U.S. MAGNET DEVELOPMENT PROGRAM

Recent results of the US Magnet Development Program and outlook to the future

Presentation to the HL-LHC CM, 14 October 2019

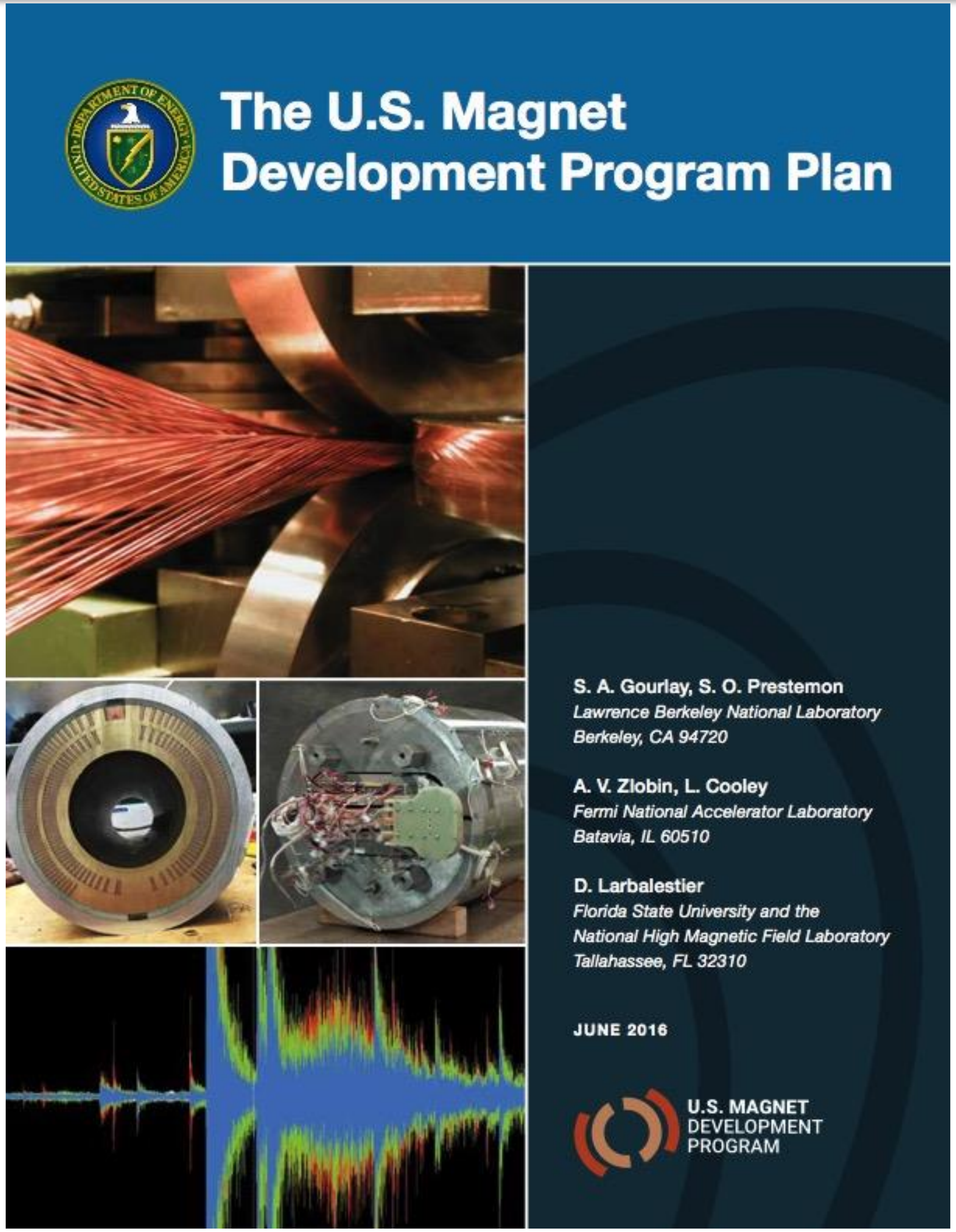
Alexander Zlobin
for the US Magnet Development Program

U.S. MAGNET DEVELOPMENT PROGRAM

The US MDP Team with Collaborators and Guests at CM3 at Fermilab, 11-13 January 2019

Outline:
- US-MDP goals, structure, directions and tasks
- Work status
- MDPCT1 fabrication, first test and next steps
- US-MDP outlook to the future

The US Magnet Development Program



- US-MDP was founded by DOE-OHEP in 2016 (FY17) to advance superconducting magnet technology for future colliders
- Strong support from the Physics Prioritization Panel (P5) and its sub-panel on Accelerator R&D
- A clear set of goals guides the program
- Technology roadmaps for each area:
  - LTS and HTS magnets,
  - Technology
  - Conductor R&D

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.

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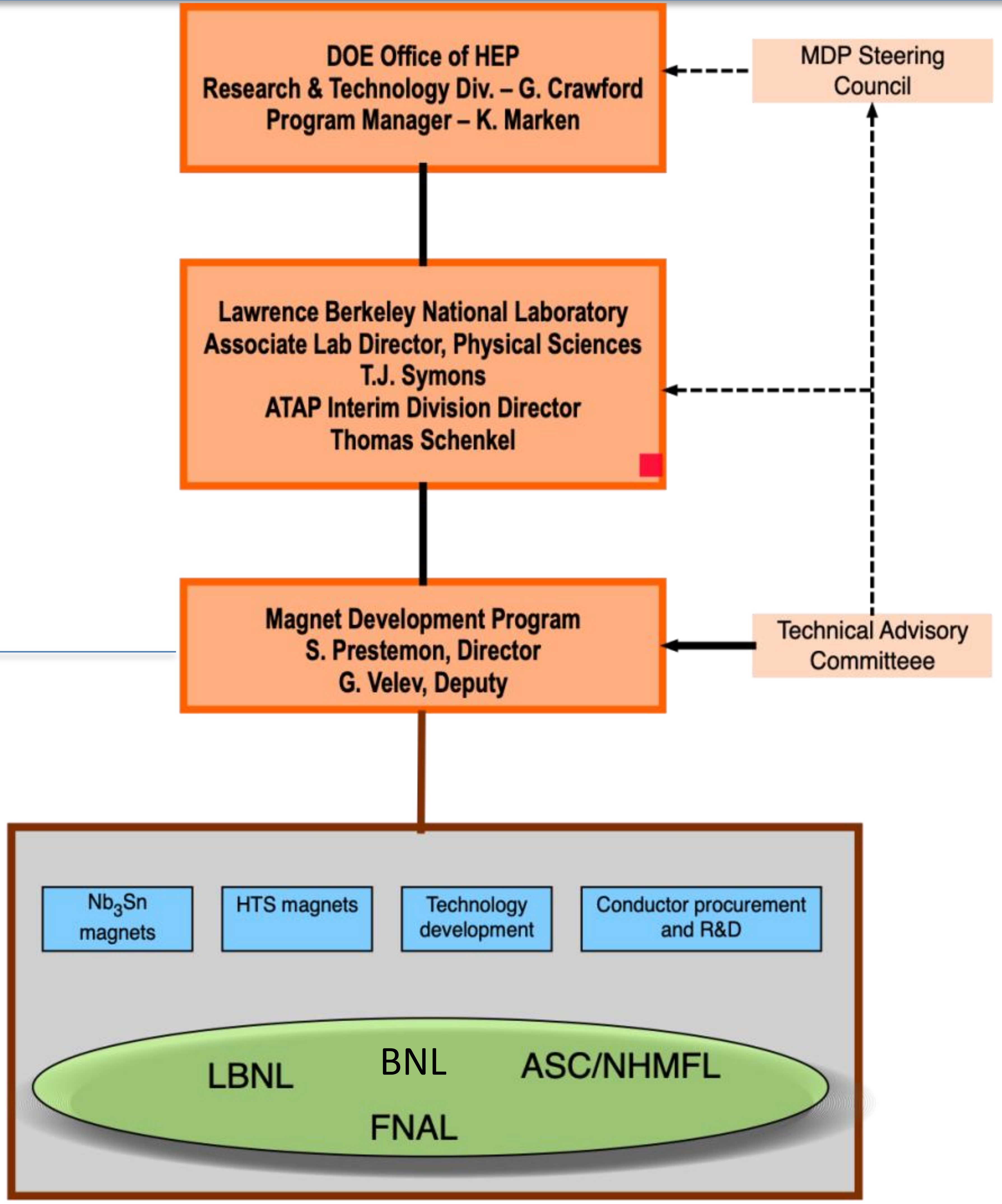
US-MDP Management Structure



MDP Management Group ("G7")
- S. Prestemon, S. Gourlay (LBNL)
- G. Velev, A. Zlobin (FNAL)
- L. Cooley, D. Larbalestier (FSU)
- K. Amm (BNL)

Steering Council
- Harry Weerts (ANL), DOE appointed – ***Chair***
- Mike Harrison (BNL), DOE appointed
- Mike Witherell/James Symons (LBNL)
- Nigel Lockyer/Sergey Belomestnykh (FNAL)
- Greg Boebinger/Eric Palm (NHMFL)

Technical Advisory Committee
- Andrew Lankford (UC Irvine) – ***Chair***
- Davide Tommasini (CERN)
- Akira Yamamoto (KEK)
- Joe Minervini (MIT)
- Giorgio Apollinari (FNAL)
- Mark Palmer (BNL)

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Program Directions and Tasks

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

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

Conductor Procurement and R&D	Lance Cooley

US Magnet Development Program (MDP) Goals:

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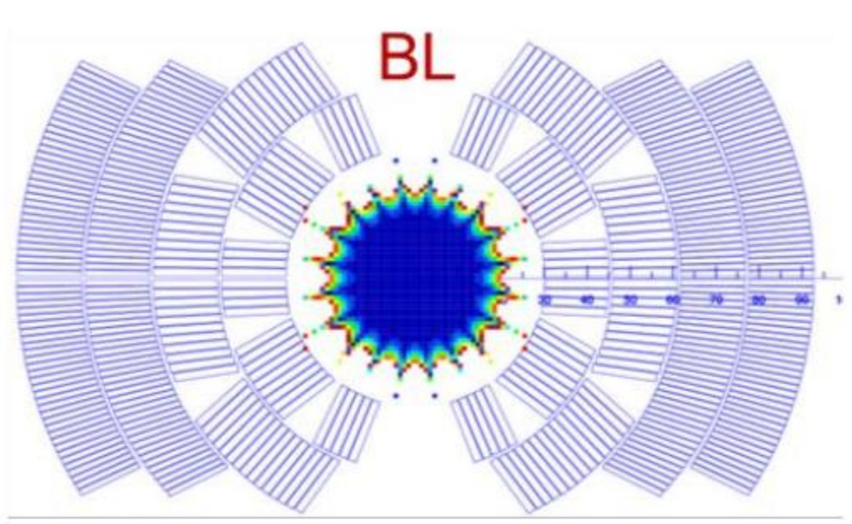
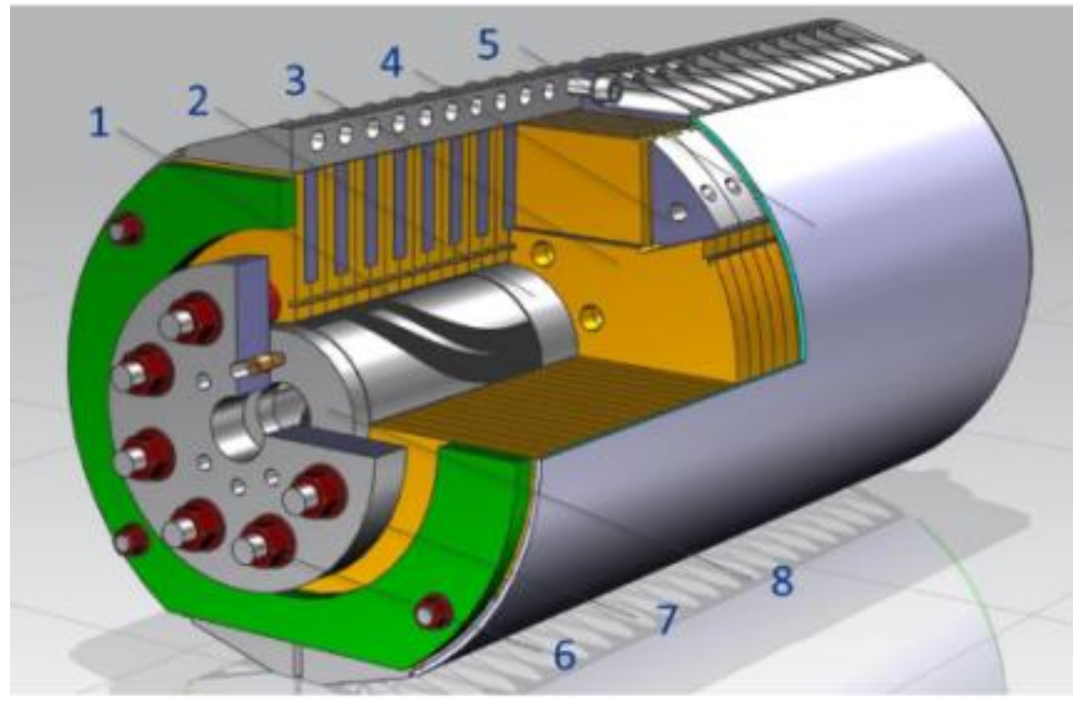
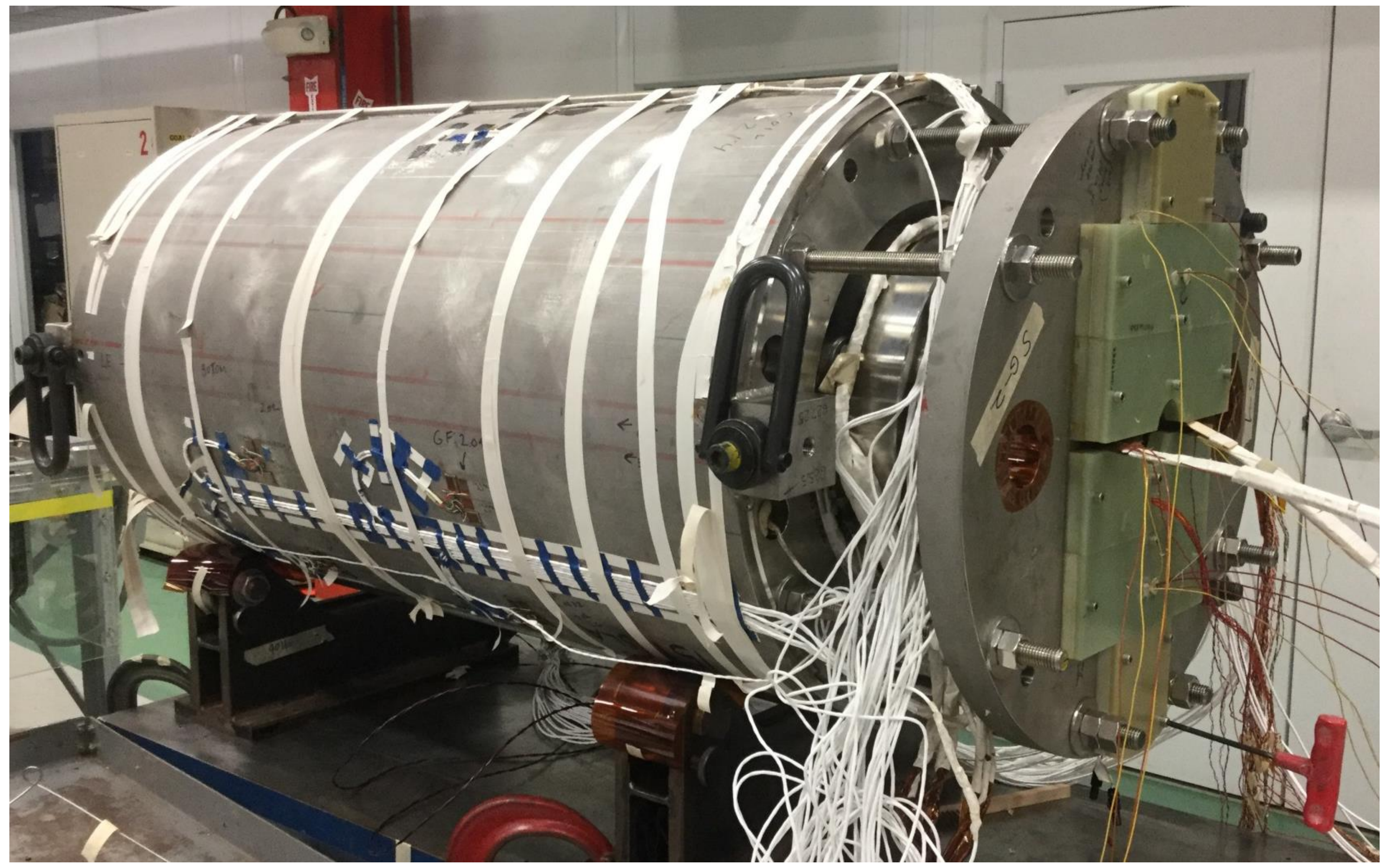
Nb_3Sn Magnets

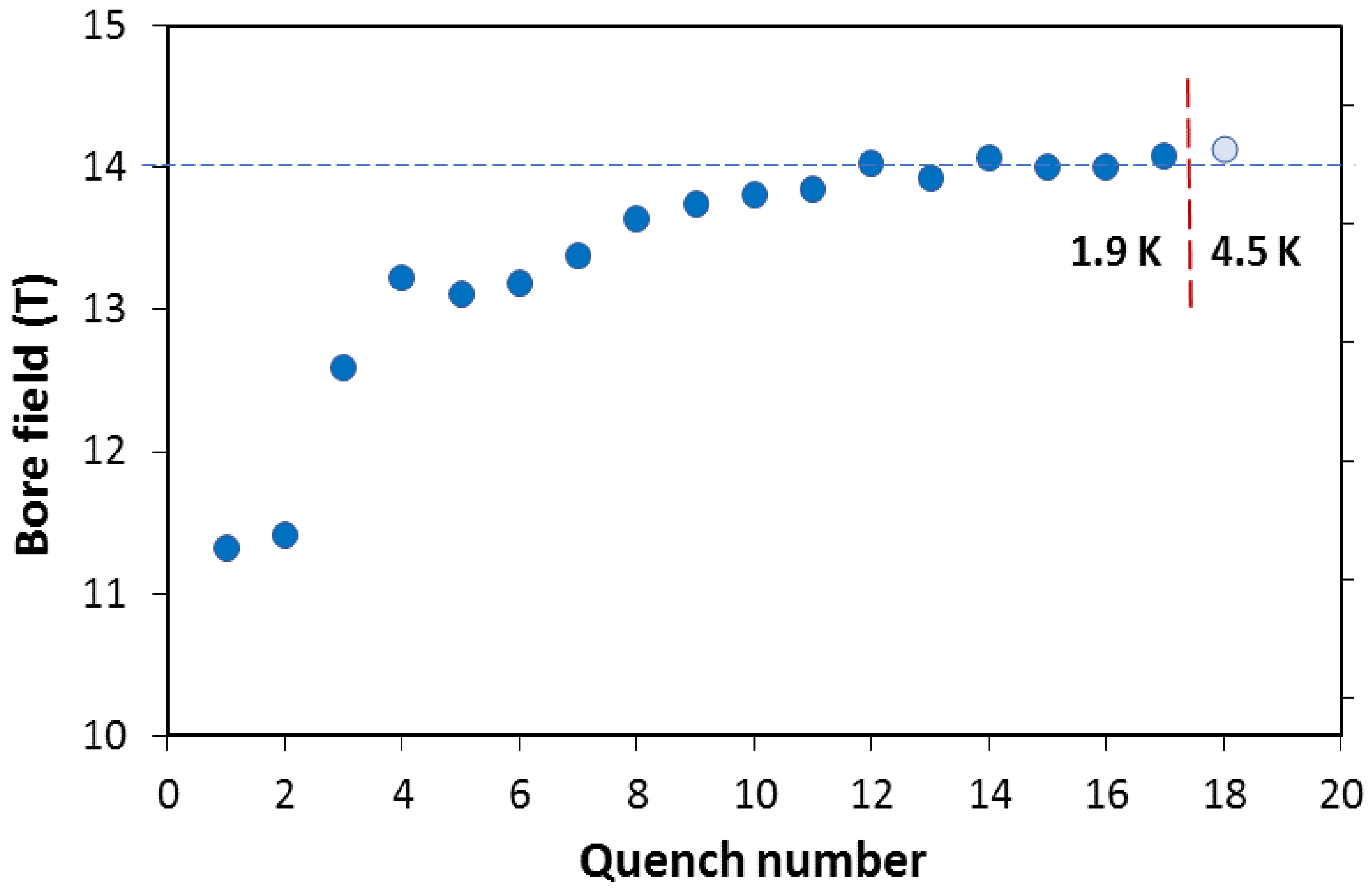
A Cos(θ) design with minimized mid-plane stress

- 60-mm aperture, 4-layer graded coil



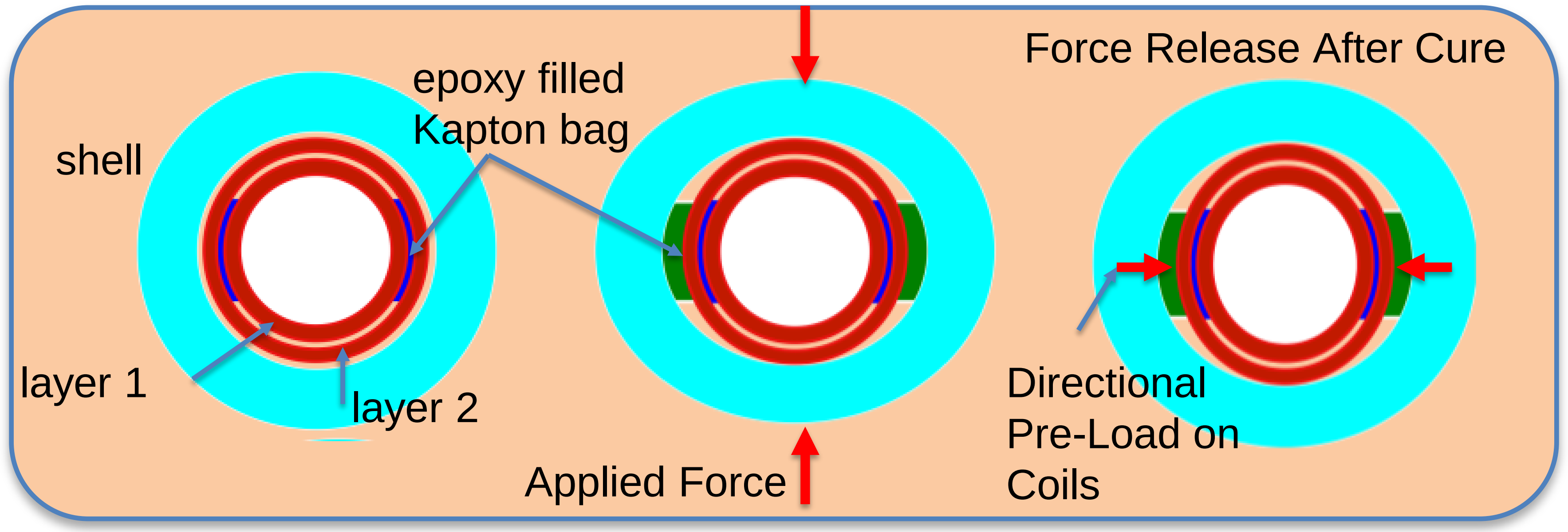


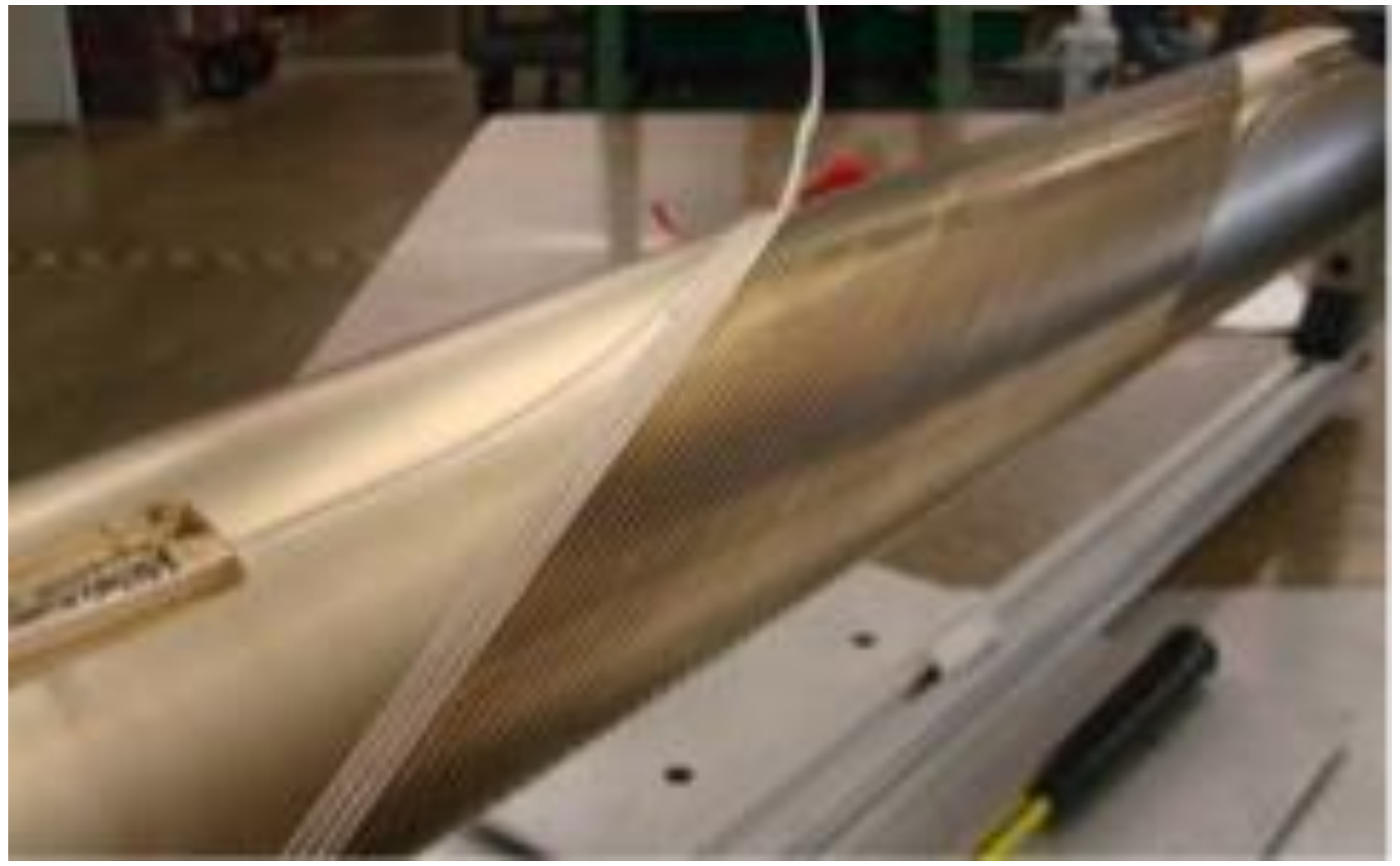


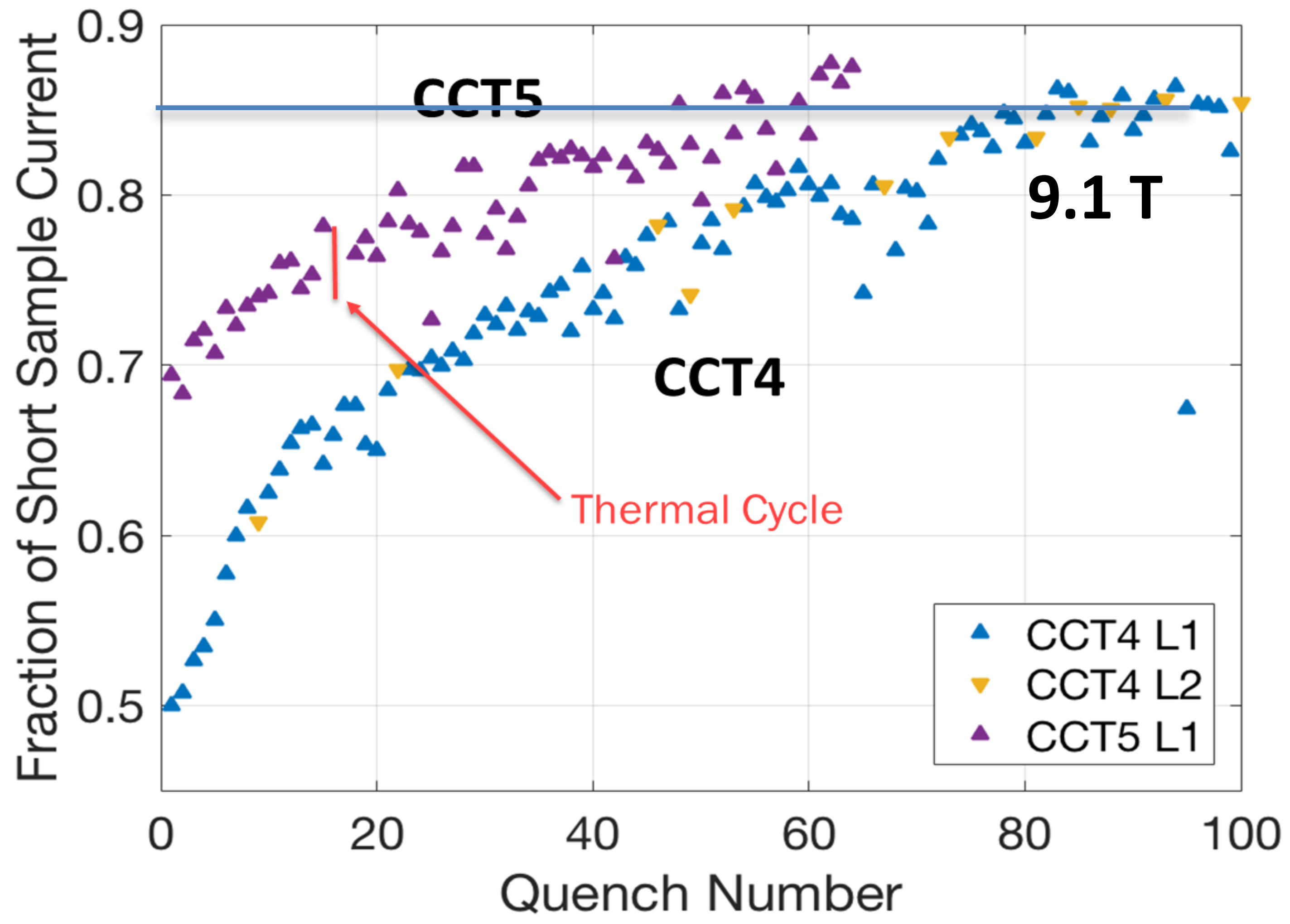


Canted Cosine-theta:

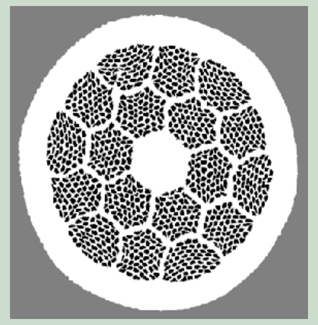
- New concept - high-risk high-reward
- Introduce "stress management" to scale to higher field







HTS Magnets



nGimat

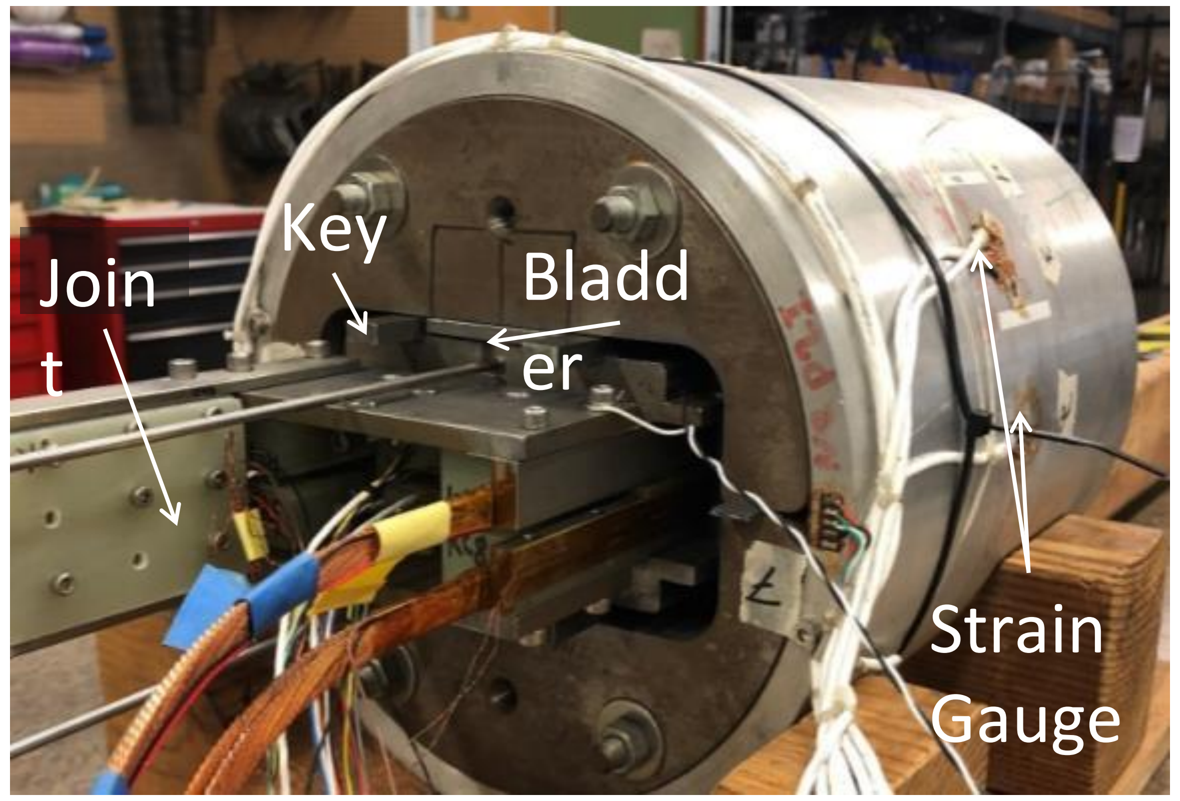
NATIONAL MAGLAB ASC

BRUKER

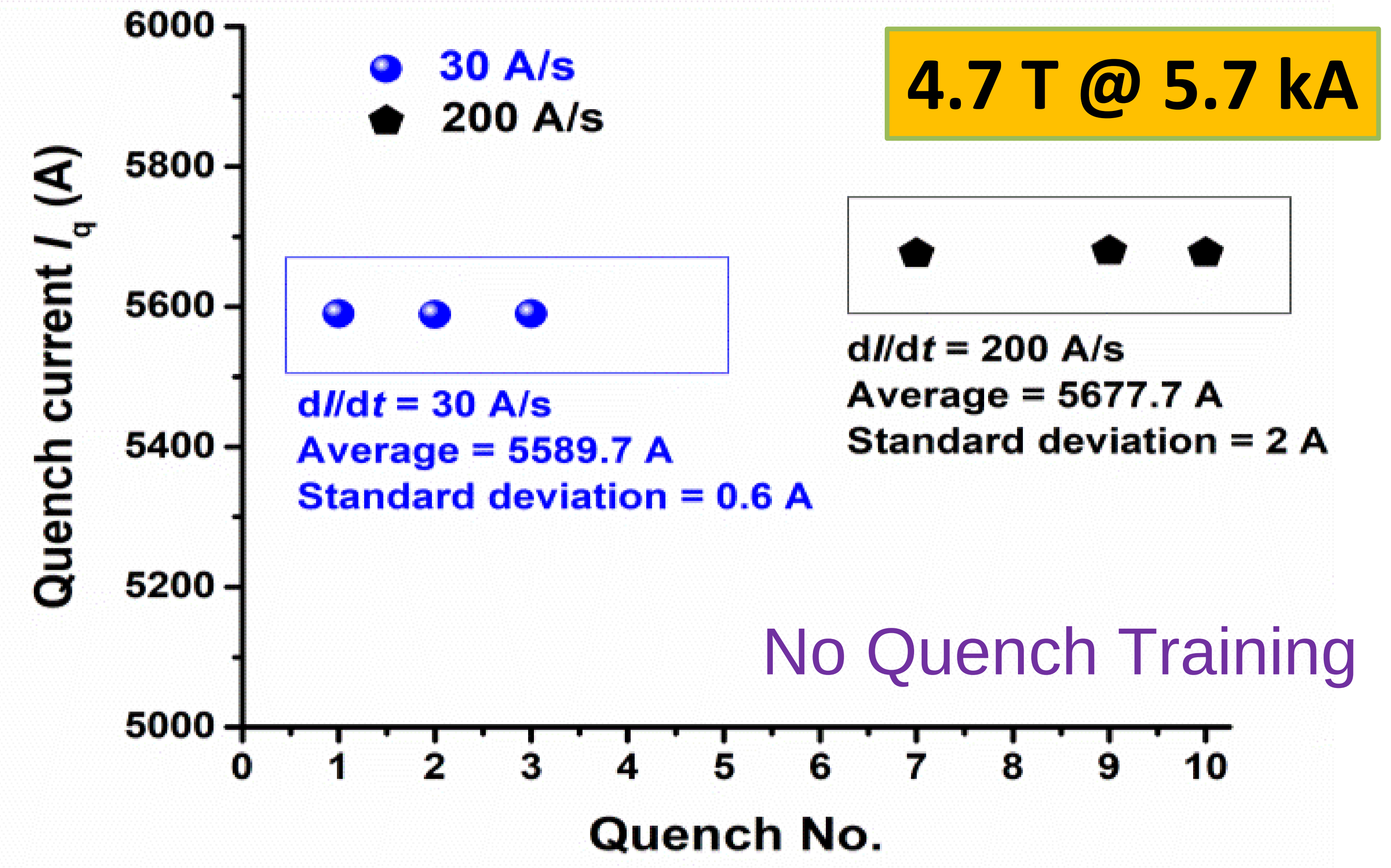
BERKELEY LAB

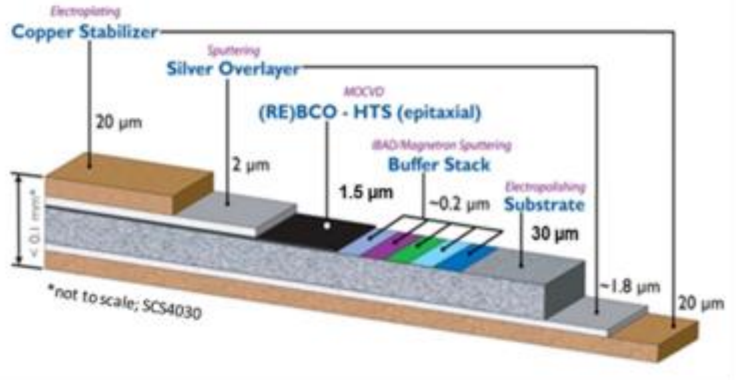
Bi2212 – multi-filamentary round wire

- **Nano-spray combustion powder technology**
- **J_e(15T)- 1365 A/mm²**
- **Bi2212 now *exceeds RRP J_E at 11T!***



Conductor improvements =>magnet improvements

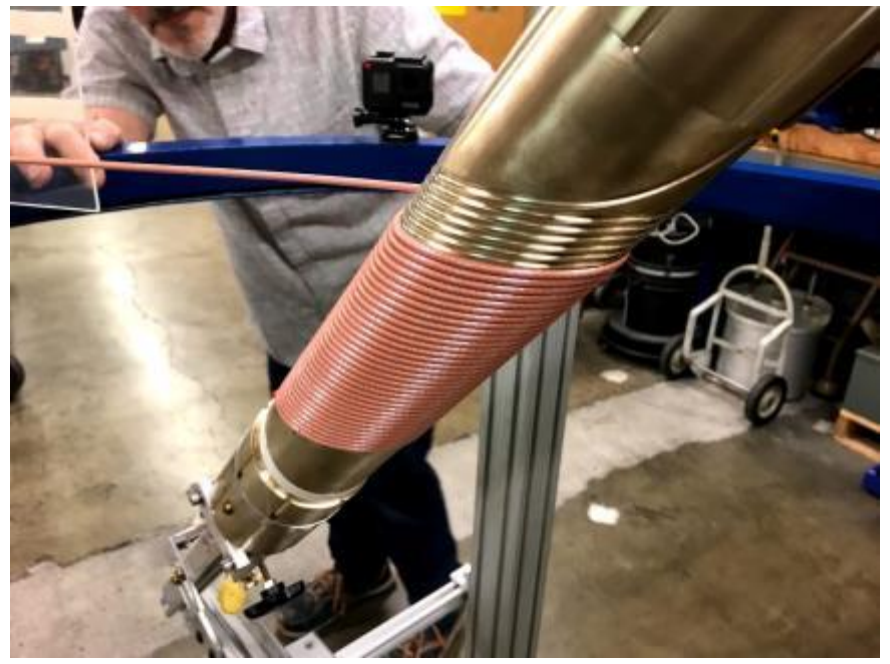




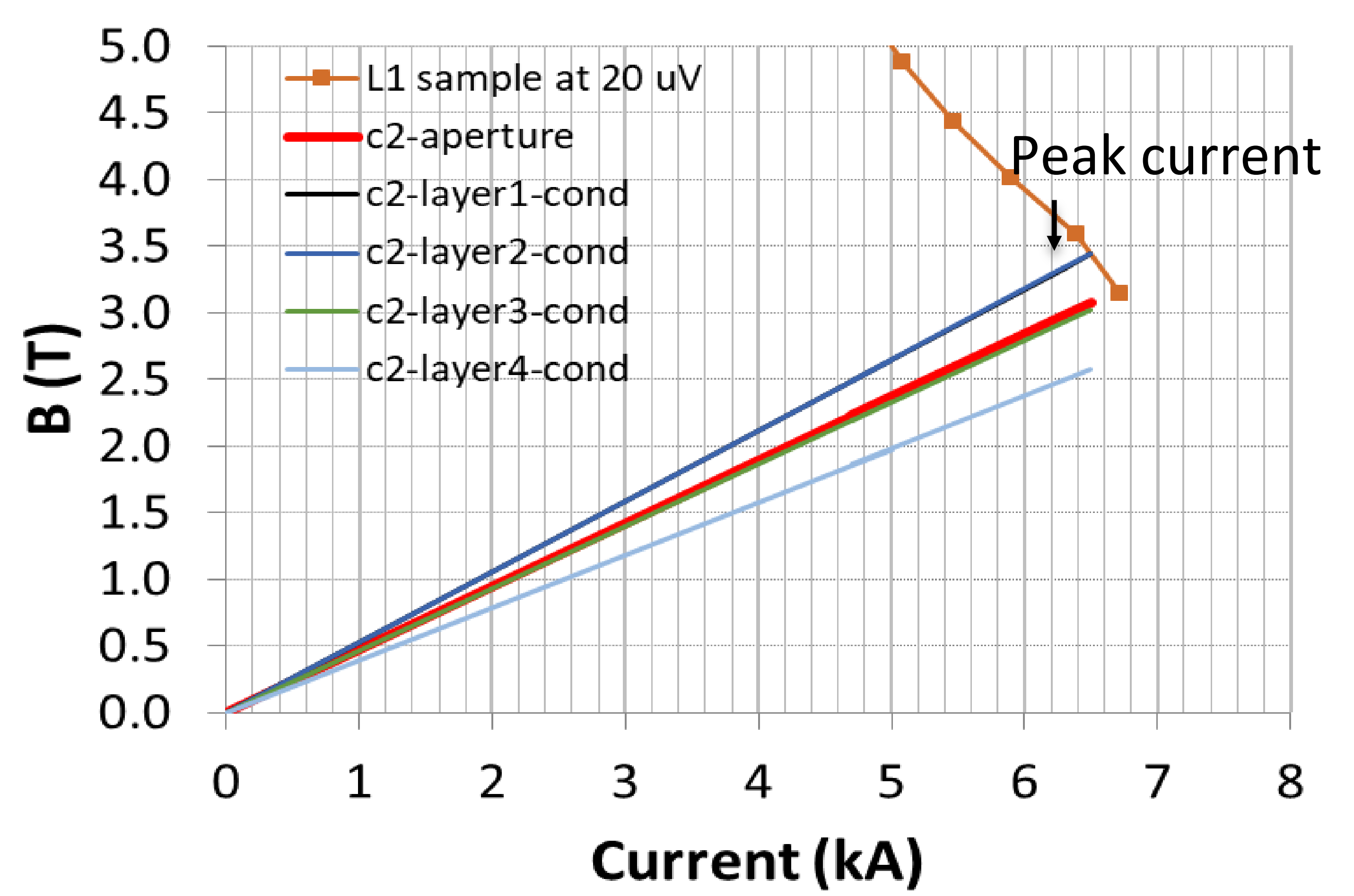
REBCO tape

SuperPower Inc.
A Furukawa Company

Advanced Conductor Technologies LLC
www.advancedconductor.com



- **C2 reached 2.9 T, 98% of the expected value**
- **Reproducible V(I) transition between ramps**



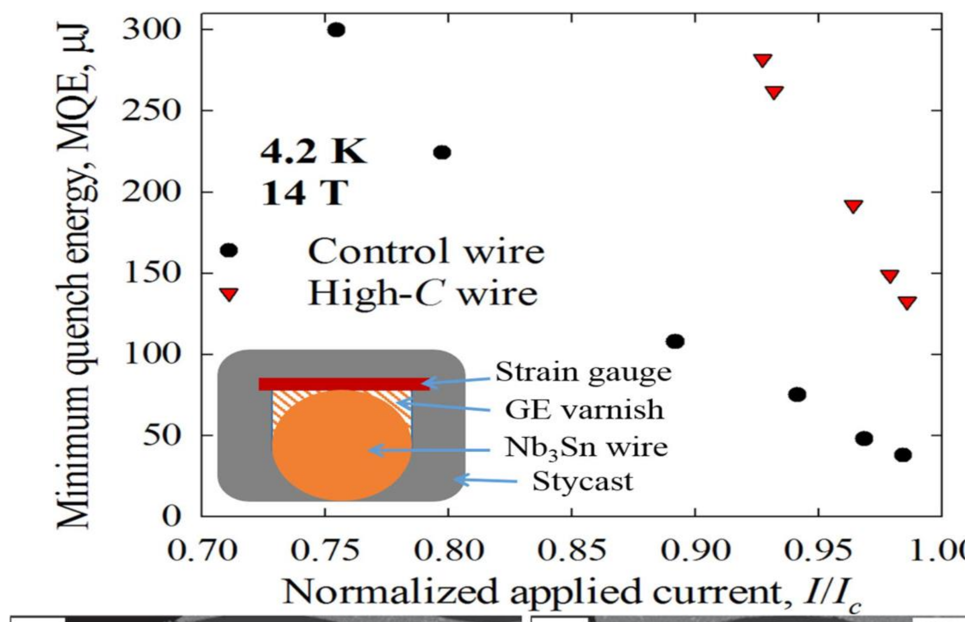
- Today: 220 A/mm² at 21 T, 4.2 K, 30 mm bend radius
- Goal: Minimum J_e(21 T, 4.2 K) at 3.7 mm wire diam.: 540 A/mm² at 15 mm bend radius

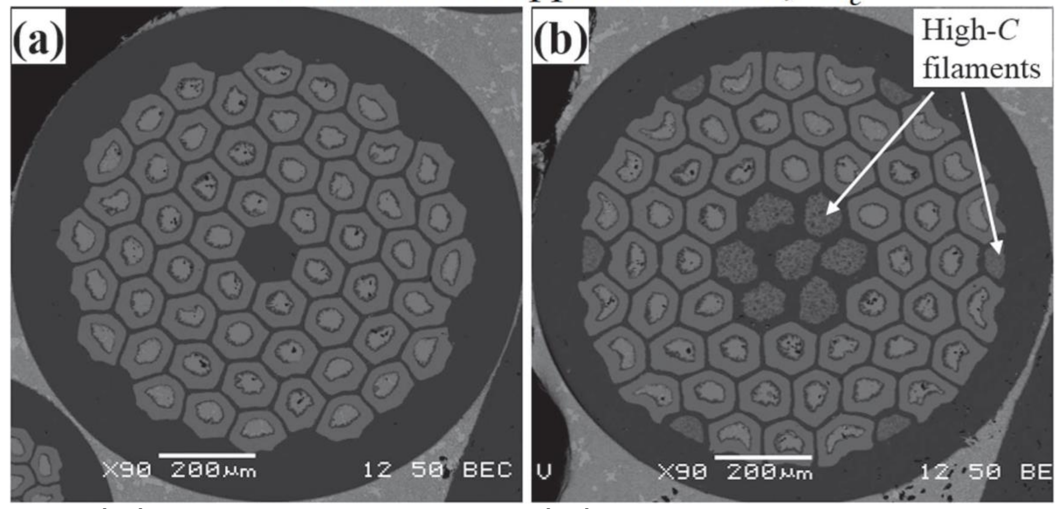
Magnet Technology R&D

- Recent publications
  - Investigation of Thermoplastic Matrix Materials for Nb_3Sn Superconducting Coils
  - Development of custom FEA elements and sharing with community
  - Structural diagnostics of superconducting magnets using diffuse field ultrasound
  - A Tear-Drop Bifilar Sample Holder for Full Excitation and Stability Studies of HTS Cables at 4.2 K Using a SC Transformer
  - An Electric-Circuit Model on the Inter-Tape Contact Resistance and Current Sharing for REBCO Cable and Magnet Applications
  - Bi-2212 High Field Magnet Development
  - QCD (quench current-boosting device)
  - … and many others!
- The First Workshop on Instrumentation and Diagnostics for Superconducting Magnets (IDSM01) https://idsm01.lbl.gov/

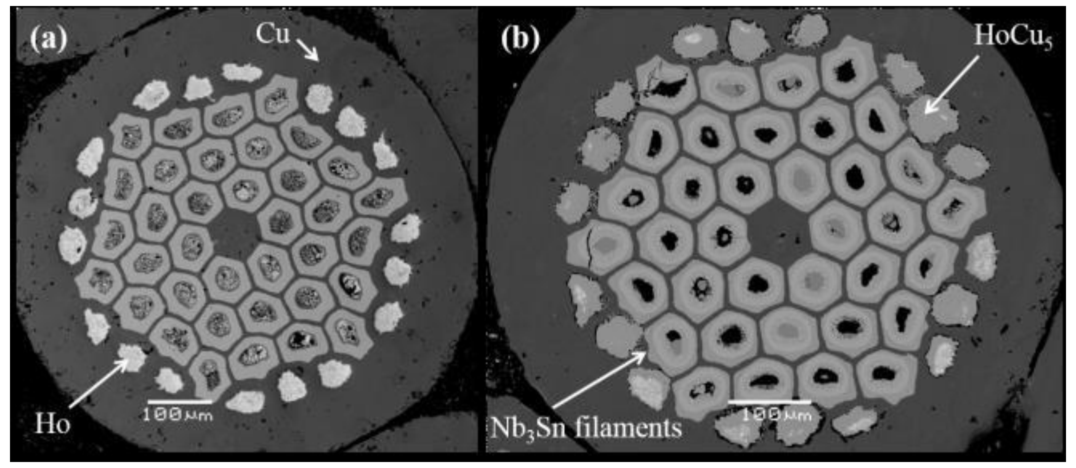
Nb_3Sn Superconductor R&D

X. Xu *et al.* on high-Cp wire



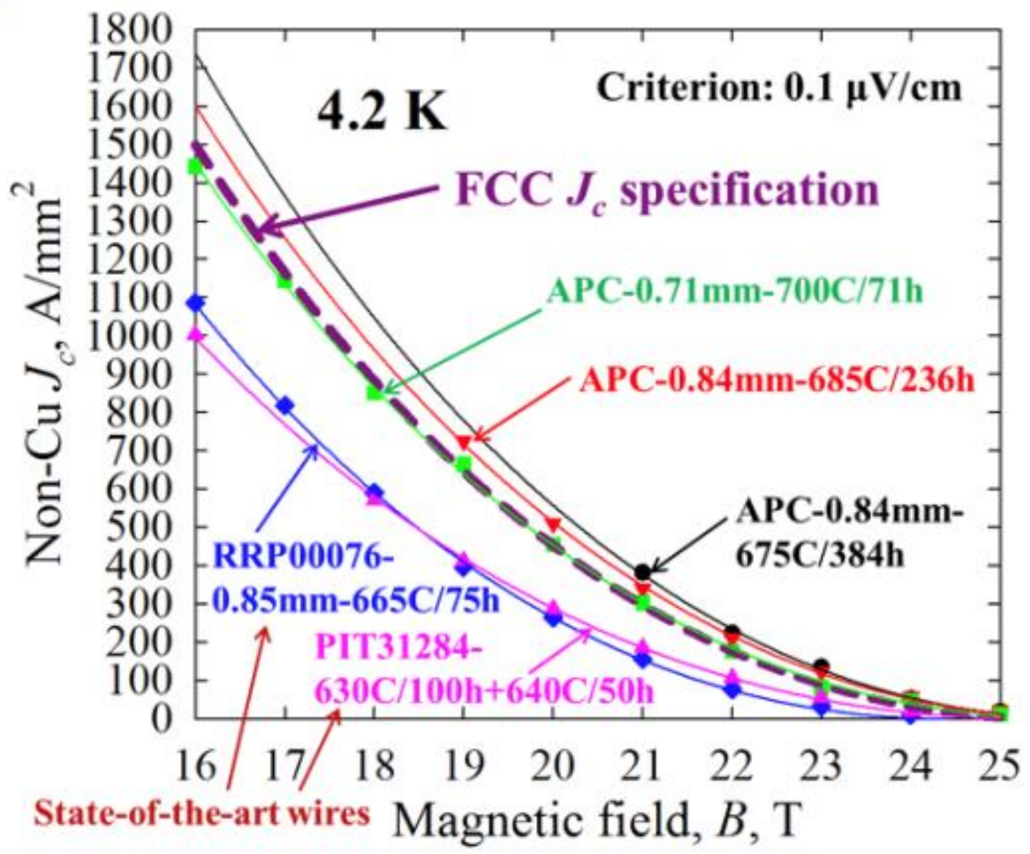


(a) the control wire, (b) the high-C wire



(a) unreacted wire with Ho-powder filaments,
(b) the wire after reaction at 640 °C for 120 hrs.

Xingchen Xu *et al.* on Artificial Pinning Center



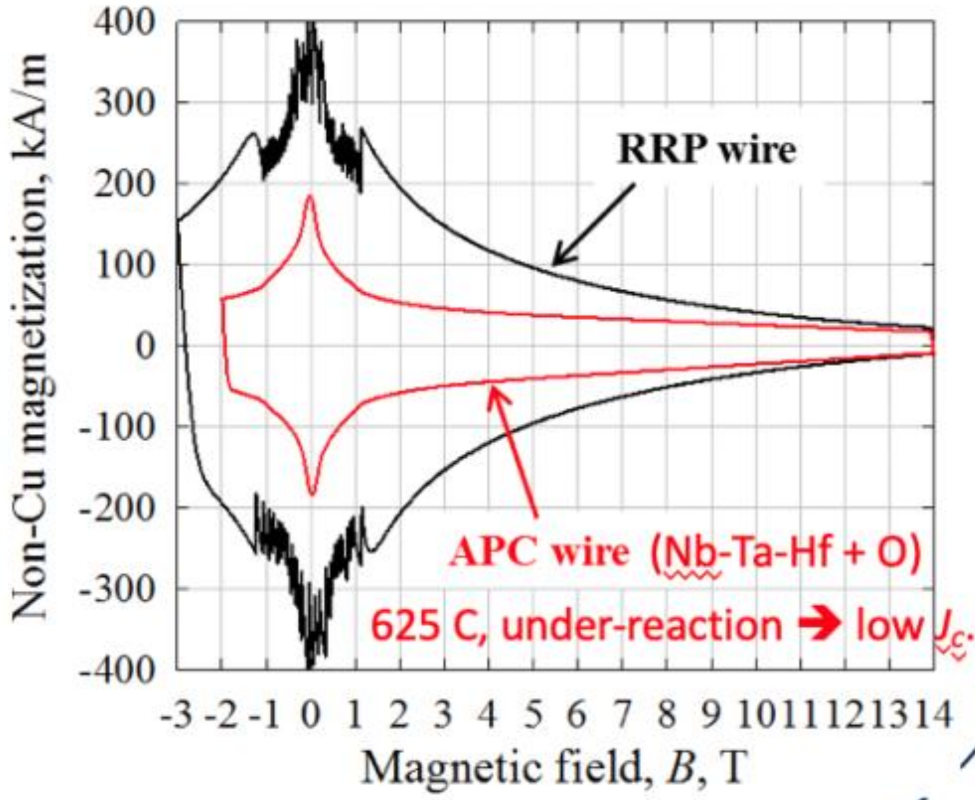
Internal oxidation of Nb-1%Zr
⇒ ZrO_2 particles
⇒ point pinning
⇒ enhance Jc

Exceptional Jc achieved, but stability <16T compromised; further optimization required

Nb3Sn has significant untapped potential

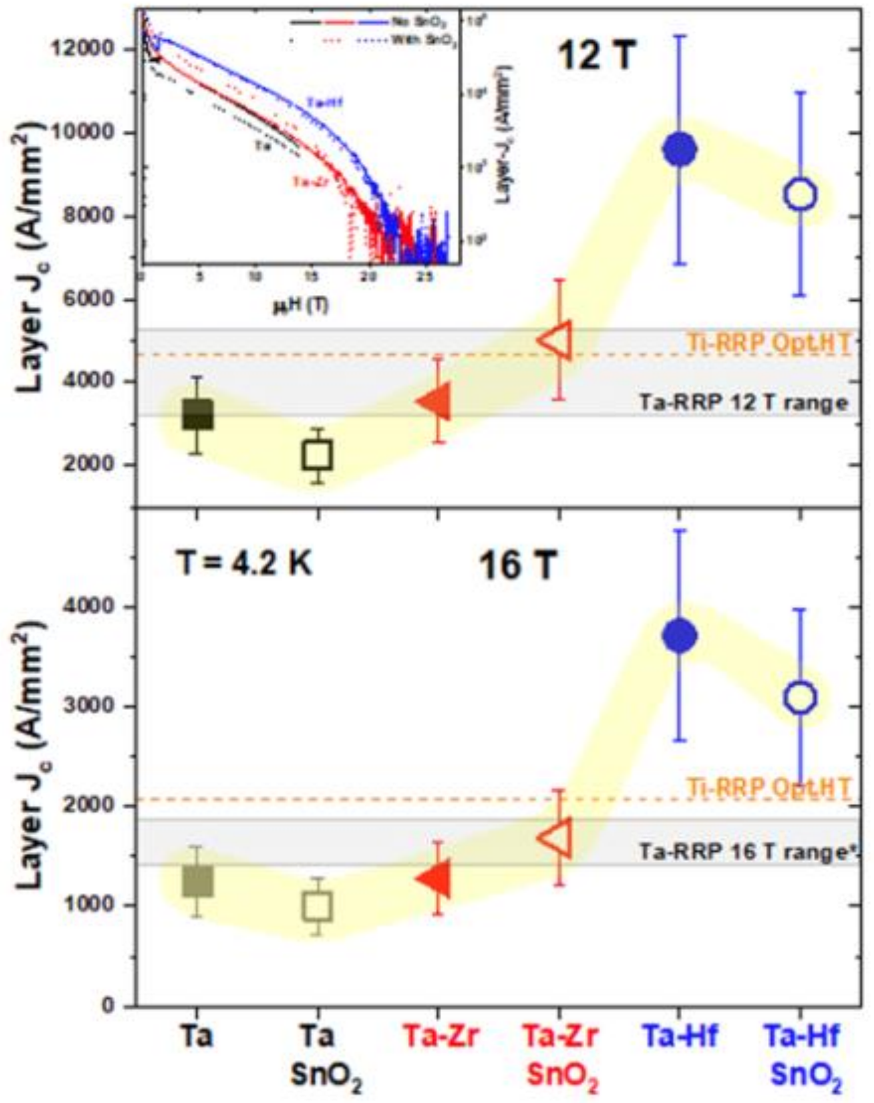
Collaboration between FNAL [LDRD], Hypertech and OSU

APC can shift Fp-B peak and flatten the magnetization curve (but compromised J_c)



09/2019

Shreyas Balachandran *et al.* on Hf alloying of Nb-Ta



550°C/100h+ 670°C/100h

- Nb-Ta-Hf alloy maintains the irreversibility field (4.2K) of 23.5T
- Fine-grain Nb_3Sn can be obtained without O additions
=> Nb or NbTa rods can be replaced by Nb-Ta-Hf alloy without change of architecture

Alloy	SnO_2	J_{clayer} (A/mm²) 12 T	16 T	Eq. RRP non-Cu J_c (A/mm²)
Nb-Ta	No	3209 ± 916	1245 ± 355	747 ± 213
Nb-Ta	Yes	2237 ± 639	1003 ± 286	602 ± 172
Nb-Ta-Zr	No	3545 ±1012	1281 ± 366	768 ± 219
Nb-Ta-Zr	Yes	5017 ±1433	1684 ± 481	1010 ± 289
Nb-Ta-Hf	No	9609 ±2744	3714 ±1061	2229 ± 636
Nb-Ta-Hf	Yes	8523 ±2434	3093 ± 883	1856 ± 530

Extrapolated values

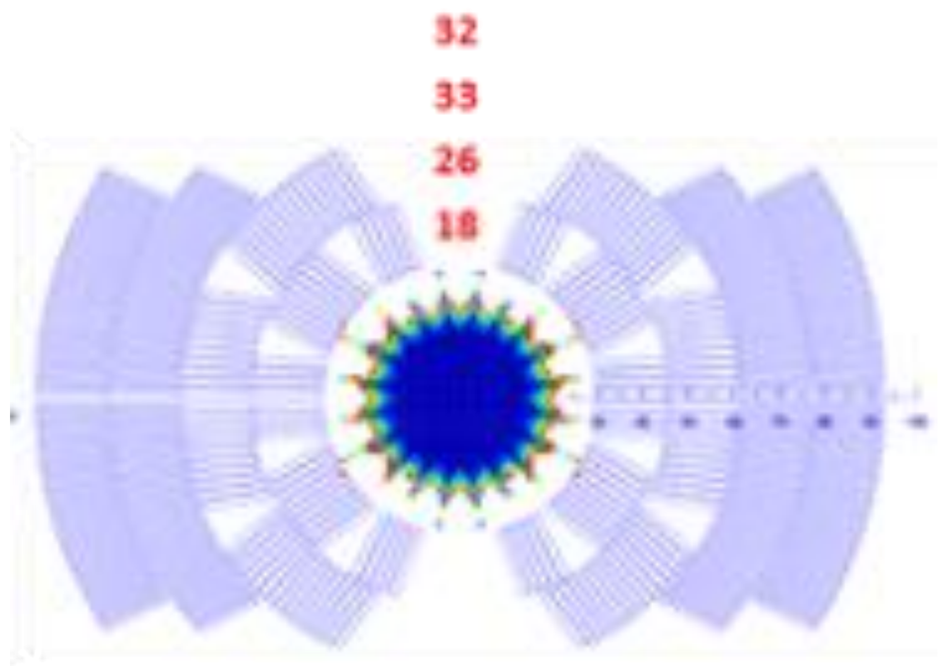
ASC/NHMFL, FSU

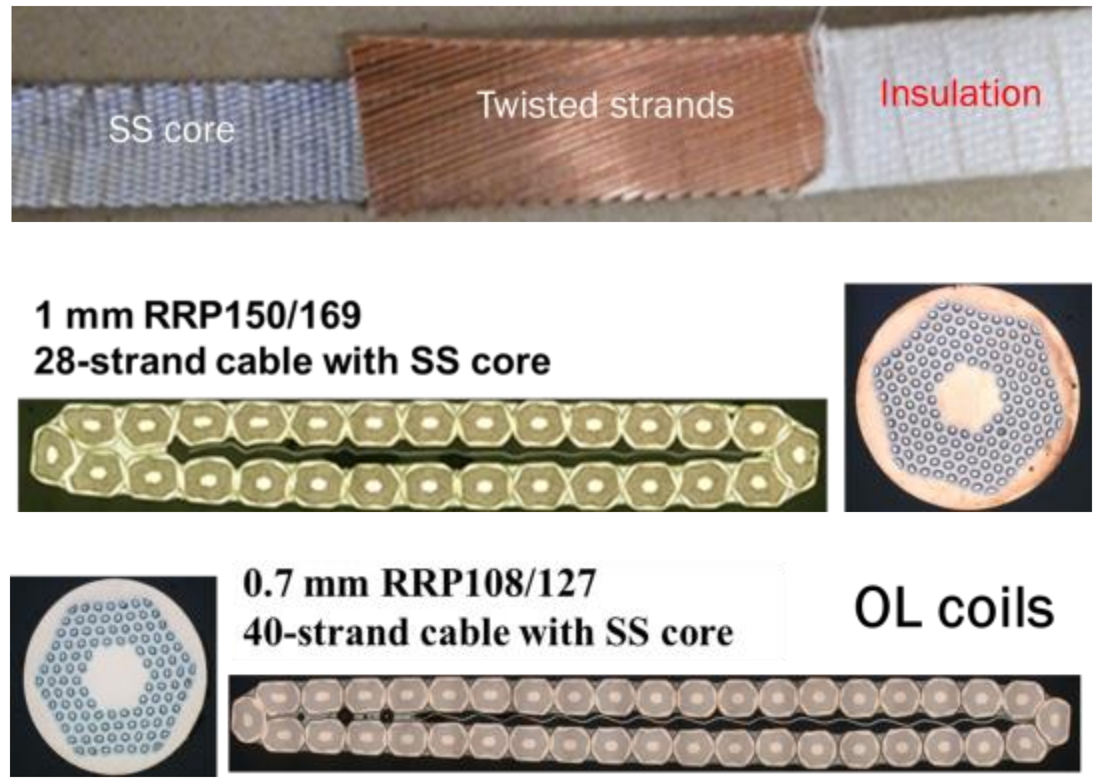
Jan Evetts SUST Award 2019

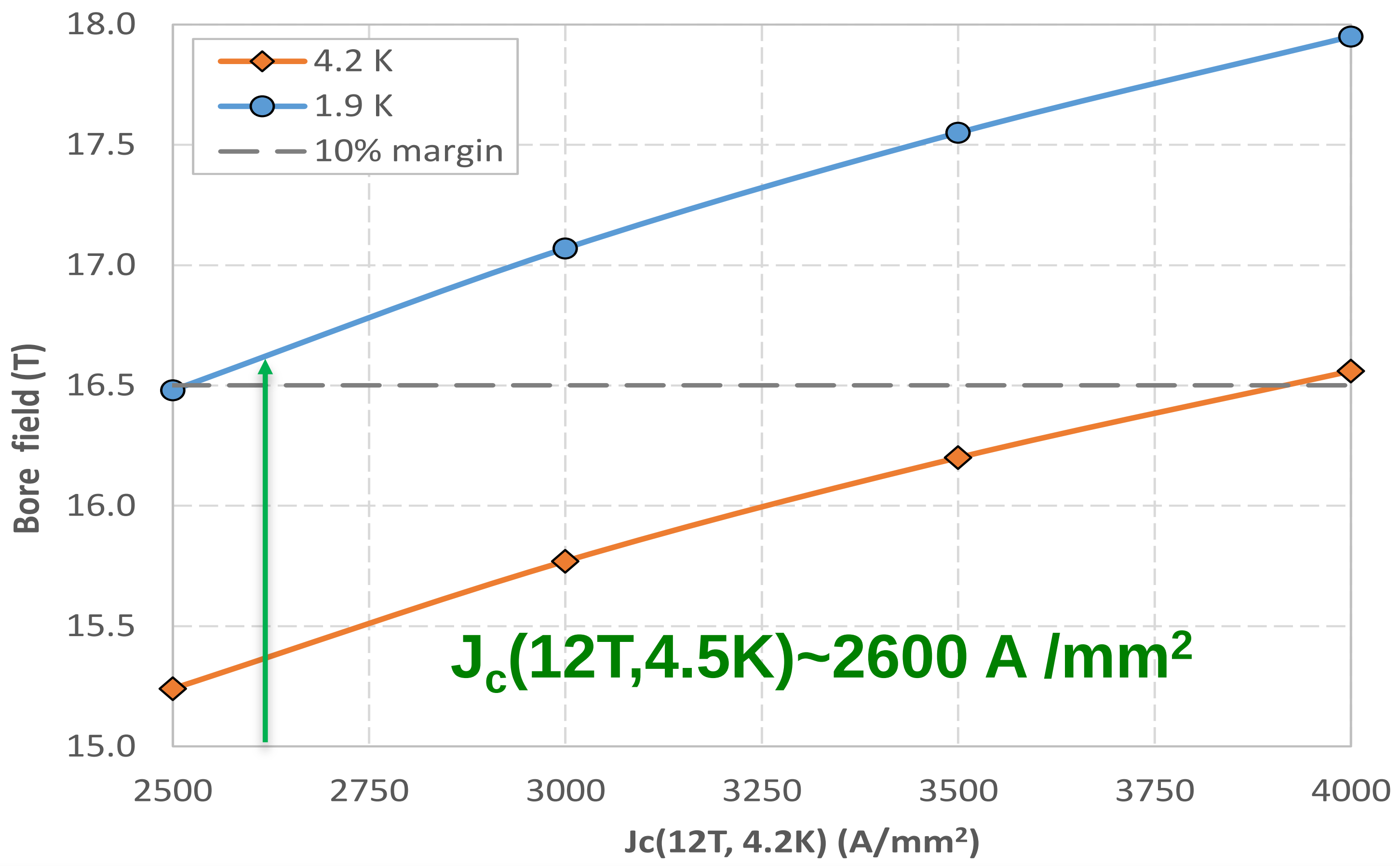
2

15 T Dipole Demonstrator (MDPCT1)

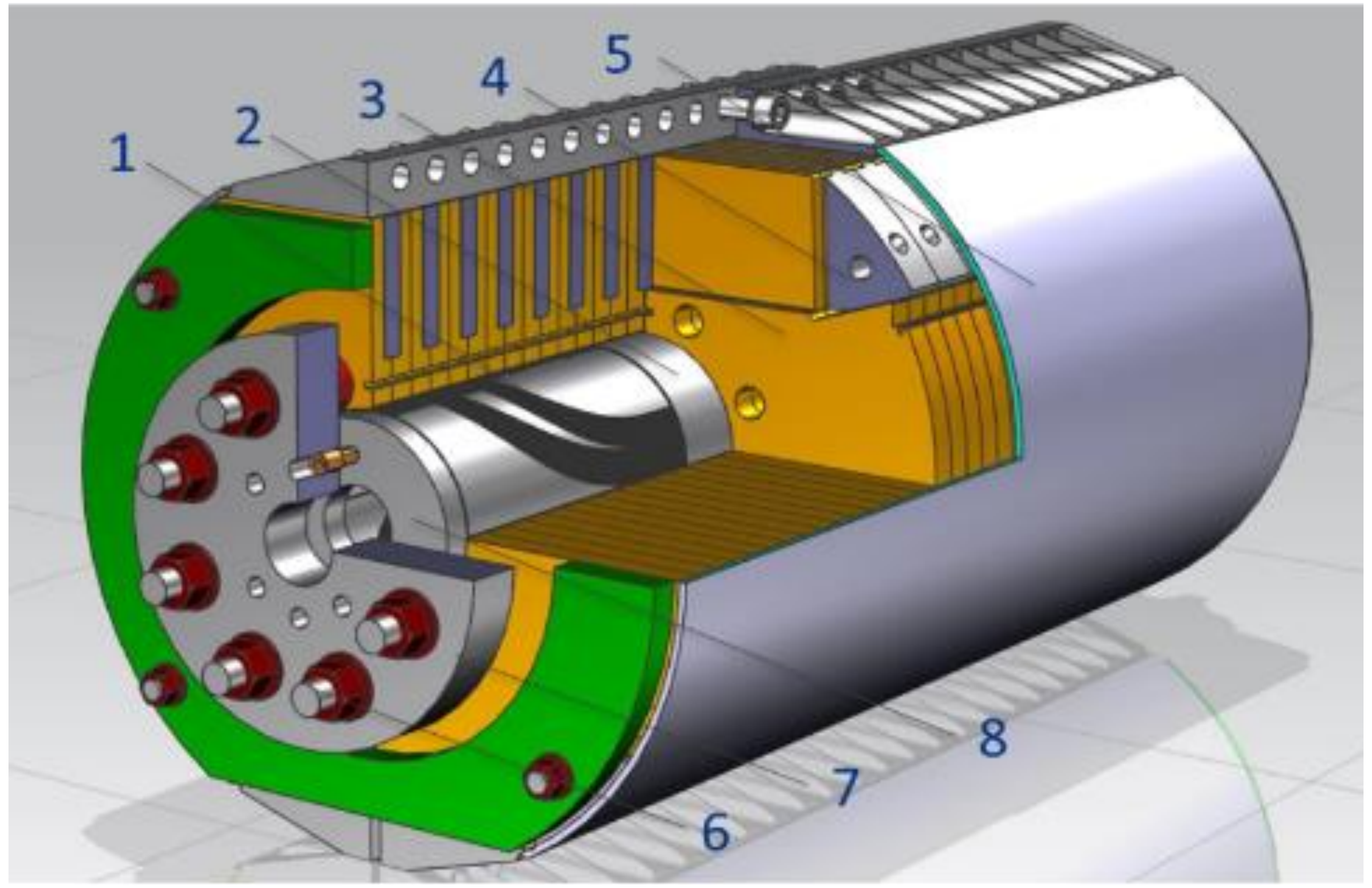
Coil geometry:
- 60-mm aperture
- Min conductor volume
- 4-layer graded shell-type coil
- Optimization criteria:
  B_{max}, FQ, forces, protection







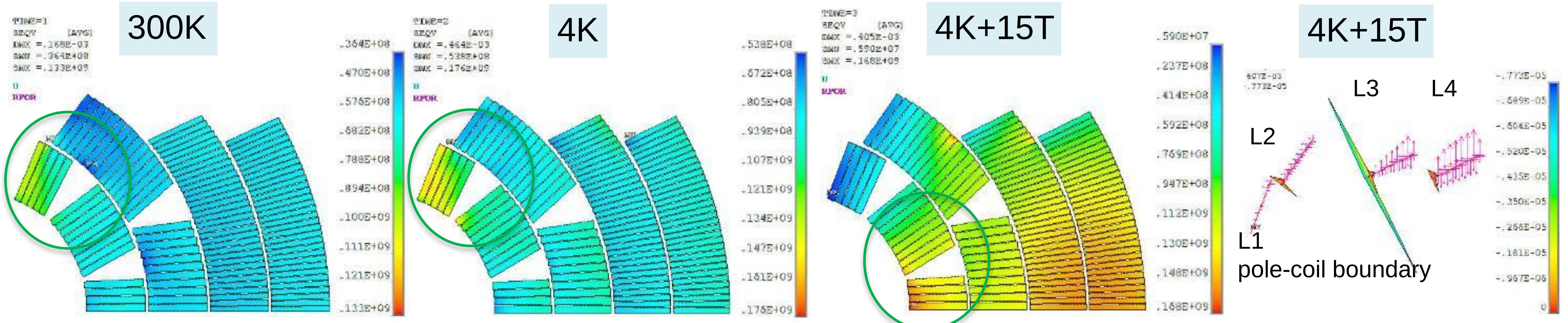
Innovative mechanical design:
- Vertically split iron yoke
- Aluminum I-clamps
- SS 12.5mm thick welded skin
- Cold mass OD=612mm
- Optimization criteria:
  structural integrity, coil stress and deformation



Magnet ***conductor limit*** for the wire J_c(12T,4.2K)~2.6 kA/mm^2

- B_{ap}=15.3T @4.5K
- B_{ap}=16.7T @1.9K

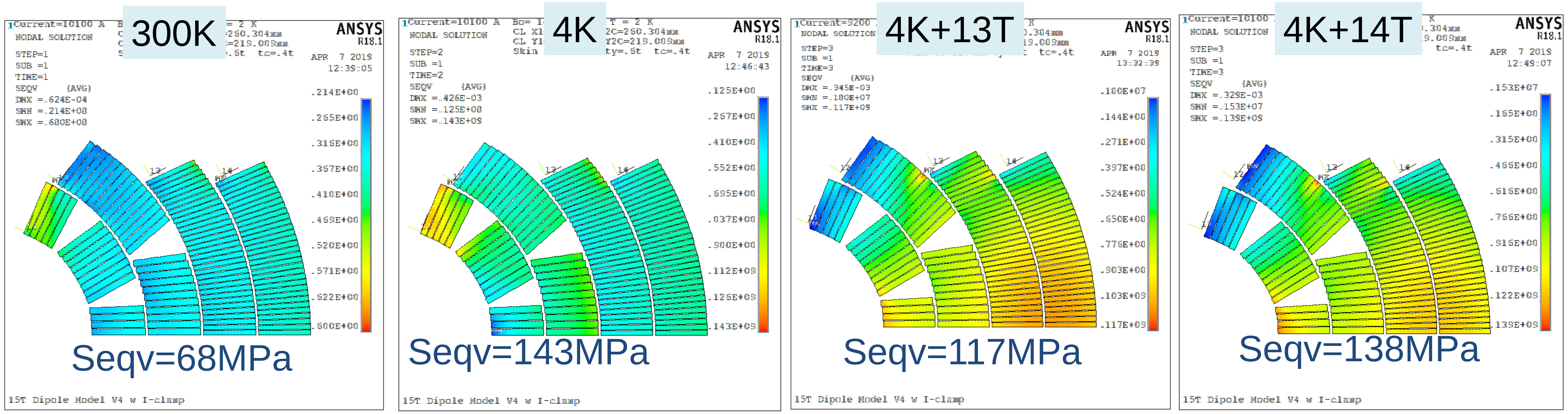
Mechanical Limit and Target Pre-load for 1st test



S_{eqv}=133 MPa S_{eqv}=176 MPa S_{eqv}=168 MPa Pole Gap < 0.7e-5 mm

Magnet *mechanical design limit* ~15T bore field

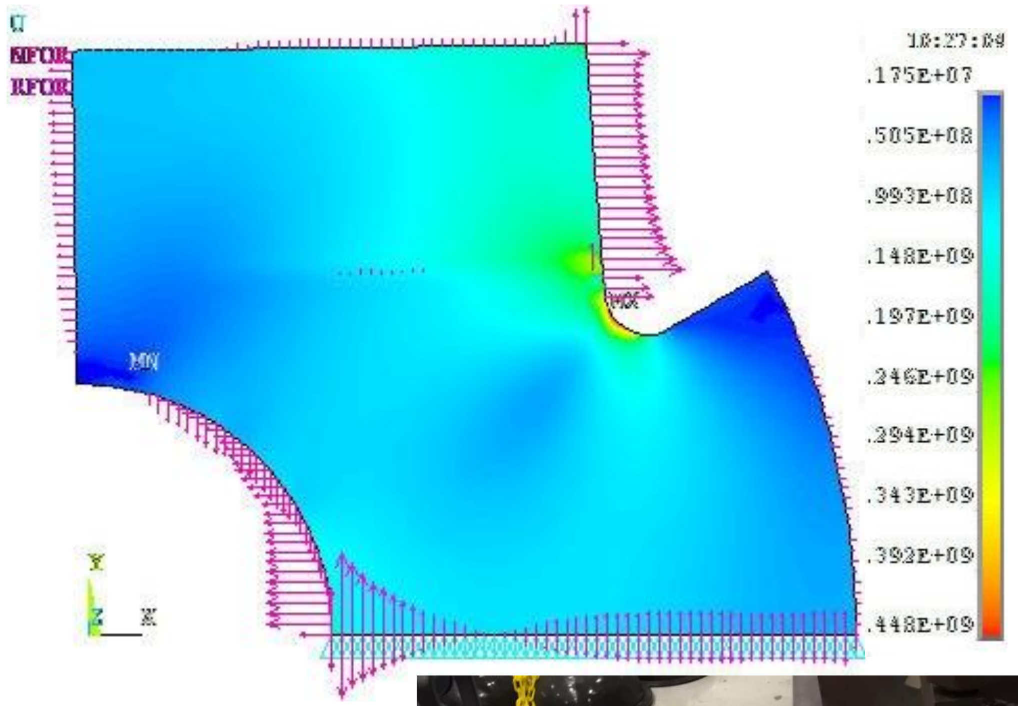
- determined by the coil maximum stress and the coil turn separation from poles



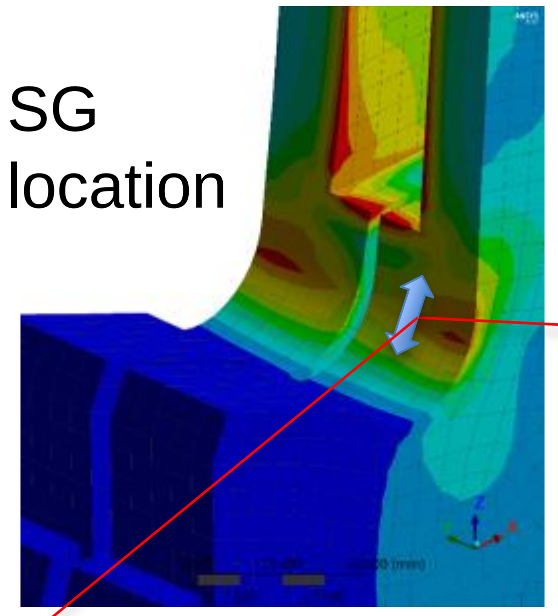
***Conservative coil pre-stress for the 1st test*:**

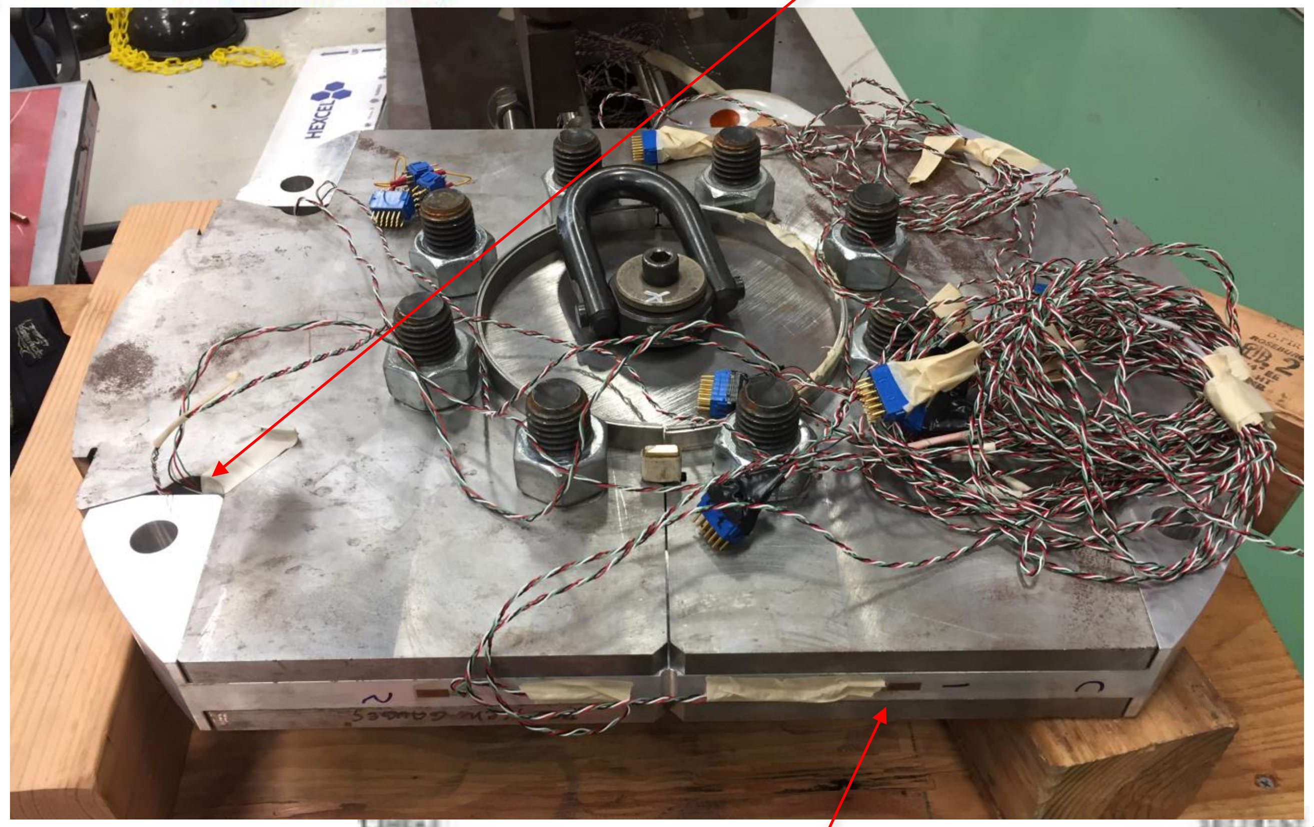
- S_{max} at all steps <150 MPa
- 13 T - tension starts to develop between IL poles and coil pole turns
- 14 T - max tension < 30MPa

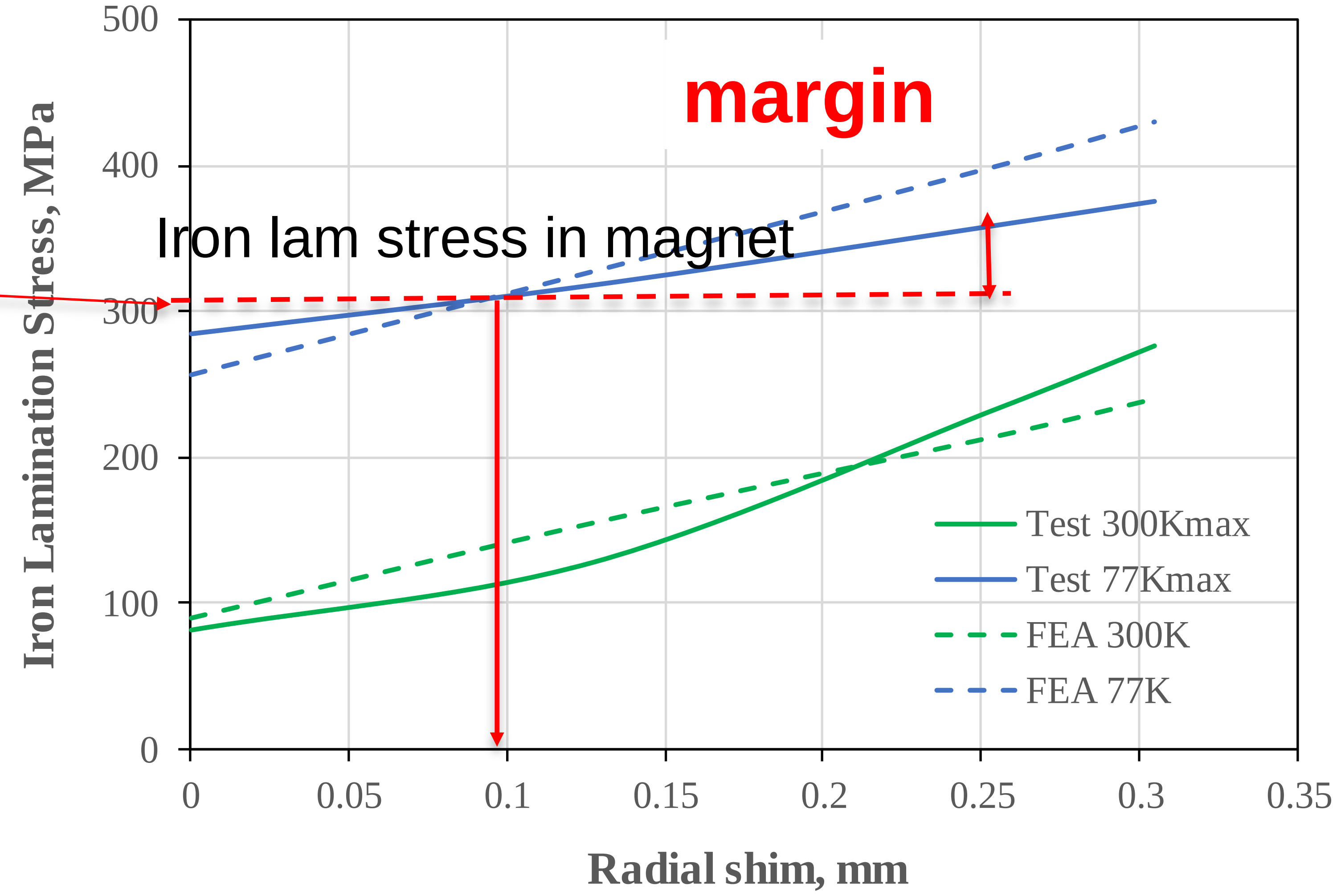
Mechanical Model Tests

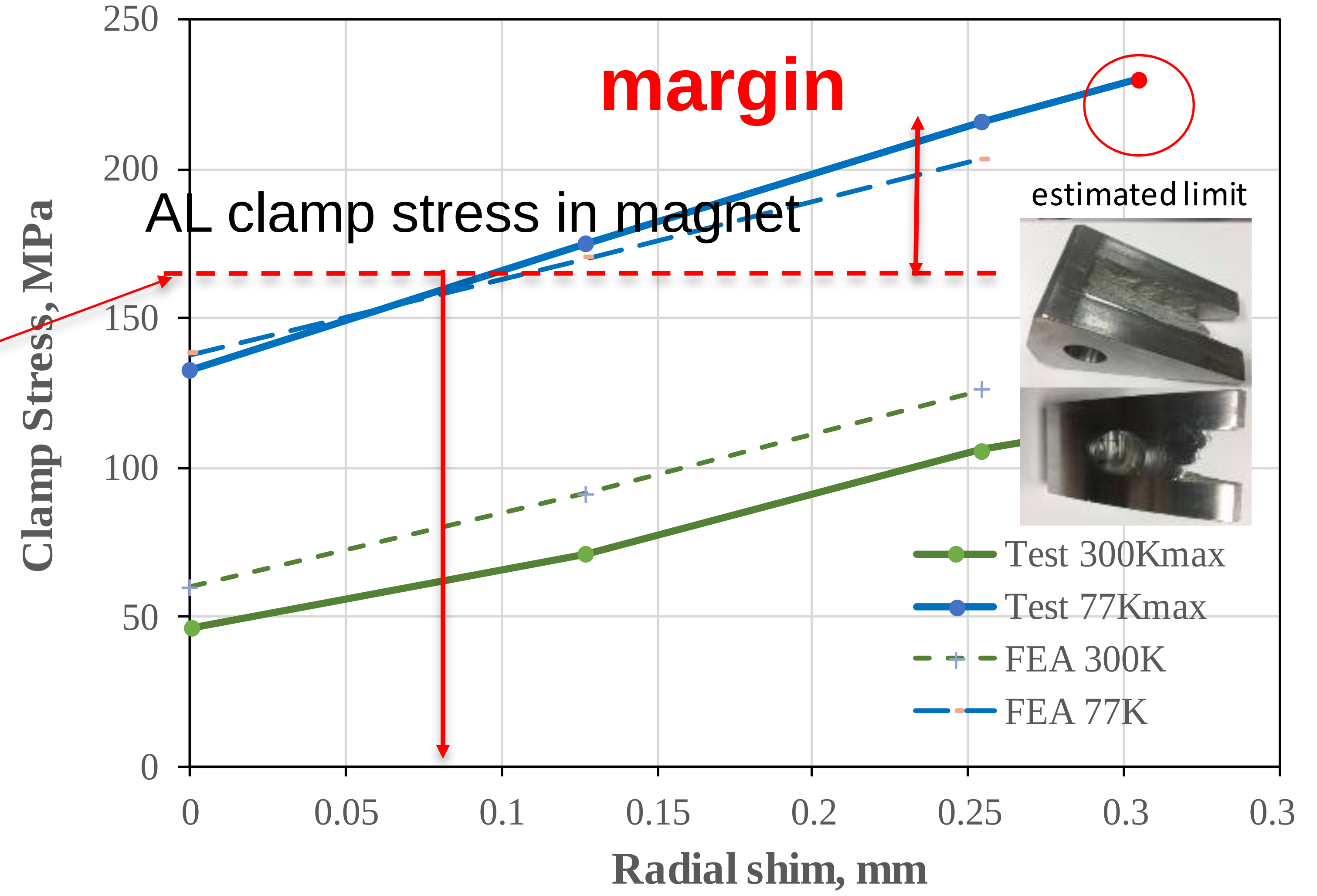


SG
location



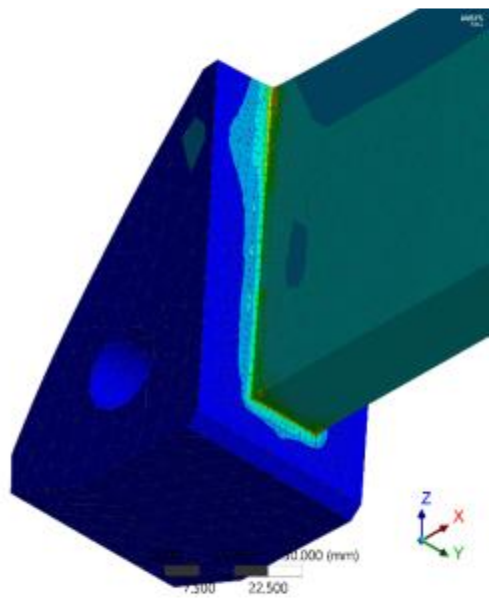


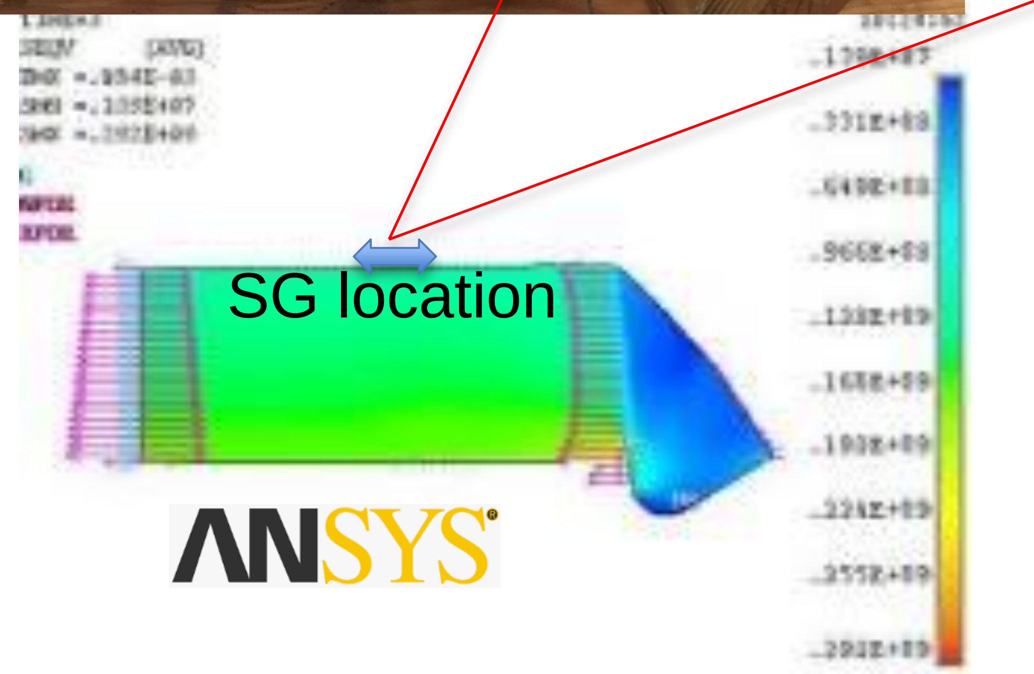




MM Goals:

- Test brittle yoke and clamps
- Validate 2D and 3D mechanical analysis
- Develop coil pre-stress targets





Coil Components

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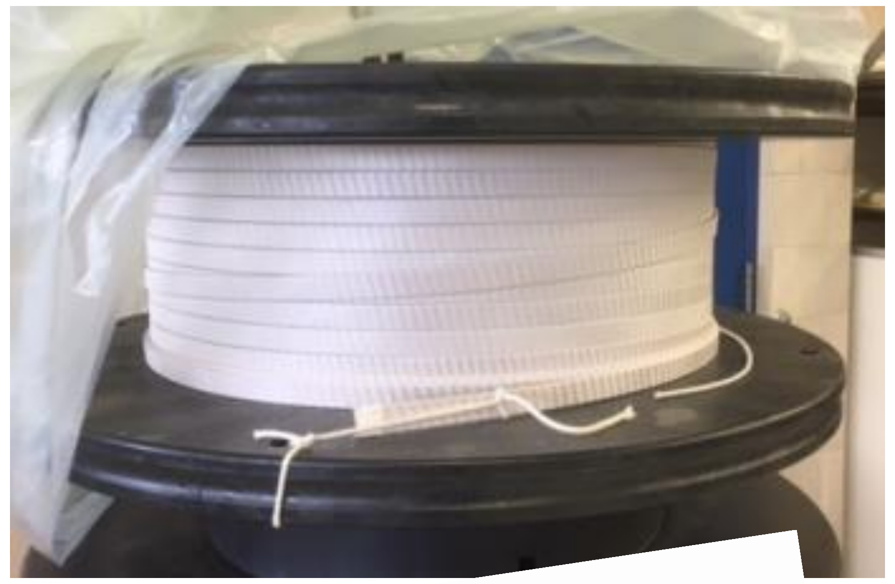
Cable (FNAL)



L3/4 parts (FNAL)

3 sets

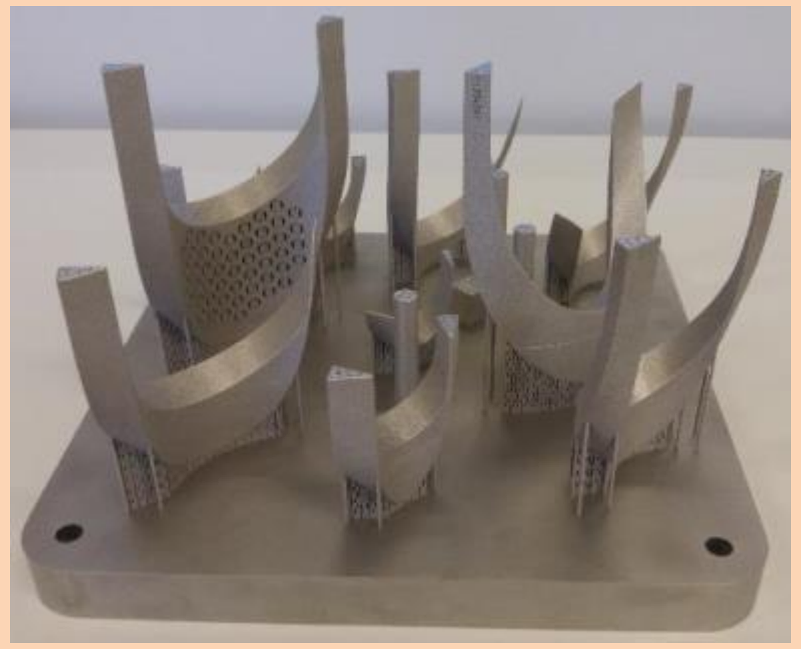
4 sets

Traces (LBNL/FNAL)

L2

L4

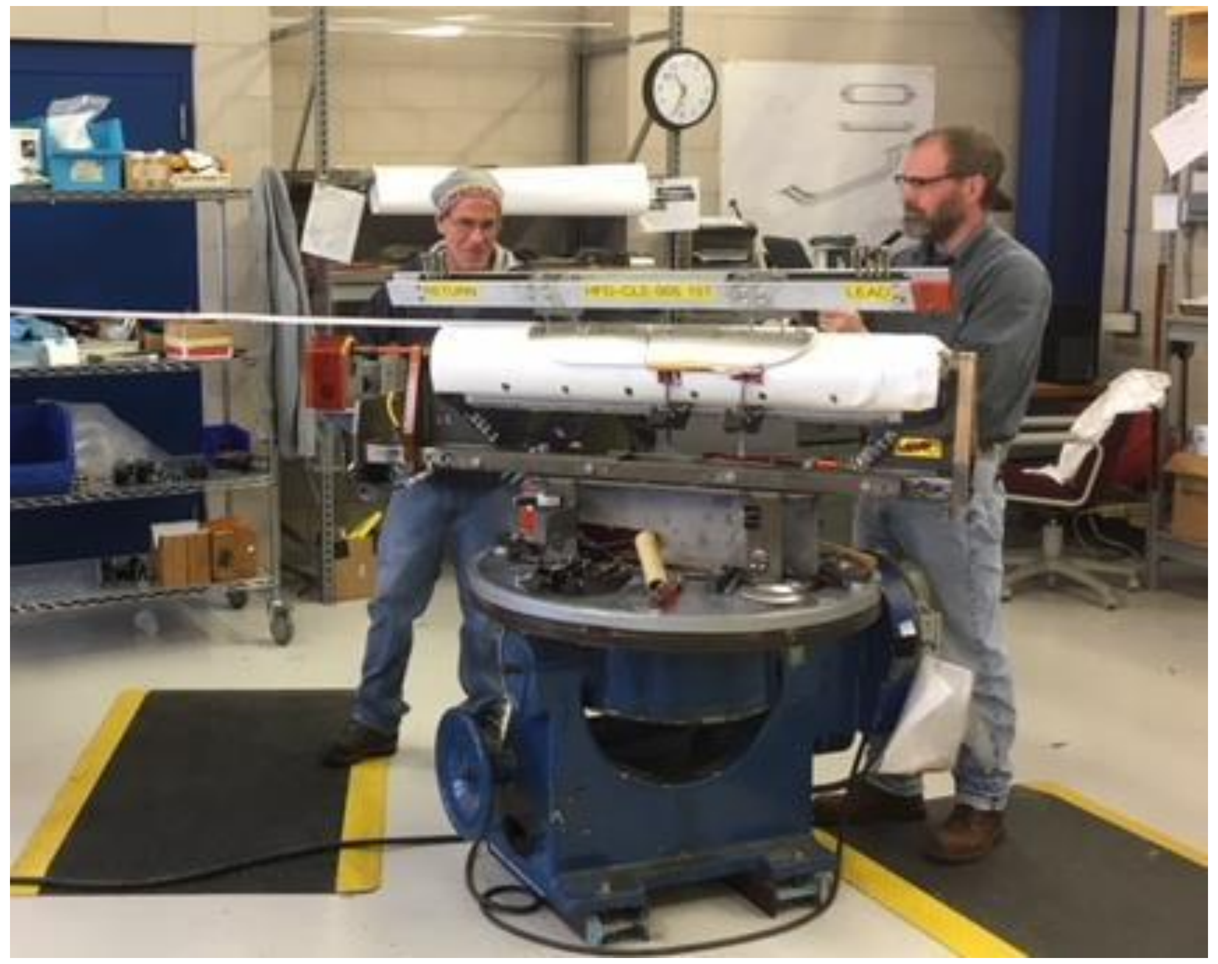
L1/2 parts (CERN contribution)



Ti and Cop Wedges

Ti poles and spacers, SS saddles

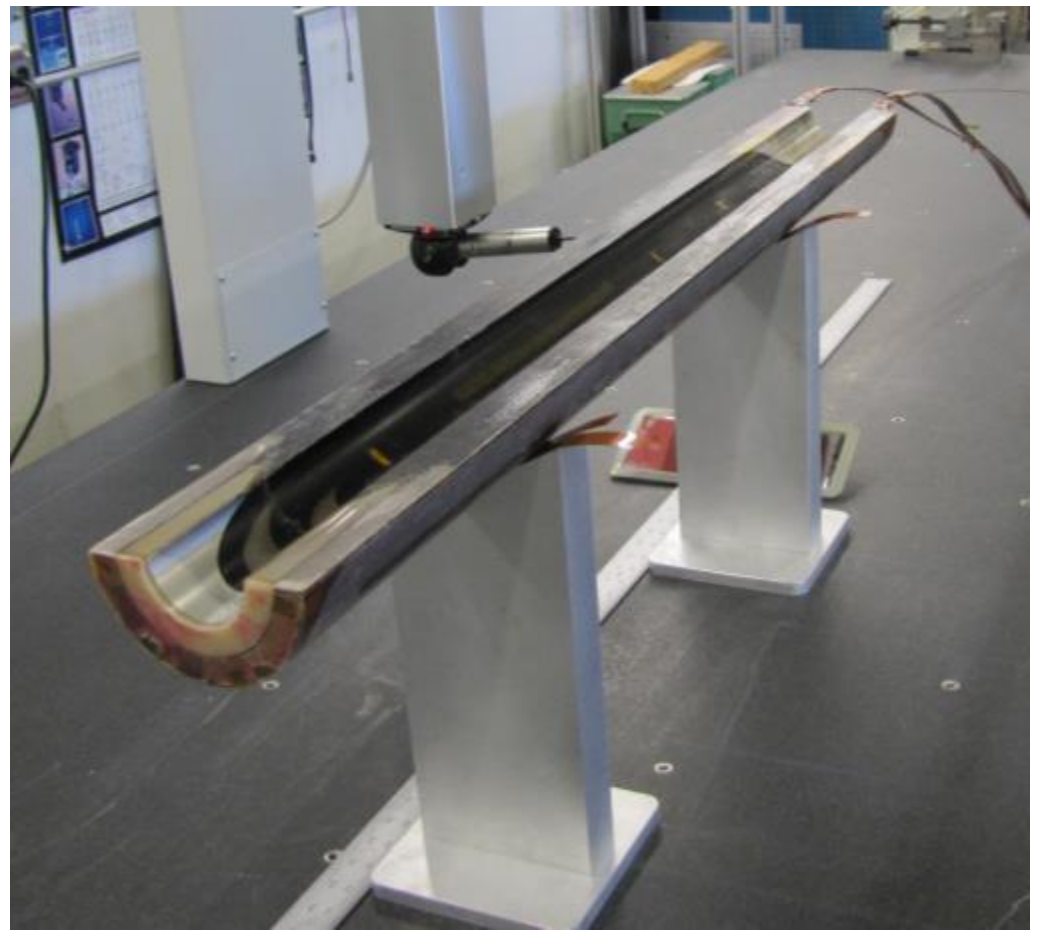
Coil Fabrication, Measurements and Instrumentation



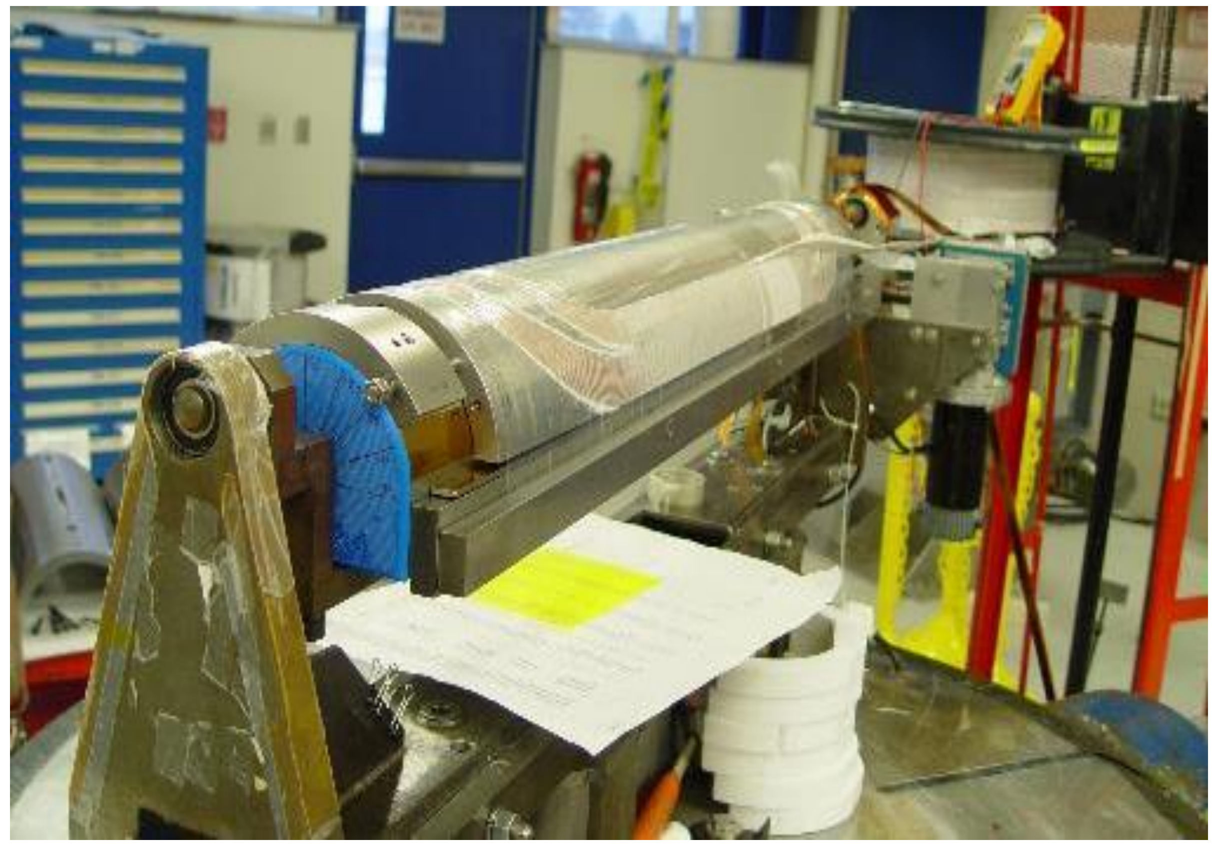
Coil winding and curing using ceramic binder

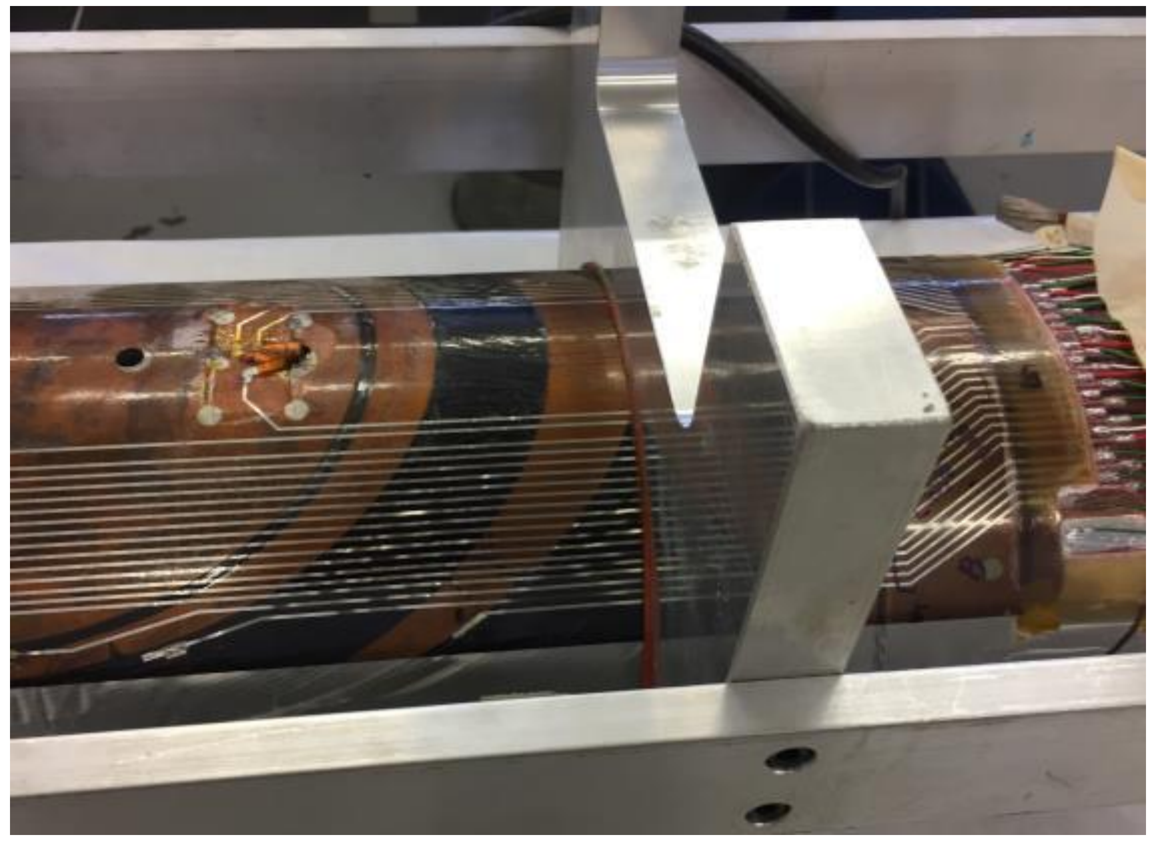
Coil reaction

Coil lead splicing, epoxy impregnation



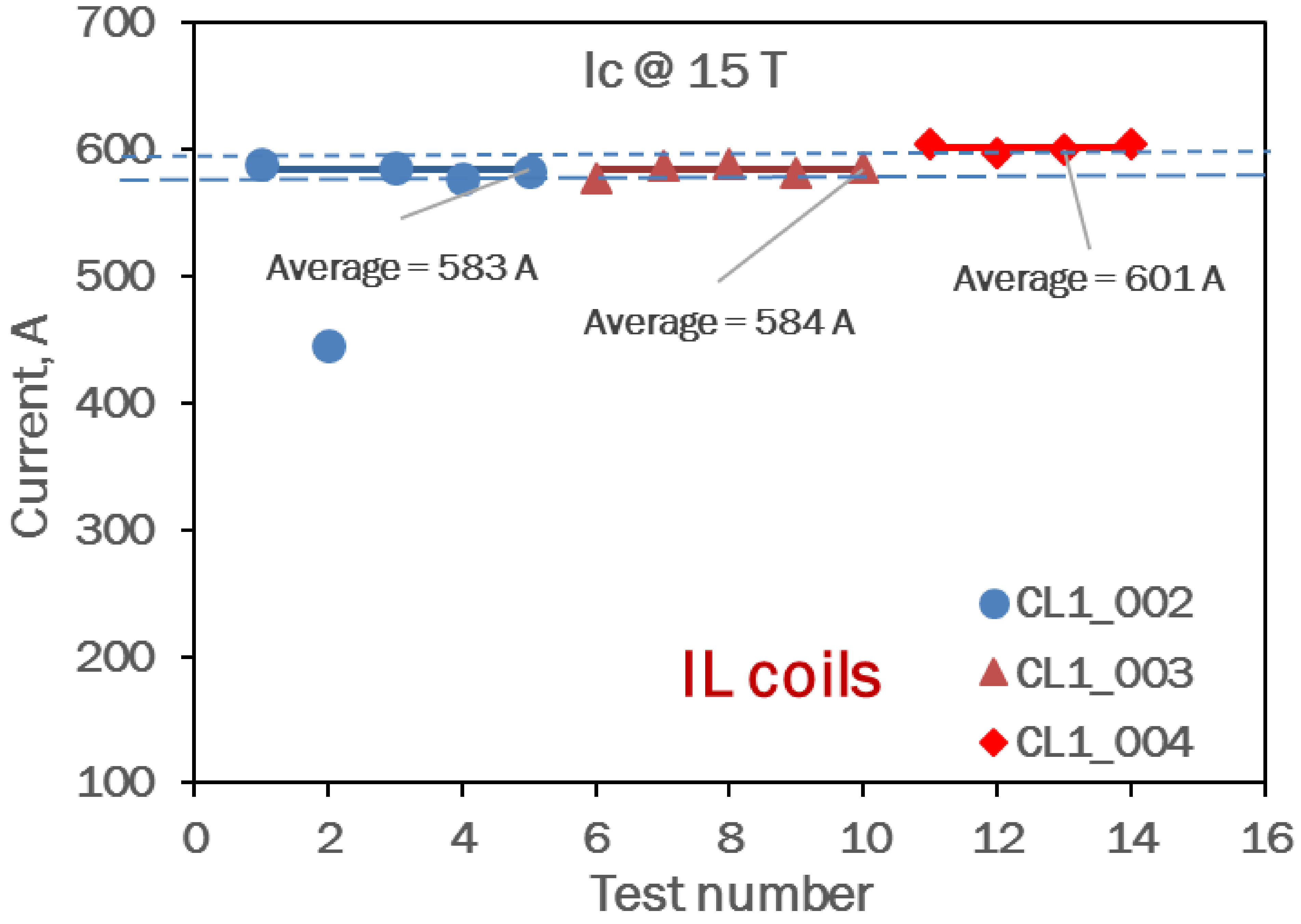
Coil size measurement, instrumentation

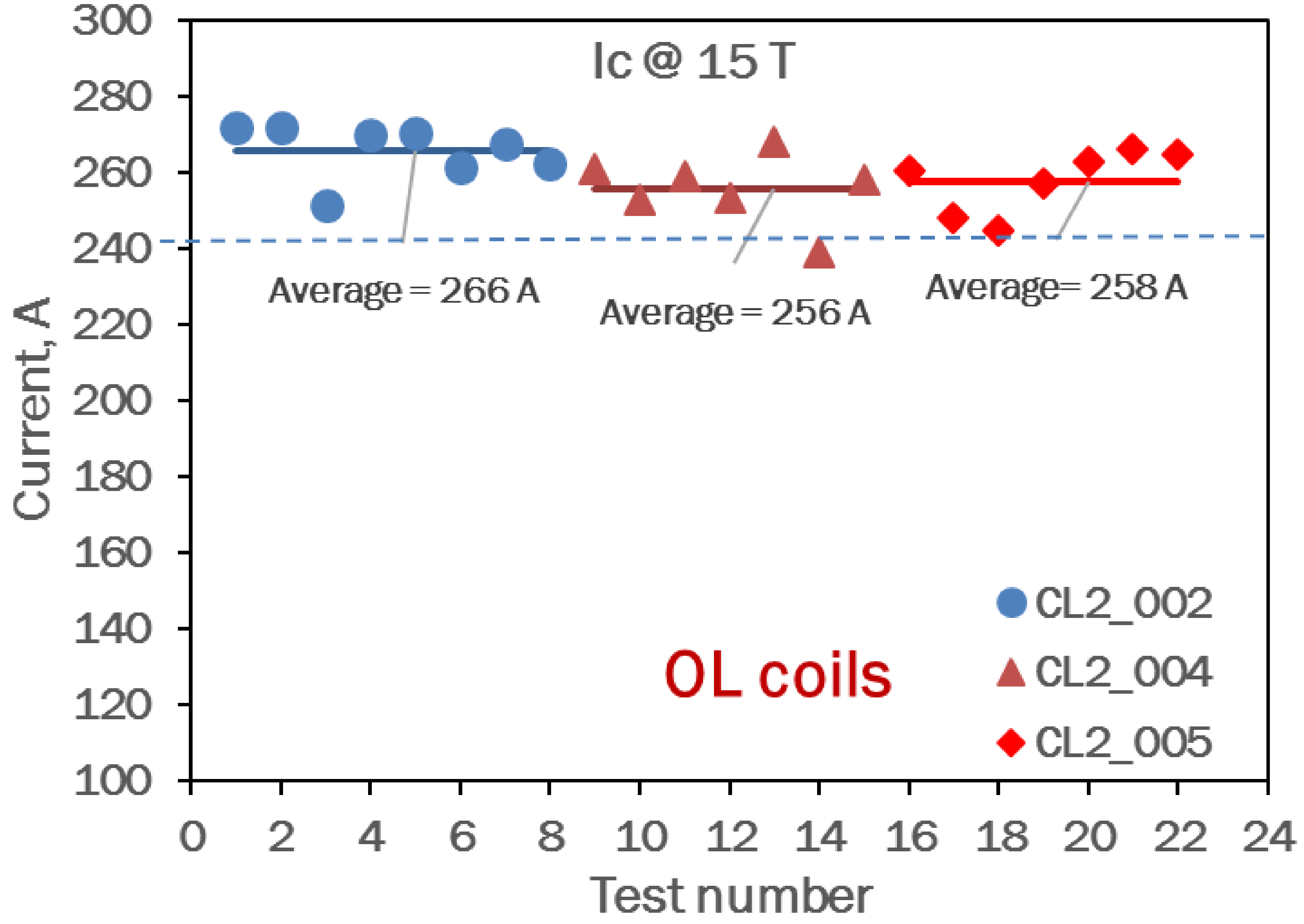




Coil fabrication, measurement and instrumentation time ~3 months

Witness Sample Data and Magnet SSL

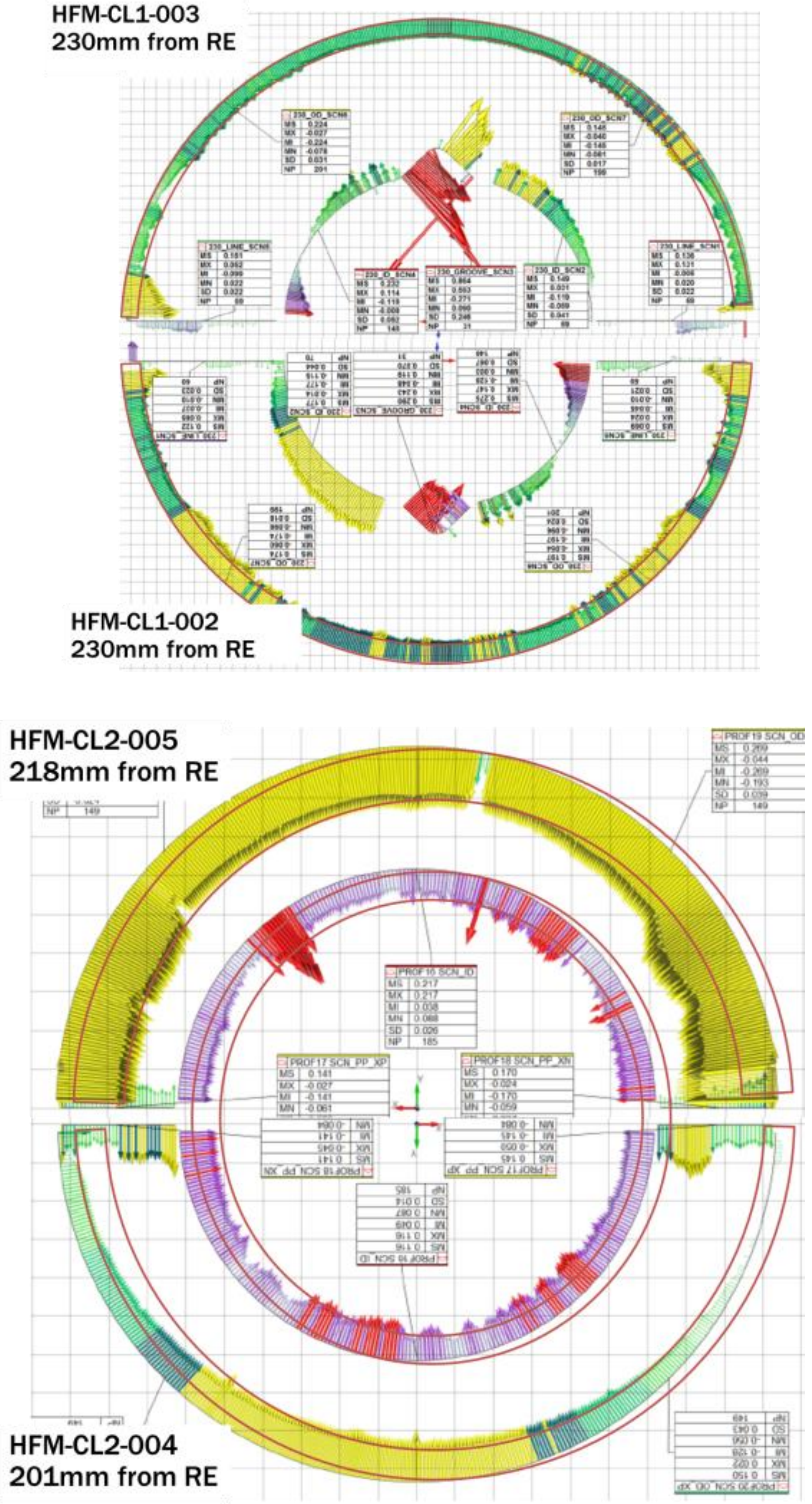


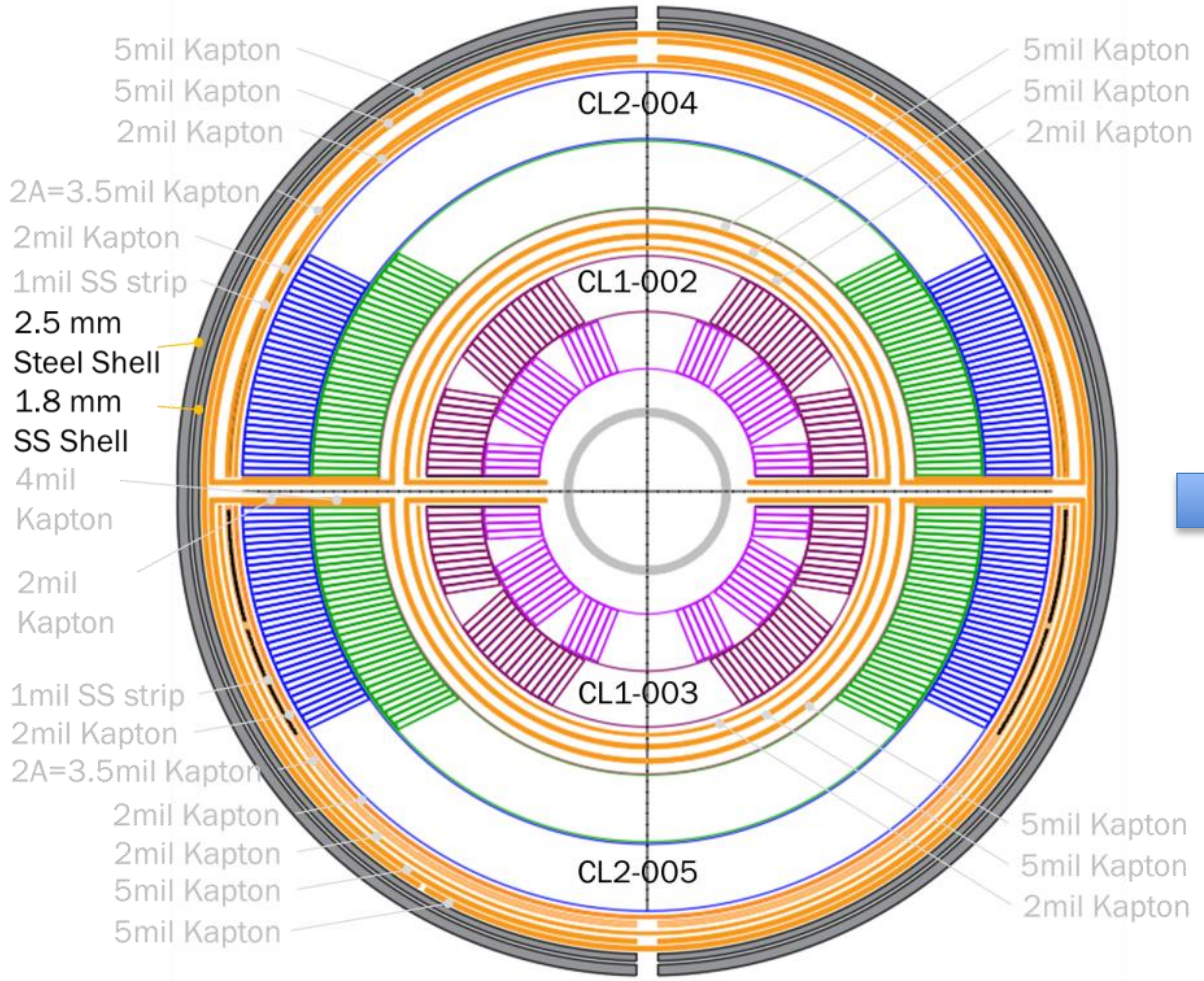


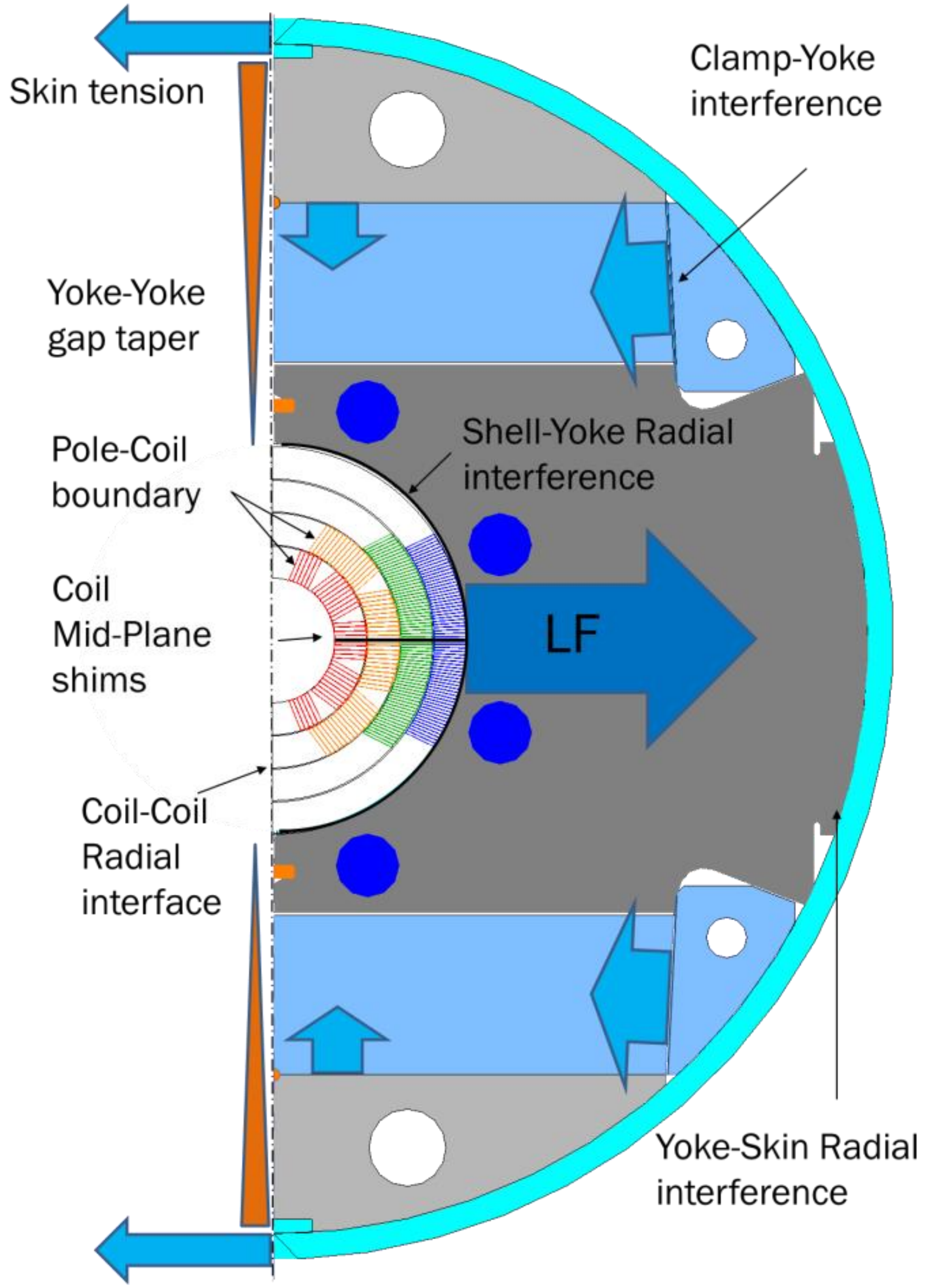
- **Witness sample data are close to the target I_c**
- **Good reproducibility of witness sample data for IL and OL coils**

Magnet *short sample limit*: 15.16 T @4.5K and 16.84 T @1.9K

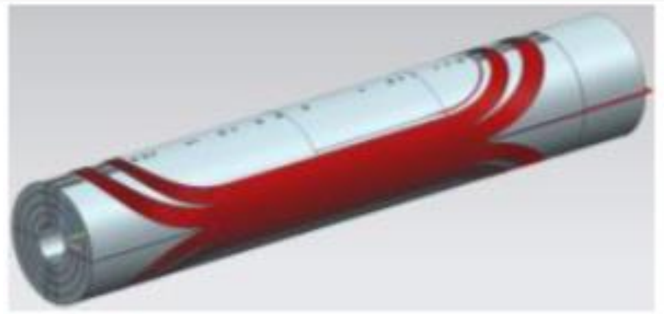
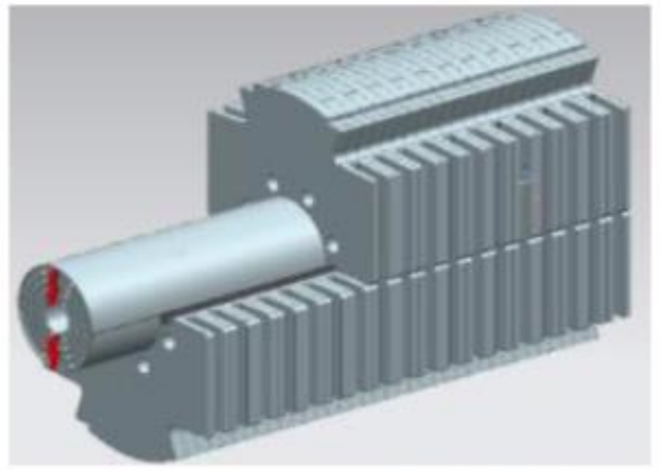
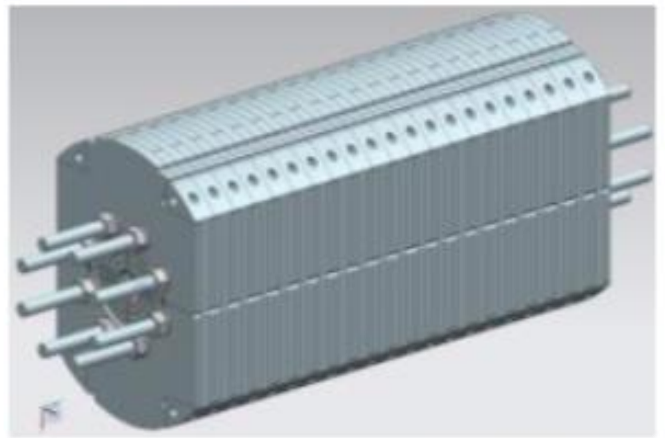
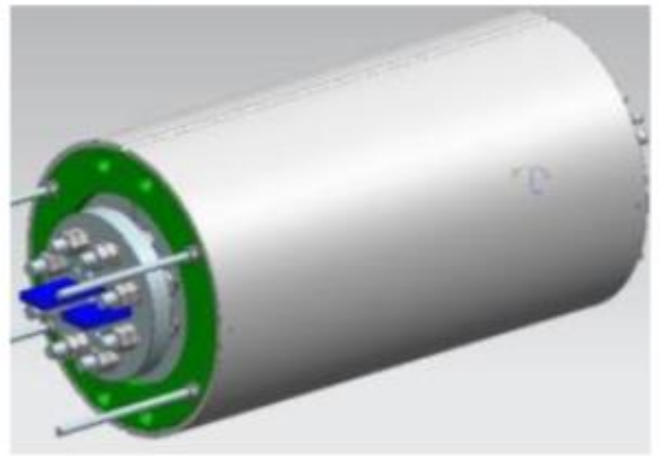
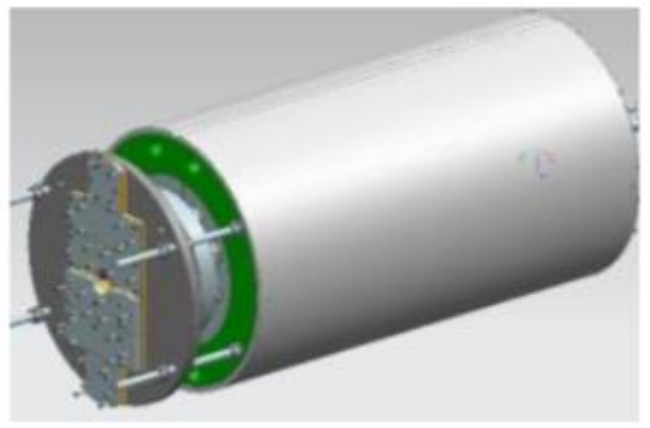
Coil Assembly and Preload Scheme



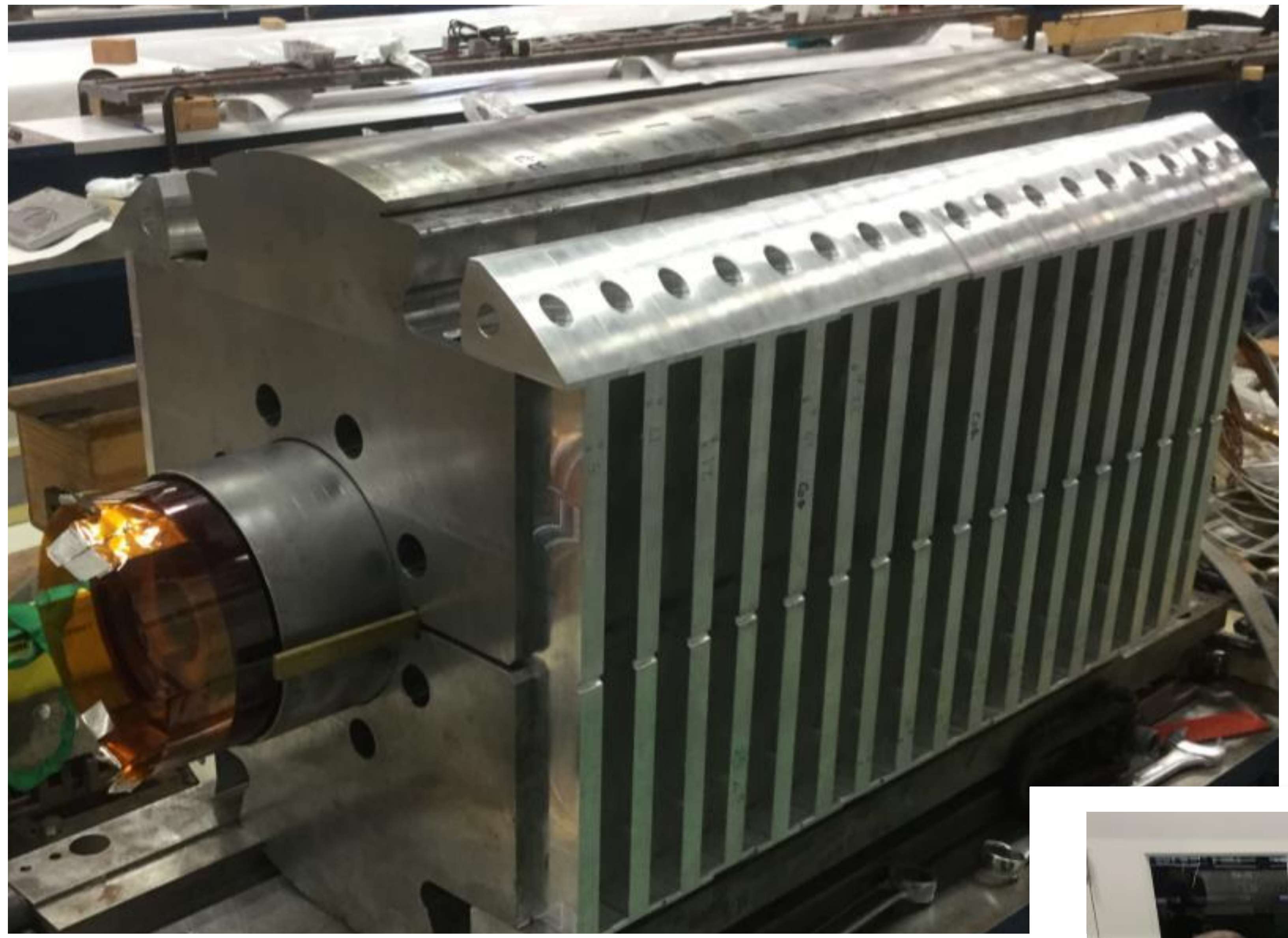


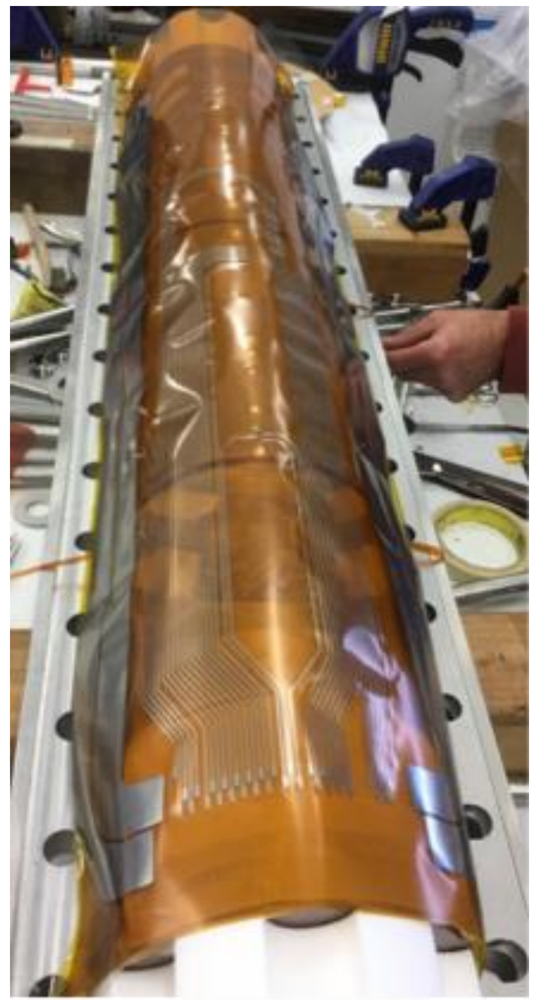


Coil Assembly, Yoking and Skinning

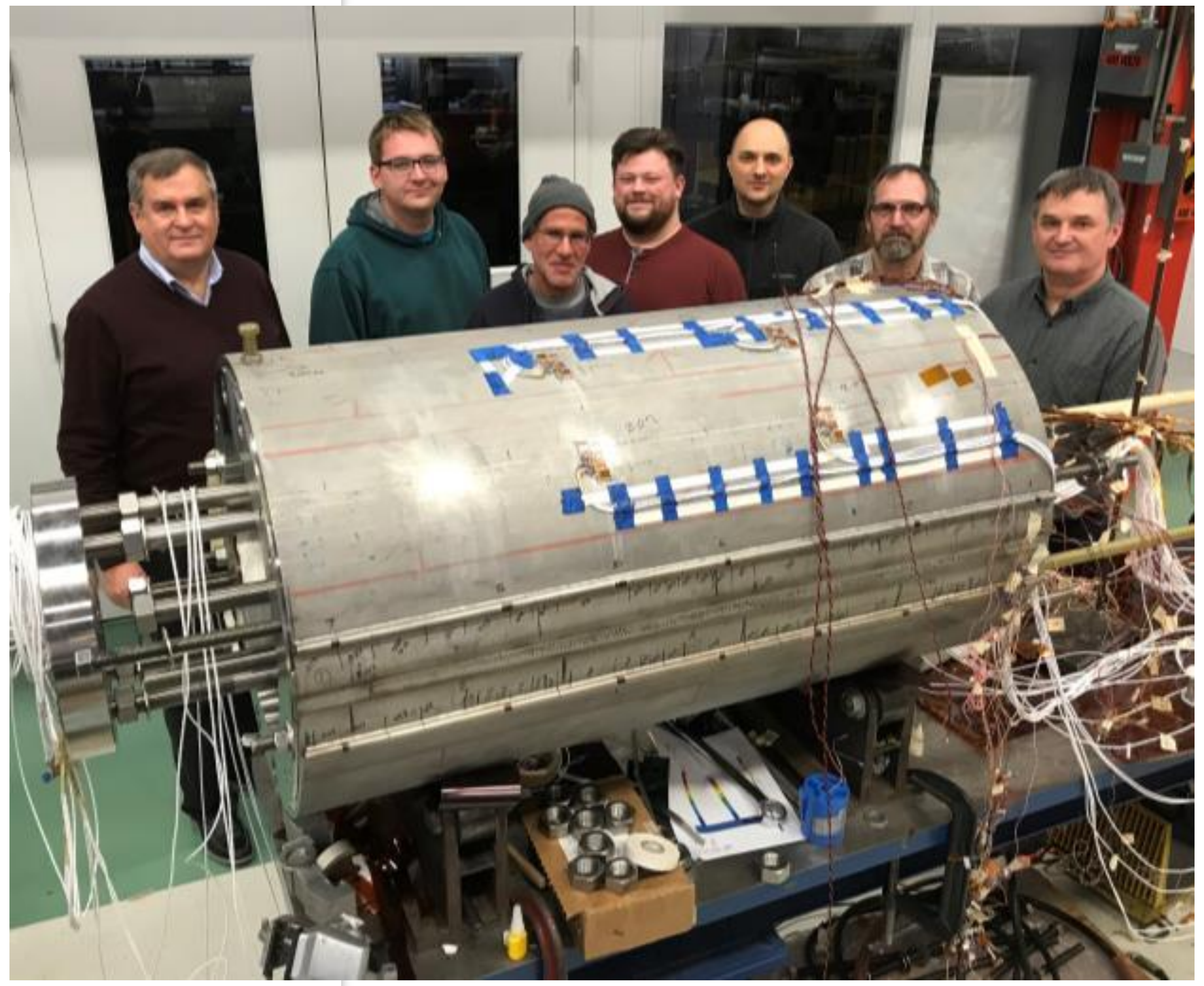








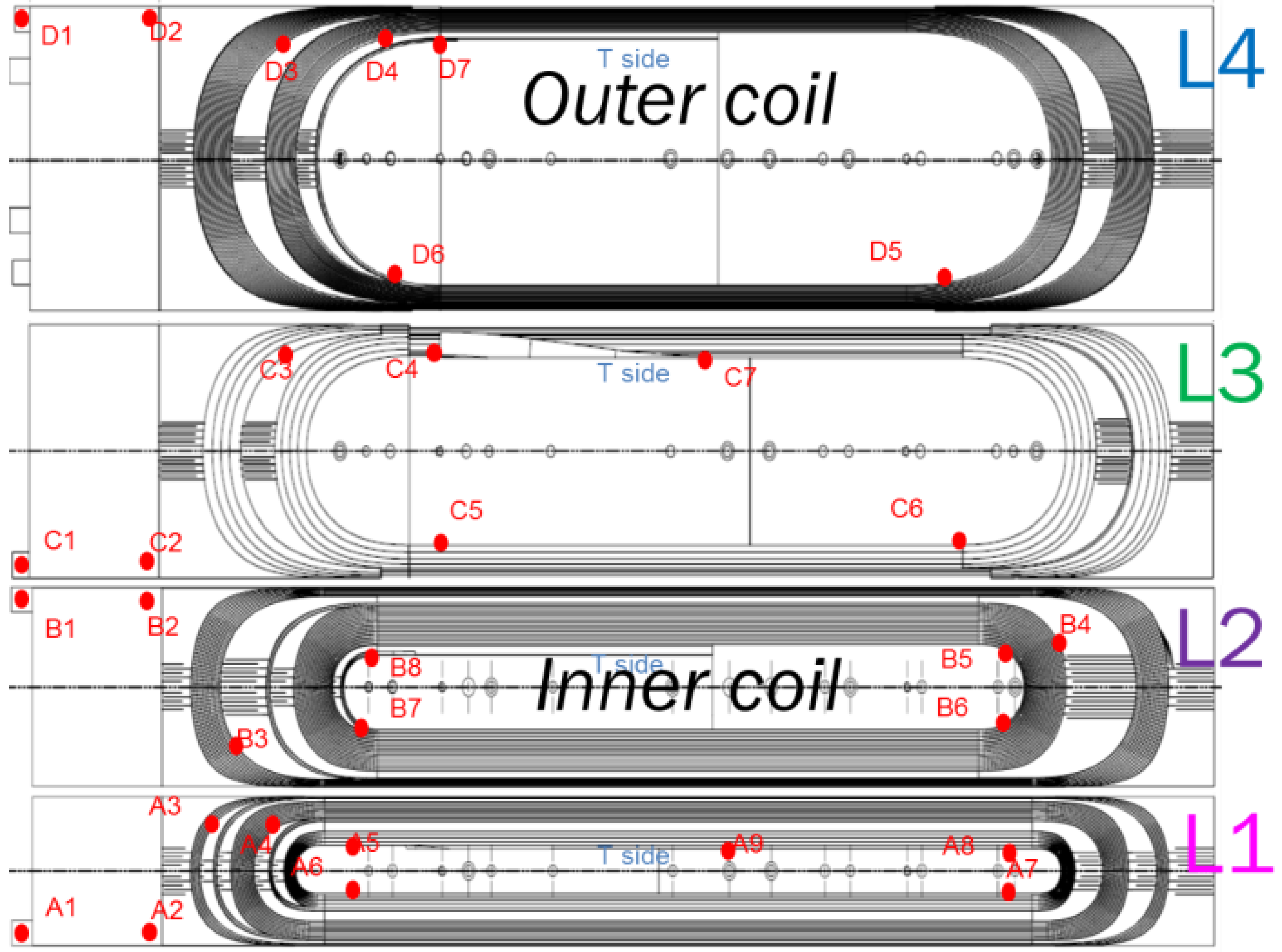




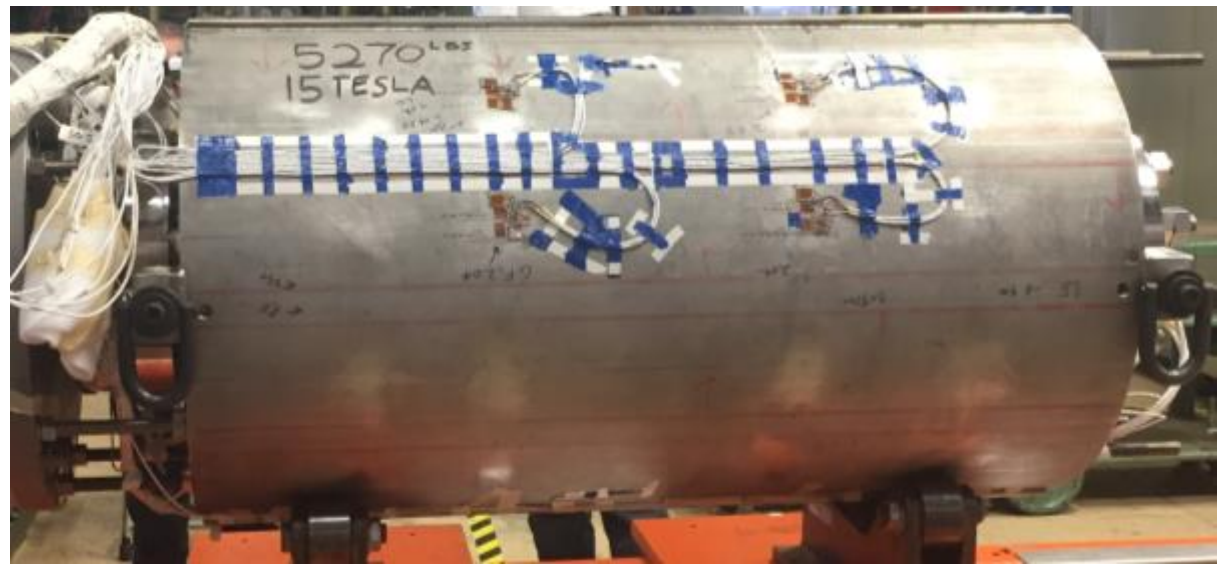

Magnet assembly~3 months

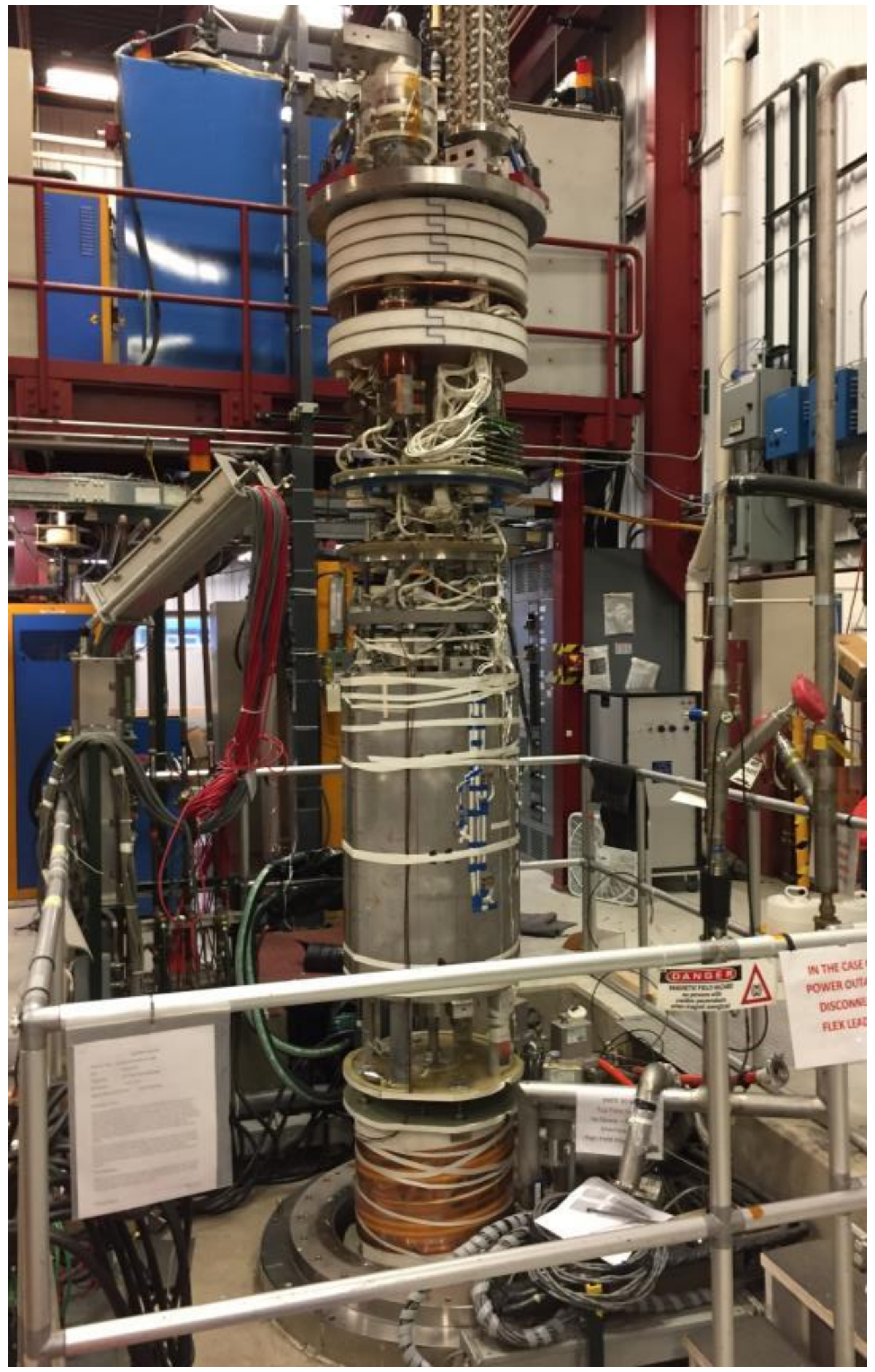



Magnet Instrumentation and Test Preparation



VT location

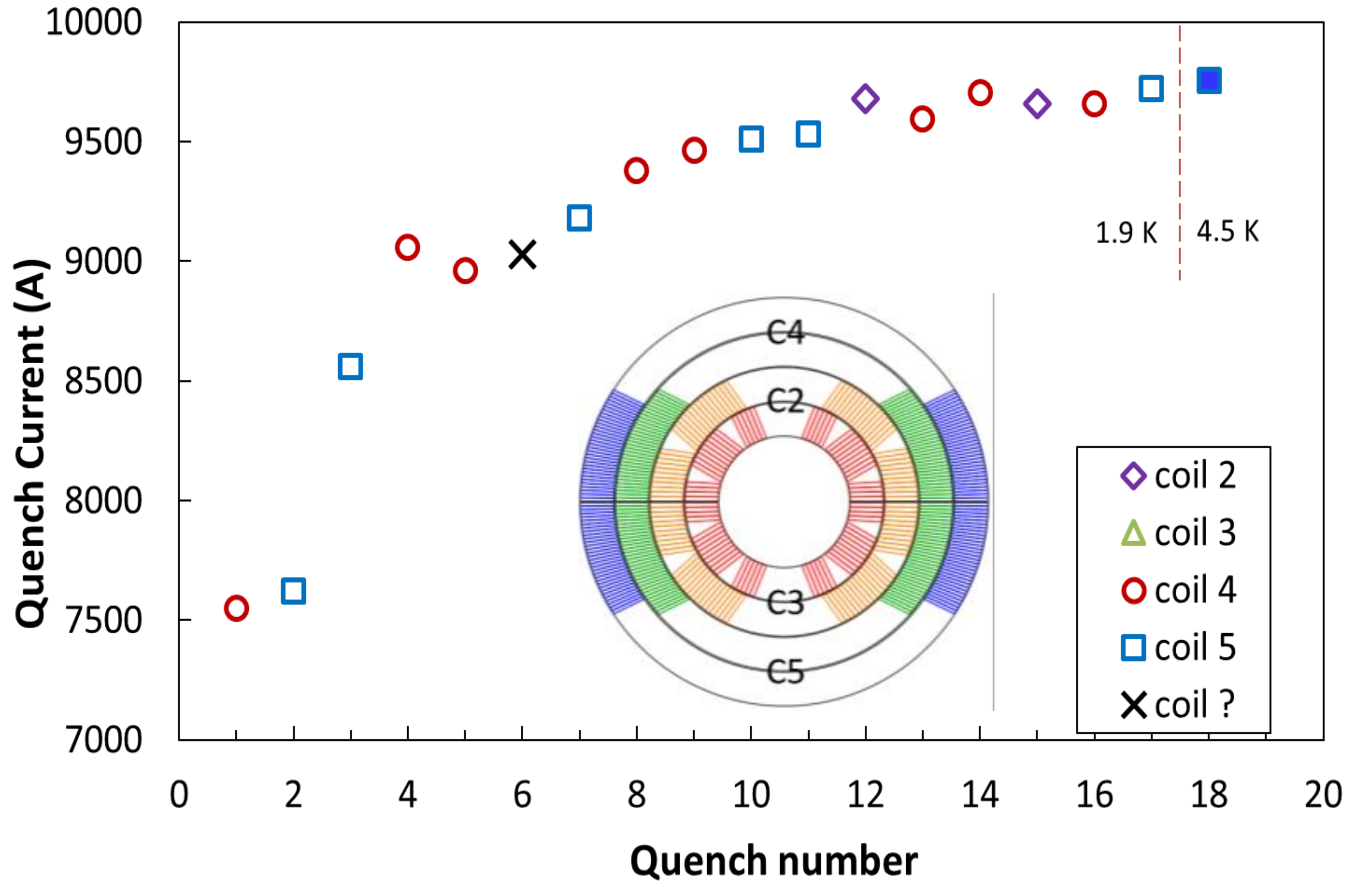

Skin gauges location



- **Instrumentation:**
  - **Voltage taps**
  - **Strain Gauges**
    - **skin, clamps, bullets, poles, coils**
  - **Quench antennas**
  - **Acoustic sensors**

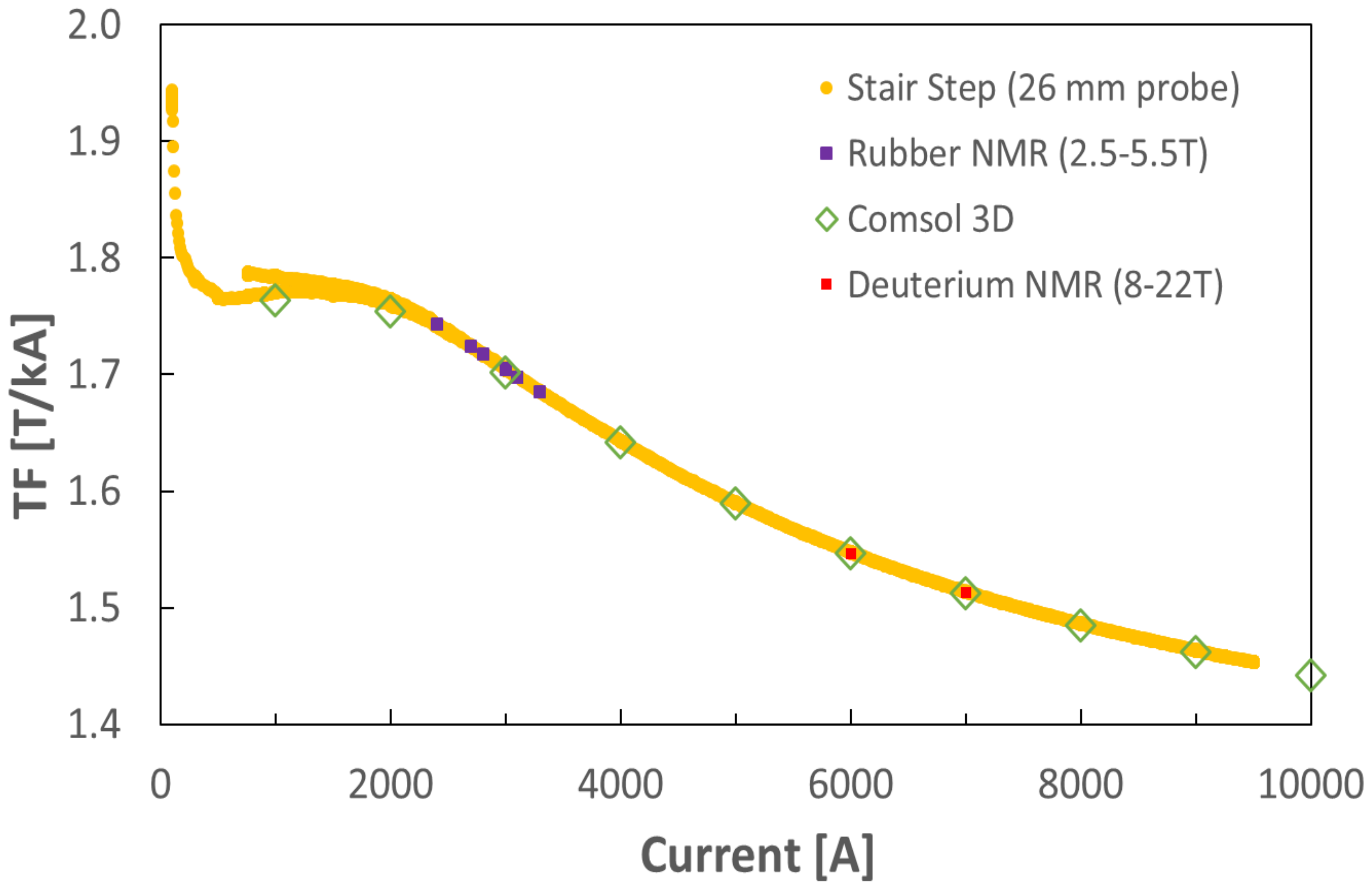
Test preparation ~1.5 months

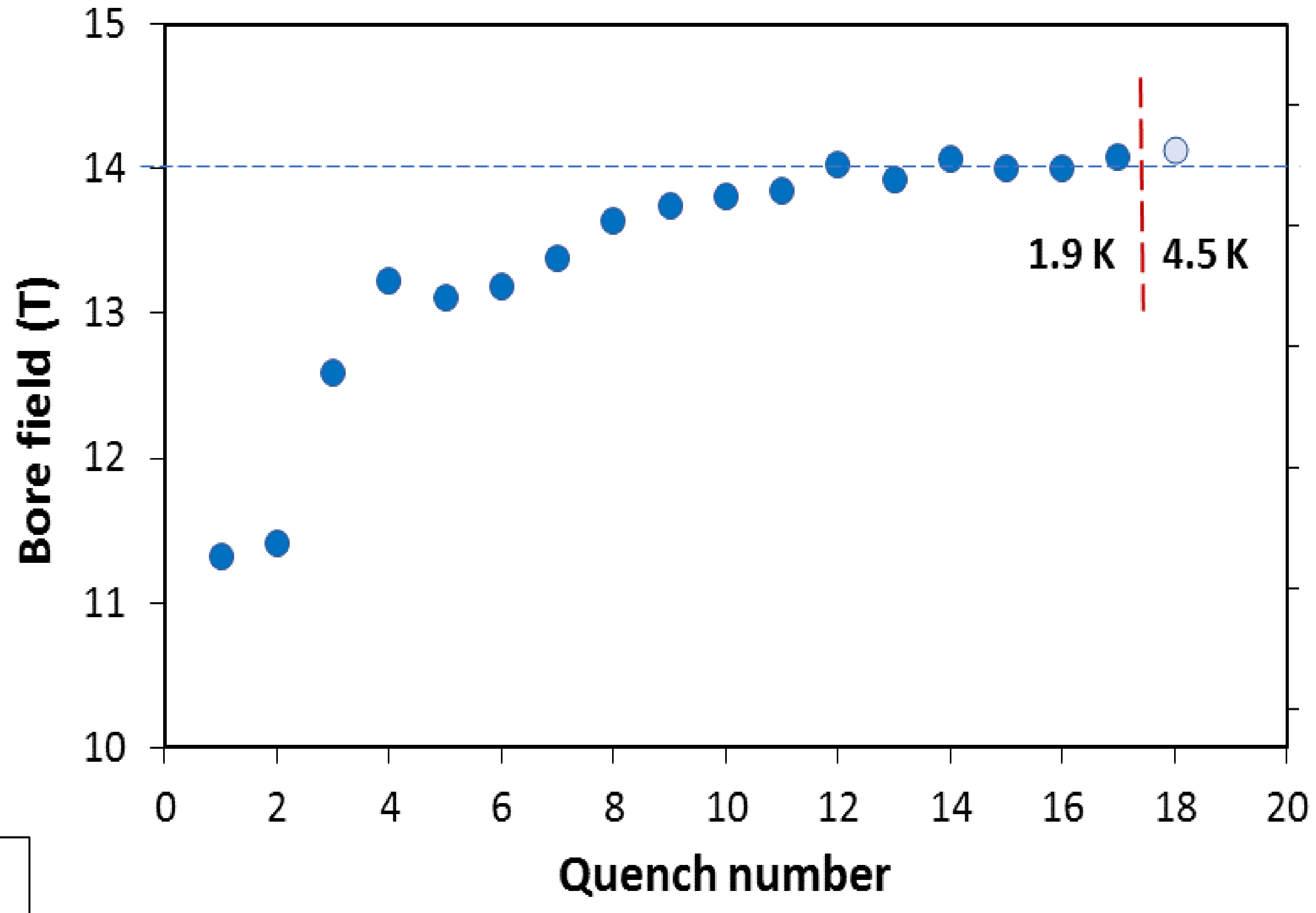
Quench Performance (Training)



- Magnet was trained at 1.9K
- Training plateau after 11 quenches
- IL quenches: 2 in coil 2
- OL quenches: 8 in coil 4
  7 in coil 5

- 2D and 3D analysis based on the actual yoke material properties and the final magnet geometry
- Measurements have been verified with NMR probes (provided by GMW)



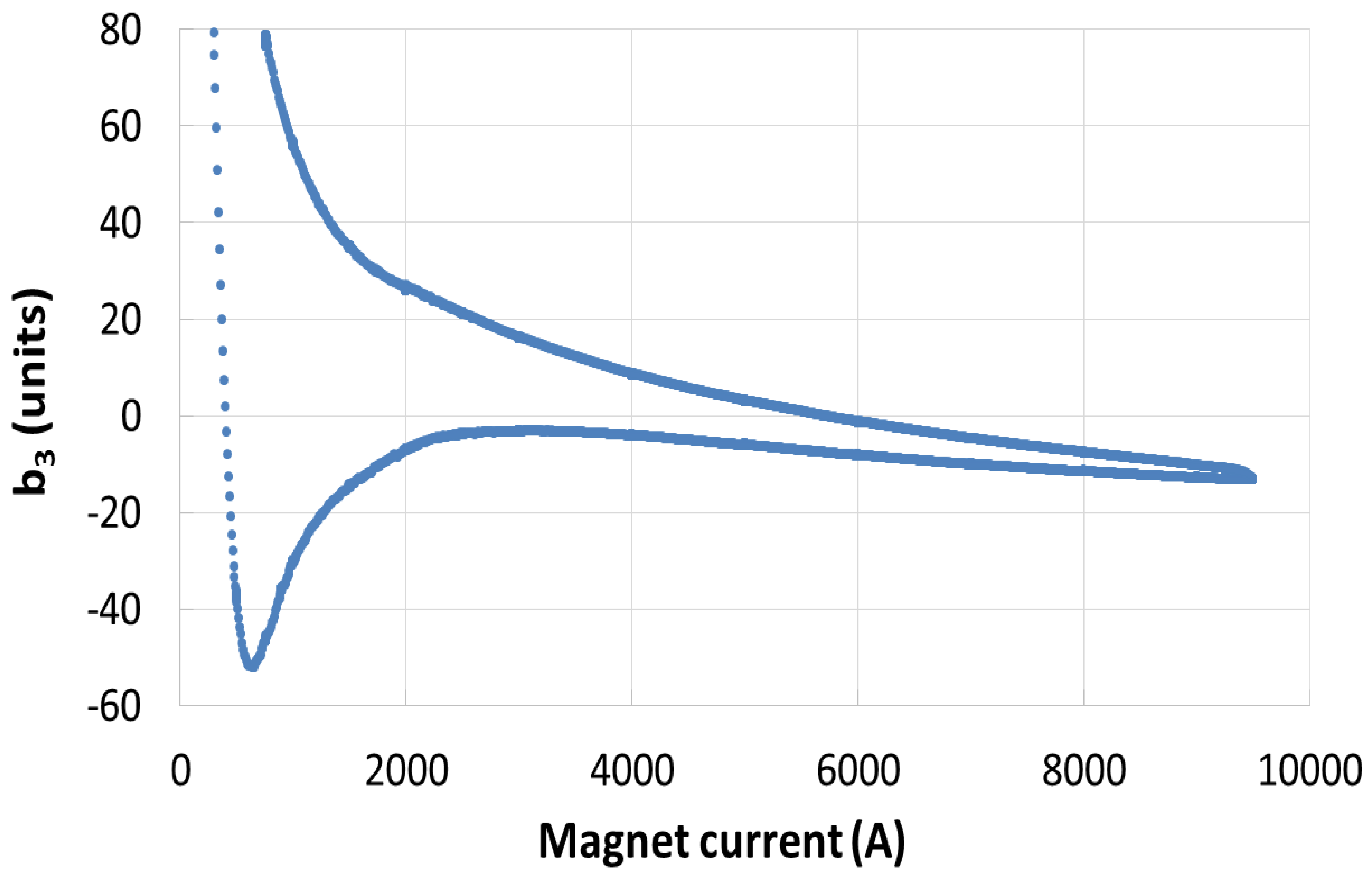


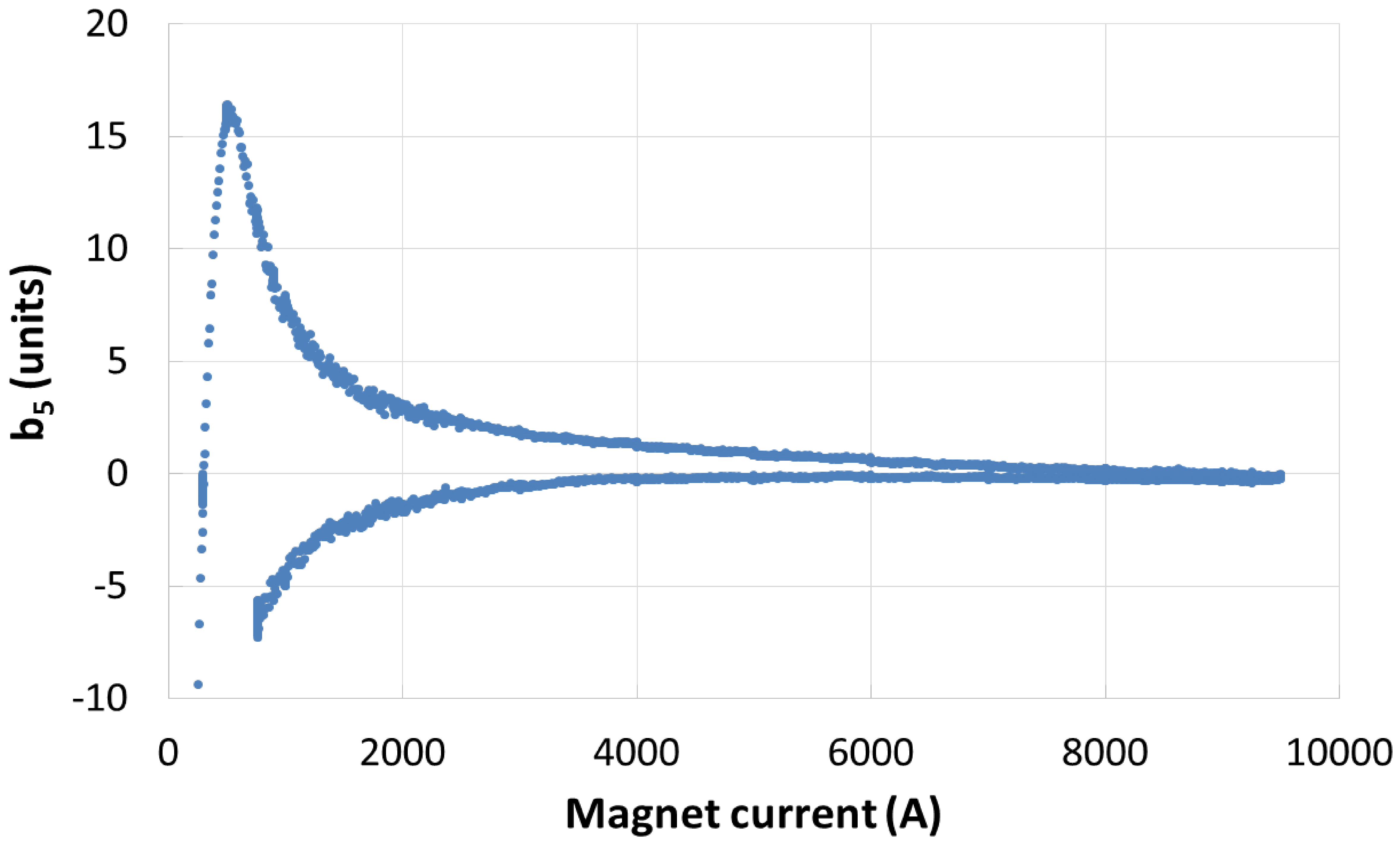
- First quenches above 11 T
- Last quench at 4.5K:

  B_{meas} -14.10±0.04 T

  B_{calc} -14.112 T

Field Quality





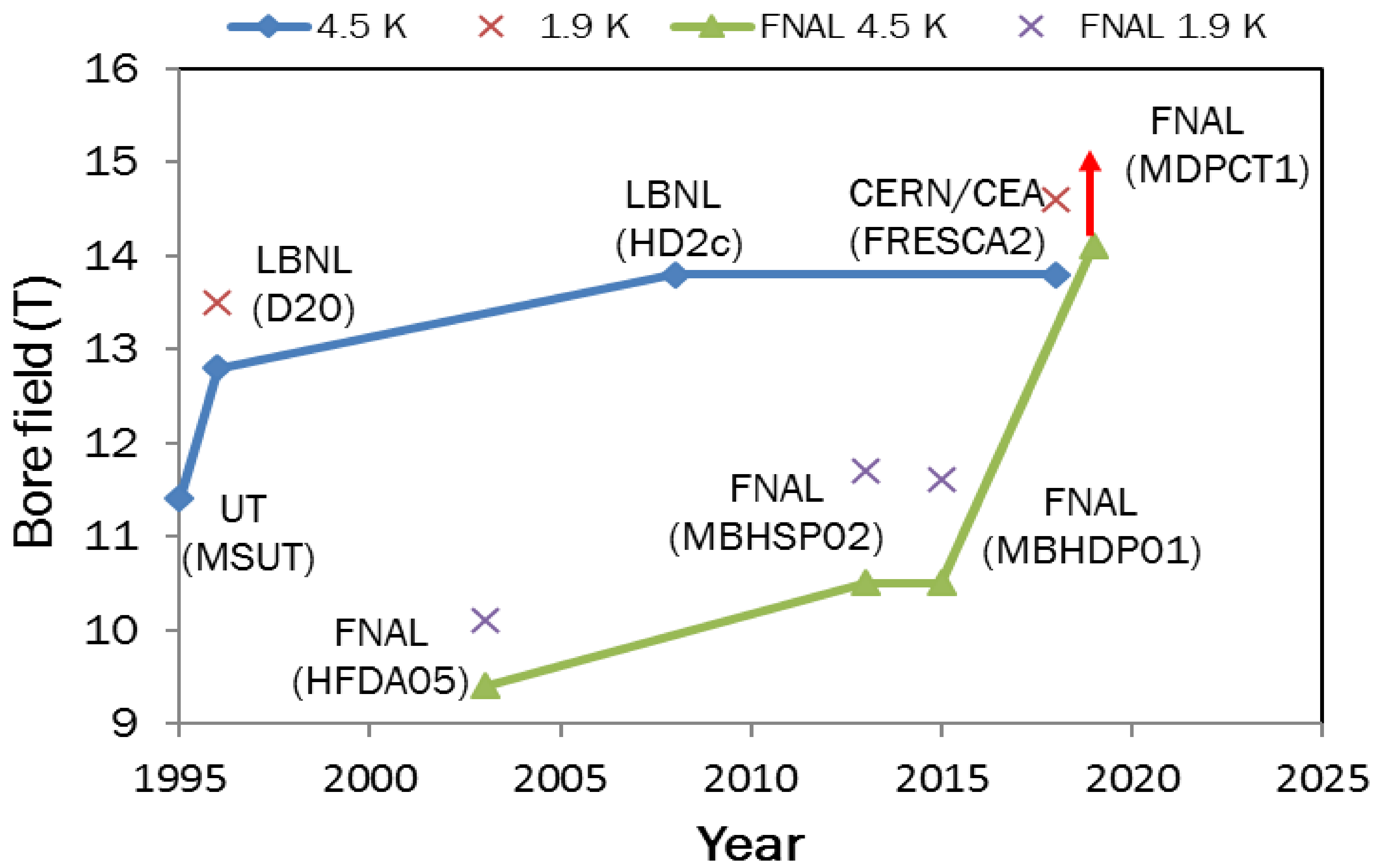
Geometrical harmonics at R_{ref}=17 mm (I=2.5 kA)

n	2	3	4	5	6	7	8	9	10
b_n	0.8	8.8	-0.4	0.7	0.1	1.0	0.0	0.2	-0.4
a_n	-2.2	-3.5	0.3	0.1	0.1	0.1	-0.1	0.2	-0.3

MDPCT1 Summary and Next Steps

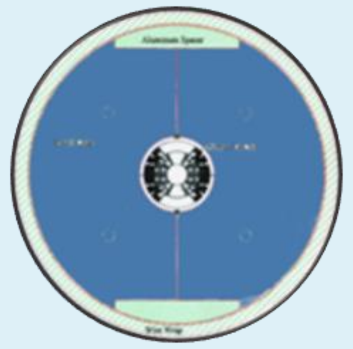
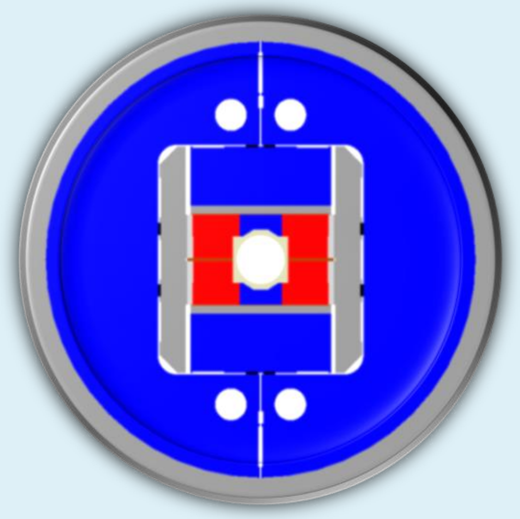
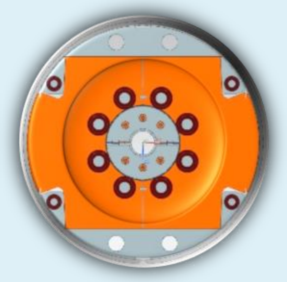
The goals of the first test have been achieved:

- graded 4-layer coil design, innovative support structure and magnet fabricated procedure have been tested
- B_{max} = 14.10±0.04 T - ***record field at 4.5 K for accelerator magnets!***



Next steps:

- Magnet re-assembly
  - increase azimuthal and coil pre-load and axial support to achieve the goal of 15 T
  - improve instrumentation
- Magnet second test in January of 2020

Parameter	D20 (LBNL)	HD2 (LBNL)	FRESCA2 (CERN)	MDPCT1 (FNAL-MDP)
				
Test year	1997	2008	2017	2018 (plan)
Max bore field [T]	13.35 (14.7*)	15.4	16.5 (18*)	15.2 (16.5*)
Design field B_{des} [T]	13.35	15.4	13	15
Design margin B_{des}/B_{max}	1.0 (0.9*)	1.0	0.8 (0.7*)	0.96 (0.89*)
Achieved B_{max} [T]	12.8 (13.5*)	13.8	13.9 (14.6)	14.1
St. energy at B_{des} [MJ/m]	0.82	0.84	4.6	1.7
F_x/quad at B_{des} [MN/m]	4.8	5.6	7.7	7.4
F_y/quad at B_{des} [MN/m]	-2.4	-2.6	-4.1	-4.5
Coil aperture [mm]	50	45	100	60
Magnet (iron) OD [mm]	812 (762)	705 (625)	1140 (1000)	612 (587)

U.S. MAGNET DEVELOPMENT PROGRAM

Outlook to the future

- The initial 3-year plan is almost complete.
- The new plan is being prepared, some elements under consideration include:
  1. Cos-theta Nb_3Sn magnets:
     - 120-mm aperture 2-layer and 4-layer SM dipole coils
       - ➢ practice 2-layer coil with plastic parts was wound with Cu cable and impregnated
     - 4-layer 17 T Nb_3Sn dipoles with 60-mm aperture and SM
     - Large-aperture 11-15 T SM coils allows also HTS insert tests
  2. Canted Cos-theta Nb_3Sn magnets:
     - 4-Layer, 90–120 mm bore CCT design with option for HTS insert
     - Target bore field of 12–13 T at ~80-85% of short sample
  3. HTS magnets
     - ~5 T HTS inserts based on both Bi2212 and REBCO CORC
     - Canted cos-theta and slotted cos-theta coil structures
  4. Continue the work on various aspects of Technology and SC R&D
- The Nb_3Sn magnet plan will be reviewed in December 2019
- The plan will be finalized at the US-MDP CM4 in February 2020