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U.S. MAGNET
DEVELOPMENT
PROGRAM

Superconducting Magnet Development for Next-Generation Accelerator Capabilities

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For the US MDP Team

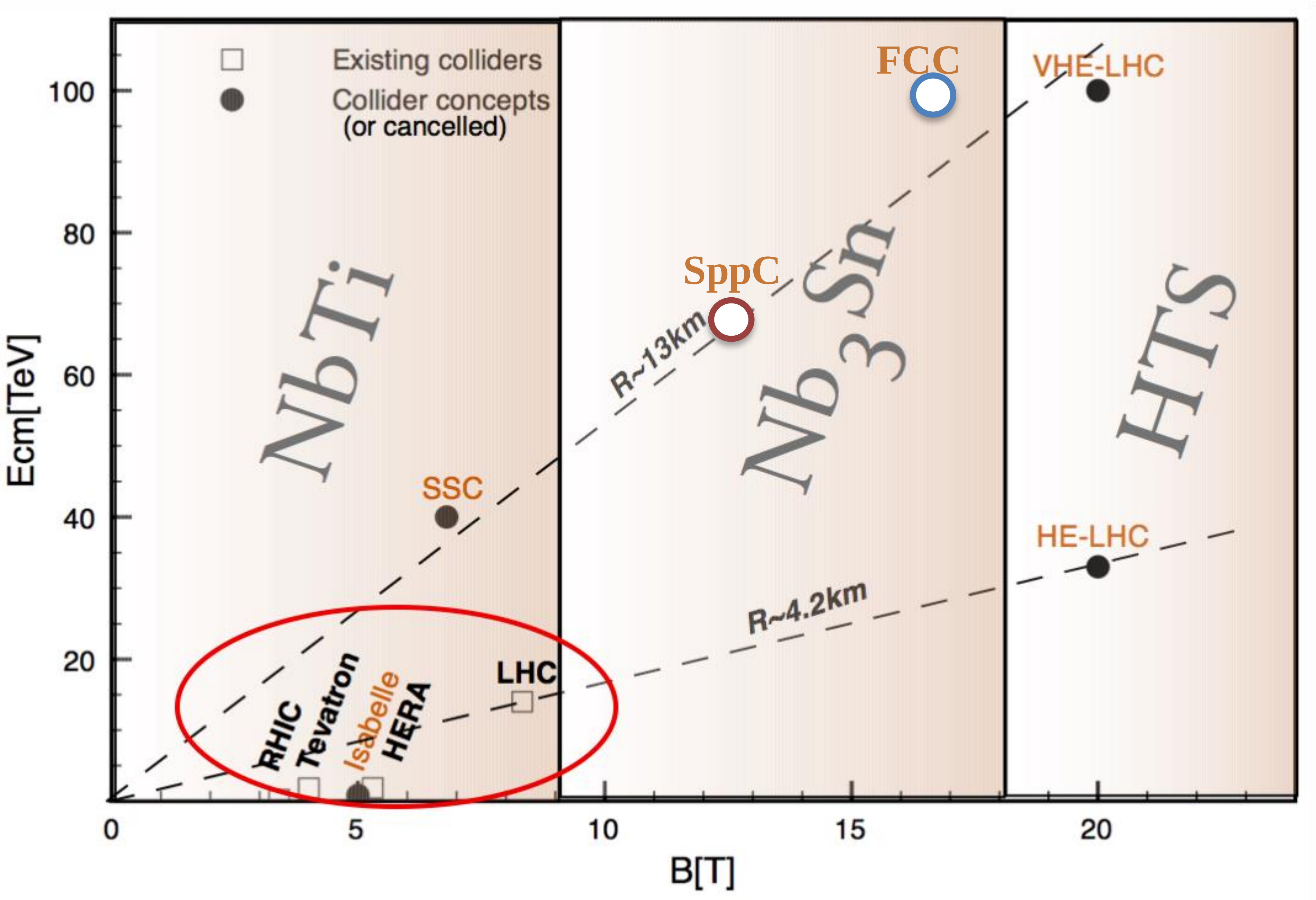
**Note: The data shown in these slides
are the result of work from Scientists and Engineers in the US MDP**

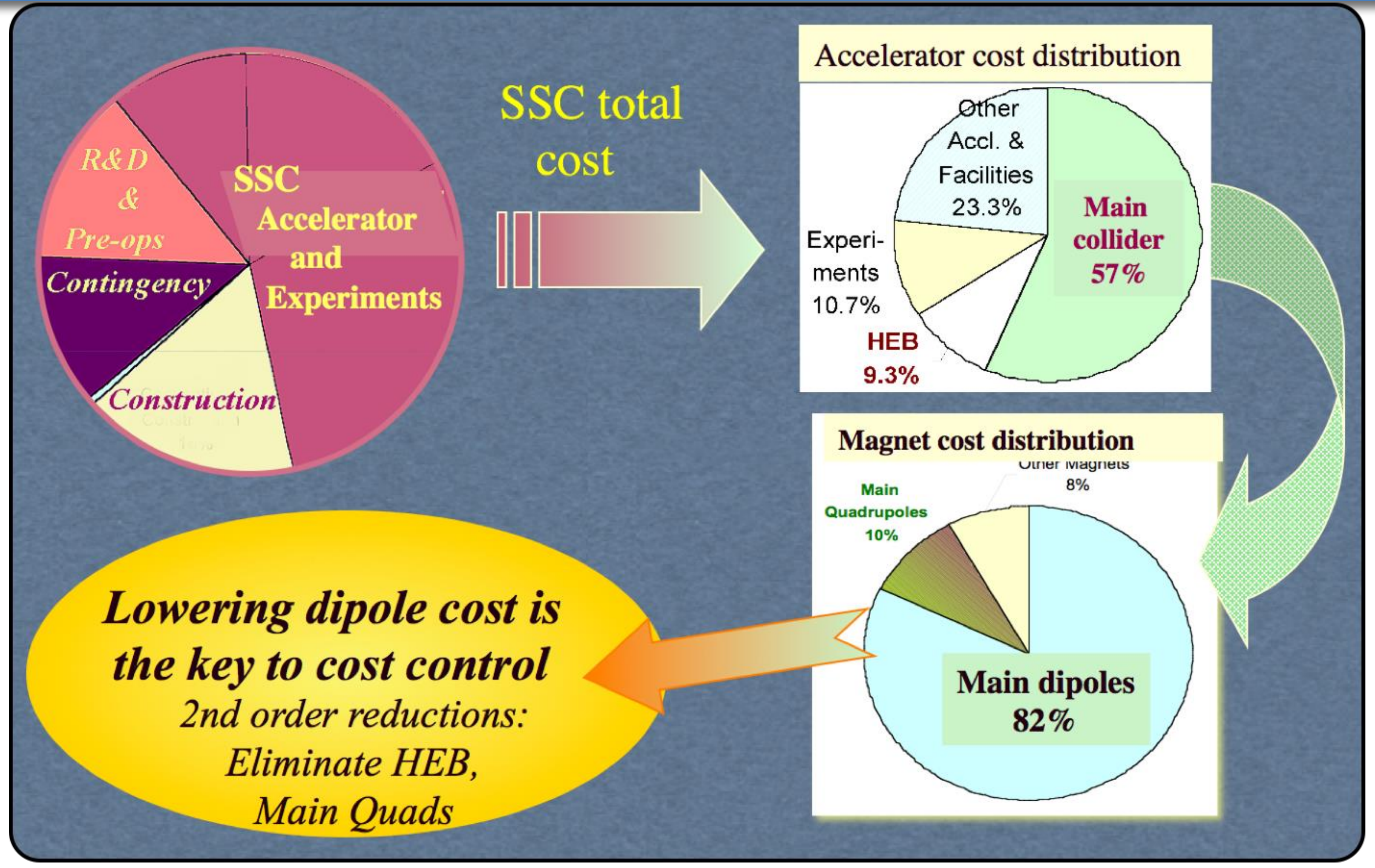
U.S. MAGNET DEVELOPMENT PROGRAM

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
- Next steps
- Summary

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





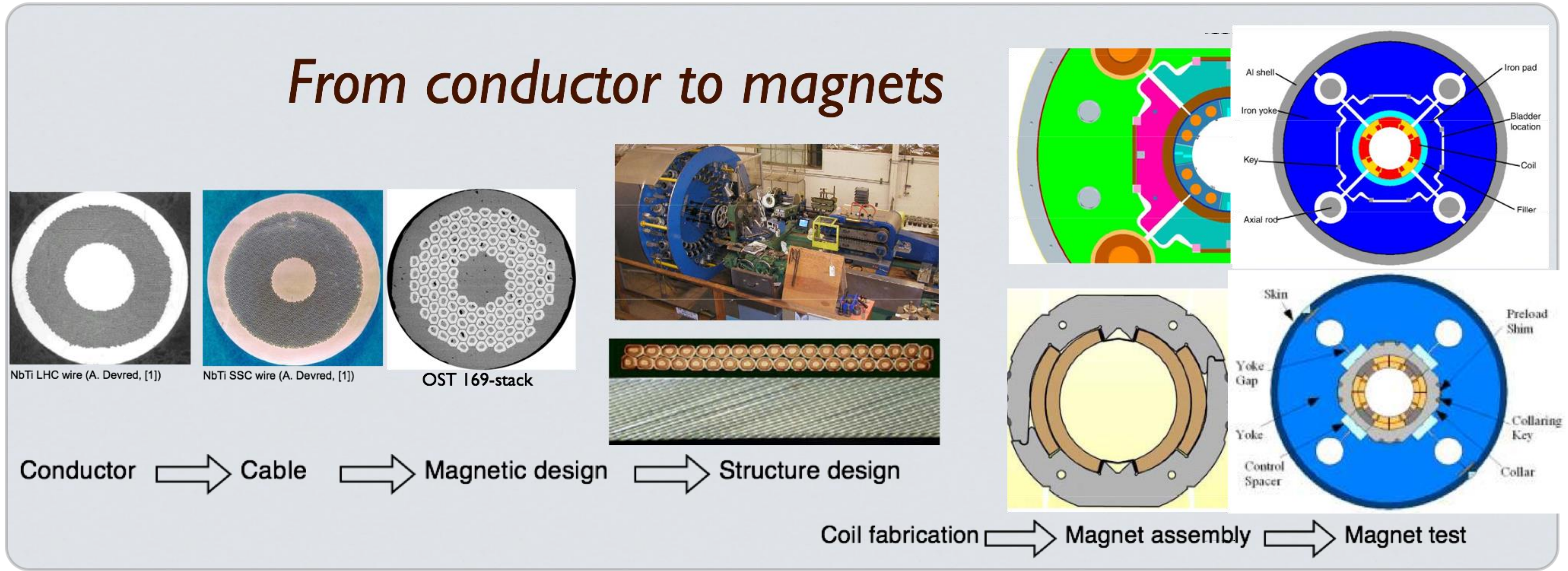
Lowering dipole cost is the key to cost control
2nd order reductions:
Eliminate HEB,
Main Quads

Barletta

CERN cost estimates*:
$\$_{magnets}/\$_{tot}$

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

*L. Rossi, "TOE" talk



From conductor to magnets

Conductor ⇒ Cable ⇒ Magnetic design ⇒ Structure design

Coil fabrication ⇒ Magnet assembly ⇒ Magnet test

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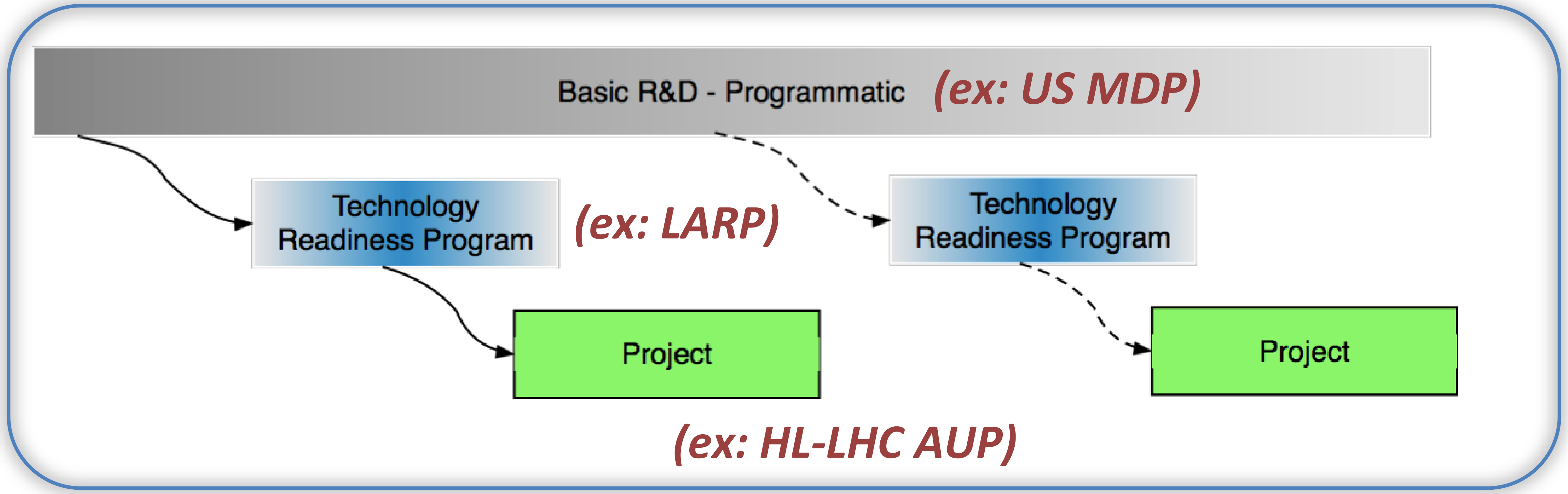
Nb_3Sn accelerator magnet technology is finally being installed in a collider - in the interaction region quadrupoles of the LH-LHC



Basic R&D - Programmatic *(ex: US MDP)*

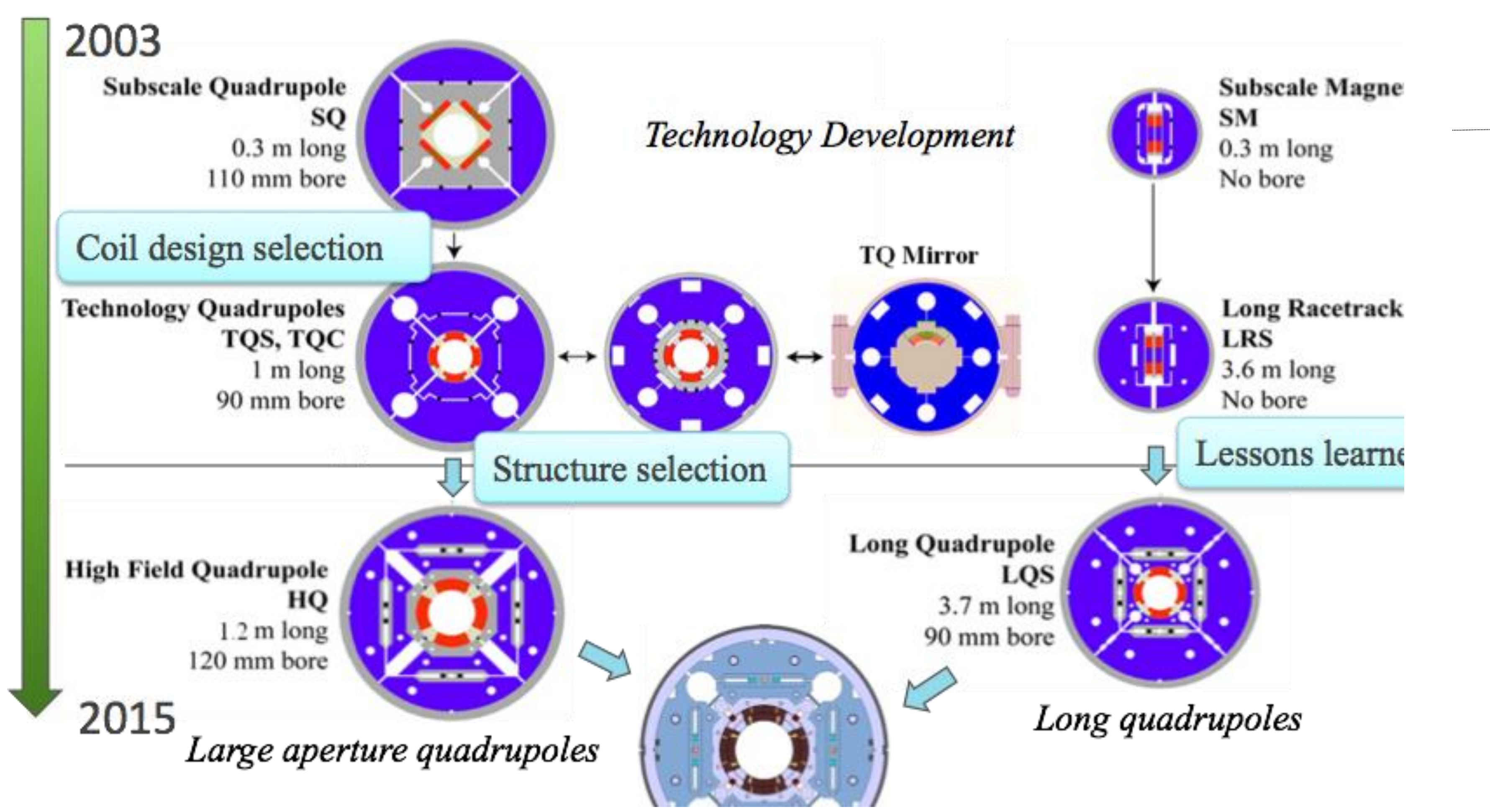
Technology Readiness Program *(ex: LARP)*

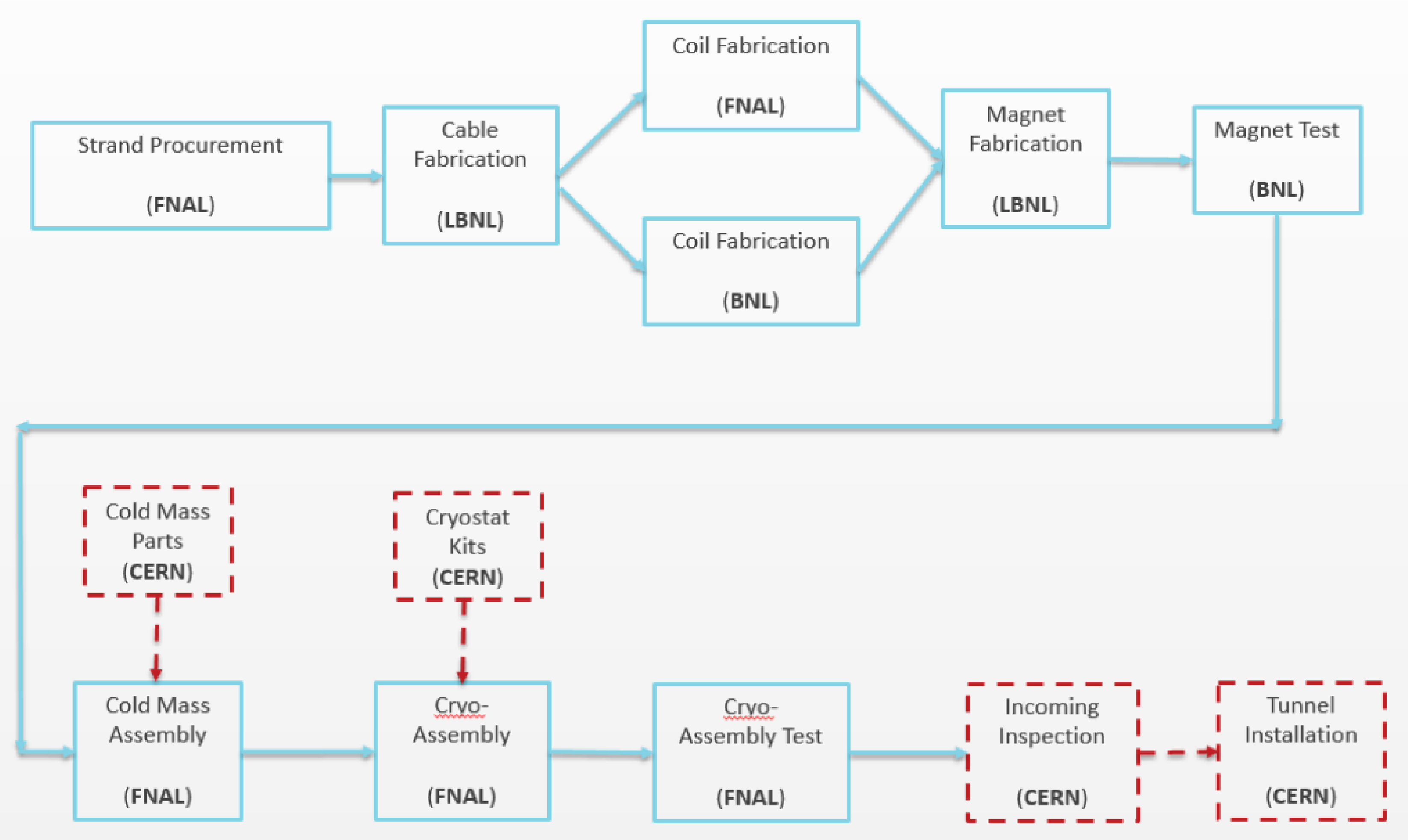
Technology Readiness Program

Project

Project

(ex: HL-LHC AUP)





Strand Procurement (FNAL)

Cable Fabrication (LBNL)

Coil Fabrication (FNAL)

Coil Fabrication (BNL)

Magnet Fabrication (LBNL)

Magnet Test (BNL)

Cold Mass Parts (CERN)

Cryostat Kits (CERN)

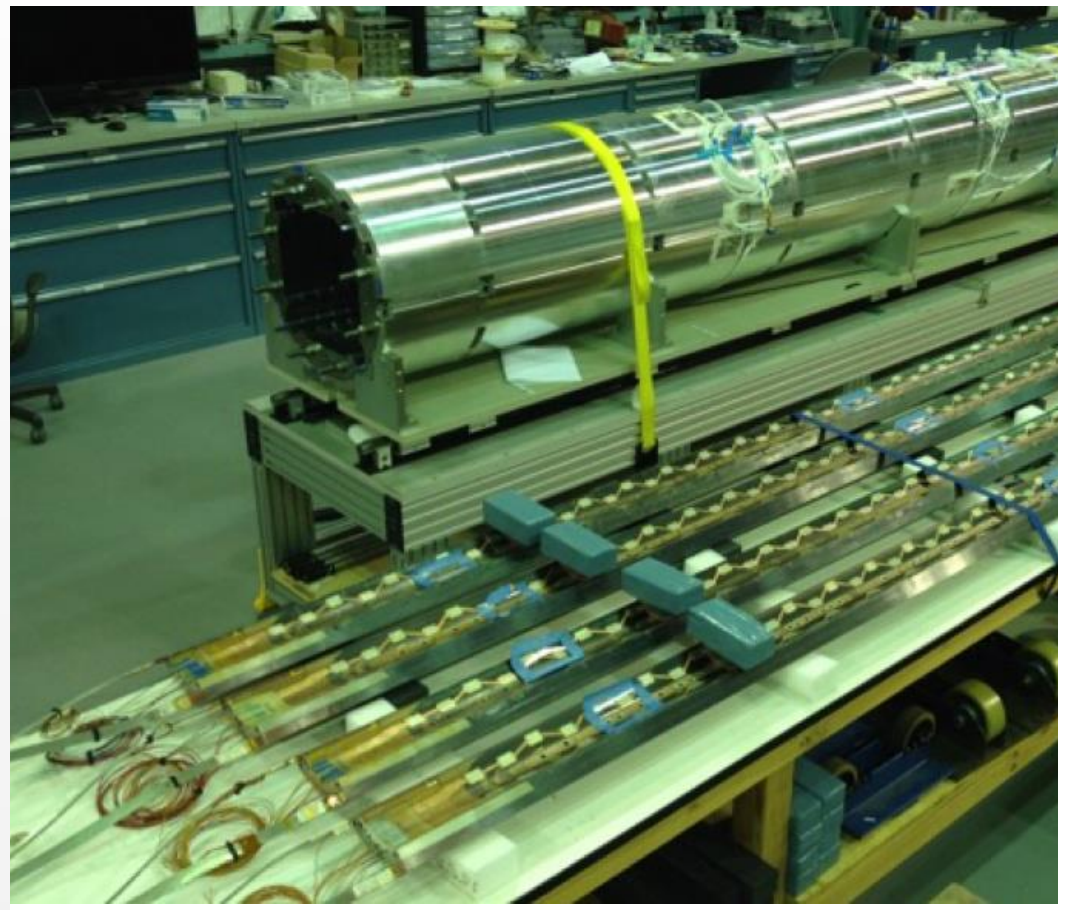
Cold Mass Assembly (FNAL)

Cryo-Assembly (FNAL)

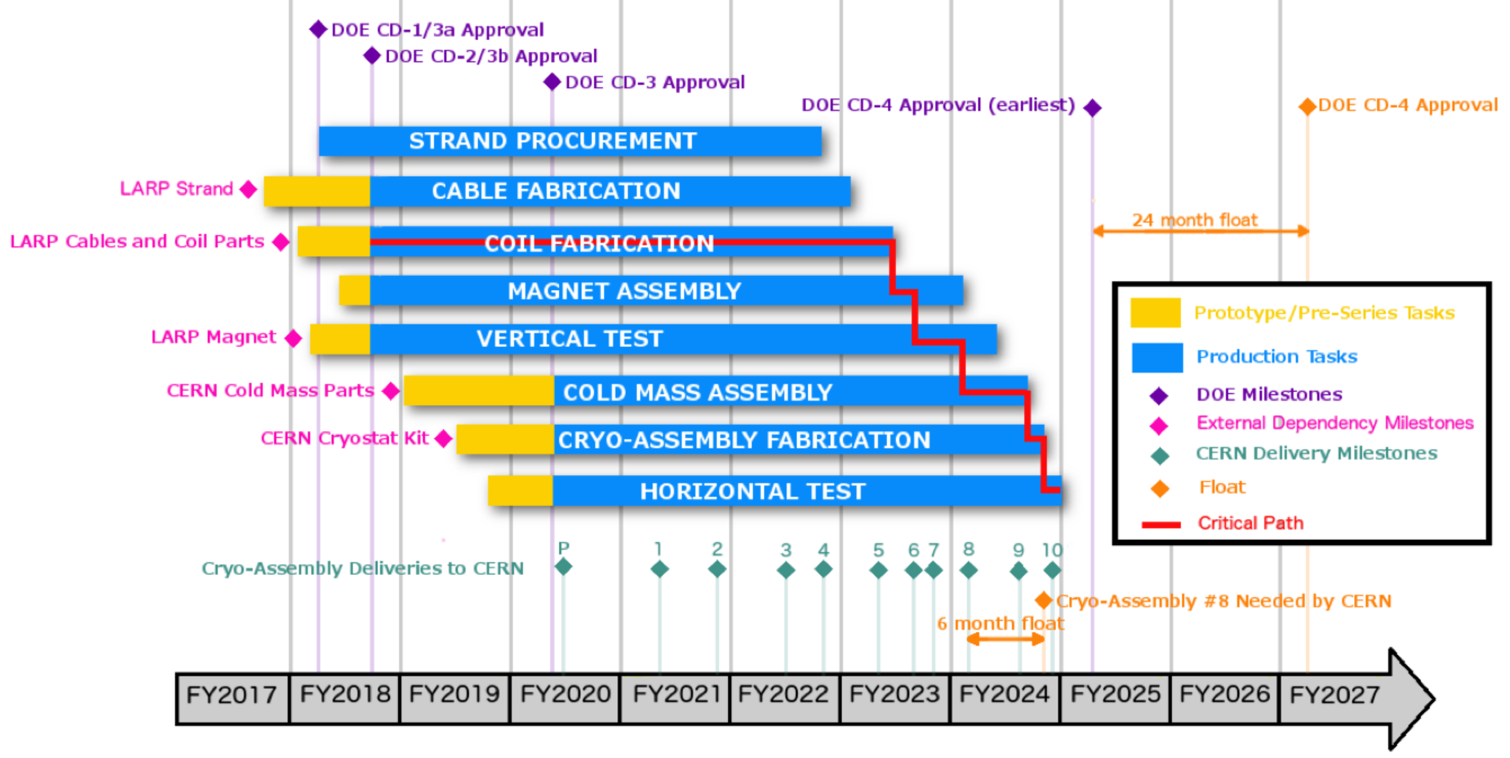
Cryo-Assembly Test (FNAL)

Incoming Inspection (CERN)

Tunnel Installation (CERN)



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



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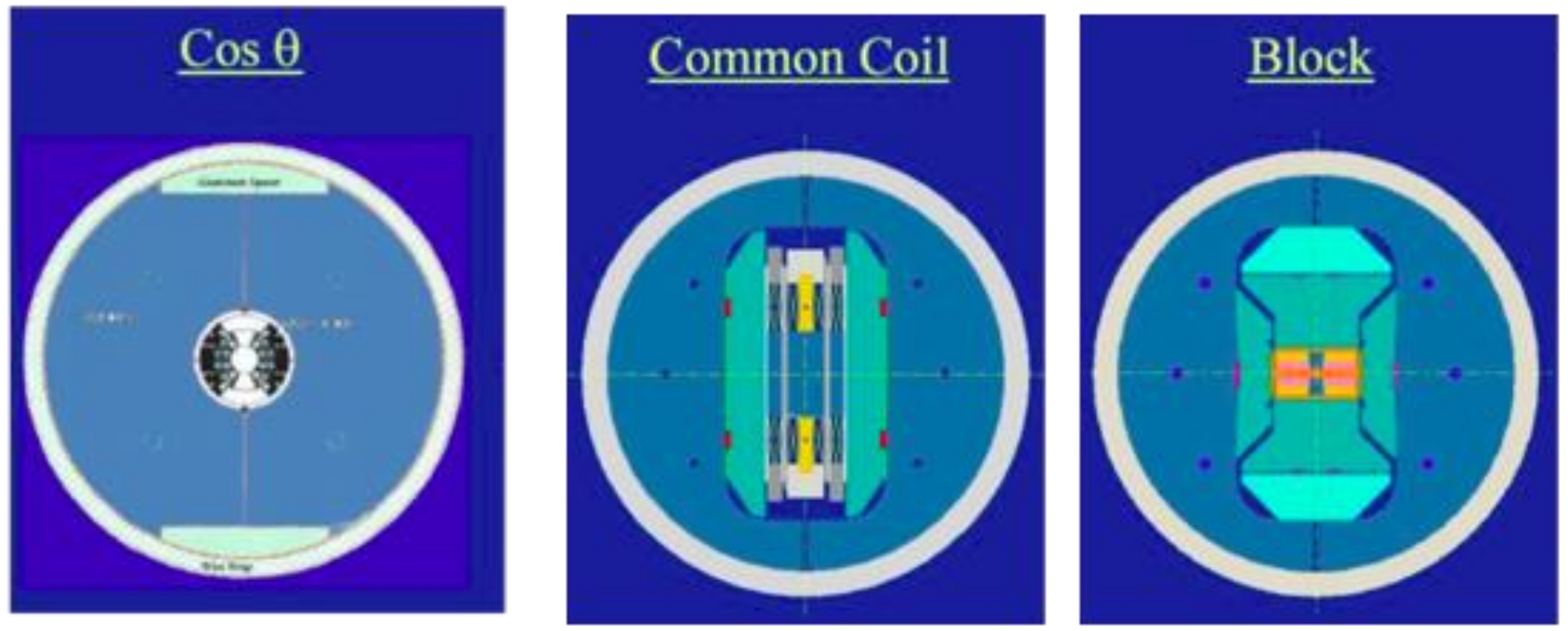
The “magnet zoo” in colliders are all based on Cos(t) designs, whereas accelerator R&D magnets explore other options

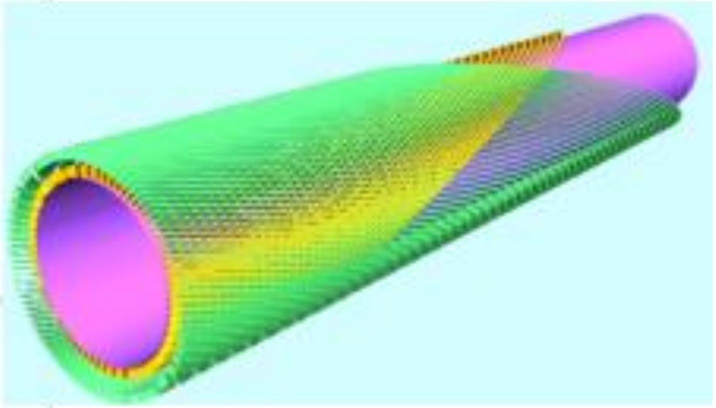
- R&D magnet designs explore layouts that attempt to address issues associated with conductor strain (to avoid degradation) and reduction of conductor/coil motion (to minimize training)

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

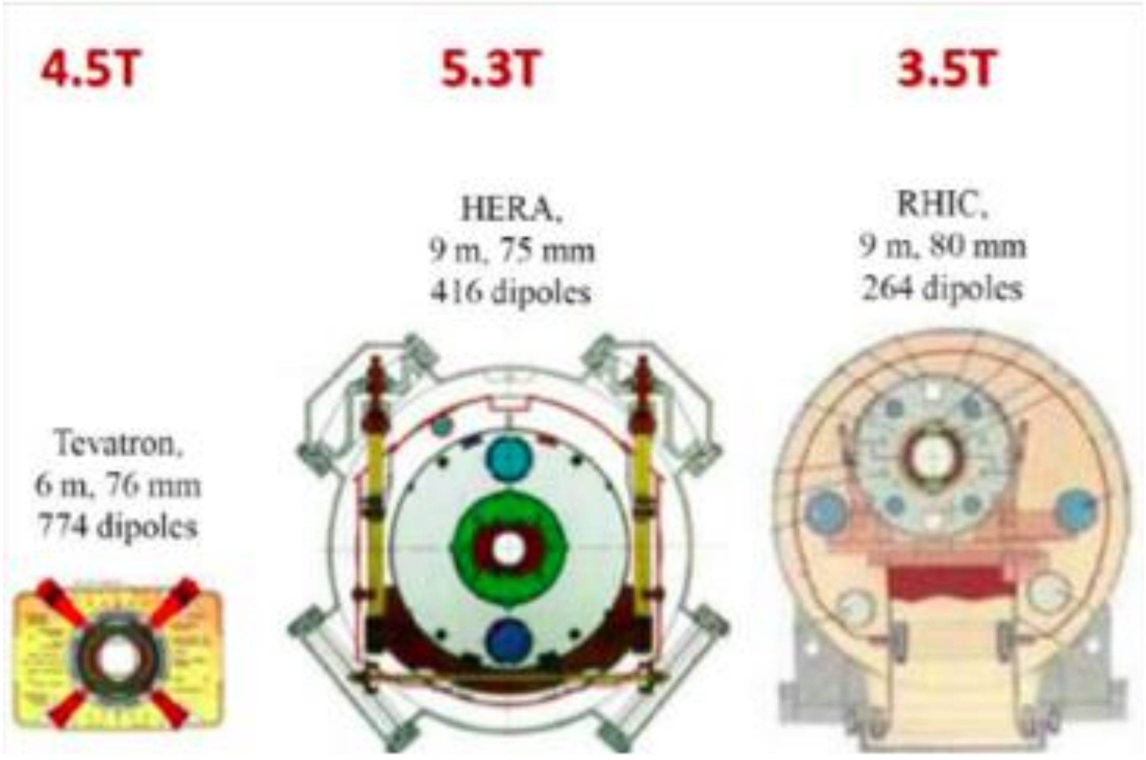


LBNL/BNL

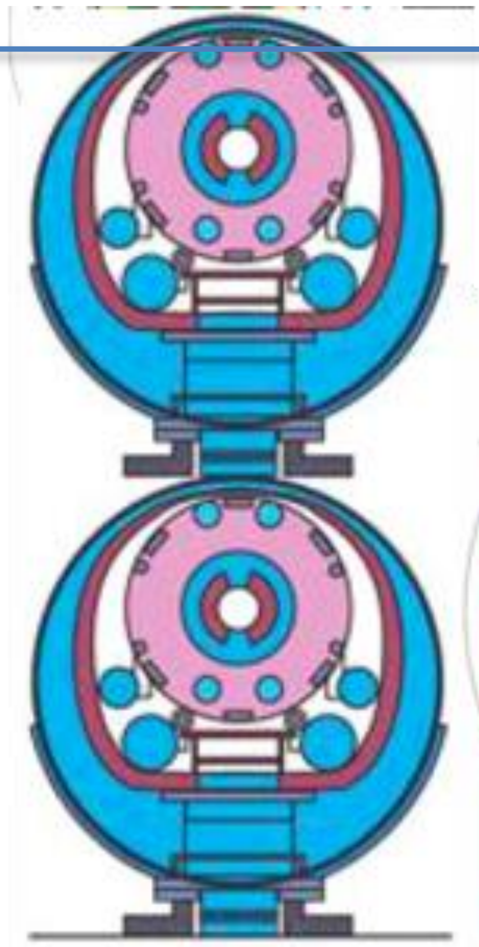
TAMU



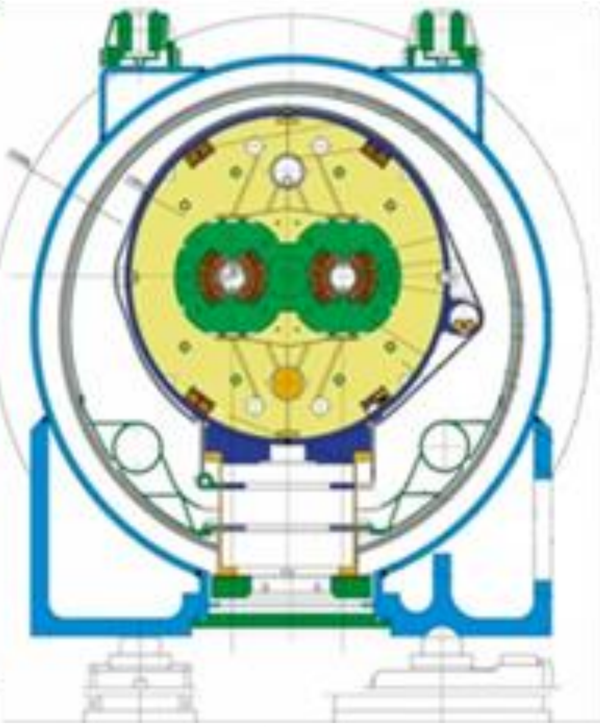
CCT



Shiltsev/Zlobin, (FNAL)

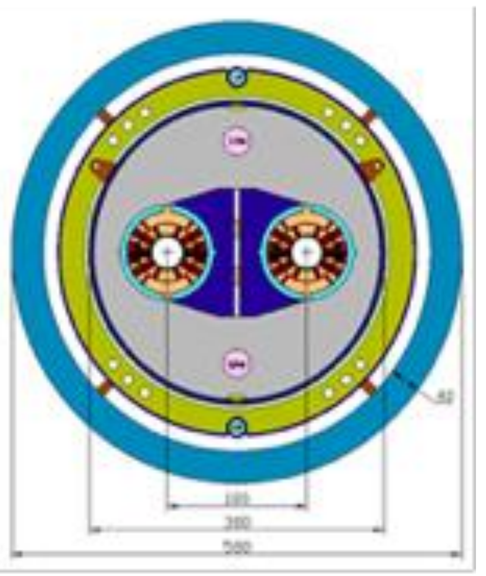


SSC, 50mm
6.6T, 4.3K



LHC, 56mm
8.3T, 1.9K

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



VLHC, 43mm
10T, 4.5K

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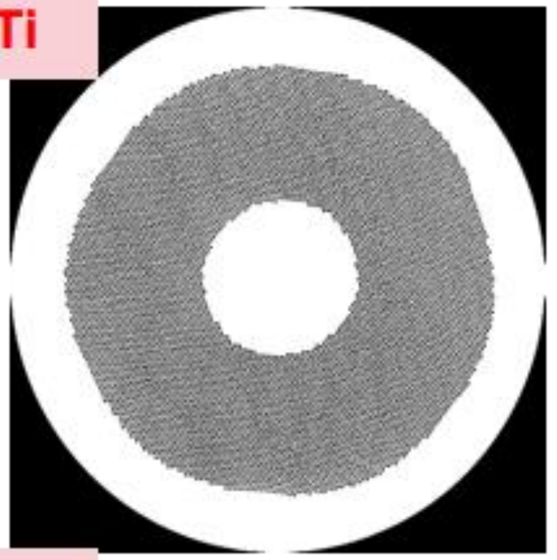
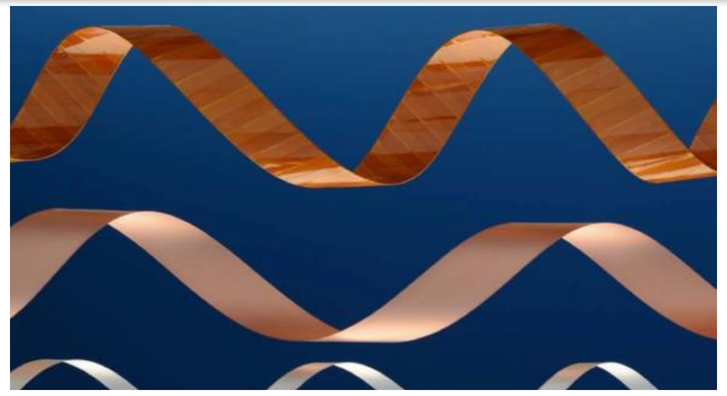
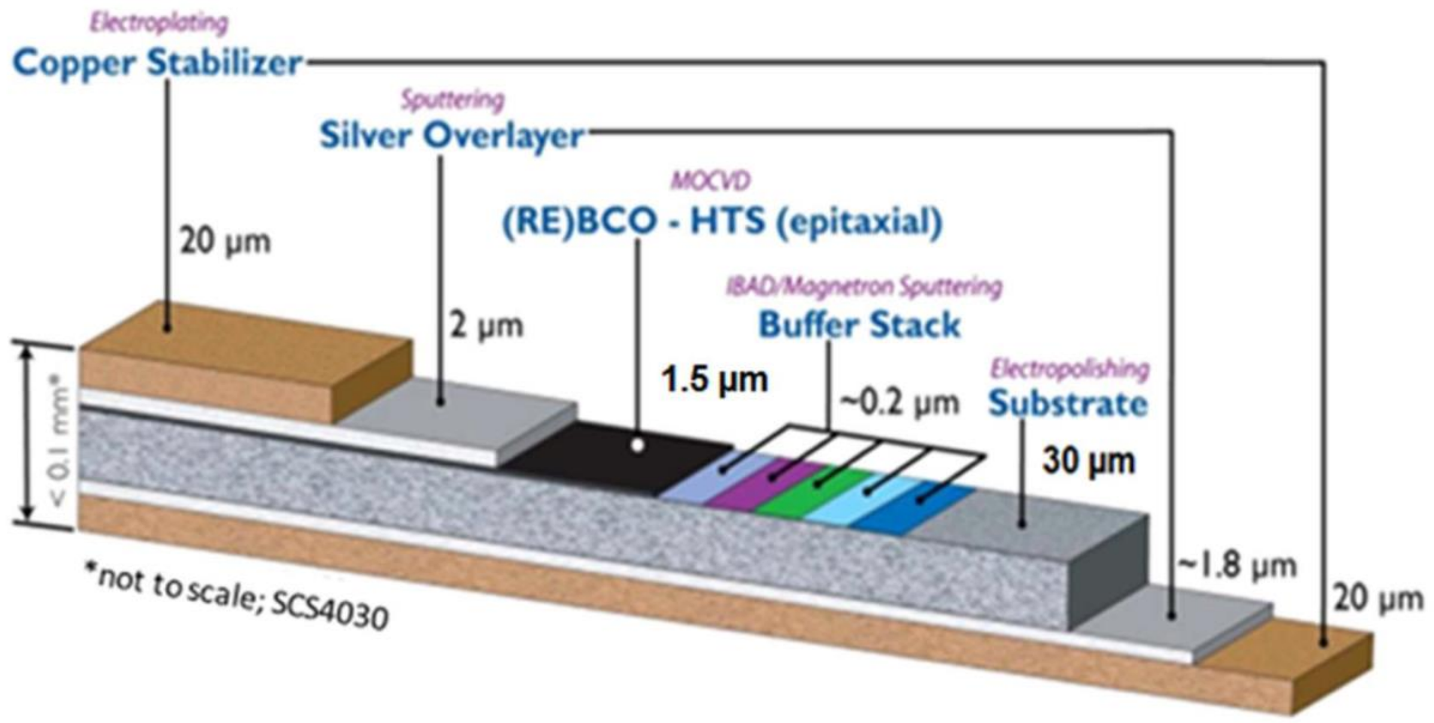
Magnets start with the superconductor: we are about to put Nb_3Sn into a collider for the first time, and are investigating the potential of HTS

Nb-Ti

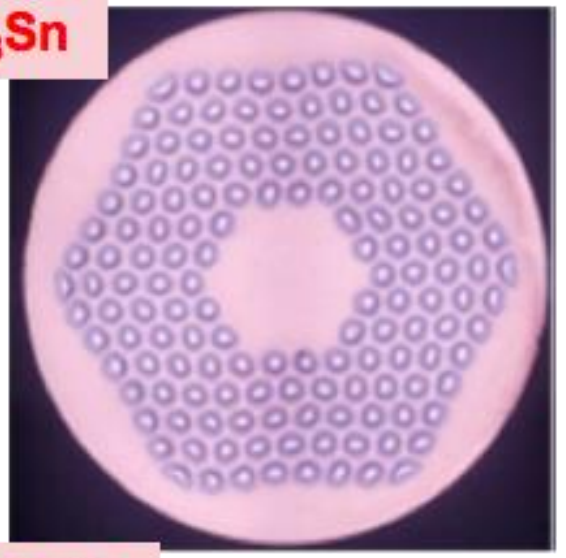




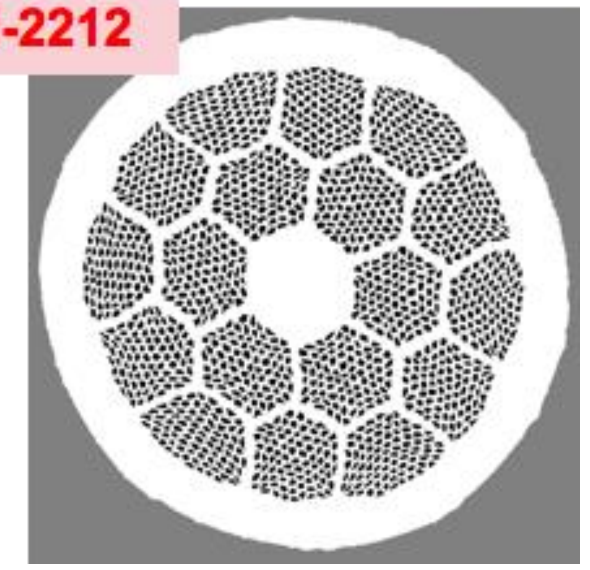
SuperPower Inc

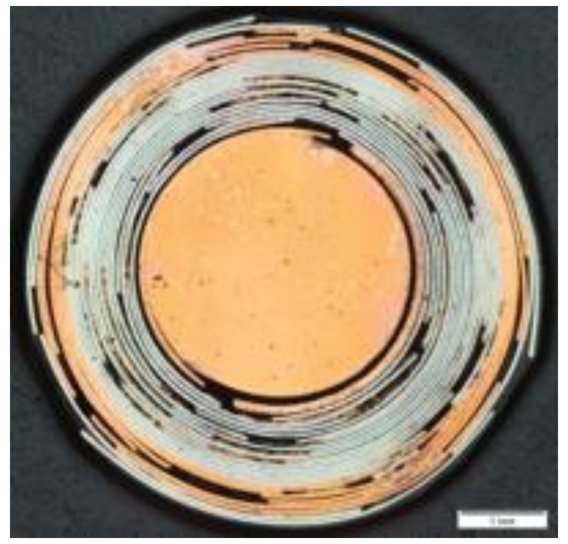


Nb_3Sn



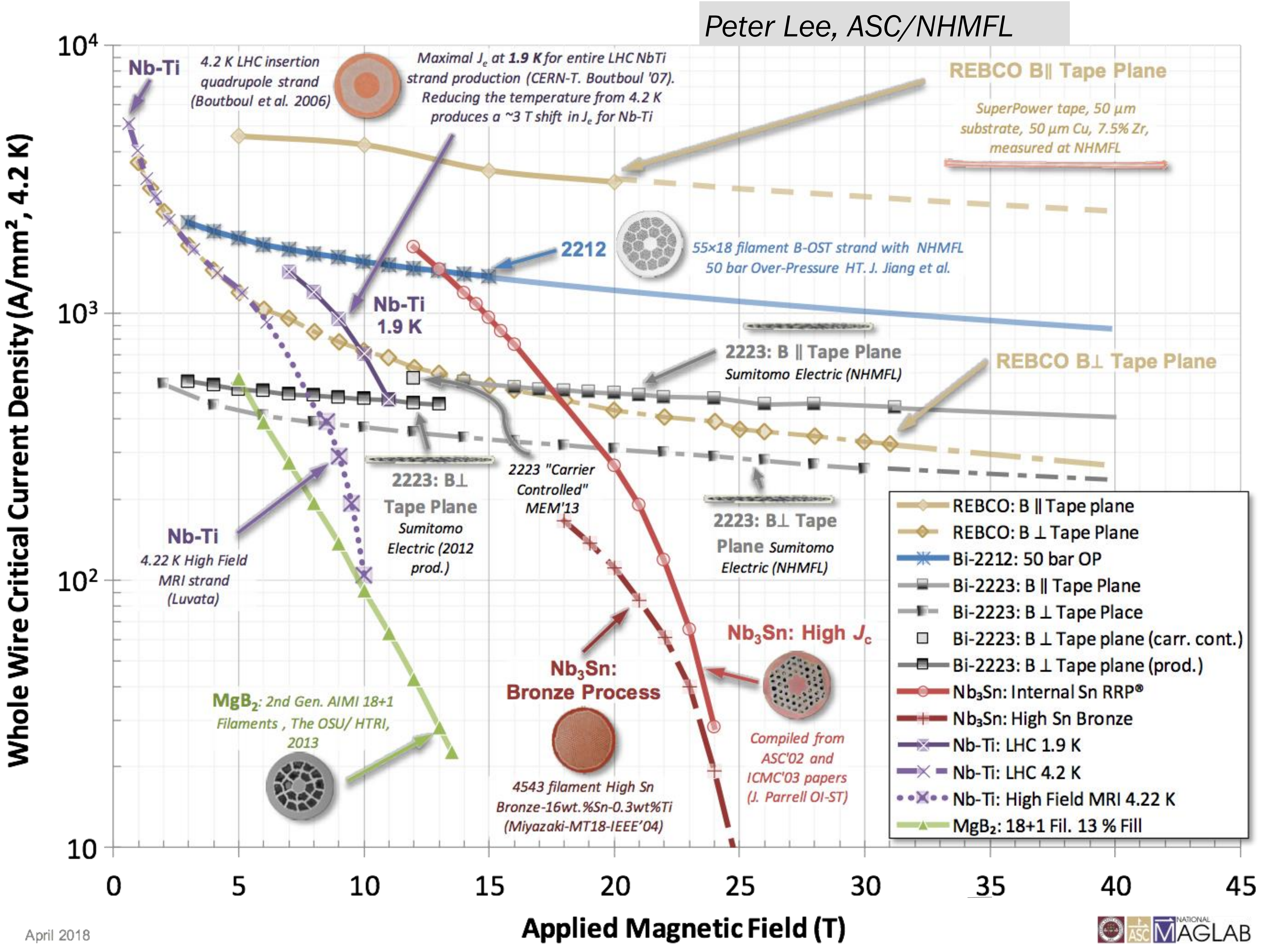
Bi-2212





CORC®
ACT LLC

Peter Lee, ASC/NHMFL



U.S. DEPARTMENT OF ENERGY | Office of Science

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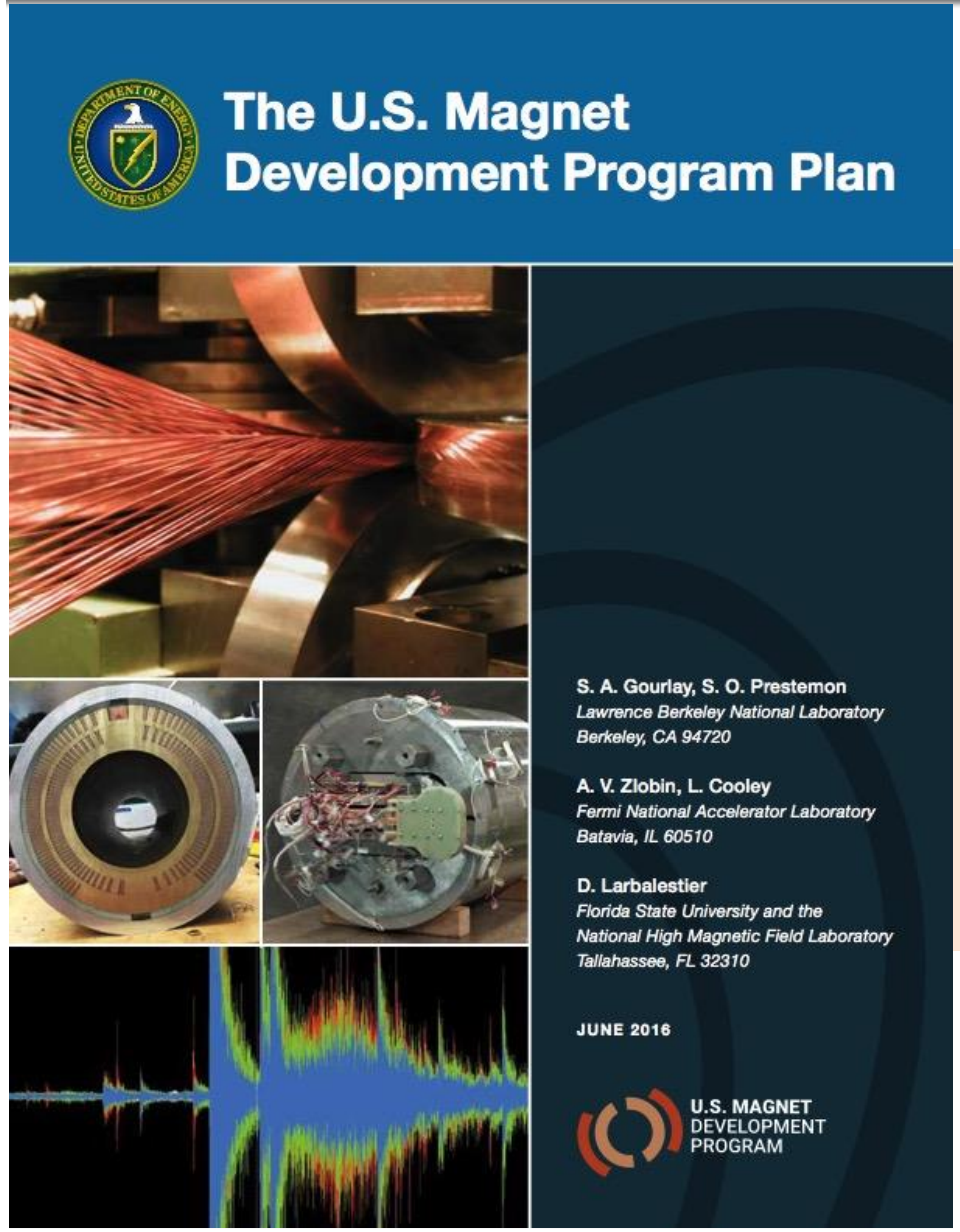
The US HEP Superconducting Magnet Programs are now integrated into the US Magnet Development Program



The U.S. Magnet Development Program Plan

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D. Larbalestier
Florida State University and the
National High Magnetic Field Laboratory
Tallahassee, FL 32310

JUNE 2016

U.S. MAGNET
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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.

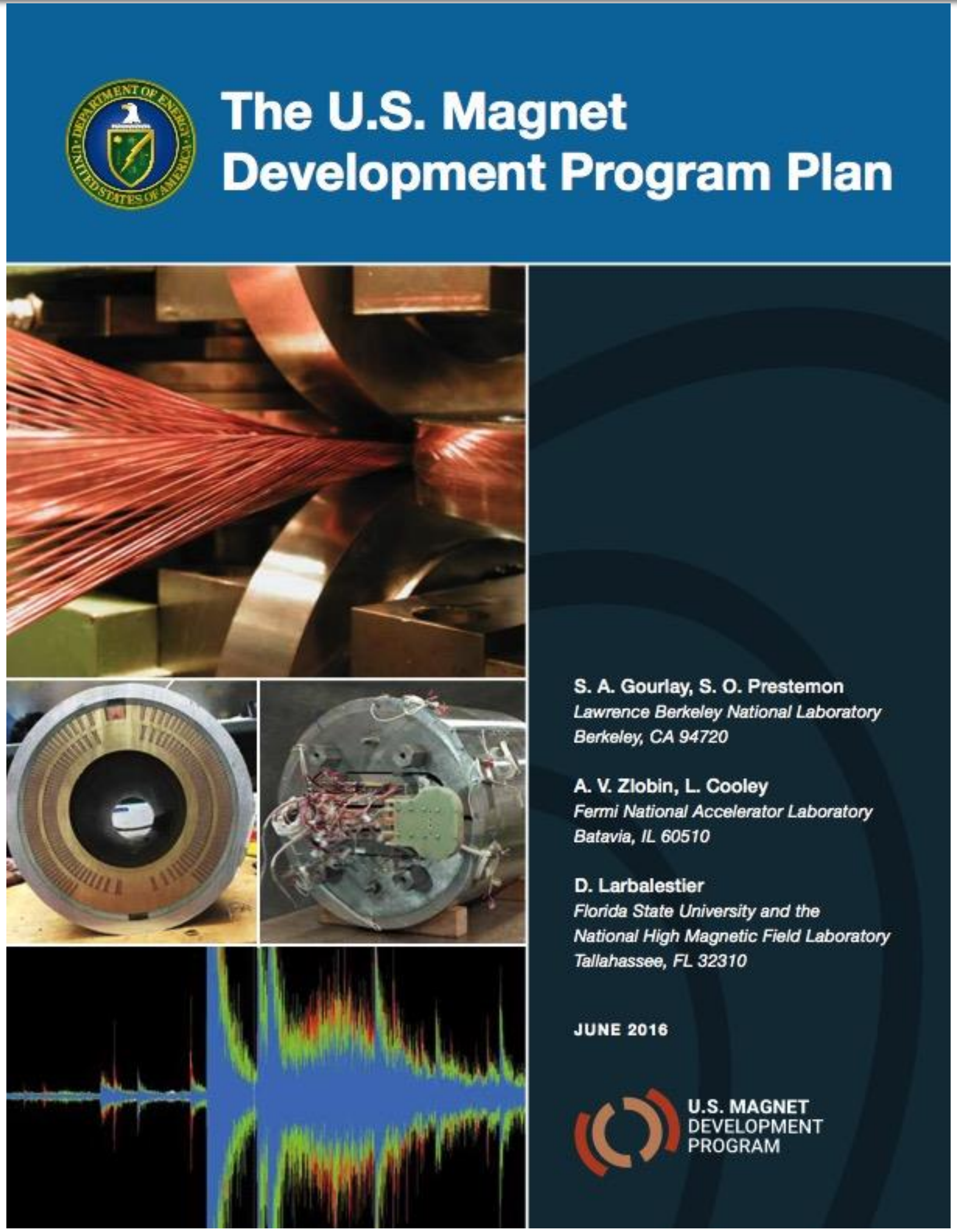
Recommendation 5c. Aggressively pursue the development of Nb_3Sn magnets suitable for use in a very high-energy proton-proton collider.

Recommendation 5d. Establish and execute a high-temperature superconducting (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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JUNE 2016

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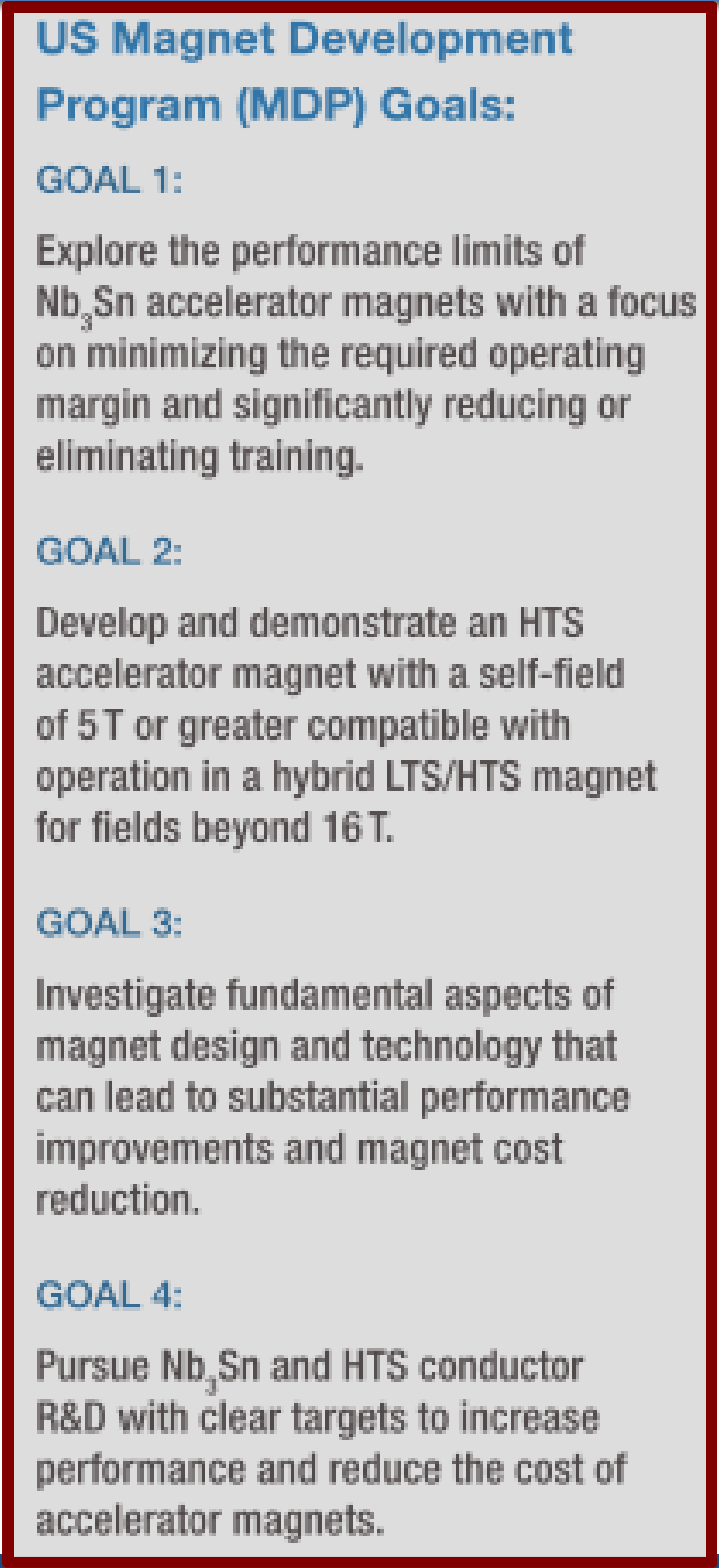
Strong support from the Physics Prioritization Panel (P5) and its sub-panel on Accelerator R&D

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.

U.S. MAGNET
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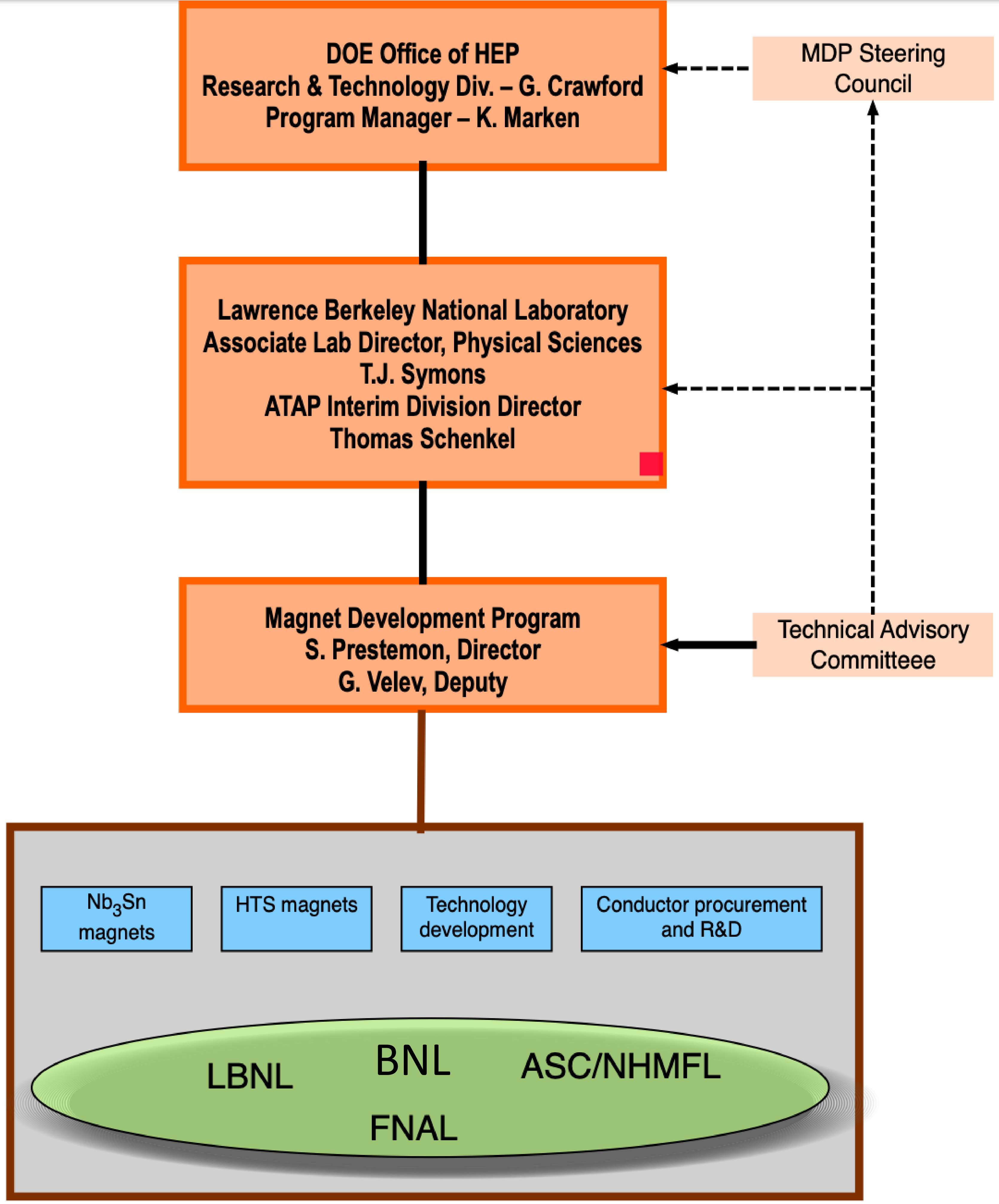
The management structure of the MDP is well defined and the program is fully functioning



DOE Office of HEP
Research & Technology Div. – G. Crawford
Program Manager – K. Marken

MDP Steering Council

Lawrence Berkeley National Laboratory
Associate Lab Director, Physical Sciences
T.J. Symons
ATAP Interim Division Director
Thomas Schenkel

Magnet Development Program
S. Prestemon, Director
G. Velev, Deputy

Technical Advisory Committeee

Nb_3Sn magnets

HTS magnets

Technology development

Conductor procurement and R&D

LBNL

BNL

ASC/NHMFL

FNAL

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

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

U.S. MAGNET
DEVELOPMENT
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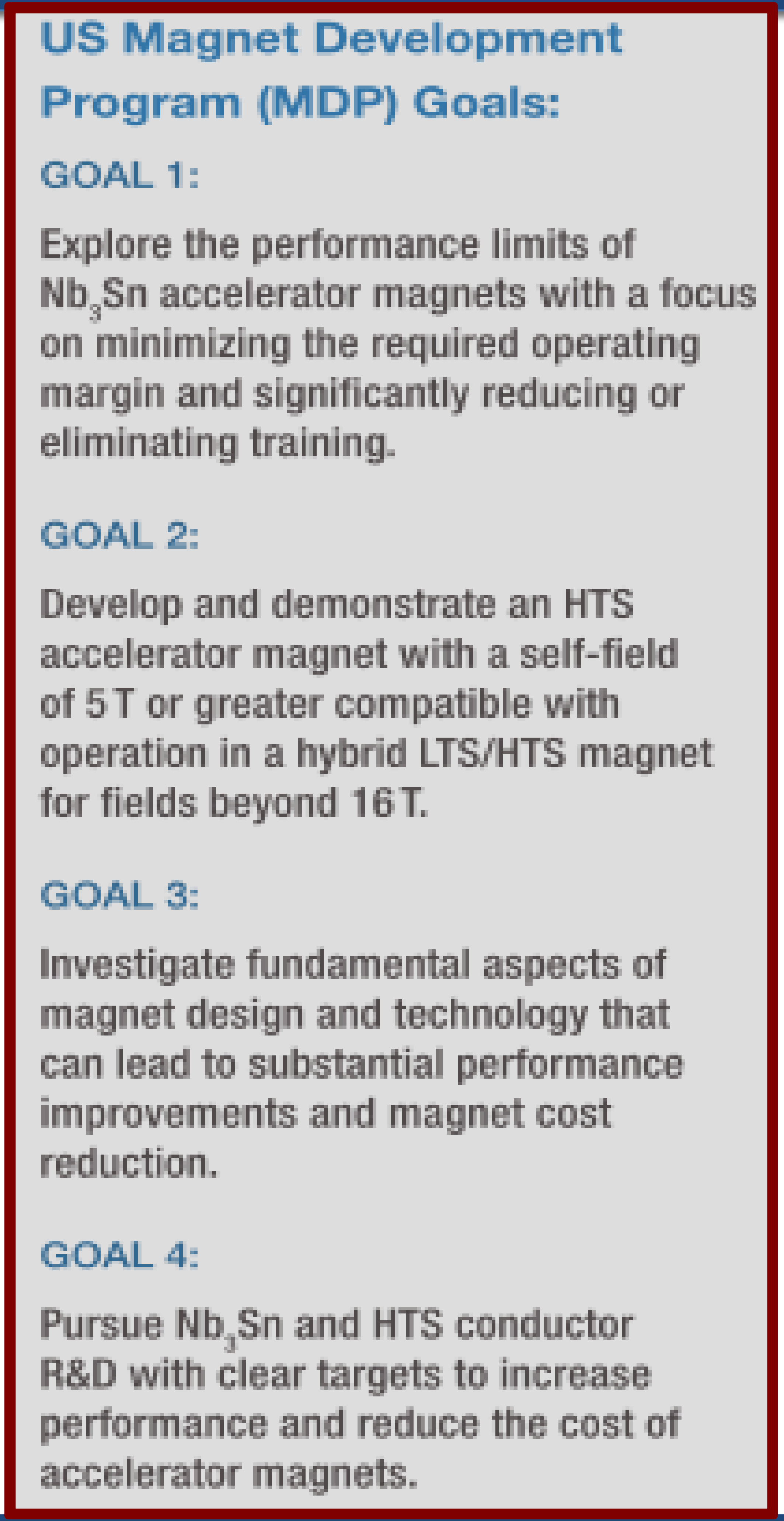
The program has well-defined goals, and is structured with technical leads who are responsible for delivery

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

Technology Area	LBNL POC	FNAL POC	BNL POC	ASC POC
Modeling and Simulation	Lucas Brouwer	Vadim Kashikhin	Ramesh Gupta	TBD
Training and Diagnostics	Maxim Marchevsky	Stoyan Stoynev	Piyush Joshi	TBD
Instrumentation and quench protection	Maxim Marchevsky	Thomas Strauss	Piyush Joshi	Dan Davis
Materials studies – superconductors and structural materials properties	Tengming Shen	Steve Krave	TBD	TBD

Cond Proc and R&D	Lance Cooley



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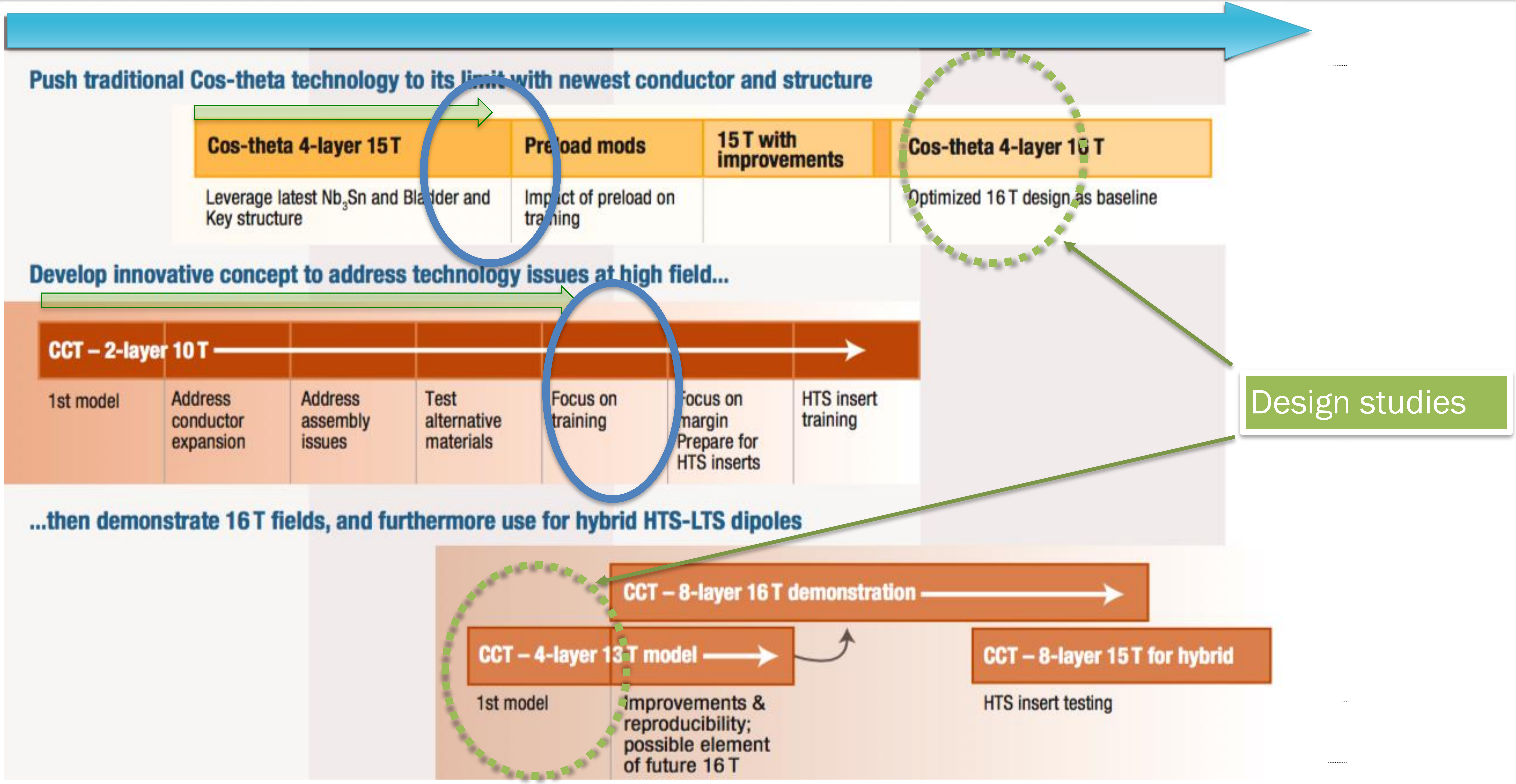
GOAL 4:

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

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



Push traditional Cos-theta technology to its limit with newest conductor and structure

Cos-theta 4-layer 15 T	Preload mods	15 T with improvements	Cos-theta 4-layer 16 T
Leverage latest Nb_3Sn and Bladder and Key structure	Impact of preload on training		Optimized 16 T design as baseline

Develop innovative concept to address technology issues at high field...

CCT – 2-layer 10 T

1st model	Address conductor expansion	Address assembly issues	Test alternative materials	Focus on training	Focus on margin Prepare for HTS inserts	HTS insert training

...then demonstrate 16 T fields, and furthermore use for hybrid HTS-LTS dipoles

CCT – 8-layer 16 T demonstration

CCT – 4-layer 13 T model

1st model

improvements & reproducibility; possible element of future 16 T

CCT – 8-layer 15 T for hybrid

HTS insert testing

Design studies

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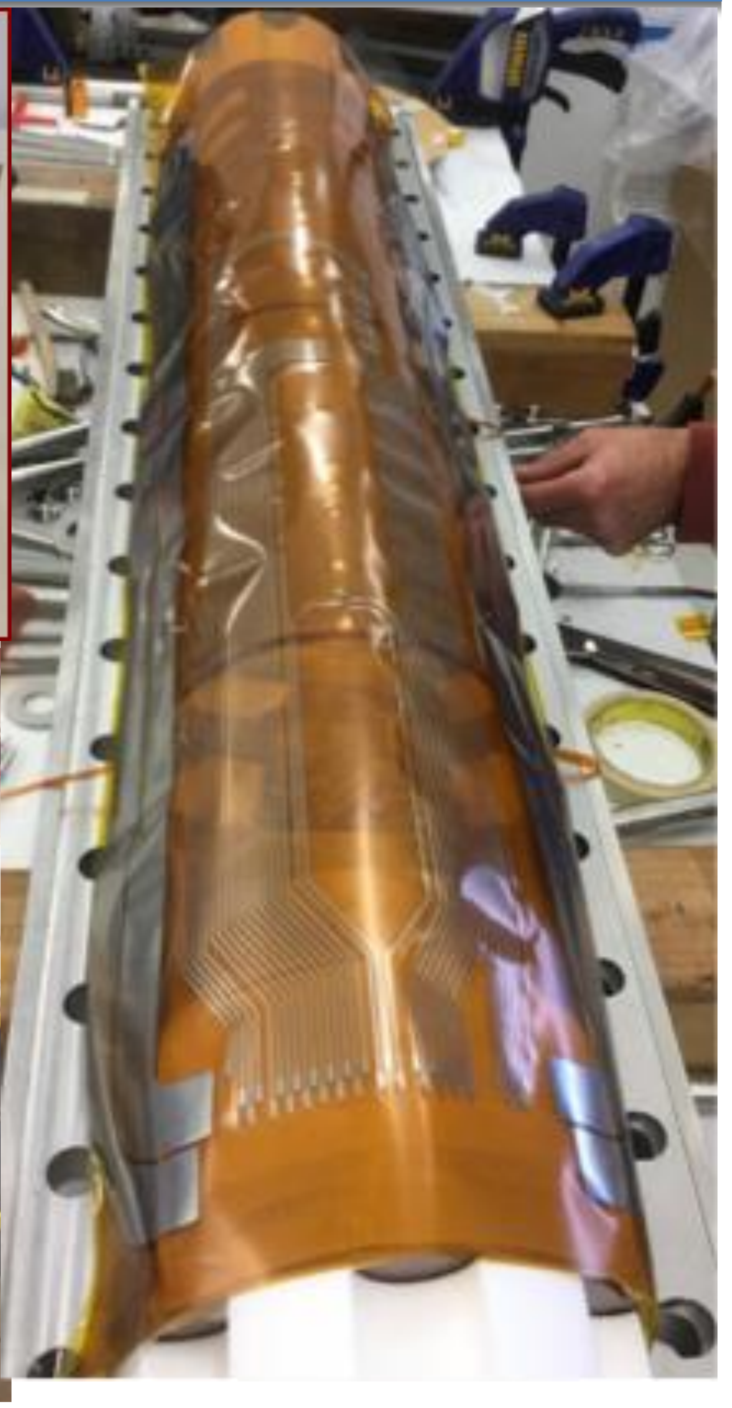
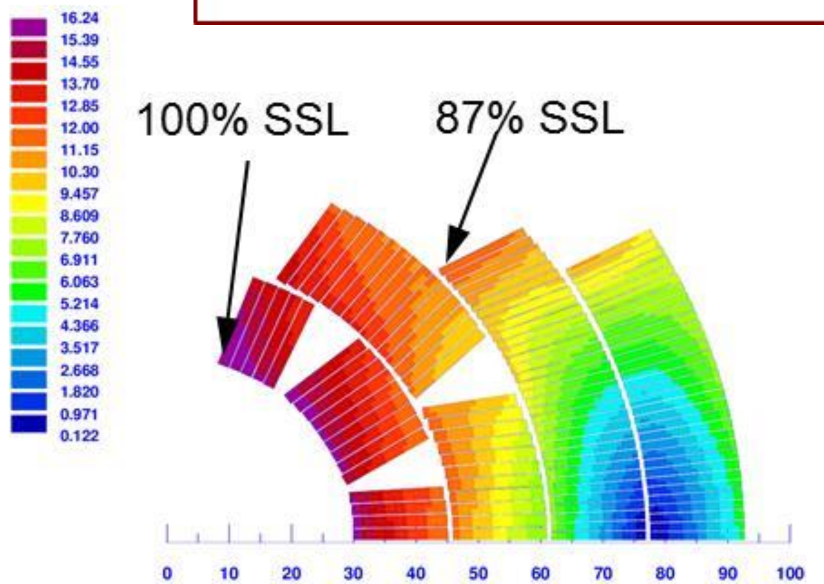
A Cos(t) 4-layer design led by FNAL is being pursued with the ultimate goal of achieving ~15T

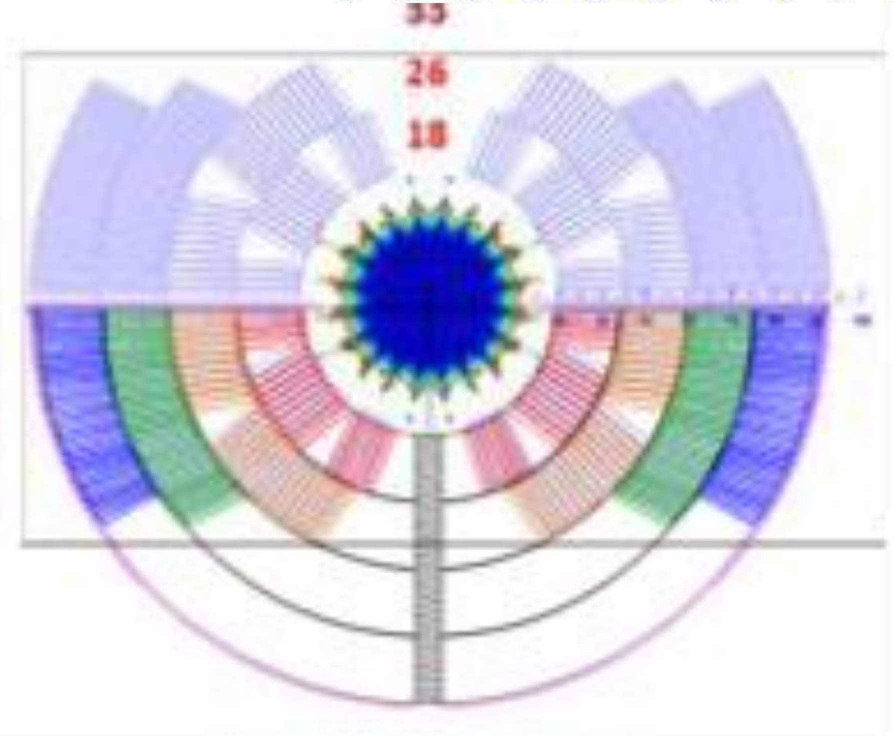
- Design minimizes midplane stress for highest field
- A technical challenge is to provide adequate prestress on inner coils
  - Intrinsic difficulty with 4 layers
  - Collared-structure approach includes new features that provide some prestress increase during cool down

- Status:
  - Magnet built
  - 1st test completed – world record!
  - Magnet disassembled, inspected
  - Coil support and end design improved
  - Reassembly readiness review completed
  - Magnet re-assembly underway
  - 15T test early next year

Thanks to CERN!



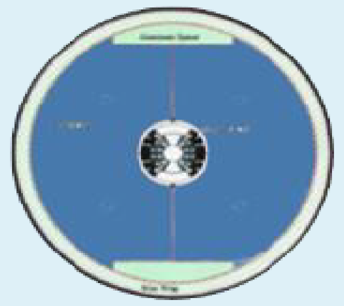
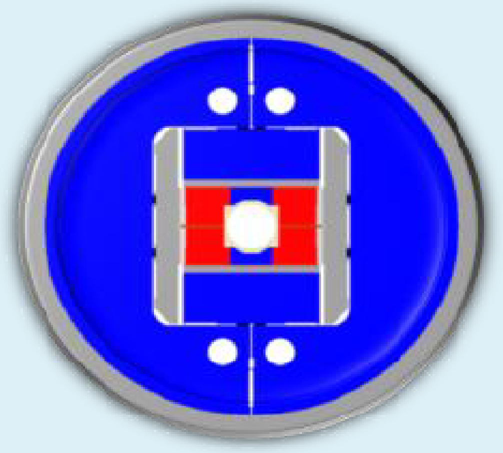
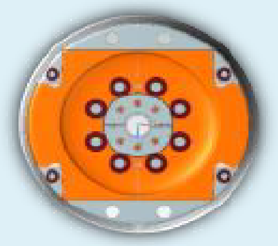


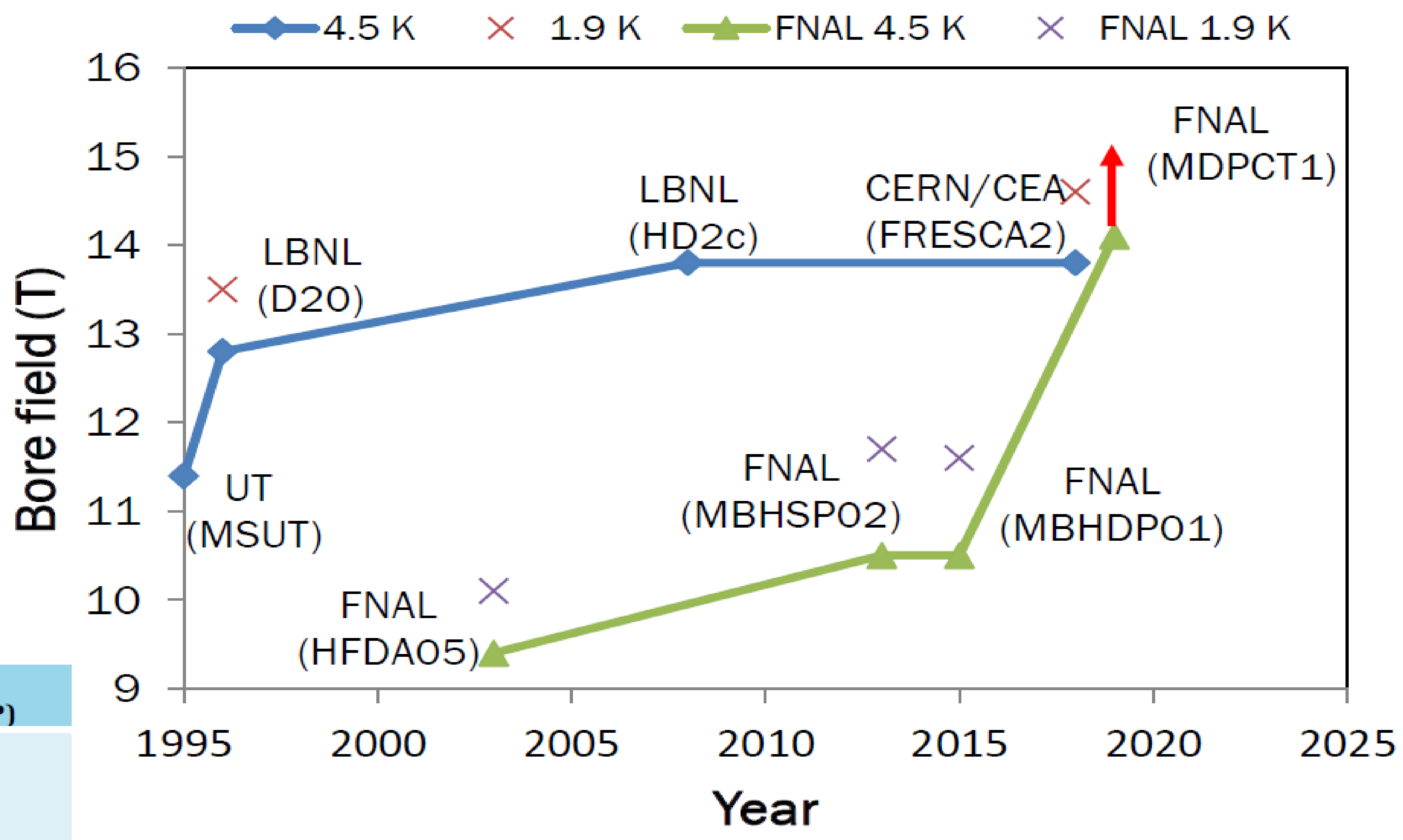


60-mm aperture, 4-layer graded coil

Results of 1st test

- The goal of the 1st test has been achieved
    - graded 4-layer coil design, innovative support structure and magnet fabricated procedure have been tested

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)



B_{max} = 14.10±0.04 T – *record field at 4.5 K for accelerator magnets!*

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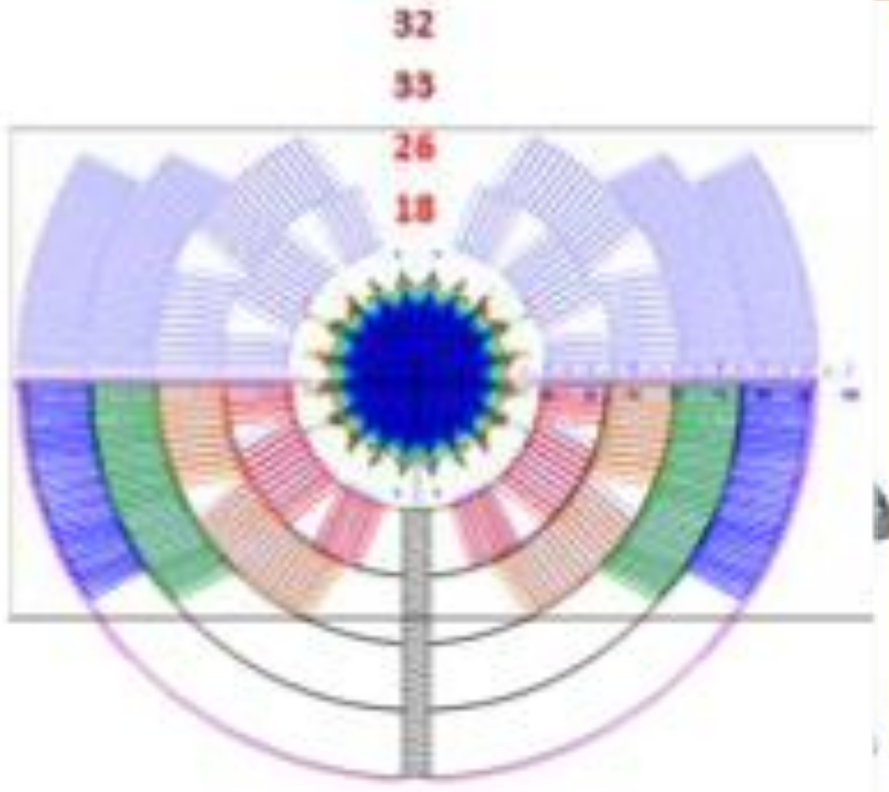
Cos-theta has come to fruition – record field! - and subscale CCTs are under development to probe training

- A Cos(θ) design that minimizes midplane stress for highest field
  - Leverages advances in Nb_3Sn - HEP-driven conductor development

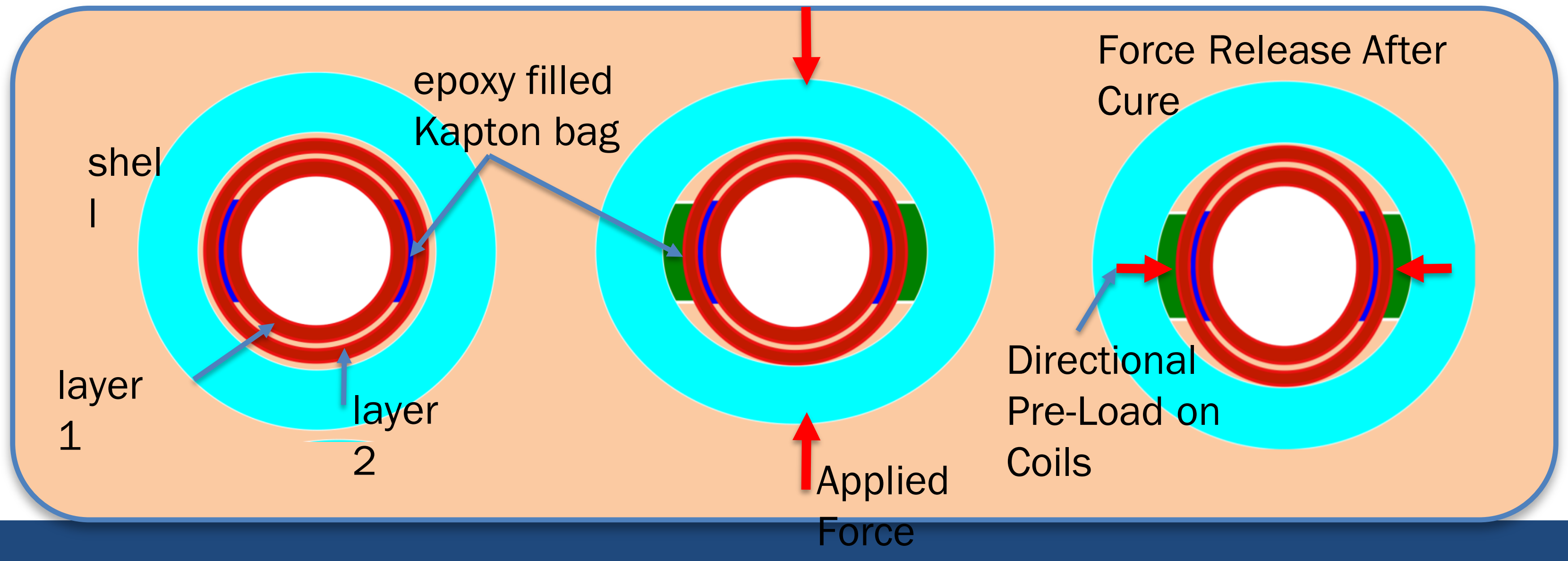
⇒Recent record Cos(θ) dipole field - 14T!
Maintaining US leadership - record fields for 20+ years

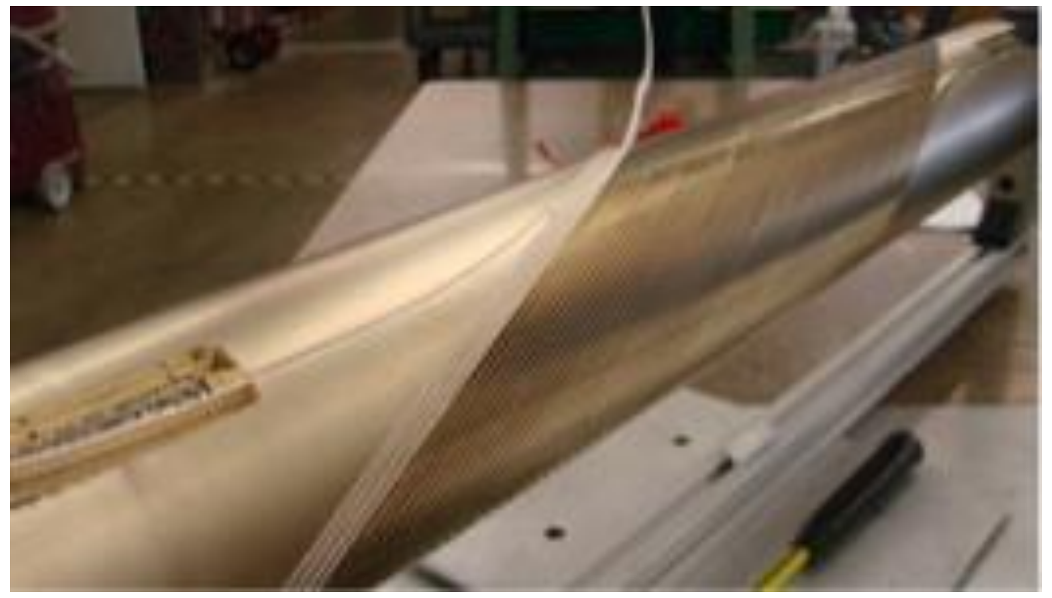


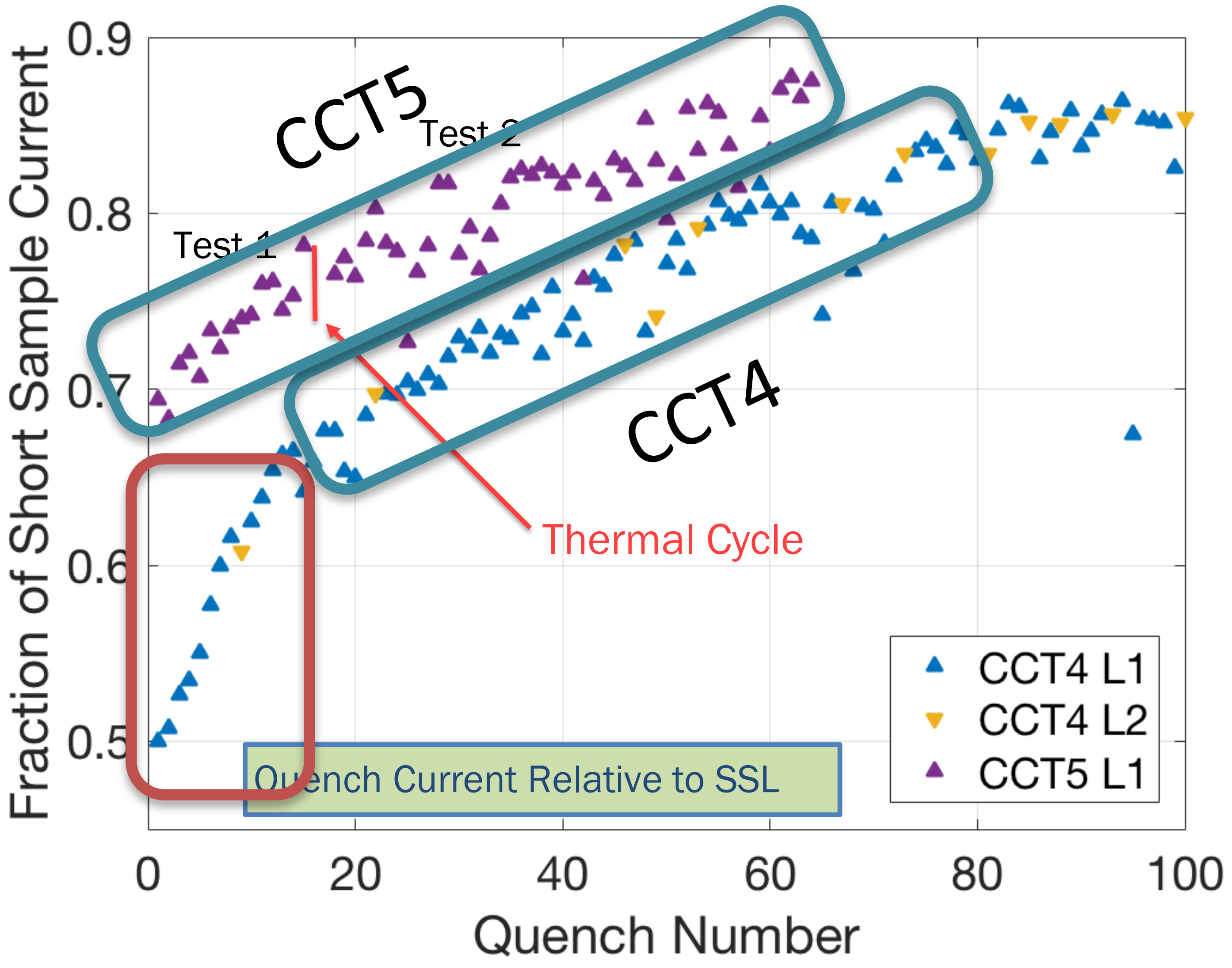

Thanks to CERN!

60-mm aperture, 4-layer graded coil

- Canted Cosine-theta:
  - New concept - high-risk high-reward
  - Introduce “stress management” to scale to higher field







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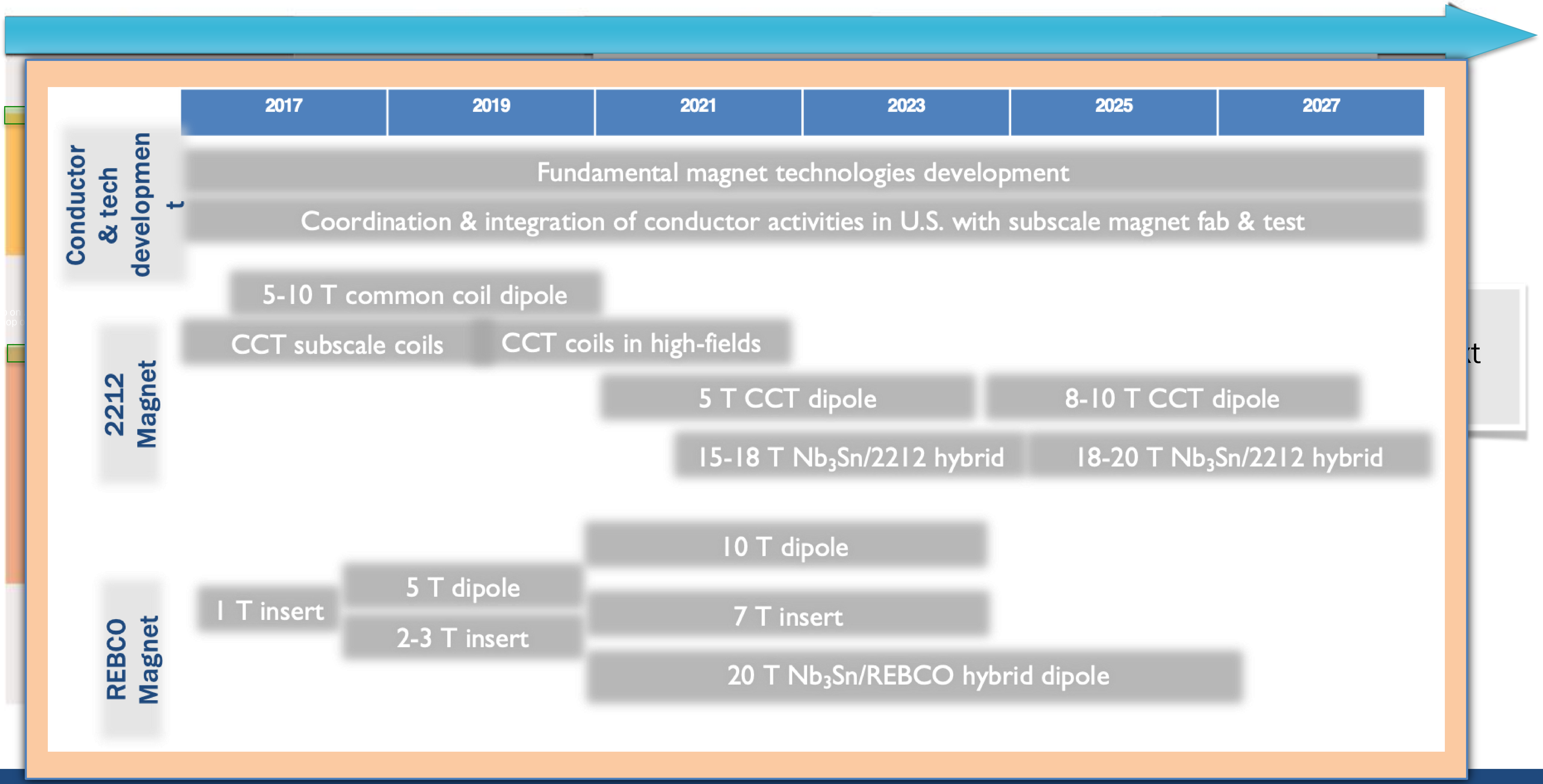
The MDP HTS magnet development is progressing well, and the long-term vision is starting to be fleshed out

Area II:

HTS magnet technology



2017 | 2019 | 2021 | 2023 | 2025 | 2027

Conductor & tech development
- Fundamental magnet technologies development
- Coordination & integration of conductor activities in U.S. with subscale magnet fab & test

2212 Magnet
- 5-10 T common coil dipole
- CCT subscale coils
- CCT coils in high-fields
- 5 T CCT dipole
- 8-10 T CCT dipole
- 15-18 T Nb_3Sn/2212 hybrid
- 18-20 T Nb_3Sn/2212 hybrid

REBCO Magnet
- 1 T insert
- 5 T dipole
- 2-3 T insert
- 10 T dipole
- 7 T insert
- 20 T Nb_3Sn/REBCO hybrid dipole

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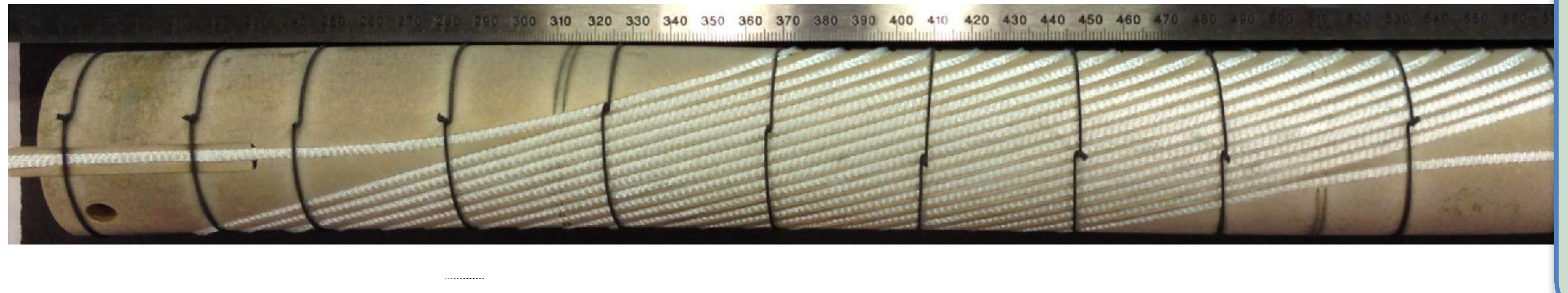
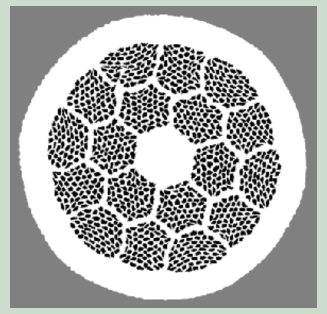
HTS accelerator magnets are making steady progress, and continue to exhibit stable performance – no training!

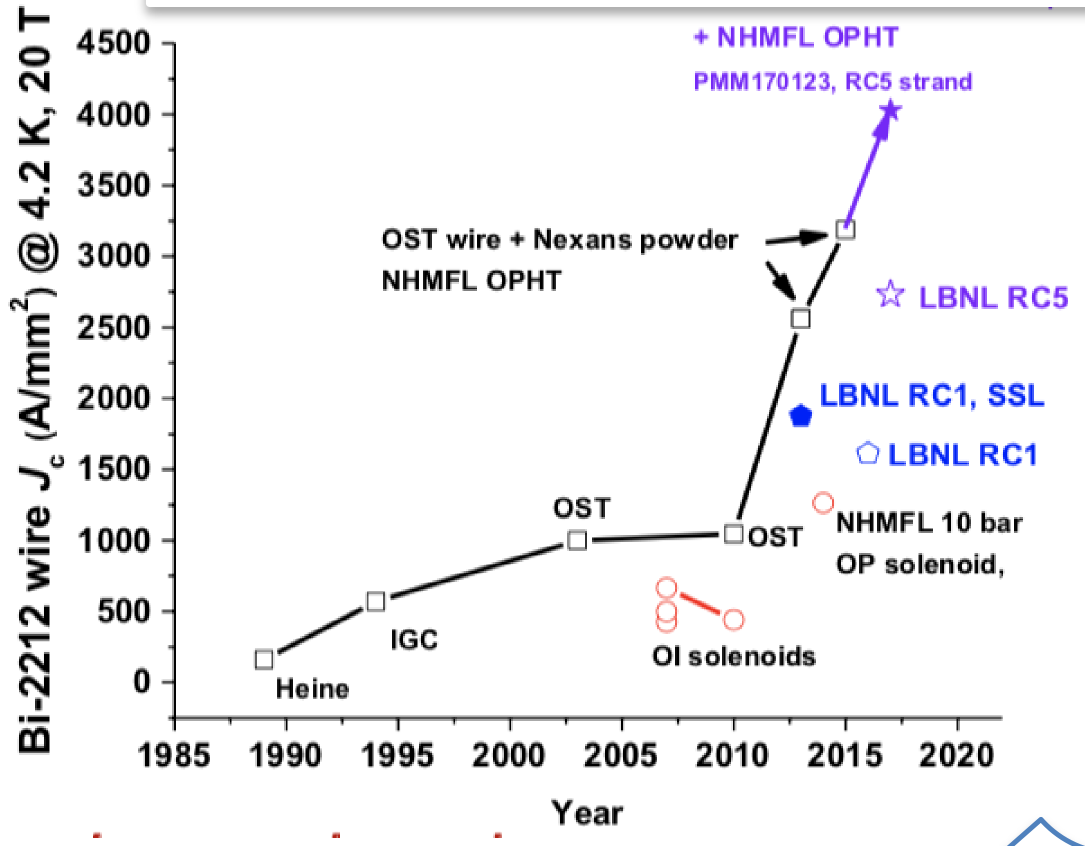
- Nano-spray combustion powder technology
- At 15 T, J_e - 1365 A/mm^2
  - *twice the target desired by the FCC Nb$_3$Sn strands!*
- Bi2212 now *exceeds RRP J_E at 11T!*
- At 27 T, J_e - 1000 A/mm^2, adequate for 1.3 GHz NMR.



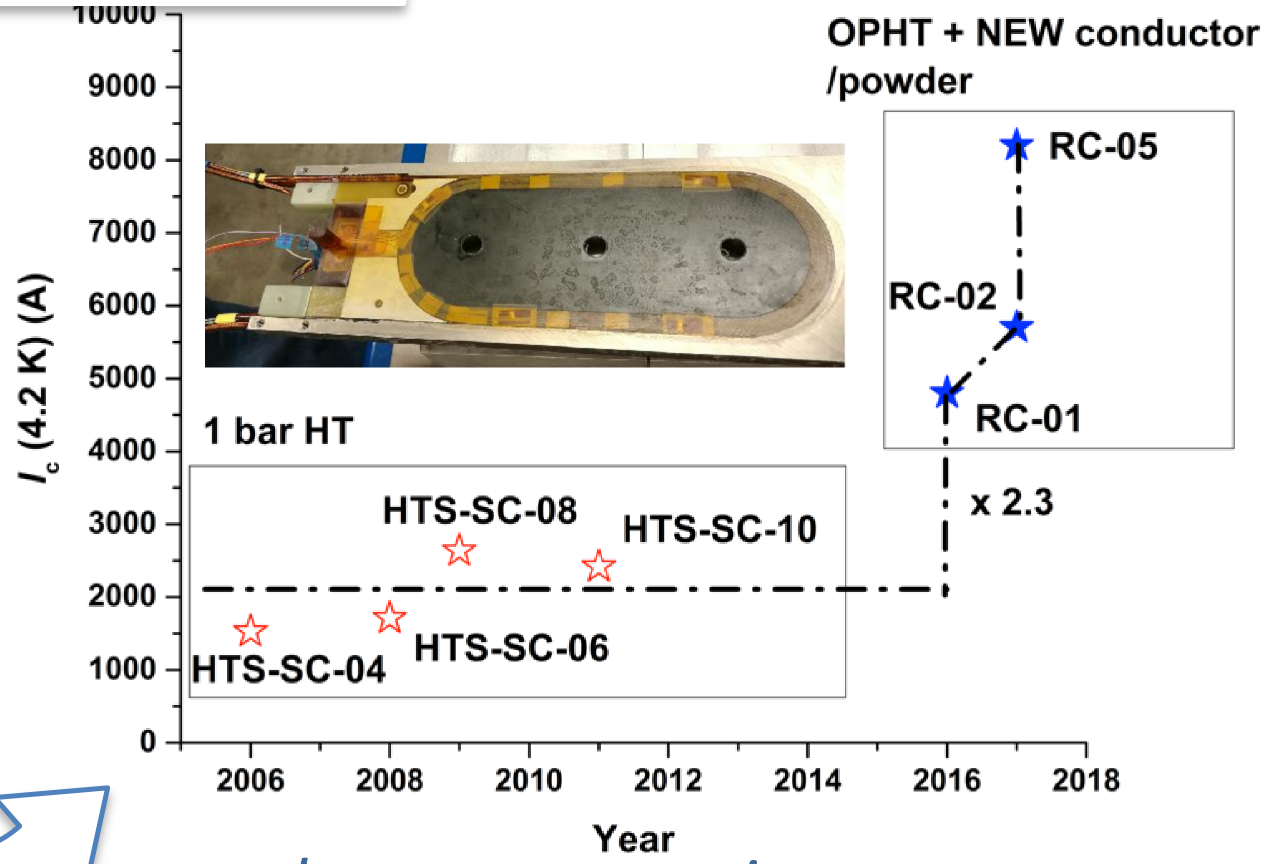


nGimat
ASC NATIONAL MAGLAB
BRUKER
BERKELEY LAB

Bi2212 - multi filamentary round wire



Conductor improvements

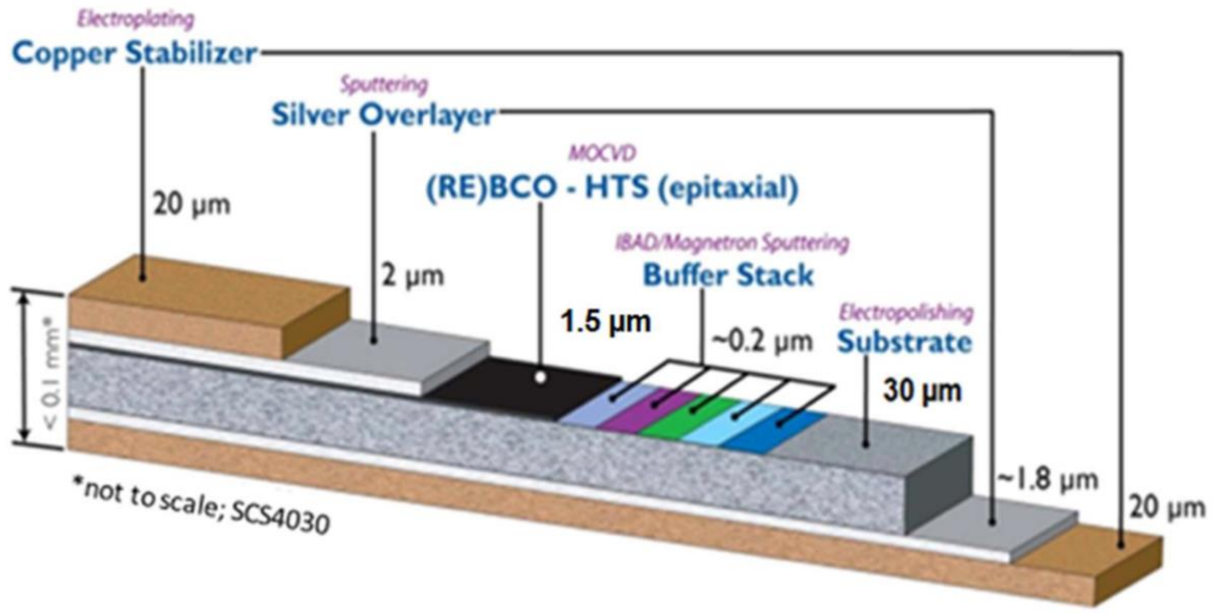


translate to magnet improvements

- Note groundbreaking application at high field by NHMFL - 45.5T!
  - *S. Hahn et al, Nature*

Advanced Conductor Technologies LLC
www.advancedconductor.com

SuperPower Inc.
A Furukawa Company



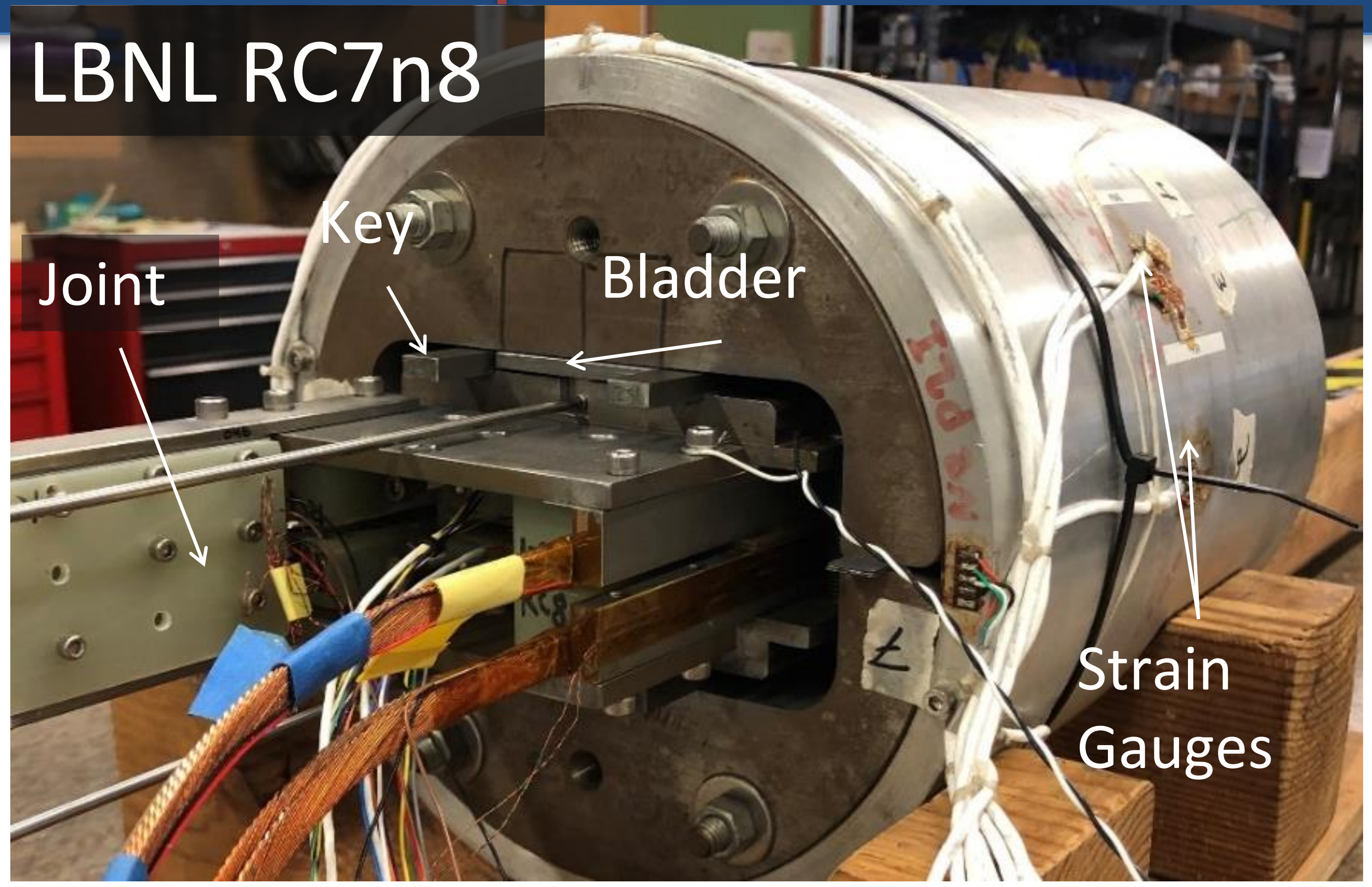
- Today: 220 A/mm^2 at 21 T, 4.2 K, 30 mm bend radius
- Goal: Minimum J_e(21 T, 4.2 K) at 3.7 mm wire diam.: 540 A/mm^2 at 15 mm bend radius

REBCO - "coated conductor", tape

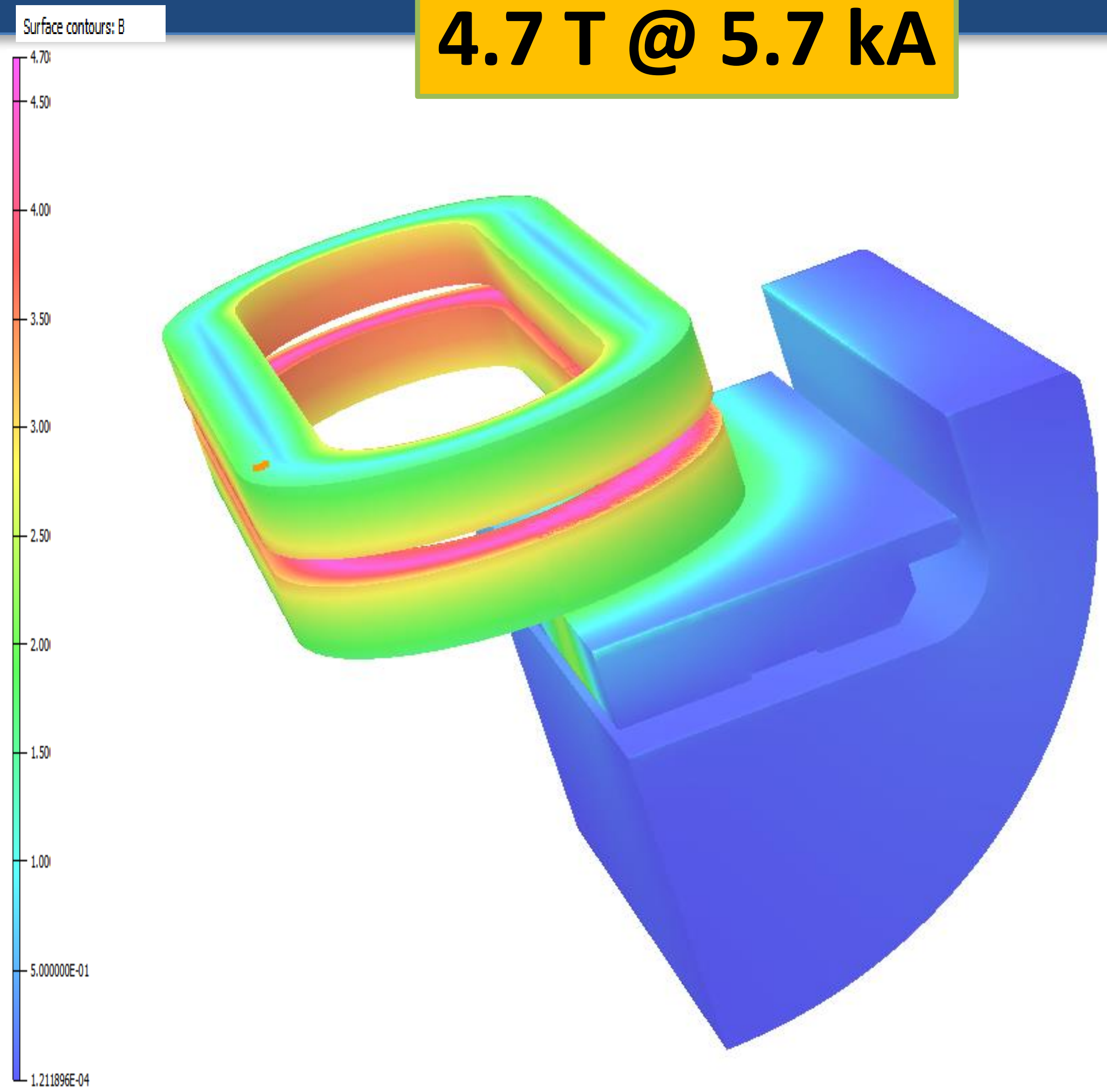
U.S. DEPARTMENT OF ENERGY | Office of Science

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2020.
Plenary presentation PL2-INV given at ISS, 3-5 December 2019, Kyoto, Japan.

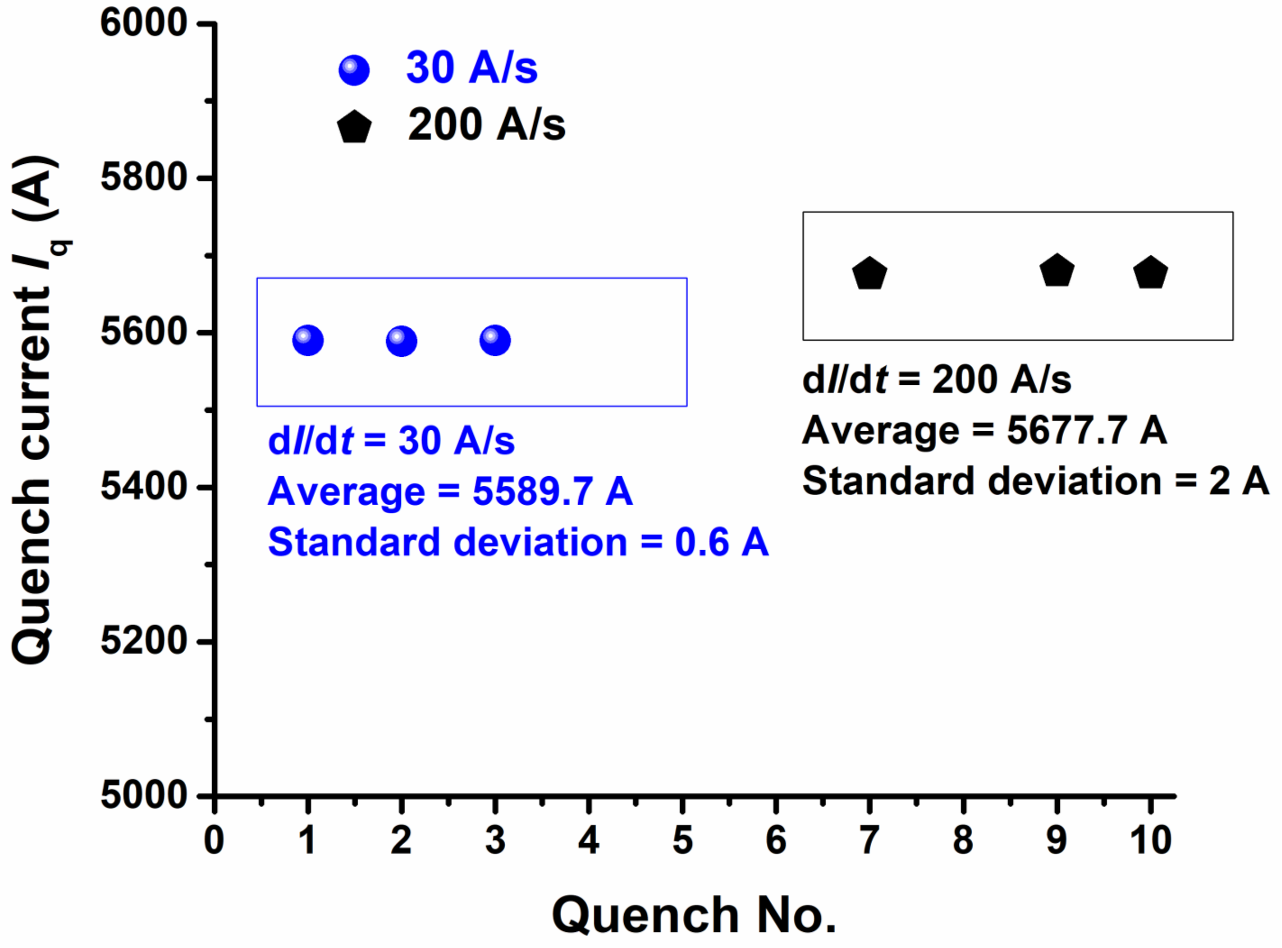
Bi-2212 RC7n8, the first 4.7 T dipole: demonstrated no quench training, stable performance => practical magnet engineering possible with HTS wires



4.7 T @ 5.7 kA

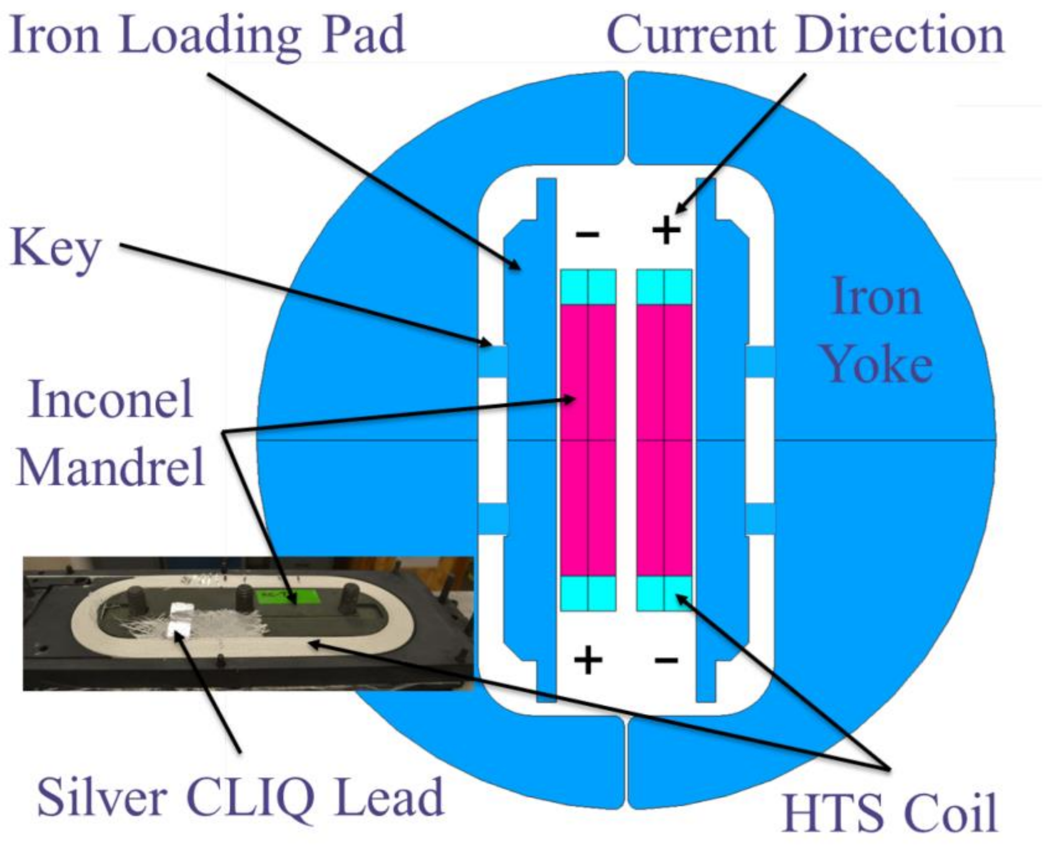


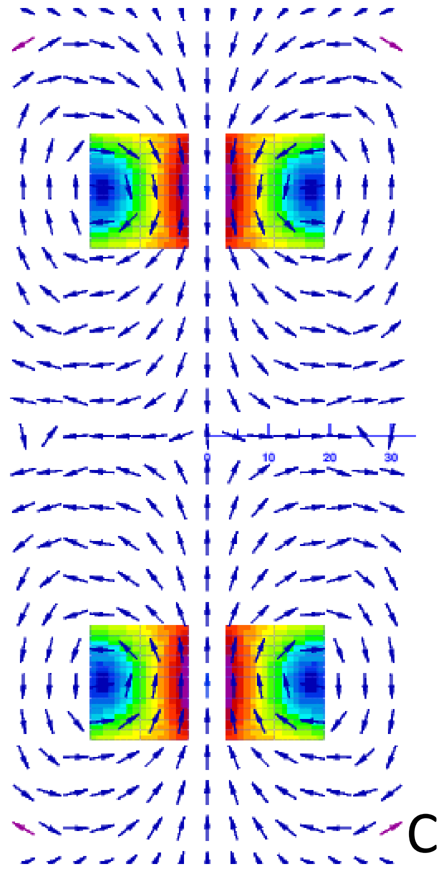
No Quench Training

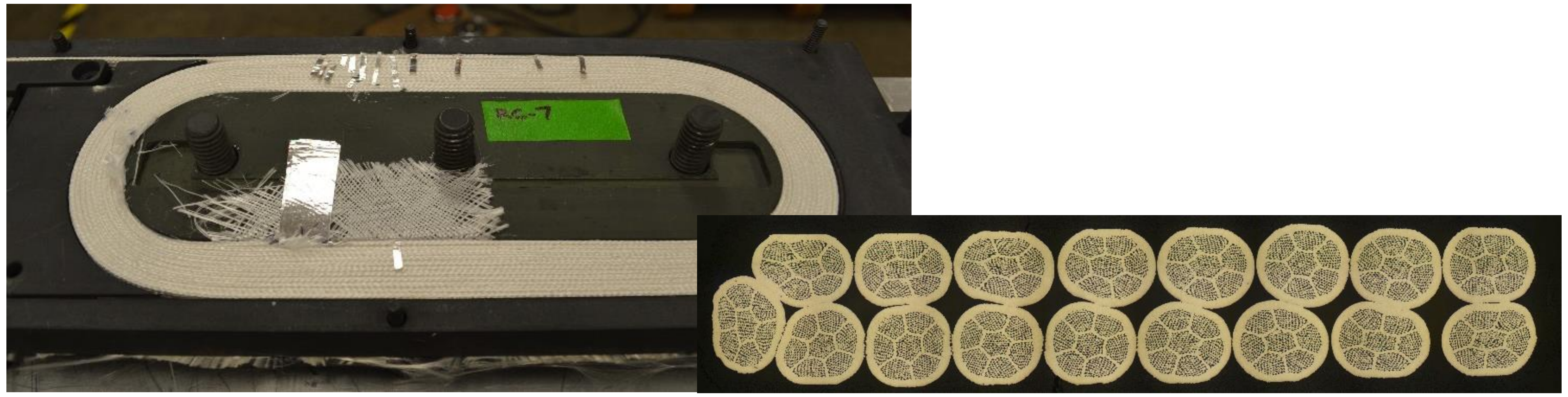


d*I*/d*t* = 30 A/s
Average = 5589.7 A
Standard deviation = 0.6 A

d*I*/d*t* = 200 A/s
Average = 5677.7 A
Standard deviation = 2 A







Collaboration with NHMFL where OPHT was performed. Graphs by Daniel Davis, Laura Garcia Fajardo, Tengming Shen

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2020.
Plenary presentation PL2-INV given at ISS, 3-5 December 2019, Kyoto, Japan.

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

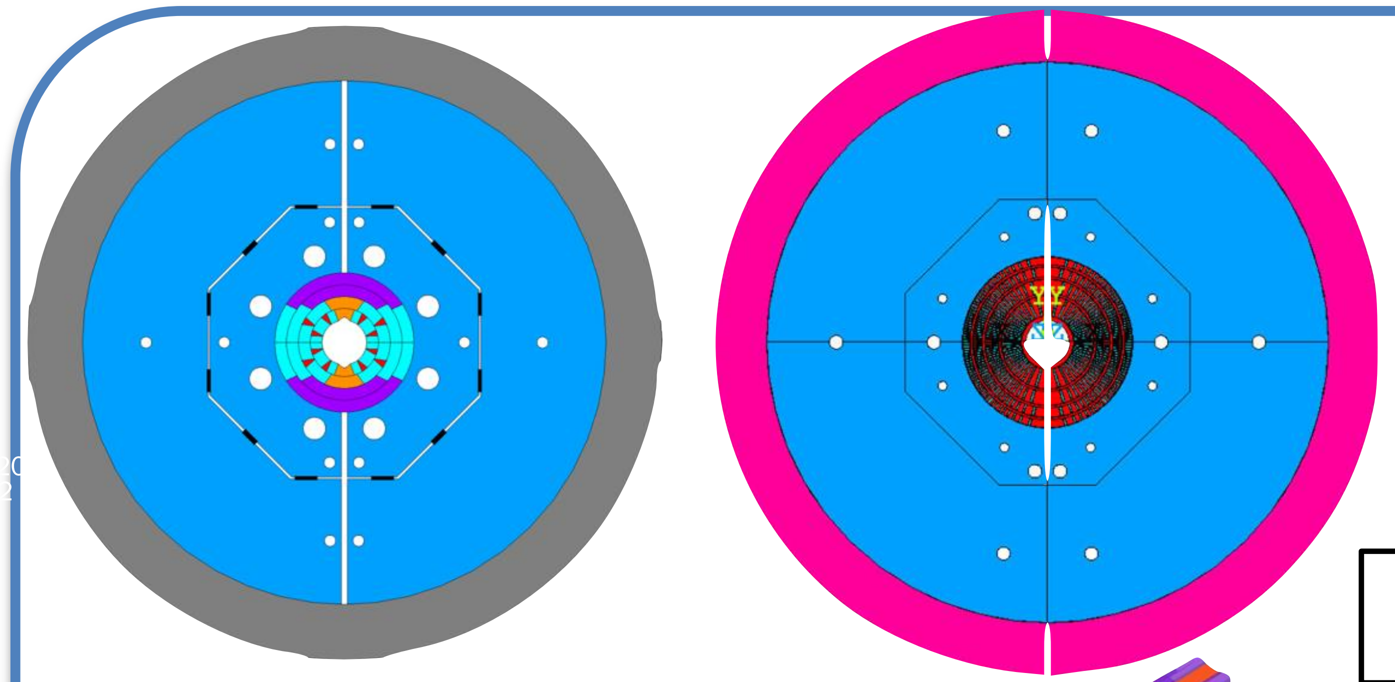
Design Team
16 T Dipole design:
Leads: Zlobin and Sabbi

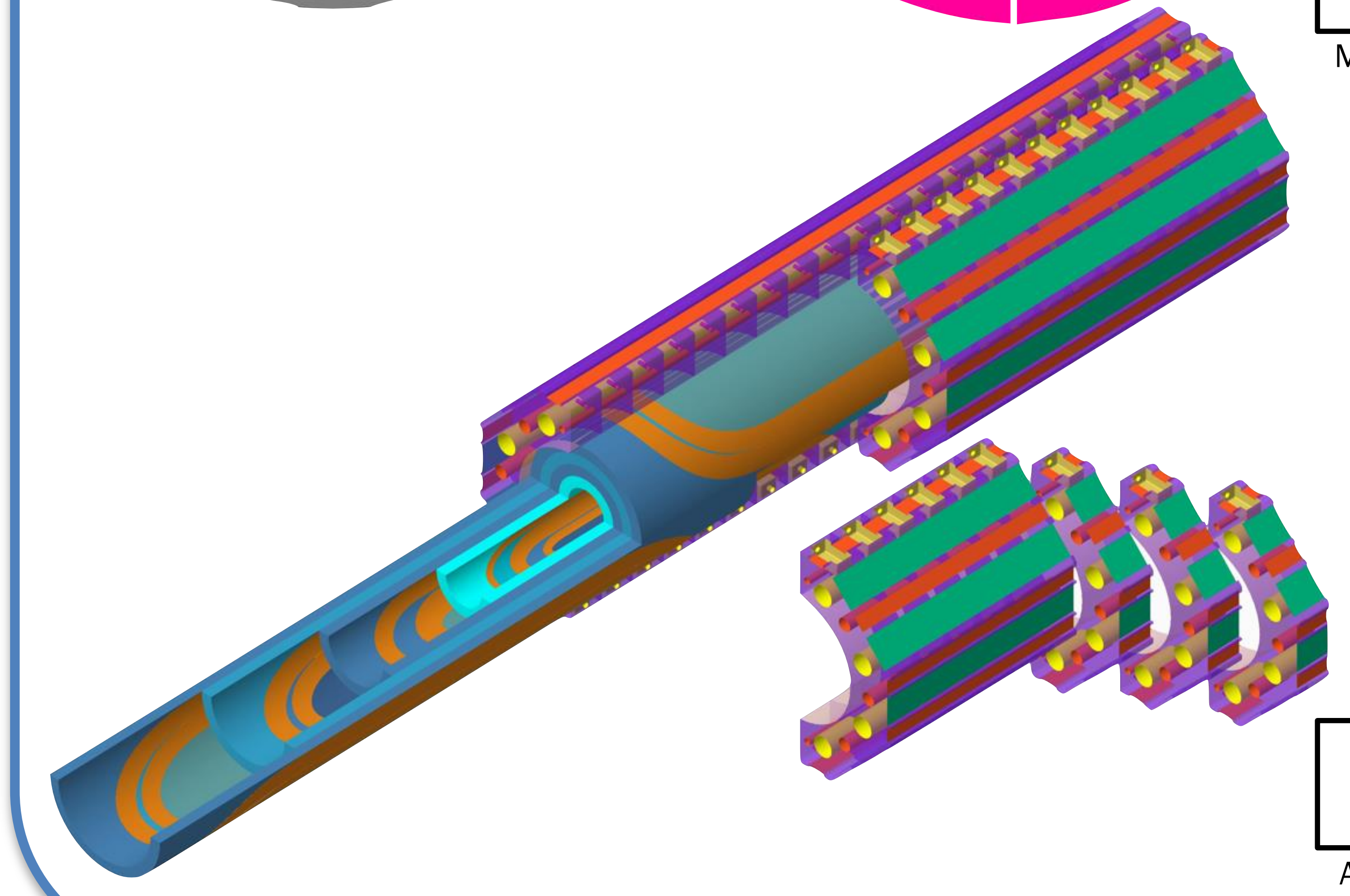
Design Team
Utility Structure design:
Lead: Mariusz Juchno

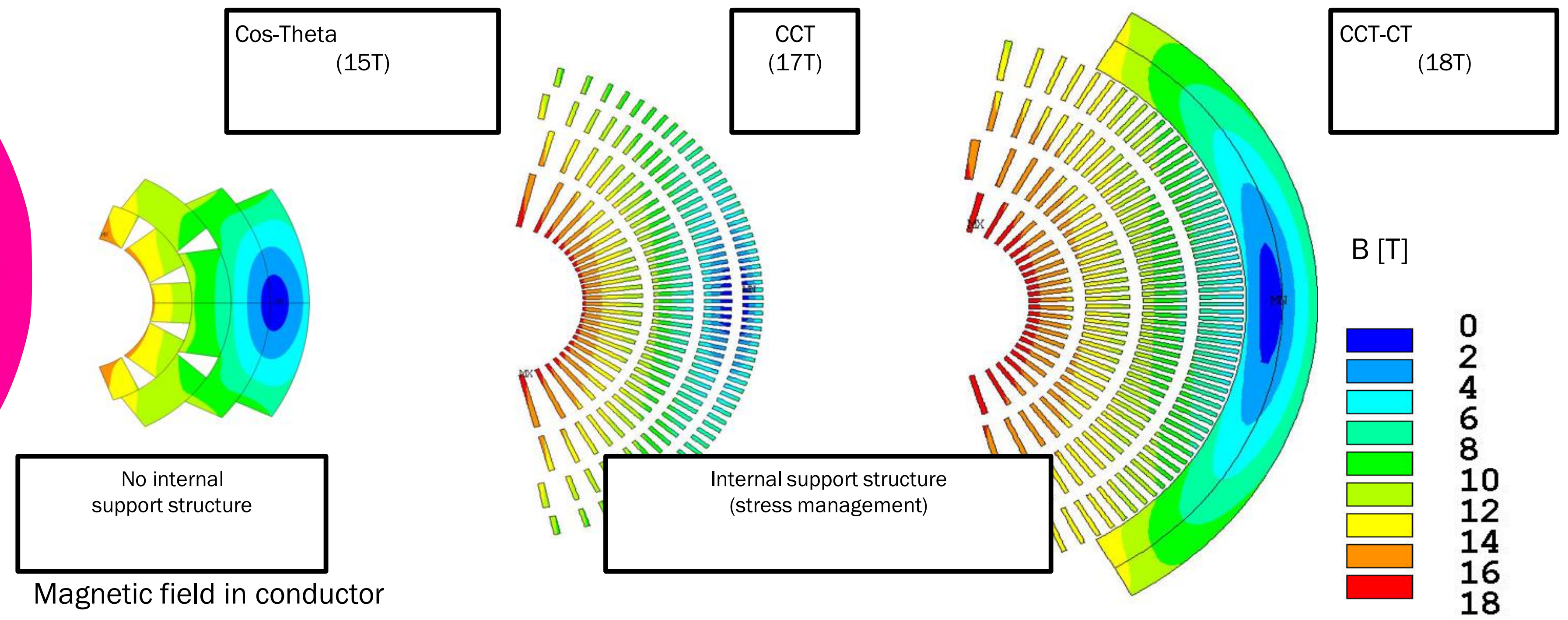
Nb_3Sn design targets

Each magnet concept should provide

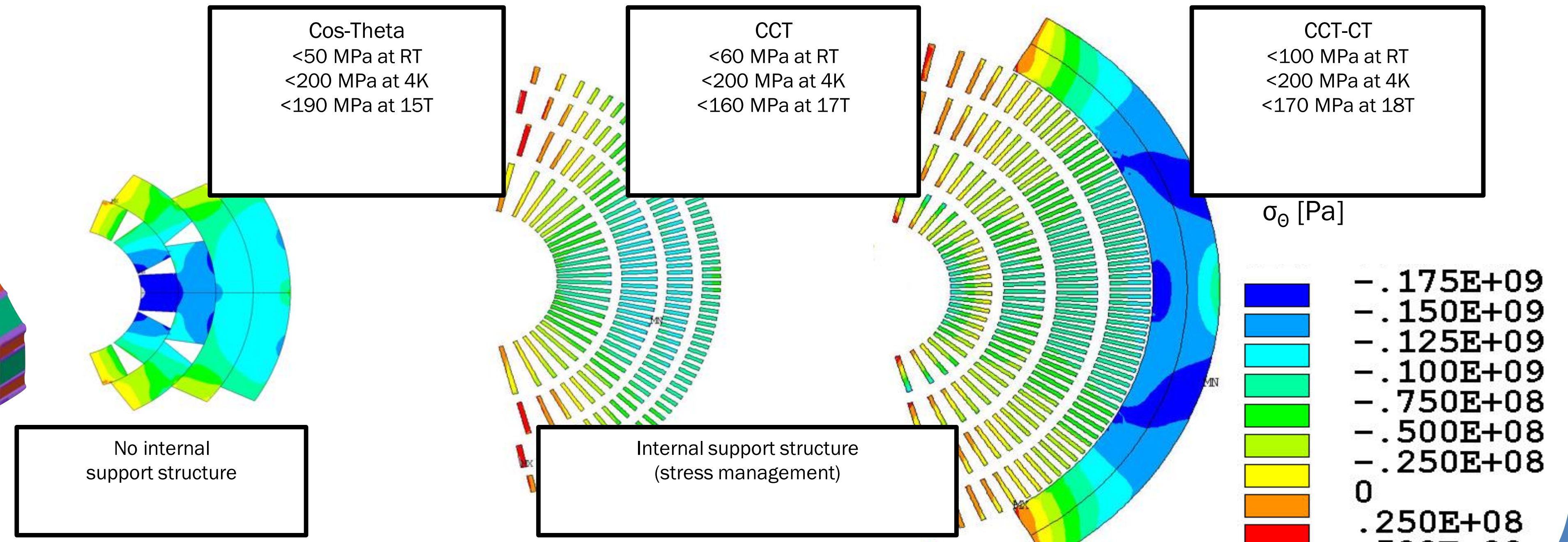
- Description of magnet design including
    - Strand, cable and insulation (before and after reaction)
    - Coil cross-section (number of layers, number of turns, conductor weight/m/aperture)
    - Coil end design concept
    - Magnet support structure including transverse and axial support
    - Quench 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







Magnetic field in conductor



Azimuthal stress in conductor

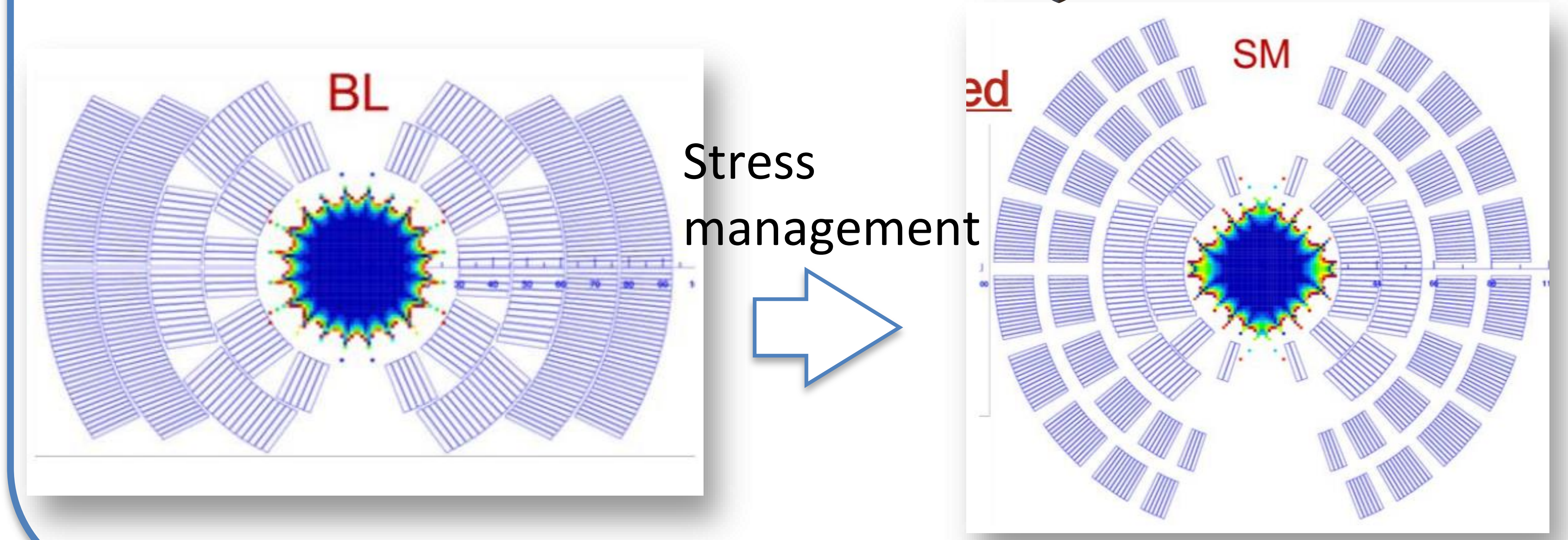
We are looking closely at options for future high-field magnet designs that build on current efforts

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)

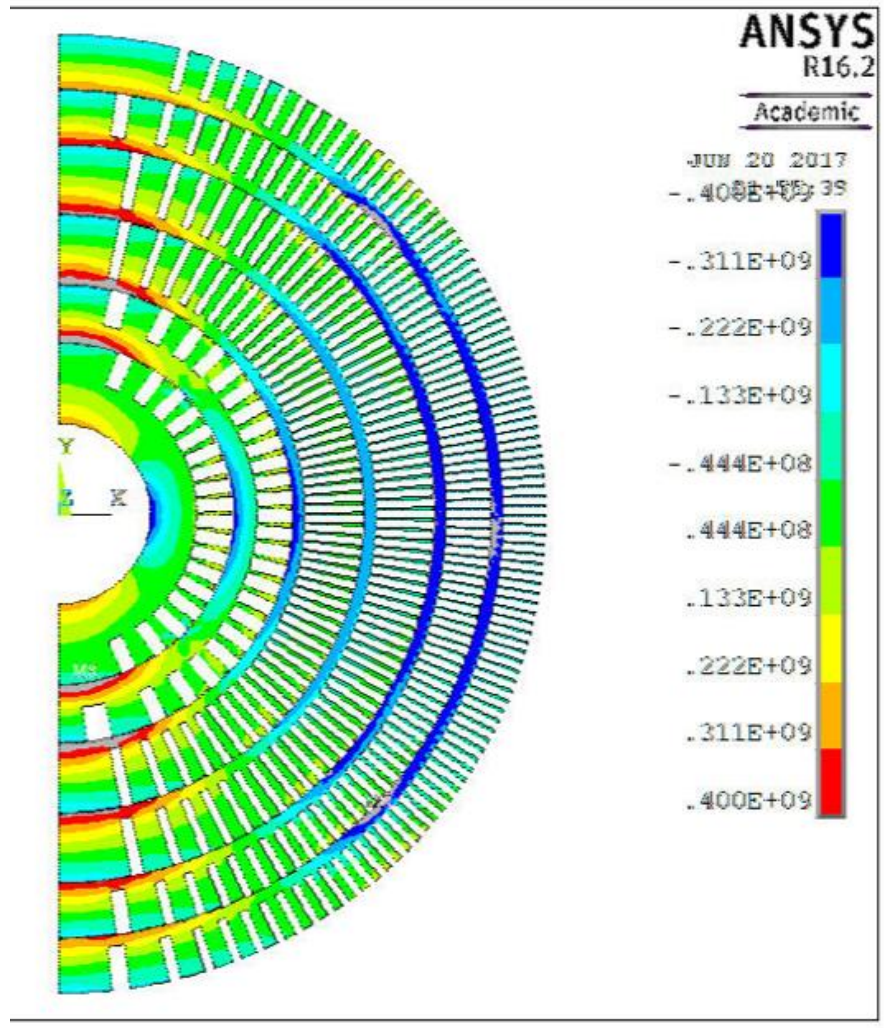


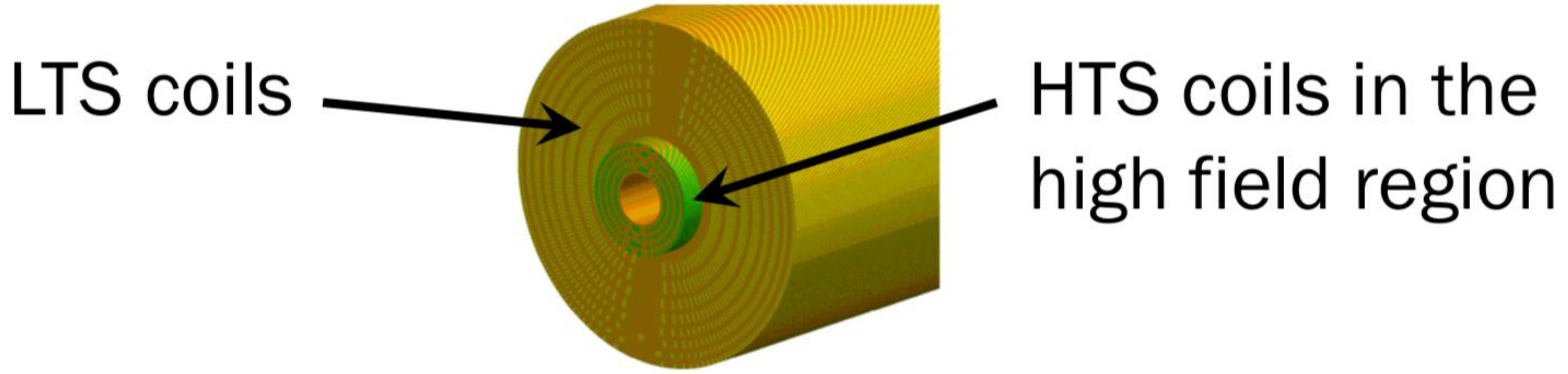
Stress management

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





U.S. MAGNET
DEVELOPMENT
PROGRAM

SMD: Opportunities for DOE and Industry Return to the MDP program

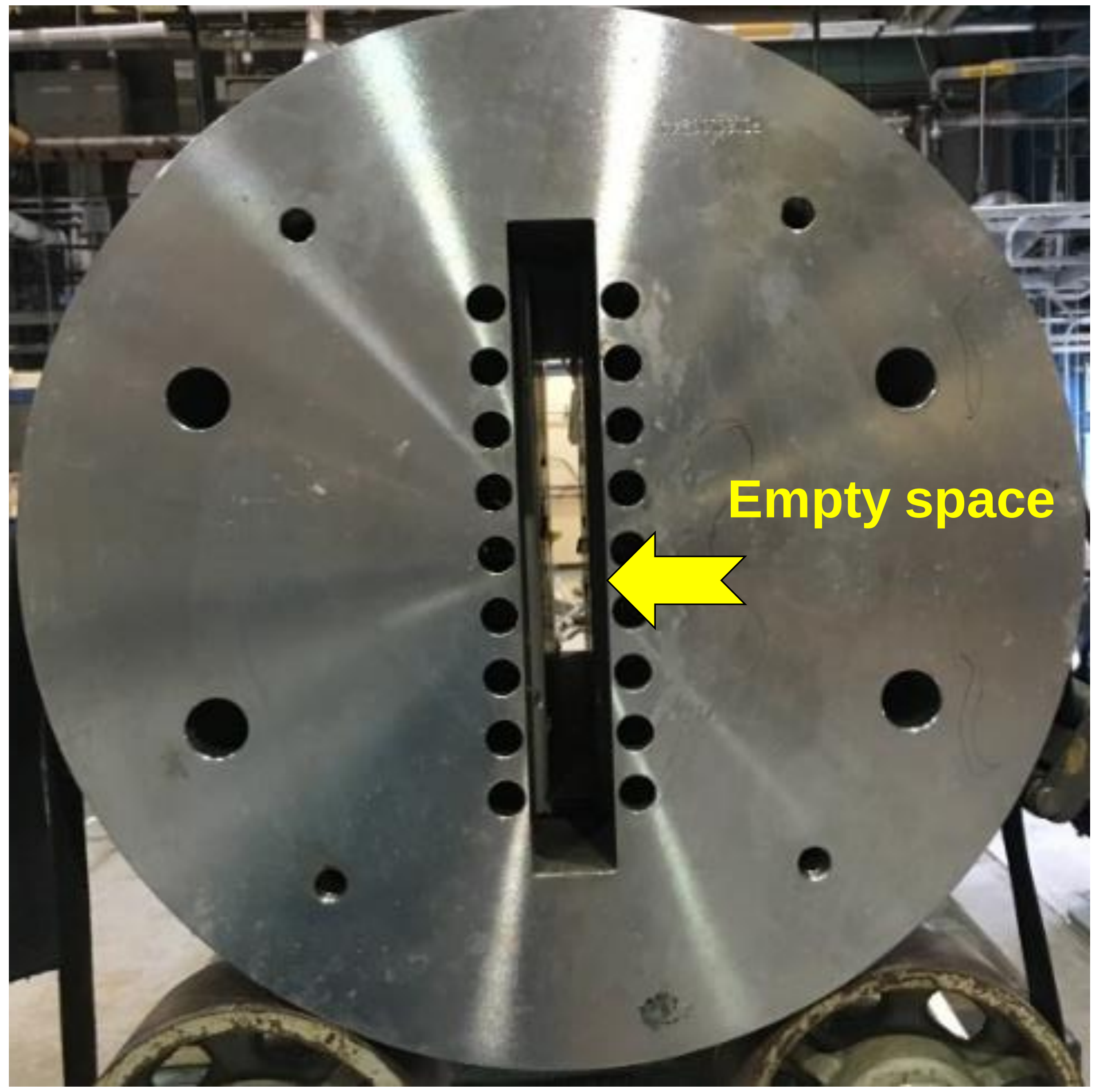
- Brookhaven has unique capabilities and experience in HTS along with a high field test facility (>10T) for small test coils
- MDP is utilizing this capability to address the technology issues of interest today
    - CORC hybrid magnet quench propagation studies
    - Rapid testing of sample coils at high fields to address/understand coil components impacting quench at high fields in REBCO tape coils and field parallel magnetization measurements
- Studying conductor/coil coil configurations at high fields – what technology is needed above 20T?
- BNL is fully engaged with the MDP program to develop the roadmap and utilize its capabilities fully in the MDP program
    - Capability to produce magnet designs and prototypes – both conventional SC magnets and direct wind
    - Extensive testing and magnet characterization capability – utilized by NP and NSLS II
- Synergistic with industry interest in capabilities

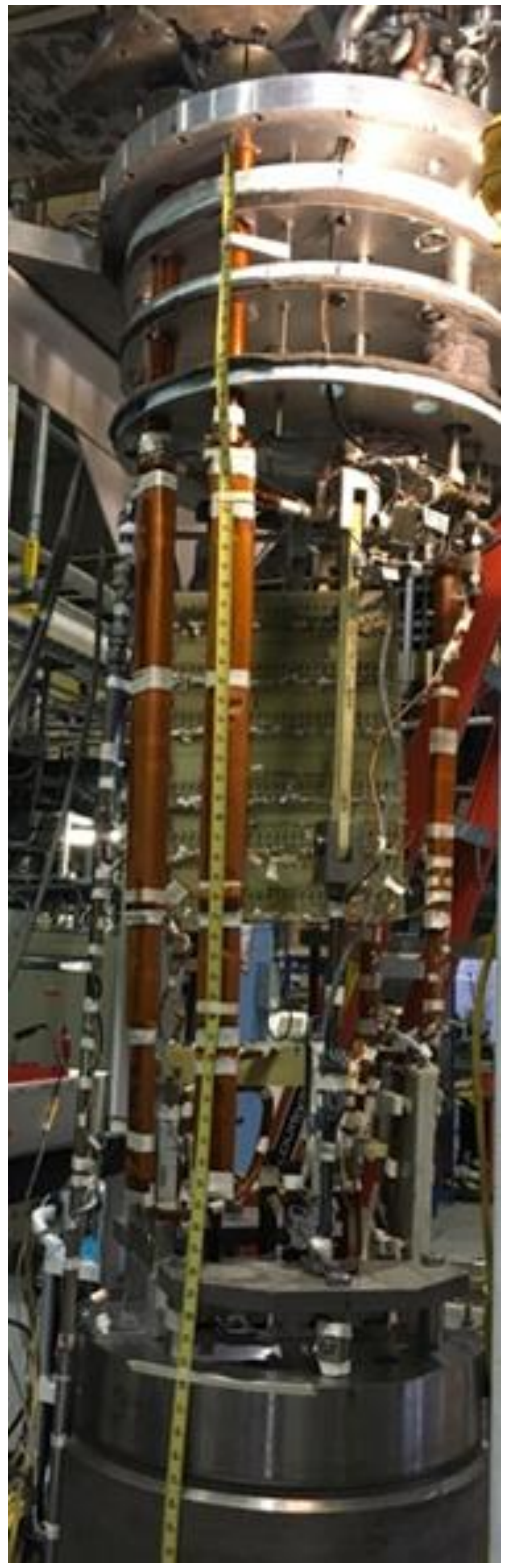
BROOKHAVEN Newsroom Media & Communications Office

U.S. Energy Secretary Honors Brookhaven Lab Team for Building Large Hadron Collider Magnets

U.S. MAGNET DEVELOPMENT PROGRAM

BNL Nb_3Sn Common coil dipole - A Unique Test Facility for MDP

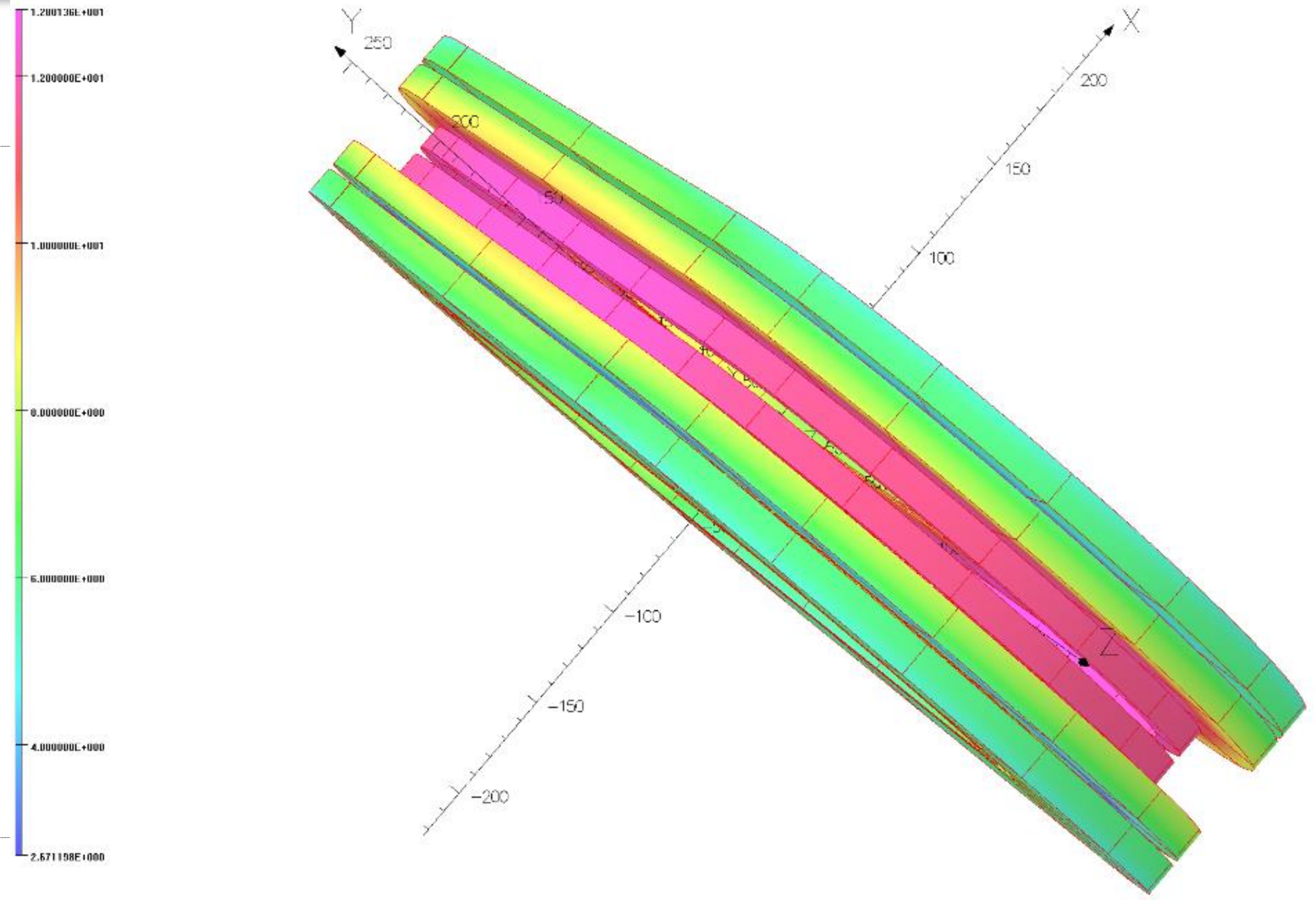




- A Nb_3Sn dipole providing a background field up to 10 T
- Large open space: 31 mm wide and 335 mm high
- Cable with large bend radius can be easily accommodated
- Cable can be looped inside the high field region for a long length in-field test
- To be used for HTS magnetization and CORC studies

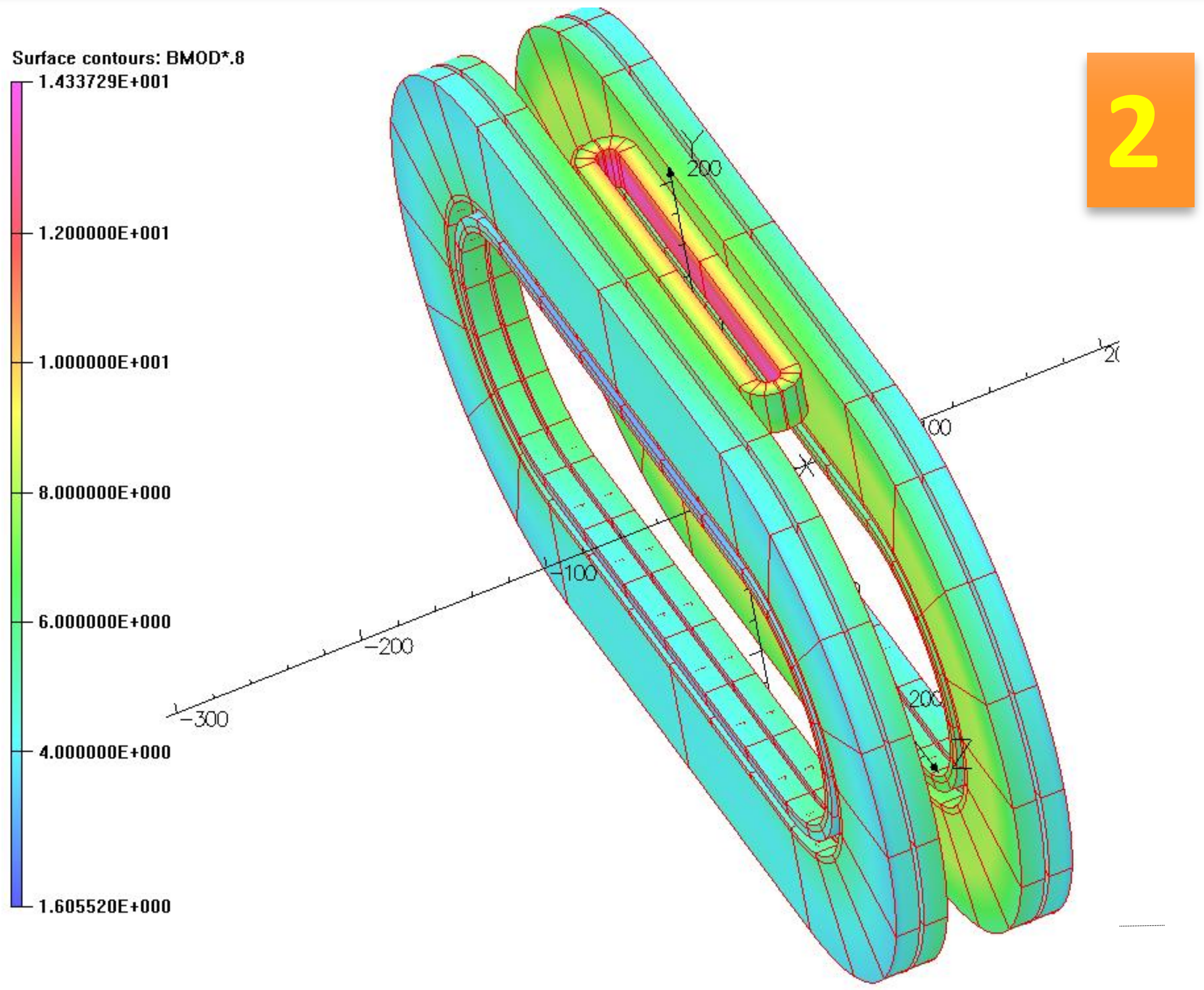
Four Possible Configurations for Insert Coils and Cable Tests

Standard insert coil test configuration



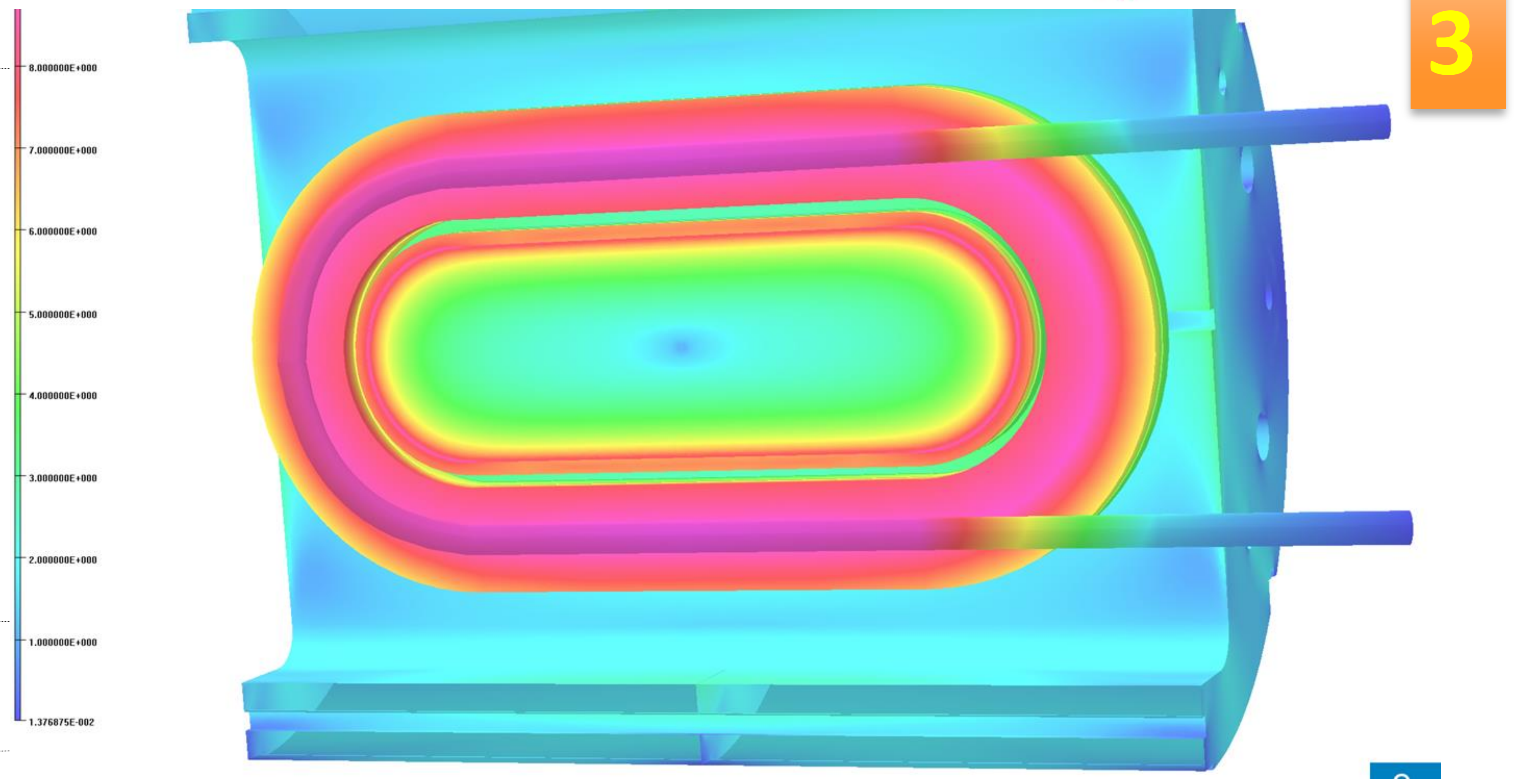
1

2



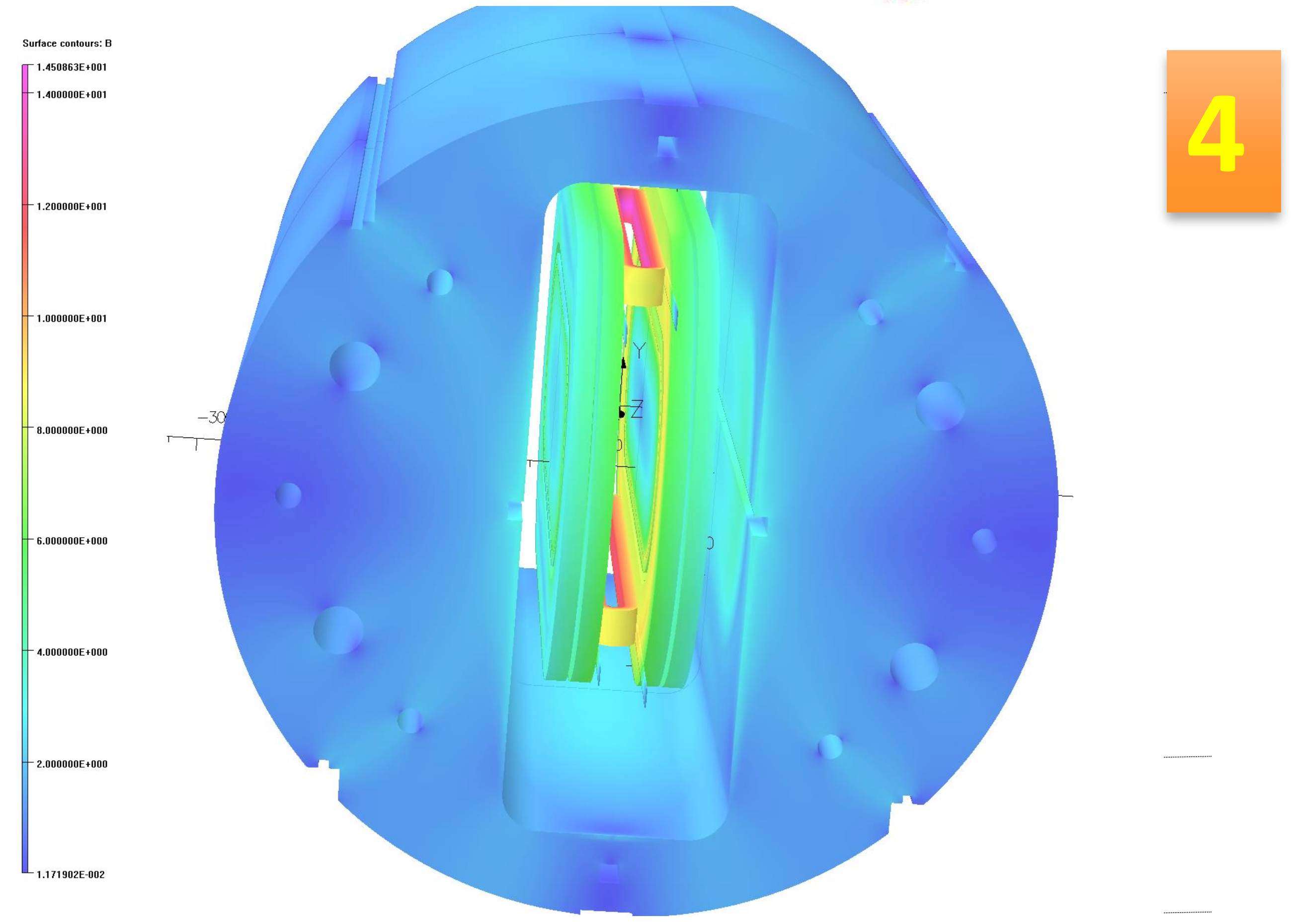
One insert coil in one aperture

Cable test configuration



3

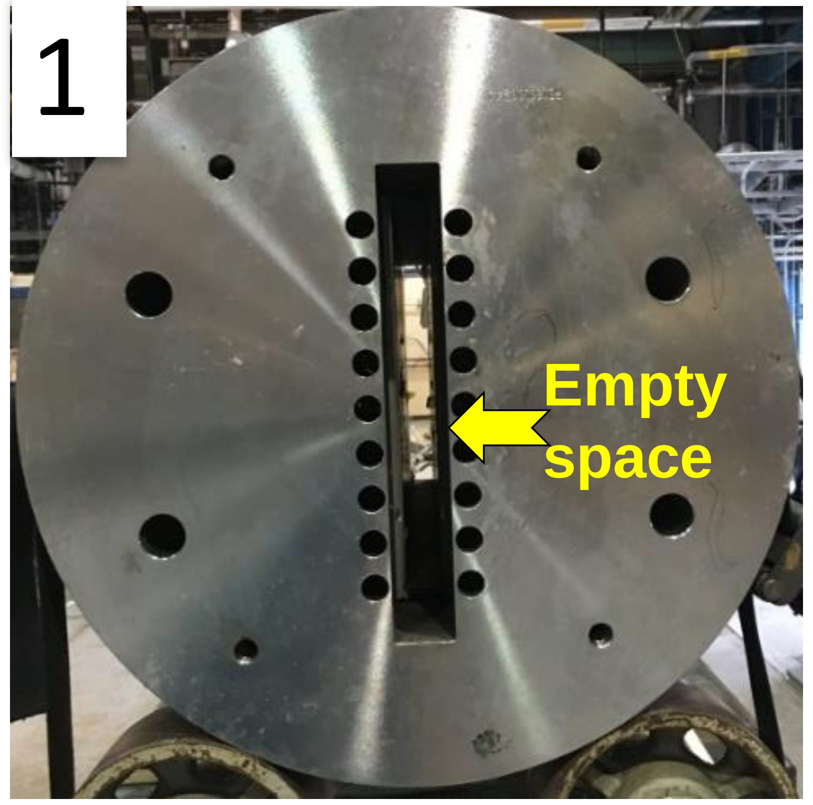
4



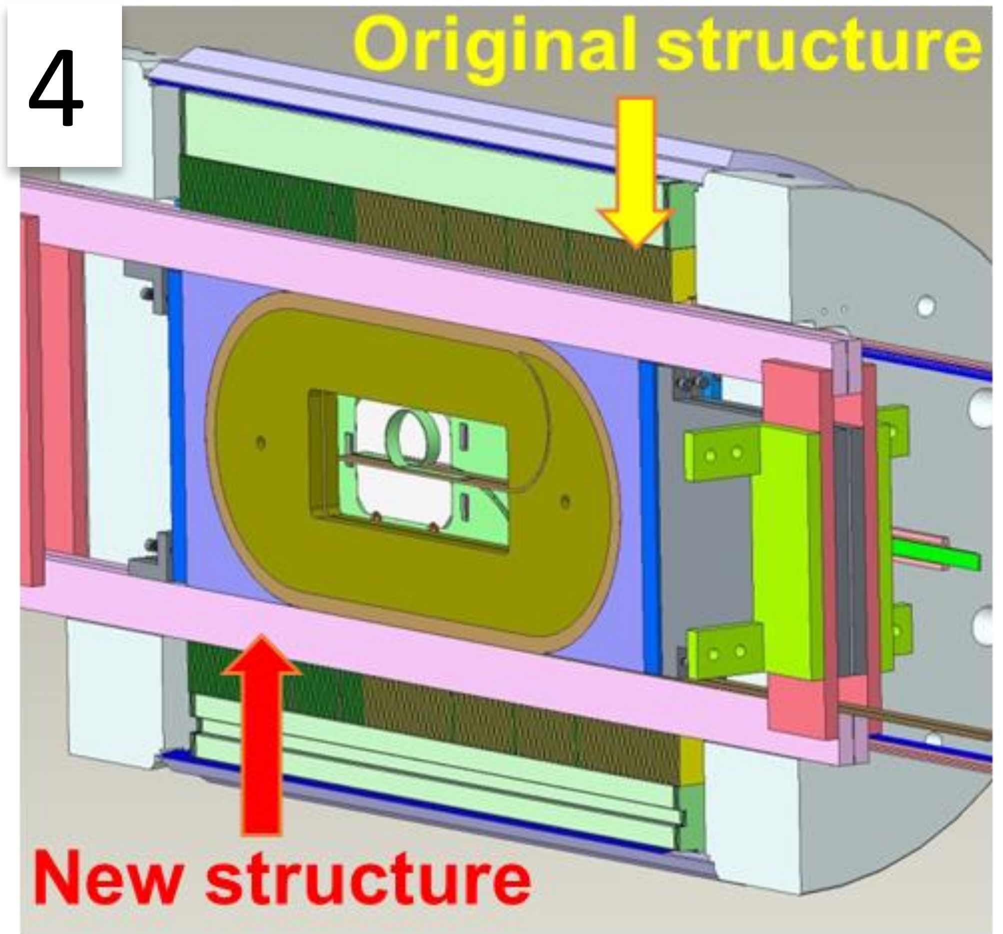
Two independent insert coils in two aperture

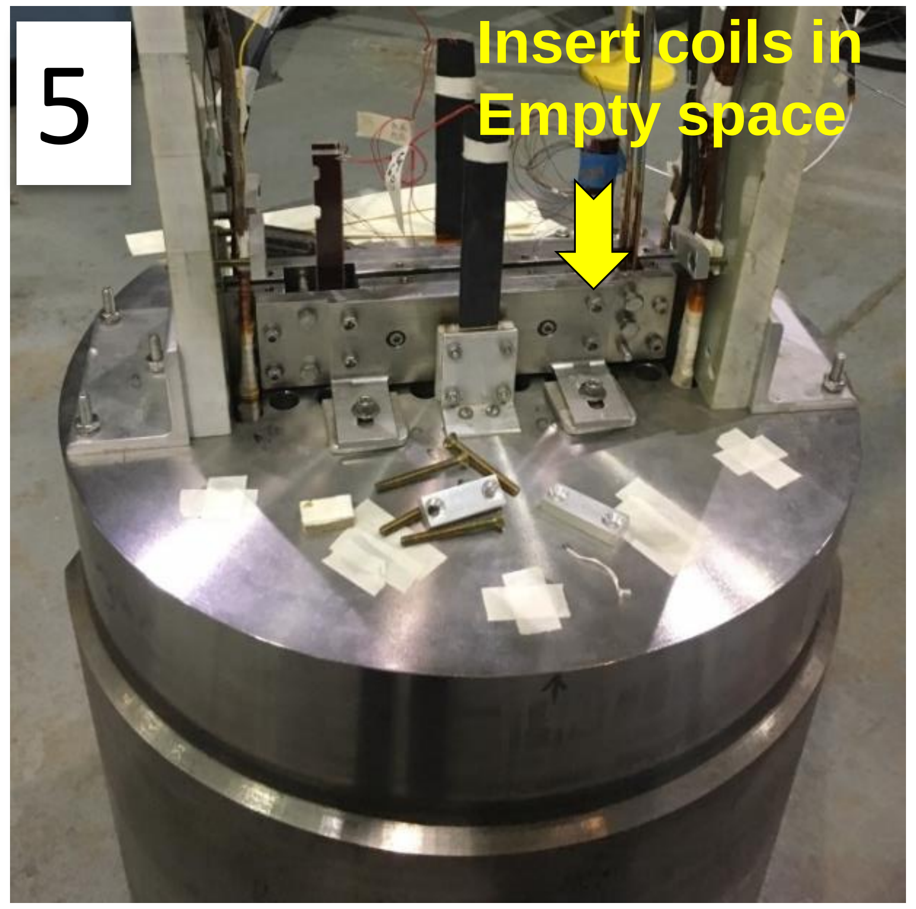
Rapid turn-around, Low-cost Hybrid Tests of R&D HTS Coils (total field: ~15 T)

Five Simple Steps/Components



1. Magnet (dipole) with a large open space
2. Coil for high field testing
3. Slide coil in the magnet
4. Coils become an integral part of the magnet
5. Magnet with new coil(s) ready for testing



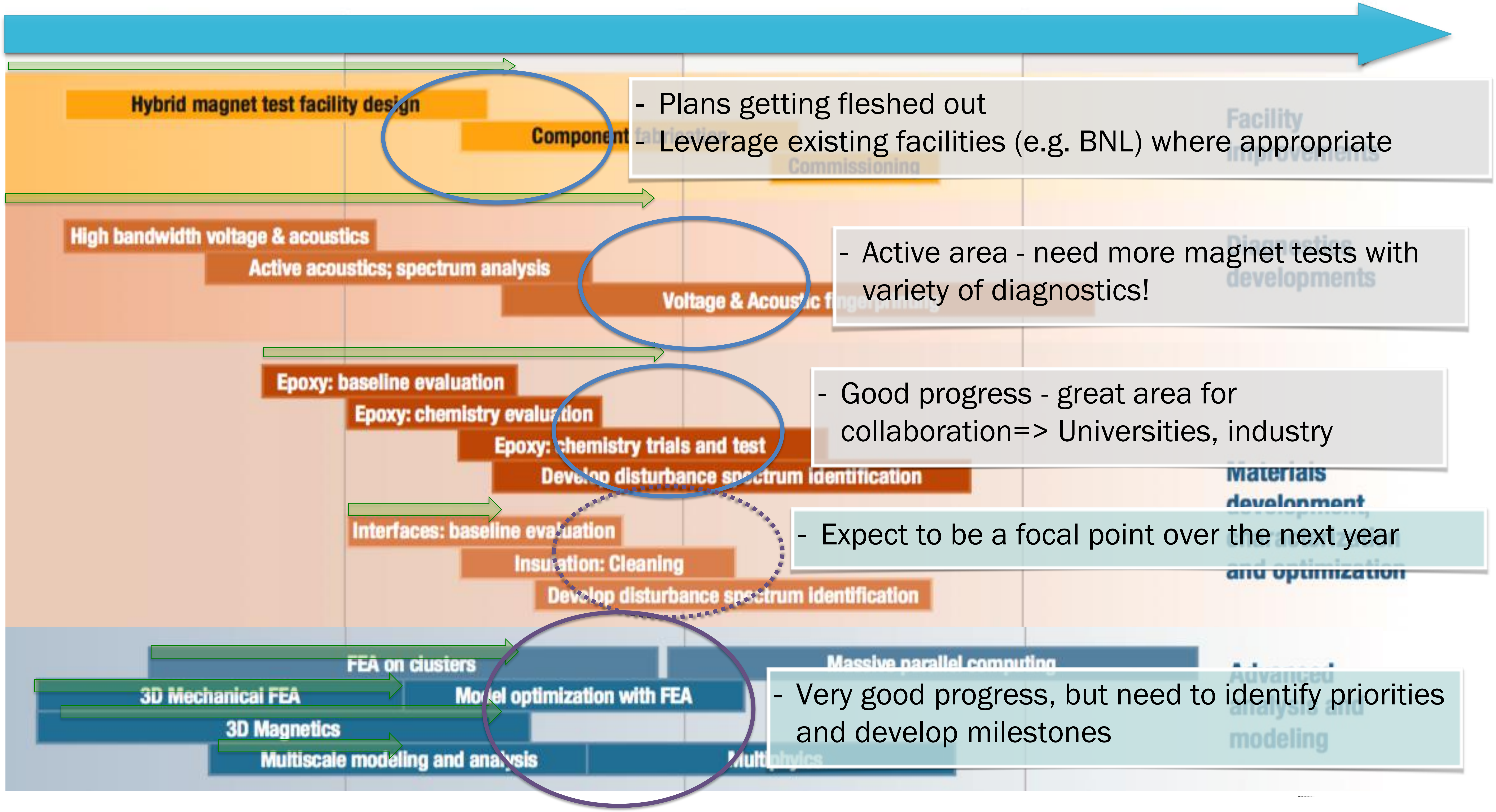


Brookhaven is ready to test hybrid racetrack dipoles today at combined fields approaching 15T

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



- Plans getting fleshed out
- Leverage existing facilities (e.g. BNL) where appropriate

- Active area - need more magnet tests with variety of diagnostics!

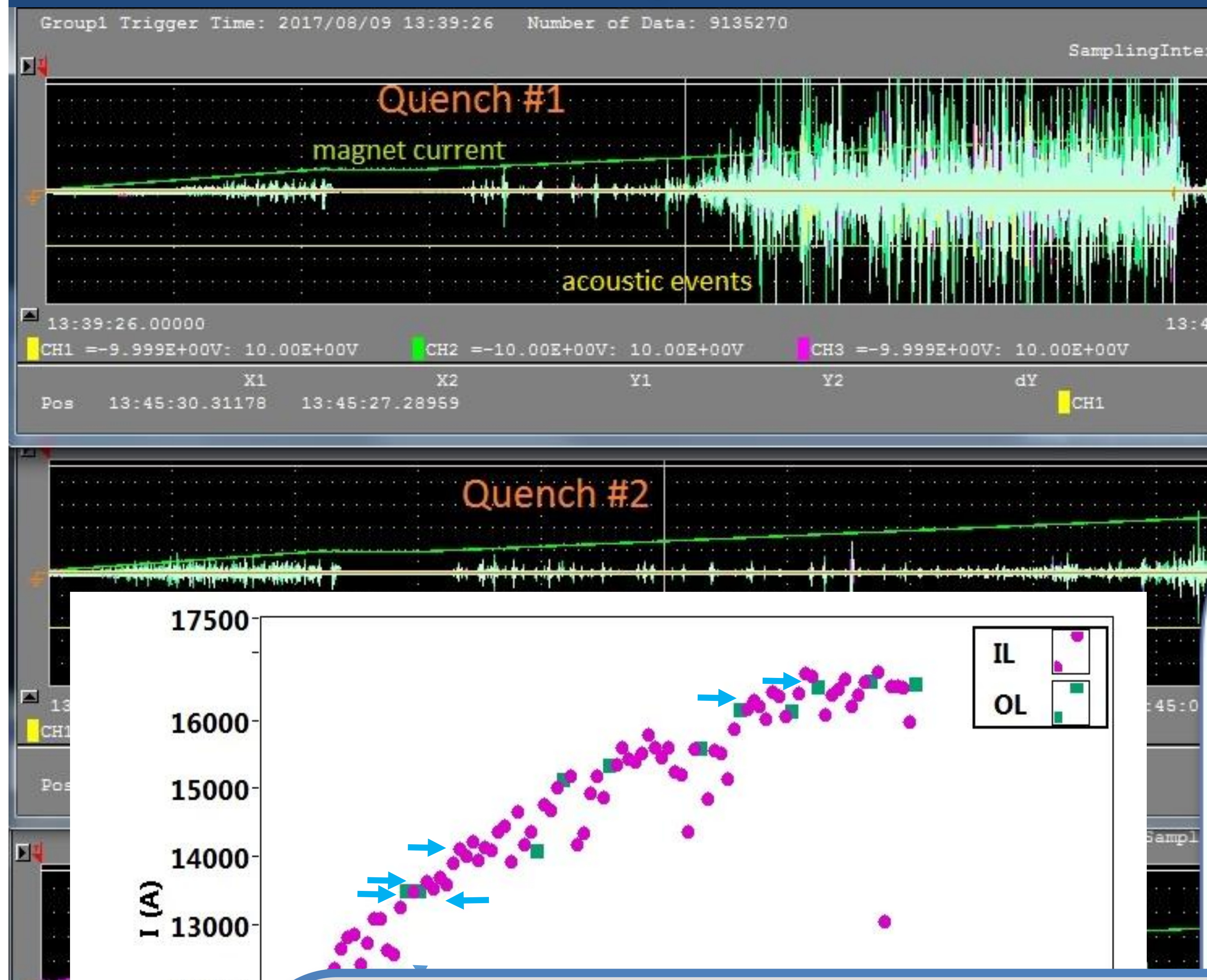
- Good progress - great area for collaboration=> Universities, industry

- Expect to be a focal point over the next year

- Very good progress, but need to identify priorities and develop milestones

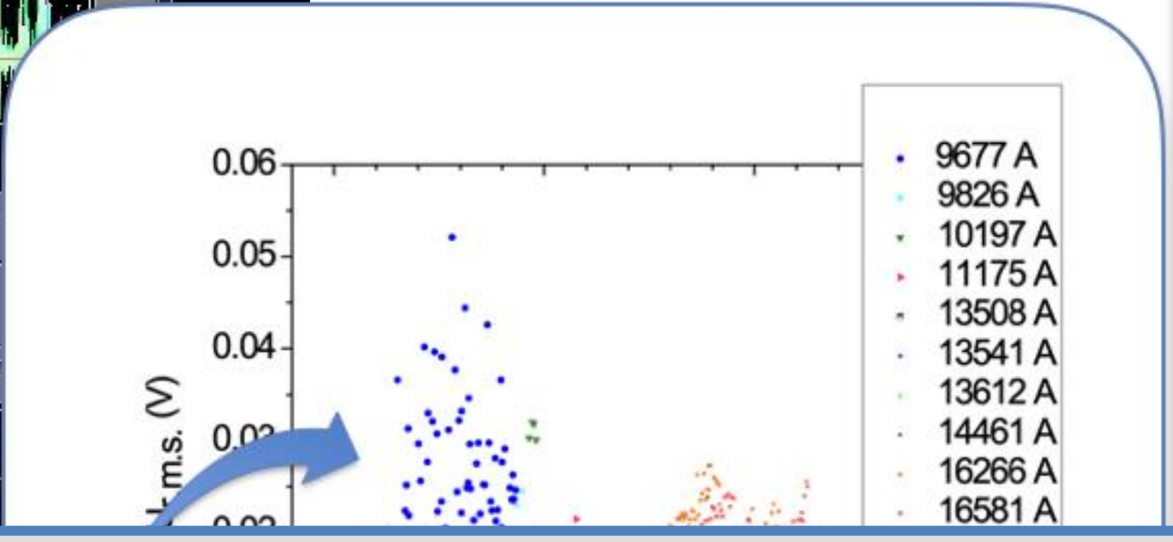
U.S. MAGNET DEVELOPMENT PROGRAM

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

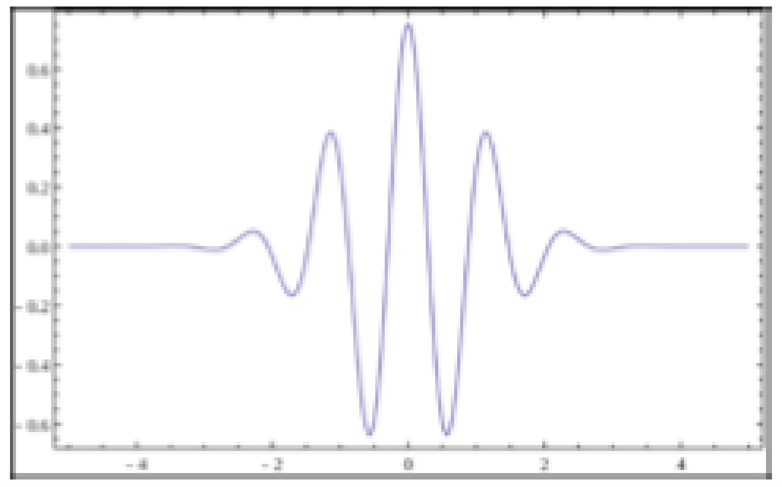


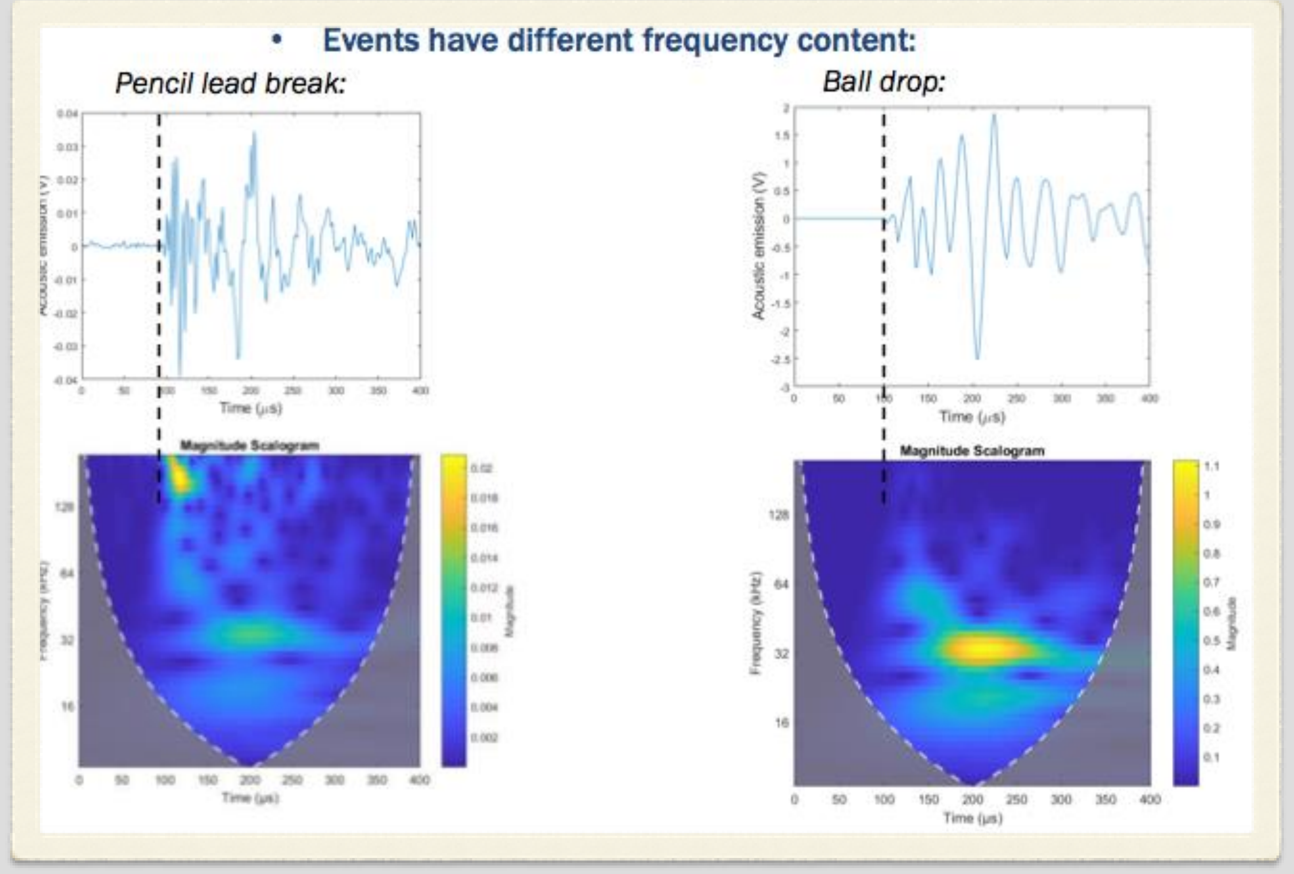
```
Group1 Trigger Time: 2017/08/09 13:39:26   Number of Data: 9135270
                                                SamplingInterval:40.000us
13:39:26.00000                                            13:45:31.41076
CH1 =-9.999E+00V: 10.00E+00V   CH2 =-10.00E+00V: 10.00E+00V   CH3 =-9.999E+00V: 10.00E+00V
          X1               X2              Y1        Y2        dY          X1
Pos   13:45:30.31178   13:45:27.28959                          CH1     6.5537mV
```

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



Wavelet analysis provides robust mathematical platform for transient signal analysis

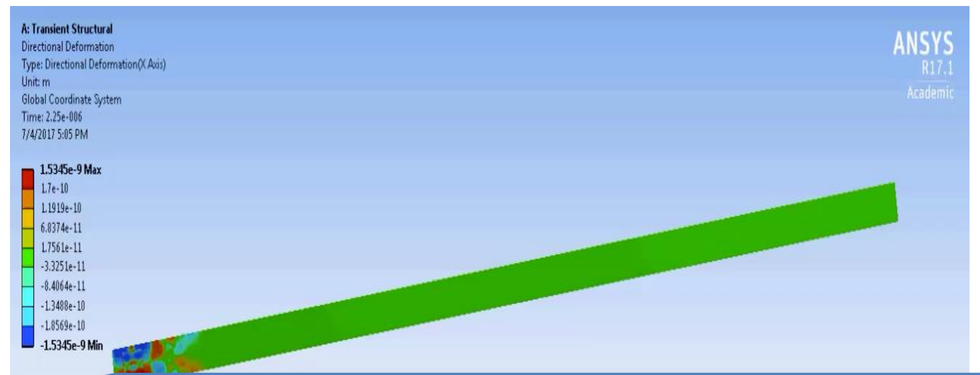


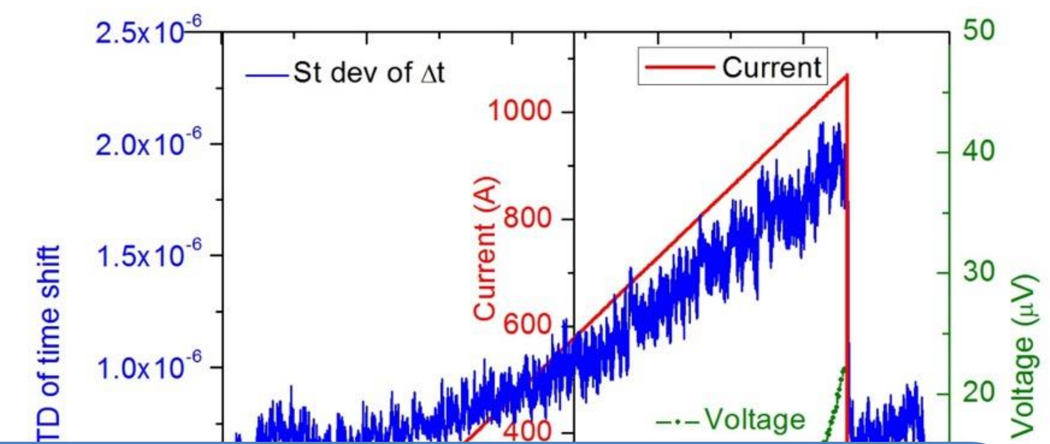


- Events have different frequency content:

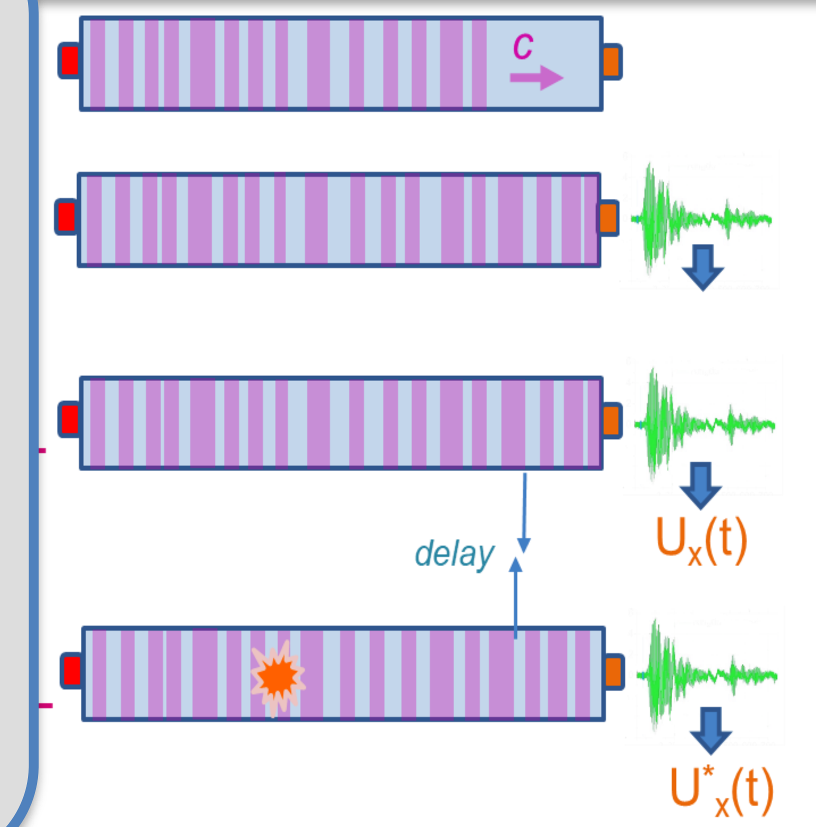
Active acoustics can utilize phase-shift of the complex signal response pattern to identify thermal changes in the system => independent mechanism to see transition

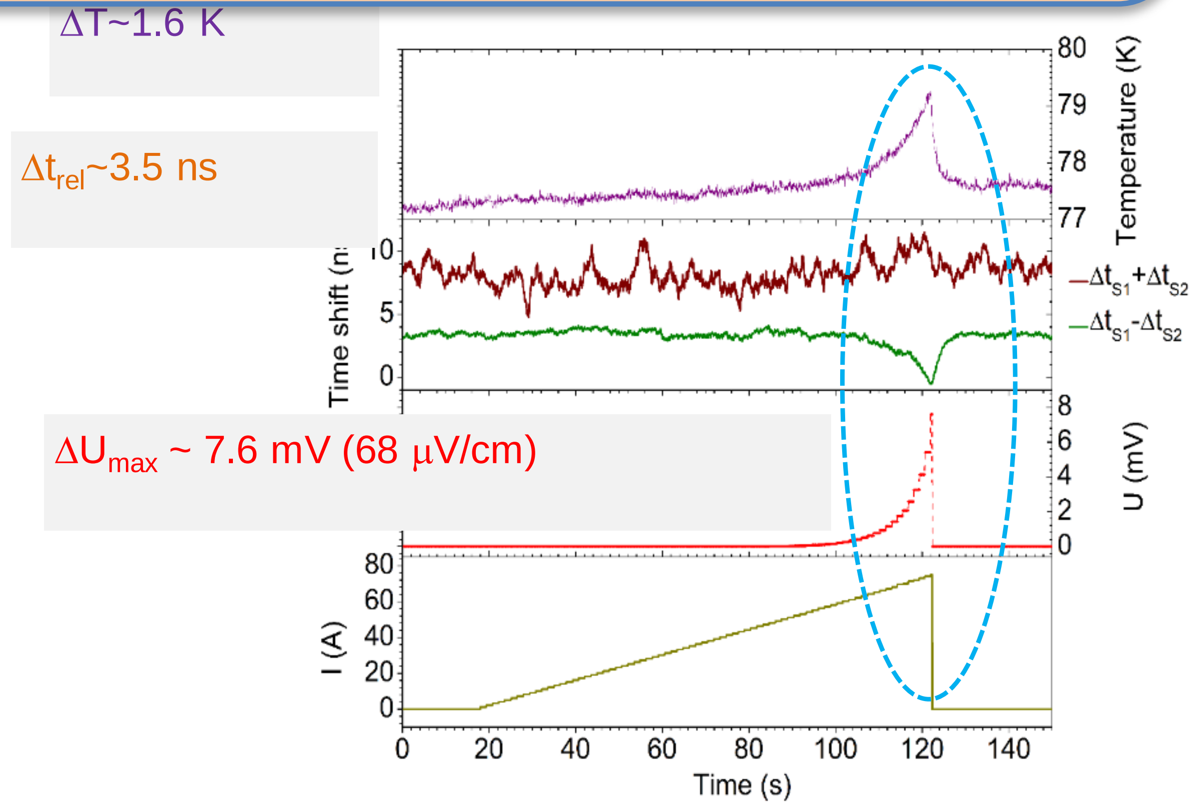
ReBCO tape experiment





- "**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

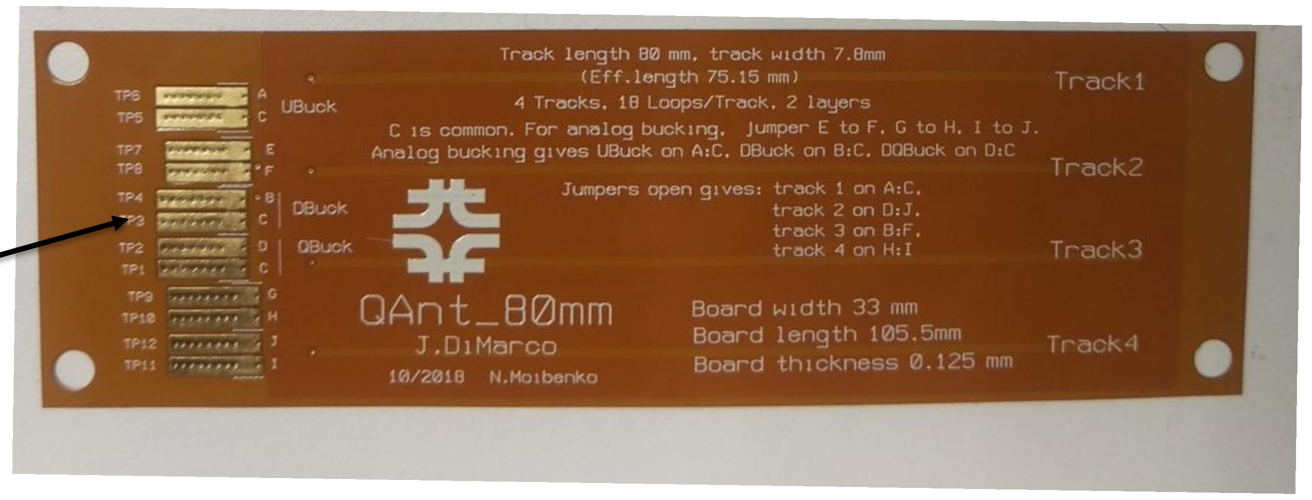




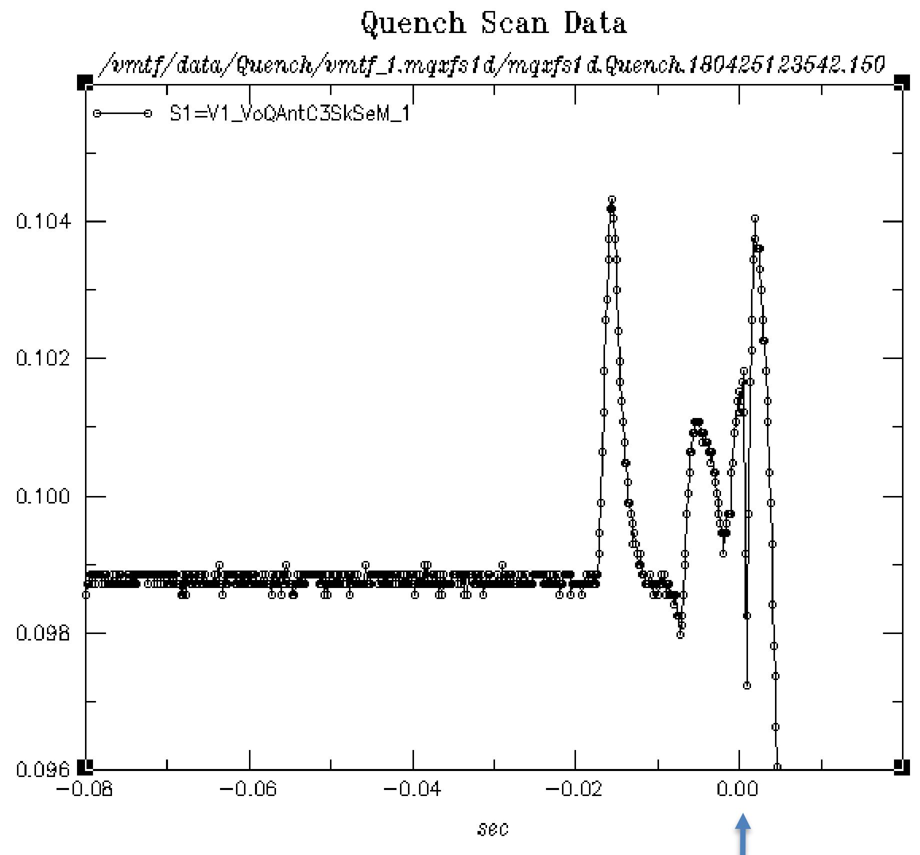
Novel magnetic measurement and quench antennae designs are providing new and complementary insight into magnet behavior

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.**

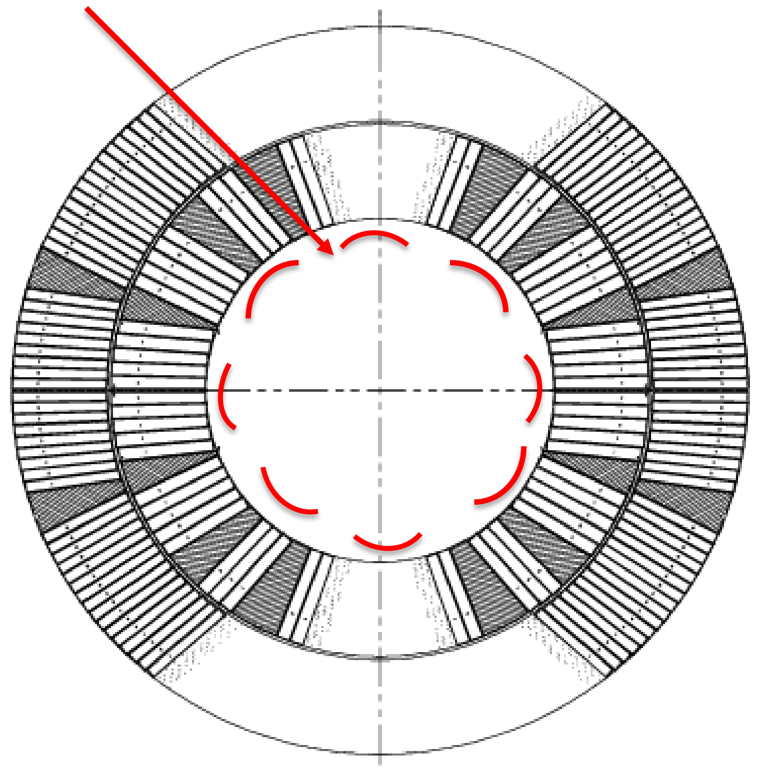


Pads improved to withstand more heat during soldering

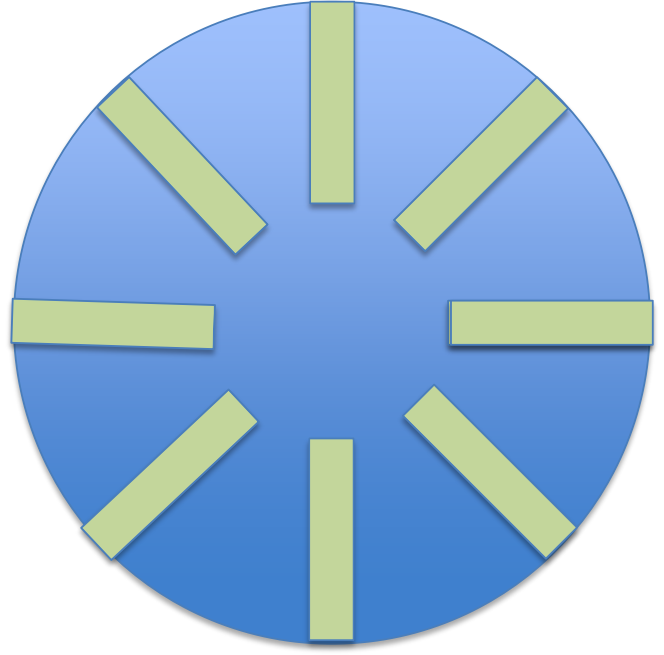


Quench detection trigger

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.

IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2020.
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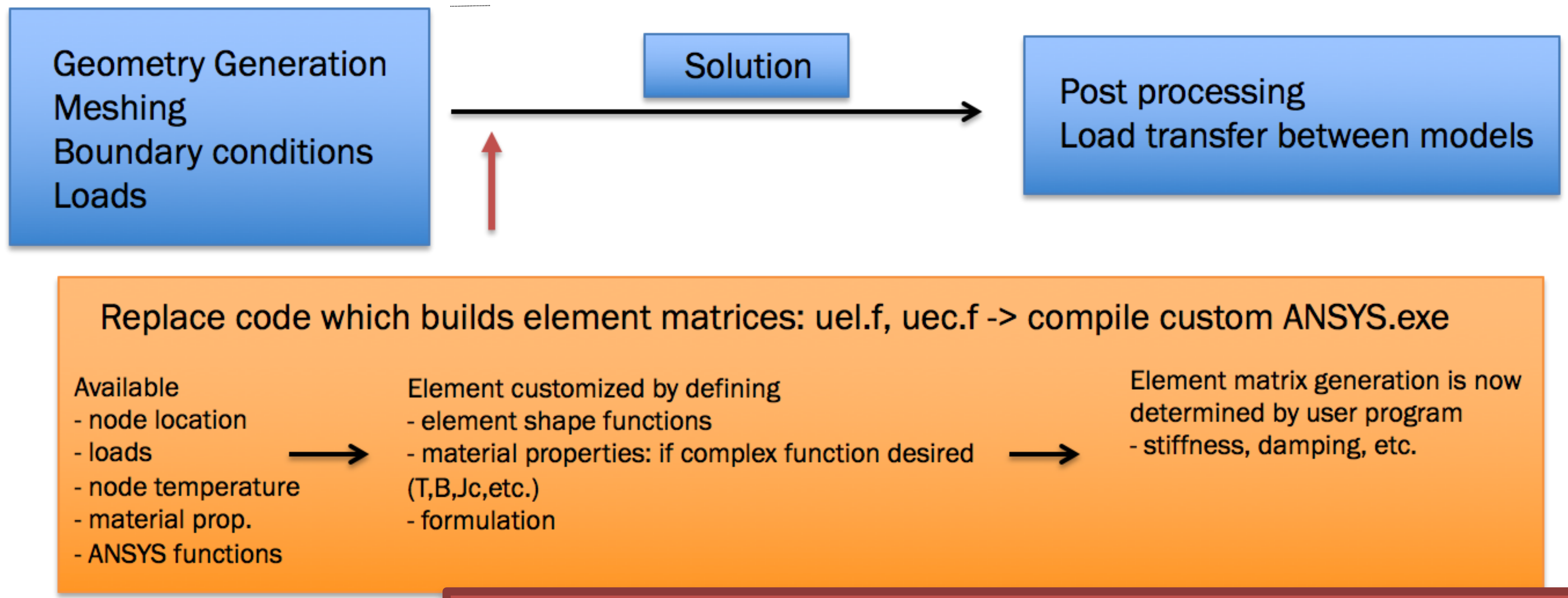
Modeling capabilities continue to be developed that have broad applicability to superconducting magnet technology

- 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

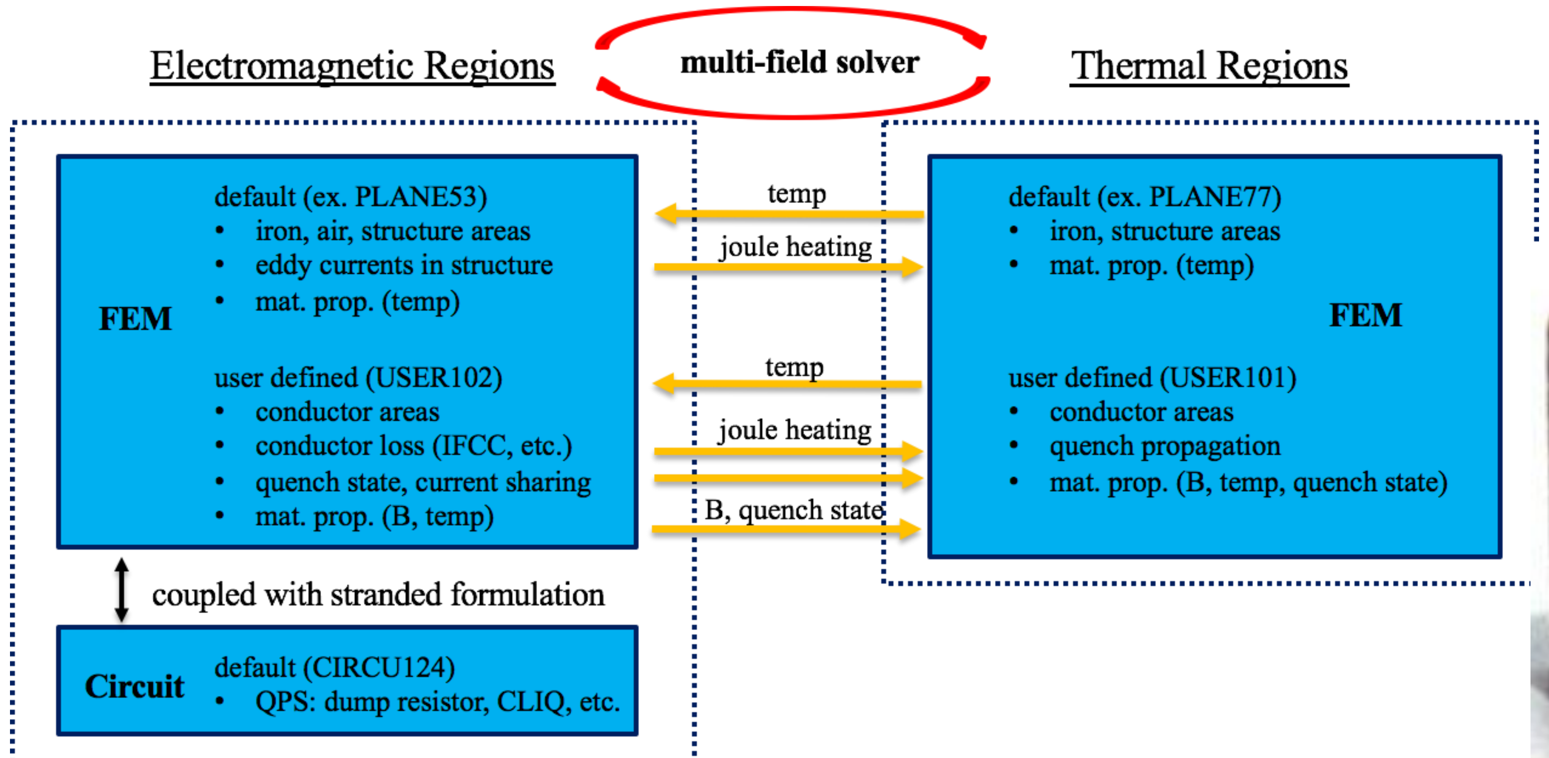
Available
- node location
- loads
- node temperature
- material prop.
- ANSYS functions

→

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.



Electromagnetic Regions | multi-field solver | Thermal Regions

FEM

default (ex. PLANE53)
- iron, air, structure areas
- eddy currents in structure
- mat. prop. (temp)

user defined (USER102)
- conductor areas
- conductor loss (IFCC, etc.)
- quench state, current sharing
- mat. prop. (B, temp)

coupled with stranded formulation

Circuit

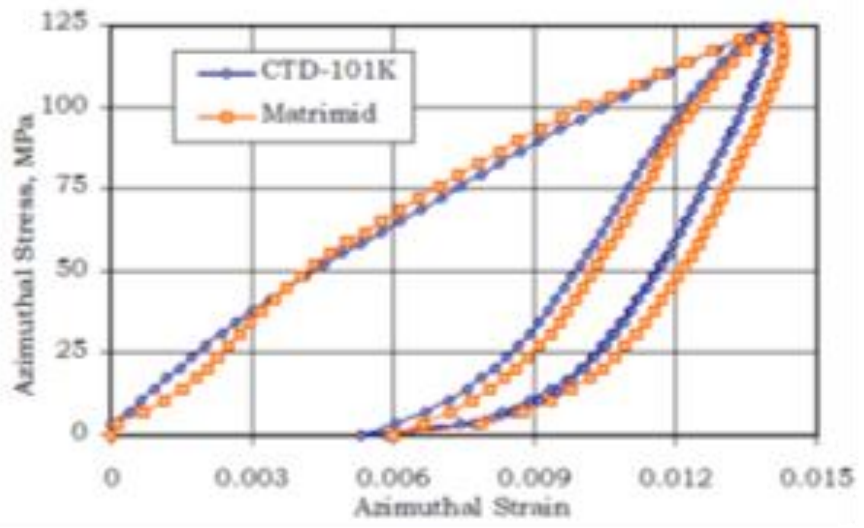
default (CIRCU124)
- QPS: dump resistor, CLIQ, etc.

FEM

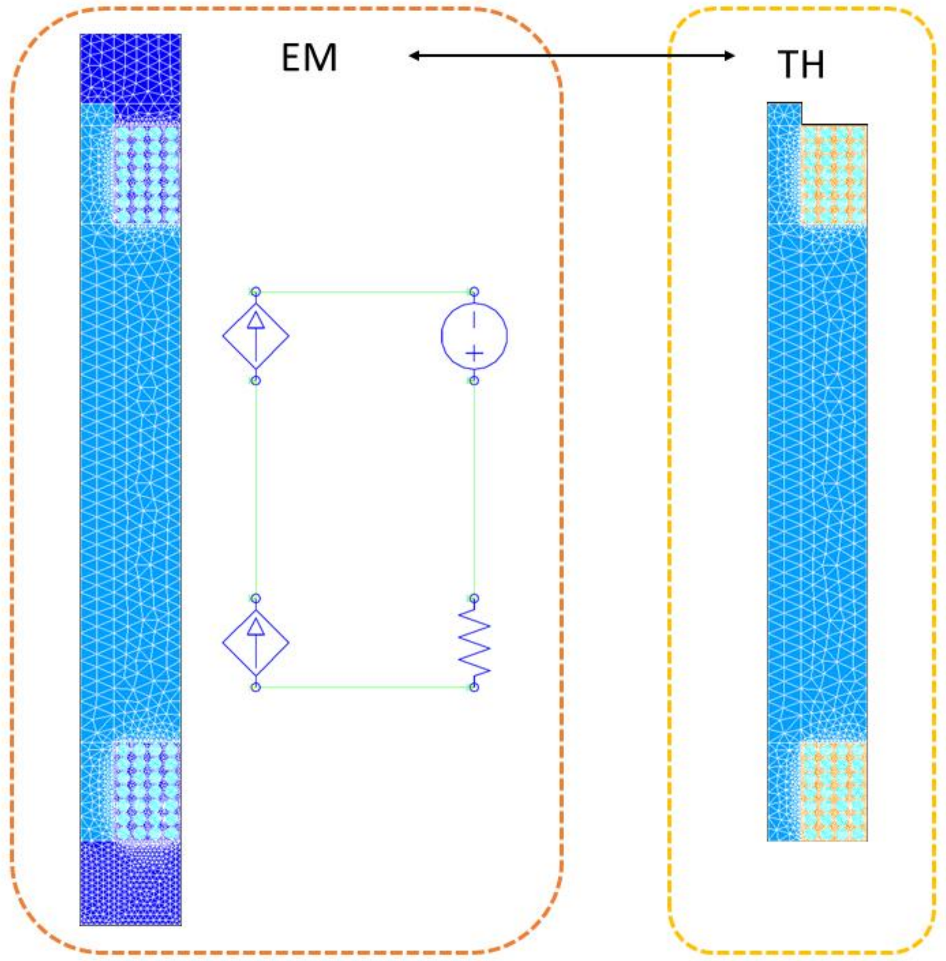
default (ex. PLANE77)
- iron, structure areas
- mat. prop. (temp)

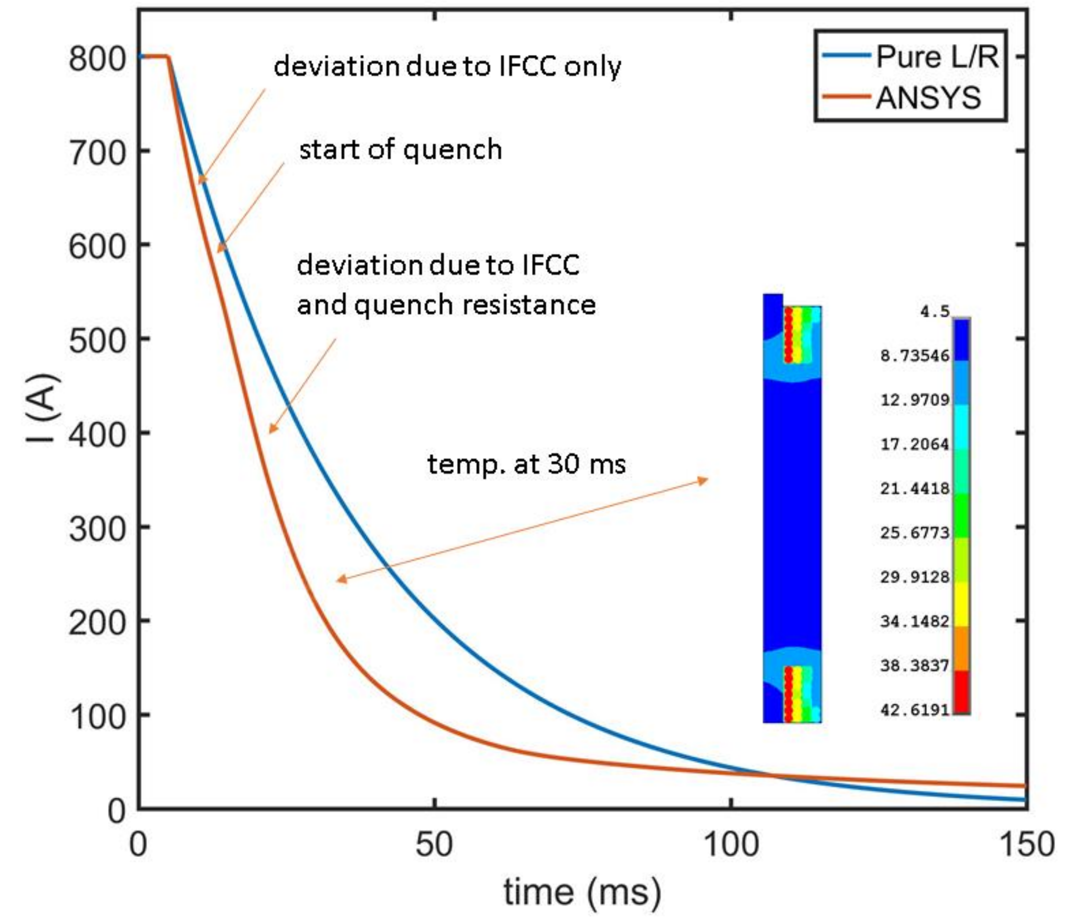
user defined (USER101)
- conductor areas
- quench propagation
- mat. prop. (B, temp, quench state)

S. Krave, FNAL



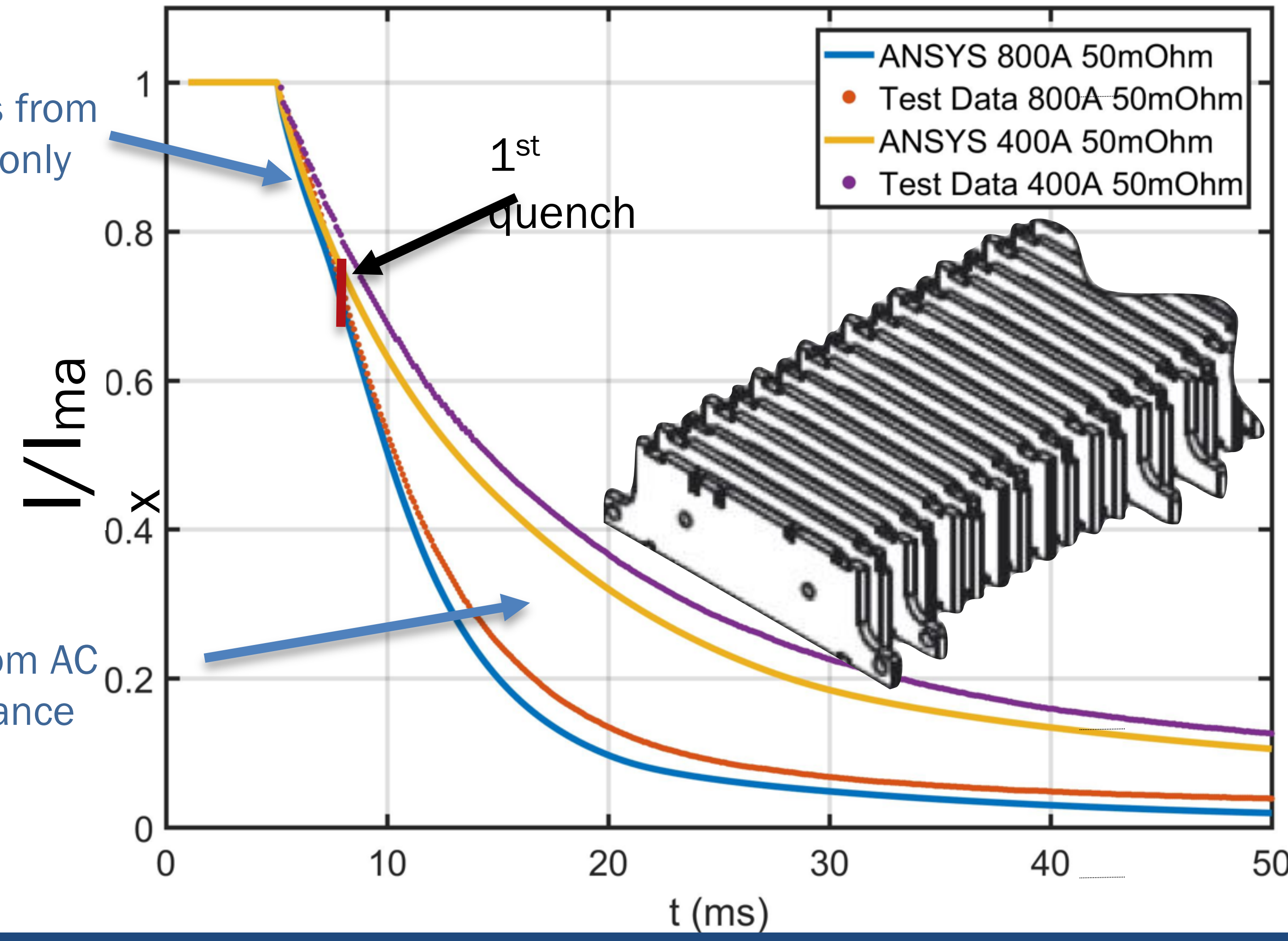
Brouwer, LBNL; Auchmann, PSI/CERN





Deviations from AC losses only

Deviations from AC losses, resistance growth, yoke saturation



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**

Session Ia - Magnet Pull - High Energy Physics

Session Chairs: Dave Sutter & Bruce Strauss

35 years of exceptional service to the community

ASC NATIONAL MAGLAB

U.S. MAGNET DEVELOPMENT PROGRAM

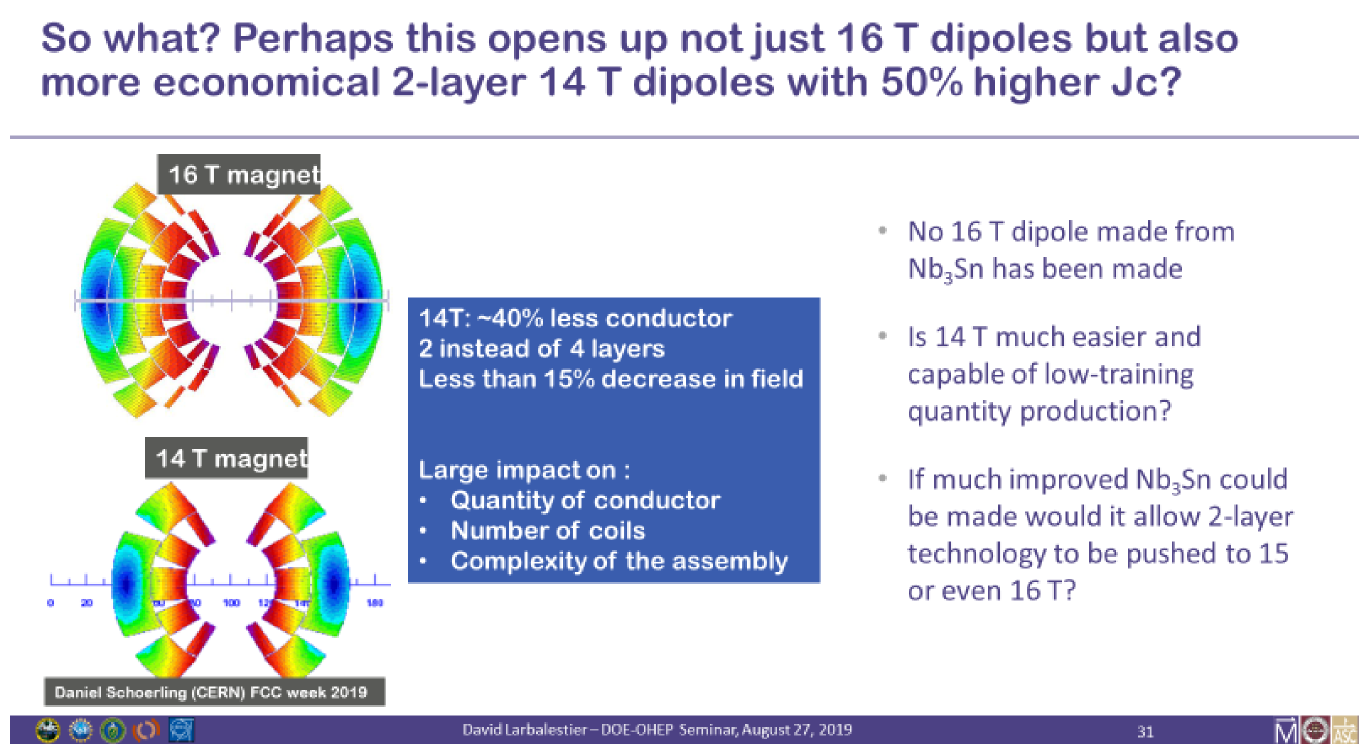
Lance Cooley, Ph.D.
Head, Conductor Procurement and R&D Program
US HEP Magnet Development Program
Applied Superconductivity Center, National High Magnetic Field Laboratory
2031 E. Paul Dirac Dr, Tallahassee, FL 32310-3711 USA
ldcooley@asc.magnet.fsu.edu

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

Covering DOE FY 2018

There is a path forward for Nb_3Sn to higher fields!

- **Hf additions to Nb-4Ta provide <<100 nm Nb_3Sn grain size due to additional GB diffusion paths provided by enhanced recrystallization temperature.**
    - Demonstrated in both ASC monofilaments and Hypertech-Fermilab multifilament conductors for Nb_3Sn reaction heat treatments at 625°C-675°C.
    - Enhanced H_{max} (4.2 K) and unsuppressed H_{irr}(4.2 K) is verified by Hyper Tech multi-filament conductor
    - Hyper Tech wires with Sn-oxide may provides additional interesting opportunities also.
- **Nb-Ta-Hf conductors provide avenues in various architecture types.**
    - Fine-grain (~50 nm) Nb_3Sn by optimization of Hf doping provides a direct avenue to implement the new alloy in RRP, bronze route, and PIT configurations.
    - Additions of oxygen as advanced by Ohio State-Hypertech-Fermilab seems to enhance H_{max} and are being evaluated in PIT conductor form by them.



So what? Perhaps this opens up not just 16 T dipoles but also more economical 2-layer 14 T dipoles with 50% higher Jc?

Daniel Schoerling (CERN) FCC week 2019

14T: ~40% less conductor
2 instead of 4 layers
Less than 15% decrease in field

Large impact on :
- Quantity of conductor
- Number of coils
- Complexity of the assembly

- No 16 T dipole made from Nb_3Sn has been made
- Is 14 T much easier and capable of low-training quantity production?
- If much improved Nb_3Sn could be made would it allow 2-layer technology to be pushed to 15 or even 16 T?

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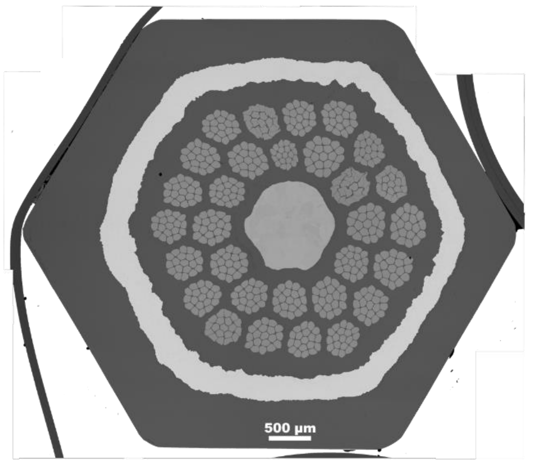
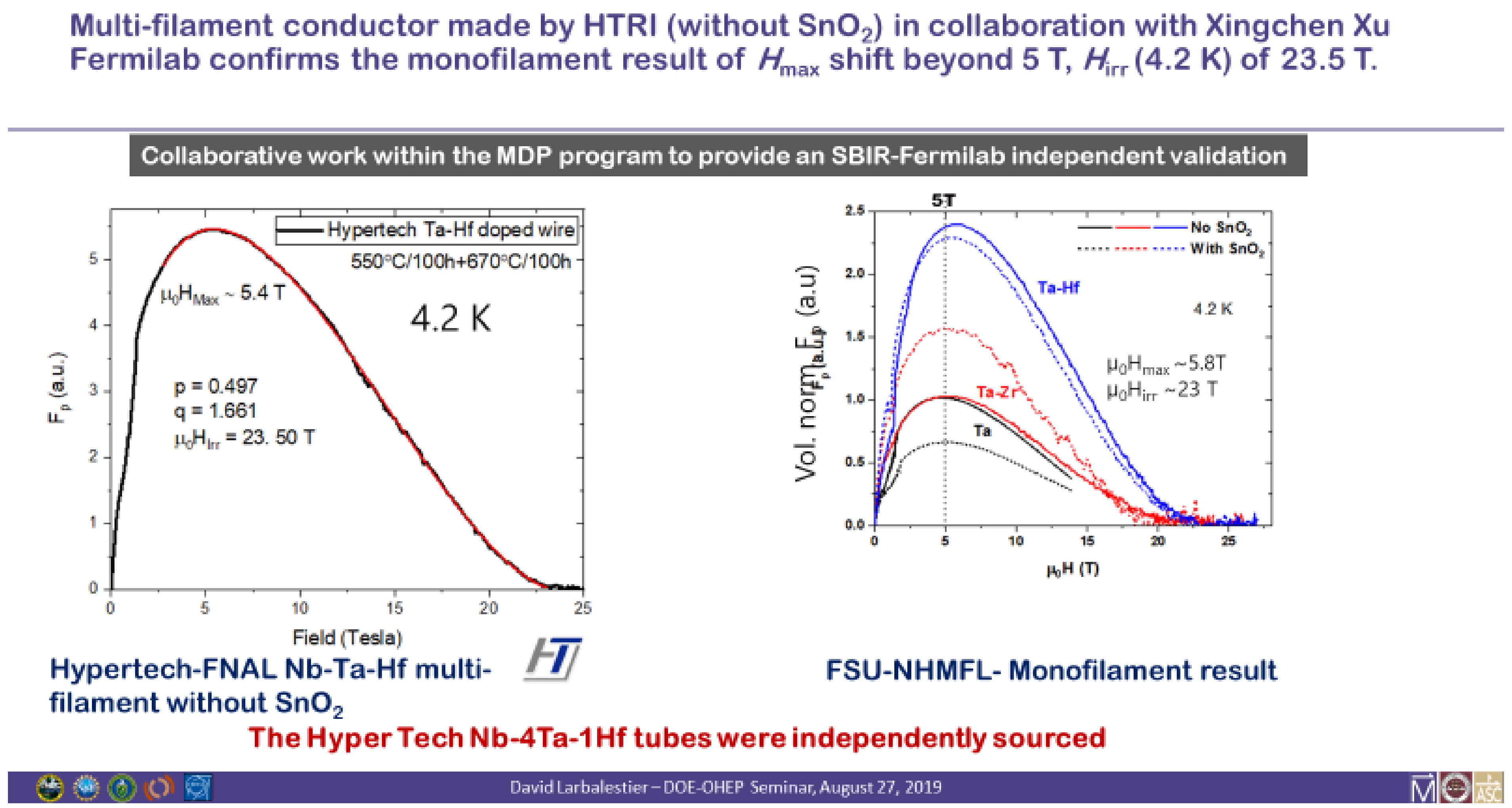
Nb-4Ta filaments are at 100µm.
Nb-4Ta total true strain of 10.6.





Multi-filament conductor made by HTRI (without SnO_2) in collaboration with Xingchen Xu Fermilab confirms the monofilament result of H_{max} shift beyond 5 T, H_{irr} (4.2 K) of 23.5 T.

Collaborative work within the MDP program to provide an SBIR-Fermilab independent validation

Hypertech-FNAL Nb-Ta-Hf multi-filament without SnO_2

FSU-NHMFL- Monofilament result

The Hyper Tech Nb-4Ta-1Hf tubes were independently sourced

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IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2020.
Plenary presentation PL2-INV given at ISS, 3-5 December 2019, Kyoto, Japan.

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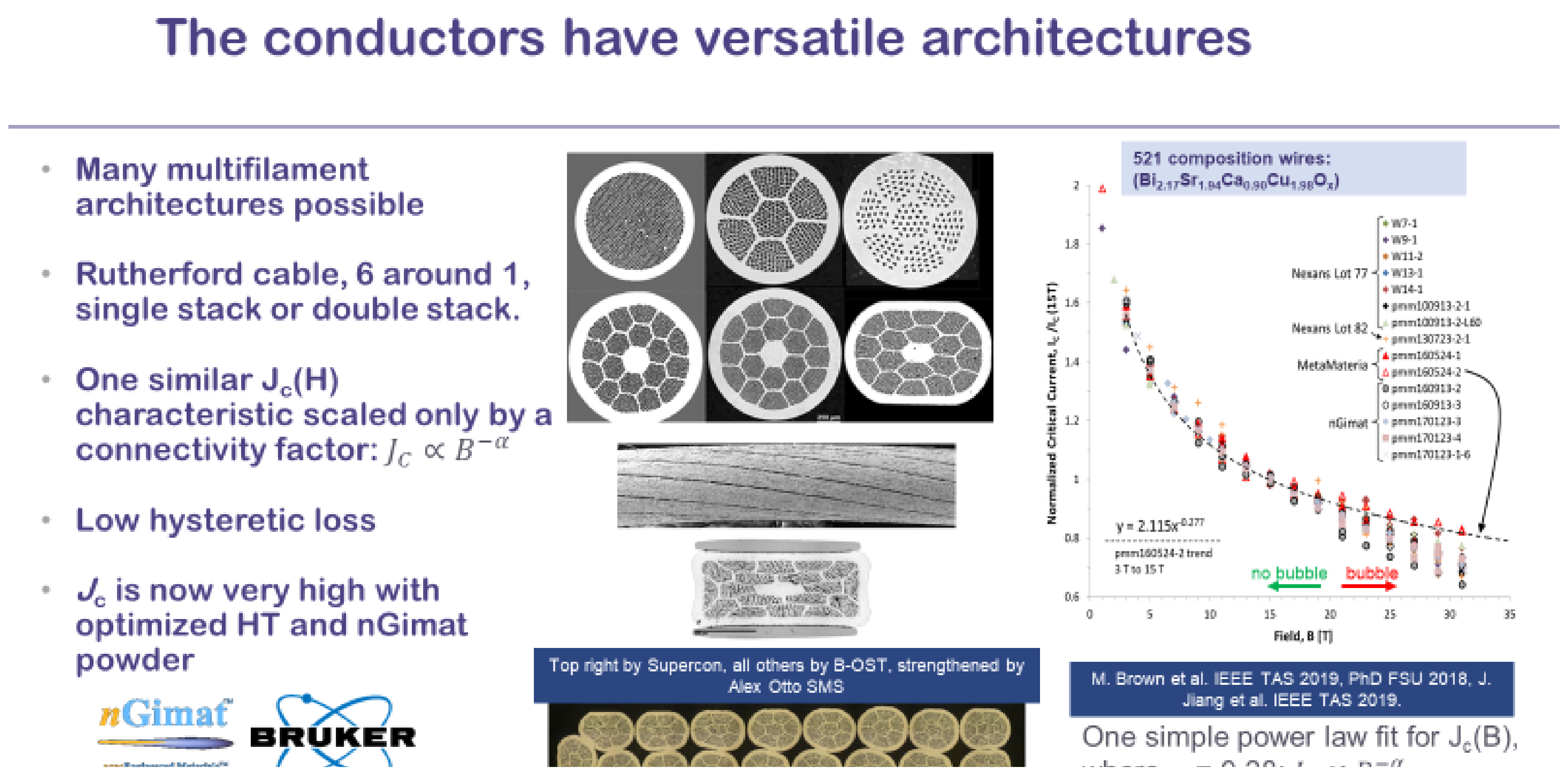
Bi-2212 Update: HTS conductors are test magnet ready

- Bi-2212 is now a magnet technology well into serious test magnets
  - 2212 conductor fabrication is by far the easiest of any HTS conductor and its present high price is artificial. Powder quality is now high and becoming well understood: large-scale pricing should be close to RRP Nb_3Sn, not present day boutique pricing
- The isotropic properties and truly multifilament architecture approximate Nb-Ti and Nb_3Sn low loss conductors suitable for magnets with high field quality. High RRR of Ag matrix does not require diffusion barriers that can break during cabling.
- The concerns about HTS magnet quench protection that especially exist with REBCO are very much reduced
  - Both in Rutherford cable dipoles and single-strand insulated solenoids, stable transition to the dissipative state can be used to trigger quench protection
- 50 bar overpressure heat treatment is not trivial but it is not "black magic" either. Compatibility with insulation and conductor strengthening has been demonstrated.



The conductors have versatile architectures

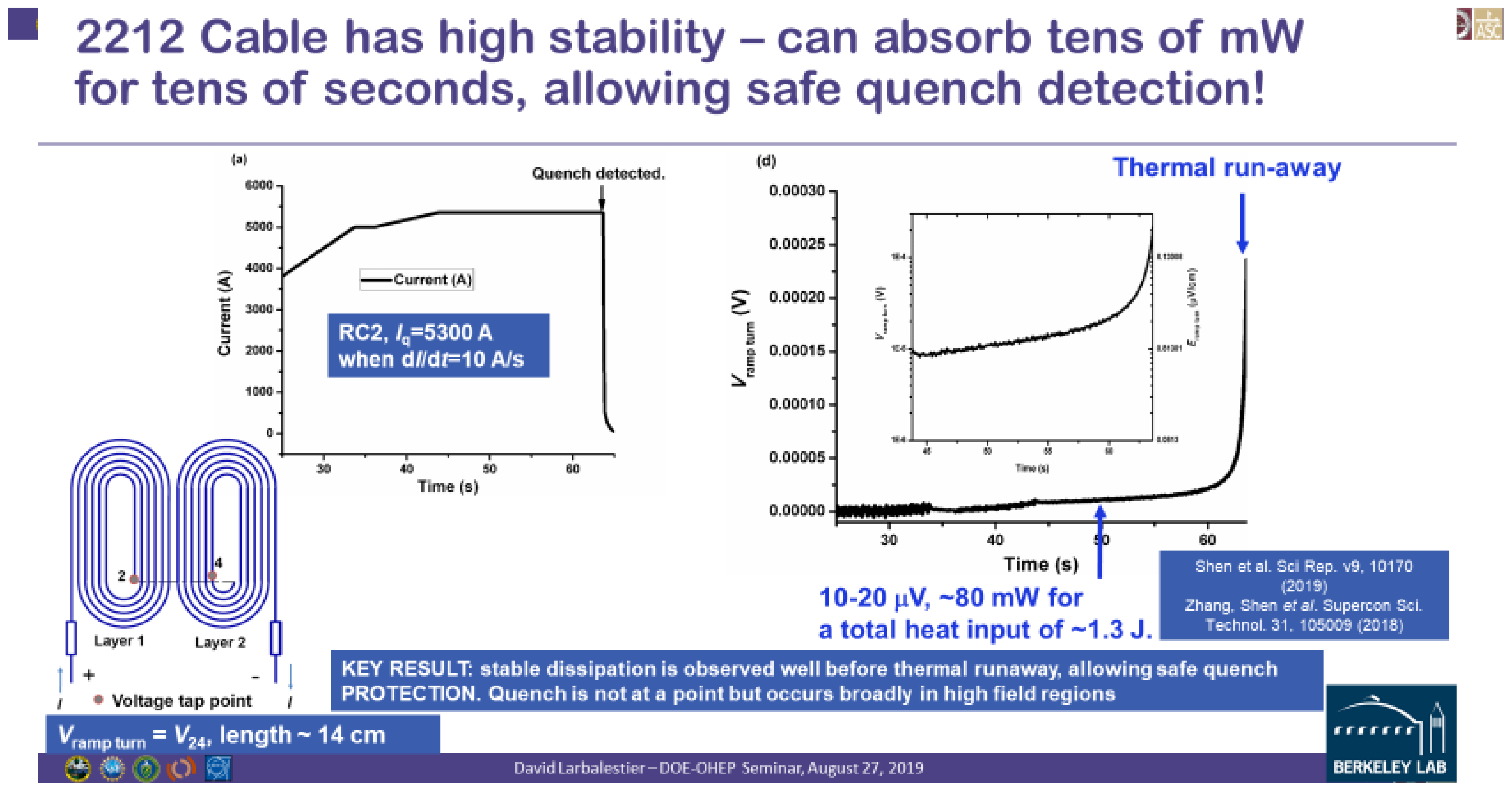
- Many multifilament architectures possible
- Rutherford cable, 6 around 1, single stack or double stack.
- One similar $J_c(H)$ characteristic scaled only by a connectivity factor: $J_c \propto B^{-\alpha}$
- Low hysteretic loss
- J_c is now very high with optimized HT and nGimat powder

Top right by Supercon, all others by B-OST, strengthened by Alex Otto SMS

521 composition wires: $(Bi_{2.17}Sr_{1.94}Ca_{0.90}Cu_{1.98}O_x)$

M. Brown et al. IEEE TAS 2019, PhD FSU 2018, J. Jiang et al. IEEE TAS 2019.

One simple power law fit for $J_c(B)$,



2212 Cable has high stability – can absorb tens of mW for tens of seconds, allowing safe quench detection!

RC2, I_q=5300 A when dI/dt=10 A/s

10-20 μV, ~80 mW for a total heat input of ~1.3 J.

Shen et al. Sci Rep. v9, 10170 (2019)
Zhang, Shen *et al.* Supercon Sci. Technol. 31, 105009 (2018)

KEY RESULT: stable dissipation is observed well before thermal runaway, allowing safe quench PROTECTION. Quench is not at a point but occurs broadly in high field regions

$V_{ramp\ turn} = V_{24}$, length ~ 14 cm

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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

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The US MDP Team at 2019 Collaboration Meeting

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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