U.S. MAGNET DEVELOPMENT PROGRAM

The US Magnet Development Program Developments and Status Updates

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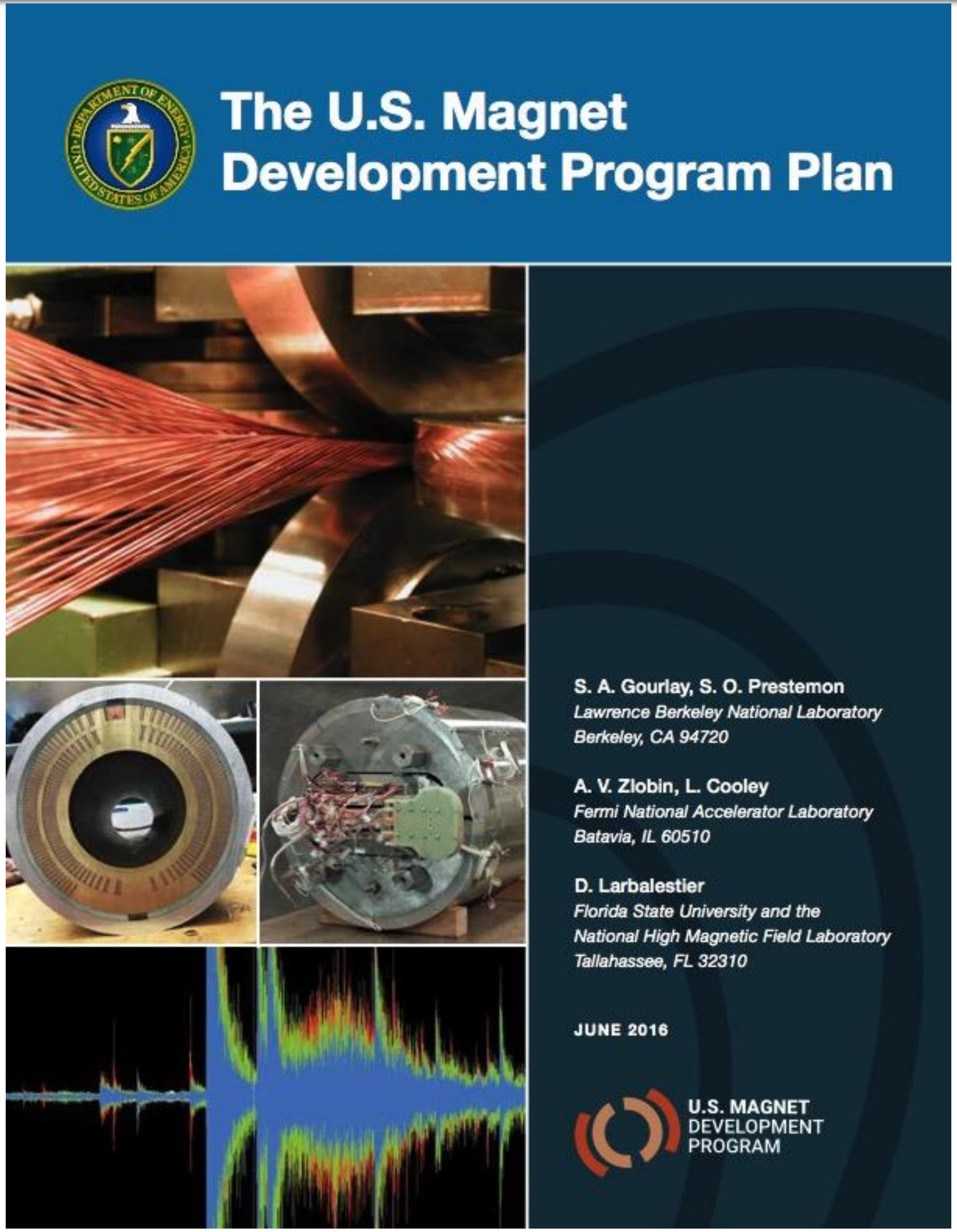
Lawrence Berkeley National Laboratory

For the US MDP Team:
The data shown in these slides
are the result of work from Scientists and Engineers in the US MDP

Outline

- Introduction
- The US MDP Program
  - main goals and…
  - roadmaps to achieve them
- Technology development highlights
  - LTS magnets
  - HTS magnets
  - Technology development
  - Materials
- Summary

The US Magnet Development Program was founded by DOE-OHEP 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 serve to guide the program

Technology roadmaps for each area:
LTS and HTS magnets, Technology, and 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.

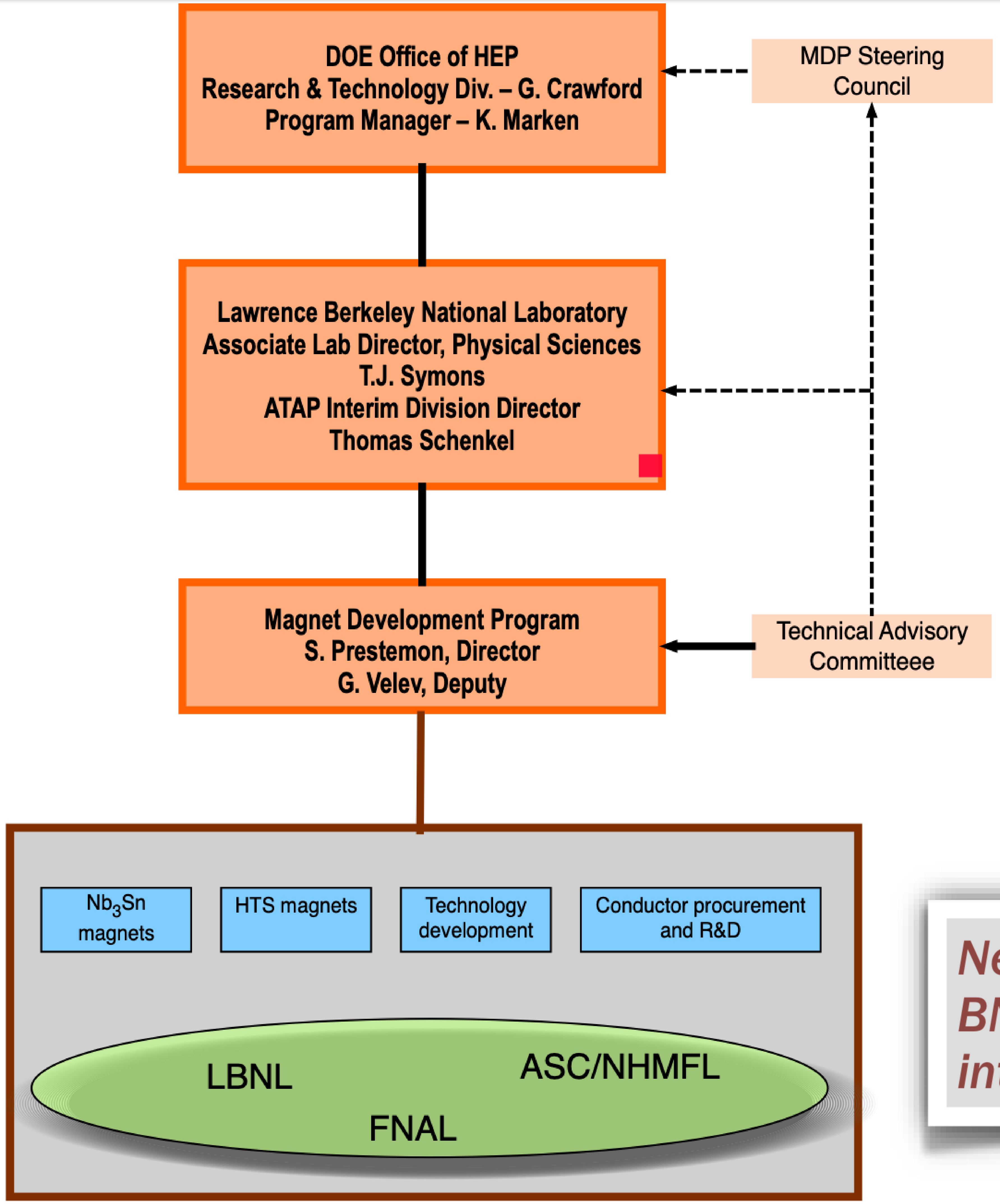
GOAL 4:

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

US MDP: vision

- ***Maintain and strengthen US Leadership*** in high-field accelerator magnet technology for future colliders
- **Focus on the *four primary goals* identified in the the original MDP Plan**
  - **Explore the performance limits of Nb_3Sn accelerator magnets, with a focus on minimizing the required operating margin and significantly reducing or eliminating training**
  - **Develop and demonstrate an HTS accelerator magnet with a self-field of 5T or greater, compatible with operation in a hybrid HTS/LTS magnet for fields beyond 16T**
  - **Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction**
  - **Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets**
- **Further *develop and integrate the teams* across the partner laboratories and Universities for maximum value and effectiveness to the program**
- **Identify and *nurture cross-cutting / synergistic activities* with other programs to more rapidly advance progress towards our goals**

The management structure of the MDP is well defined and the program is fully functioning



Steering Council
Harry Weerts (ANL), DOE appointed Chairman
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

New!
BNL has joined the MDP and will integrate its expertise into the program

MDP Management Group ("G6")
S. Prestemon, S. Gourlay, LBNL
G. Velev, A. Zlobin, FNAL
L. Cooley, D. Larbalestier, FSU

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The program is structured with technical elements directly aligned with program goals

Magnets	Lead
Cosine-theta 4-layer	Sasha 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

Cond Proc and R&D	Lance Cooley

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We have yearly collaboration meetings - excellent turnout, great opportunity for staff to present ideas and results and for technical discussions

- Collaboration meeting I, Feb. 17-19, 2017: Napa, California
- Collaboration meeting II: Jacksonville, Florida
- Collaboration meeting III, Jan. 11-13, 2019: FNAL, Illinois

- So far meetings have been designed to precede the LTSW
  - ~30% overlap of attendance; MDP serves as "magnet pull" for conductor development

- TAC members are actively engaged
  - Same members (and chair!) since the beginning of the MDP - provides continuity, good awareness of issues and progress

- Issue identified in 2019:
  - Significant number of presentations - very active group => may need 3 full days (have used 2.5 days to-date)

Example:
FY19 attendance

- 56 registrants
  - 14 attendees from LBNL; 13 talks
  - 17 attendees from FNAL; 12 talks
  - 6 attendees from ASC/NHMFL; 9 talks
  - 2 attendees from BNL; 2 talks
- Also OSU; CERN, KEK, PSI; (5 talks)
- Industry (SBIR)

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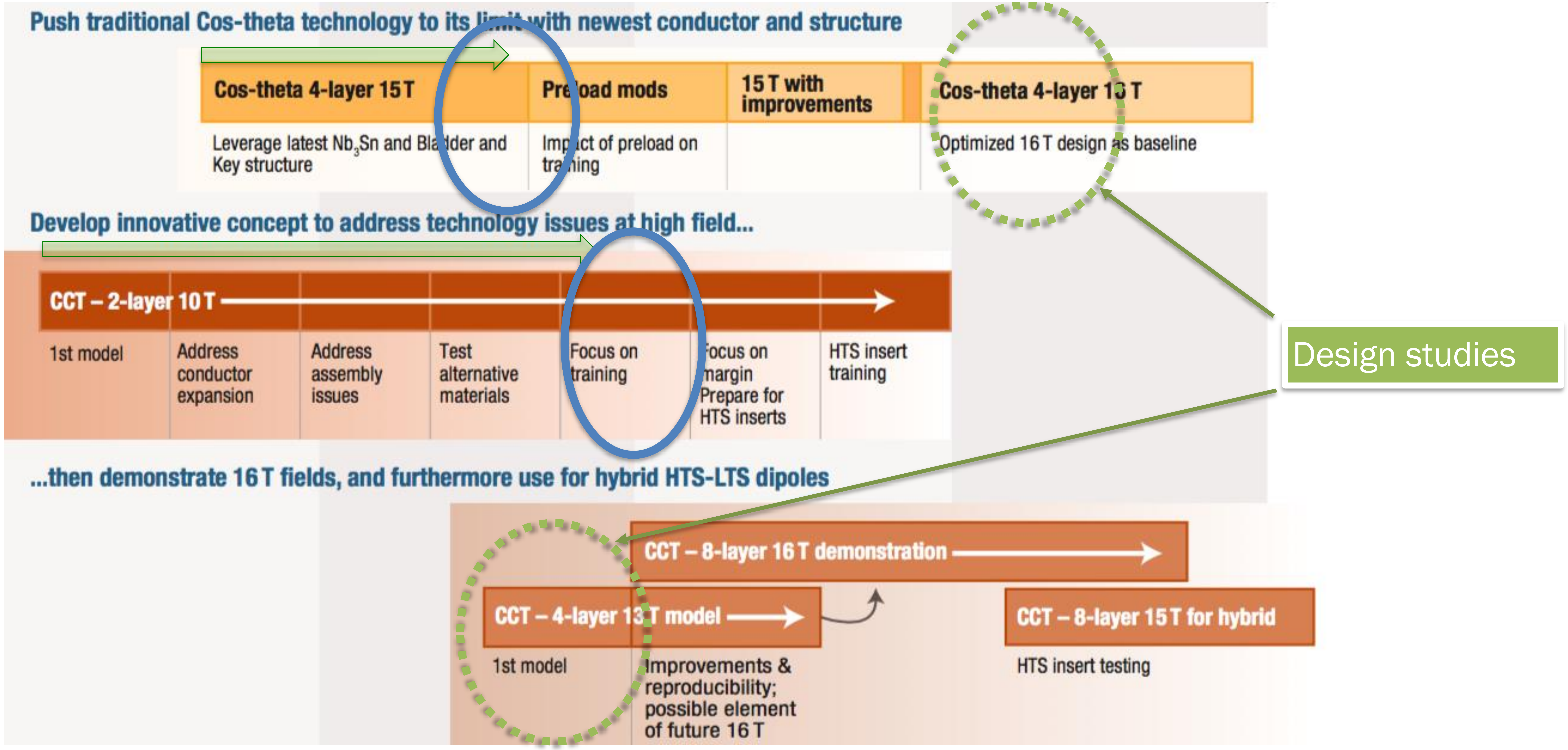
The MDP Nb_3Sn magnet efforts continue to progress as outlined in the MDP Plan document, but the evolution will depend on results

Area I:

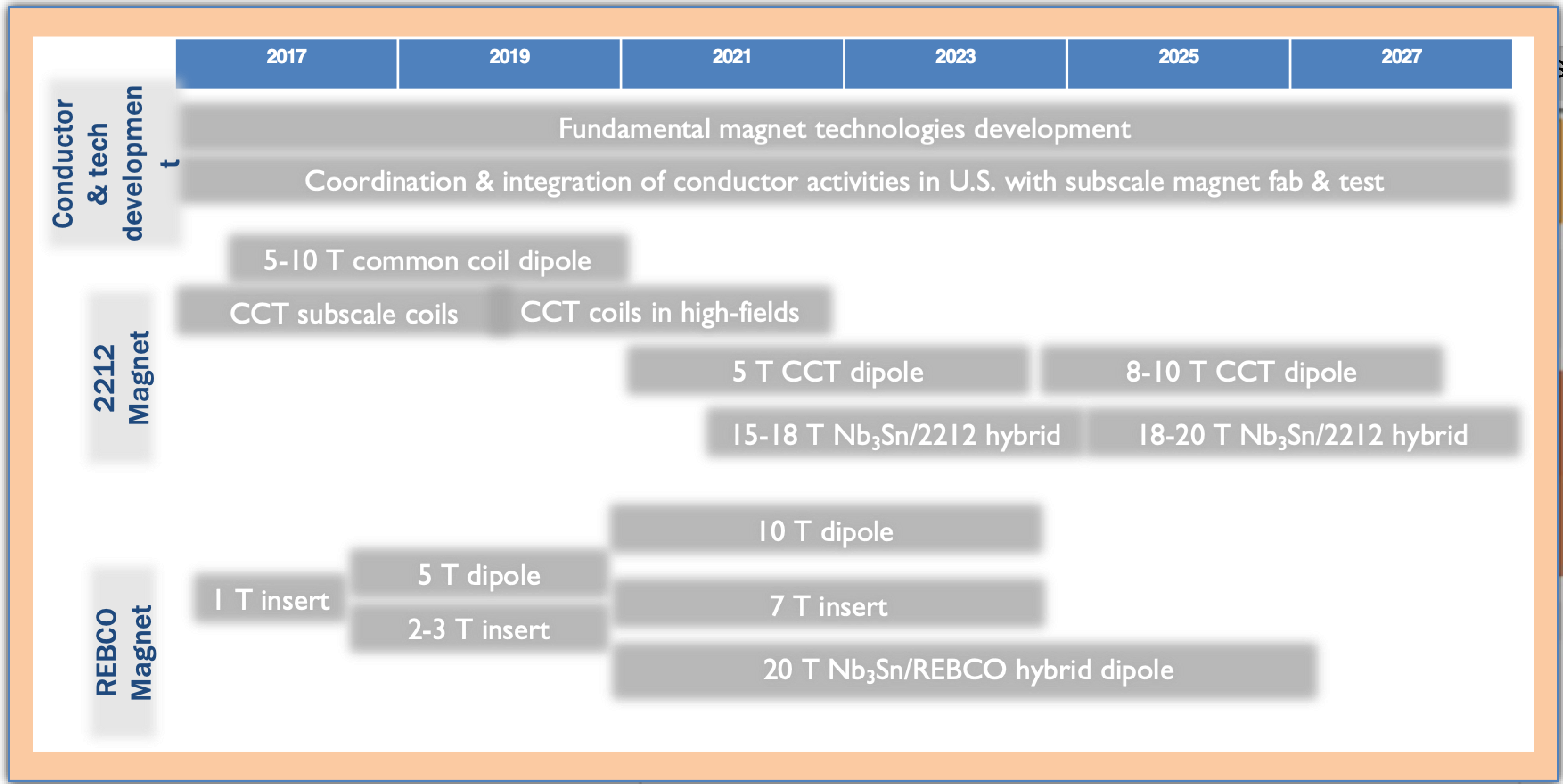
Nb_3Sn magnets



The MDP HTS magnet development is progressing well, and the long-term vision is starting to be fleshed out

Area II:

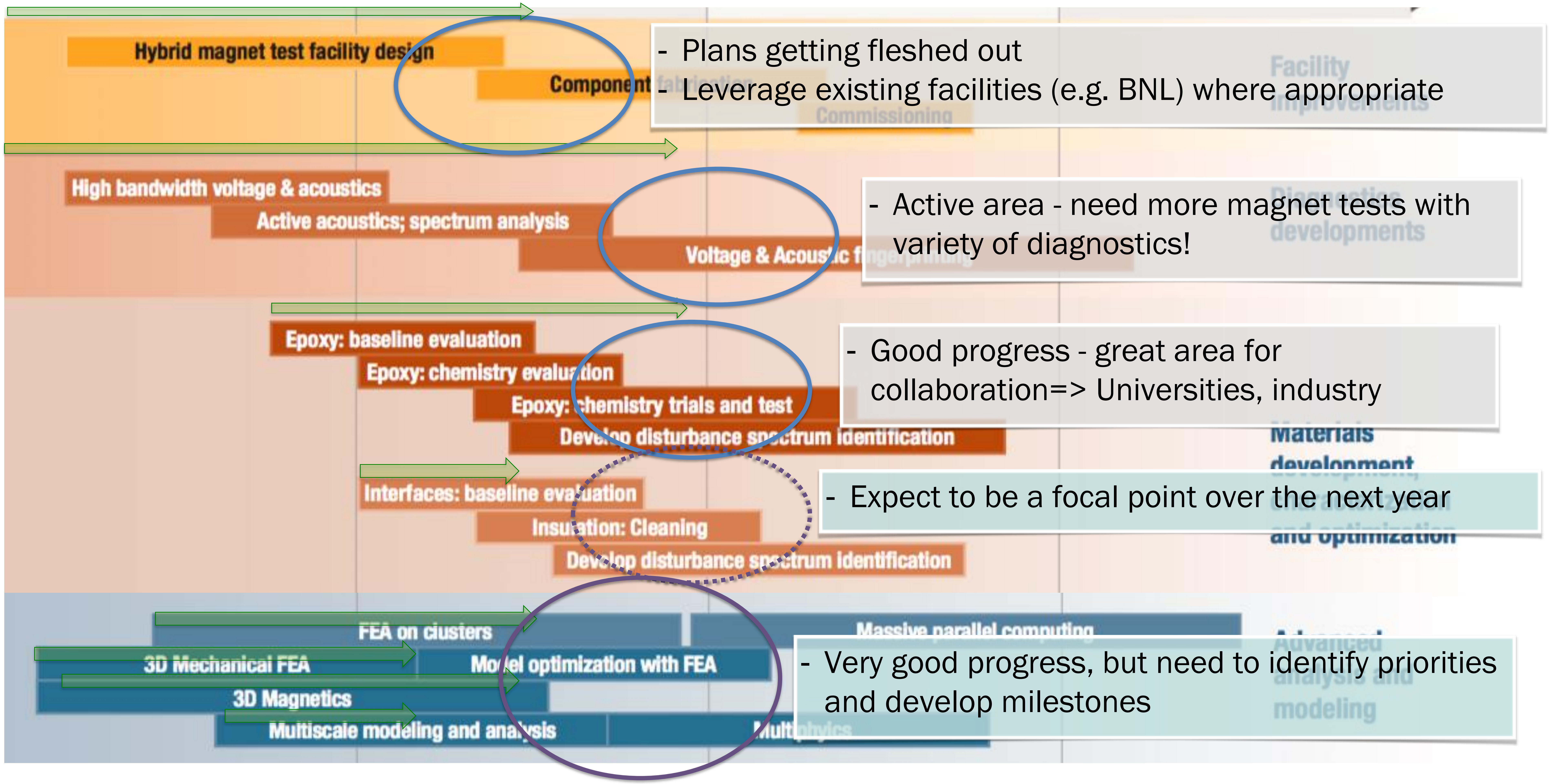
HTS magnet technology



Key science components of the MDP Plan are Technology Development and Conductor R&D - major developments underway

Area III:

The science of magnets: identifying and addressing the sources of training and magnet performance limitations via advanced diagnostics, materials development, and modeling



Conductor development is pursued through leveraged investments and coordination of industrial efforts

- A Roadmap has been developed to clarify CPRD's vision of furthering conductor development, supporting ongoing magnet development needs, and coordinating critical R&D from other funding sources in support of MDP goals (e.g. SBIR program)
- Nb_3Sn advances continue to be pushed
- Advances in Bi2212 powder processing + overpressure processing…
  - …and resulting progress in magnet performance

See Larbalestier, "Recent progress on the development of high performance Bi-2212 wires and coils"

- REBCO development focused on leveraging SBIR and complementary programs;
  - MDP provides measurements and conductor performance feedback to developers and vendors


LTSW 2018

The 2018 Low Temperature/ High Field Superconductor Workshop

Program

MONDAY, FEBRUARY 12, 2018	
7:30 am	Registration & Continental Breakfast
Session Ia - Magnet Pull – High Energy Physics	
Session Chairs: Dave Sutter & Bruce Strauss	

35 years of exceptional service to the community

Lance Cooley, Ph.D.
Head, Conductor Procurement and R&D Program
US HEP Magnet Development Program
Applied Superconductivity Center, National High Magnetic Field Laboratory
2031 E. Paul Dirac Dr, Tallahassee, FL 32310-3711 USA
ldcooley@asc.magnet.fsu.edu

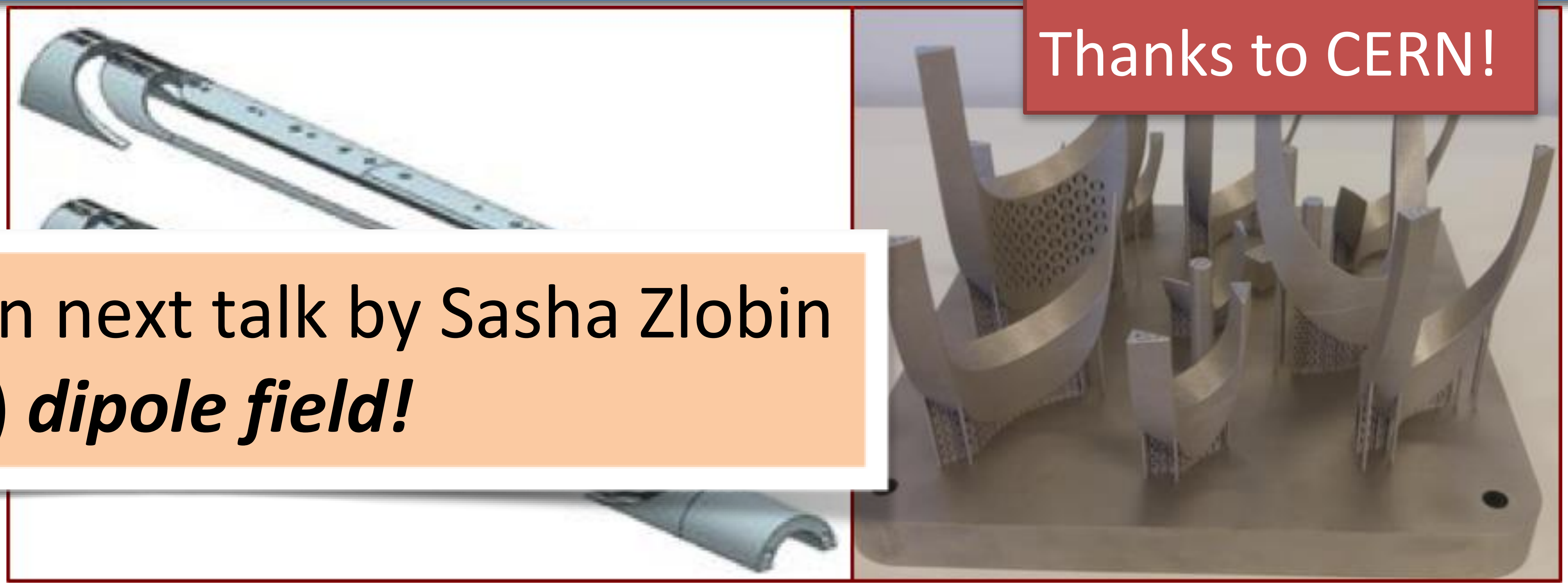
Roadmap for Conductor Procurement, Research and Development
October 6, 2017

Covering DOE FY 2018

Some progress updates in the key program areas

A Cos(θ) 4-layer design, led by FNAL, is being pursued with the ultimate goal of achieving ~15T

- Design minimizes midplane stress for highest field
- A technical challenge is to provide adequate prestress on inner coils
  - Intrinsic difficulty with 4 layers
  - Collared-structure approach includes new fe
    provide some prestress increase during cool down

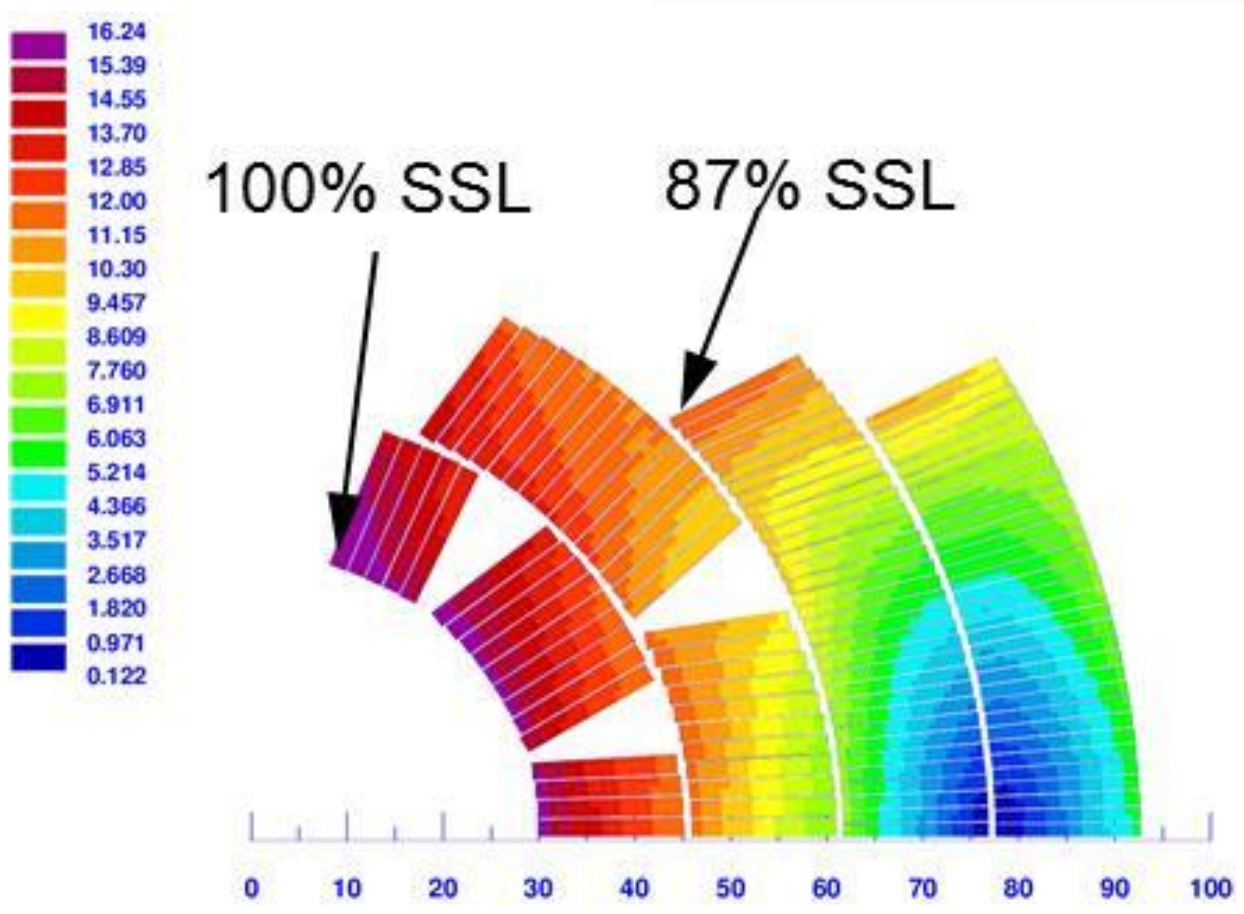


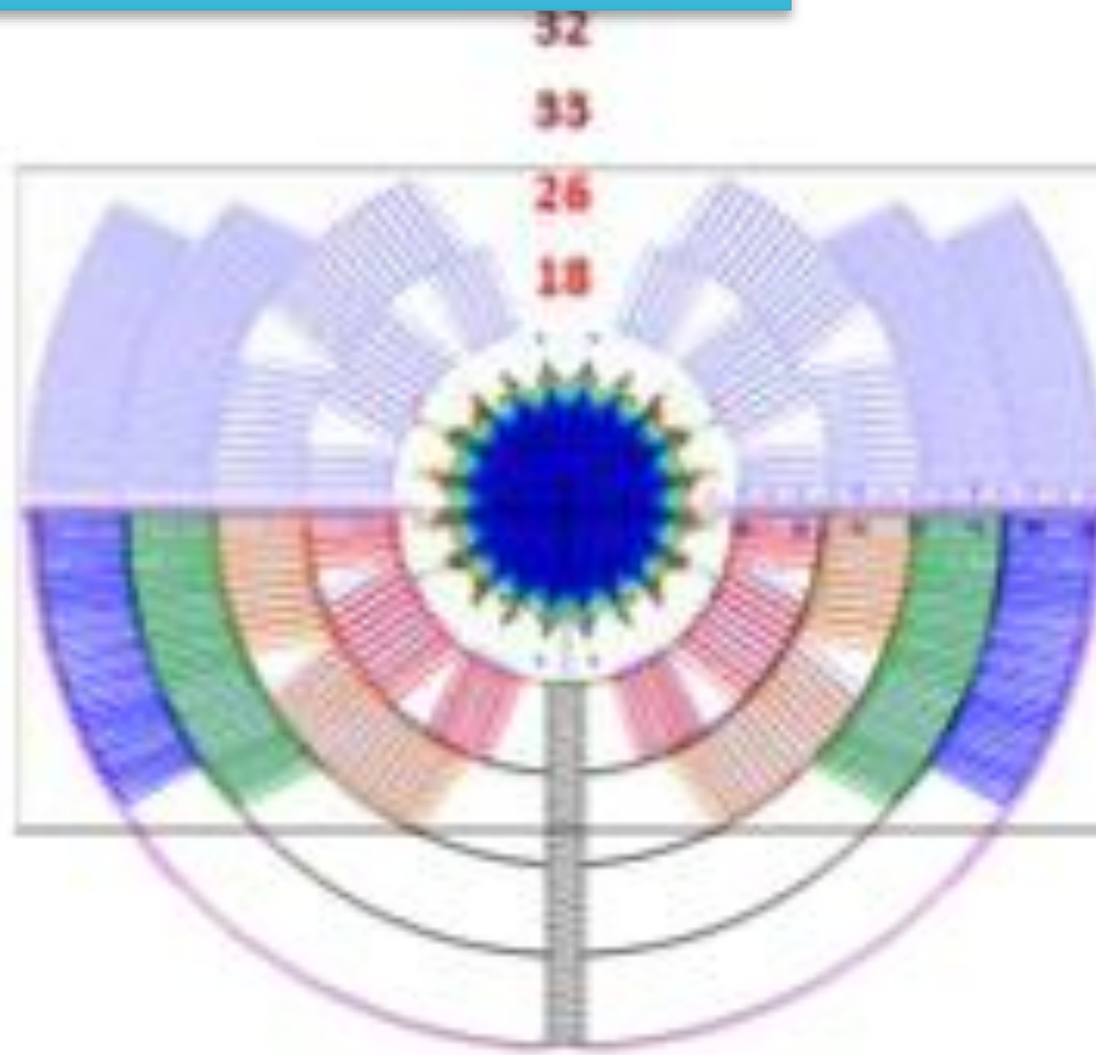
Thanks to CERN!

See test results in next talk by Sasha Zlobin
⇒ ***Record Cos(θ) dipole field!***

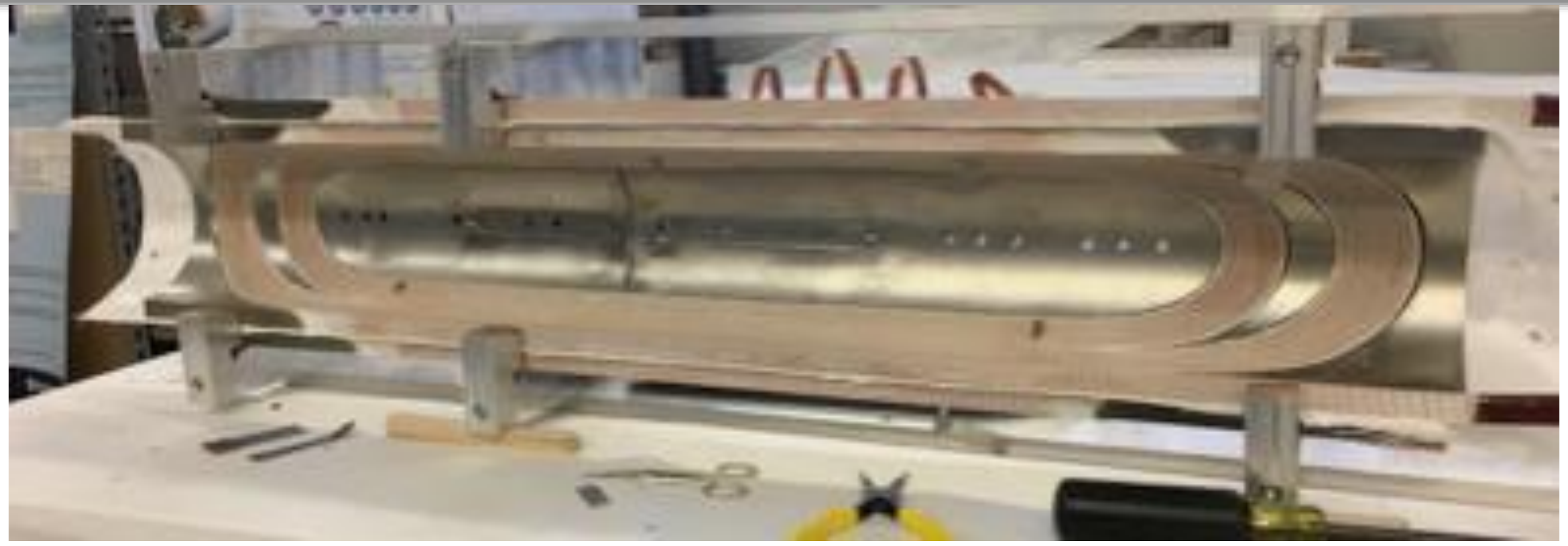
- Status:
  - Coils fabricated✓
  - Structure designed, fabricated✓
  - Mechanical model assembly completed✓
  - Assembly readiness review completed ✓
  - Test completed ✓
  - Reload at higher prestress
  - Retest

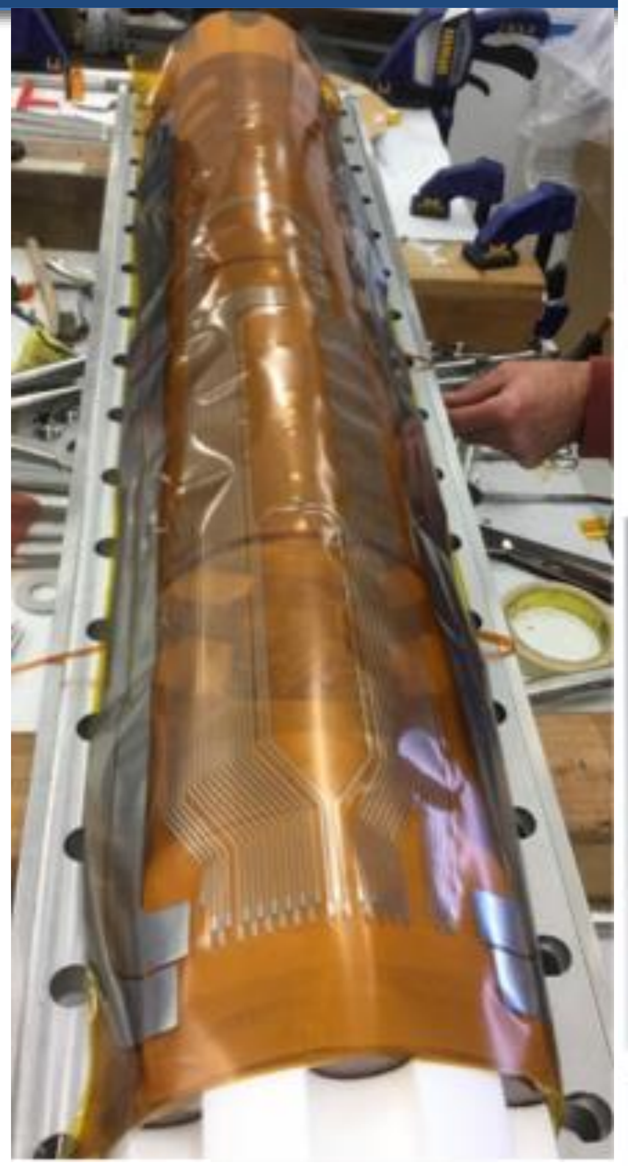
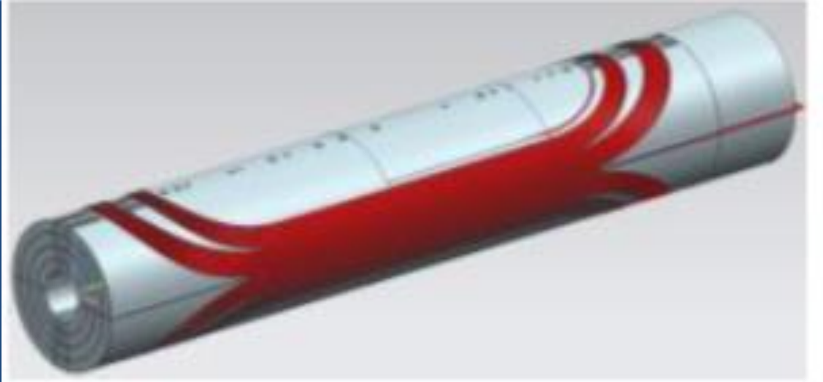
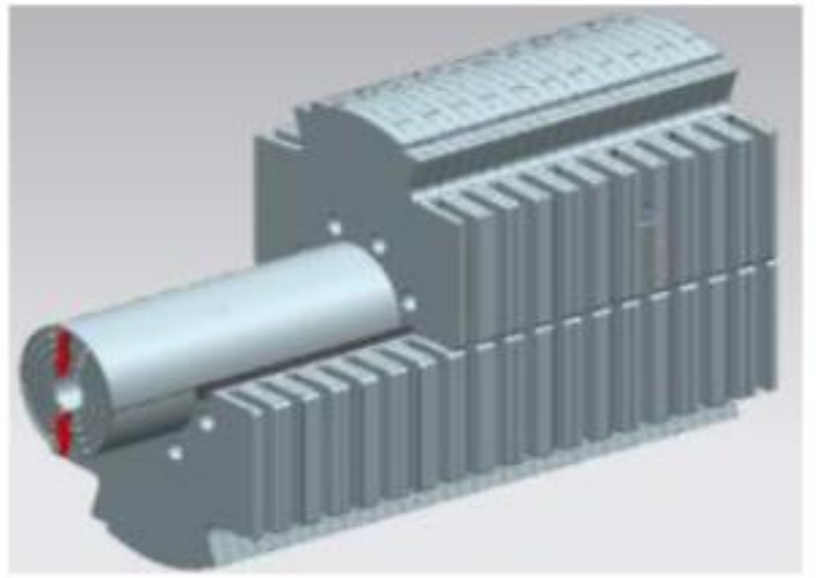
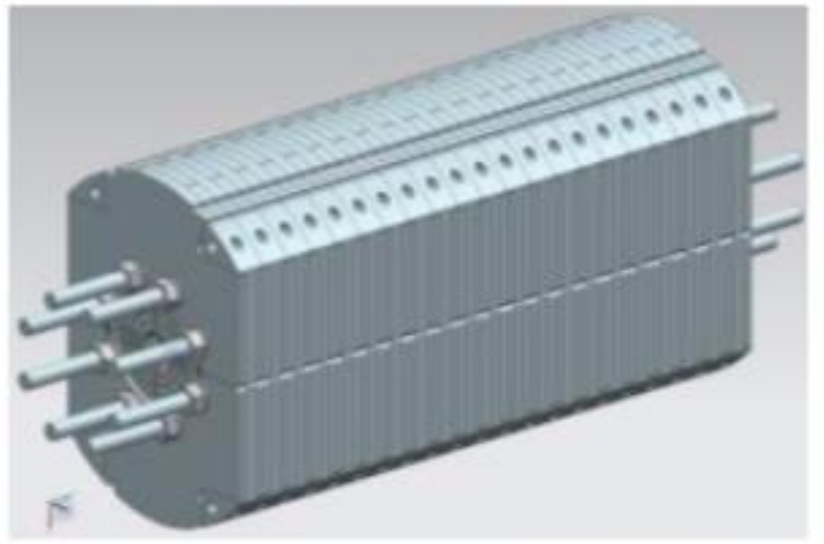
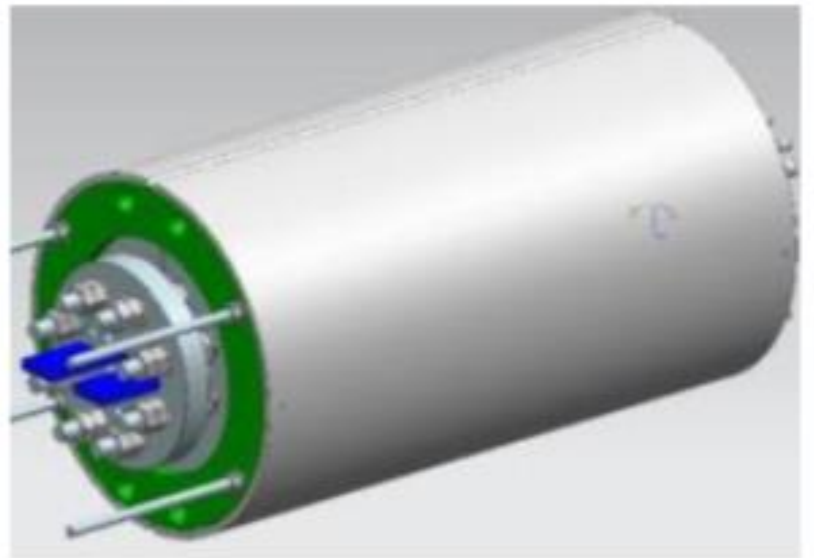
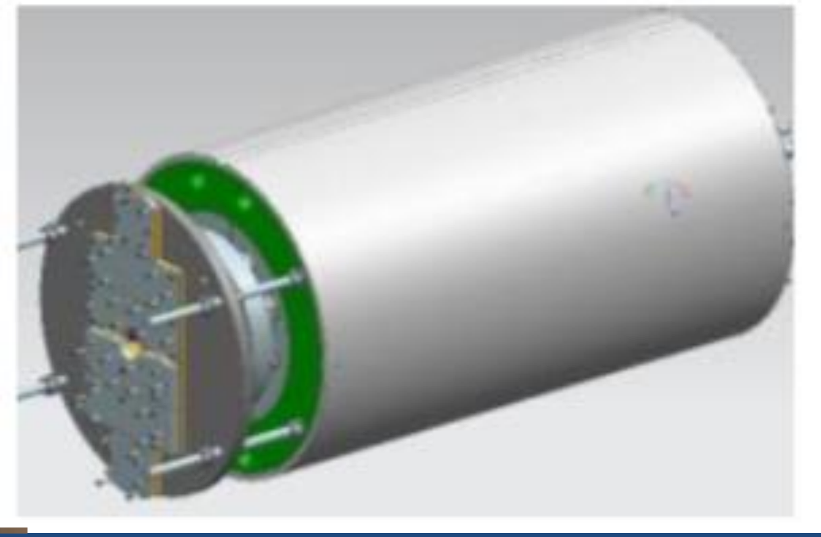
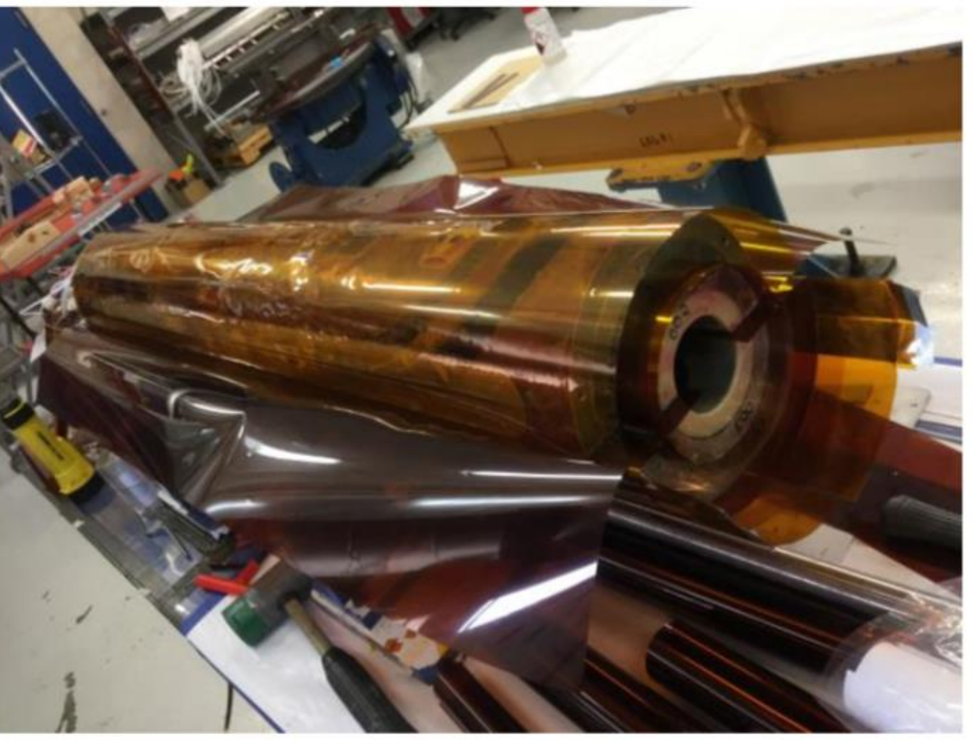
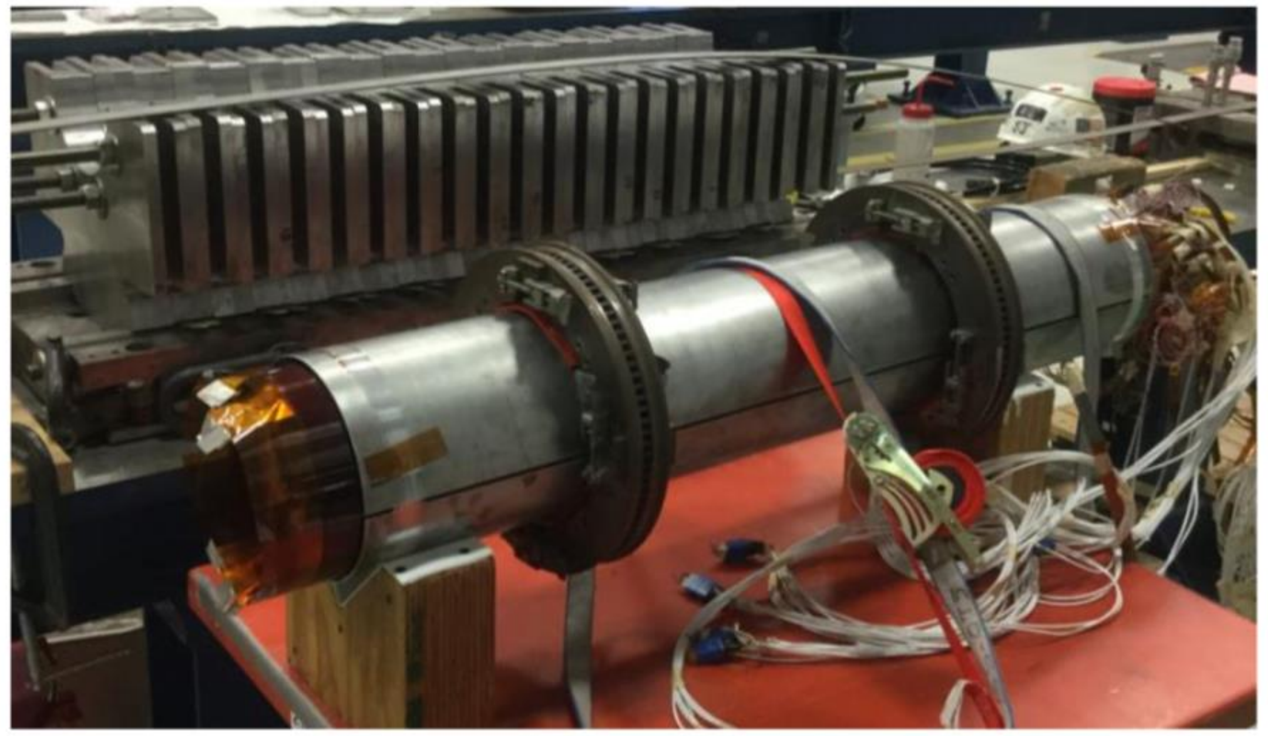
60-mm aperture, 4-layer graded coil

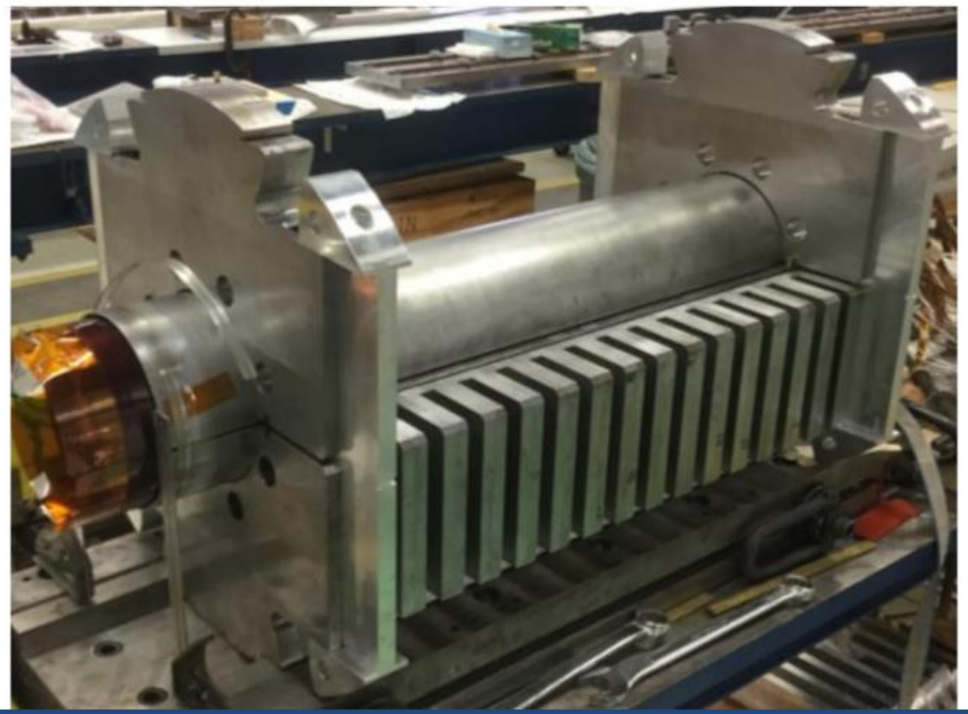




Very significant effort to to develop the 4-layer Cos(θ) magnet - coils, structure, instrumentation

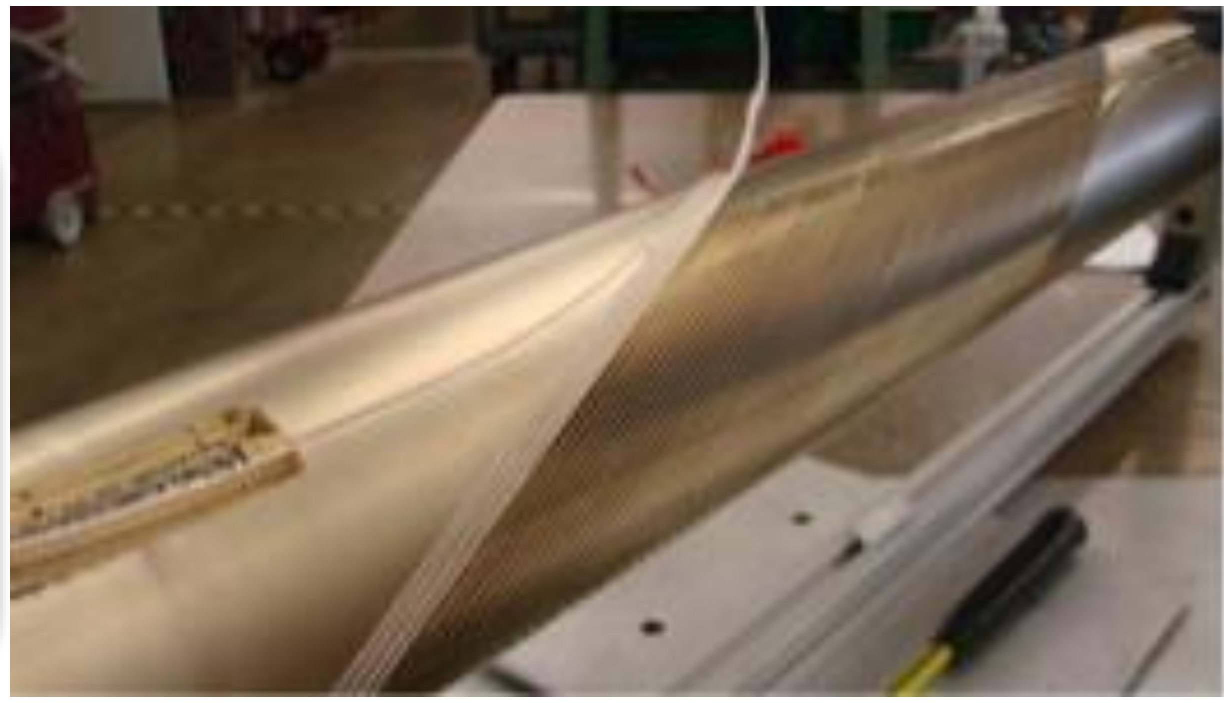


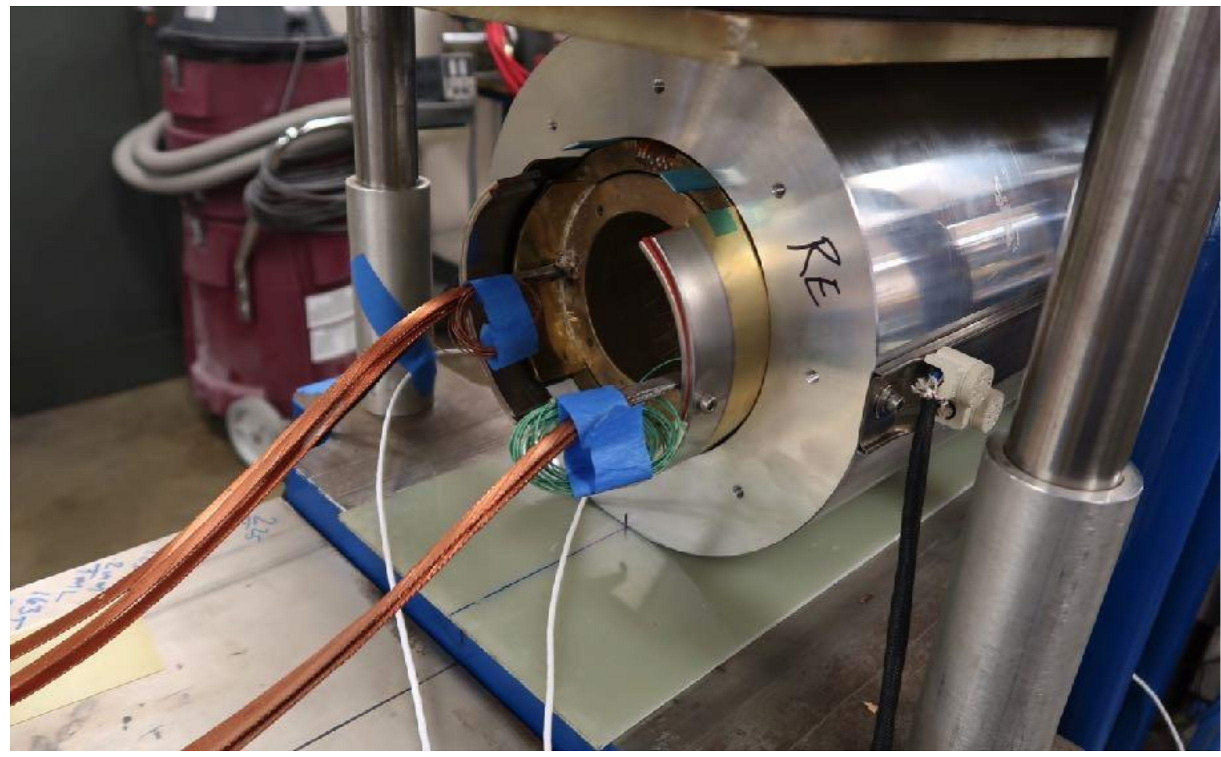













The Canted-Cos(θ) concept, led by LBNL, is being explored as an alternative for high-field magnets

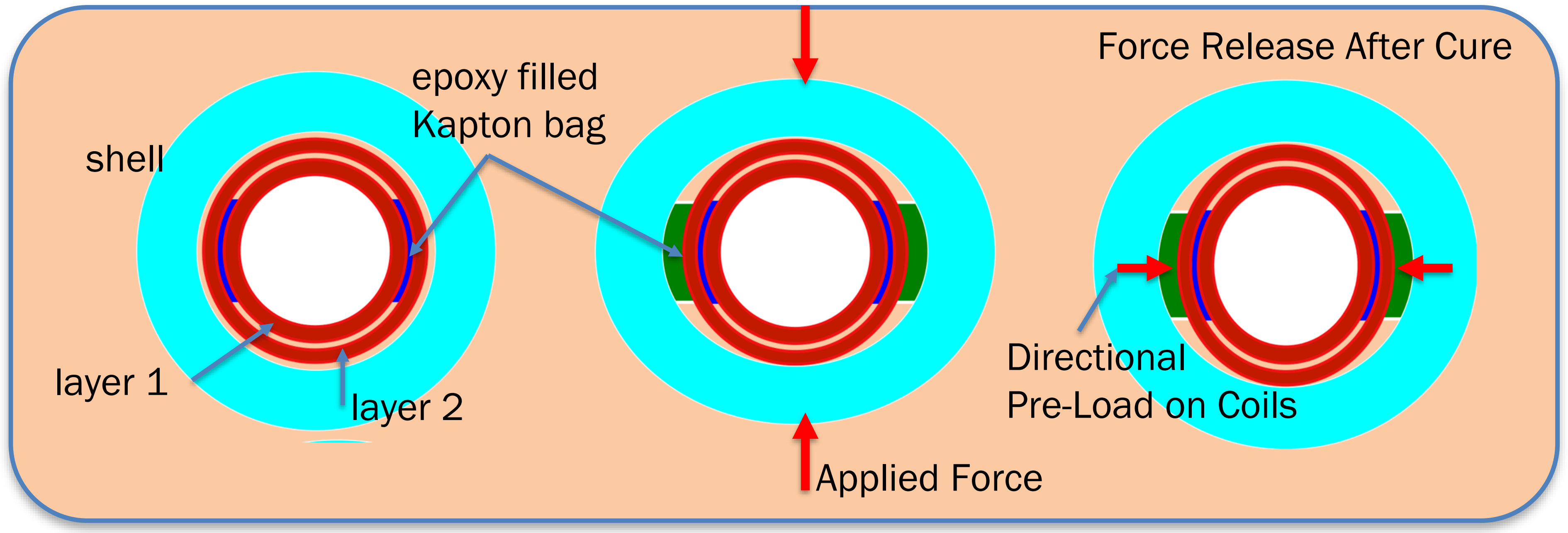
- Canted Cosine-theta:
  - CCT4 (the second Nb_3Sn CCT 2-layer magnet) was tested, and thermally cycled
  - CCT5 incorporated modifications based on CC4 experience
    - Magnet was tested and thermally cycled
  - Subscale CCT currently being pursued for fast turn-around technology development



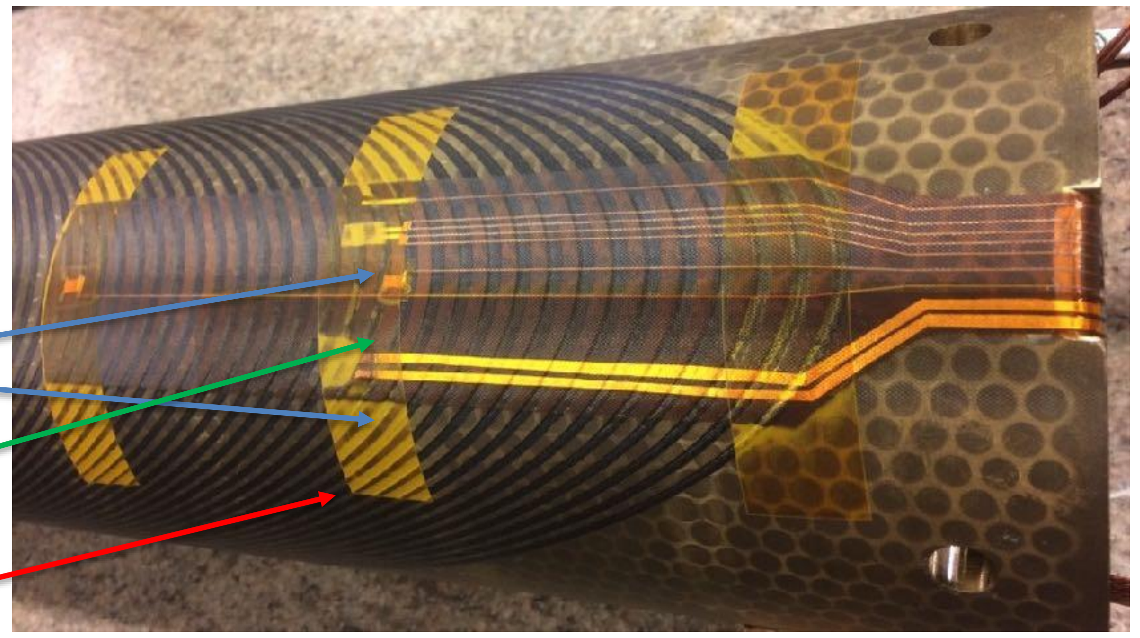


	CCT3	CCT4	CCT5
Bore size [mm]	90	90	90
Groove design	constant width	1.25 mm gap at pole	1.65 mm gap at pole
Conductor	RRP 54/61 Ta doped	RRP 54/61 Ta doped	RRP 108/127 Ti doped
HT Temp [C]	650	660	665
Potting configuration	full magnet	full magnet	individual layers
Epoxy	CTD-101K	CTD-101K	FSU Mix 61
Layer-to-layer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

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

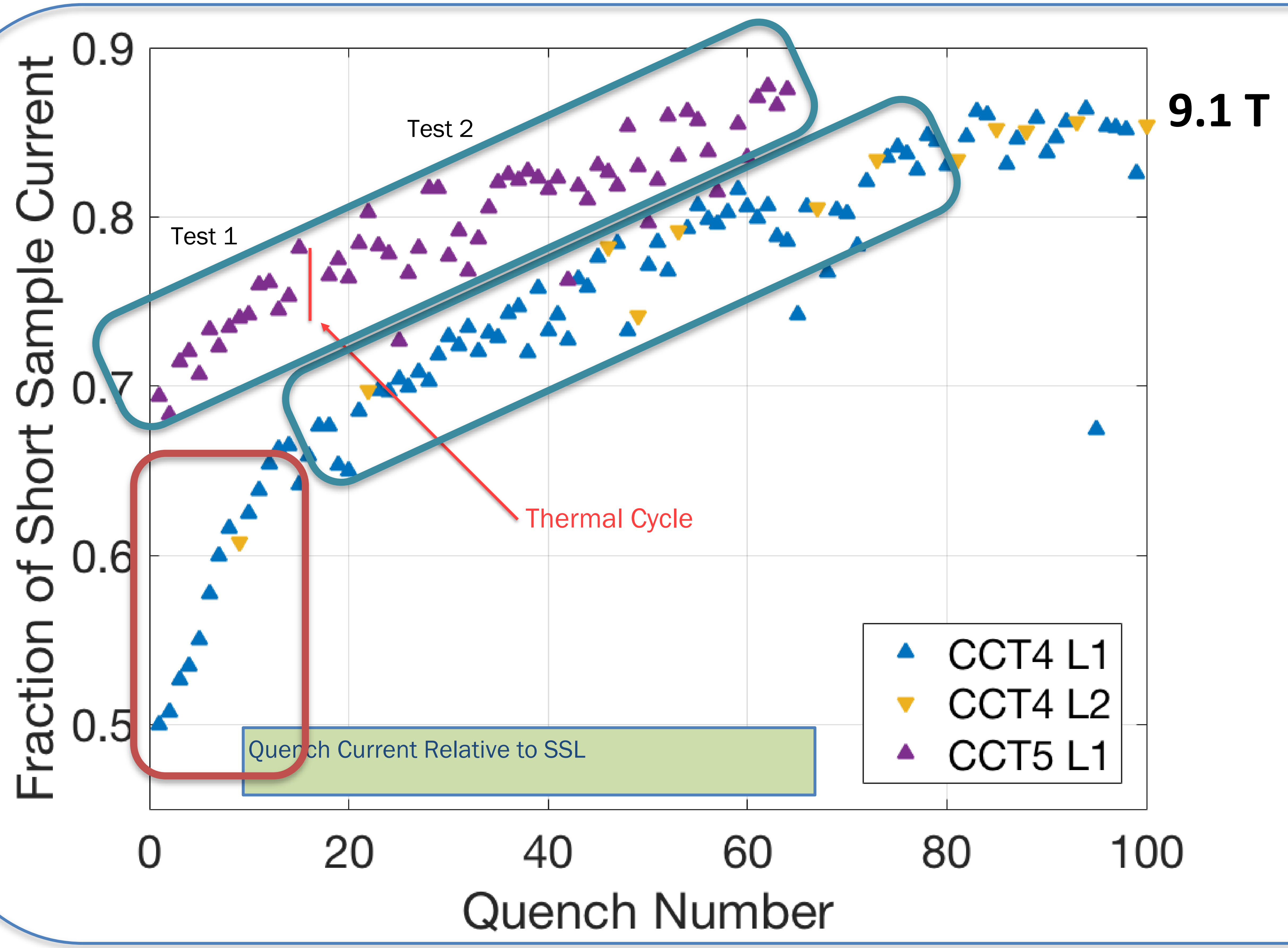


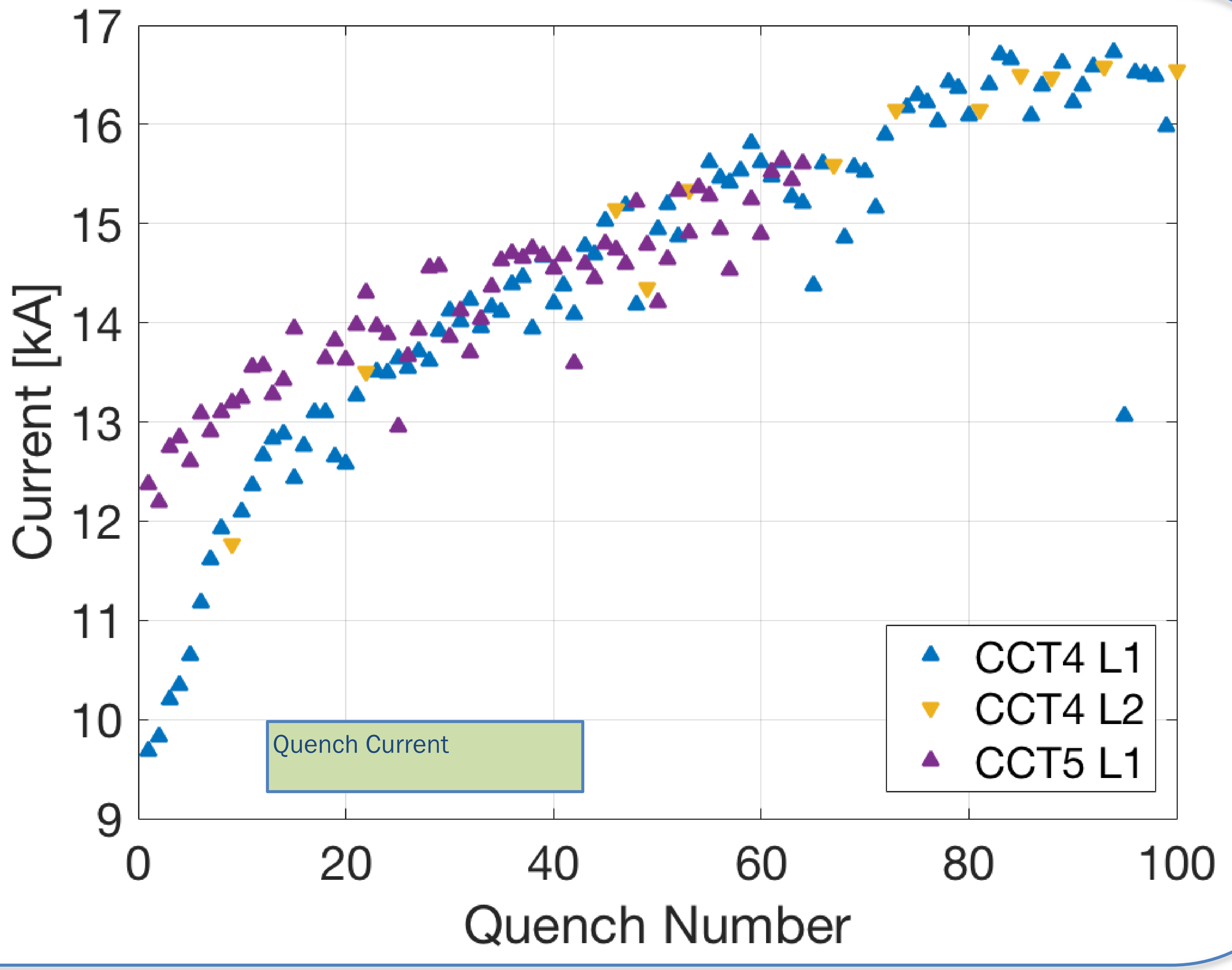
Instrumentation Trace After Potting



The use of novel diagnostics supported feedback that improved magnet performance - gaining insight in training mechanisms

CCT5 Training Behavior

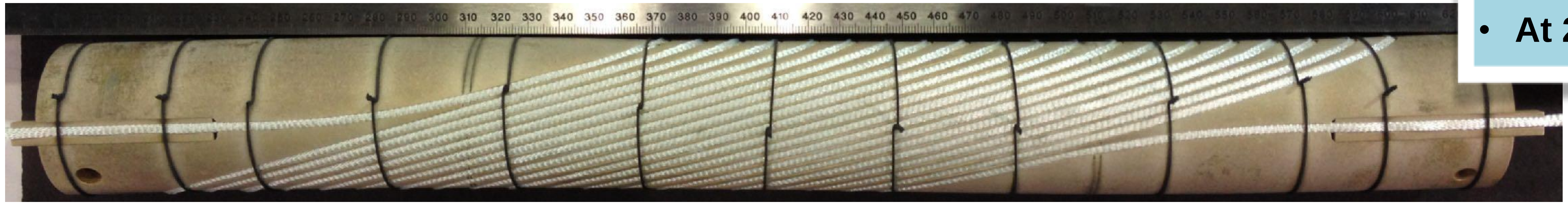


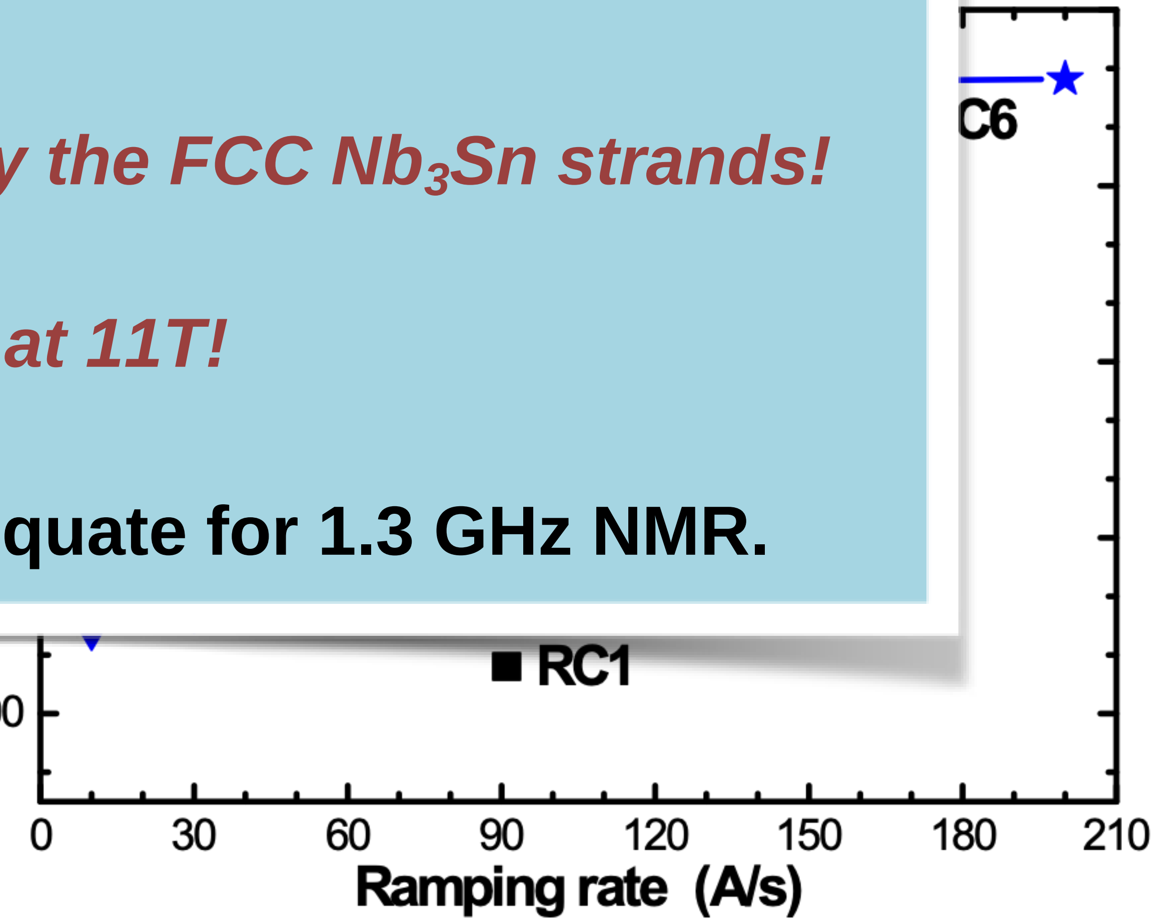


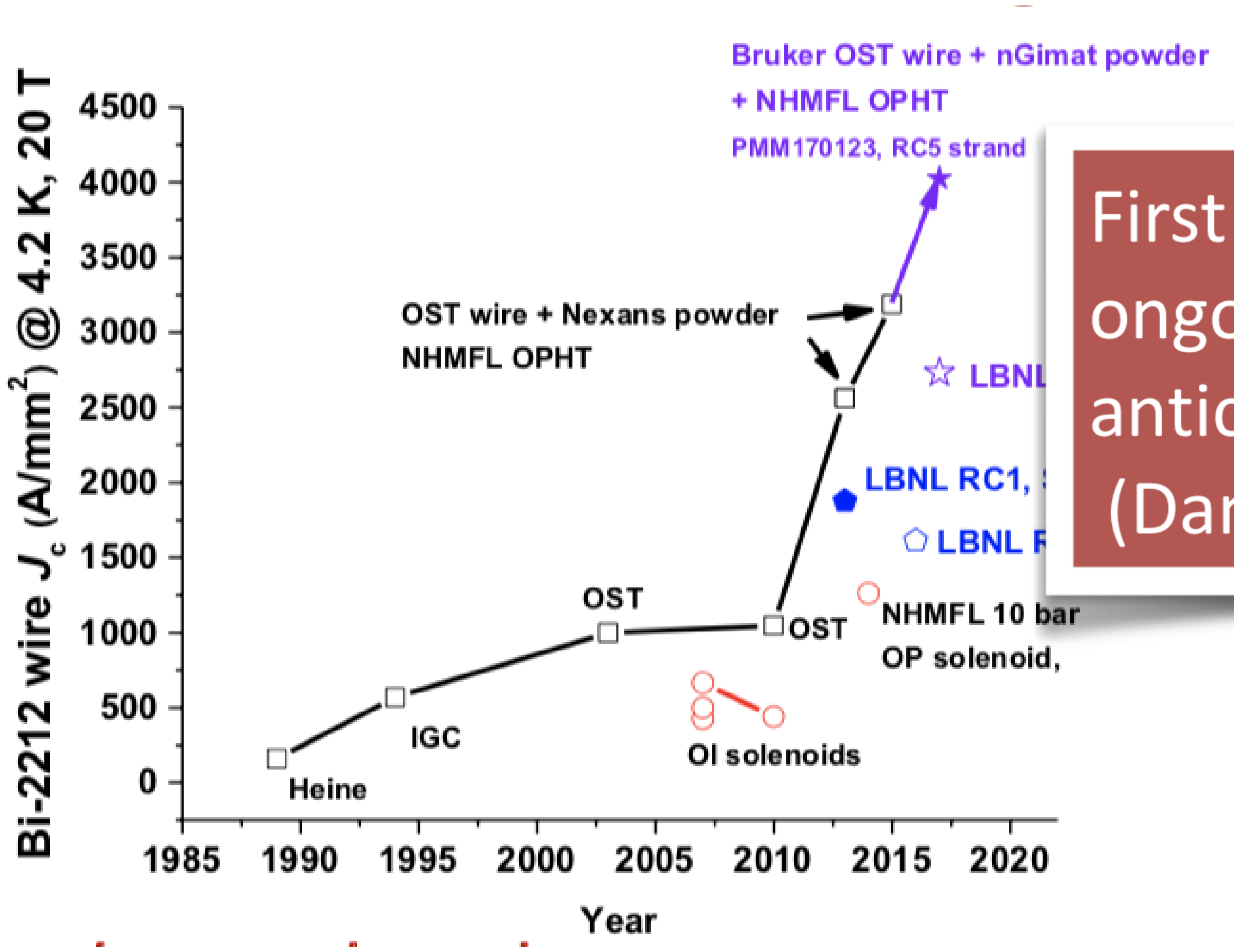
On the HTS magnet front, Bi2212 has matured to become a magnet-ready conductor

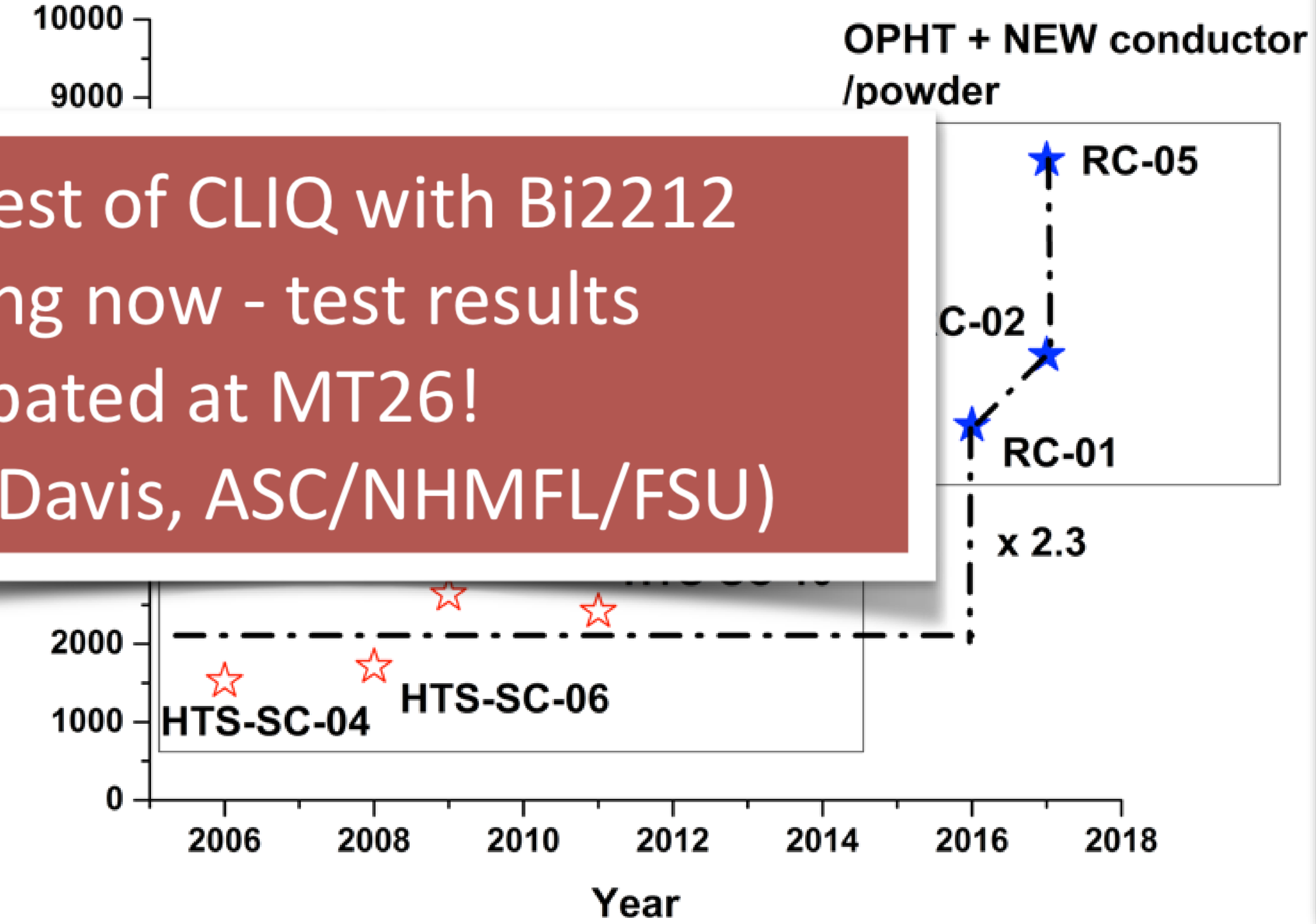
- Bi2212 has made dramatic strides in J_c over last 3 years => ready for magnets
  - Wire has been cabled and tested in racetrack configuration (RC5)
  - First Bi2212 CCT dipoles have been wound and await reaction and testing soon
  - Roadmap integrates Bi2212 CCT in a high-field hybrid magnet design

- **Nano-spray combustion powder technology**
- **At 15 T, J_e - 1365 A/mm^2**
  - ***twice the target desired by the FCC Nb_3Sn strands!***
- **Bi2212 now *exceeds RRP J_E at 11T!***
- **At 27 T, J_e - 1000 A/mm^2, adequate for 1.3 GHz NMR.**

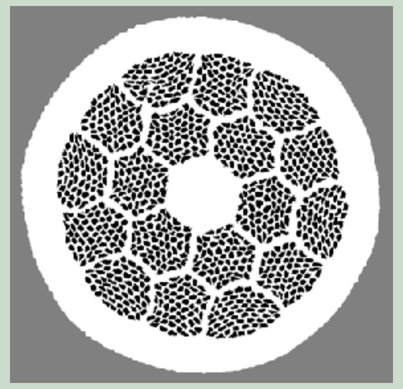




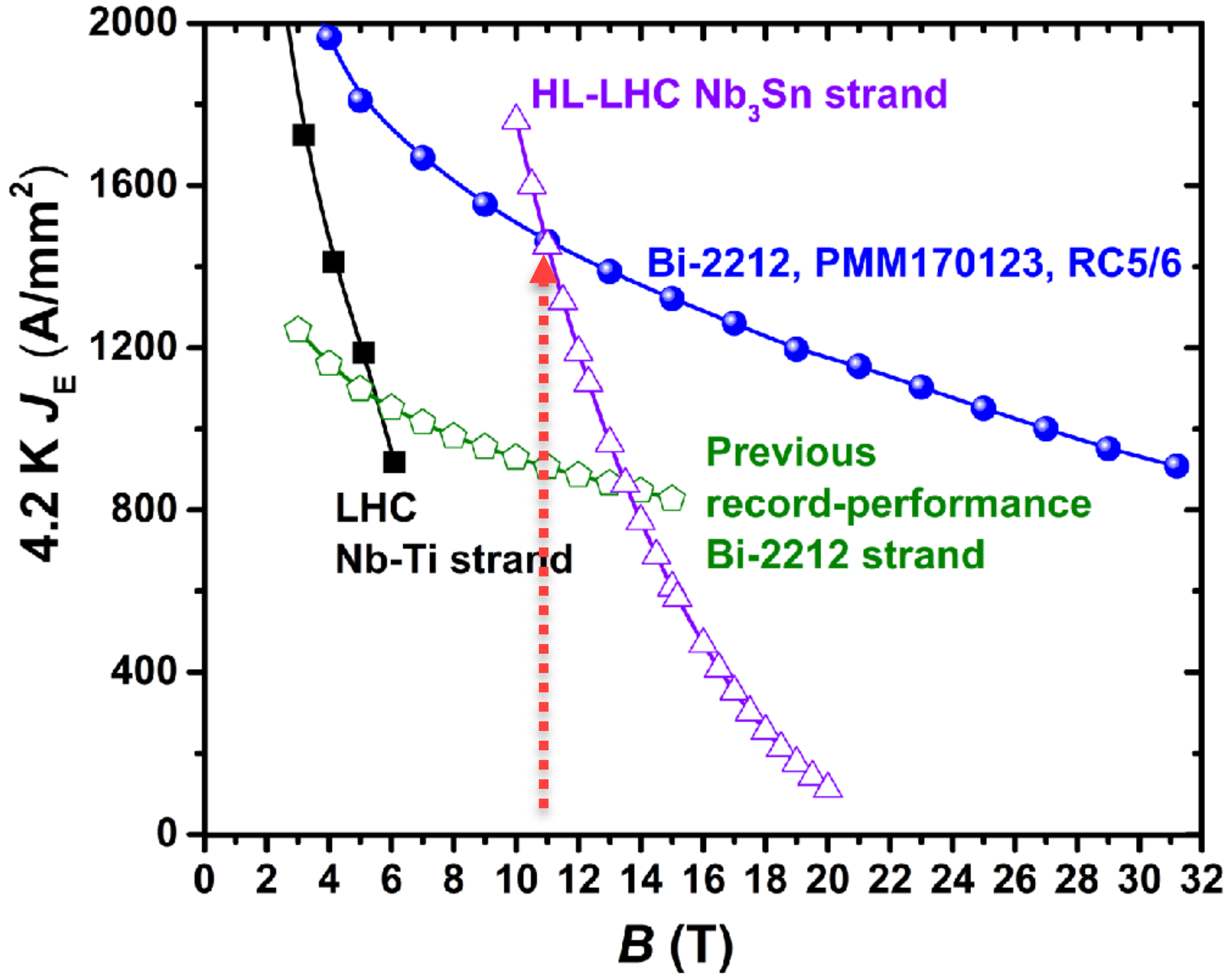




First test of CLIQ with Bi2212 ongoing now - test results anticipated at MT26!
(Dan Davis, ASC/NHMFL/FSU)

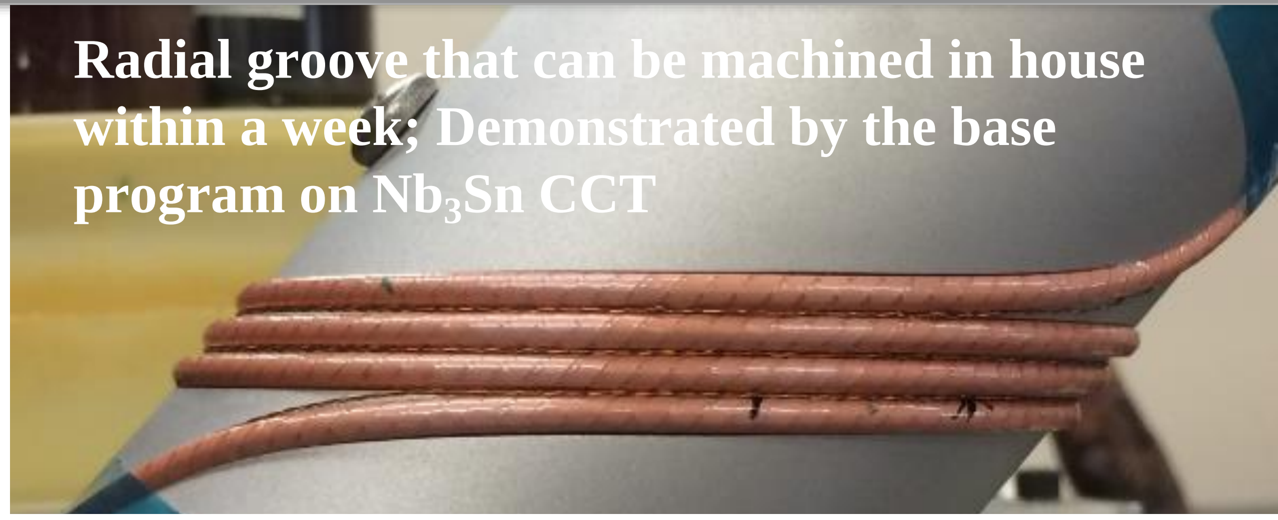


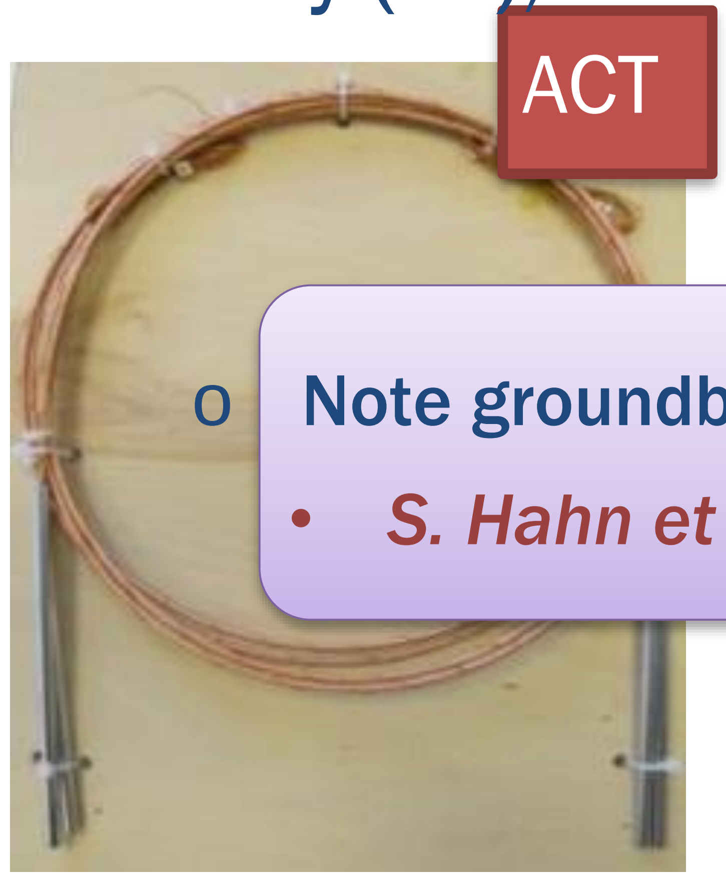
nGimat
MAGLAB
BRUKER
BERKELEY LAB

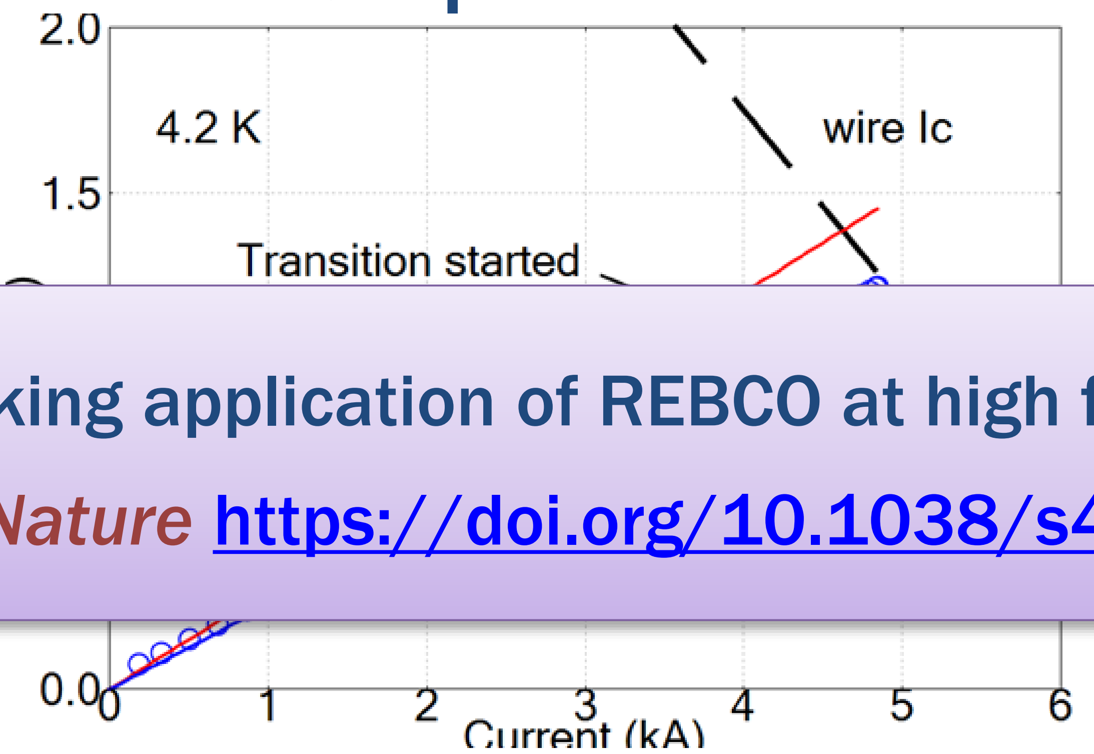


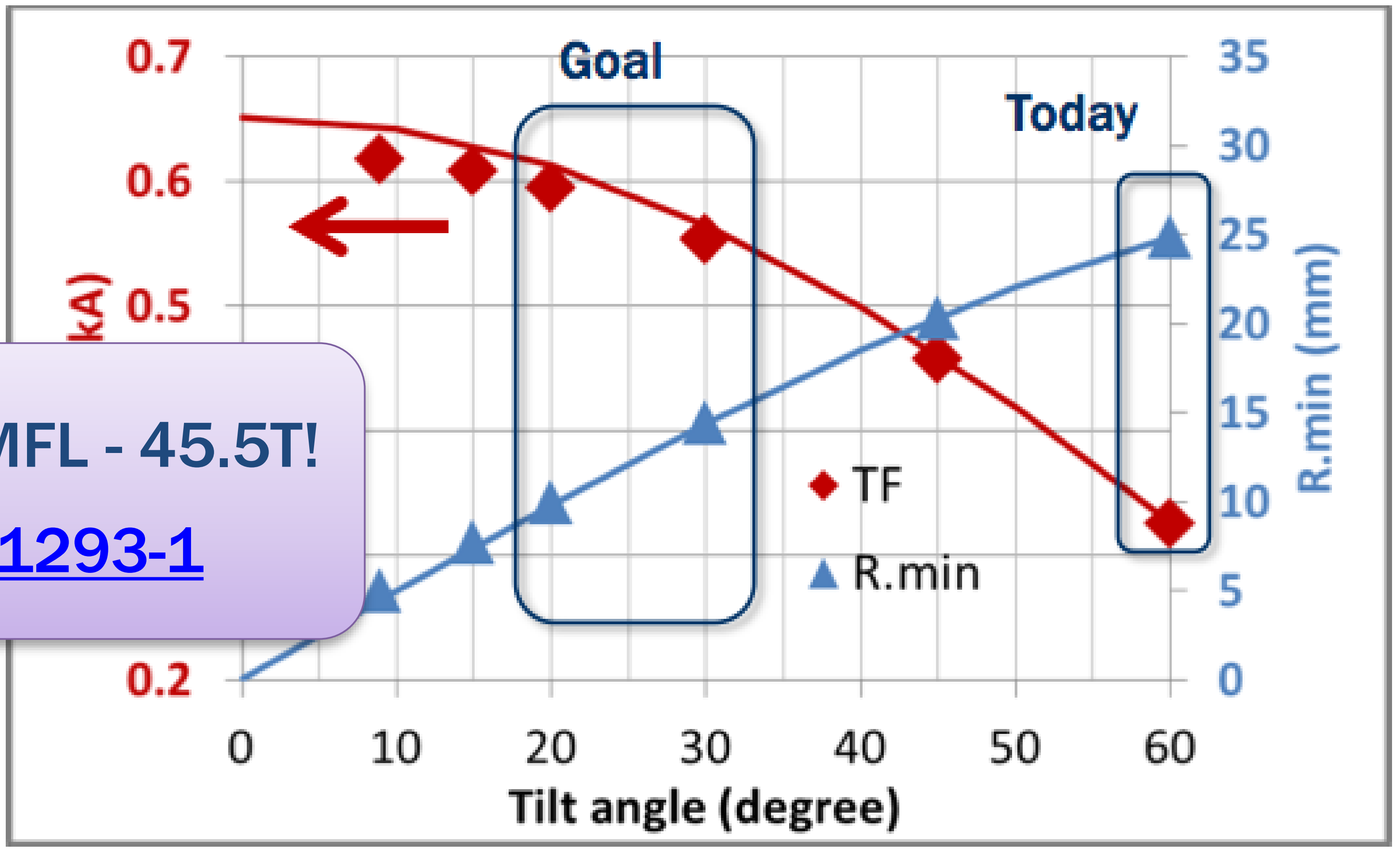
Work on REBCO is focused on the development of CORC cable in a CCT configuration - steady progress towards MDP goals

- REBCO development focused on CORC® cables and magnet technology development
  - 3-turn C0 “dipole” was used to develop winding tooling, fabrication processes
  - 40-turn C1 dipole was then fabricated and tested
  - 3-turn C2 has been fabricated and tested; full 40-turn C2 nearly completed - results by MT!
  - C3 magnet design well underway (5T); most of conductor procured

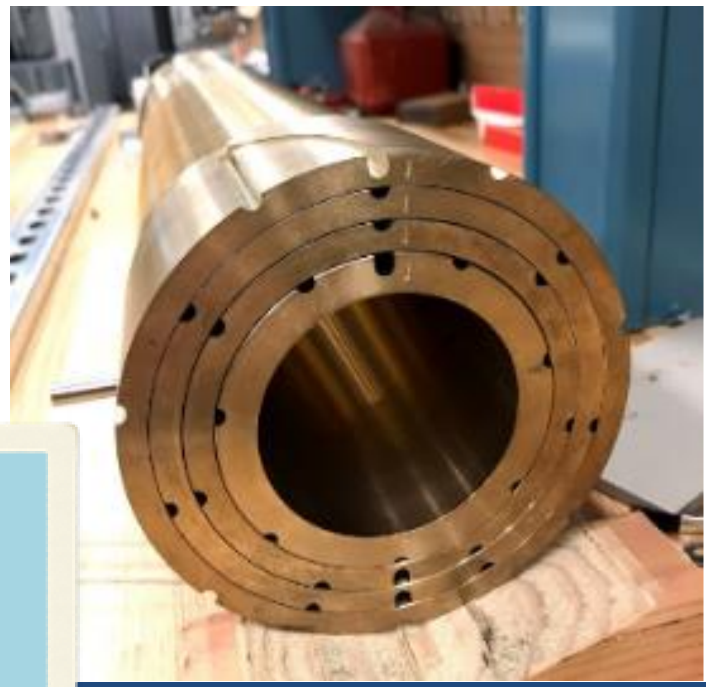

Radial groove that can be machined in house within a week; Demonstrated by the base program on Nb_3Sn CCT







- Note groundbreaking application of REBCO at high field by NHMFL - 45.5T!
  - *S. Hahn et al, Nature* https://doi.org/10.1038/s41586-019-1293-1



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

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

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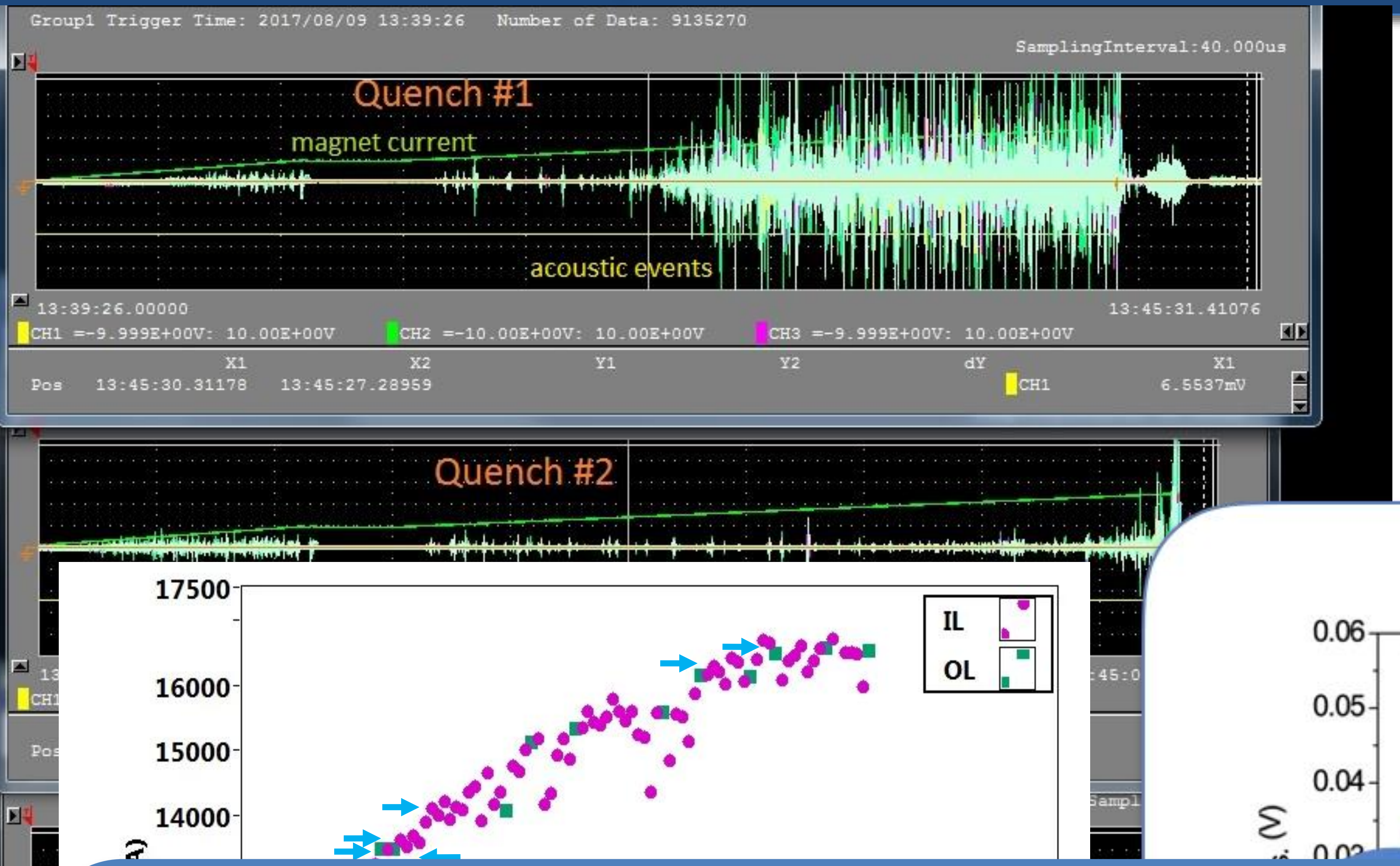
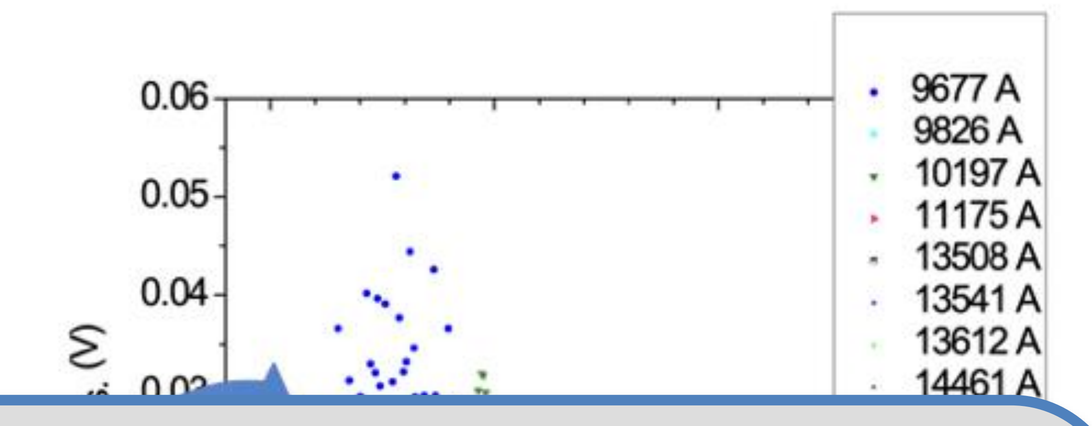
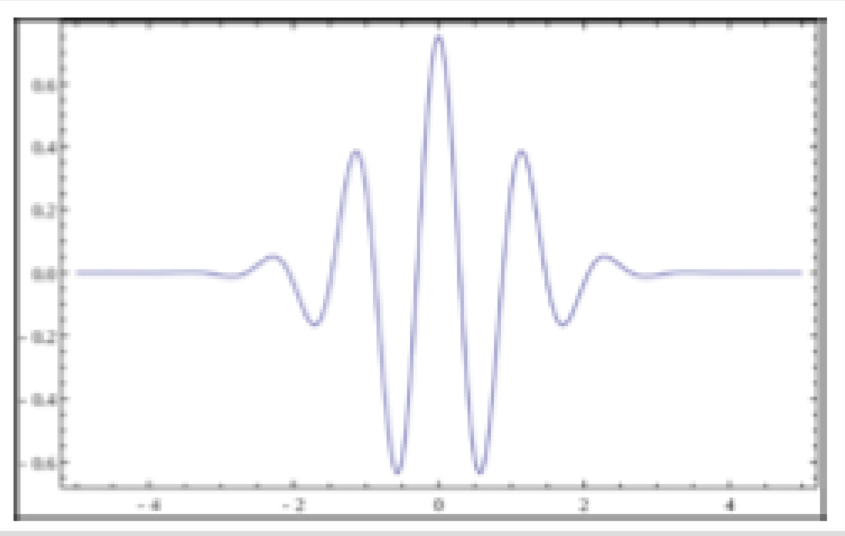
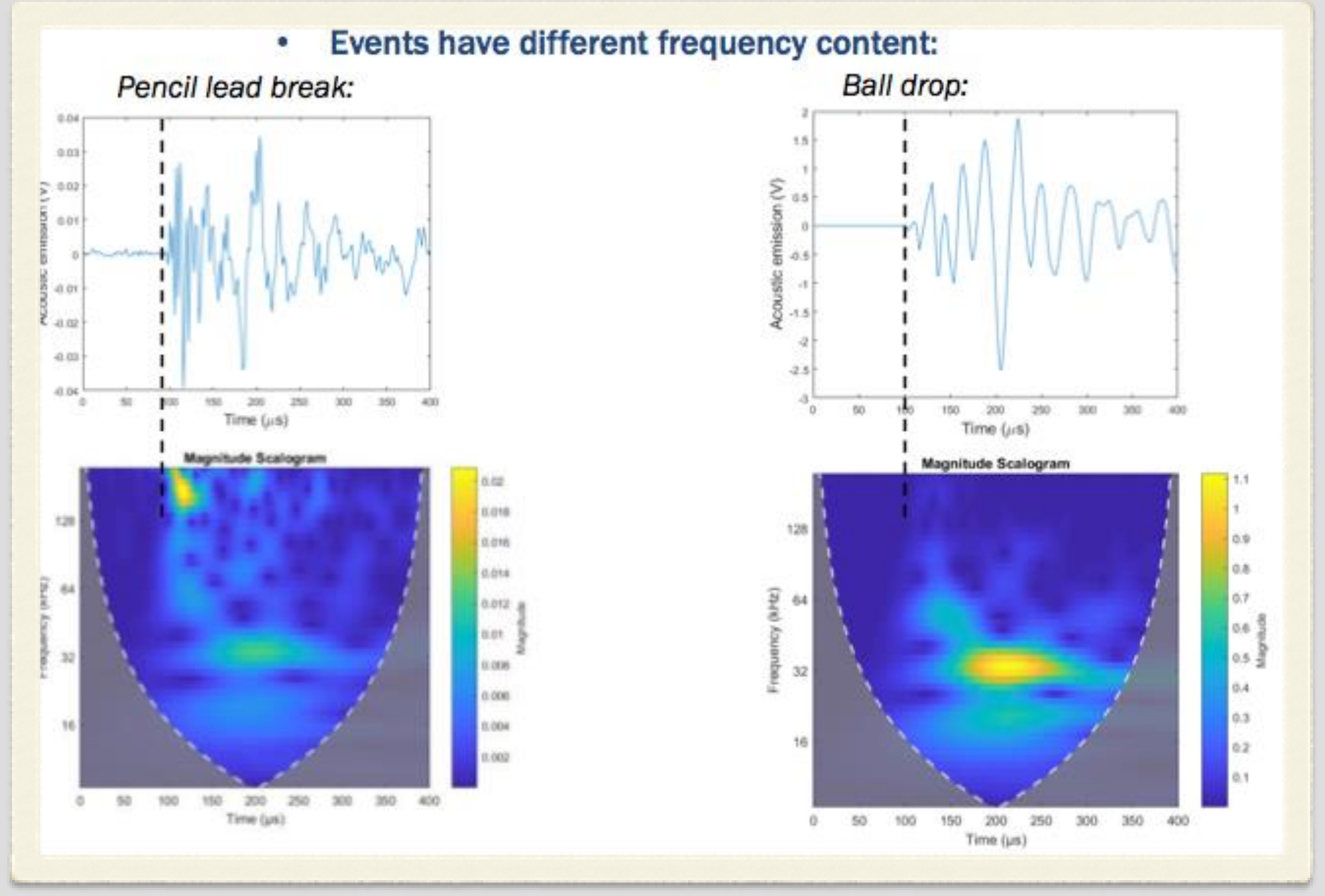


Acoustic signatures provide a wealth of data on energy perturbations in magnets



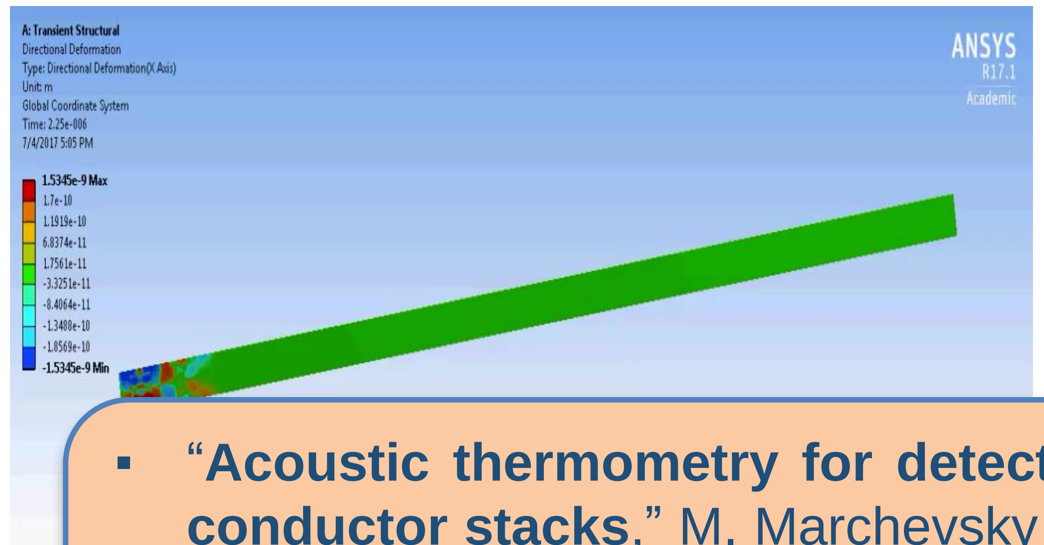
Wavelet analysis provides robust mathematics platform for transient signal analysis

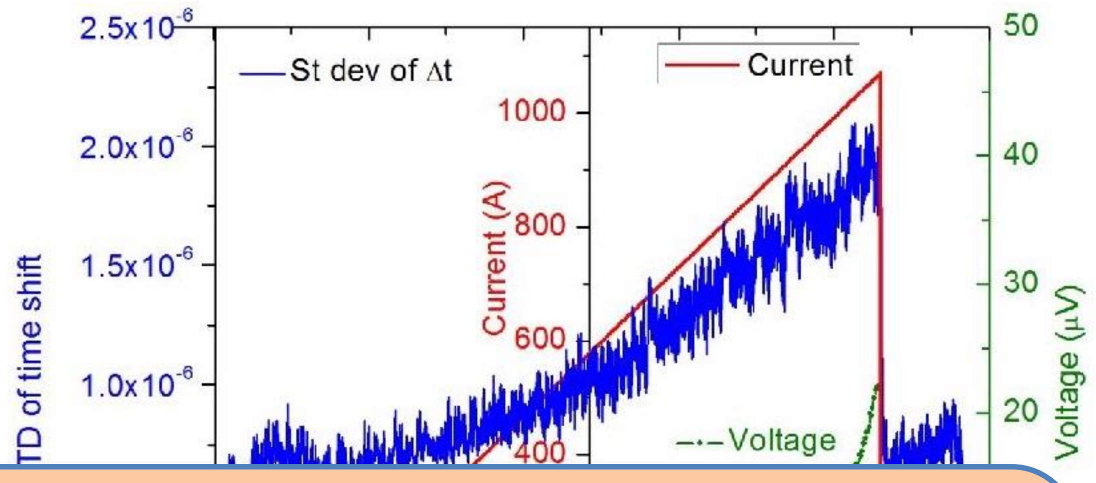




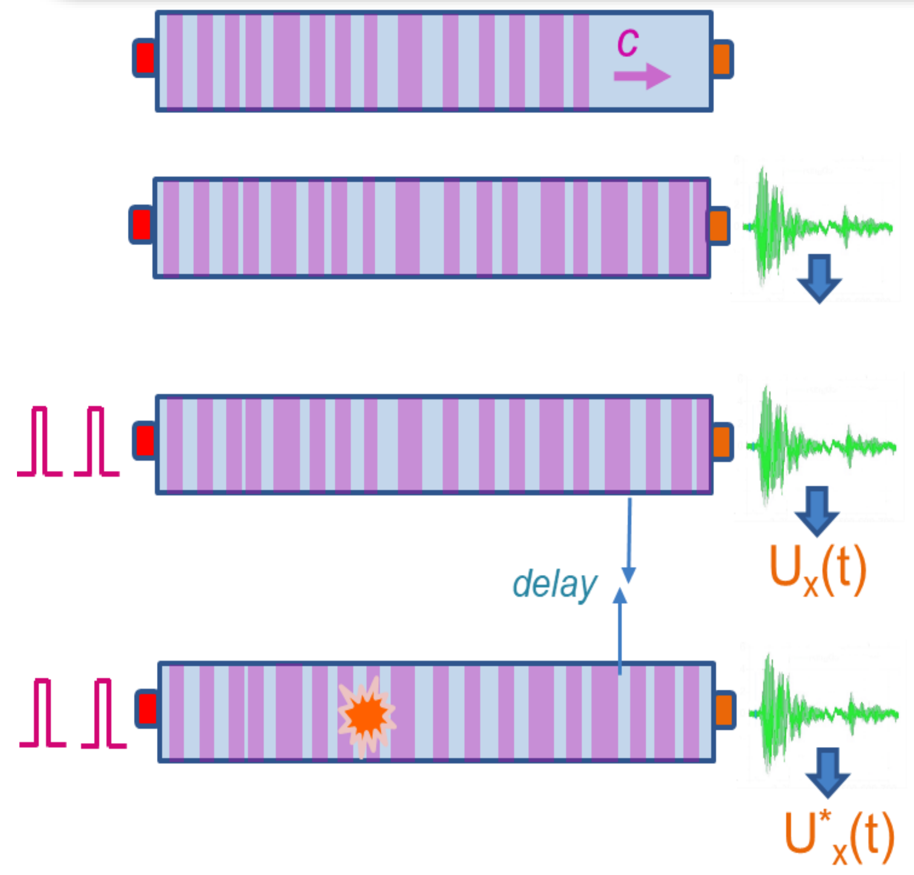
Active acoustics can utilize phase-shift of the complex signal response pattern to identify thermal changes in the system => independent mechanism to see transition

ReBCO tape experiment





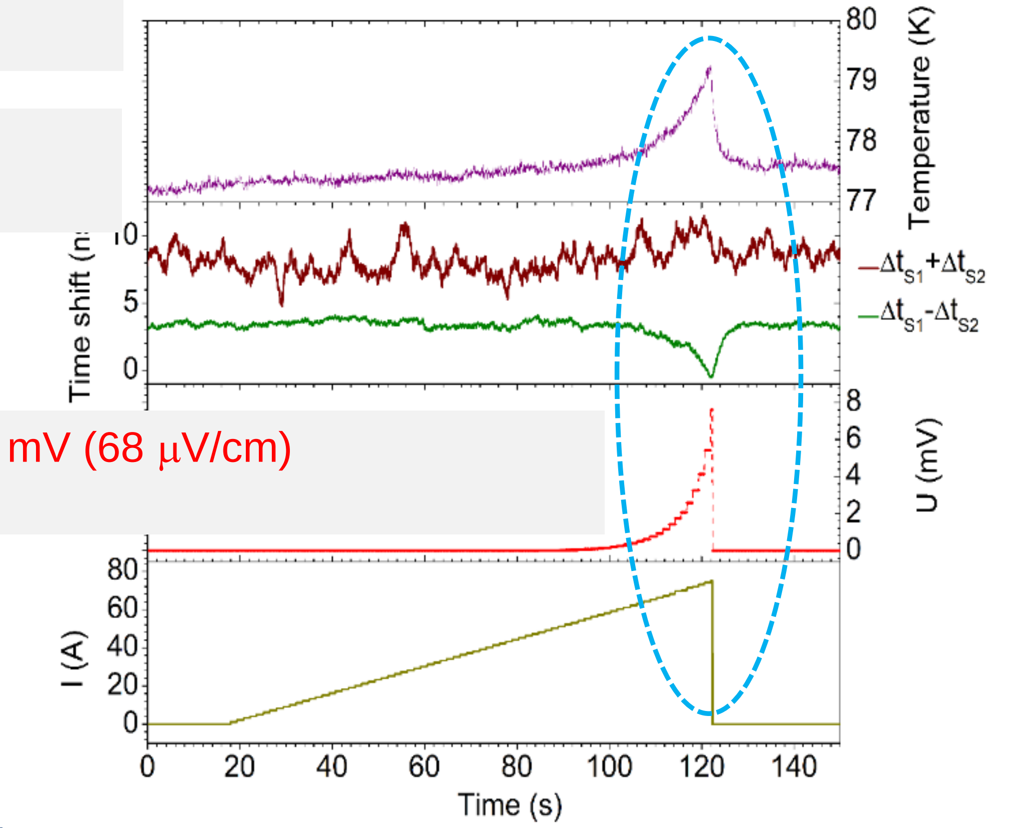
- "**Acoustic thermometry for detecting quenches in superconducting coils and conductor stacks**," M. Marchevsky and S. A. Gourlay, *Appl. Phys. Lett.*, vol. 110, p. 012601, (2017), doi:10.1063/1.4973466
- "**Quench Detection for High-Temperature Superconductor Conductors using Acoustic Thermometry** ", M. Marchevsky et al., *IEEE Trans Appl. Supercond.* vol 28, issue 4 (2018), doi:10.1109/TASC.2018.2817218



ΔT~1.6 K

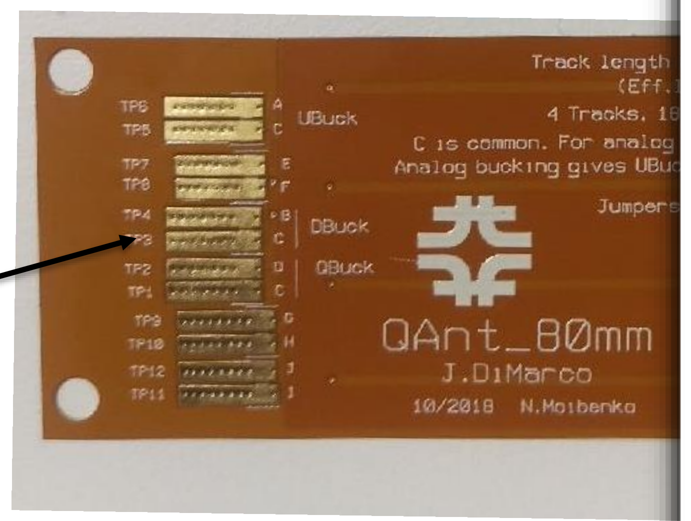
Δt_{rel}~3.5 ns

ΔU_{max} ~ 7.6 mV (68 μV/cm)

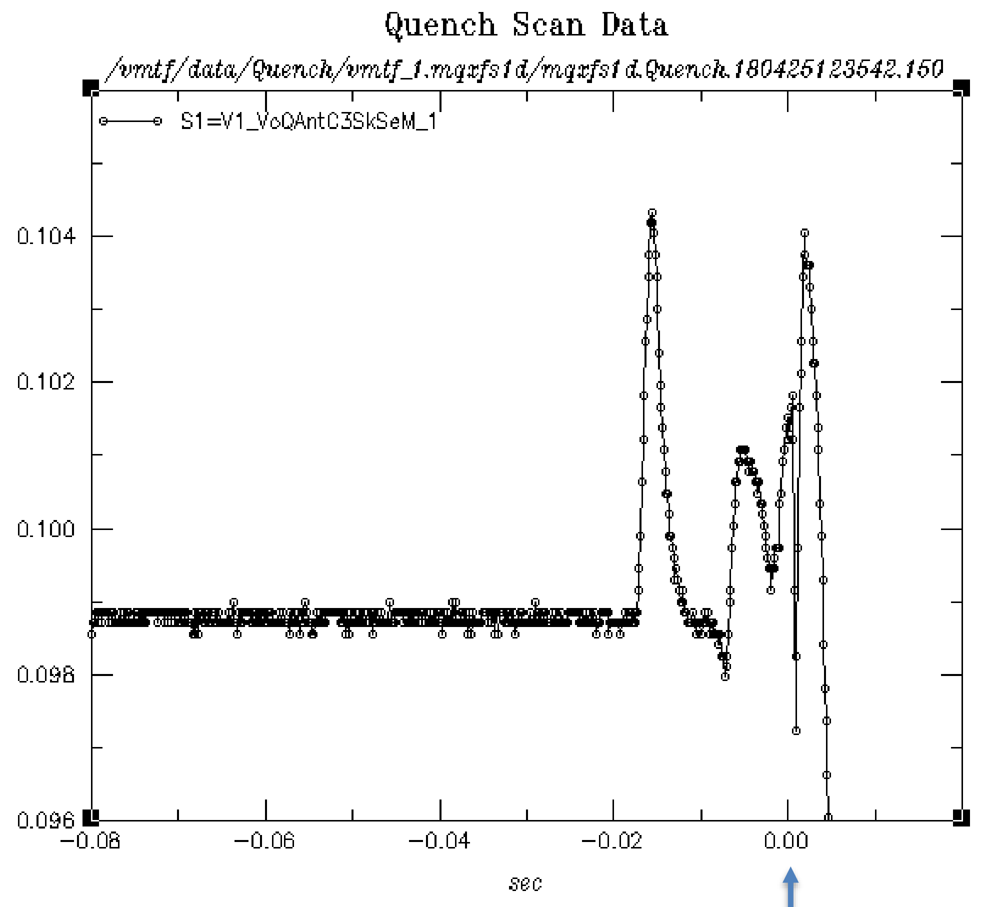


Novel magnetic measurement and quench antennae designs are providing new and complementary insight into magnet behavior

- Flexible circuit quench antennae
  - Inductive stationary pickup loop
  - Diagnostic for determining quer development => Have worked w quench.



Pads improved to withstand more heat during soldering



Quench detection trigger

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IDSM 01

FIRST WORKSHOP ON INSTRUMENTATION AND DIAGNOSTICS FOR SUPERCONDUCTING MAGNETS

24-26 APRIL 2019, BERKELEY, CALIFORNIA

TECHNICAL PROGRAM

TIMETABLE (WITH LINKS TO SLIDES)

SCOPE

PARTICIPANTS

TRAVEL

LODGING

WEATHER

ORGANIZERS

EXPLORING ON YOUR OWN

IDSM01 First Workshop on Instrumentation and Diagnostics for Superconducting Magnets

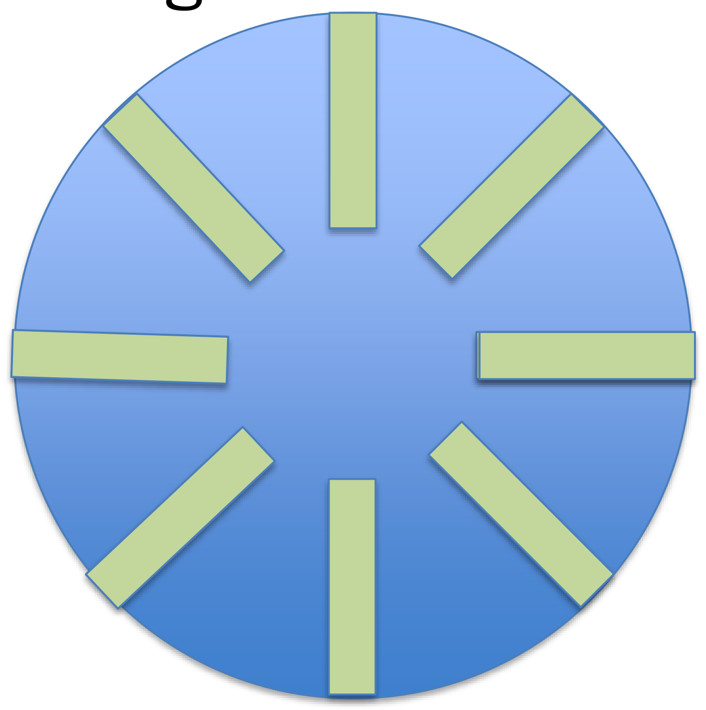
Berkeley, California, USA 24-26 April 2019

The superconducting magnet community is pushing boundaries of magnet systems operating closer than ever to the stress and current limits of technical superconductors. Obtaining such high performance heavily relies on diagnostic instrumentation and data analysis. We are witnessing a broad effort in developing novel techniques for magnet diagnostics geared towards solving long-standing problems such as training, determining quench origins, and identifying quench-driving factors.

The First Workshop on Instrumentation and Diagnostics for Superconducting Magnets (IDSM01) is aimed at defining a common strategy in diagnostics, and establish a platform for exchanging and circulating new ideas. While focusing on instrumentation and diagnostics, we also welcome contributions on forward-looking, disruptive concepts and ideas relevant to superconducting magnets and their applications.

Click for full-size, print-resolution version

gitsu, et al., "*Quench Antennas for le Accelerator Magnets*"



3 has radial
of dipole
drupole at
00

0kHz.
sturbance in all coils
by having multiple sets of MV

radius (though outer layer
oltage response of set of

dy current behavior,
ap-back at injection, magnetic
ux redistribution (spike) events,

Modeling capabilities continue to be developed that have broad applicability to superconducting magnet technology

- **Advanced multi-physics coupling using custom elements, and leveraging of computing clusters with FEA**

Geometry Generation
Meshing
Boundary conditions
Loads

Solution →

Post processing
Load transfer between models

Replace code which builds element matrices: uel.f, uec.f -> compile custom ANSYS.exe

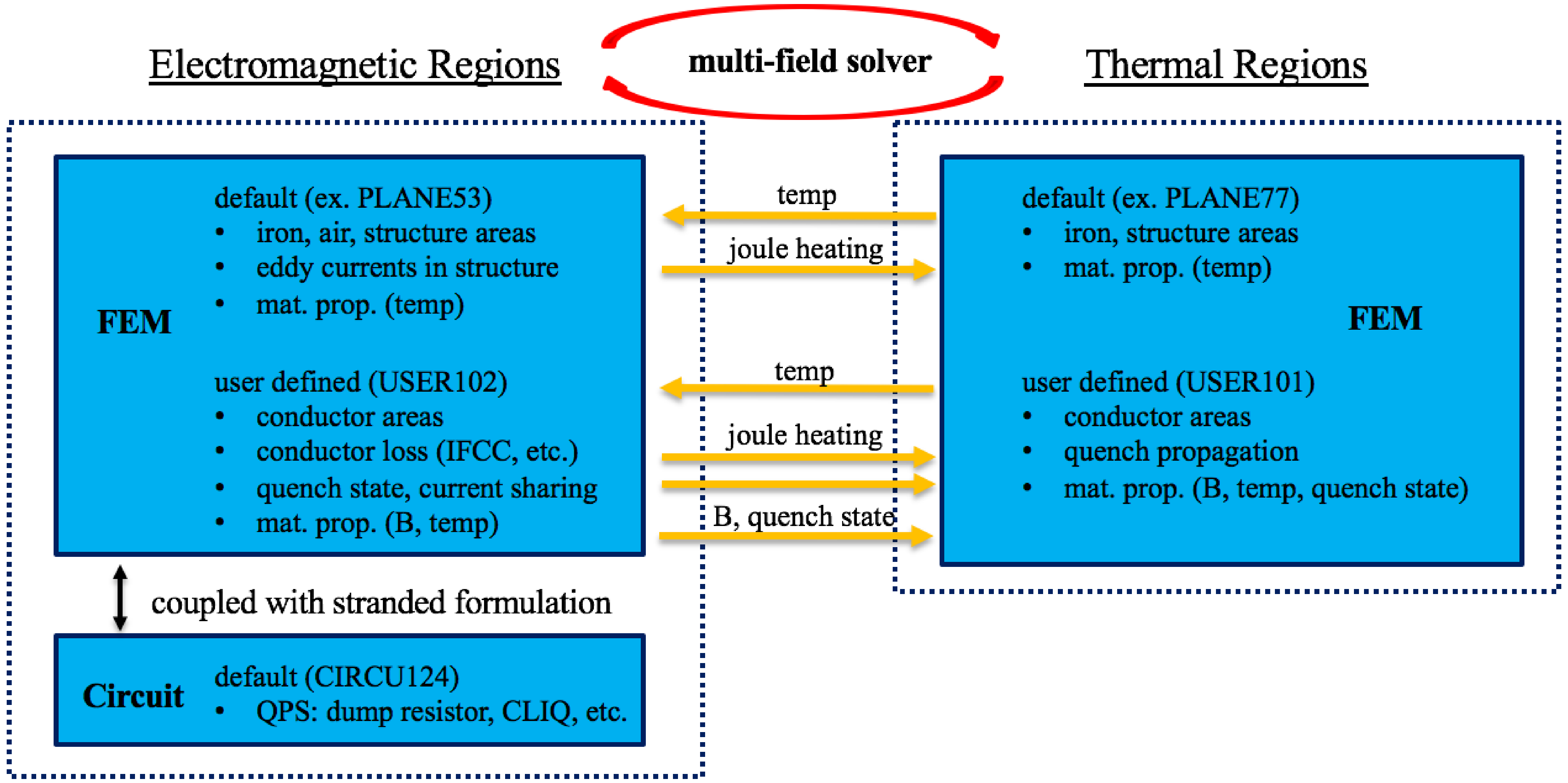
Available
- node location
- loads
- node temperature
- material prop.
- ANSYS functions

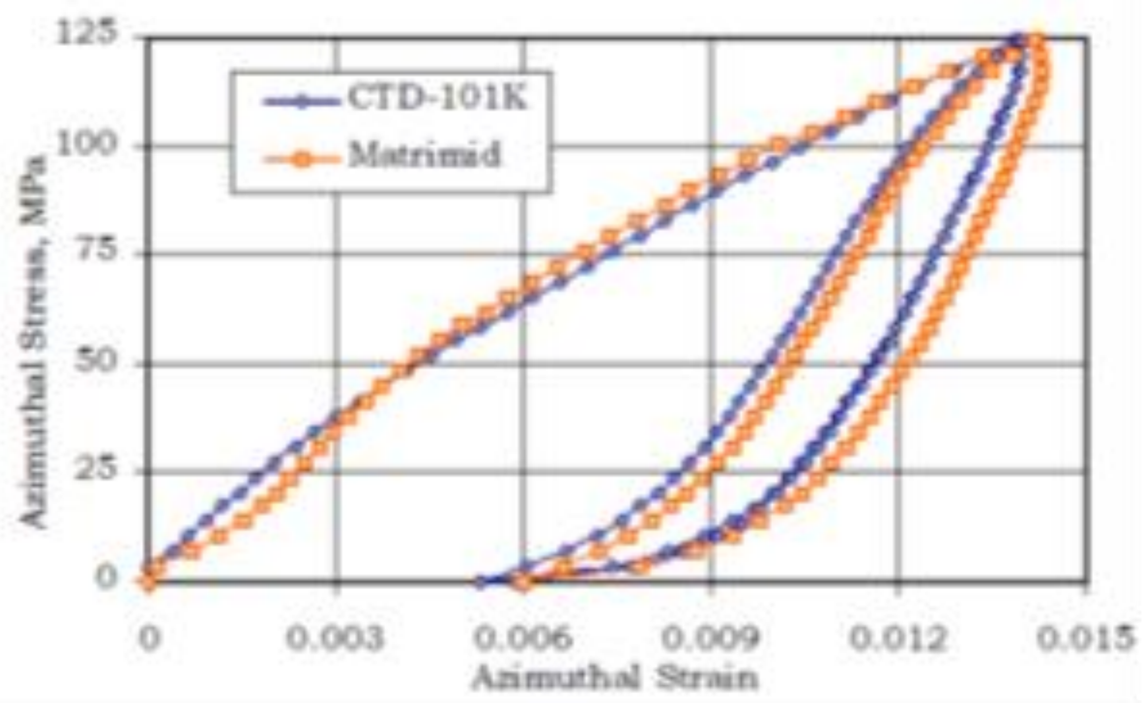
→

Element customized by defining
- element shape functions
- material properties: if complex function desired (T,B,Jc,etc.)
- formulation

→

Element matrix generation is now determined by user program
- stiffness, damping, etc.





After 1 thermal cycle

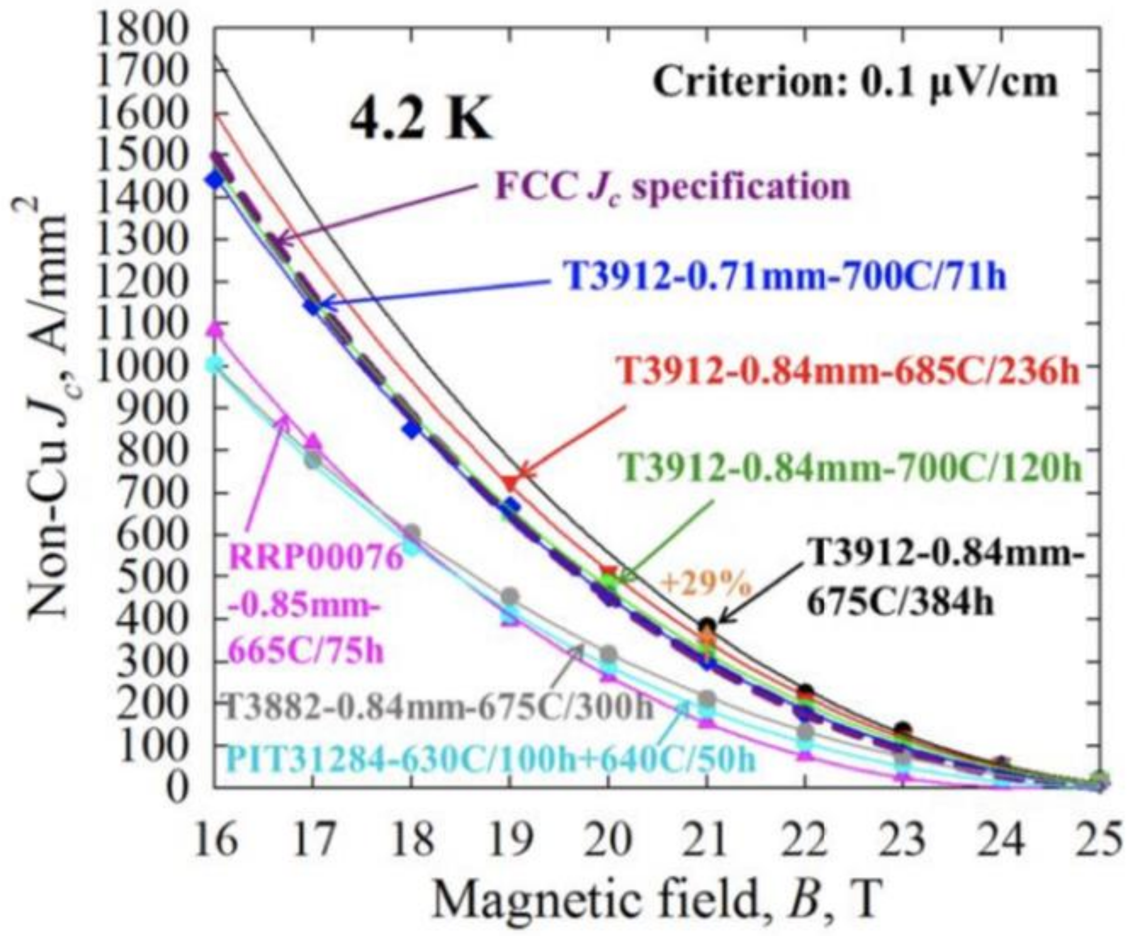
CTD-101K ITER CS NHMFL mix-61 ATLAS ECT GY282 D230

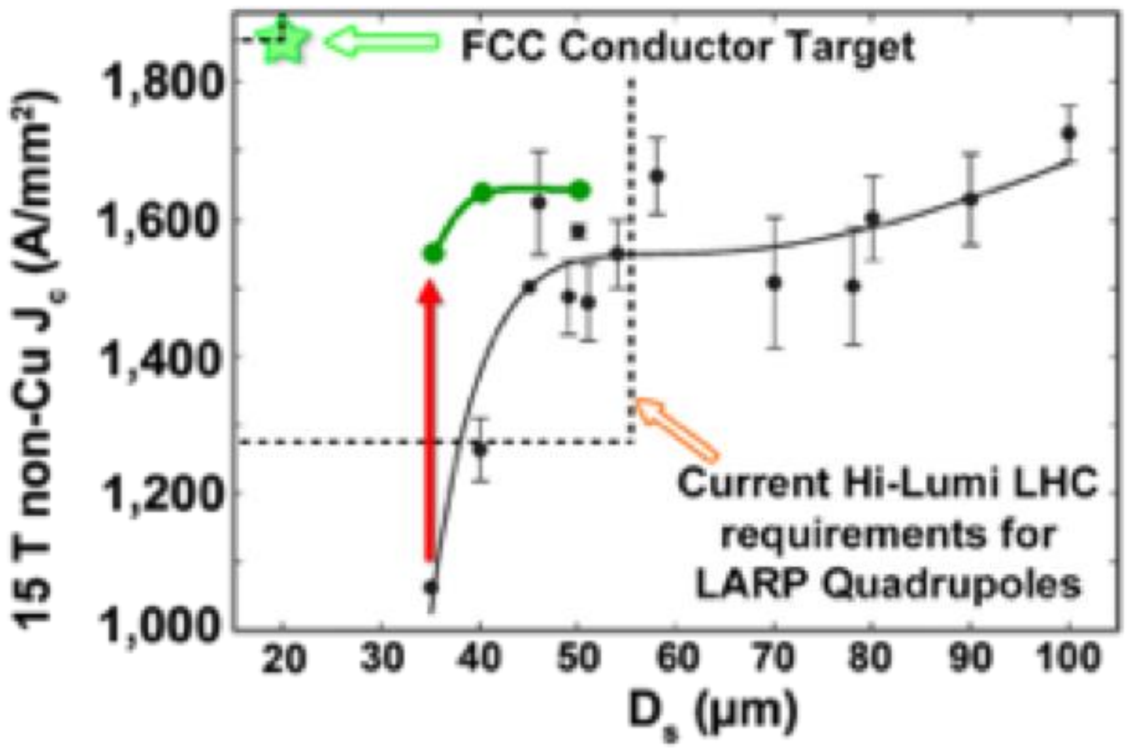
After 20 thermal cycles

Conductor R&D is a critical component of the US MDP, with very significant advances under development

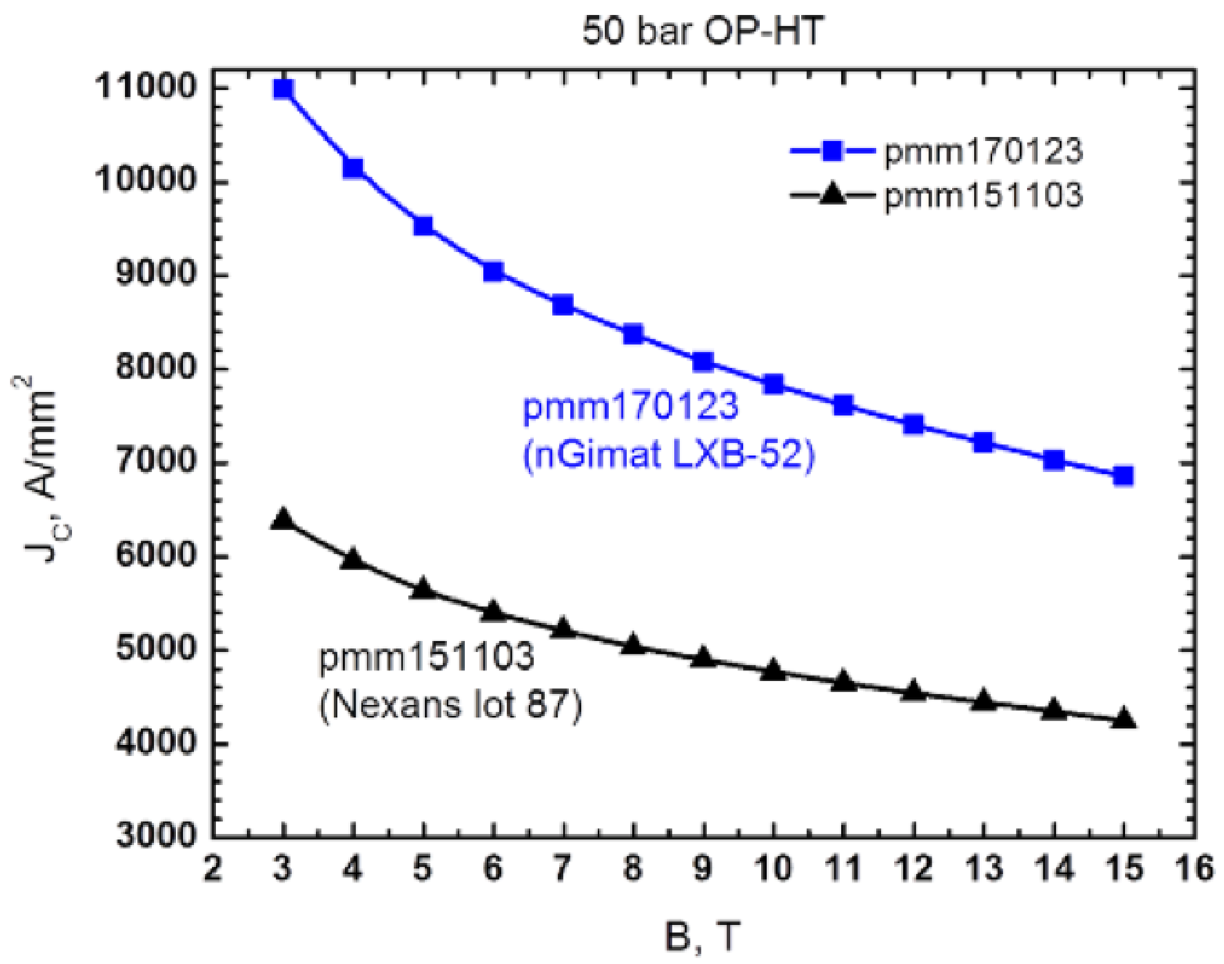
U.S. MAGNET DEVELOPMENT PROGRAM

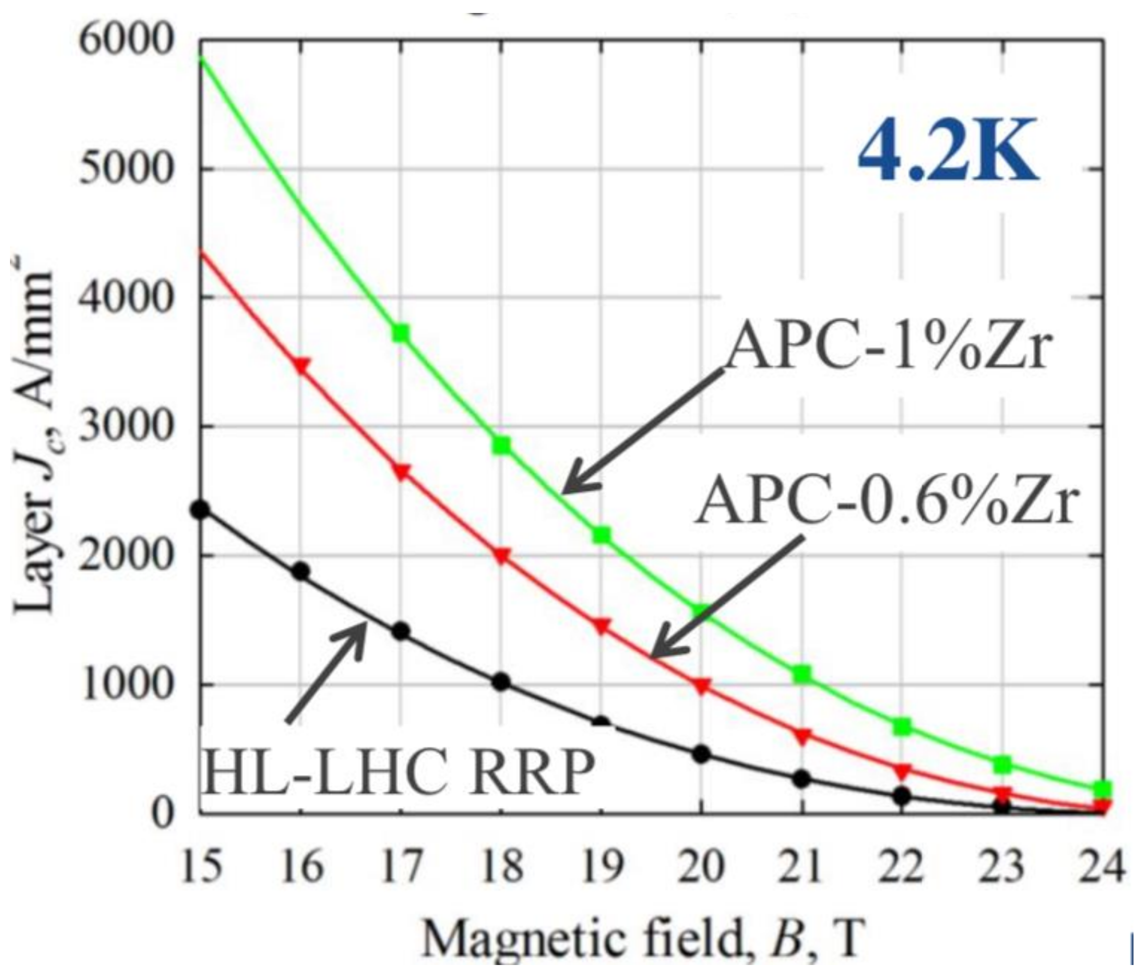
- Nb_3Sn R&D is proving the material has plenty more to offer
  - APC Nb_3Sn using Zr-doping - first demonstration of wire achieving FCC specification
    - *X. Xu et al, rXiv:1903.08121*
  - Hf-doping - *S. Balachandran et al., SUST. 32 (2019) 044006*
  - High-Cp doping with Gd_2O_3 - *X. Xu et al, SUST. (2018) vol. 31, No 3*
- Bi2212 continues to improve
  - better understanding of what drives higher J_c
- REBCO improvements with reduced substrate thickness, Zr pinning
  - *Wang et al., SUST (2018) Vol 31, No 4*

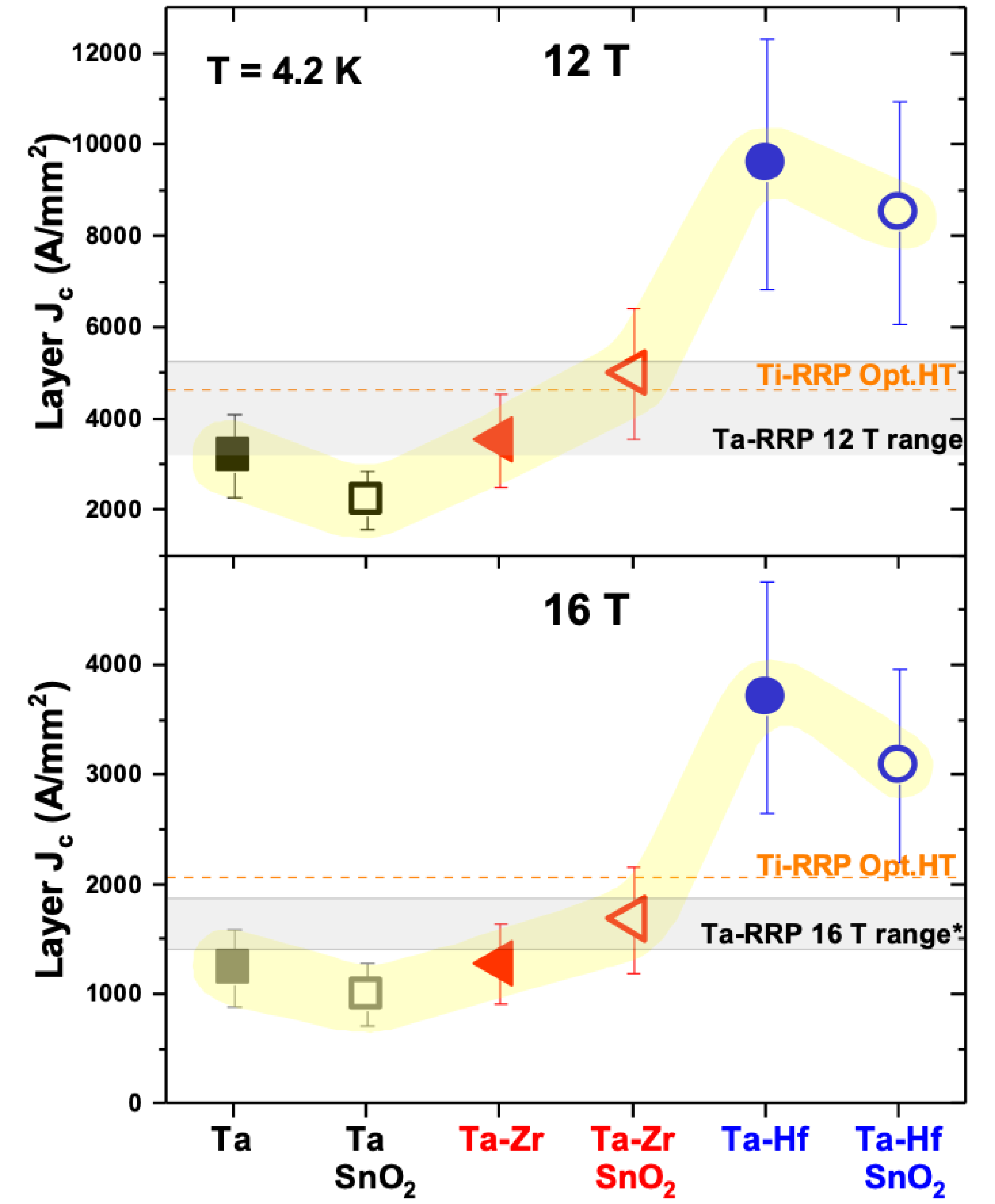




- Record J_c of ~7,000 A/mm² at 15 T was achieved by using the new nGimat powder







MDP maintains a ‘living” list of international and industrial collaborations

- **MDP provides the strategic framework for HEP high field magnet and conductor R&D in the US**
- **Leveraging well-organized collaborations is a key component for achieving the MDP goals**

- **International (9)**
  - **CERN, EuroCirCol, PSI, KEK**
- **Other OHEP-funded programs (4)**
  - **Ohio State, U. Houston, Penn State**
- **Industry (12) – Includes procurements**
- **Other** (Pending or non-HEP funded) (4)

- SBIR/STTR are important contributors (mainly HEP, but also FES and NP)

PAUL SCHERRER INSTITUT PSI

EuroCirCol

CERN

CHART
Swiss Accelerator Research and Technology

KEK

京都大学
KYOTO UNIVERSITY

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2019 International Collaborations

Activity	MDP Relevance	Collaborating Institution	Contact(s)	MDP Contact
Study of transverse loading on Rutherford cables in FRESCA II using 10mm cable with Hi-Lumi strands.	MDP Nb_3Sn Program	CERN	Bernardo Bordini	Ian Pong
Conceptual design of IR quads for FCC	Technology Development	CERN	Schoerling, D.	Velev, G.
History and Documentation of Nb_3Sn Magnet R&D	MDP Nb_3Sn Program	EuroCirCol	Schoerling, D.	Zlobin, A.
Testing CCT Nb_3Sn coil using 15 T dipole mechanical structure and L3-L4 coils as outsert*	Nb_3Sn CCT + 15 T dipole	PSI	Auchmann, B.	Zlobin, A.
CCT Development	Nb_3Sn CCT	PSI	Auchmann, B.	Brouwer, L./I. Pong
CCT Instrumentation	Nb_3Sn CCT	PSI	Auchmann, B., Montenero, G.	Marchevsky, M.

A subset of our master list of collaborations

U.S. MAGNET DEVELOPMENT PROGRAM

Summary

- The US MDP is designed to advance high-field accelerator magnet research
  - Leverages strengths of longstanding programs at the National Laboratories and Universities

- The MDP is fully functioning and working hard to achieve the program goals
  - Management structure is aligned with the mission and goals
  - The teams are steadily integrating - particularly in areas of Technology

- We are balancing our efforts to maintain progress on multiple fronts
  - Nb_3Sn magnet development, currently focused on Cos(t) and CCT
  - HTS magnet development - on both Bi2212 and REBCO fronts
  - Critical technology developments that guide magnets… and are of value to the broader community
  - Conductor R&D - with a roadmap to continue advancing performance

- We have a strong, and growing, list of national and international collaborations