U.S. MAGNET
DEVELOPMENT
PROGRAM

Superconducting Accelerator Magnet Research in the US

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Lawrence Berkeley National Laboratory

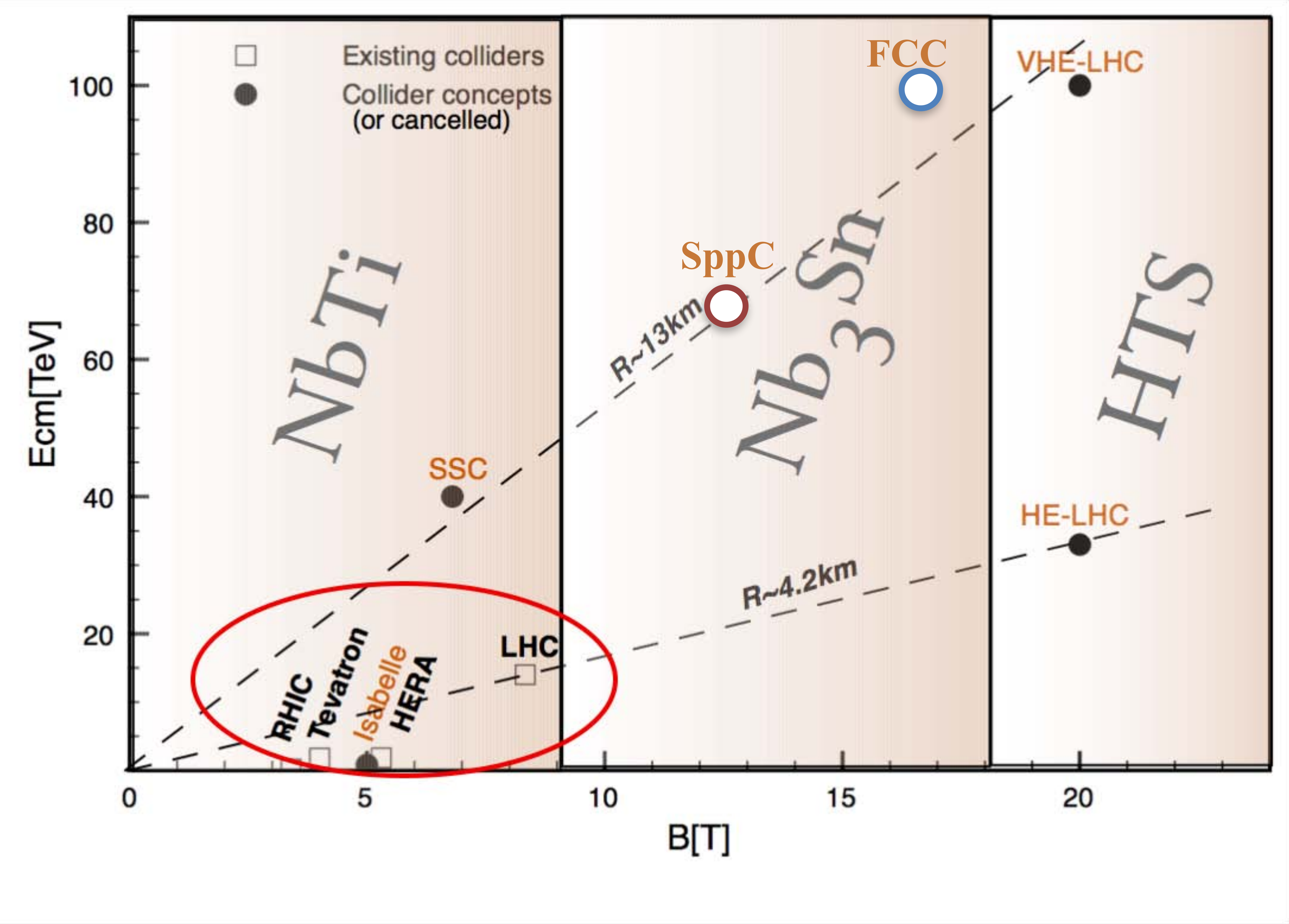
For the US MDP Team

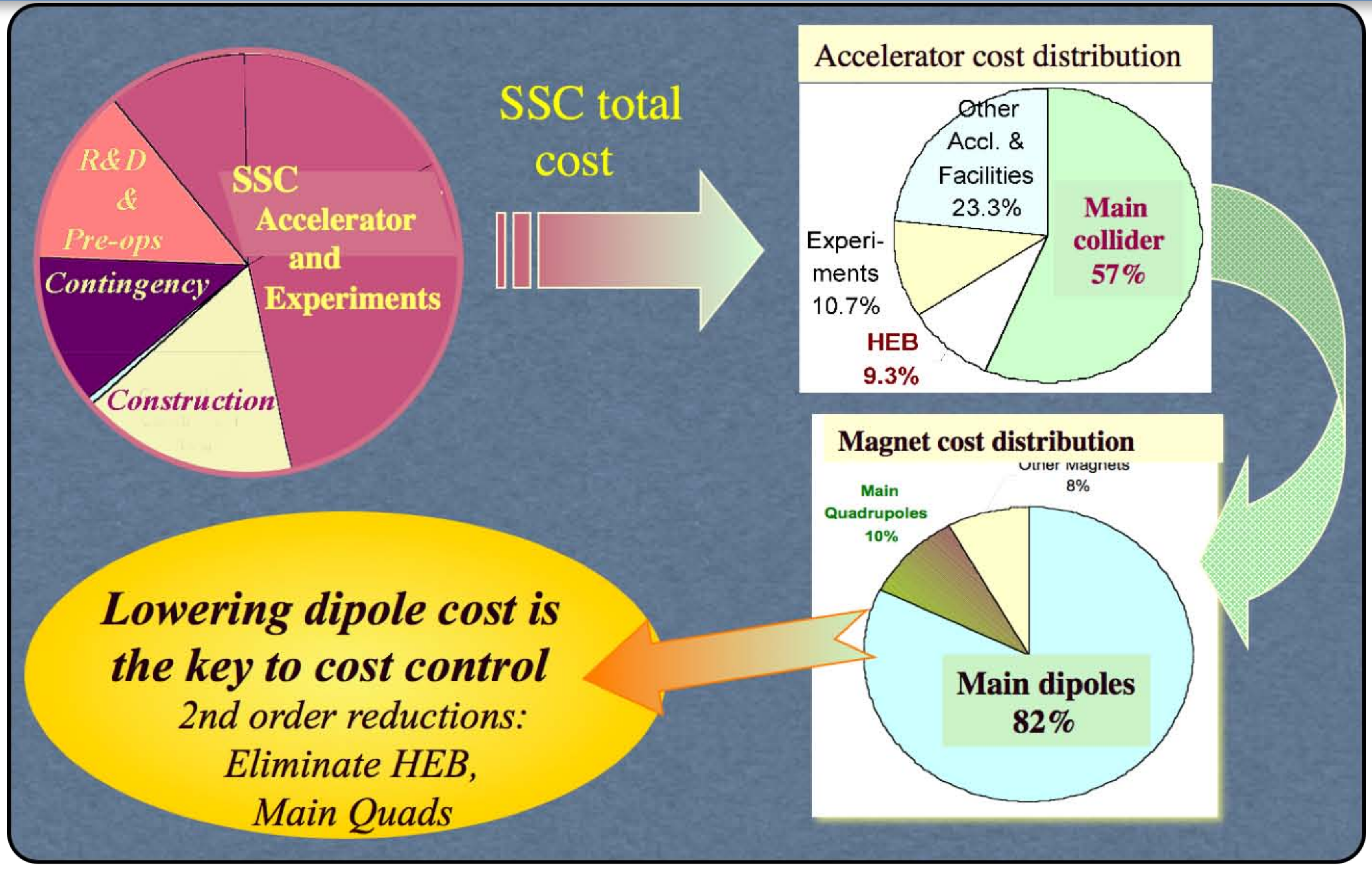
Note: The data shown in these slides are the result of work from Scientists and Engineers in the US MDP

Outline

- Motivation and background
- The US Magnet Development Program: main goals and roadmaps to achieve them
- Major technical areas being pursued
- Some key technical developments and progress
- Ongoing collaborations
- Next steps
- Summary

Magnet technology is driving the cost and reach of a future collider



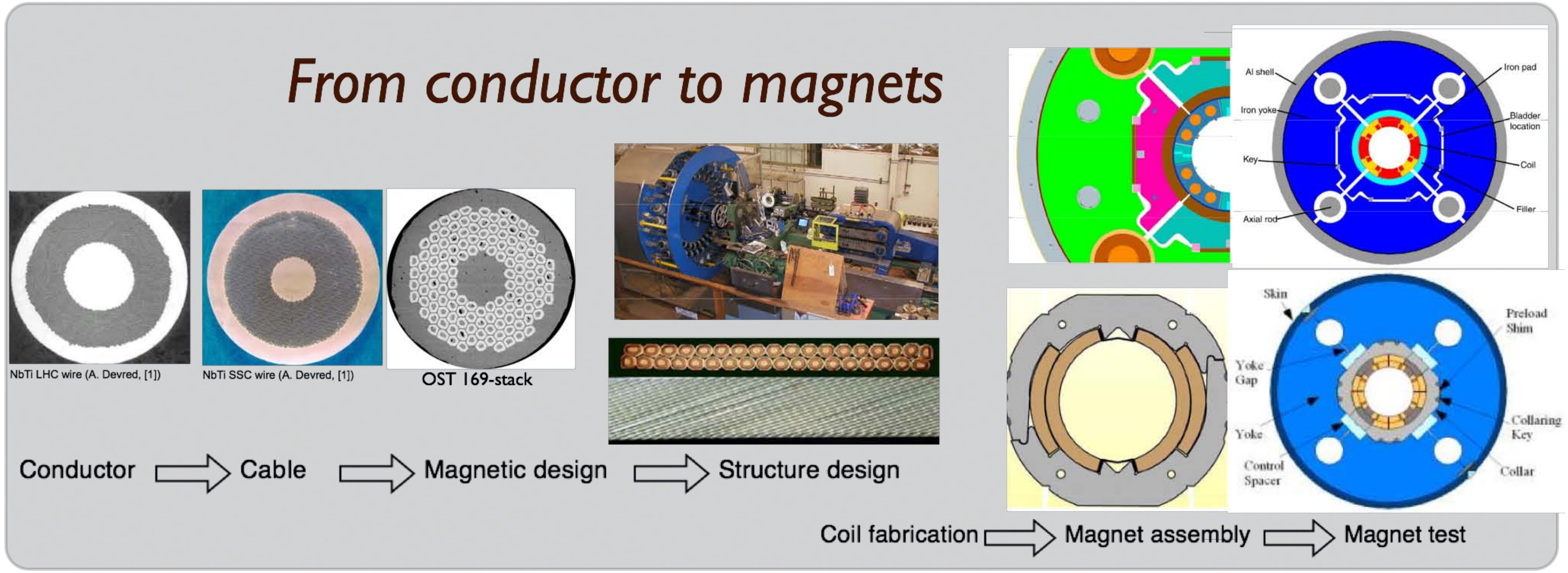


Barletta

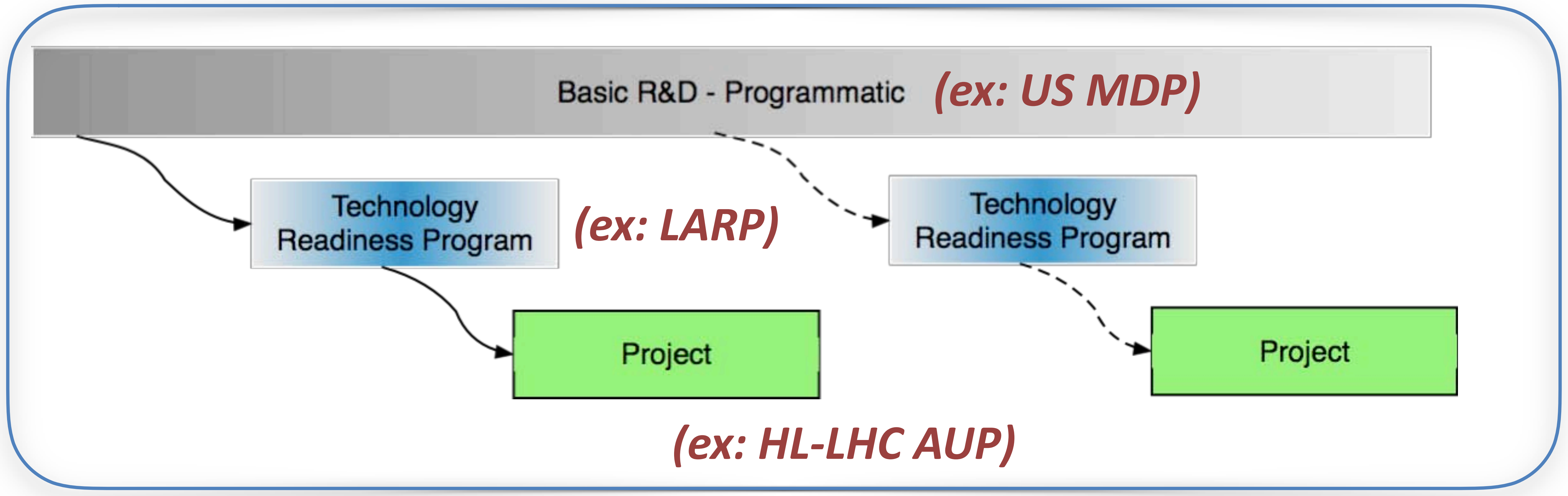
CERN cost estimates*:
$magnets/$tot

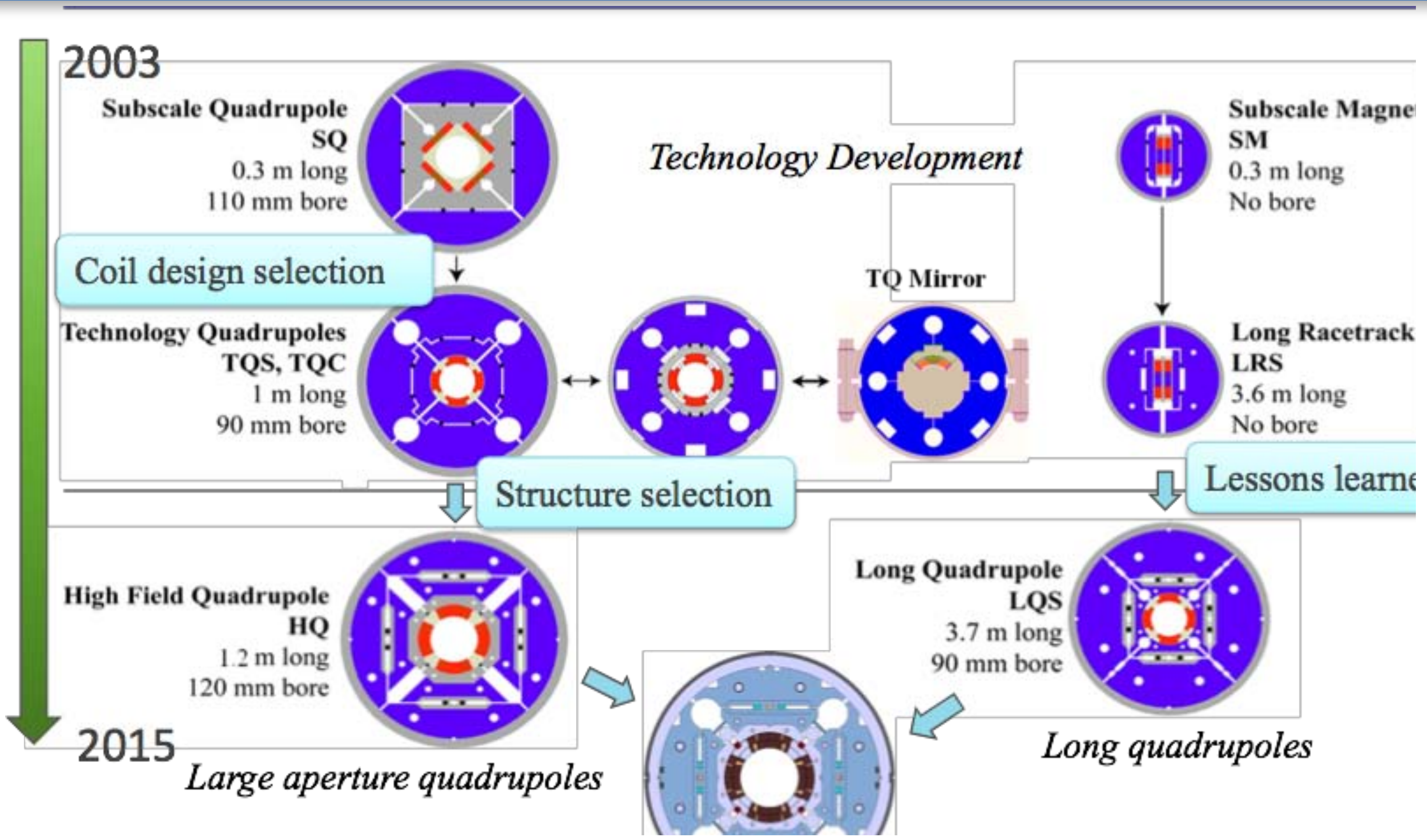
LHC: 57%
HE-LHC:
- 70% (26TeV; Nb_3Sn)
- 77% (33TeV; HTS)

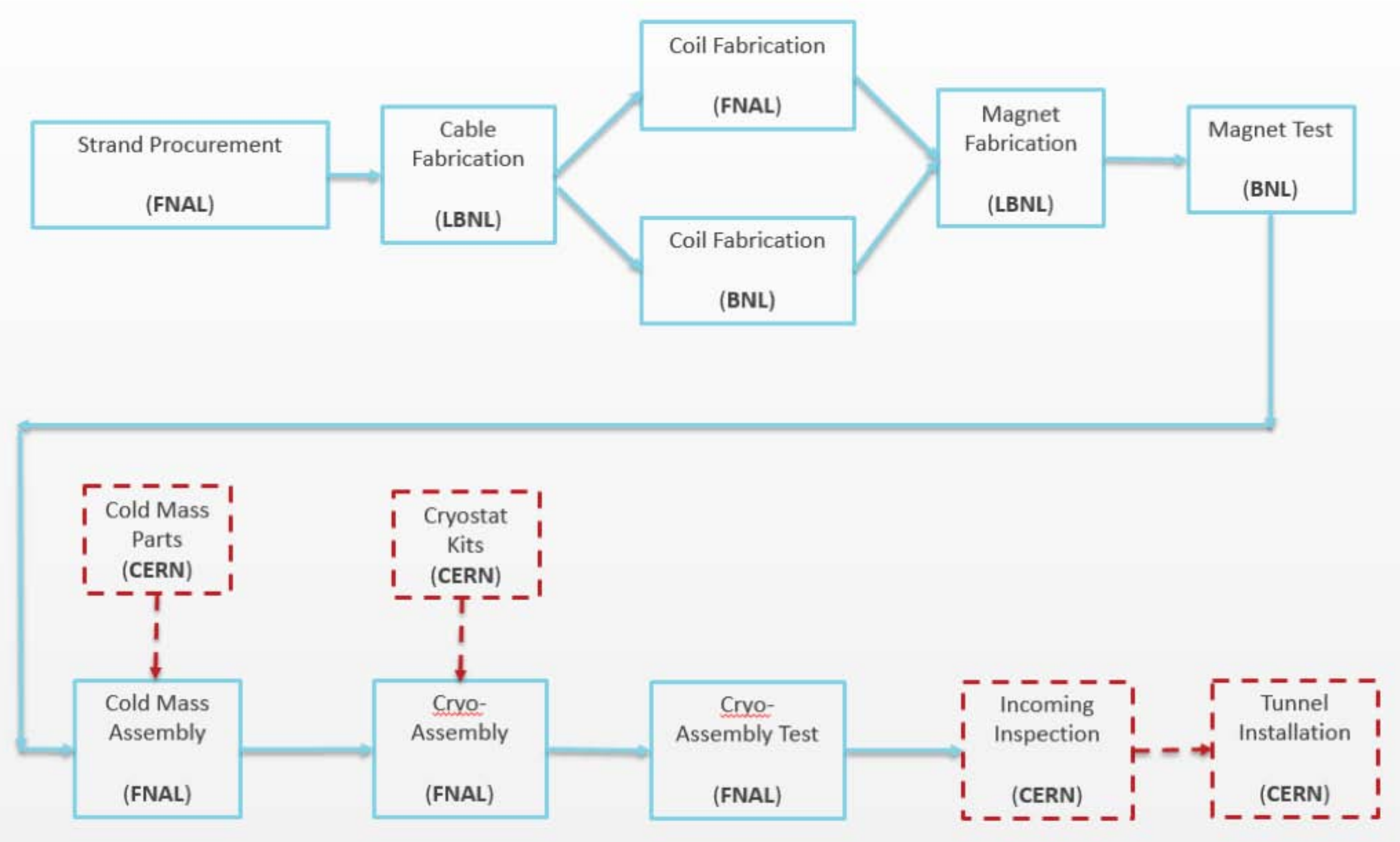
*L. Rossi, "TOE" talk

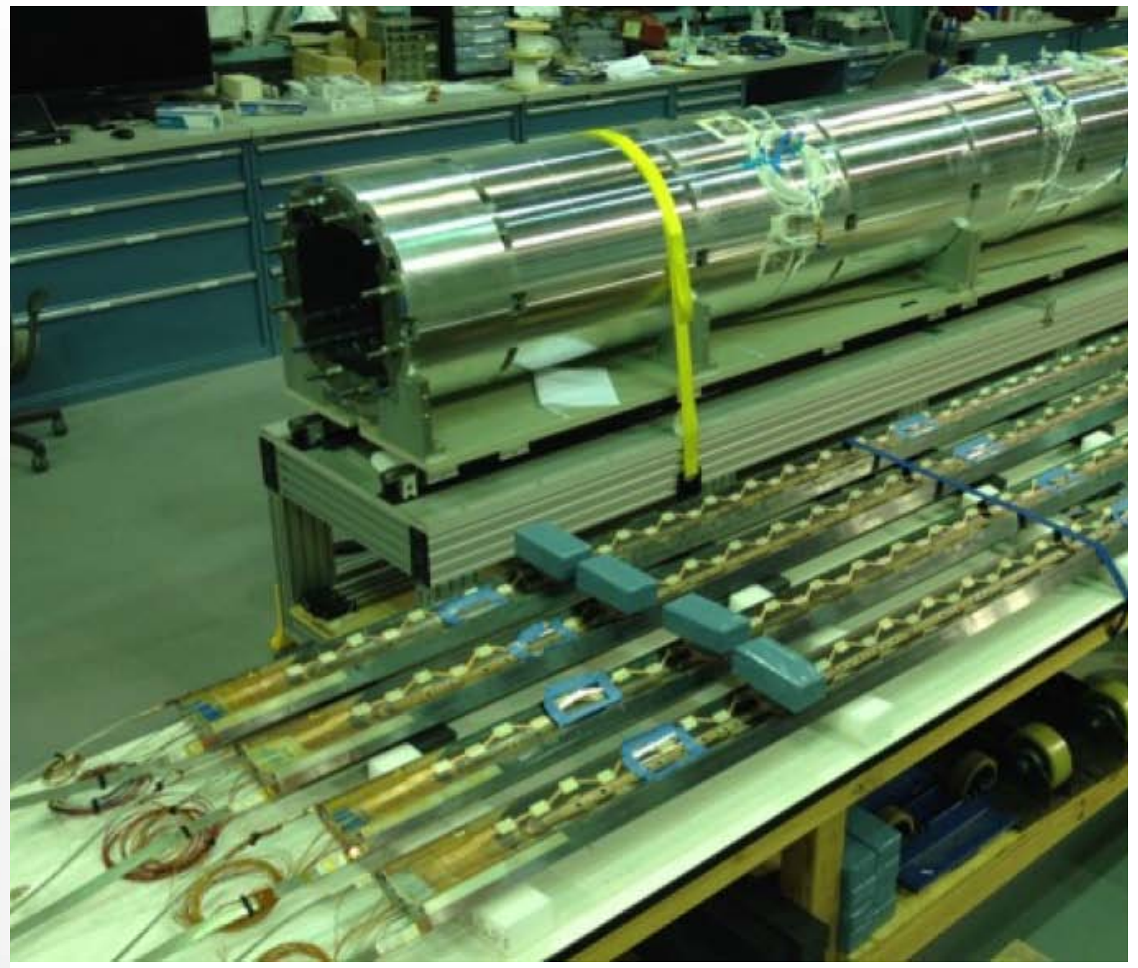


Nb_3Sn accelerator magnet technology is finally being installed in a collider - in the interaction region quadrupoles of the LH-LHC

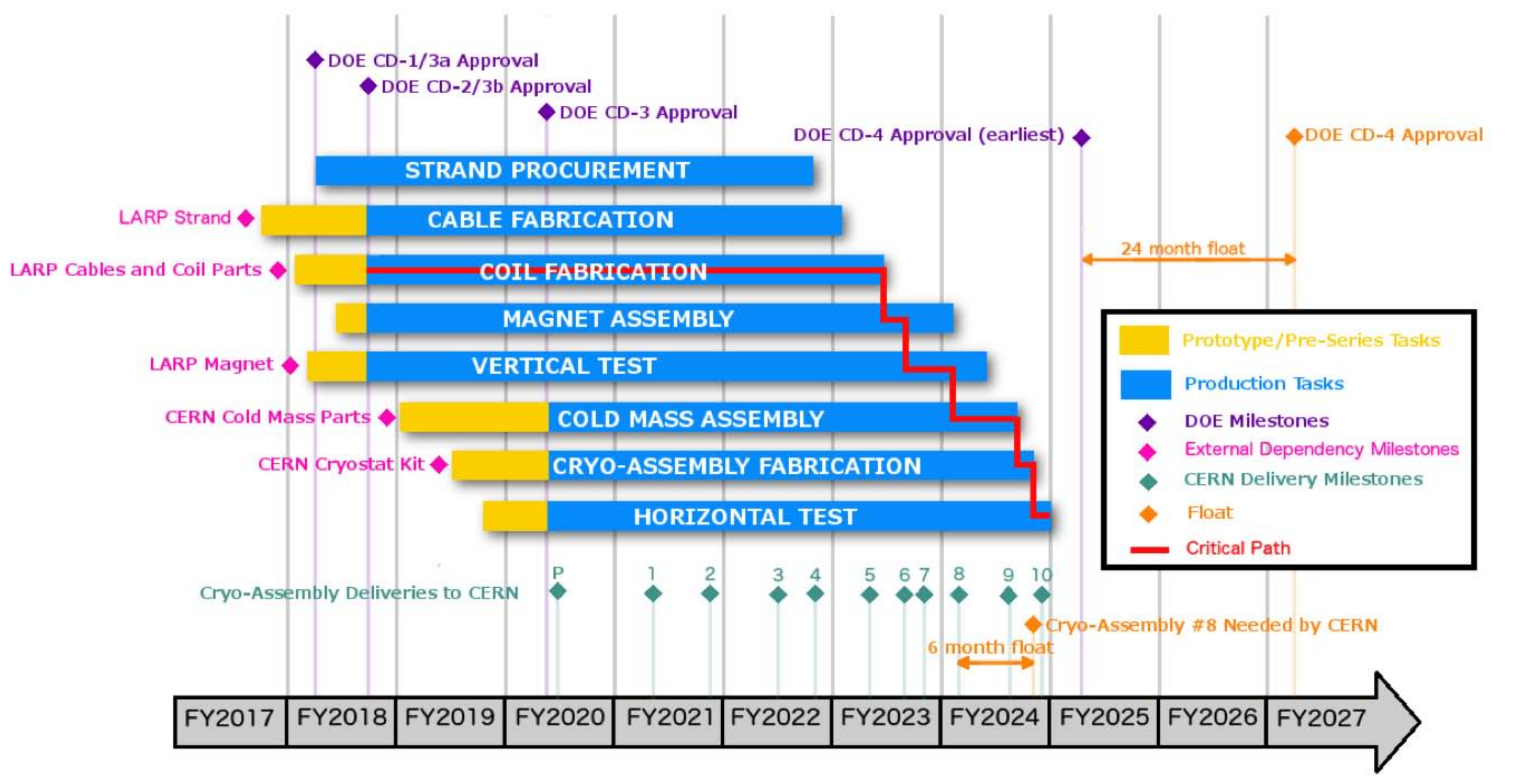








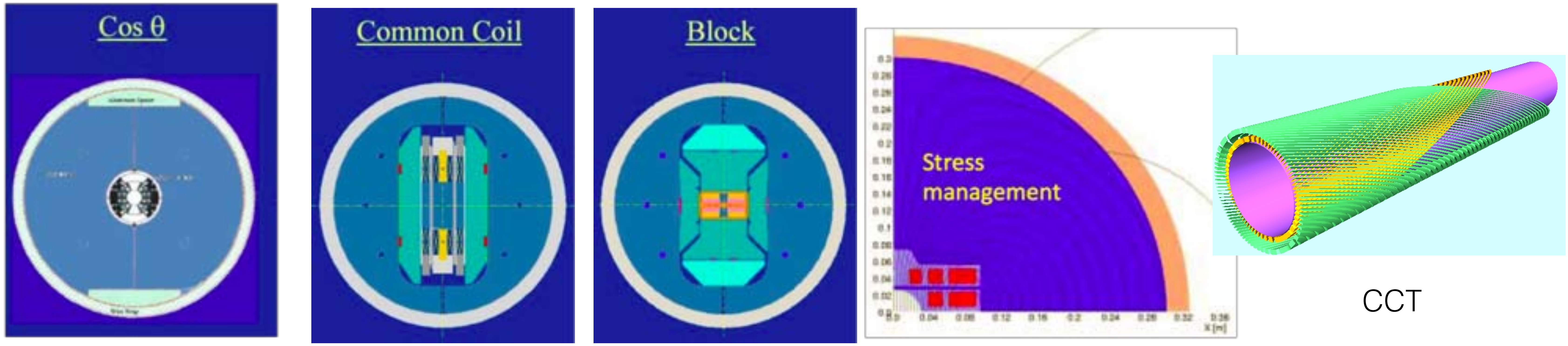
HL-LHC AUP Q1/Q3 Cryo-Assemblies Schedule Chart



The "magnet zoo" in colliders are all based on Cos(t) designs, whereas accelerator R&D magnets explore other options

- R&D magnet designs explore layouts that attempt to address issues associated with conductor strain (to avoid degradation) and reduction of conductor/coil motion (to minimize training)

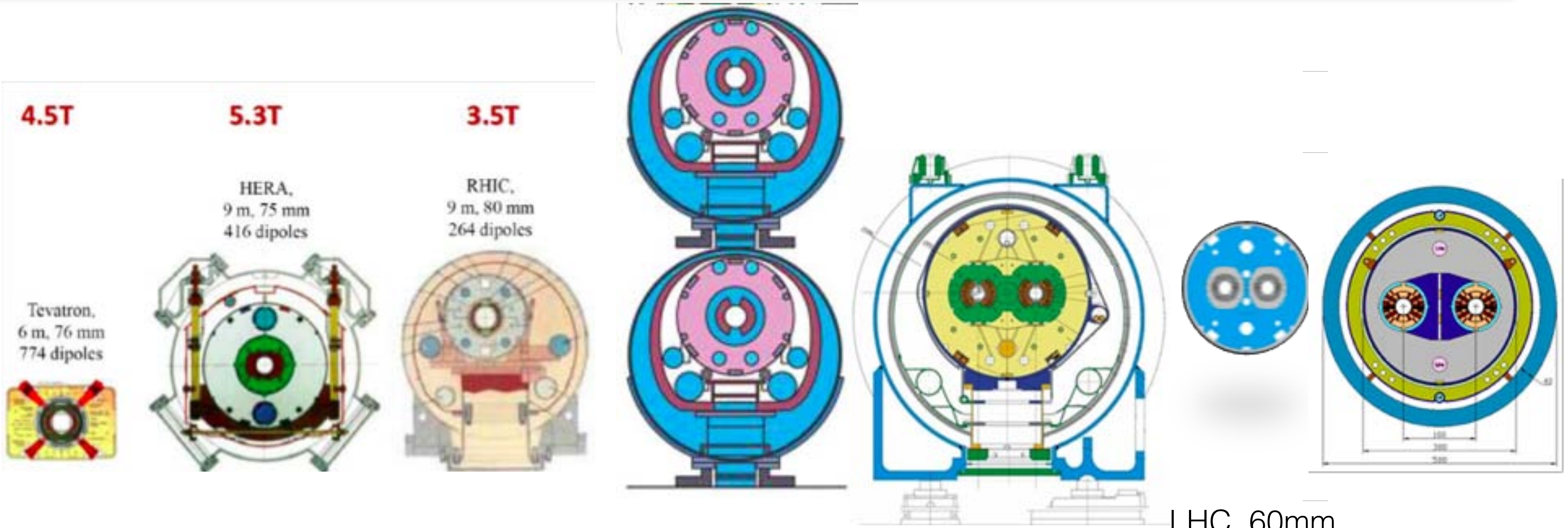
- At high field "managing" stress through judicious force interception will be required



CCT

LBNL

TAMU



Shiltsev/Zlobin, (FNAL)

SSC, 50mm
6.6T, 4.3K

LHC, 56mm
8.3T, 1.9K

LHC, 60mm
11T,1.9K
FNAL/CERN

VLHC, 43mm
10T, 4.5K

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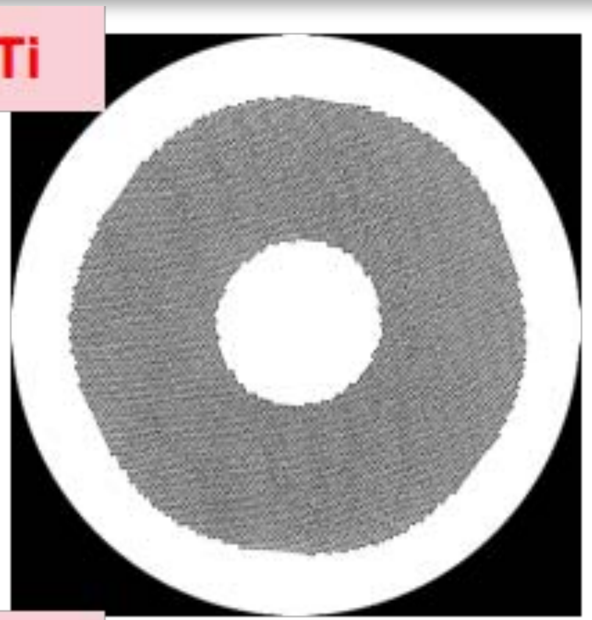
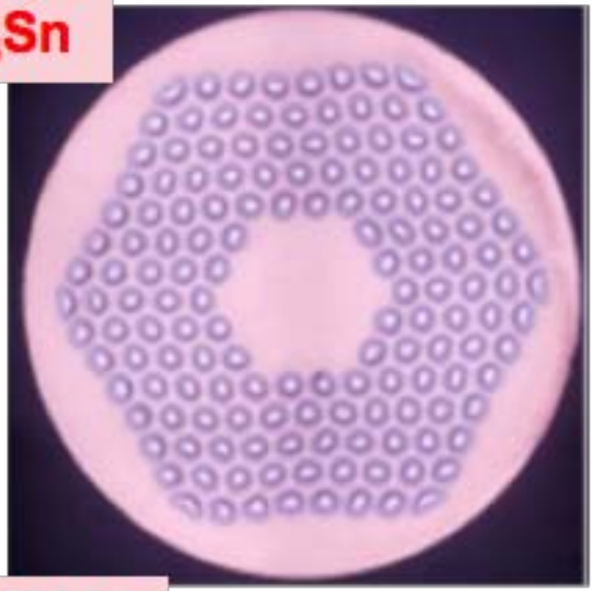
Magnets start with the superconductor: we are about to put Nb_3Sn into a collider for the first time, and are investigating the potential of HTS

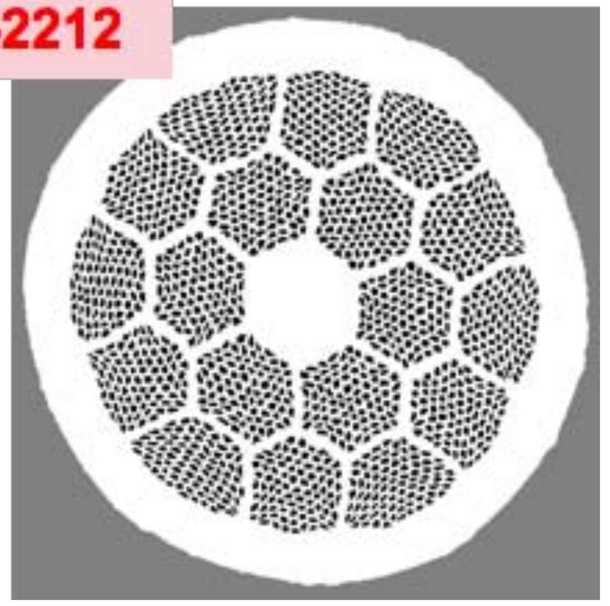
Nb-Ti

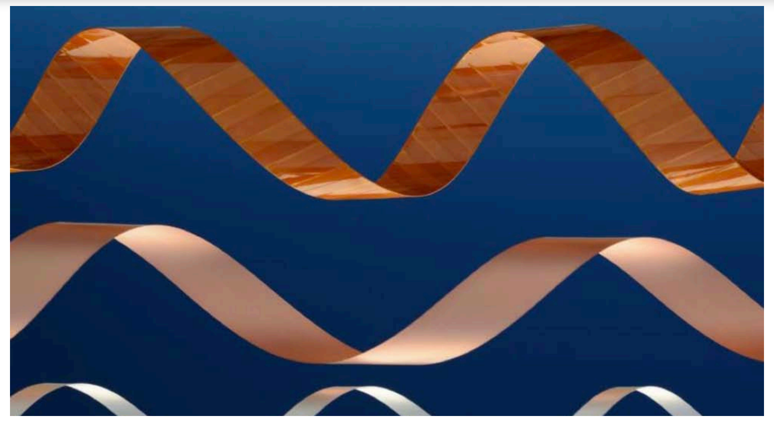


Nb_3Sn

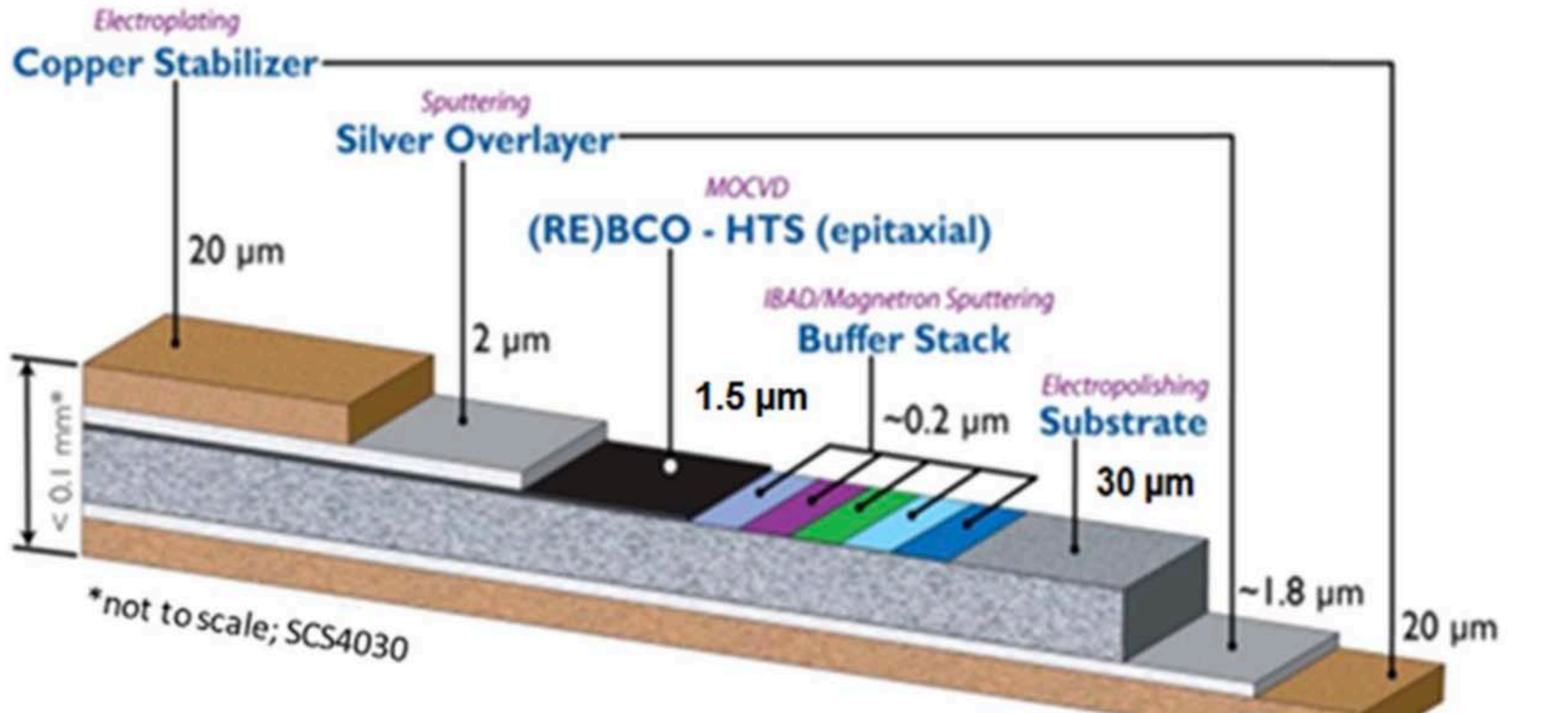


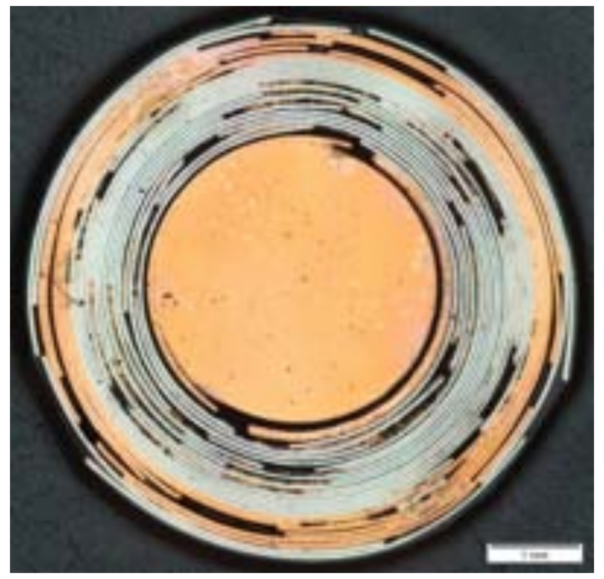
Bi-2212



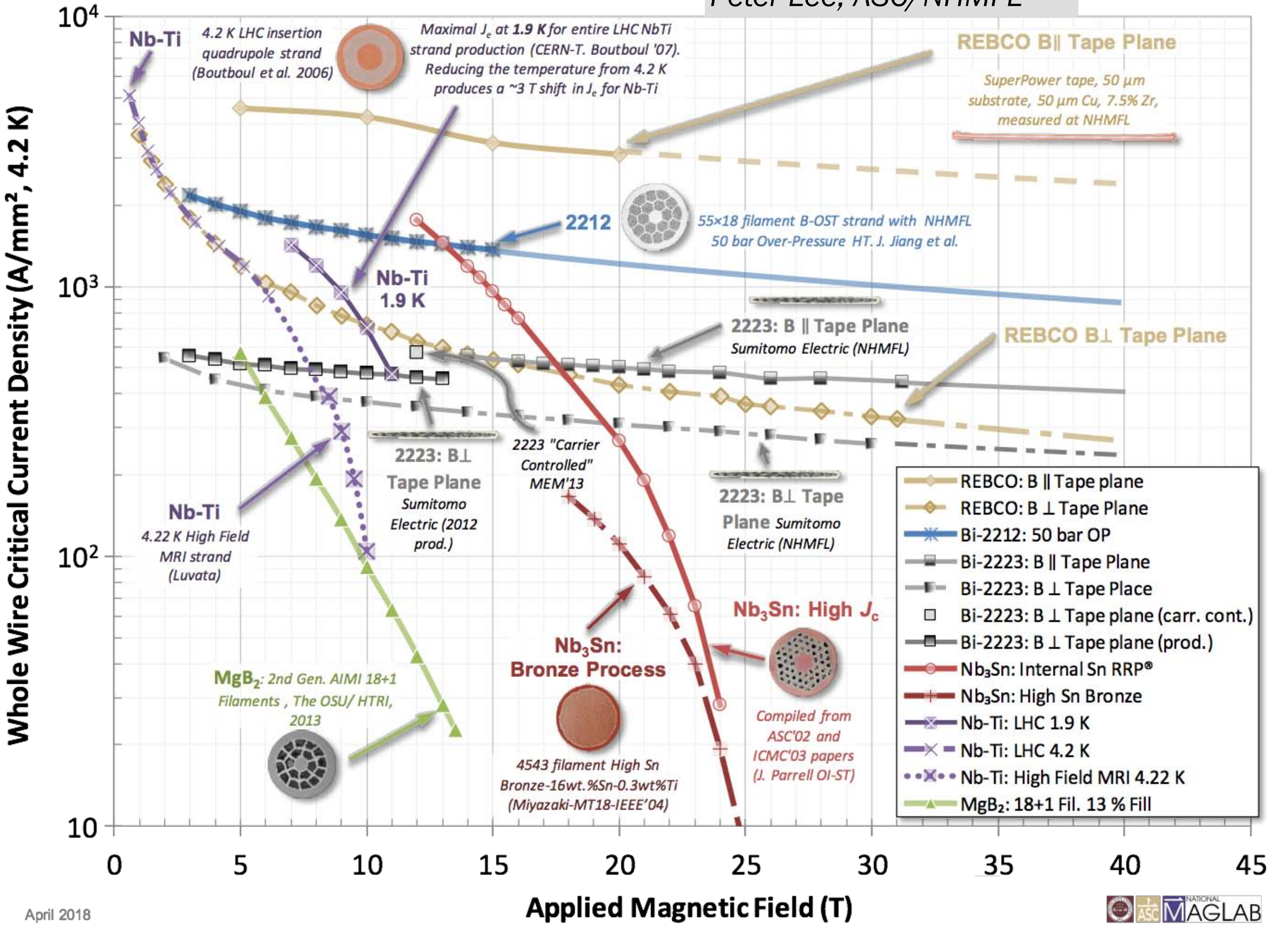


SuperPower Inc

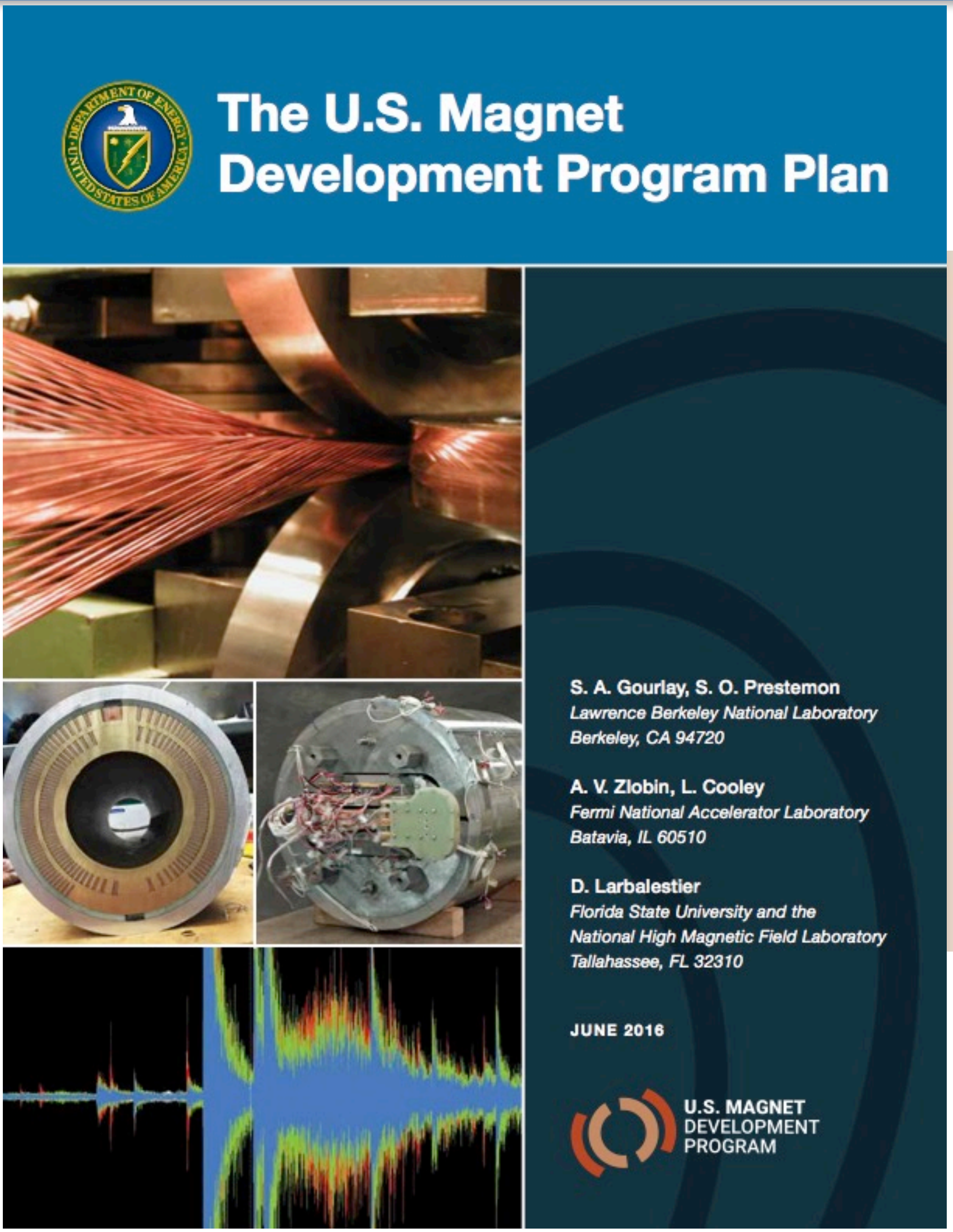




Peter Lee, ASC/NHMFL



The US HEP Superconducting Magnet Programs are now integrated into the US Magnet Development Program


The U.S. Magnet Development Program Plan

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JUNE 2016

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HEPAP Accelerator R&D Subpanel recommendations

Recommendation 5b. Form a focused U.S. high-field magnet R&D collaboration that is coordinated with global design studies for a very high-energy proton-proton collider. The over-arching goal is a large improvement in cost-performance.

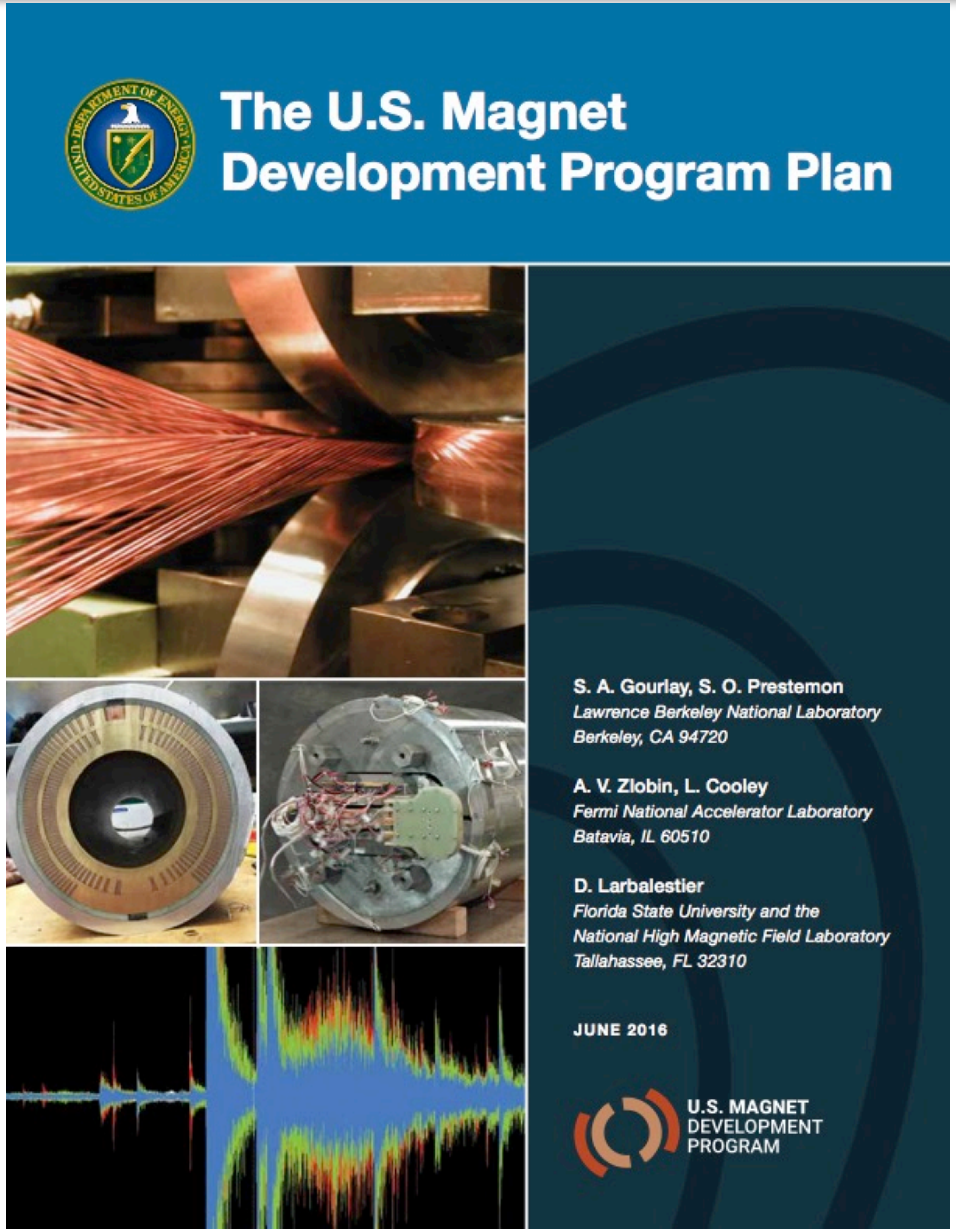
Recommendation 5c. Aggressively pursue the development of Nb_3Sn magnets suitable for use in a very high-energy proton-proton collider.

Recommendation 5d. Establish and execute a high-temperature super-conducting (HTS) material and magnet development plan with appropriate milestones to demonstrate the feasibility of cost-effective accelerator magnets using HTS.

Recommendation 5e. Engage industry and manufacturing engineering disciplines to explore techniques to both decrease the touch labor and increase the overall reliability of next-generation superconducting accelerator magnets.

Recommendation 5f. Significantly increase funding for superconducting accelerator magnet R&D in order to support aggressive development of new conductor and magnet technologies.

The US Magnet Development Program was founded by DOE-OHEP to advance superconducting magnet technology for future colliders



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Strong support from the Physics Prioritization Panel (P5) and its sub-panel on Accelerator R&D

A clear set of goals have been developed and serve to guide the program

Technology roadmaps have been developed 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.

The program has well-defined goals, and is structured with technical leads who are responsible for delivery

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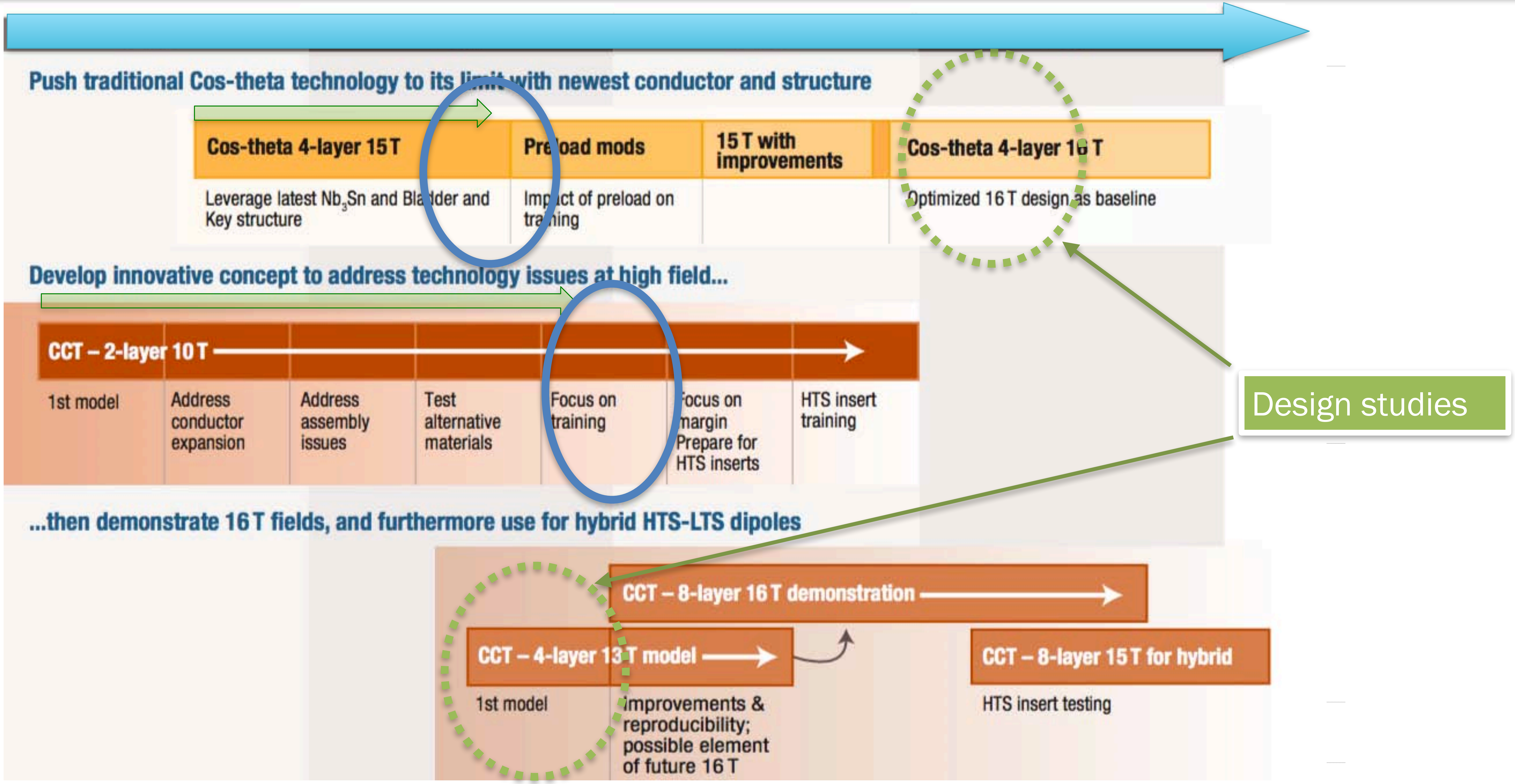
The MDP Nb_3Sn magnet efforts continue to progress as outlined in the MDP Plan document, but the evolution will depend on results

Area I:

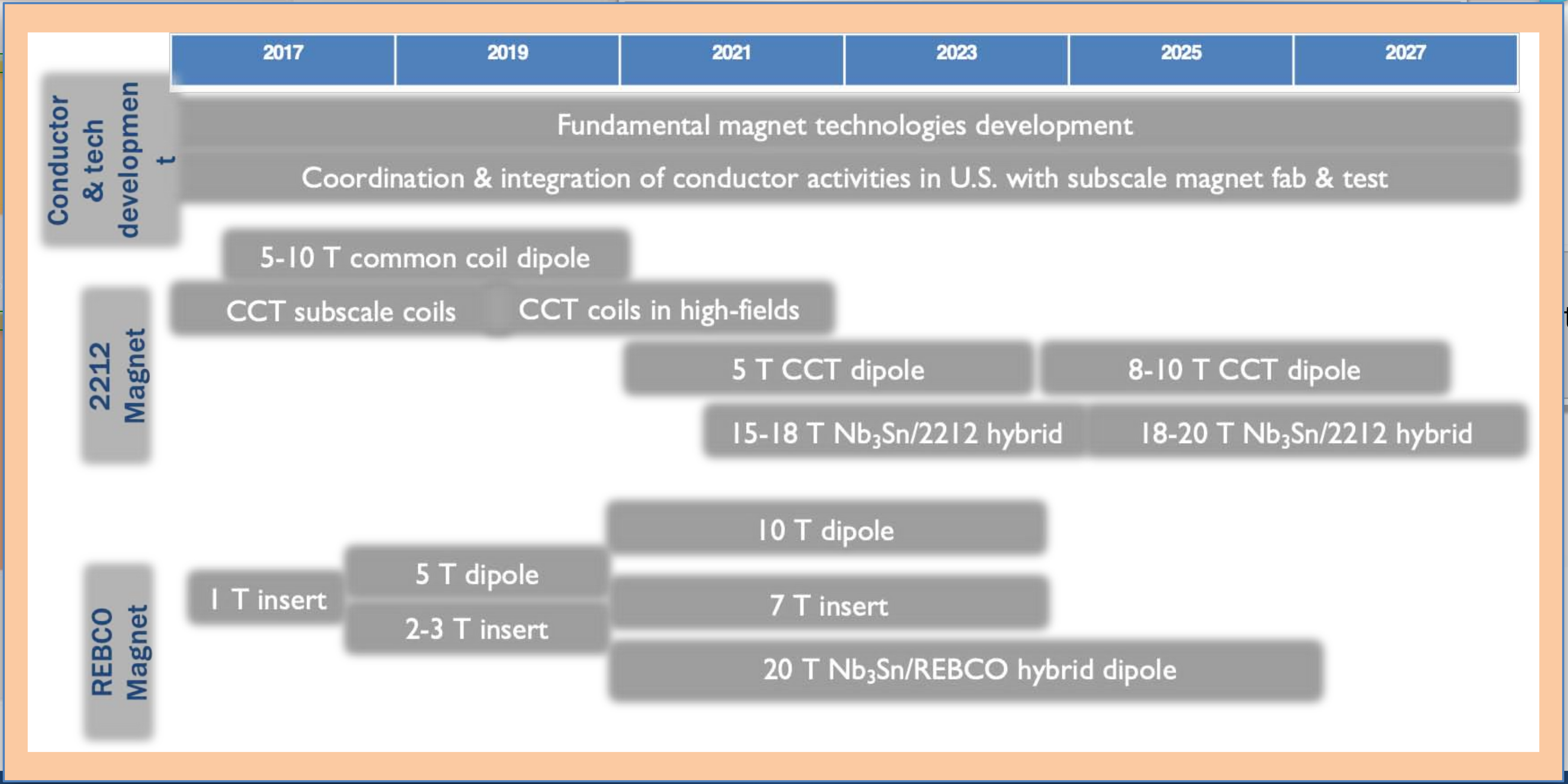
Nb_3Sn magnets



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

Area II:

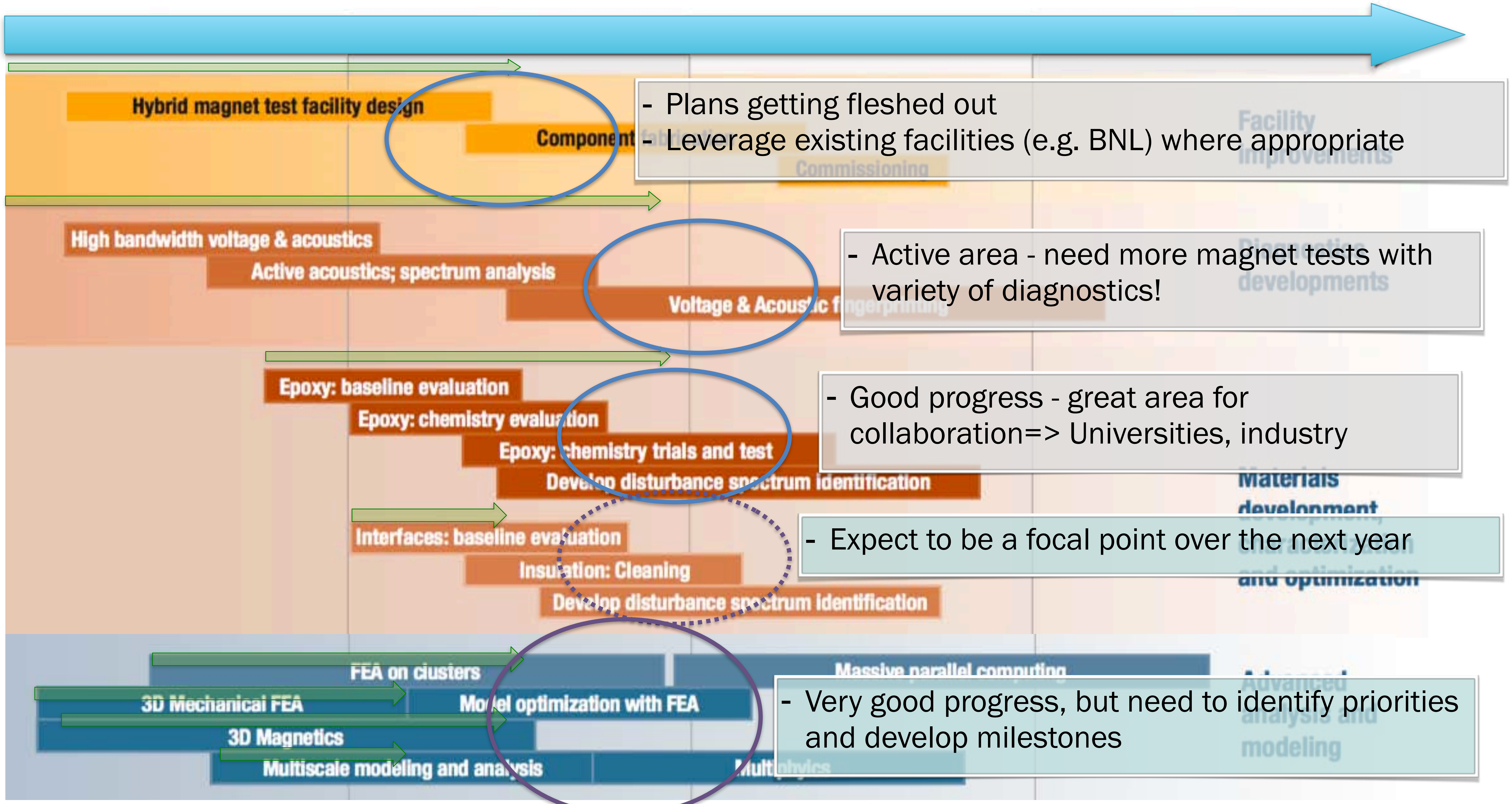
HTS magnet technology



Key science components of the MDP Plan are *Technology Development* and *Conductor R&D*

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 understanding of the chemistry of Nb_3Sn heat treatment $\Longrightarrow$ significant improvement in J_c for small d_{eff}
  - Investigate potential for APC (and other advanced…) Nb_3Sn
    - Ohio State, FNAL LDRD, FSU

- Advances in Bi2212 powder processing + overpressure processing

- 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

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

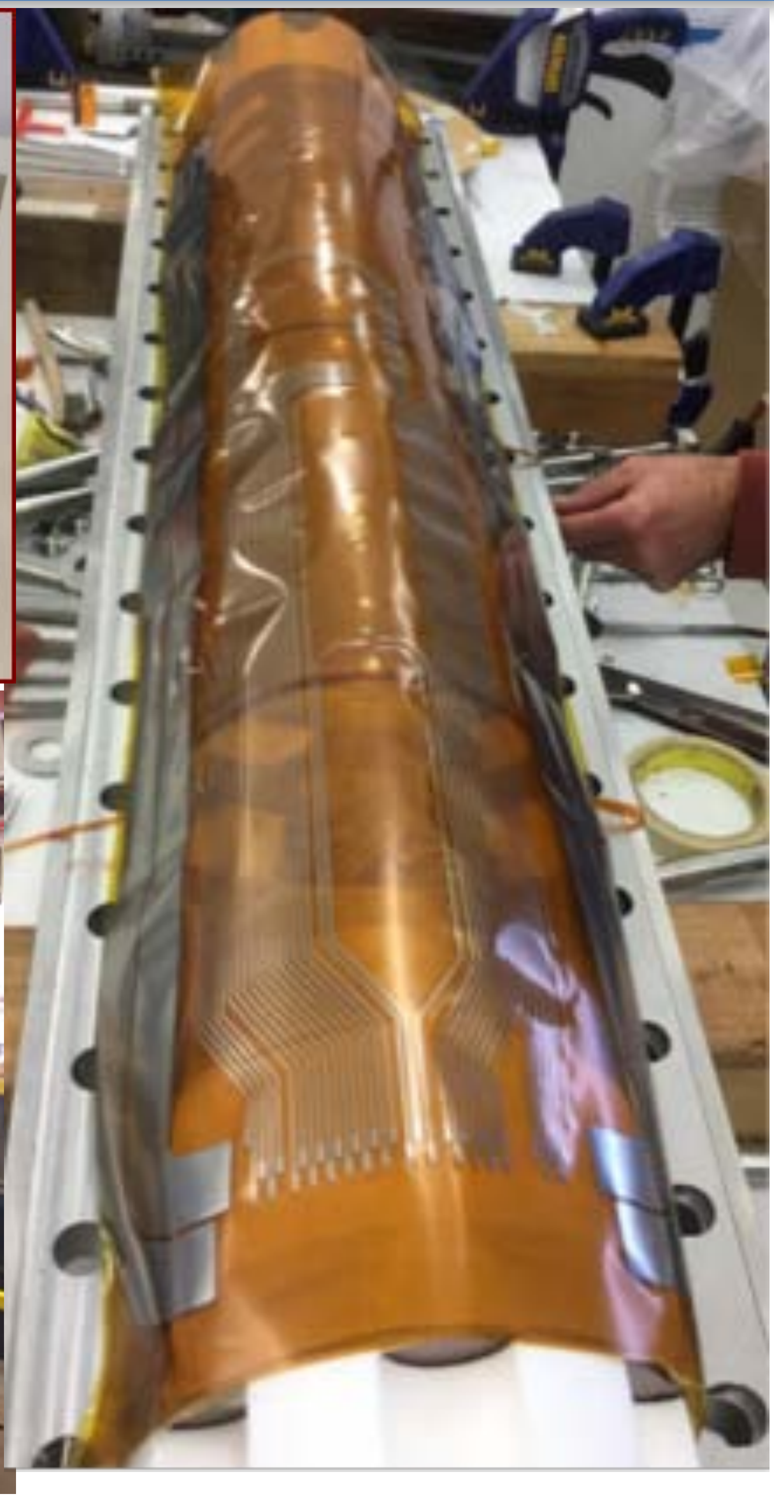
Roadmap for Conductor Procurement, Research and Development
October 6, 2017

Covering DOE FY 2018

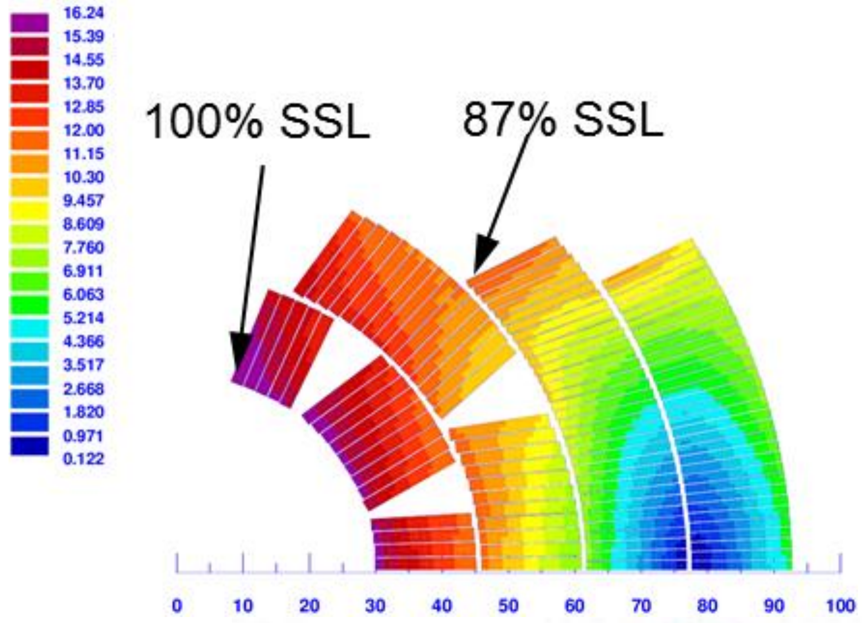
A Cos(t) 4-layer design led by FNAL is being pursued with the ultimate goal of achieving ~15T

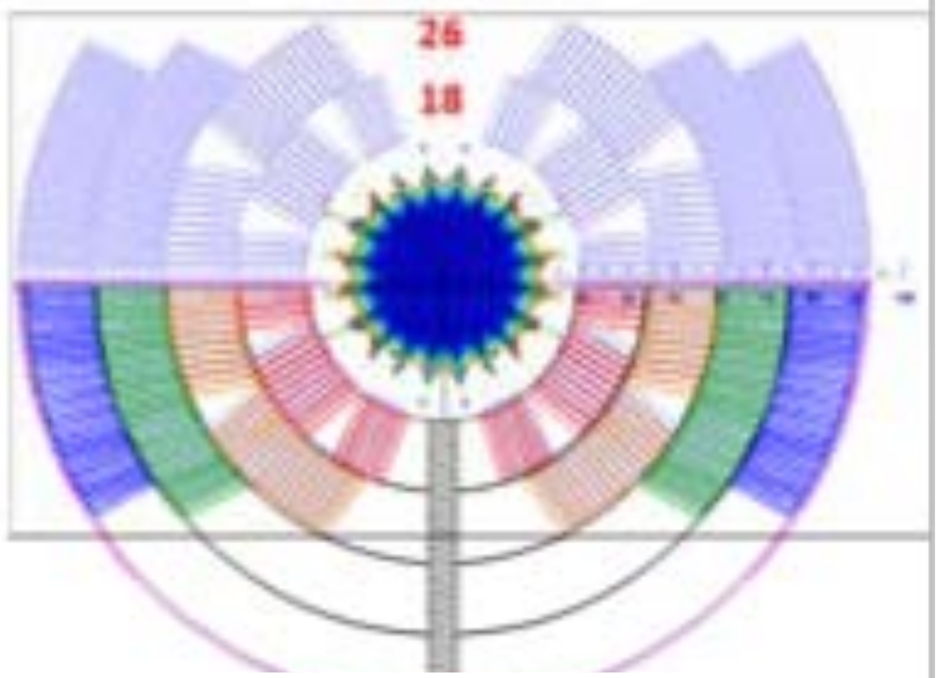
- Design minimizes midplane stress for highest field
- A technical challenge is to provide adequate prestress on inner coils
  - Intrinsic difficulty with 4 layers
  - Collared-structure approach includes new features that provide some prestress increase during cool down

- Status:
  - Coils fabricated
  - Structure designed, fabricated
  - Mechanical model assembly completed
  - Assembly readiness review completed
  - Assembly underway now

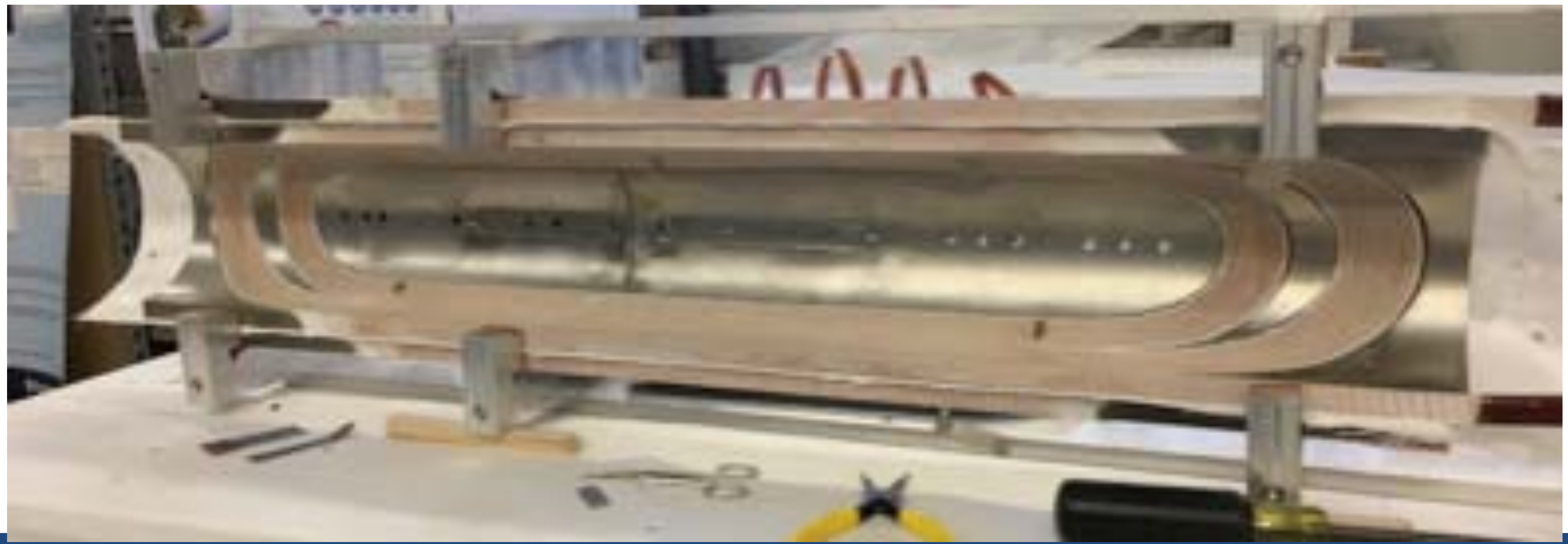


- Thin StSt coil-yoke spacer
- Vertically split iron laminations
- Aluminum I-clamps
- 12-mm thick StSt skin
- Thick end plates and StSt rods



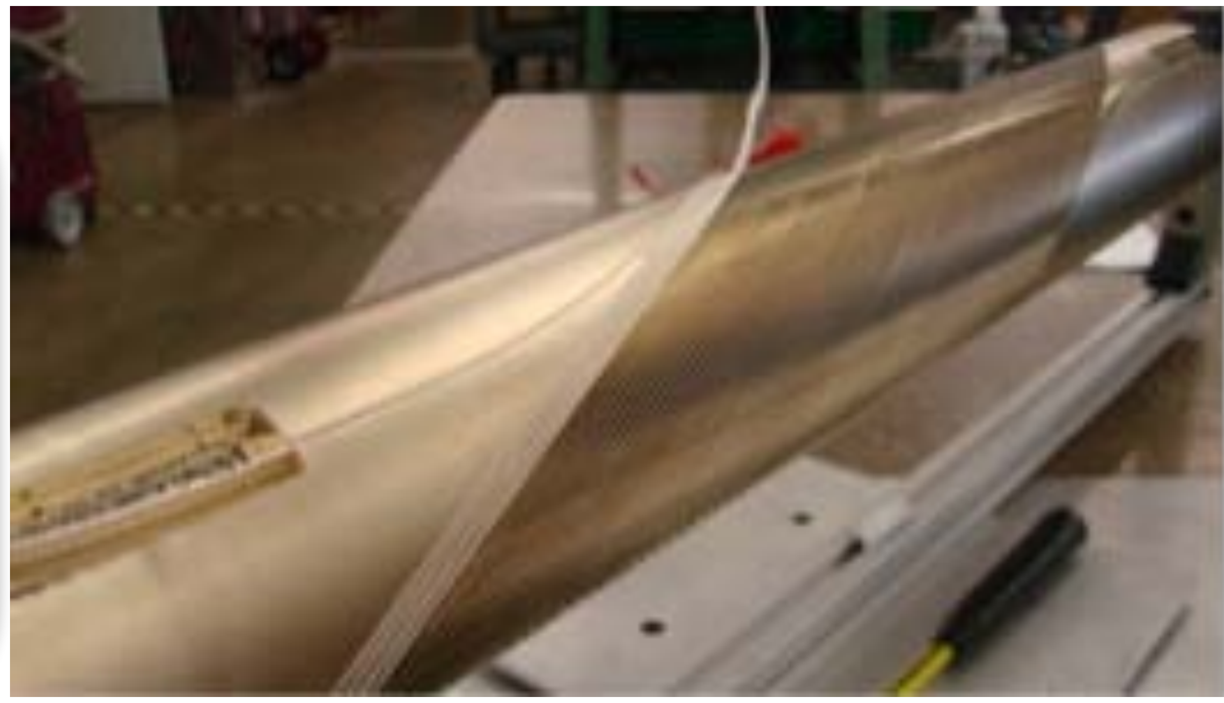


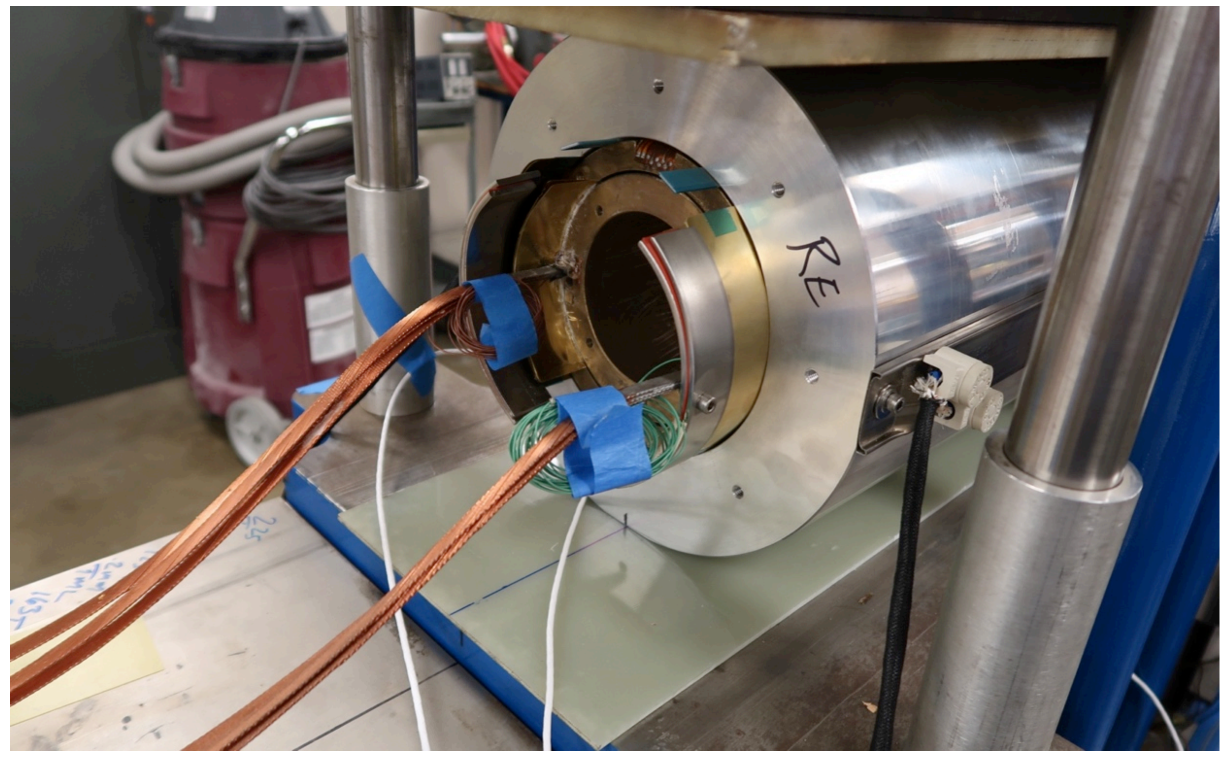
60-mm aperture, 4-layer graded coil



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

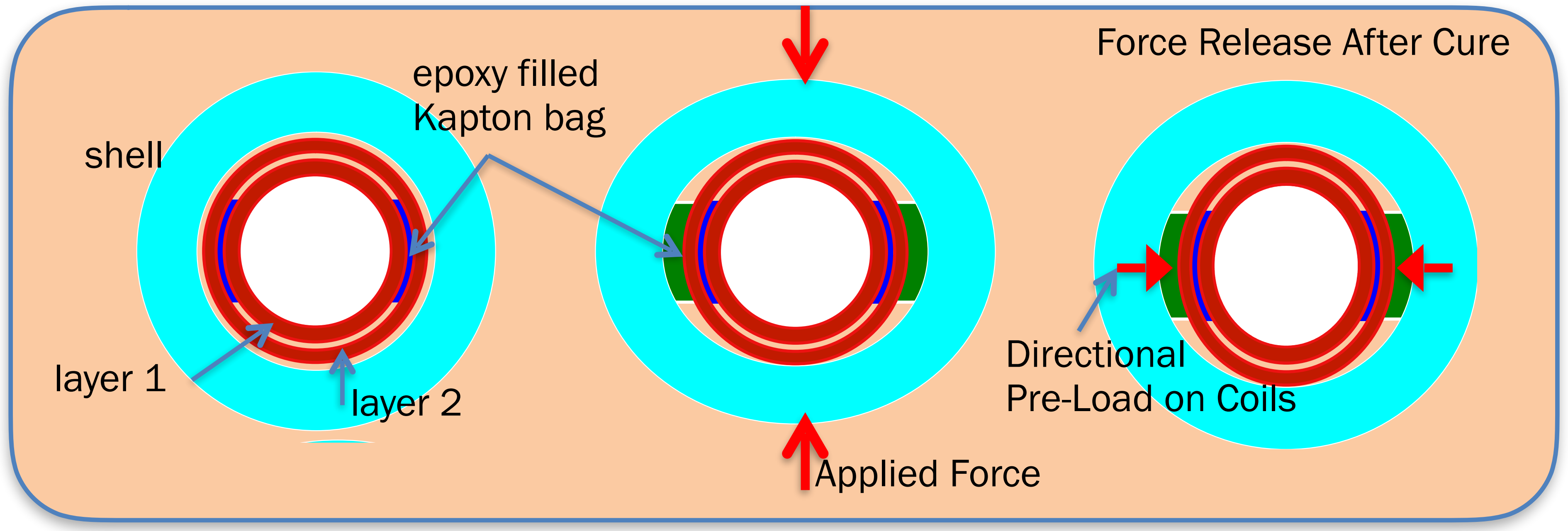
- Canted Cosine-theta:
  - CCT4 (the second Nb3Sn CCT 2-layer magnet) was tested, and thermally cycled
  - CCT5 incorporated modifications based on CC4 experience
    - Magnet was tested and thermally cycled
  - Subscale CCT currently being pursued for fast turn-around technology development



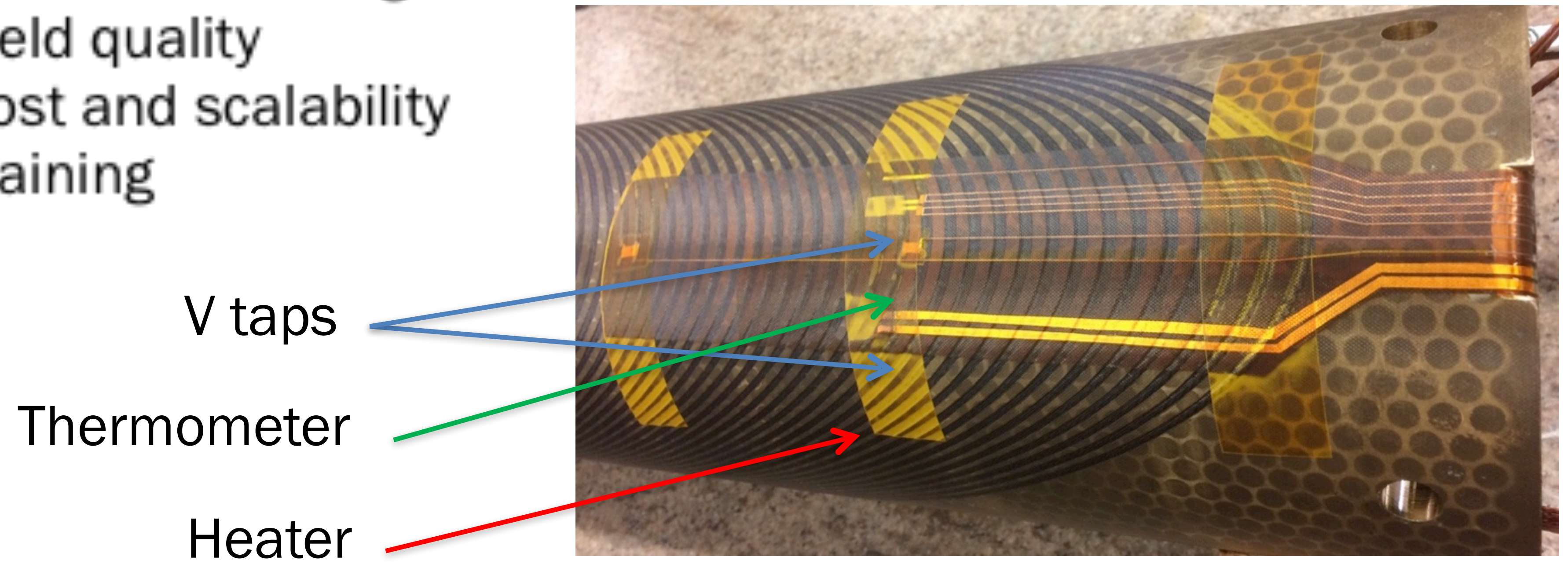


	CCT3	CCT4	CCT5
Bore size [mm]	90	90	90
Groove design	constant width	1.25 mm gap at pole	1.65 mm gap at pole
Conductor	RRP 54/61 Ta doped	RRP 54/61 Ta doped	RRP 108/127 Ti doped
HT Temp [C]	650	660	665
Potting configuration	full magnet	full magnet	individual layers
Epoxy	CTD-101K	CTD-101K	FSU Mix 61
Layer-to-layer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

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

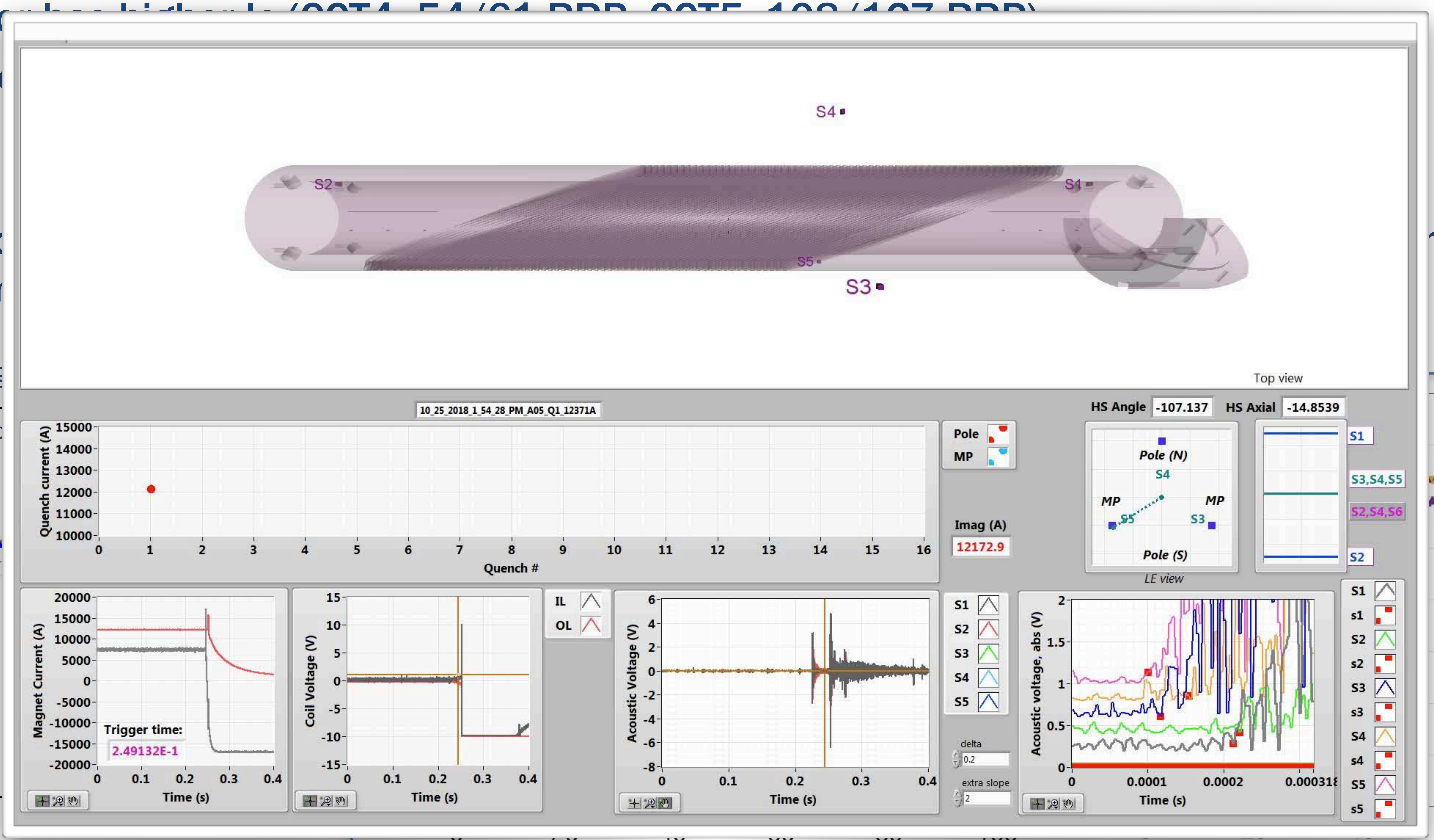


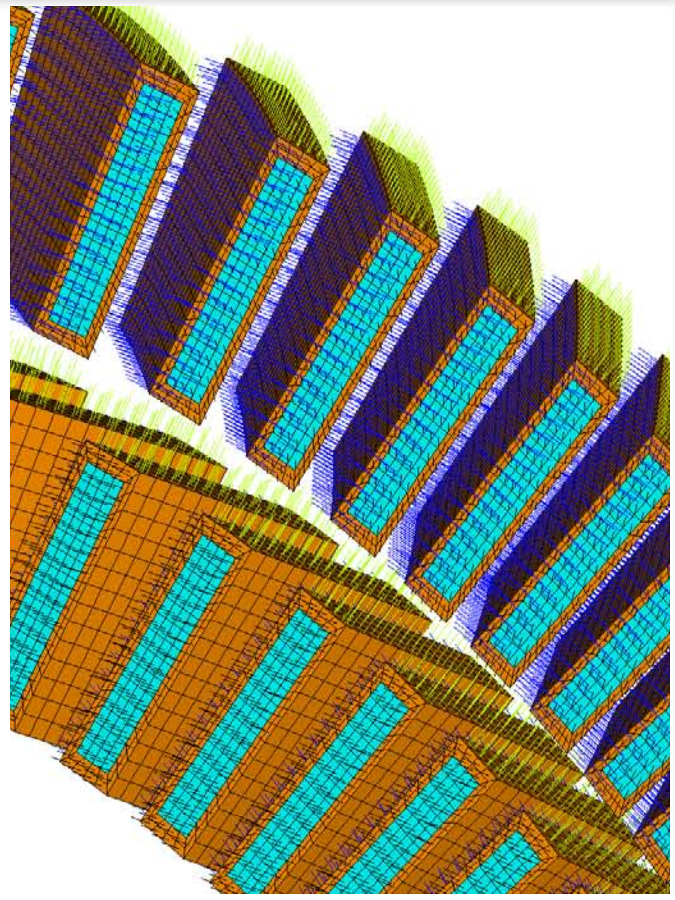
Instrumentation Trace After Potting



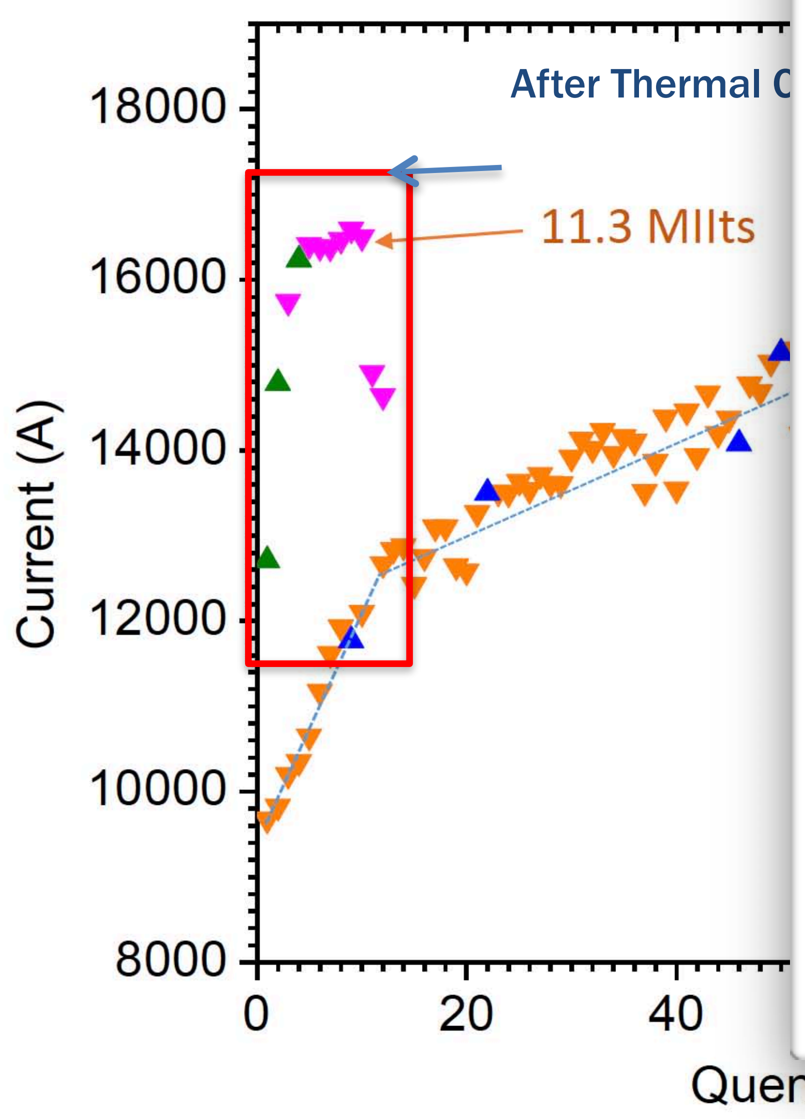
CCT test results show significant training - feedback has led to improvements, but further improvements needed

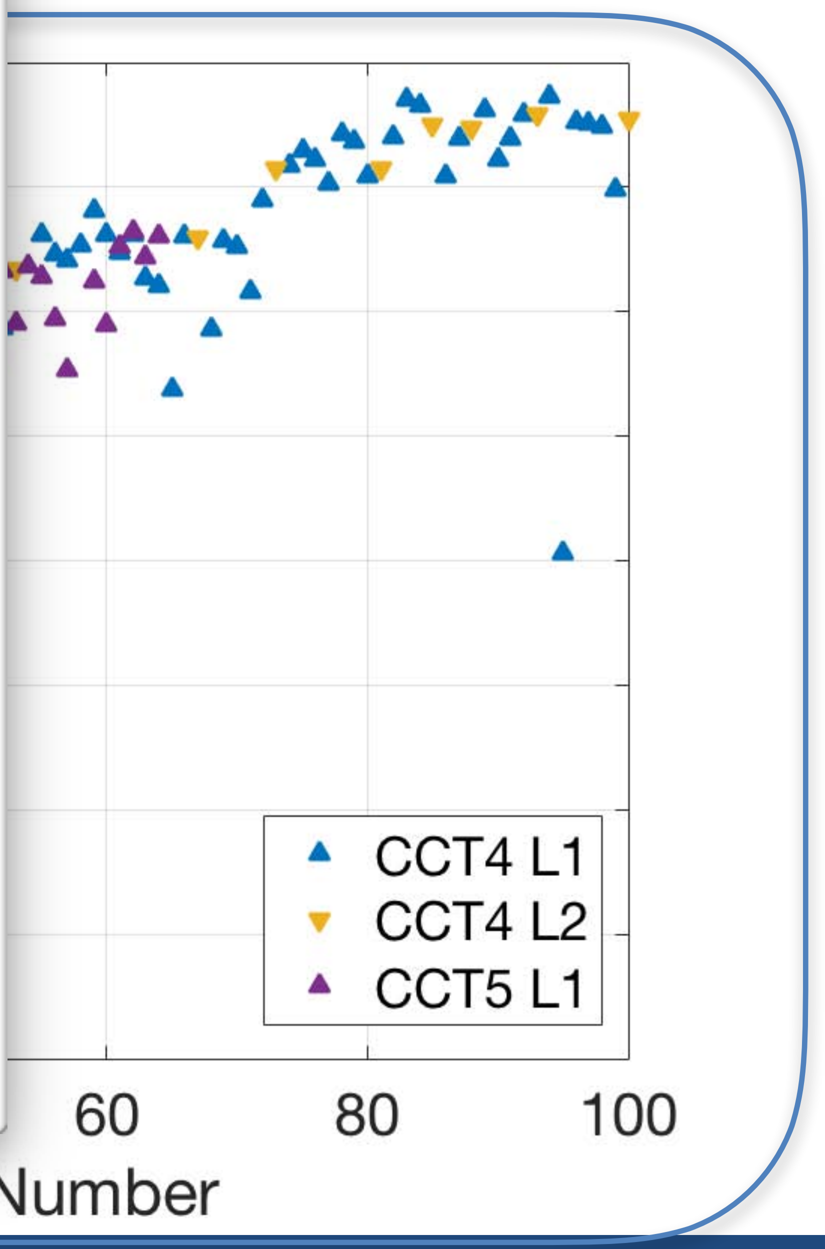
- CCT4 conduct
- CCT5: First qu training quenc
  - After initia
  - After appr current (si





CCT4 Training





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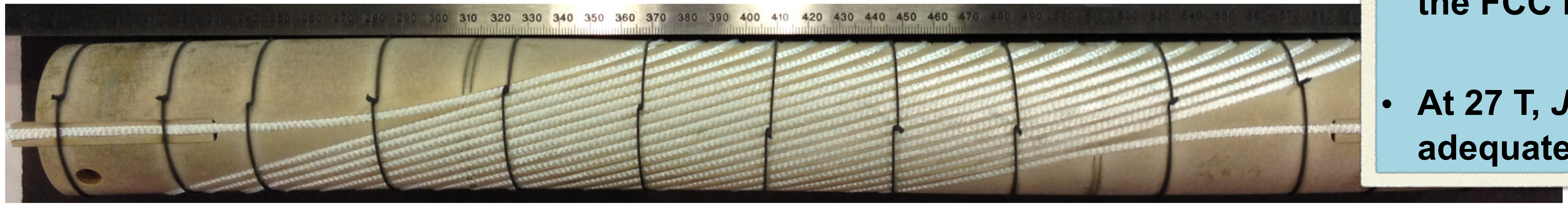
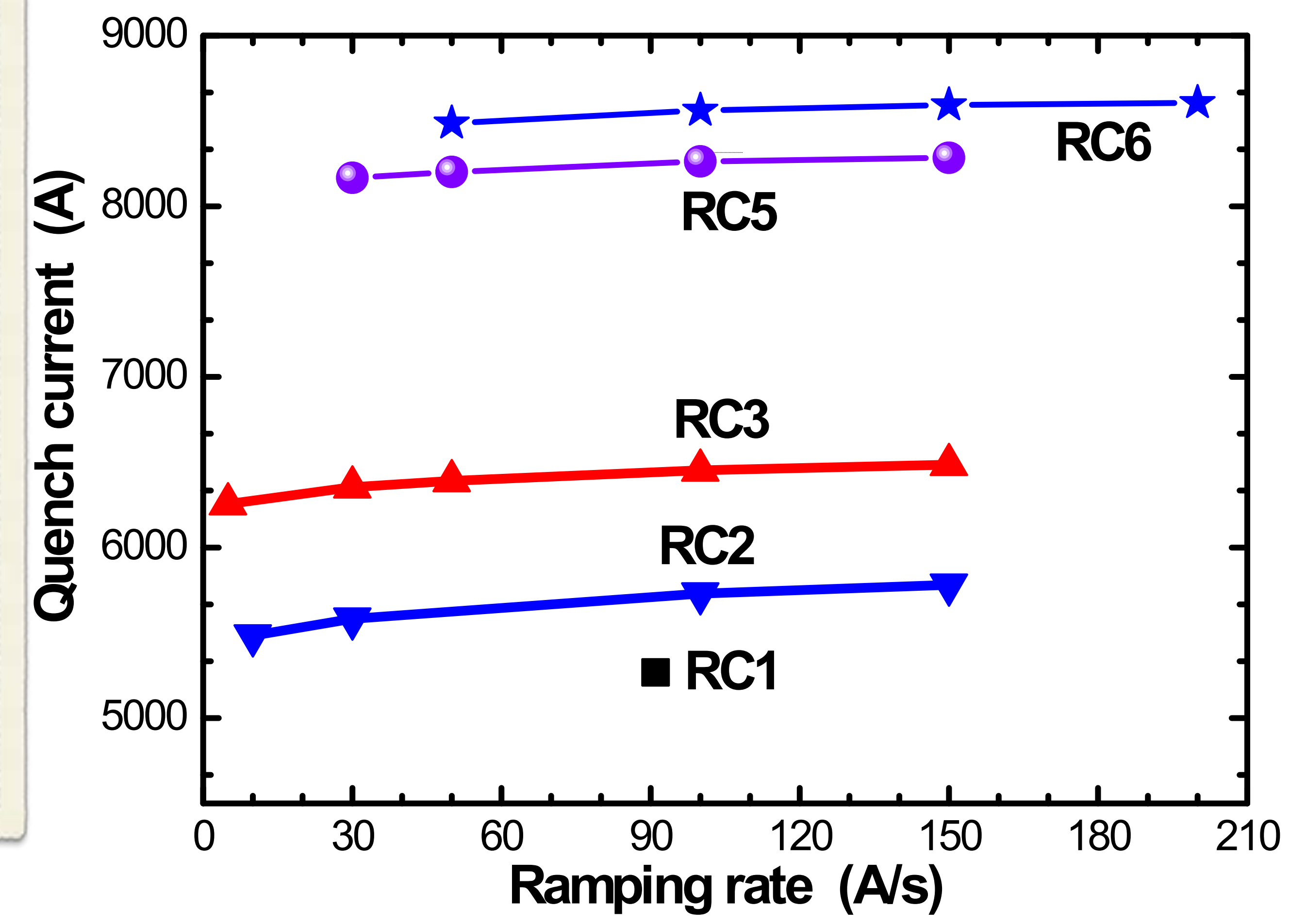
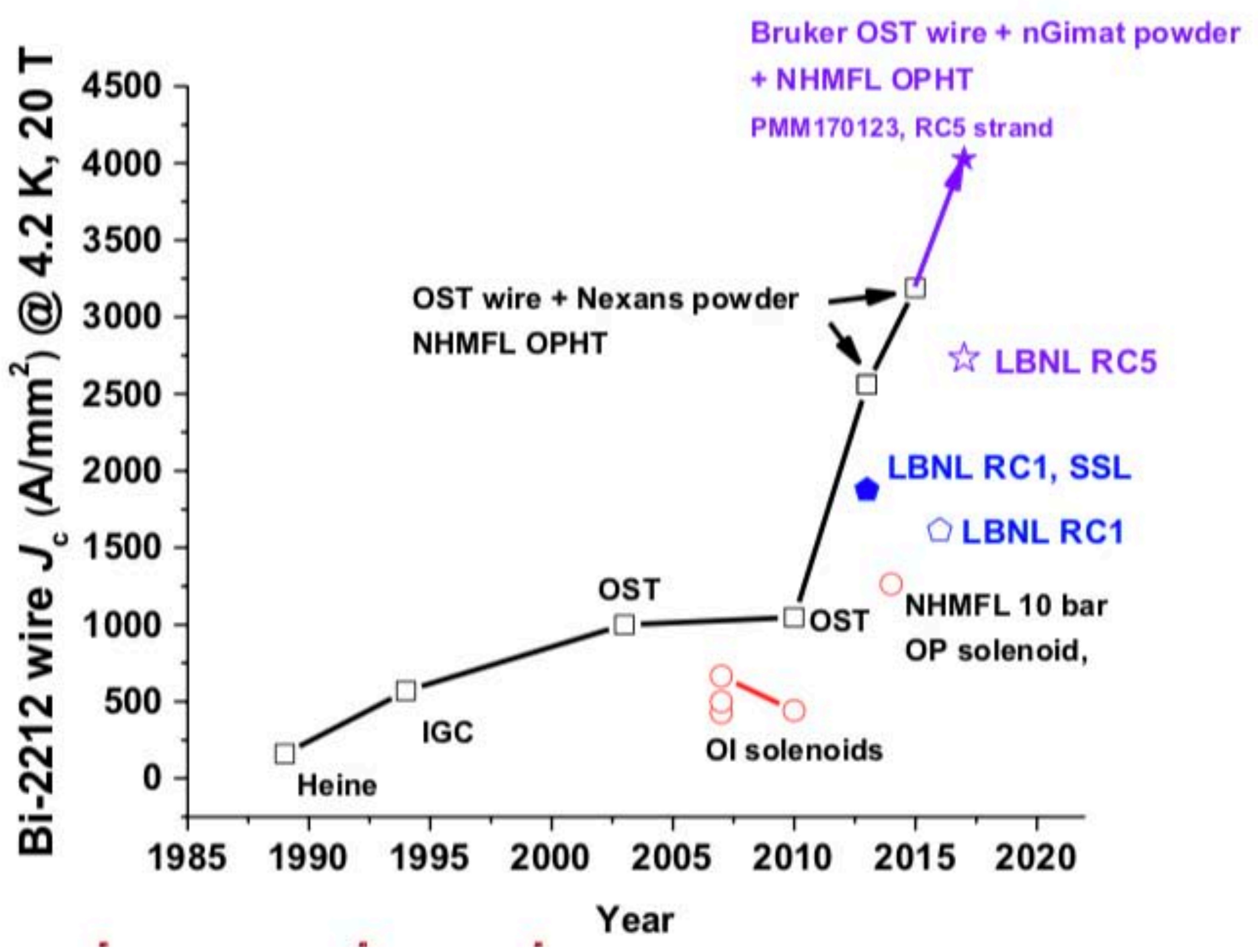
On the HTS magnet front, Bi2212 has matured to become a magnet-ready conductor

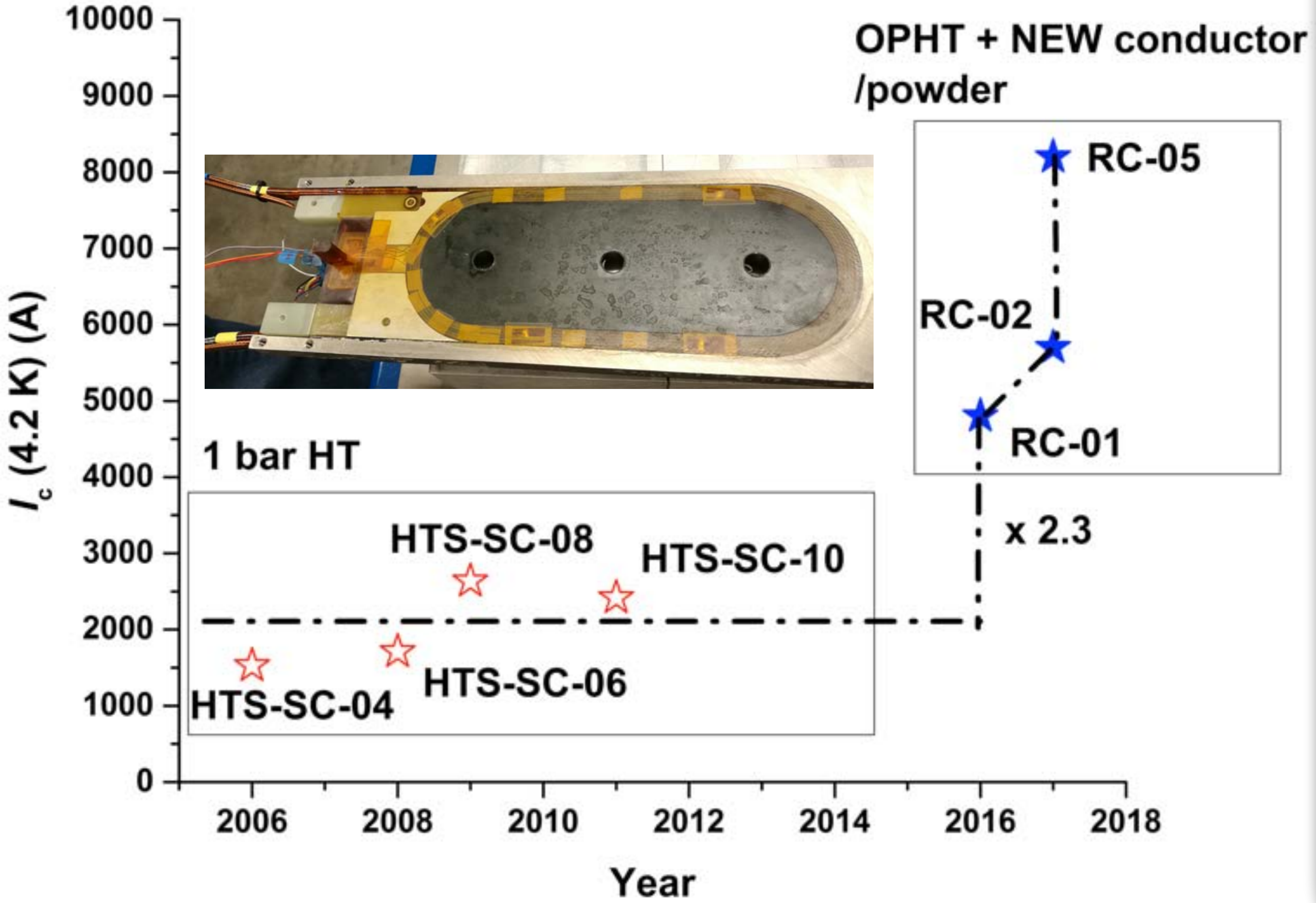
- Bi2212 has made dramatic strides in J_c over last 3 years => ready for magnets
  - Wire has been cabled and tested in racetrack configuration (RC5)
  - First Bi2212 CCT dipoles have been wound and await reaction and testing soon
  - Roadmap integrates Bi2212 CCT in a high-field hybrid magnet design

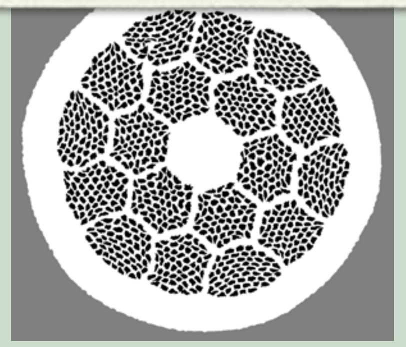


- **Nano-spray combustion powder technology**
- **55x18 wire design**
- **At 15 T, J_e - 1365 A/mm², twice the target desired by the FCC Nb_3Sn strands**
- **At 27 T, J_e - 1000 A/mm², adequate for 1.3 GHz NMR.**

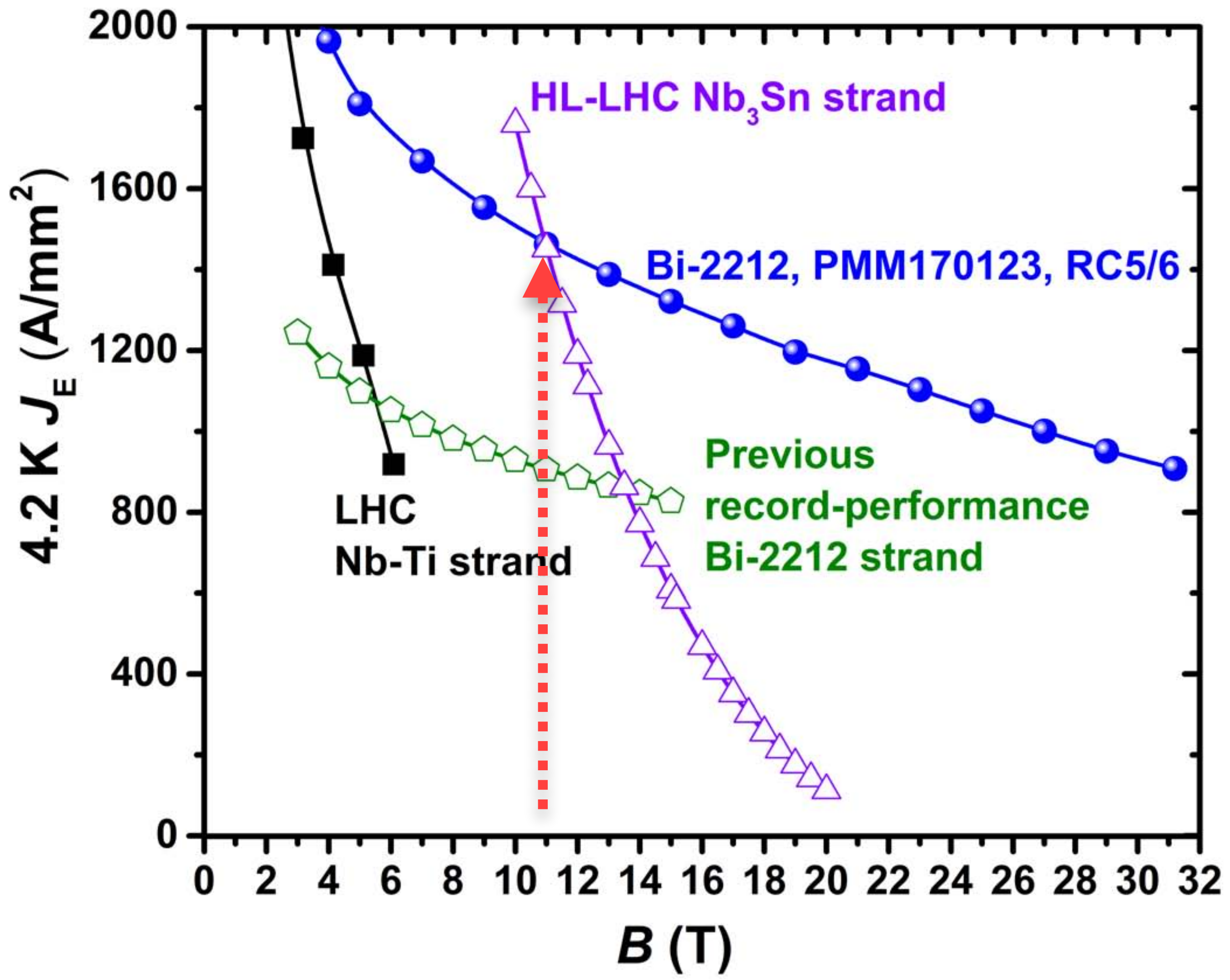






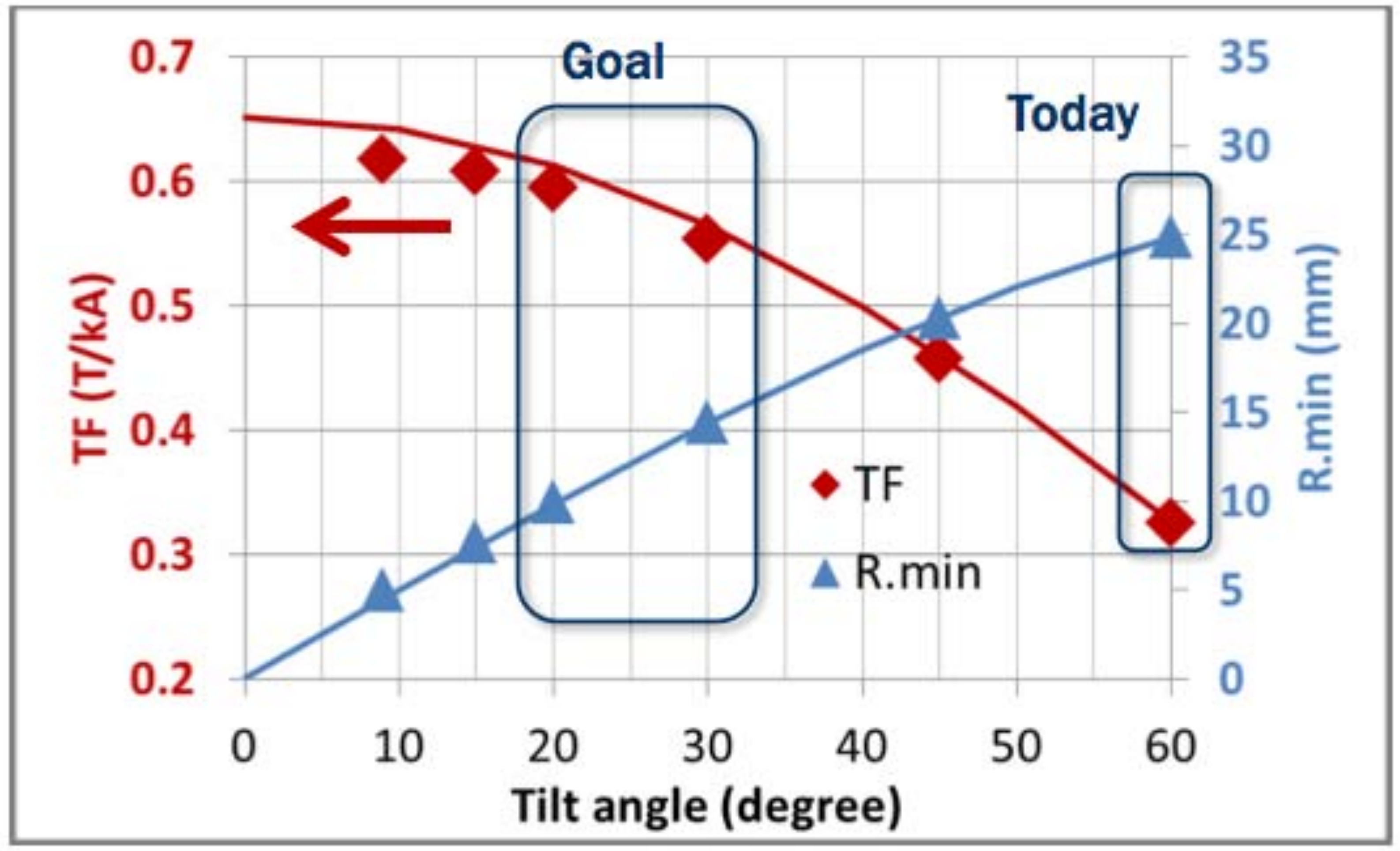


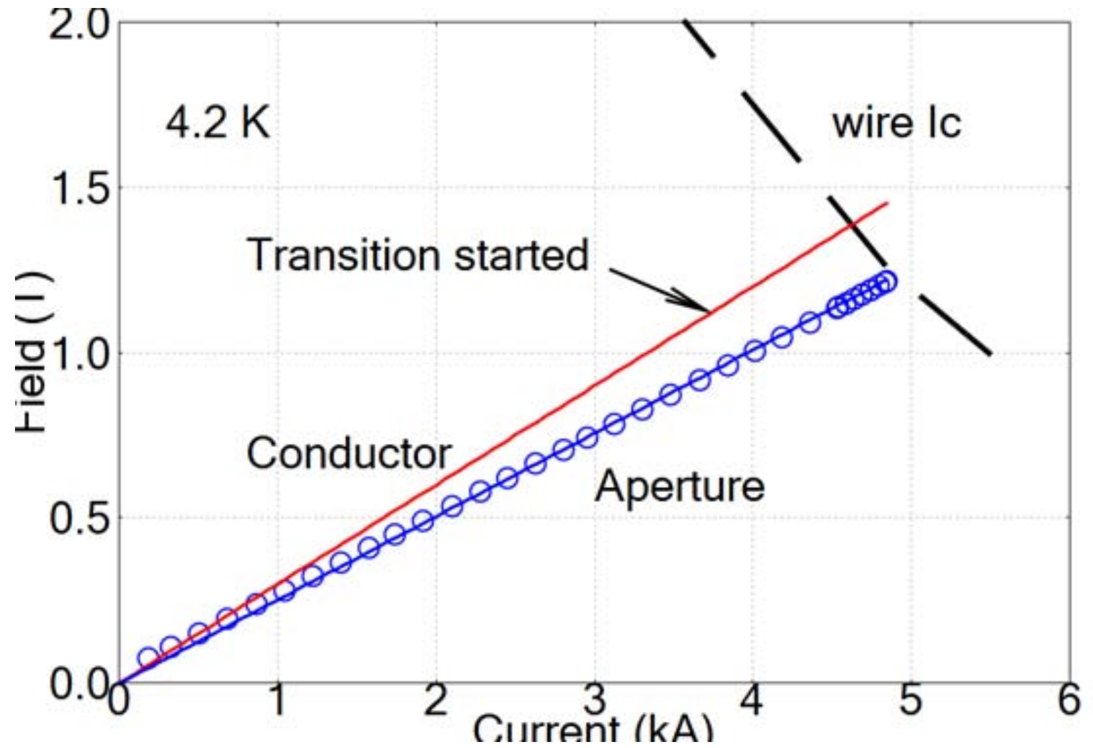
nGimat — nanoEngineered Materials
ASC NATIONAL MAGLAB
BRUKER
BERKELEY LAB

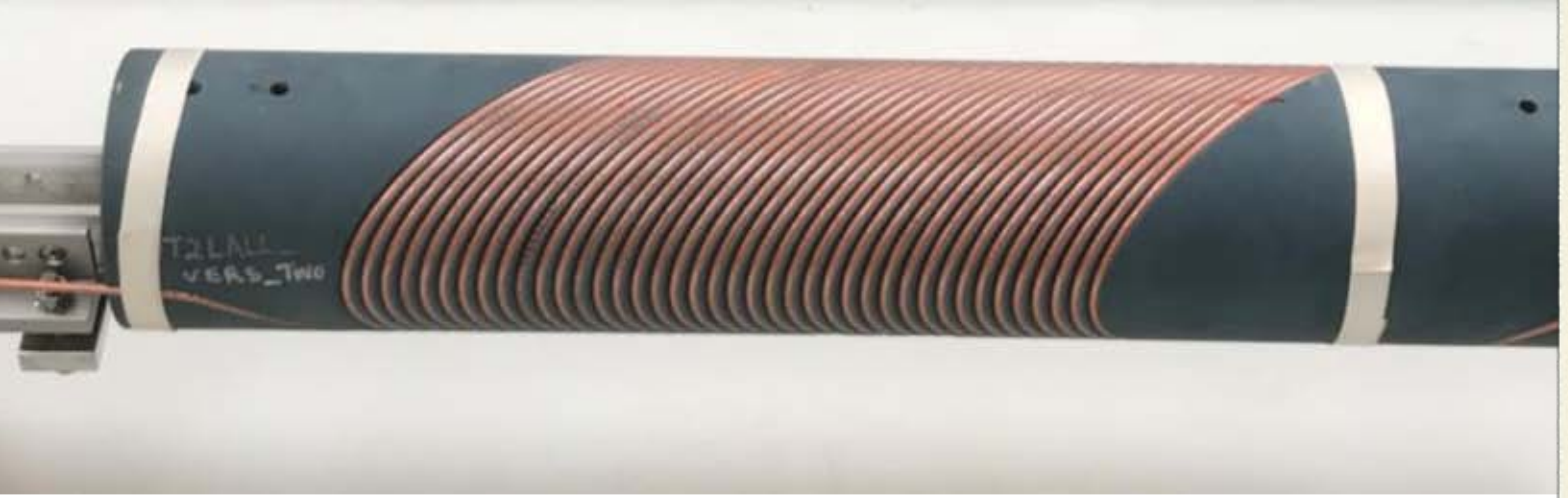


Work on REBCO is focused on the development of CORC cable in a CCT configuration - steady progress towards MDP goals

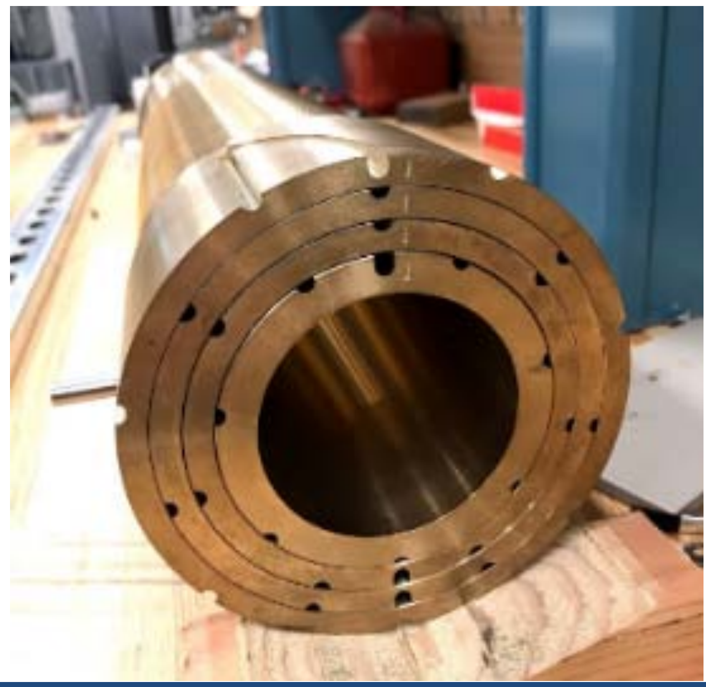
- REBCO development focused on CORC® cables and magnet technology development
  - 3-turn C0 “dipole” was used to develop winding tooling, fabrication processes
  - 40-turn C1 dipole was then fabricated and tested
  - 3-turn C2 has been fabricated and tested; full 40-turn C2 being fabricated







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



We are looking closely at options for future high-field magnet designs that build on current efforts

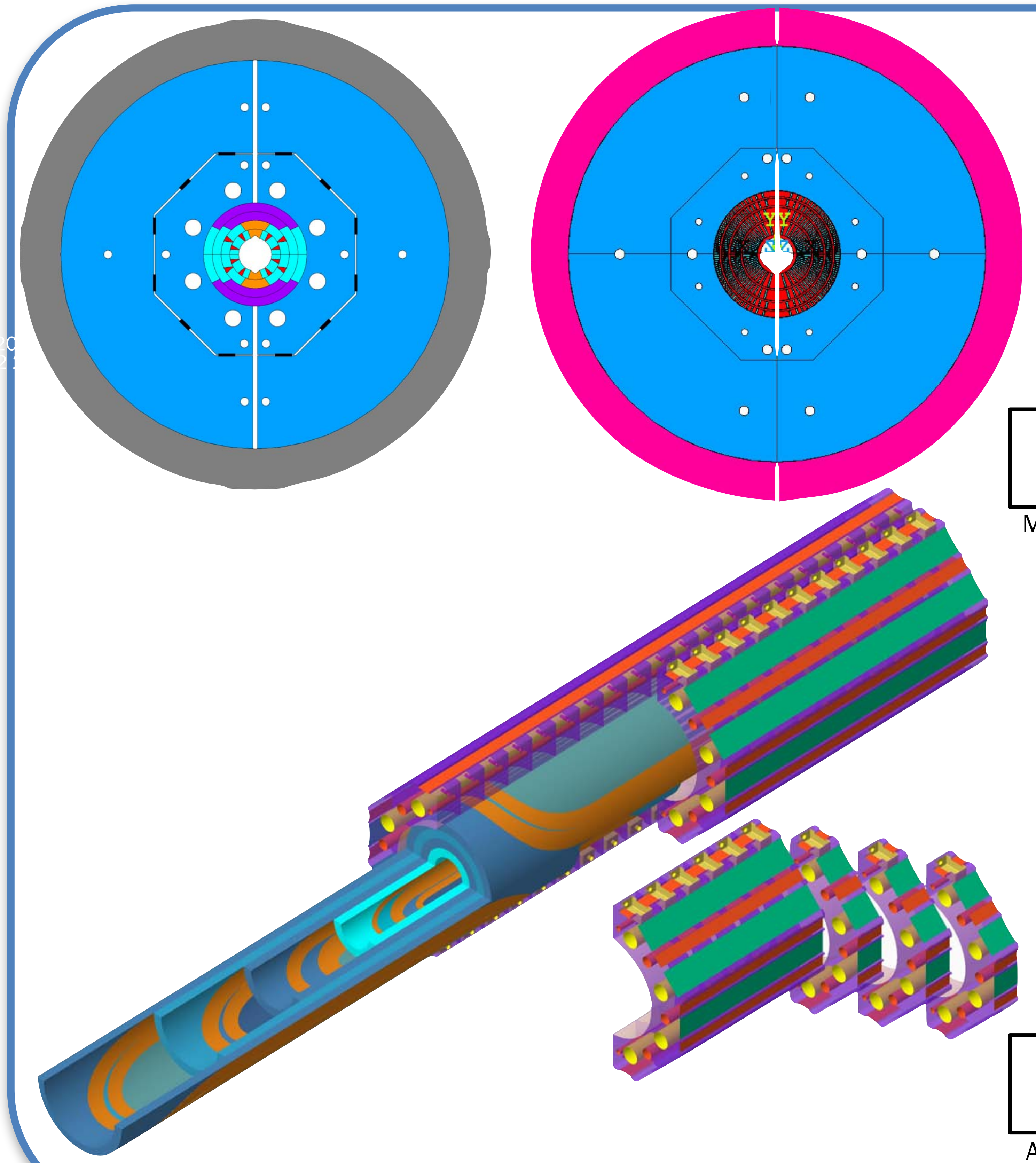
Design Team
16 T Dipole design:
Leads: Zlobin and Sabbi

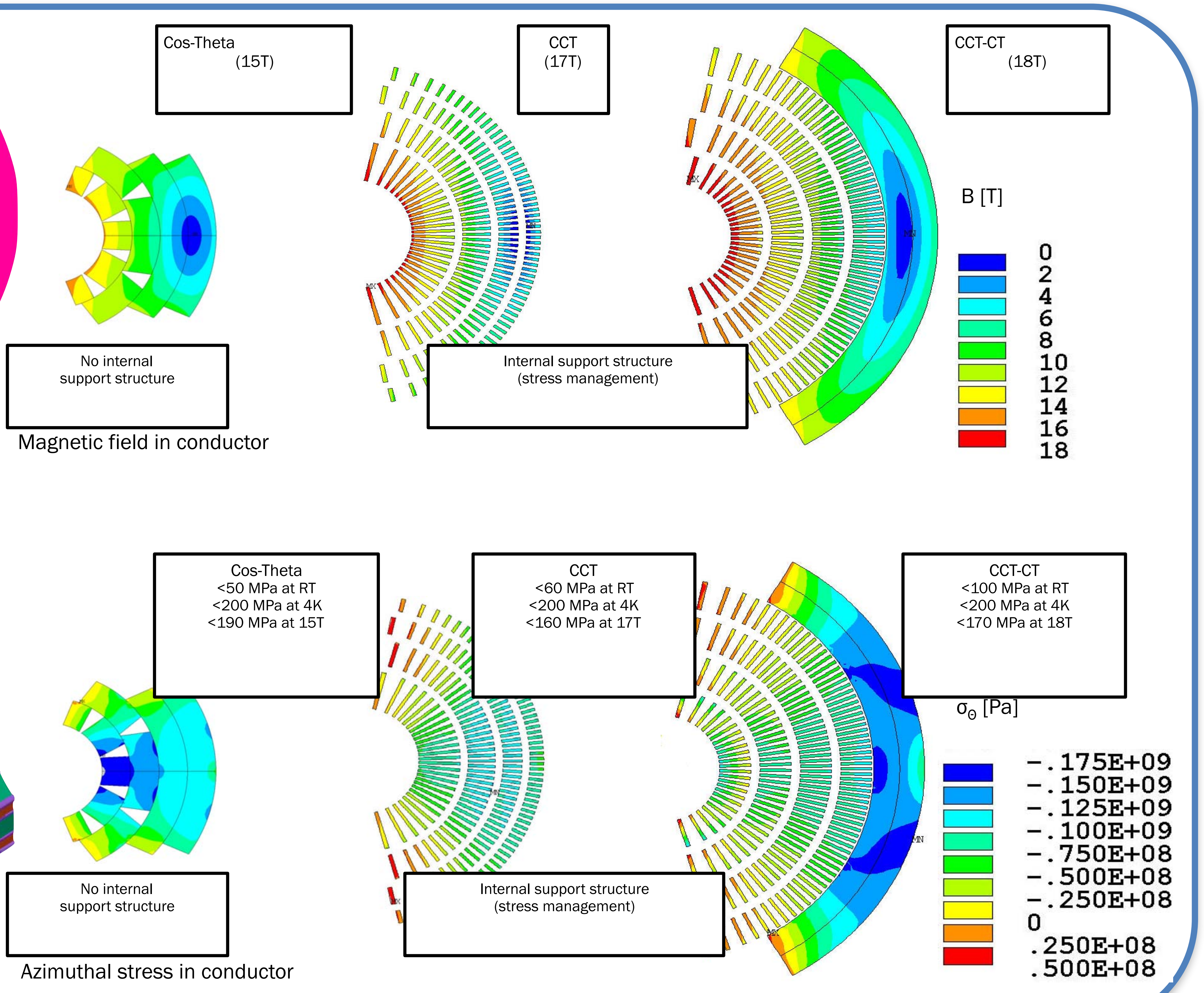
Design Team
Utility Structure design:
Lead: Mariusz Juchno

Nb_3Sn design targets

Each magnet concept should provide

- Description of magnet design including
  - Strand, cable and insulation (before and after reaction)
  - Coil cross-section (number of layers, number of turns, conductor weight/m/aperture)
  - Coil end design concept
  - Magnet support structure including transverse and axial support
  - Quench protection system in the case of no energy extraction
- Maximum magnet bore field B_{max} at conductor SSL for 1.9 K and 4.5 K
- Dependence of B_{max} on conductor J_c(16T,4.2K)
- Calculated geometrical field harmonics, coil magnetization and iron saturation effects in magnet straight section at R_{ref}=17 mm for B=1-16 T
- Stress distribution in coil and structure at room and operation temperatures and at the nominal (16 T) and design (17 T) fields
- Coil-pole interface (gap) at the nominal (16 T) and design (17 T) fields
- Coil maximum temperature and coil-to-ground voltage during quench w/o energy extraction
- Cost reduction opportunities





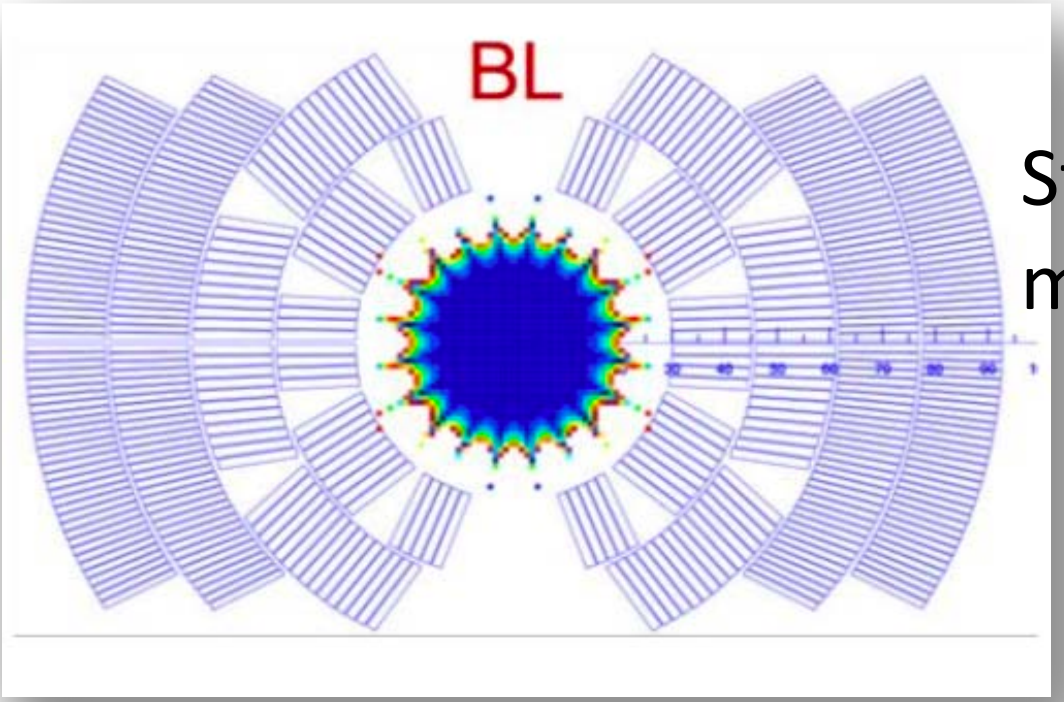
We are looking closely at options for future high-field magnet designs that build on current efforts

First look at Hybrid designs

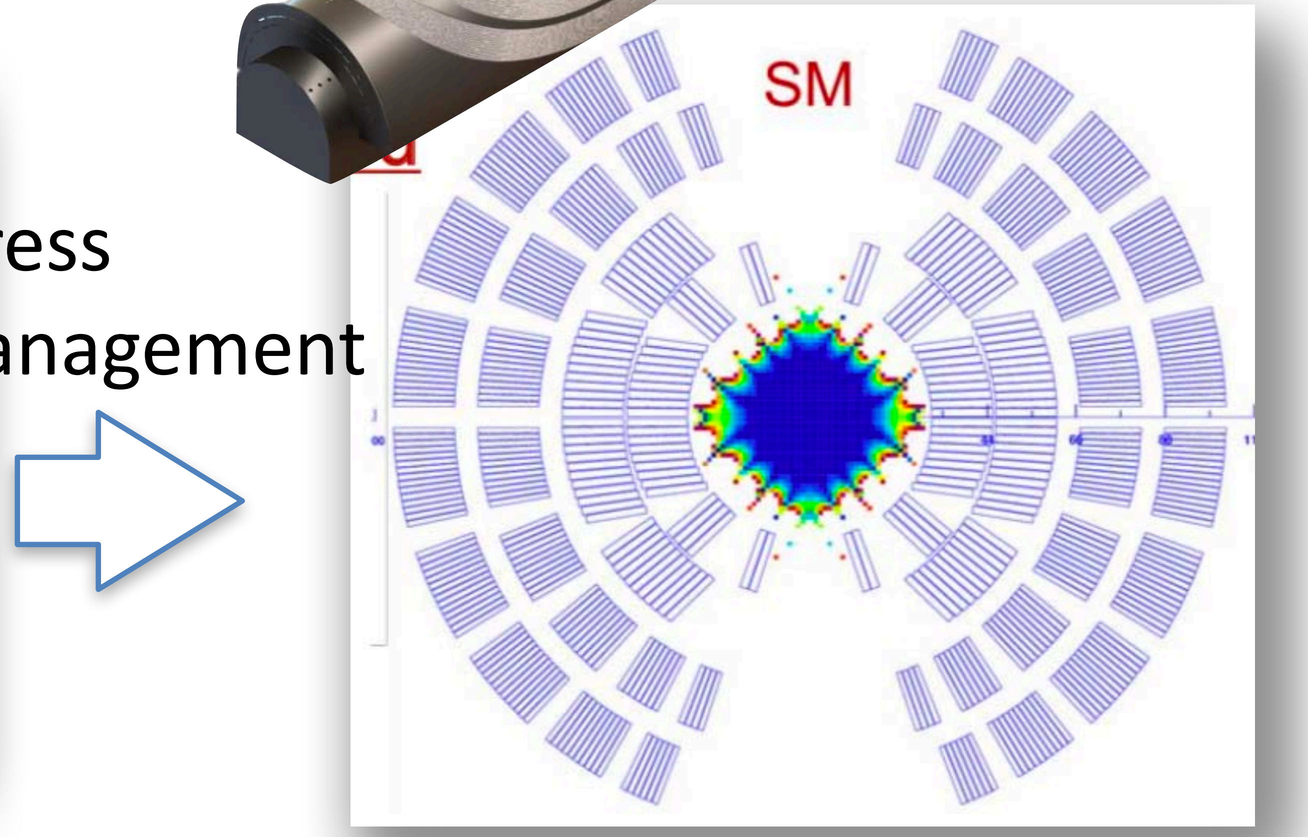
"Stress-managed Cos(t)"

- Design studies of 16 T dipole with 60-mm aperture is complete
  - 120-mm aperture SM coil design is complete
  - Large-aperture SM coil technology development has started

Justin Carmichael (FNAL-ANL)



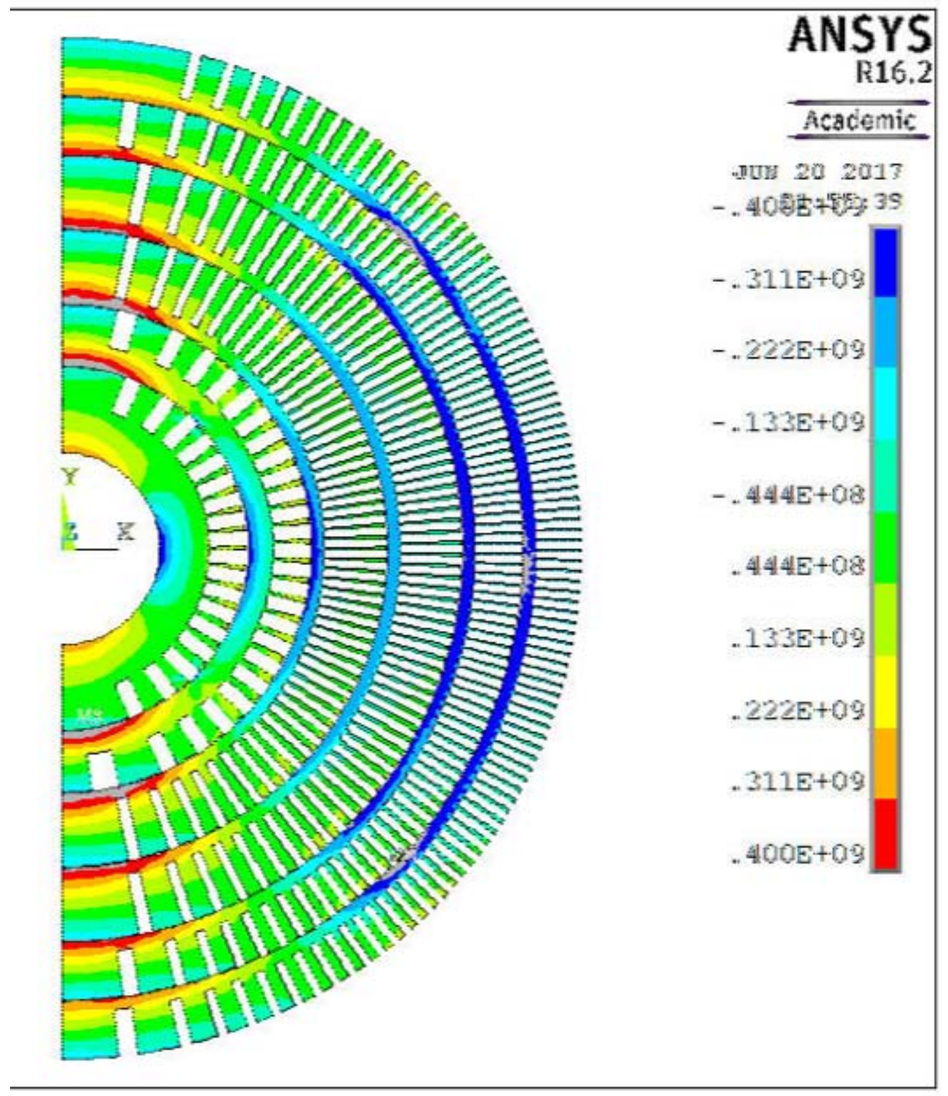
Stress management



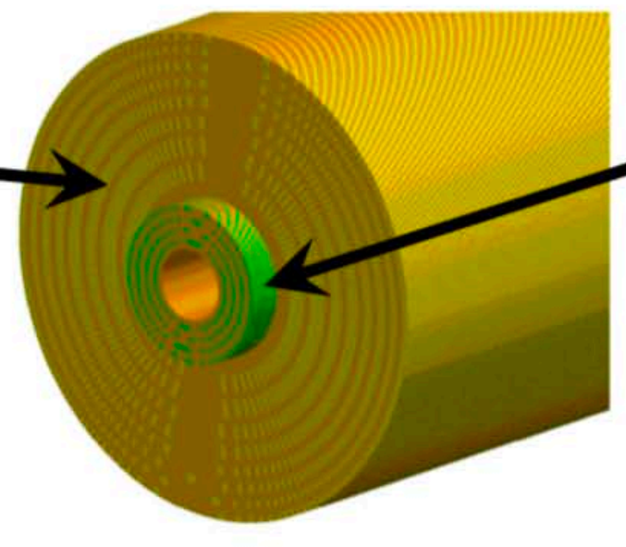
Current focus for CCT

- 4-Layer CCT Design with option for insert
  - Target bore dipole field of 12 – 13 T operating at ~ 80 - 85% of short sample to allow for insert coils
  - Bore size of 90 – 120 mm (depends on HTS needs and results of magnet design study)
- Very conceptual design studies have been to explore very high field scenarios

High-field concept



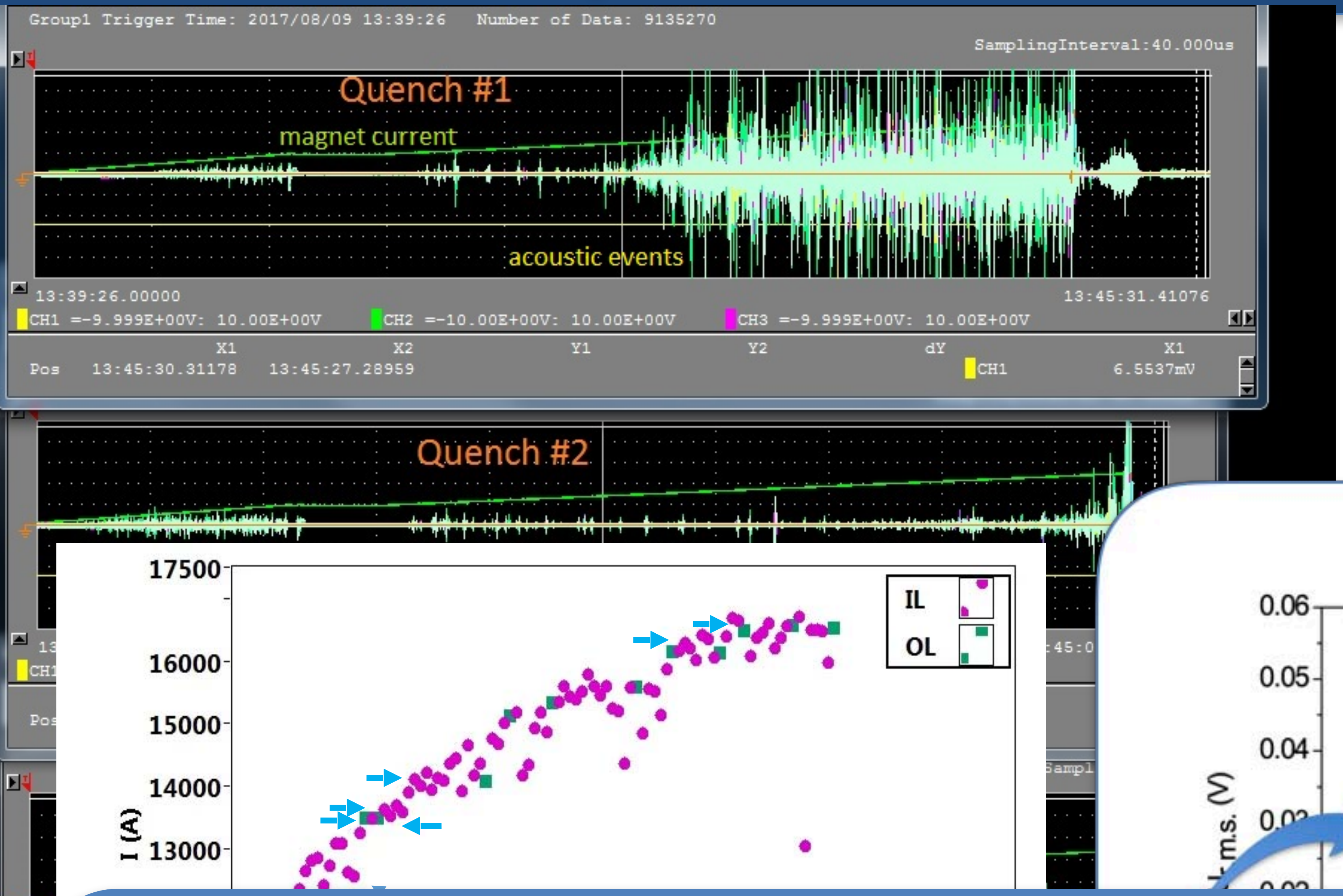
LTS coils

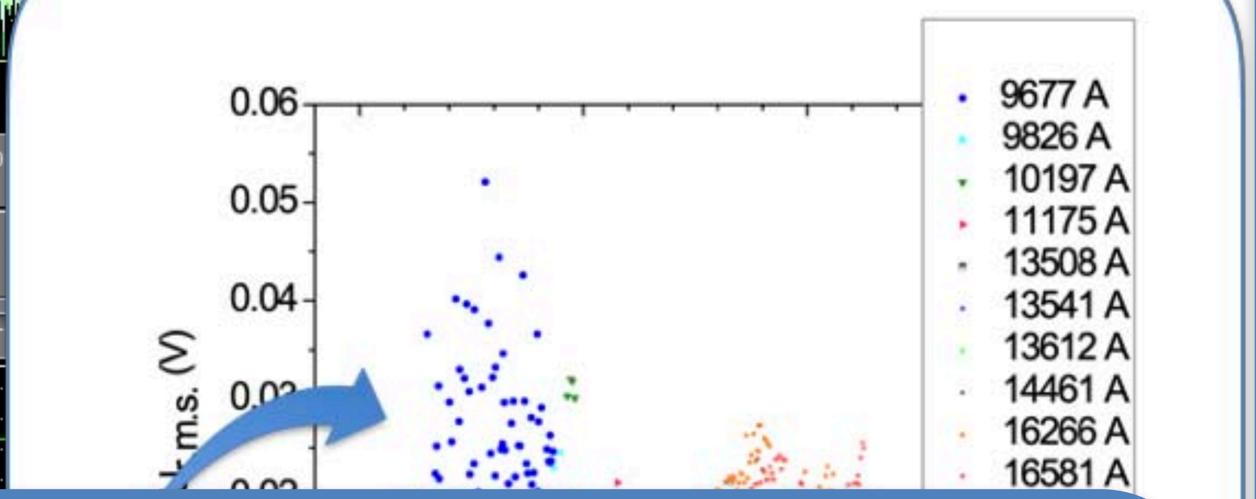


HTS coils in the high field region

U.S. MAGNET DEVELOPMENT PROGRAM

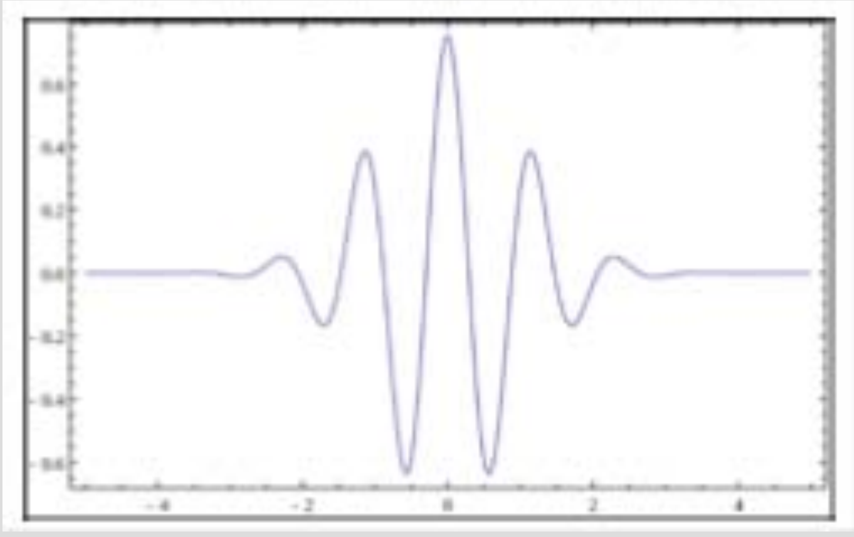
Diagnostics are critical for understanding of magnet performance and to provide feedback to magnet design

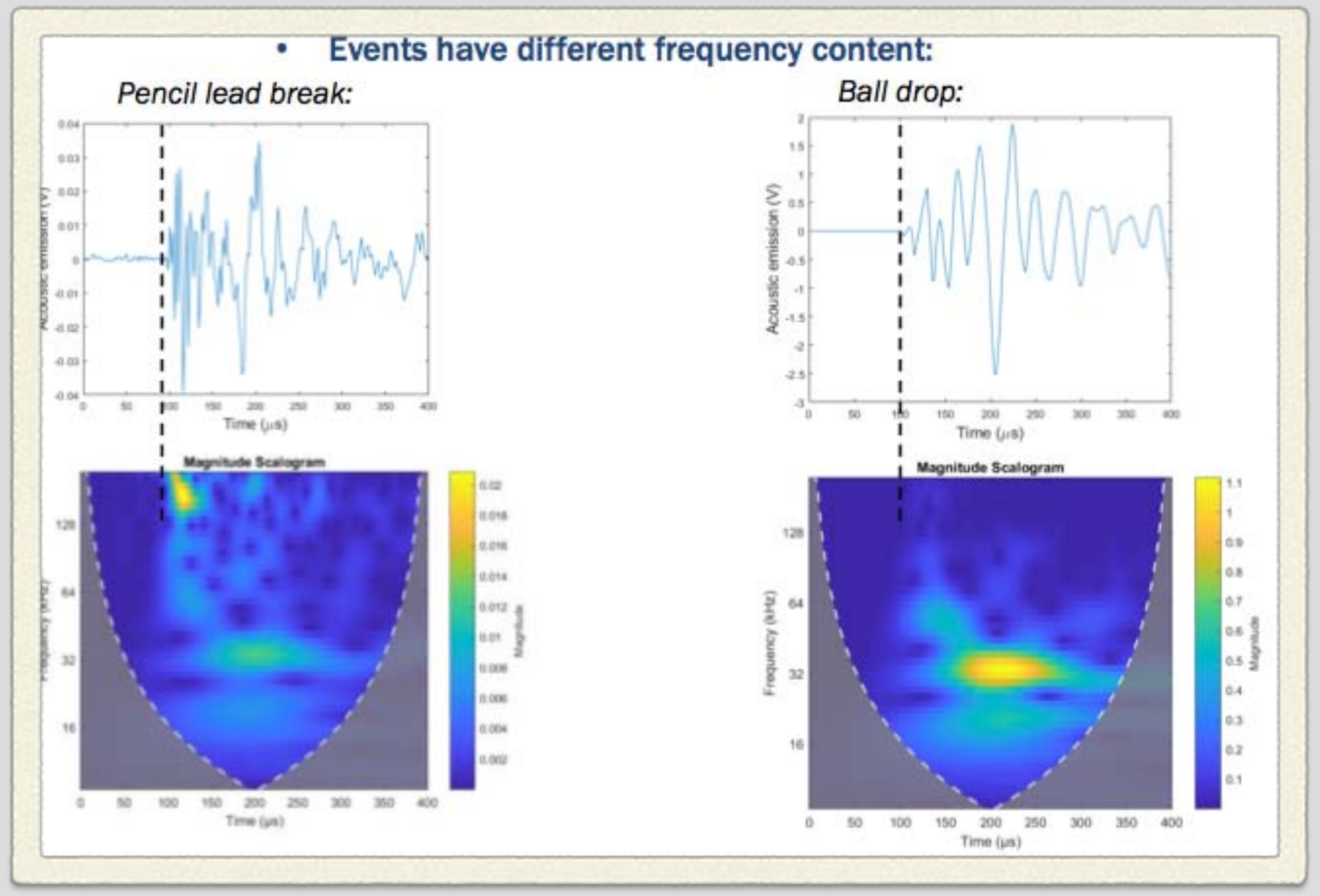




Acoustic signatures provide a wealth of data on energy perturbations in magnets

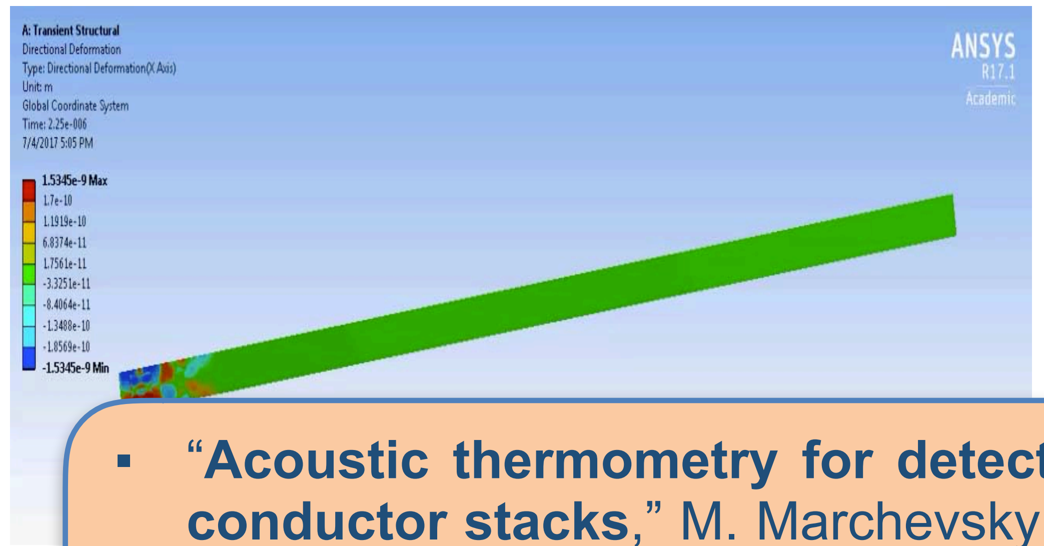
Wavelet analysis provides robust mathematics platform

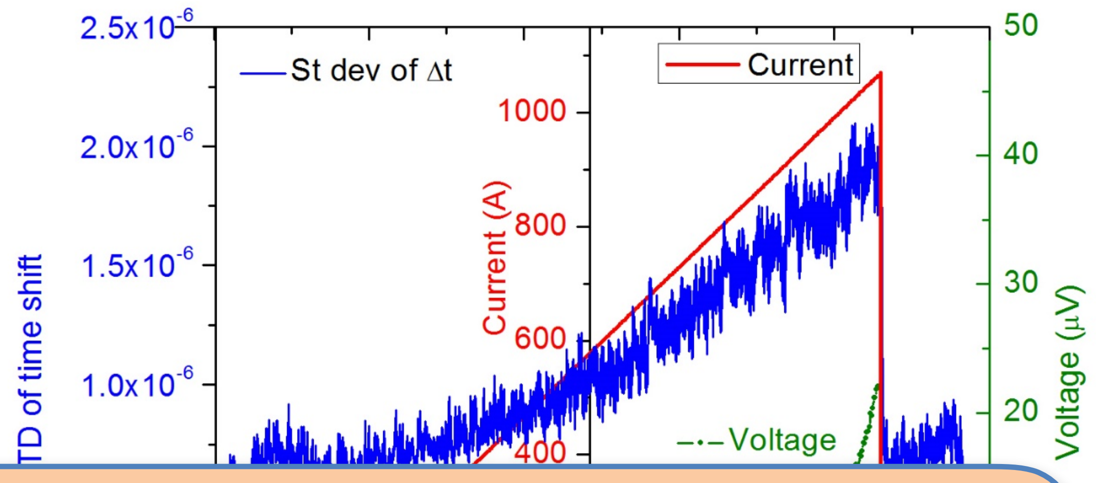




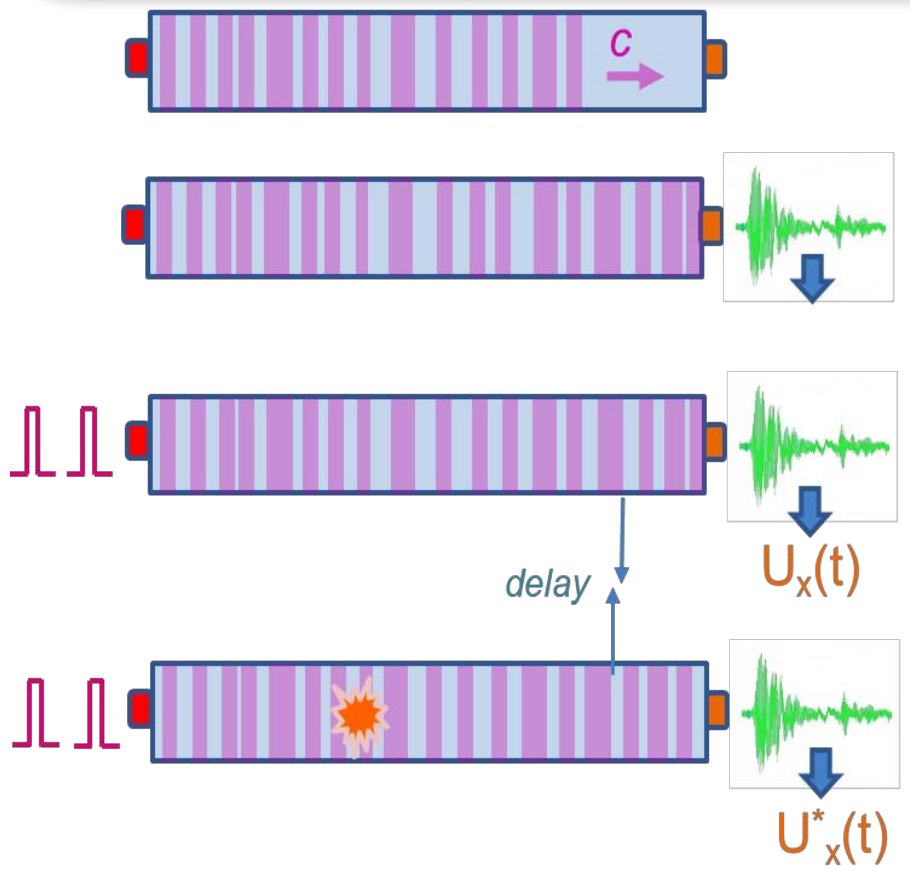
Active acoustics can utilize phase-shift of the complex signal response pattern to identify thermal changes in the system => independent mechanism to see transition

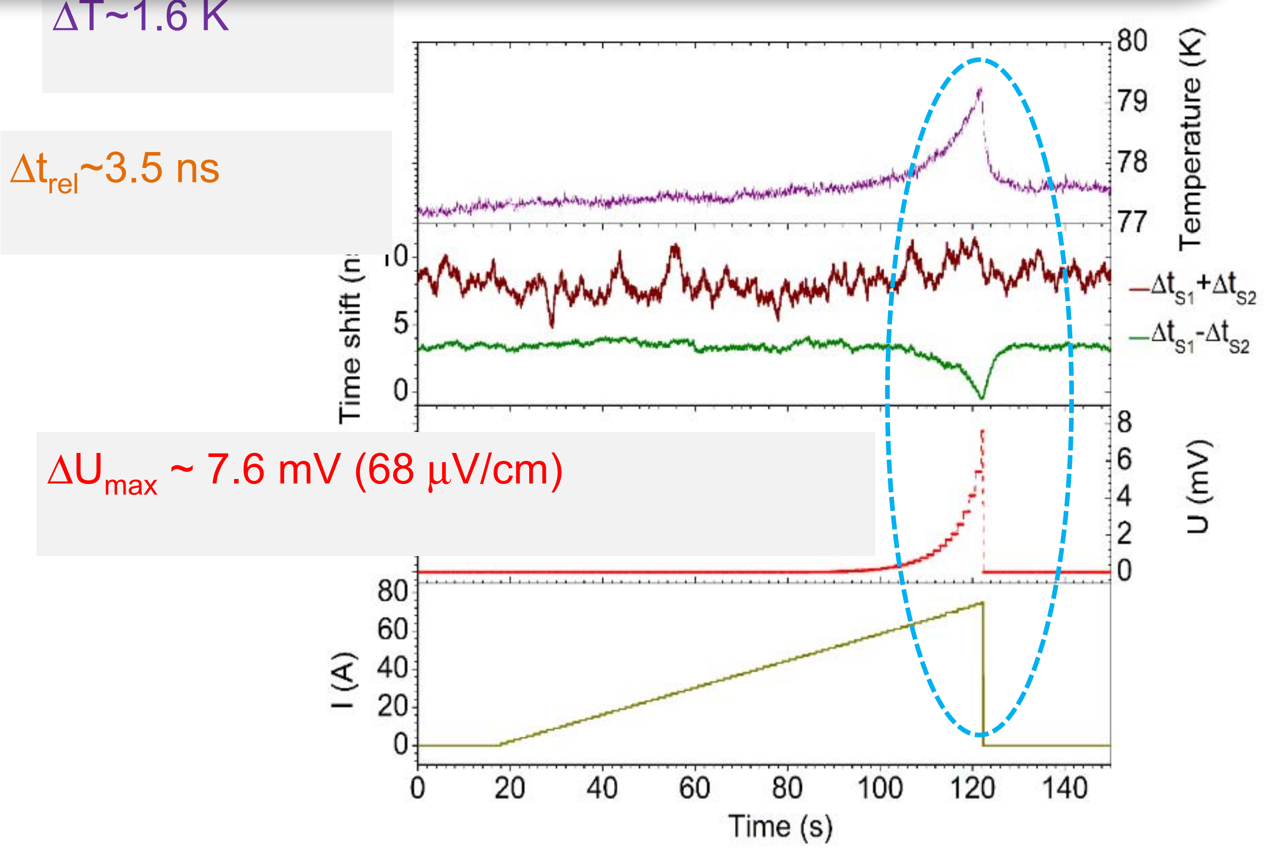
ReBCO tape experiment





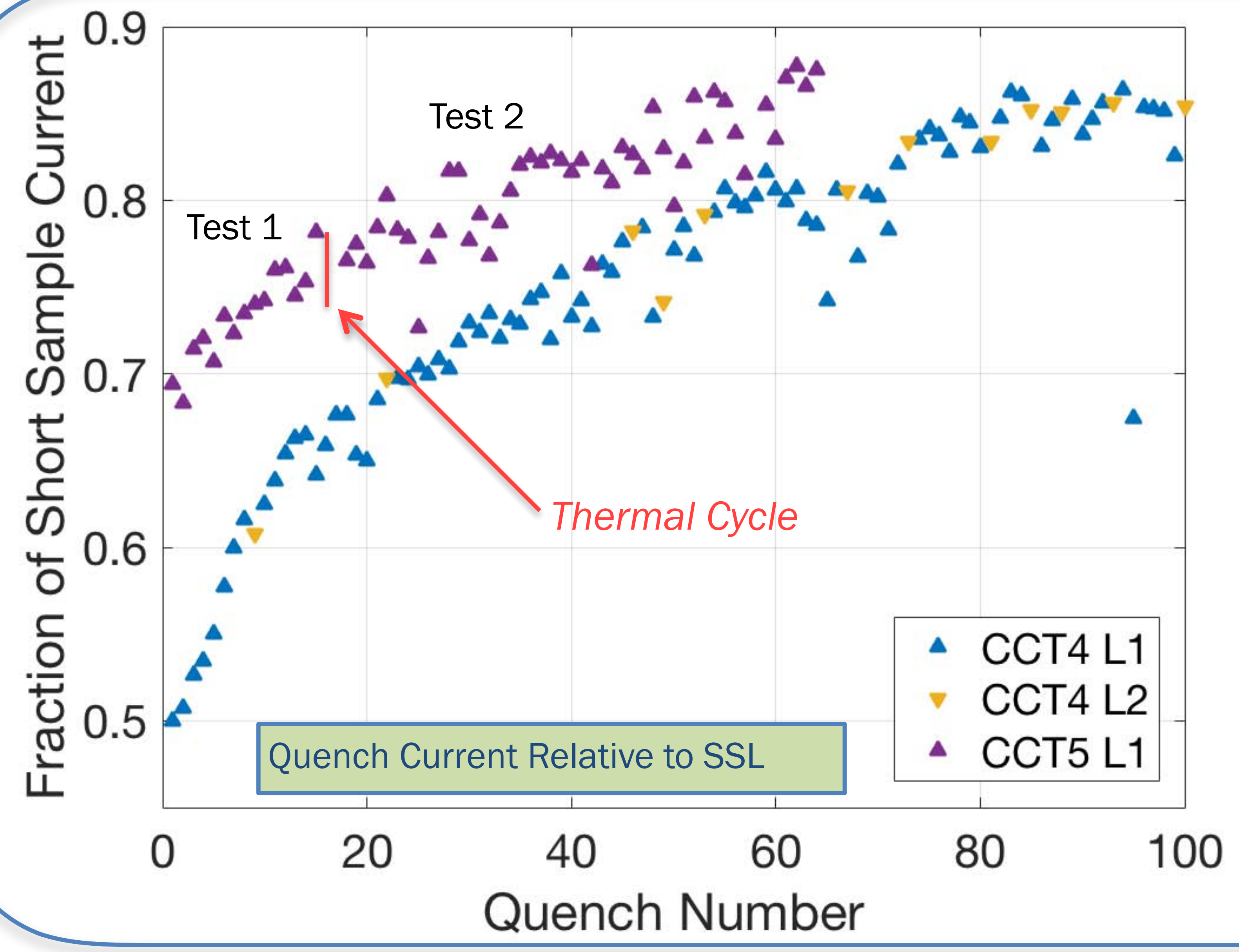
- "**Acoustic thermometry for detecting quenches in superconducting coils and conductor stacks**," M. Marchevsky and S. A. Gourlay, *Appl. Phys. Lett.*, vol. 110, p. 012601, (2017), doi:10.1063/1.4973466
- "**Quench Detection for High-Temperature Superconductor Conductors using Acoustic Thermometry**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

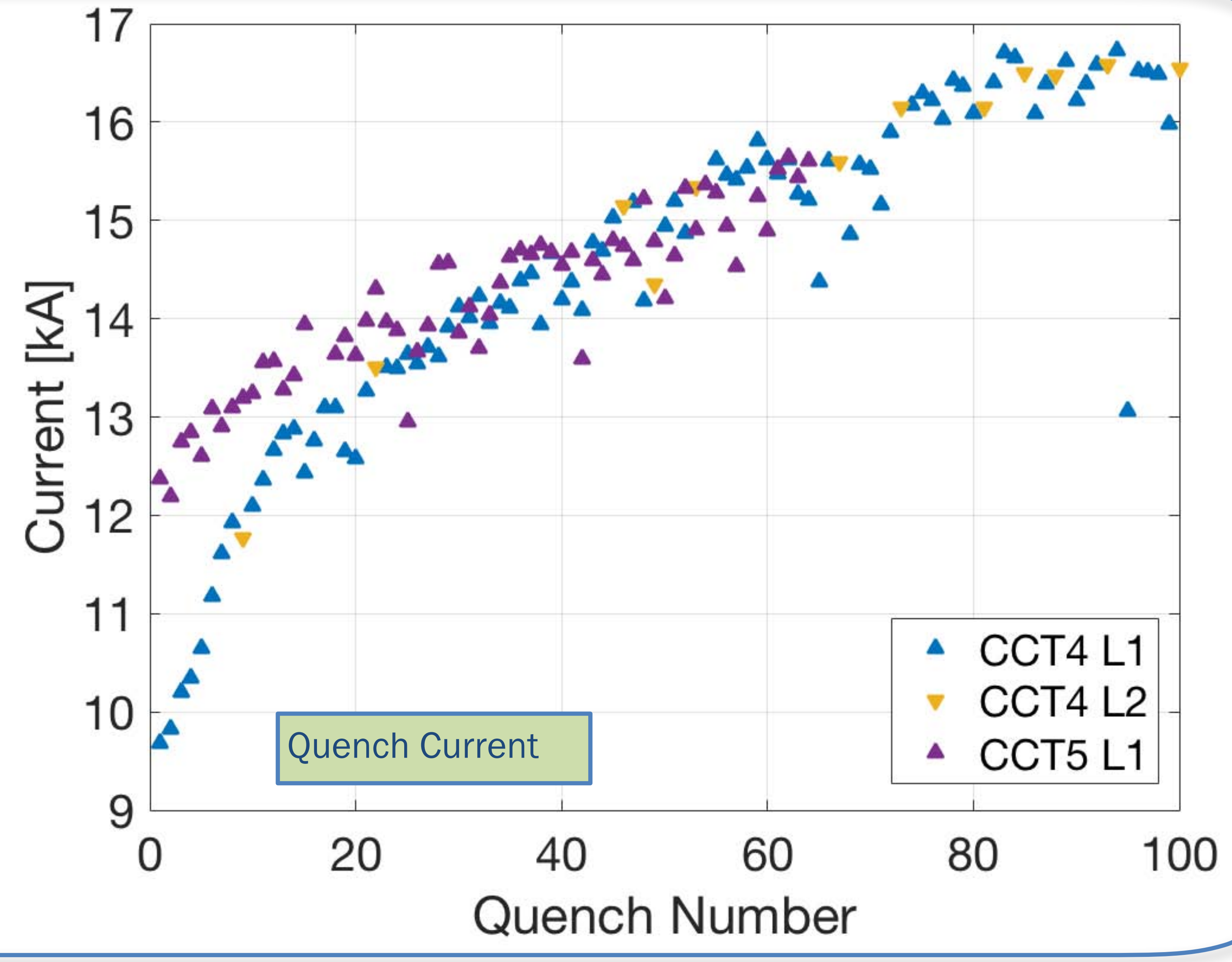




Acoustic signals are very sensitive to magnet component properties

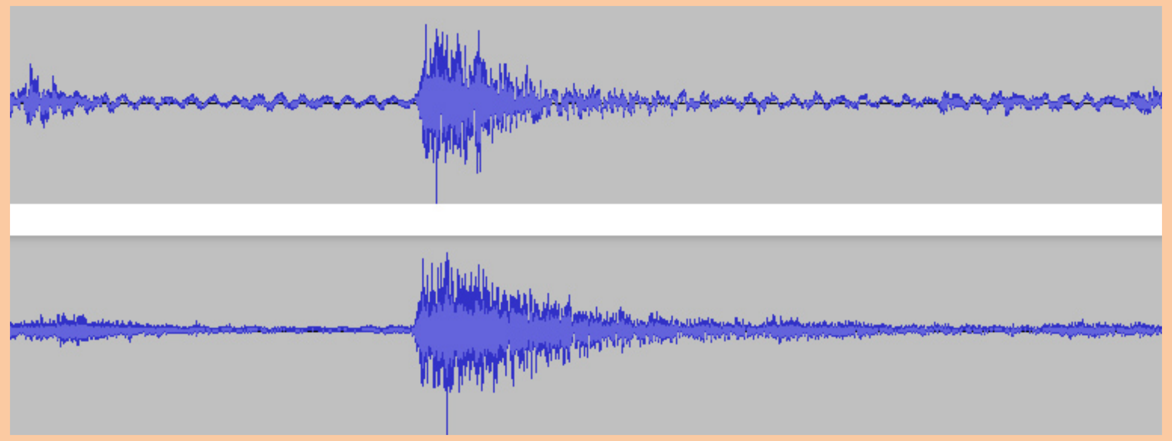
CCT5 Training Behavior





“Mix 61”

“CTD-101”



Acoustic signals were slowed the original 1 MHz rate down to 174600 Hz

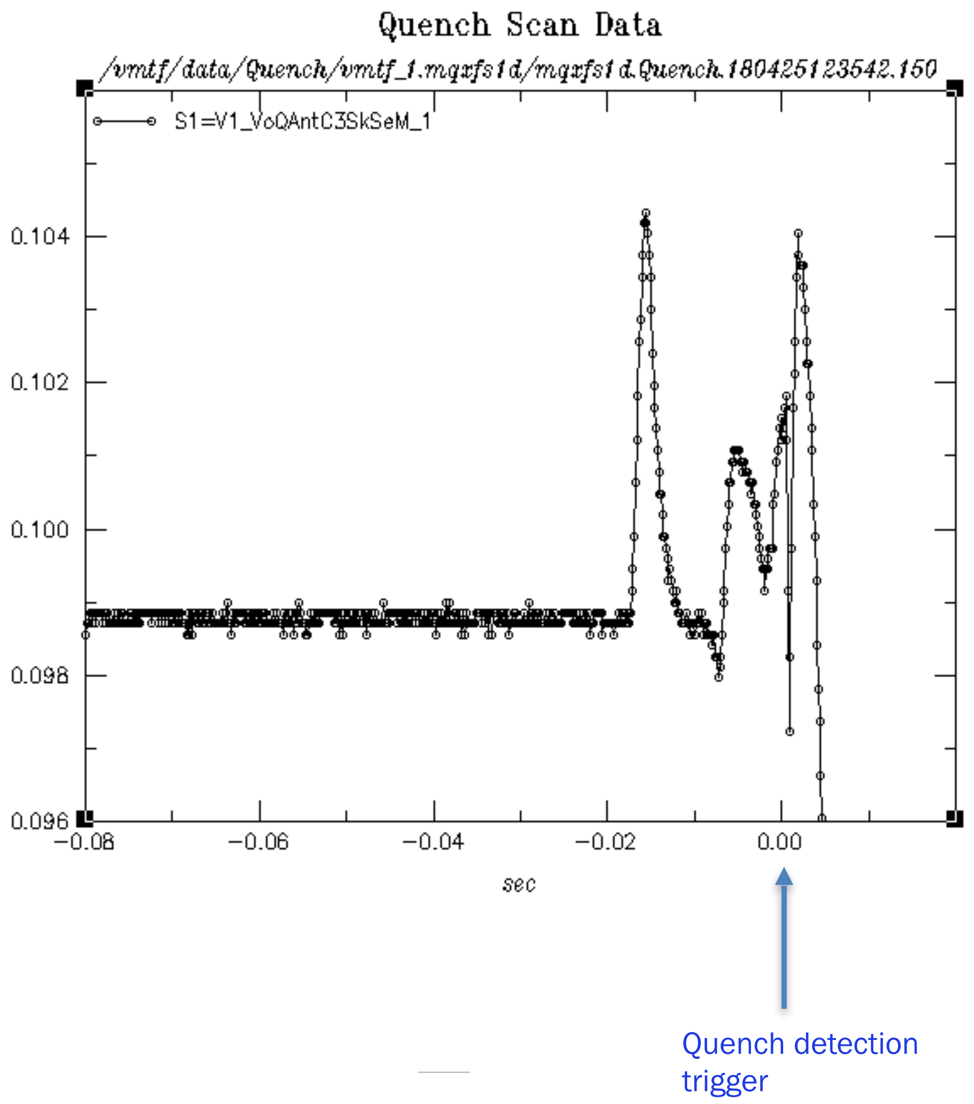
U.S. MAGNET DEVELOPMENT PROGRAM

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

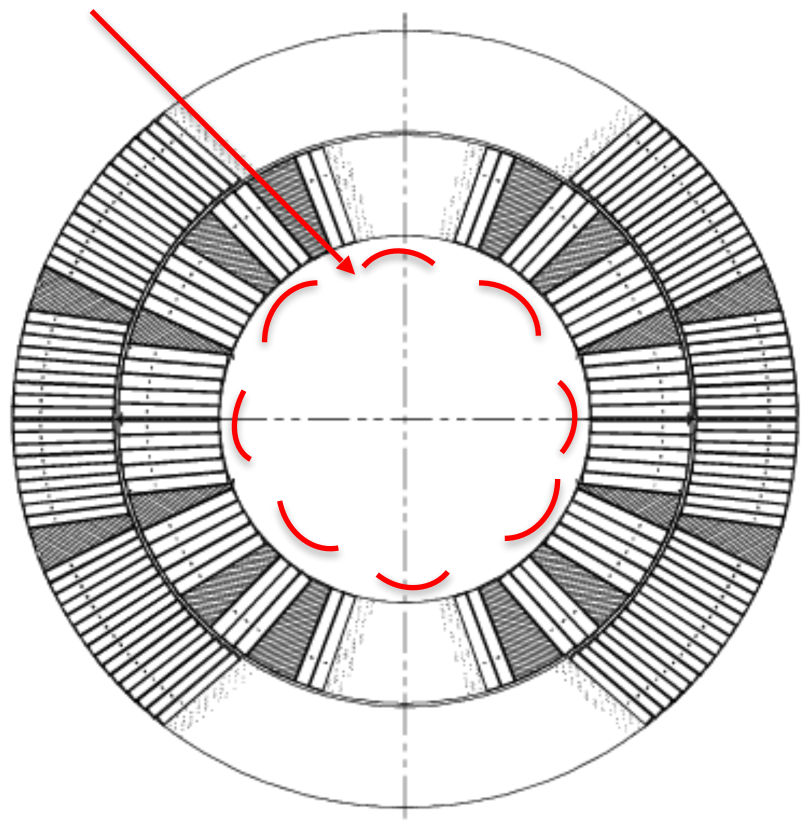
Joe DiMarco, FNAL

- **Flexible circuit quench antennae**
  - **Inductive stationary pickup loops to detect magnetic transients**
  - **Diagnostic for determining quench start location and development => Have worked well for longitudinal localization of quench.**

Pads improved to withstand more heat during soldering

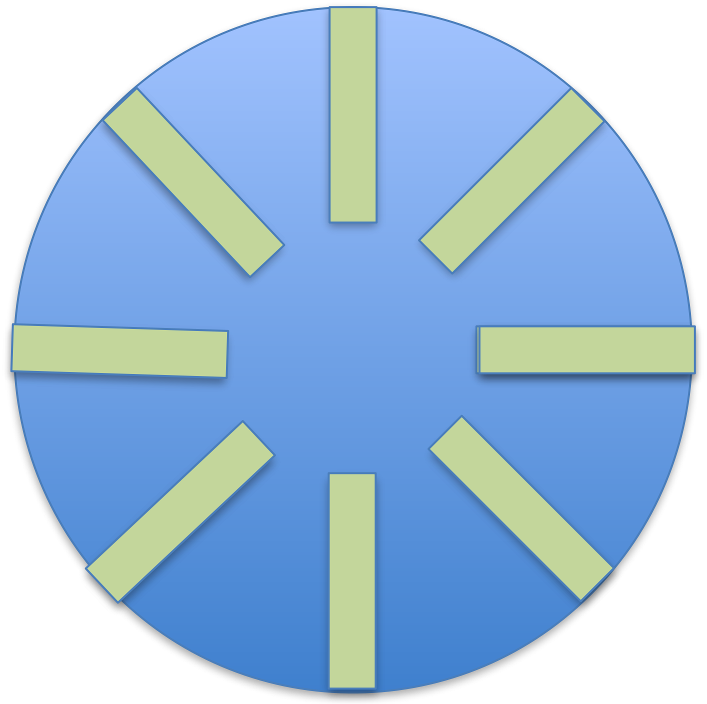


Flex QA panels within aperture (tangential mounting)



* Following idea of T. Ogitsu, et al., "*Quench Antennas for Superconducting Particle Accelerator Magnets*"

Each PCB has radial bucking of dipole and quadrupole at level of 100



- **Simultaneous sampling at 10-100kHz.**
- **Quench event detected as field disturbance in all coils**
- **Longitude quench location found by having multiple sets of MV antennas**
- **Can locate quench in azimuth and radius (though outer layer quenches difficult) by solving for voltage response of set of probes***

Strong potential for applications:

- Can characterize persistent and eddy current behavior, magnetization effects, decay and snap-back at injection, magnetic field transients from mechanics or flux redistribution (spike) events, etc.

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

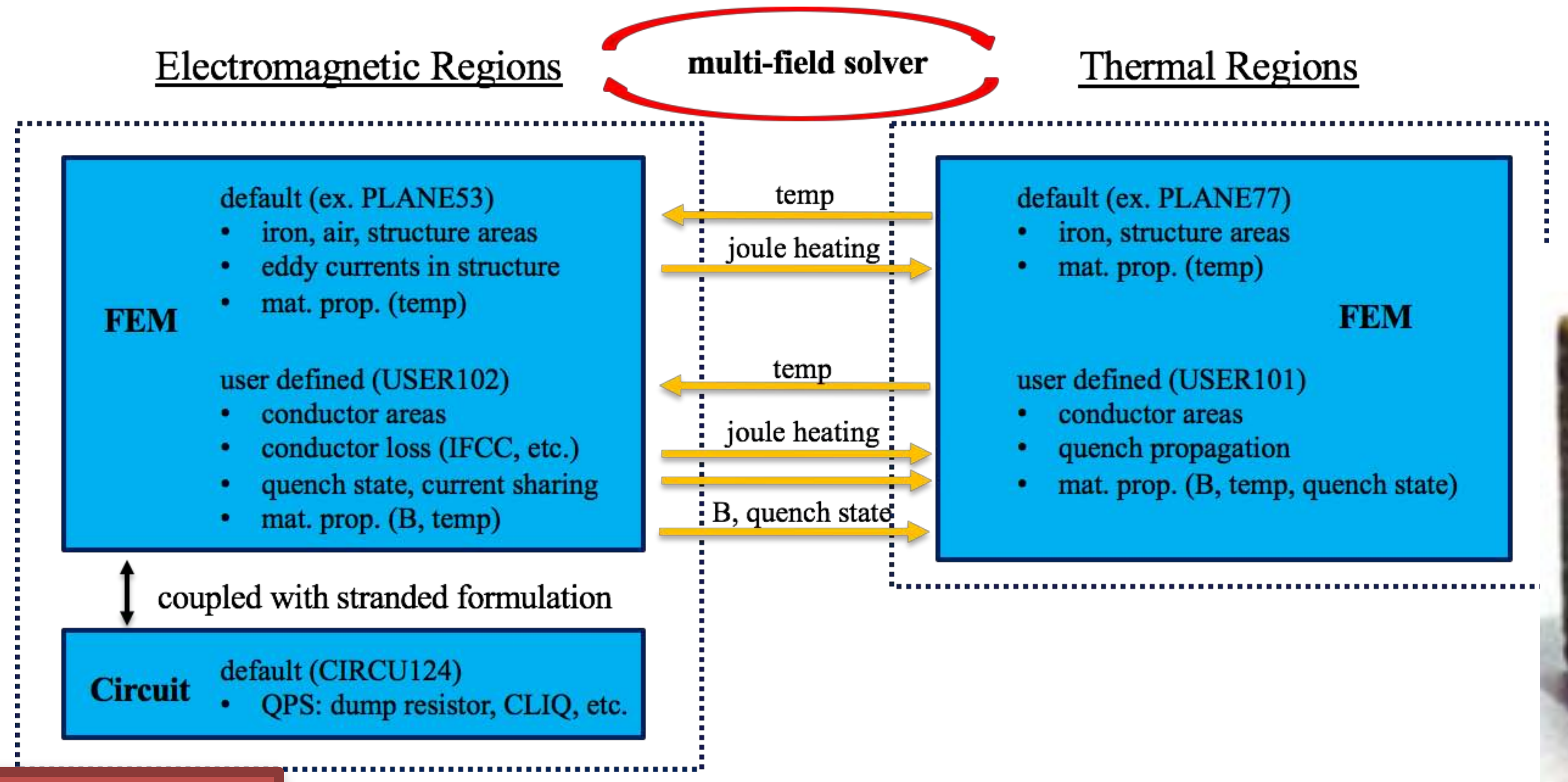
Post processing
Load transfer between models

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

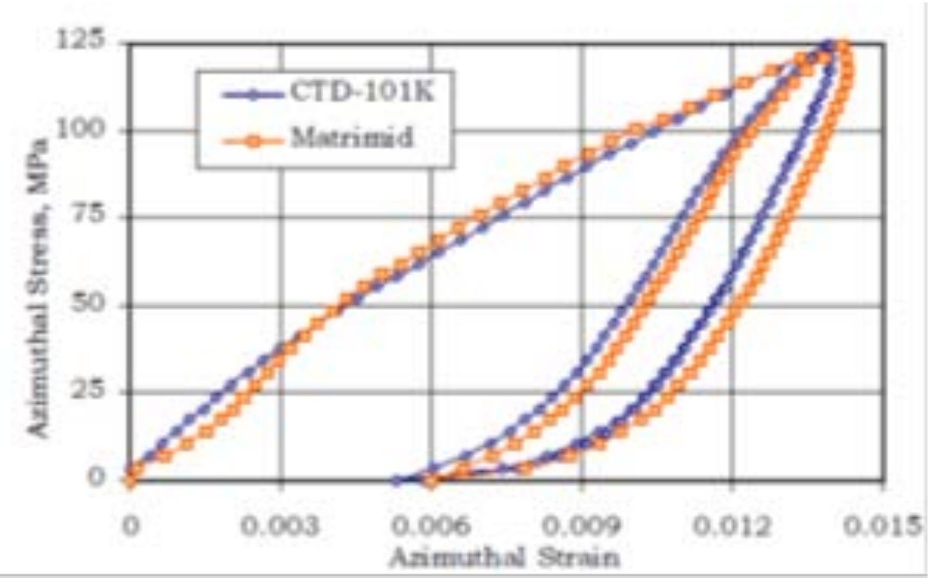
Available
- node location
- loads
- node temperature
- material prop.
- ANSYS functions

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

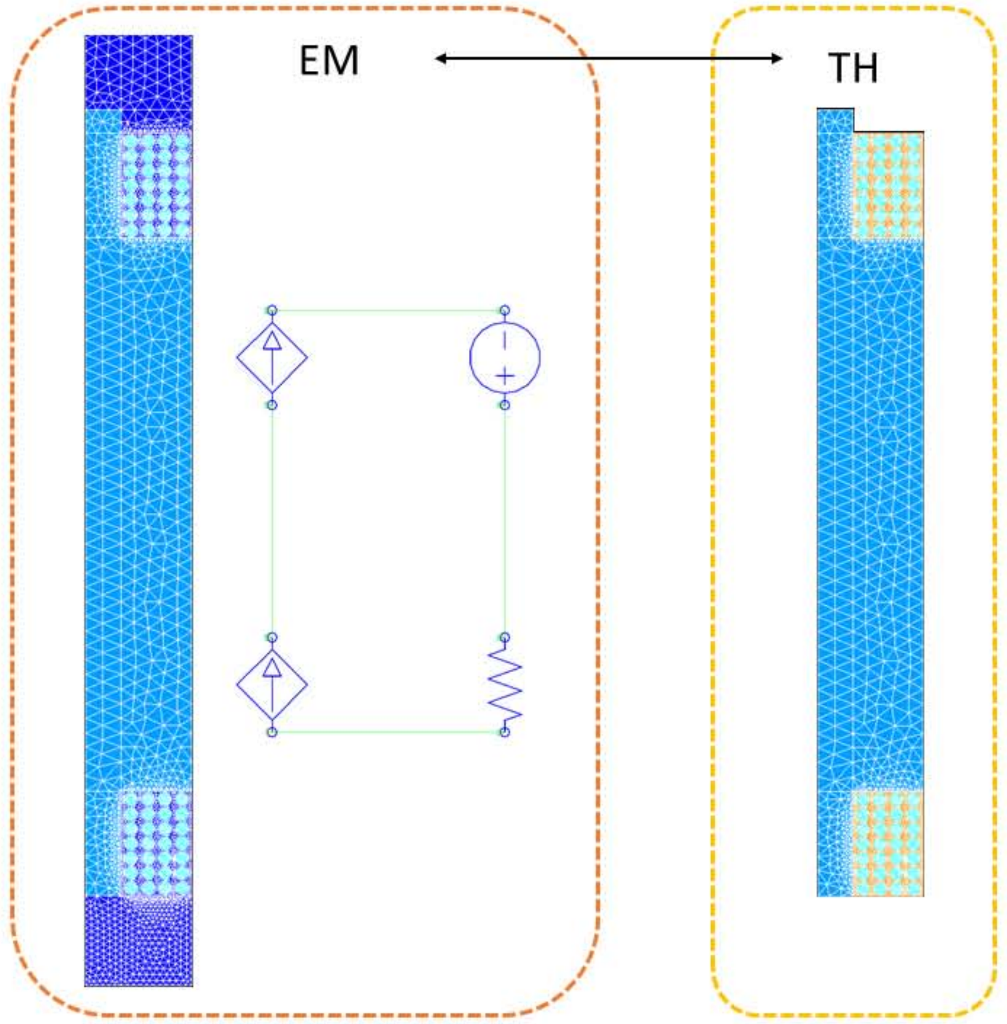
Element matrix generation is now determined by user program
- stiffness, damping, etc.

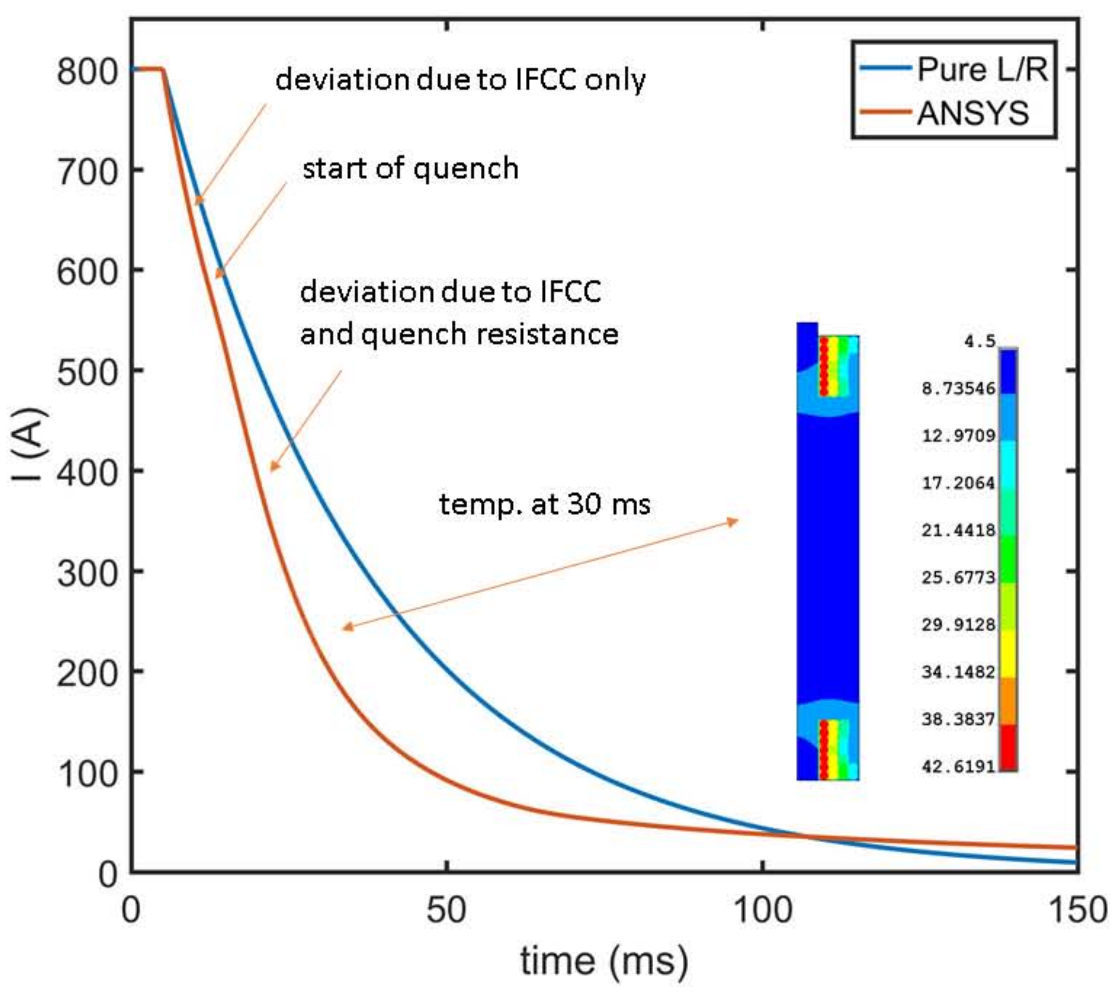


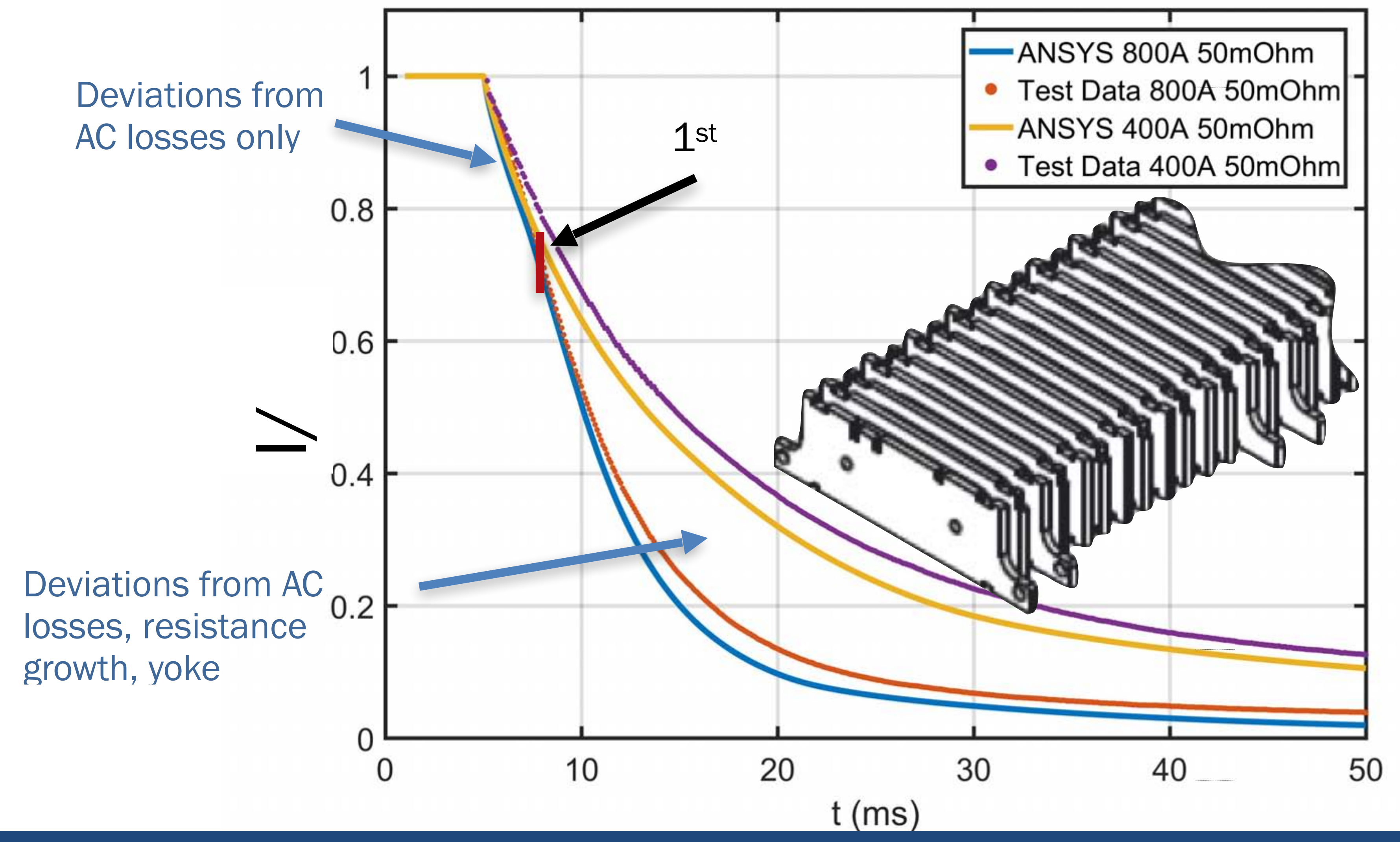
S. Krave, FNAL



Brouwer, LBNL; Auchmann, PSI/CERN







International and industrial collaborations are underway in support of the MDP mission

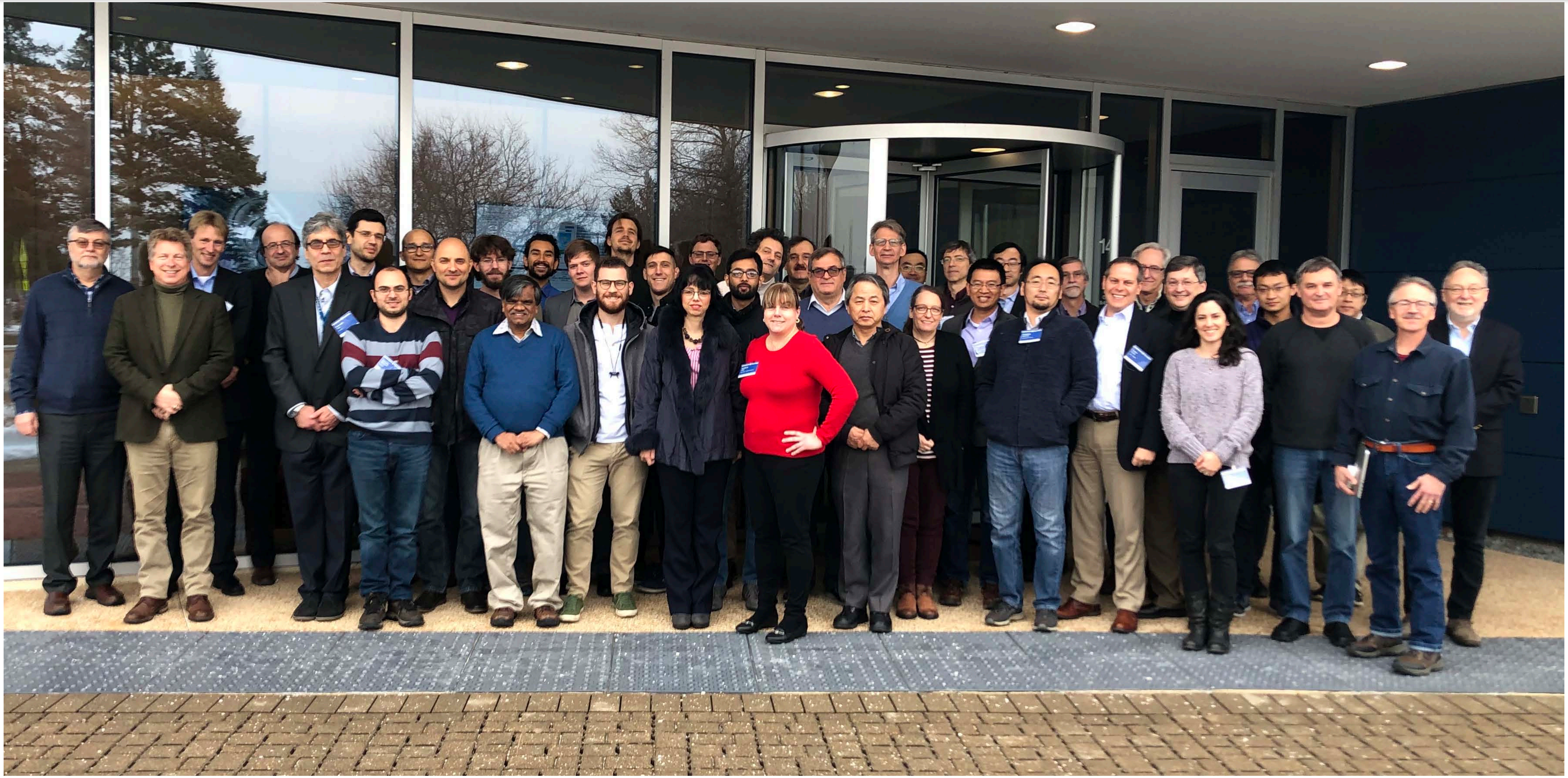
Activity	MDP Relevance	Collaborating Institution	Contact(s)	Contact(s)
International				
Provide coil parts	15T Dipole	EuroCirCol/CERN	Tommasini, D., Shoerling, D.	Zlobin, A.
Mechanical analysis	15T Dipole	CERN/U. Patras		Zlobin, A.
History and Documentation of Nb3Sn Magnet R&D	MDP Nb3Sn Program	EuroCirCol	Schoerling, D.	Zlobin, A.
CCT Development	Nb3Sn CCT	PSI	Auchmann, B.	Brouwer, L.
CCT Instrumentation	Nb3Sn CCT	PSI	Auchmann, B., Montenero, G.	Marchevsky, M.
Acoustic Sensor Development	Technology Development	Danish Technological Institute	Zangenberg, N.	Marchevsky, M.
Acoustic Sensor Development	Technology Development	CERN	Willering, G.	Marchevsky, M.
Acoustic Sensor Development	Technology Development	CERN	Kirby, G.	Marchevsky, M.

Next steps: focus on quantitative developments that provide lasting benefit to the community to enable high-field magnets

- Real progress in accelerator magnet performance will require improved understanding and control of the many (very many!) design choices, fabrication processes, and operational parameters that go into accelerator magnets
  - The priorities are somewhat different for HTS and for Nb_3Sn due to maturity of material as well as material characteristics
    - Nb_3Sn: understand and control magnet training and conductor strain,...
    - HTS: develop magnet fabrication processes, develop protection paradigms, understand and control conductor strain and degradation,...
  - Advance the “toolbox” of magnet materials and processes
    - Epoxies, structural materials, interfaces, surface prep. (e.g. eliminate Carbon residue),...
    - Simplified structures, process reproducibility, reduce parameter sensitivity,...
  - Advance the “toolbox” of diagnostics that provide feedback from conductor and magnet performance to magnet design

U.S. MAGNET DEVELOPMENT PROGRAM

The US MDP Team at last week's Collaboration Meeting



Summary

- High field magnet technology is actively progressing in the US
  - The US is playing a critical role in the interaction region quadrupoles for the LHC upgrade project
  - High field magnets are central technical elements, and the primary cost-driver, of a future collider

- DOE-OHEP initiated a national program - US MDP - to maintain leadership in high-field accelerator magnet research
  - Leverages strengths of longstanding programs at the National Laboratories and Universities

- We are balancing our efforts to maintain progress on multiple fronts
  - Significant progress on Nb_3Sn magnets
  - HTS magnet development - on both Bi2212 and REBCO fronts
  - Critical technology developments that guide magnets… and are of value to the broader community
  - We have developed a coherent conductor R&D roadmap to continue advancing performance

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