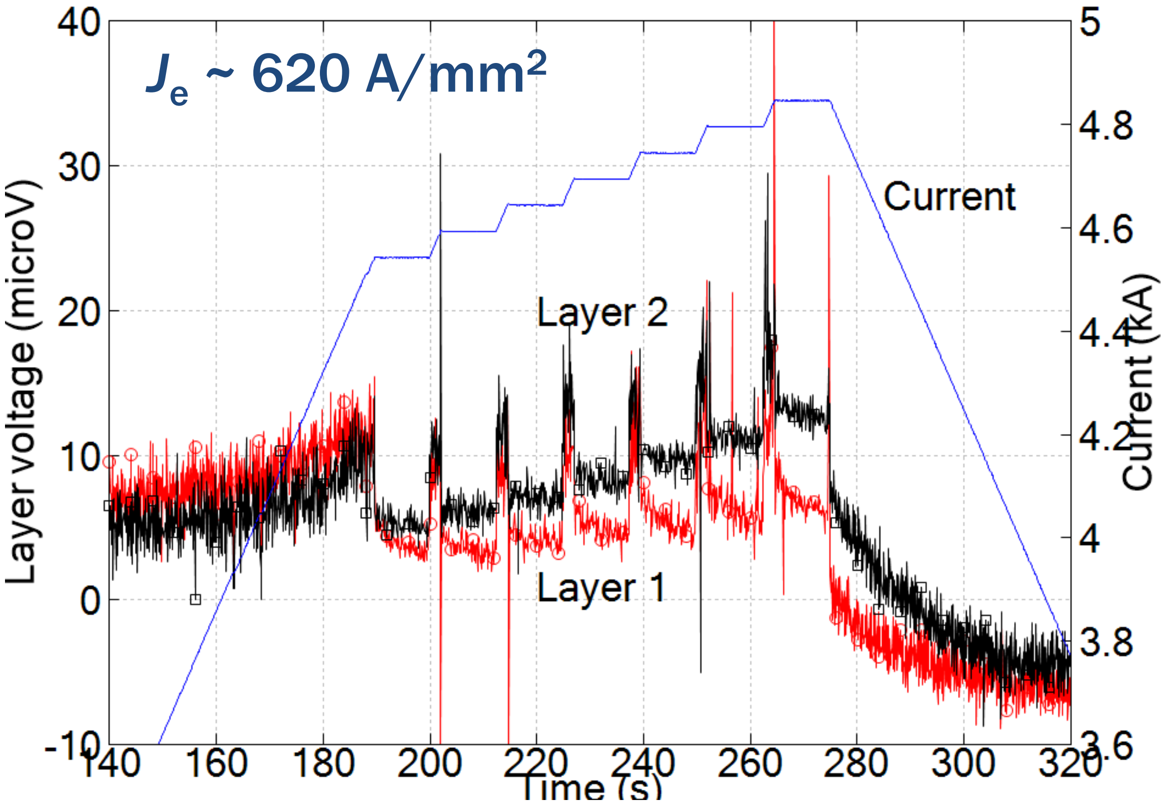


Successfully scaled up and developed C1 magnet, the first 2-layer CORC® CCT dipole magnet



C1 showed high thermal stability during the superconducting-normal transition



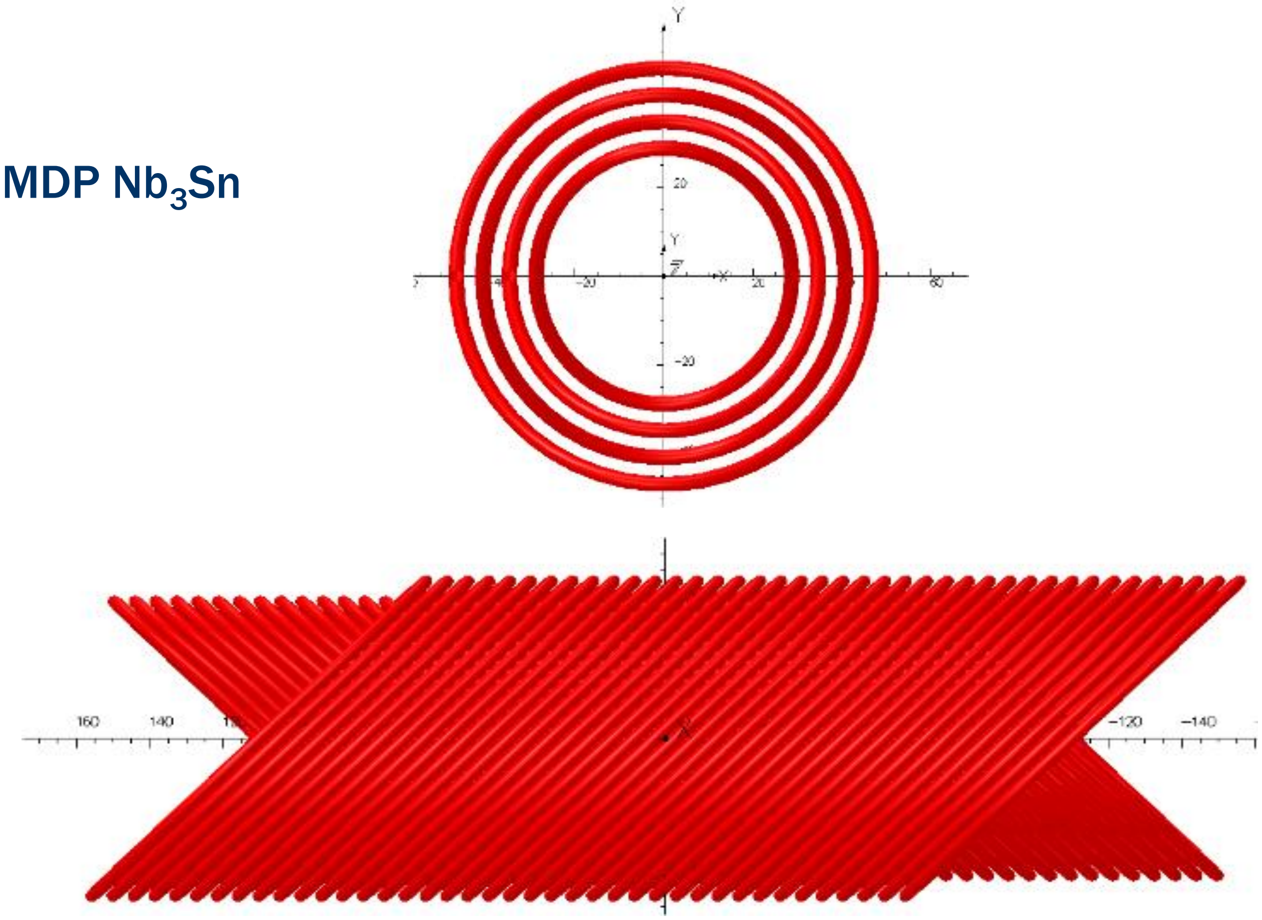


100 mW peak power generation without thermal runaway

- Enable stable magnets that have no training and can tolerate high heat load
- Next CCT magnets will be impregnated and thermal stability will be evaluated

Based on the C1 experience, we are making C2 magnet as a next step

- ## 4-layer design
  - 3 T at 4.2 K and 8 kA
  - 70 mm ID, 130 mm OD (compatible with a future MDP Nb_3Sn outsert for hybrid testing)
  - 630 mm long
  - Tilt angle: 50° for Layer 1/2; 35° for Layer 3/4
- ## 30-tape CORC® wire
  - SuperPower 30 μm substrate
  - 81 m long wire (4.2 km of tape)
  - Wire OD: 3.65 mm
  - Minimum bending radius: 30 mm



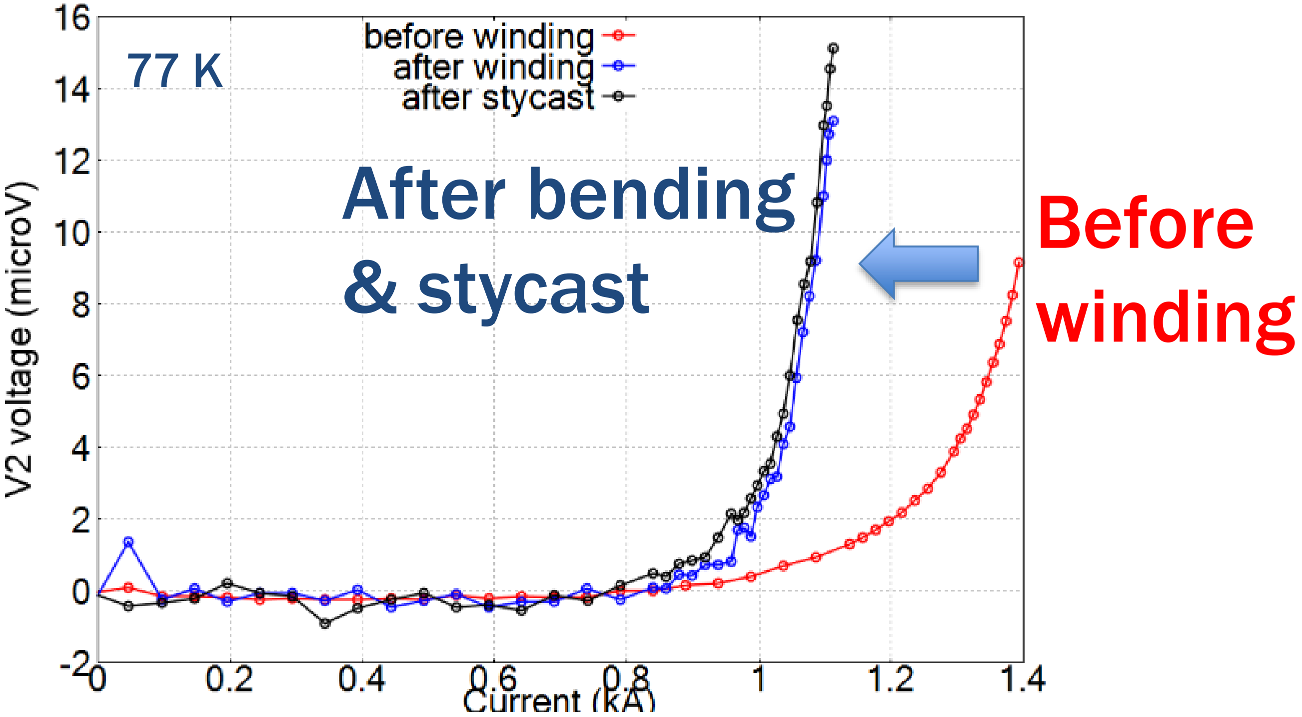
C2 will test several key technology features required for high-field REBCO accelerator insert magnets

- Develop strong metal mandrels
  - Friendly design for coil winding
  - Convenient to machine
  - Aluminum-Bronze (leveraging MDP Nb_3Sn CCT knowledge)

- Constrain conductors with epoxy
  - Stycast 2850 MT

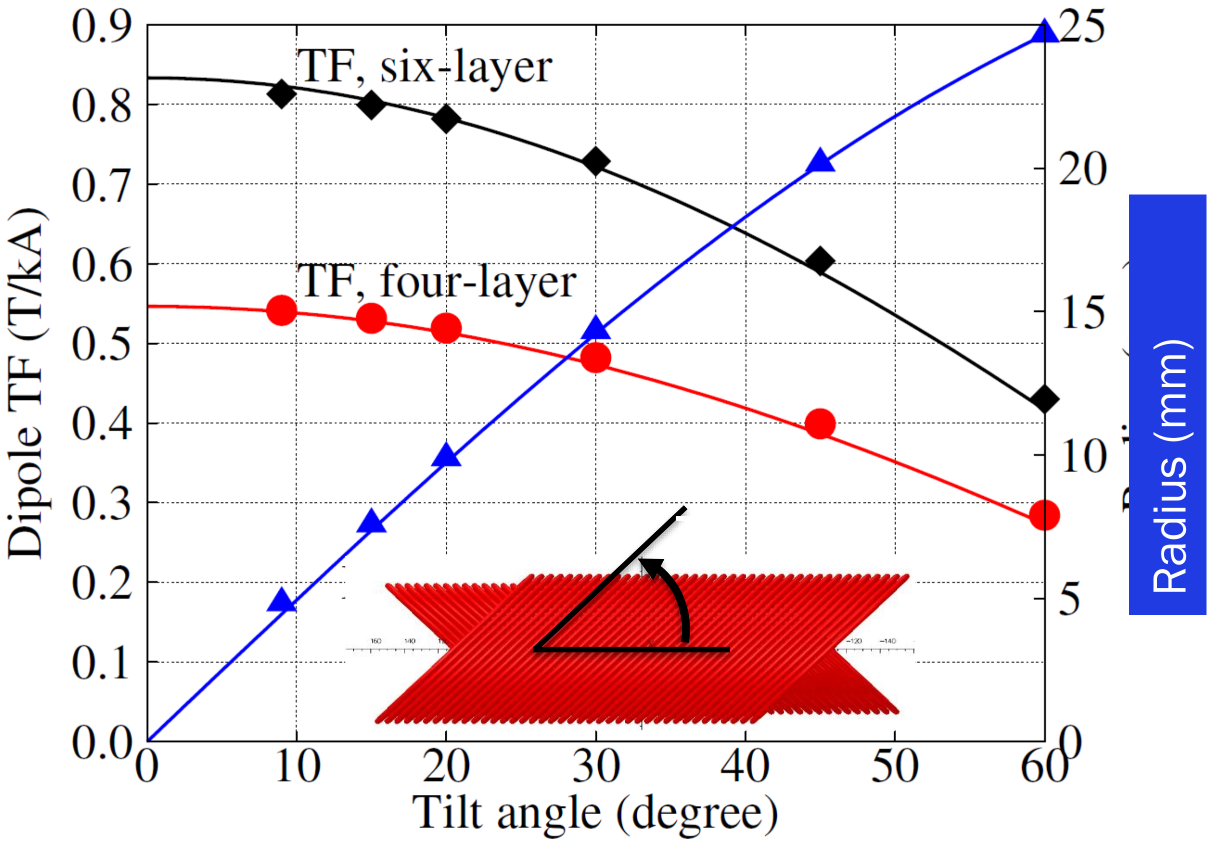
3-turn subscale coils provided first positive feedback on the wire performance for C2 magnet

C2 wires will be bent to a minimum radius of 30 mm



- 2 – 3 m long CORC® wire used for each 3-turn coil
- We observed 27% I_c reduction at 77 K after winding and applying stycast
- Stycast has negligible impact (1% I_c reduction)

More flexible high-current REBCO wires are critical to demonstrate higher dipole fields



Wang et al., 2018 SuST, 31, 045007

- Thinner tapes are the key
  - They permit smaller CORC® bending radii and tilt angles → higher dipole fields
  - 30 μm substrate → 25 μm corresponds to 25% increase in J_e
  - Increase pinning performance at 4.2 K
- The resulting tapes will have strong technology and market impact
  - Need to develop them now

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Summary comments

- This provides a snapshot of a subset of MDP activities
  - Note that significant work is ongoing at FNAL and at ASC/NHMFL as part of MDP as well

- Other areas that may serve for dedicated presentations in the future include…
  - Advances in modeling, e.g. custom FEA elements
  - Advances in diagnostics, e.g. active acoustics and machine learning
  - Advances in Nb_3Sn superconductors
  - Developments in epoxies
  - …