U.S. MAGNET DEVELOPMENT PROGRAM

Status and plans of the US Magnet Development Program

Soren Prestemon
US Magnet Development Program
Lawrence Berkeley National Laboratory

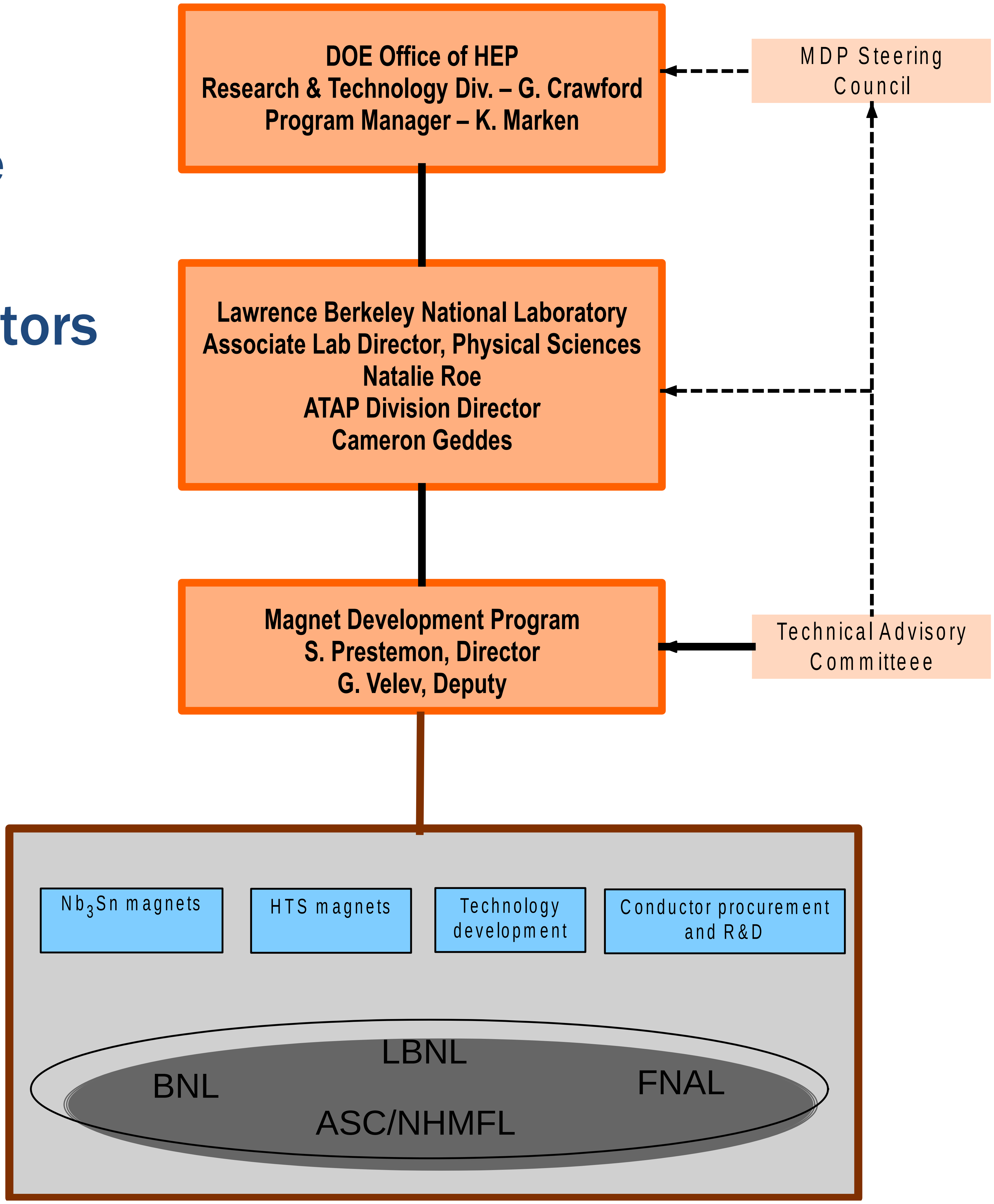
On behalf of the US MDP Collaboration

Outline

- The US Magnet Development Program – structure, vision, and goals
- Aligning the US accelerator magnet community with future collider needs
- The US Magnet Development Program – plans and progress
- Future directions:
  - New paradigms:
    - Operation and Protection of HTS magnets
    - Active/dynamic local powering of magnets for safety, field quality, etc.
    - Sustainability/energy consumption => HTS opportunity, cryo-considerations
- Opportunities to join forces: initiatives in HEP, FES, and High-Field Magnets

General management structure of the US MDP

- Integrates the teams from LBNL, FNAL, BNL and the ASC/NHMFL
- A "G7" Management Team meets weekly and provides oversight of the day-to-day progress of the MDP technical Areas
- Monthly program updates to Division and Physical Sciences Area Directors



G7 members

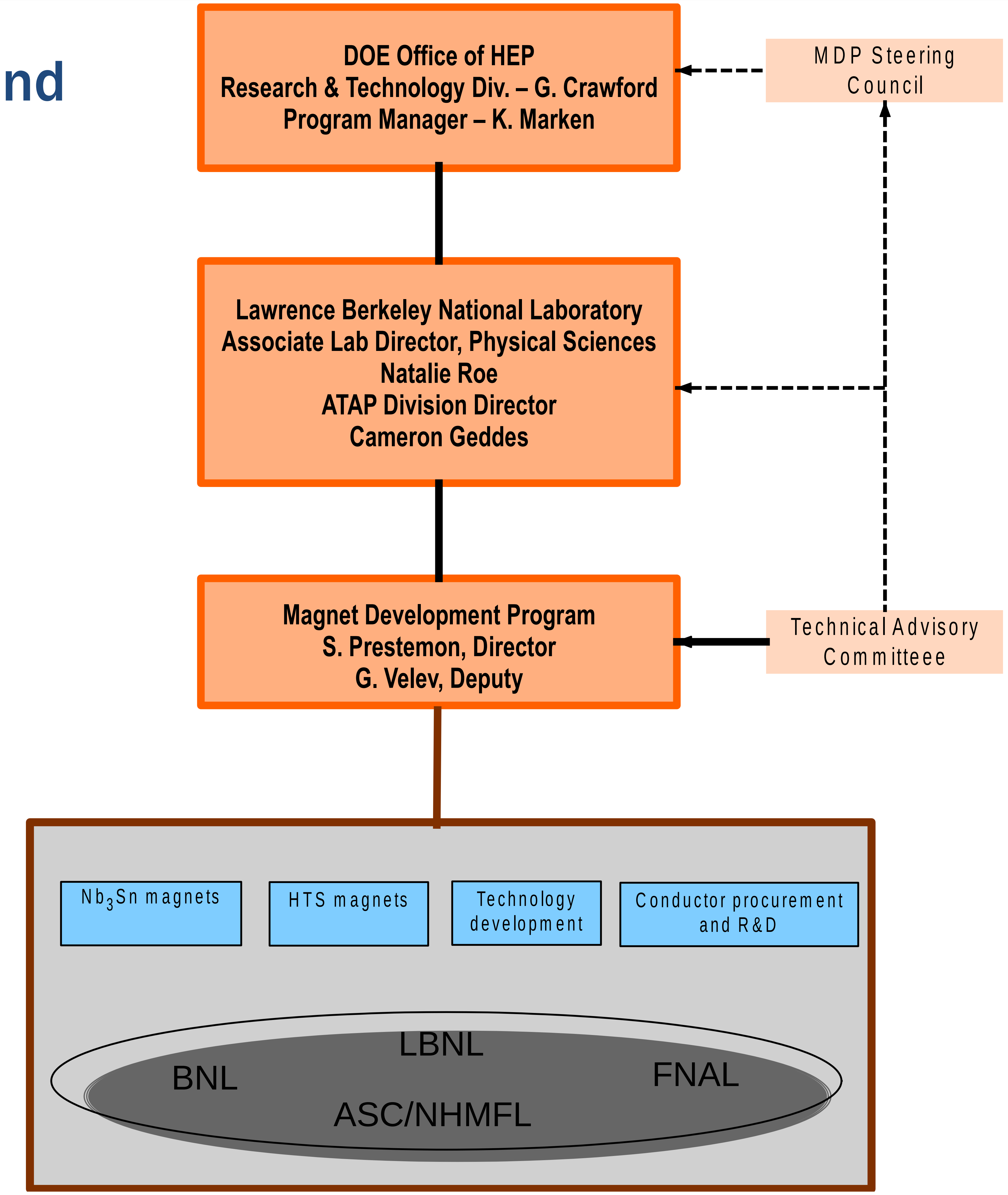
Kathleen Amm	BNL
Lance Cooley	ASC/NHMFL
Paolo Ferracin	LBNL
Steve Gourlay	FNAL
David Larbalestier	ASC/NHMFL
Soren Prestemon	LBNL *(Head)*
George Velev	FNAL *(Deputy)*

Guidance and Oversight of the US MDP

- A strong Technical Advisory Committee (TAC) advises us on strategy and technical performance
- Oversight is provided by a Steering Council

Technical Advisory Committee	
Andrew Lankford (Chair)	University of California, Irvine
Giorgio Apollinari	Fermi National Accelerator Laboratory
Joseph Minervini	Massachusetts Institute of Tech. (retired)
Mark Palmer	Brookhaven National Laboratory
Amalia Ballarino	CERN
Toru Ogitsu	KEK

Steering Council	
Harry Weerts (Chair; DOE representative)	Argonne National Laboratory (retired)
Tor Raubenheimer (DOE representative)	SLAC National Accelerator Laboratory
Michael Witherall (or designee)	Lawrence Berkeley National Laboratory
Lia Merminga (or designee)	Fermi National Accelerator Laboratory
Gregory Boebinger (or designee)	Florida State University / NHMFL
JoAnne Hewett (or designee)	Brookhaven National Laboratory



The MDP has matured and the MOA between collaborating institutions is signed and in effect

Memorandum of Agreement

among

Fermi National Accelerator Laboratory,

The Regents of the University of California, managers and operators of Lawre
Berkeley National Laboratory,

National High Magnetic Field Laboratory at Florida State University,

and

Brookhaven National Laboratory

for the

US High Energy Physics Magnet Development Program

1. Introduction

The Magnet Development Program (MDP) is a collaboration among the following instit
– Fermi National Accelerator Laboratory (FNAL), The Regents of the University of Cali
managers and operators of Lawrence Berkeley National Laboratory (LBNL), the Na
High Magnetic Field Laboratory (NHMFL) at Florida State University (FSU) and Brool
National Laboratory (BNL). This Memorandum of Agreement (MOA) provides the
framework for the business relationship among the signatories and institutions f
development of transformational technology that will drive superconducting magne
materials to substantially increased performance at lower cost. While this collabora
among a group of four separate entities, and each intends to perform work under thi
as separate entities and no new legal entity is formed as a result of this MOA or prog
is the intent that the entities engage fully among the group as partners, and the par
this MOA may be referred to as Partners or Parties (or individually as Partner or Pa
convey the strong level of commitment among the group. DOE OHEP plans to p
funding for this Research & Development (R&D) effort to the collaborating me
conducting the work pursuant to appropriate funding requests demonstrating suf
scientific and technical merit for the proposed work, and subject to availability of fun

Approvals

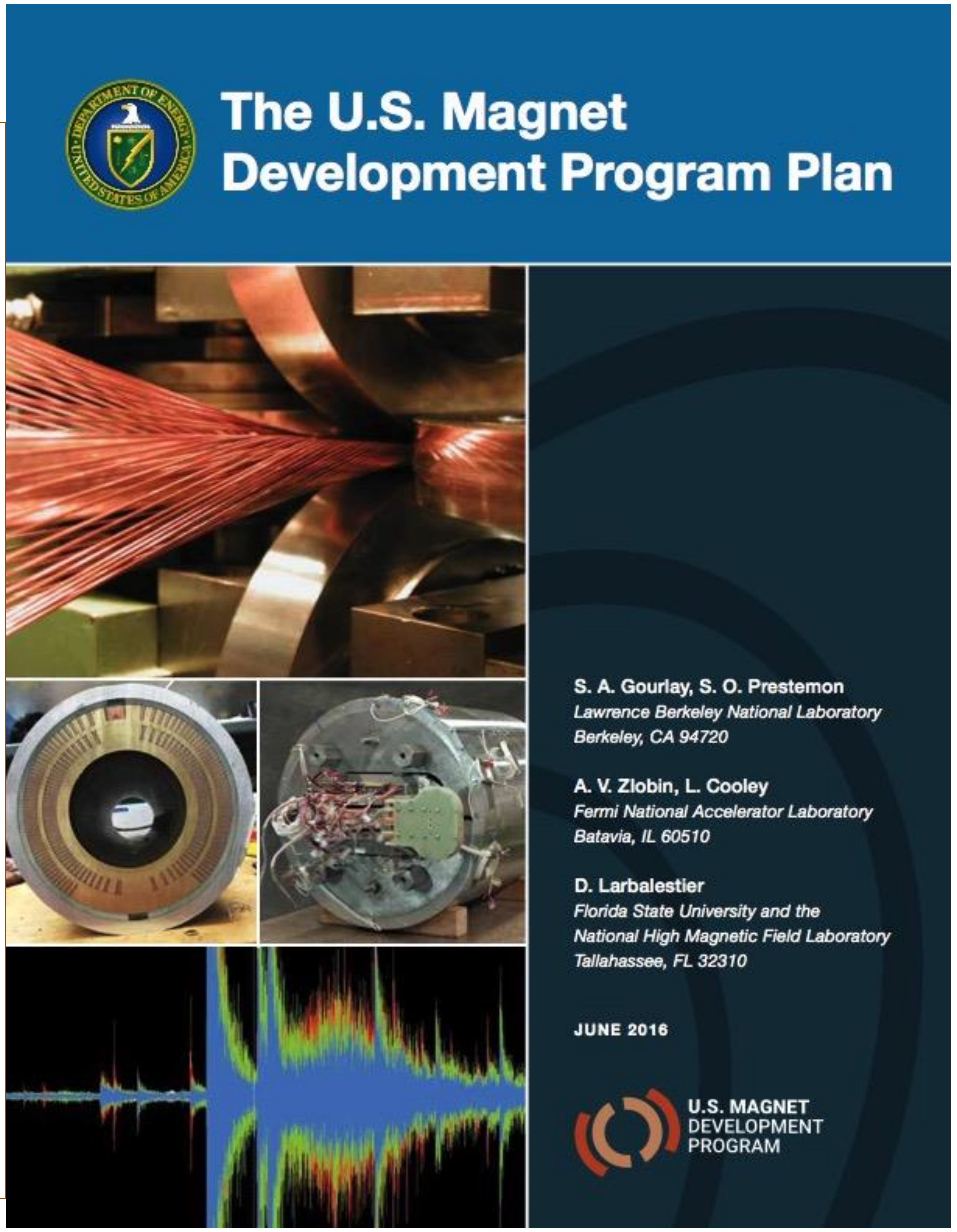
The undersigned concur with the terms of this Memorandum of Agreement:

Sergey Belomestnykh — Date: 08/05/2019
Sergey Belomestnykh
Chief Technology Officer, Fermi National Accelerator Laboratory

Michael Witherell — Date: 07/30/2019
Michael Witherell
Director, Lawrence Berkeley National Laboratory

Date: 08/05/2019
Gregory S. Boebinger
Director, National High Magnetic Field Laboratory, Florida State University

Date: 08/05/2019
Doon Gibbs
Director, Brookhaven National Laboratory



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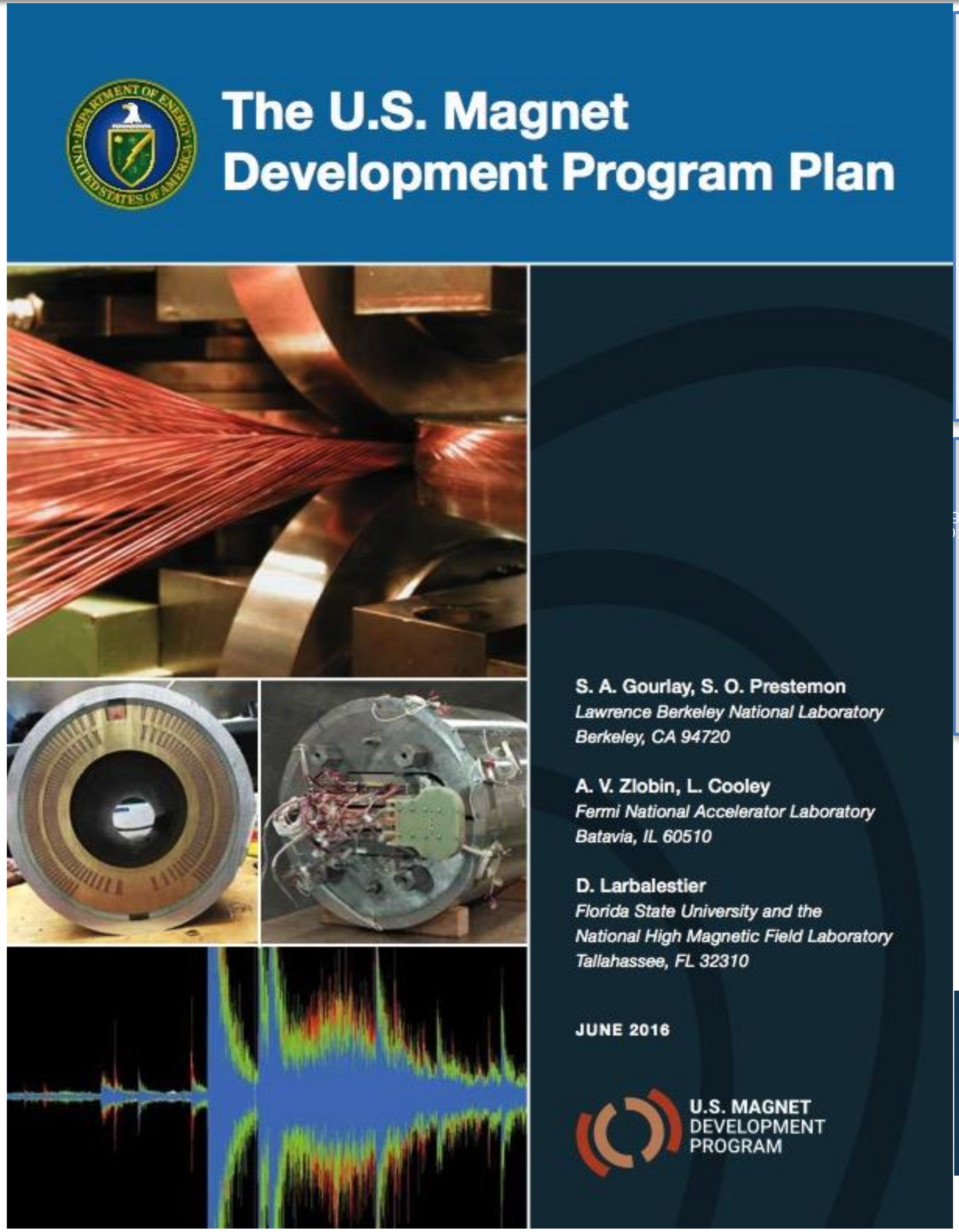
The US Magnet Development Program was founded by DOE-OHEP to advance superconducting magnet technology for future colliders



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

A clear set of goals have been developed - guide the program

Technology roadmaps have been developed for each area: LTS and HTS magnets, Technology, and Conductor R&D

Additional goals:

- Further develop and integrate the teams across the partner laboratories and Universities
- Identify and nurture cross-cutting / synergistic activities with other programs

The 2020 Updated US MDP Roadmap document:
arXiv:2011.09539

Brookhaven National Laboratory
BERKELEY LAB
Fermilab
ASC

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 coordinators who are tasked with organizing technical Areas

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

Technology area	Coordinator
Modeling & Simulation	Lucas Brouwer
Training Reduction	Stoyan Stoynev
Novel Diagnostics	Maxim Martchevsky
Material studies	Steve Krave
20T design studies	Paolo Ferracin

Conductor Procurement and R&D	Ian Pong

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The magnet community was strongly engaged in the recent US Snowmass process, and is highly organized

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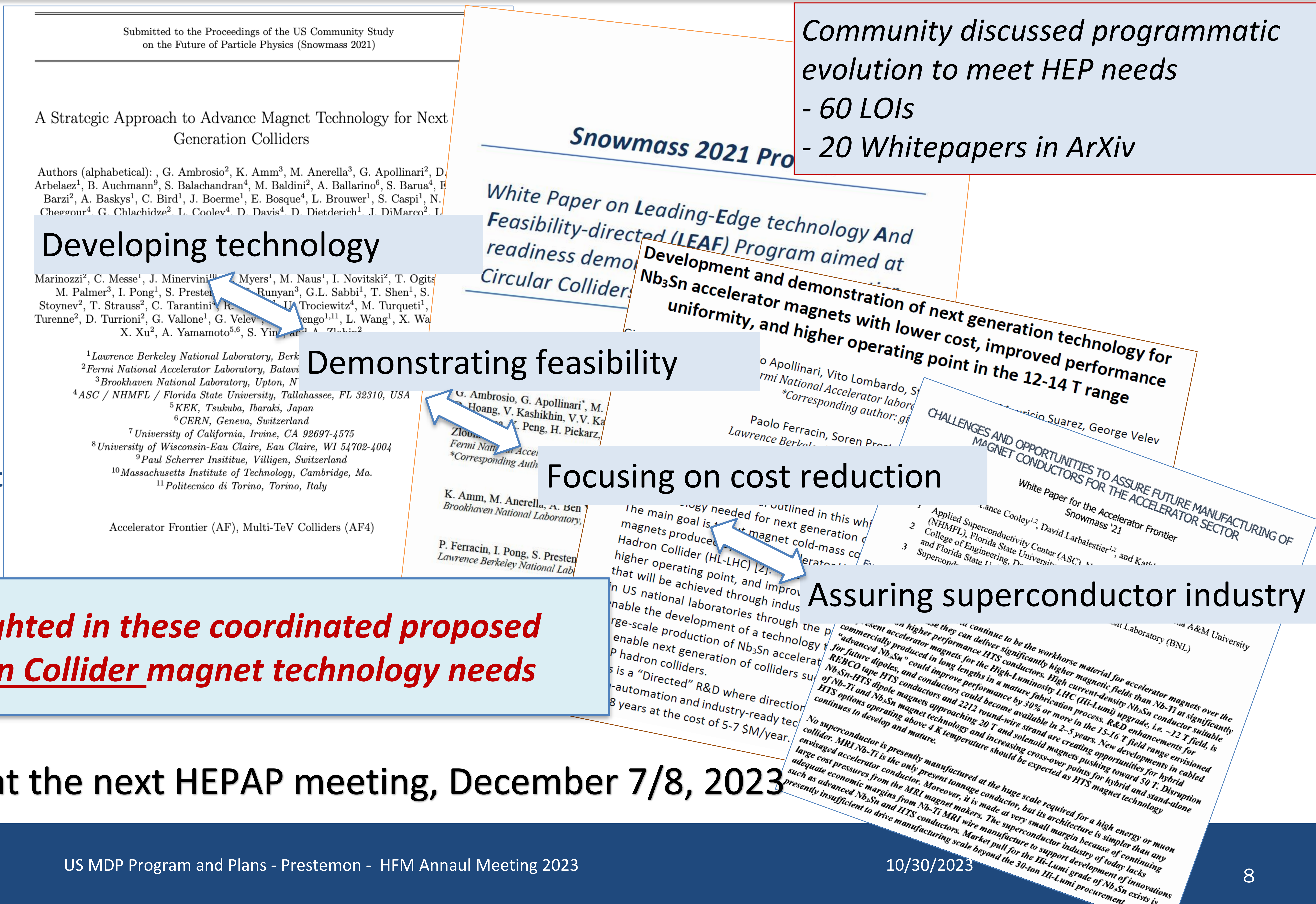
- The US MDP organizes and focuses a multi-lab team on accelerator magnet R&D in the US
    - Strong international presence, record dipole magnet, advances in HTS magnet technology,…
    - Reviewed positively by OHEP
- The HL-LHC AUP team is delivering state of the art magnets for HiLumi
    - As the project culminates, deep expertise will become available that can significantly accelerate magnet development for the next collider

Community discussed programmatic evolution to meet HEP needs
- 60 LOIs
- 20 Whitepapers in ArXiv



The magnet development scope highlighted in these coordinated proposed efforts would address <u>FCC-hh</u> and <u>Muon Collider</u> magnet technology needs

The new P5 report will be unveiled at the next HEPAP meeting, December 7/8, 2023

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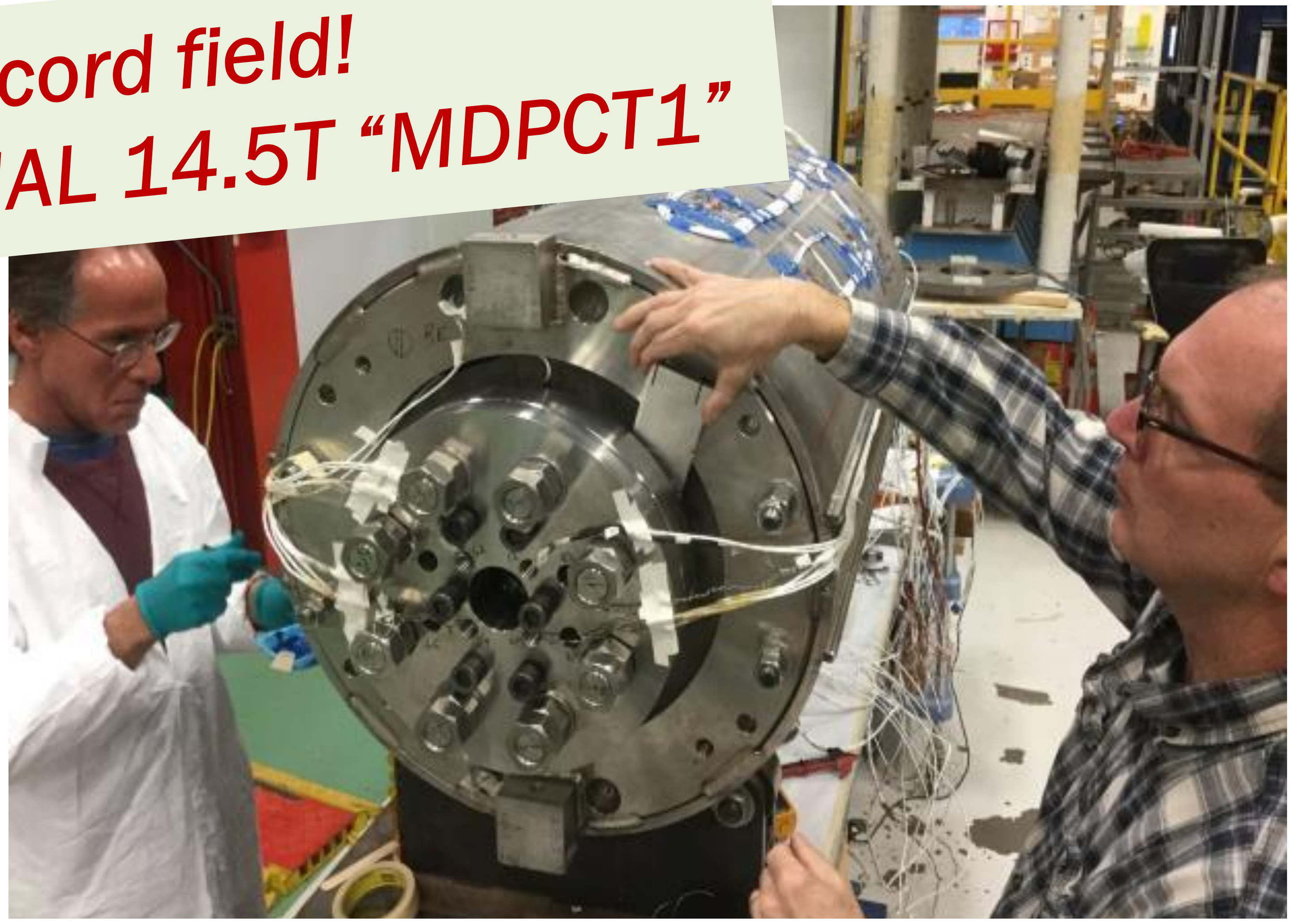
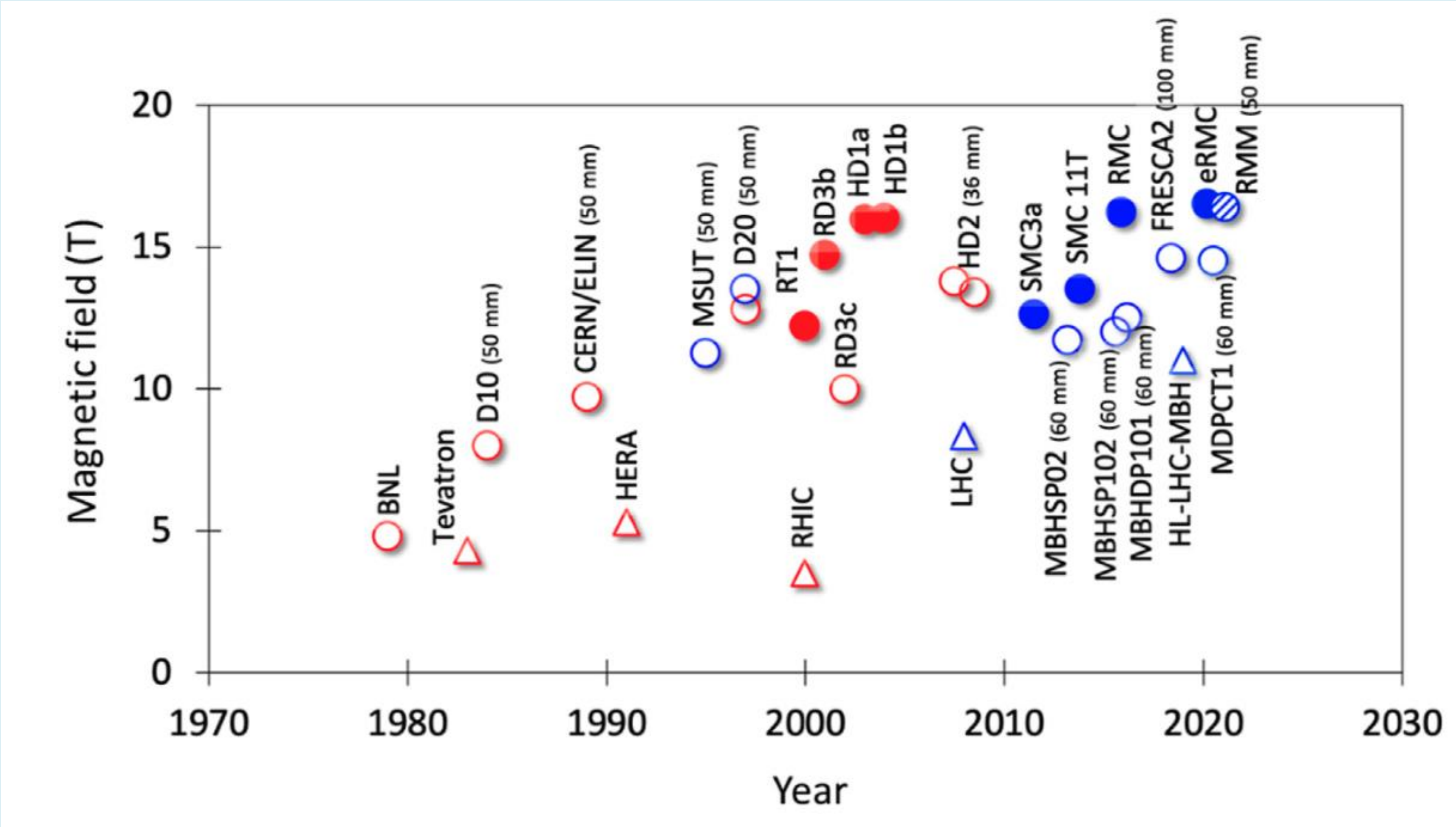
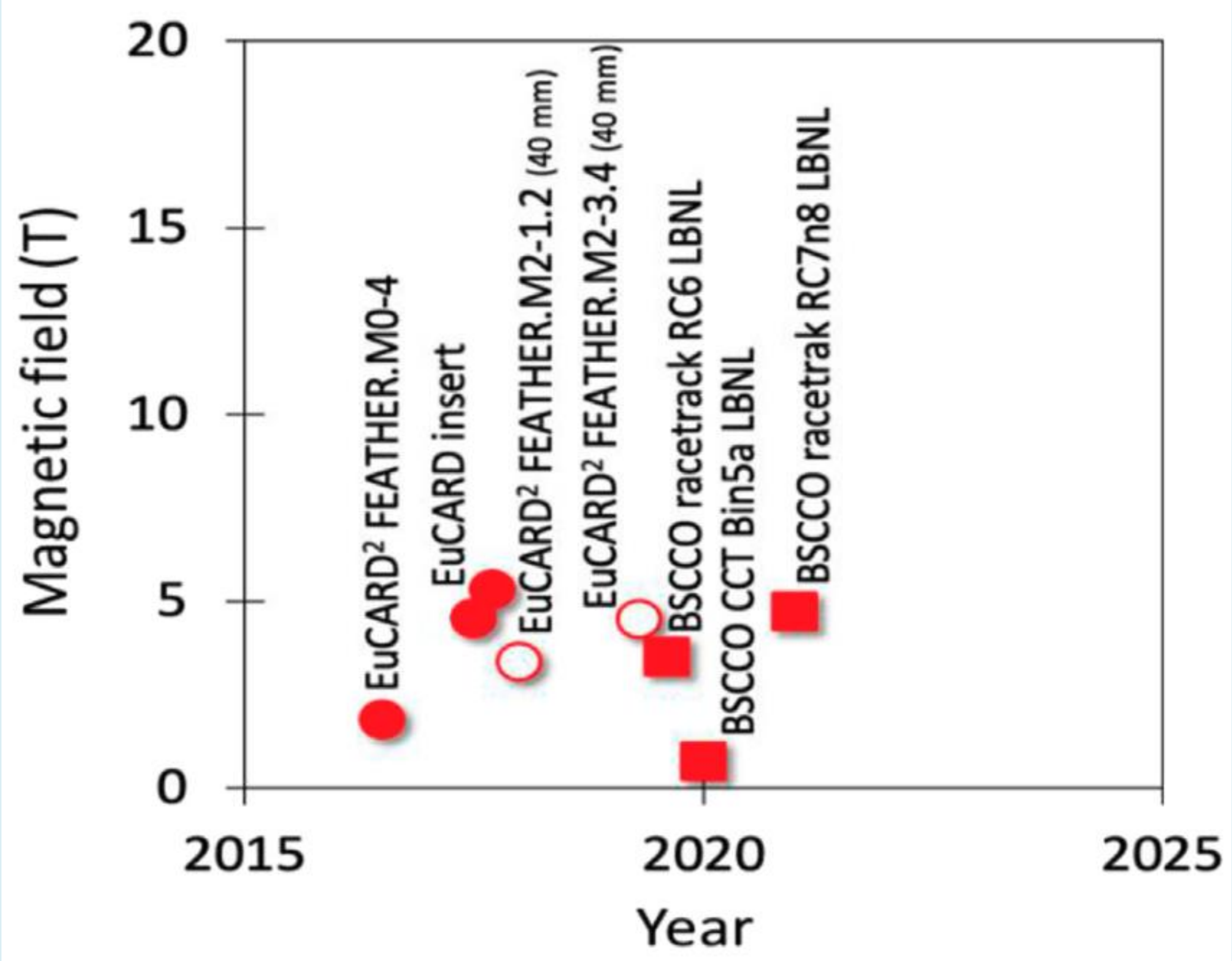
A key early MDP result was the record 14.5T “MDPCT1” dipole

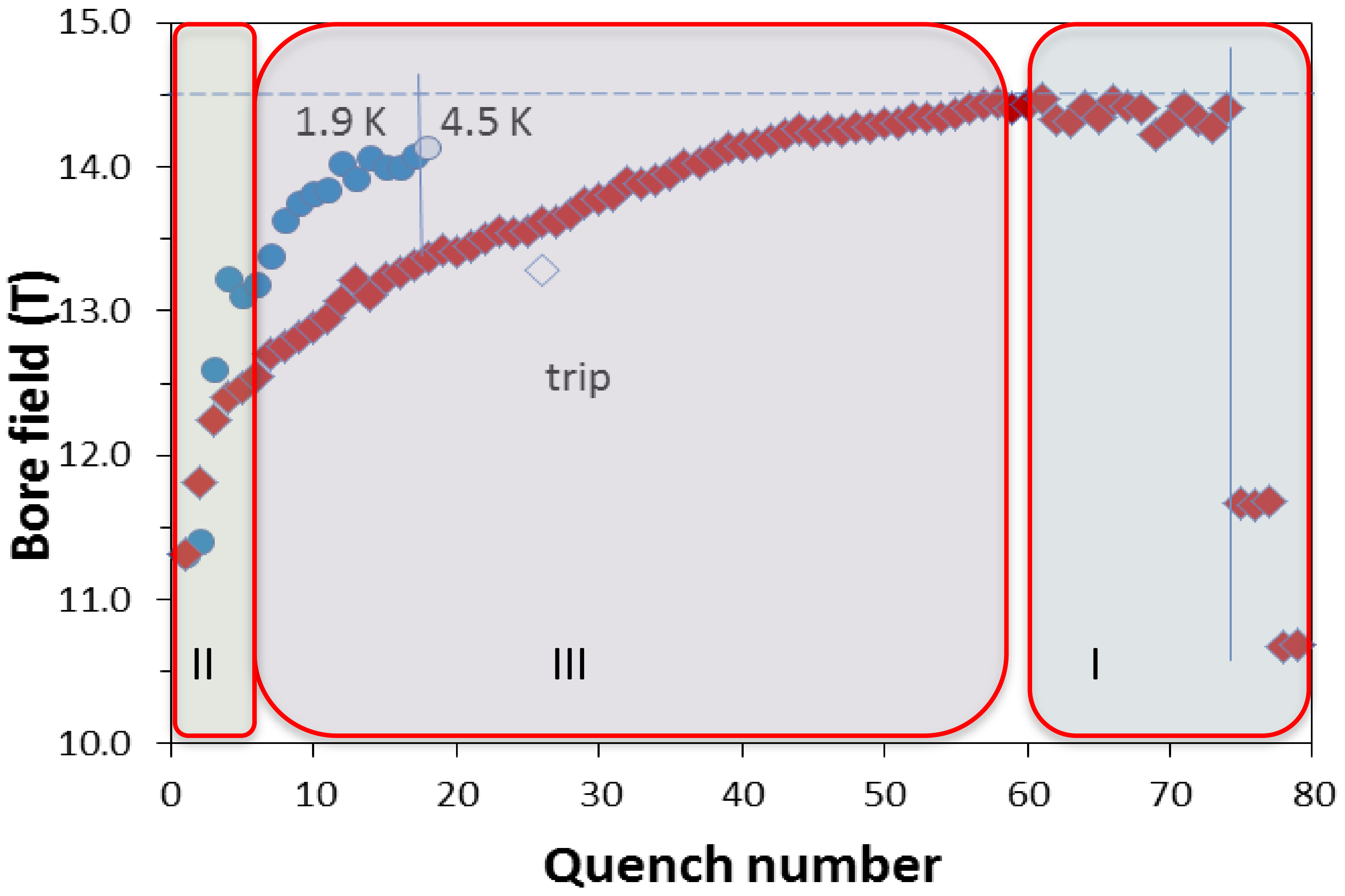
Record field!
FNAL 14.5T “MDPCT1”







Bottura, Prestemon, Rossi, & Zlobin, Front. Phys., 12 October 2022



MDP Perspective:

[I]: Highest priority issue: ***degradation*** mechanisms; design mitigation

[II]: Second priority: Initial quench current and ***memory after thermal cycle***

[III]: Third priority: ***Training rate***

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Central themes of MDP magnet R&D

- Understanding the disturbance spectrum and its control
  - Study training, operating margin, and means to mitigate/reduce
- Develop stress-management concepts to enable high-field accelerator magnets with strain-sensitive materials (Nb_3Sn, HTS)

Use fast turn-around platforms (subscale magnets, mirror magnets, etc)
Develop and apply advanced diagnostics, modeling
Explore "Quench Current-boosting", high-Cp concepts, etc.

- Develop and demonstrate REBCO and Bi2212 magnet technologies

Focus on developing conductor / cable / coil / magnet processes, identifying key issues

- Explore the viability of hybrid HTS/LTS magnets for efficient high-field accelerator magnets

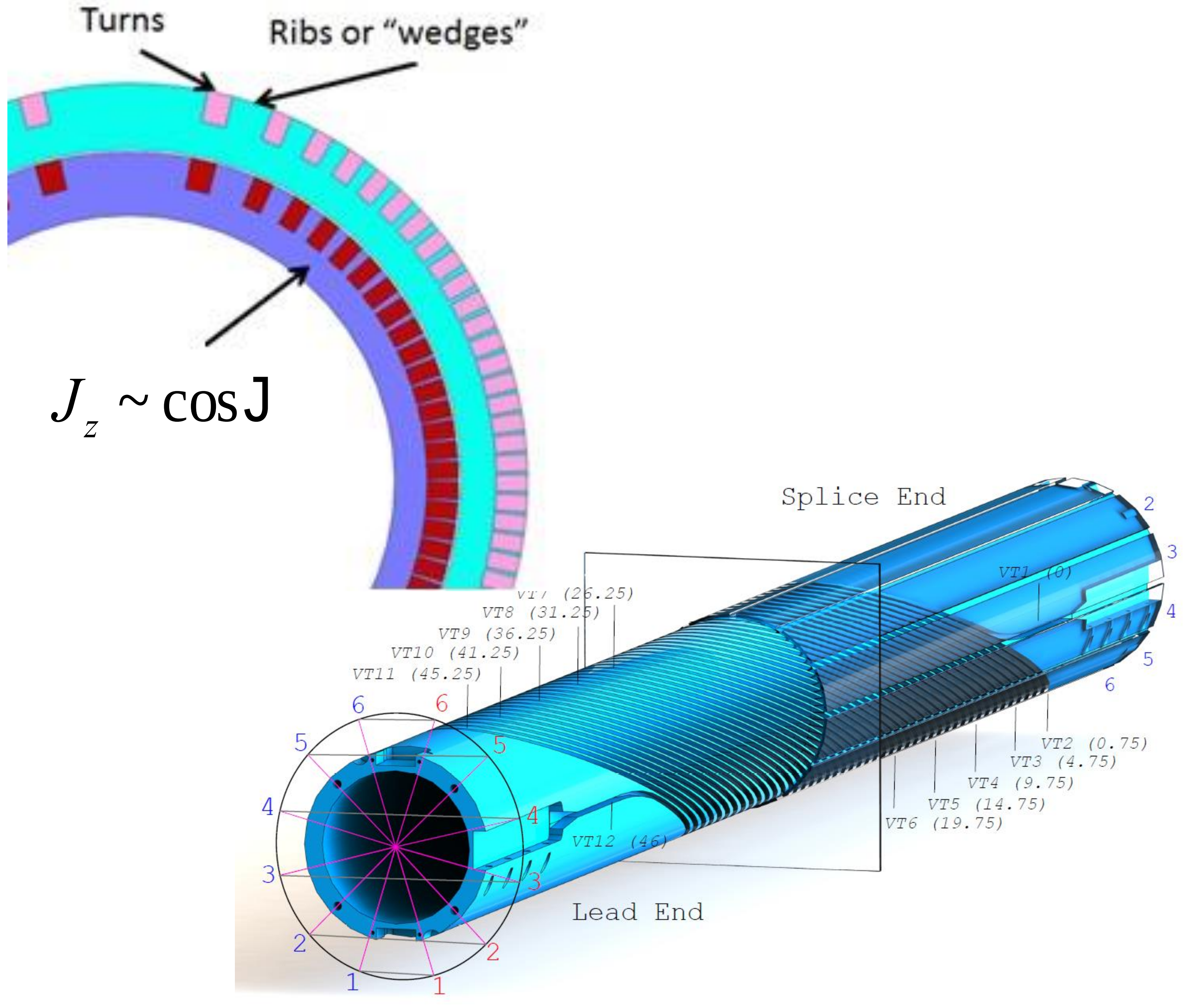
Leverage elements above to design optimized high-field configurations

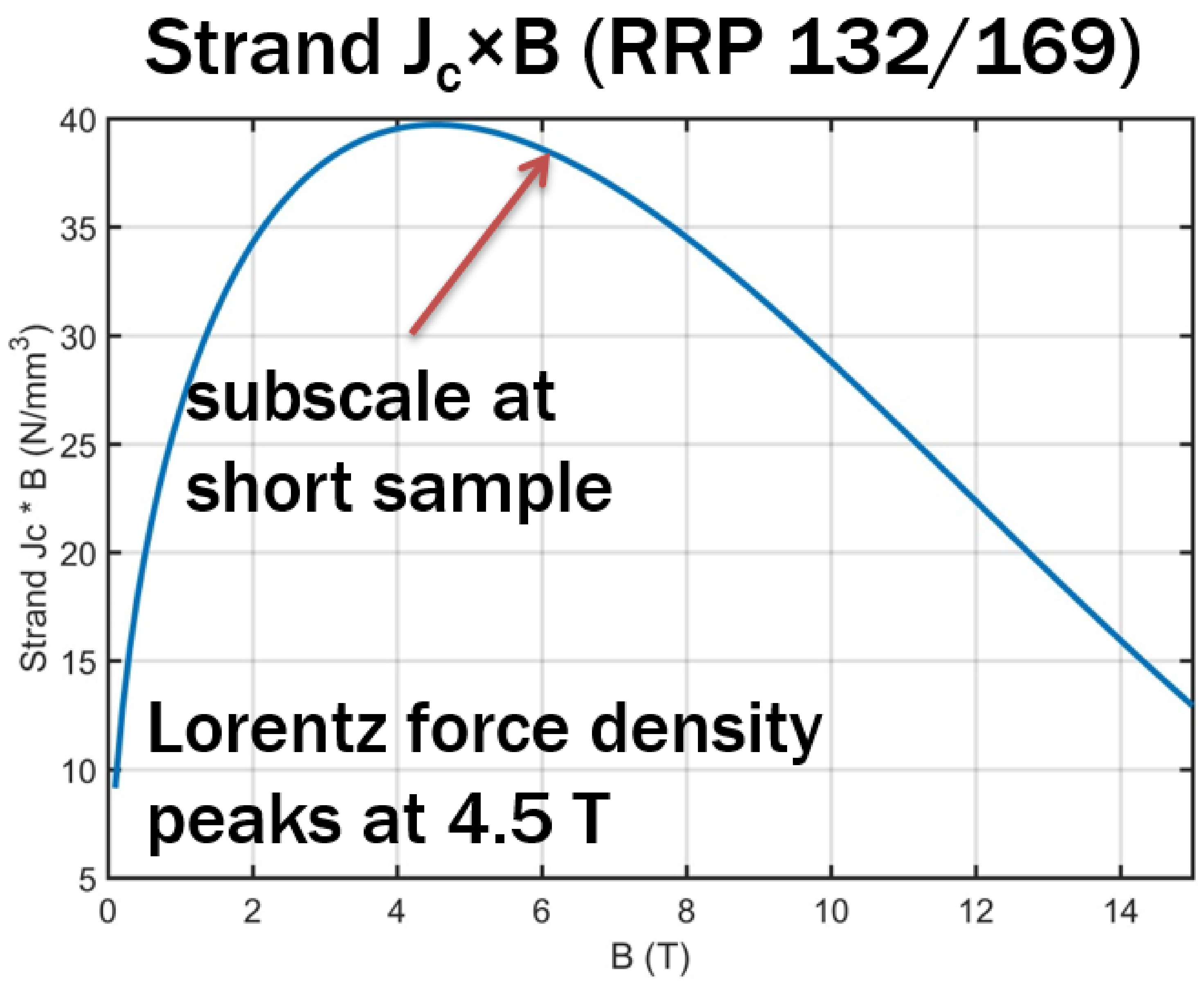
- Work with industry to advance superconductors tailored to HEP needs

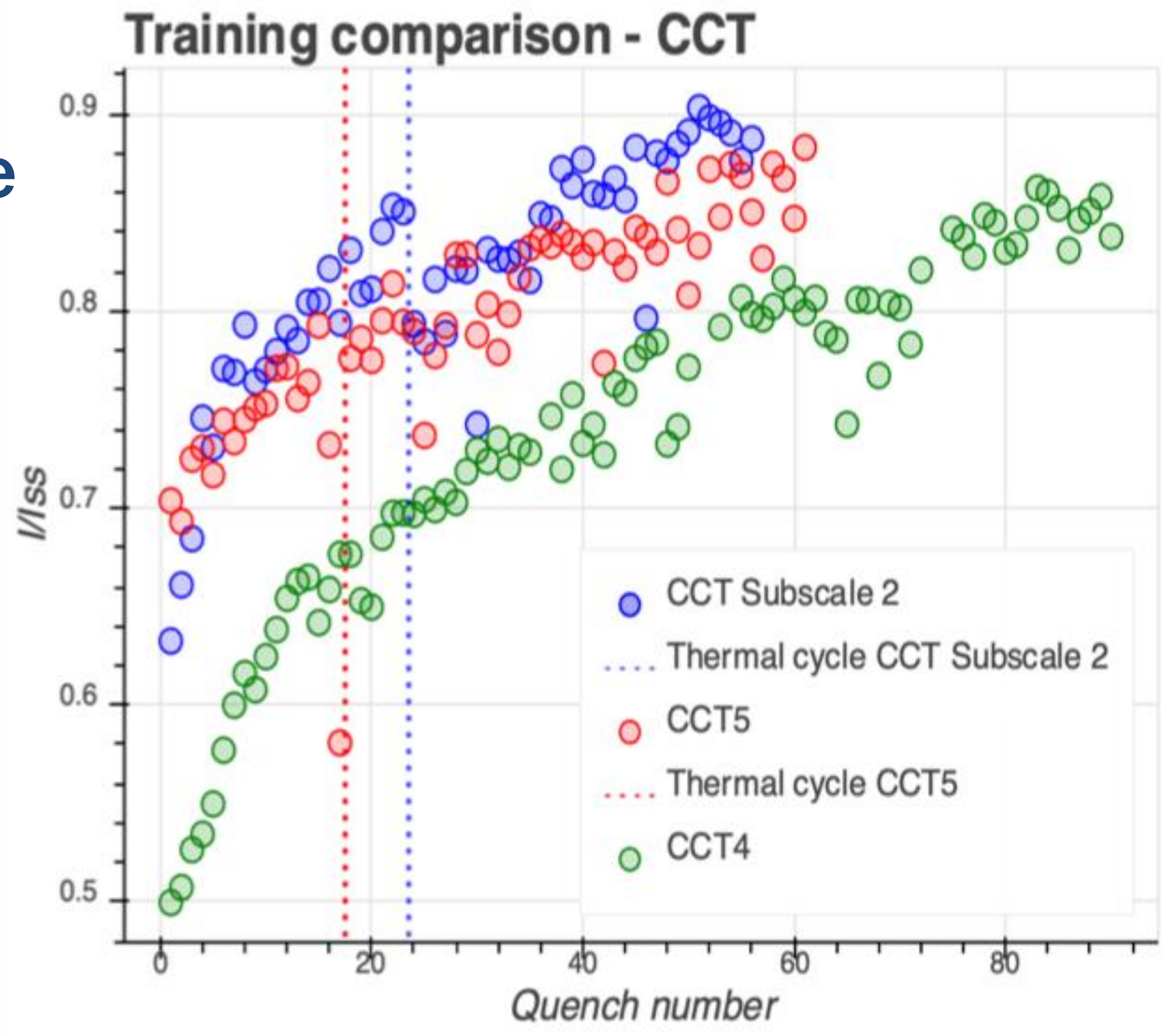
Longstanding nexus between Labs, Universities, and industry in the US
Example: Annual Low Temperature Superconductor Workshop >40+ years!

Subscale magnets as a platform for rapid development

- "Canted Cosine Theta" (CCT) is limiting case of stress-management
  - o Every turn supported – minimal azimuthal accumulation of force
  - o Subscale probes relevant stress state
- Test demonstrated that the subscale magnet exhibits similar training to "full scale"





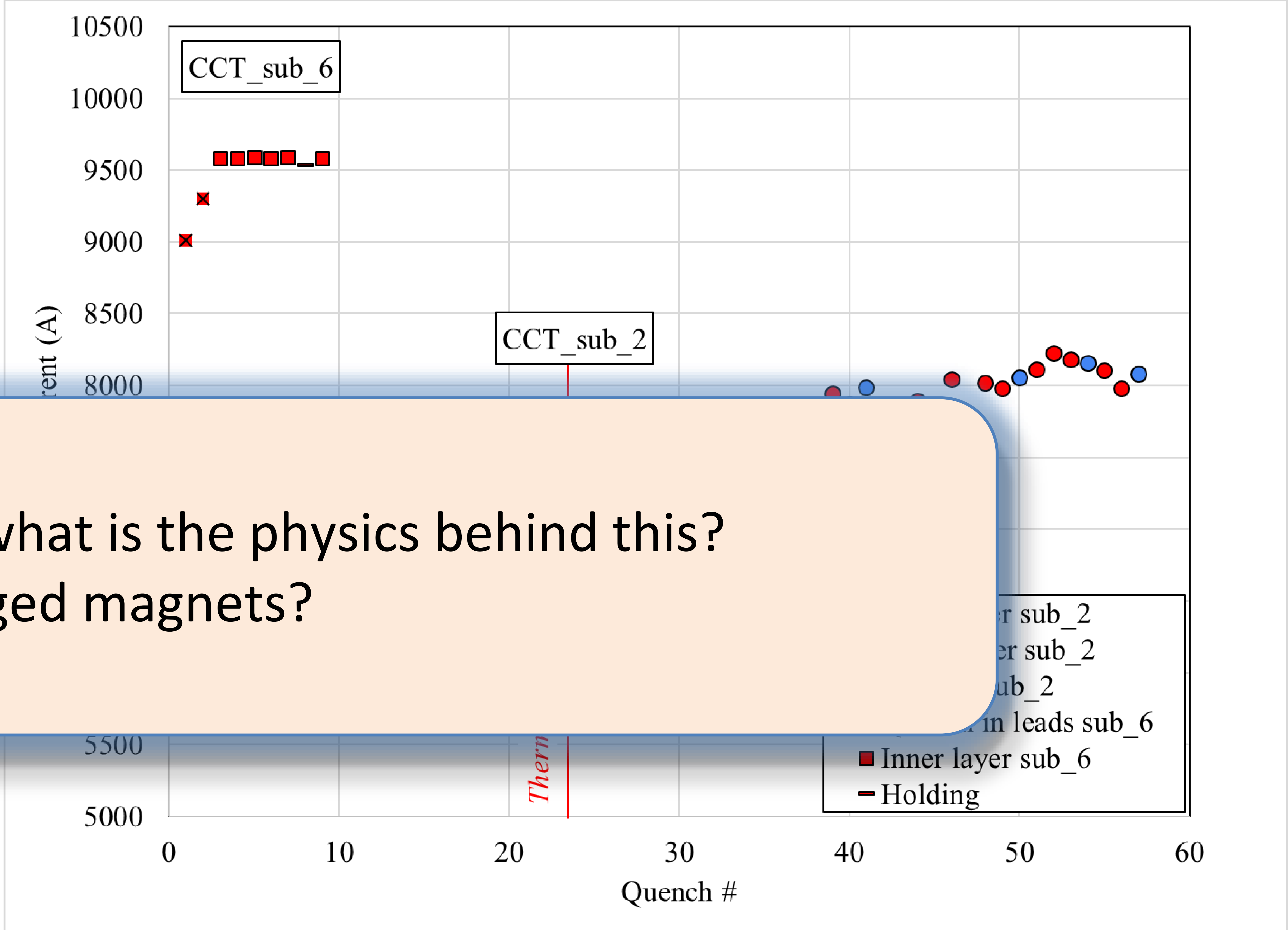


CCT4 – Epoxy filled interface (CTD 101k)
CCT5 – Bend and shim interface (FSU Mix 61)

Subscale magnets are used to evaluate impregnation materials – the return of Paraffin Wax!

- A subscale CCT (CCT_sub_6) was built with two coils, both impregnated with Paraffin wax

- **Dramatic impact on training and margin**
  - Only two "training" quenches, located in leads
  - Highly reproducible quench current (~9500A)



The test leads to critical new questions:

- What characteristics of wax are central to this result, i.e. what is the physics behind this?
- Is wax (or an equivalent) viable for high-field stress-managed magnets?
- Do these results hold through multiple thermal cycles?

Daly et al 2022 ,SUST 35 055014

- Recent tests using Telene (on a different "platform") also suggest dramatic reduction/elimination of training
  - Collaboration between FNAL, ANL and NIMS
  - ***See presentation by E. Barzi!***

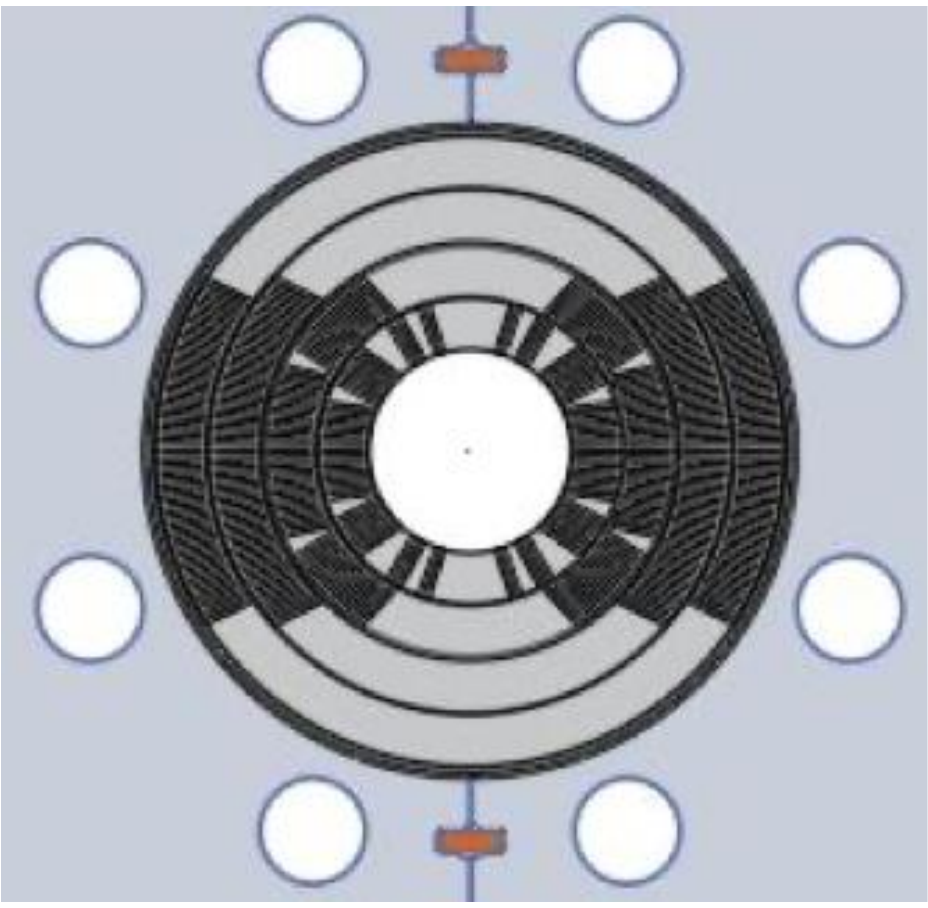
Test performed at LBNL Aug 29th, 2023

Managing mechanical stresses is key to higher fields – exploring stress-managed structures

$$B \propto wJ_0 \implies \sigma_\theta \propto J_O B r$$

"Traditional" Cos-theta

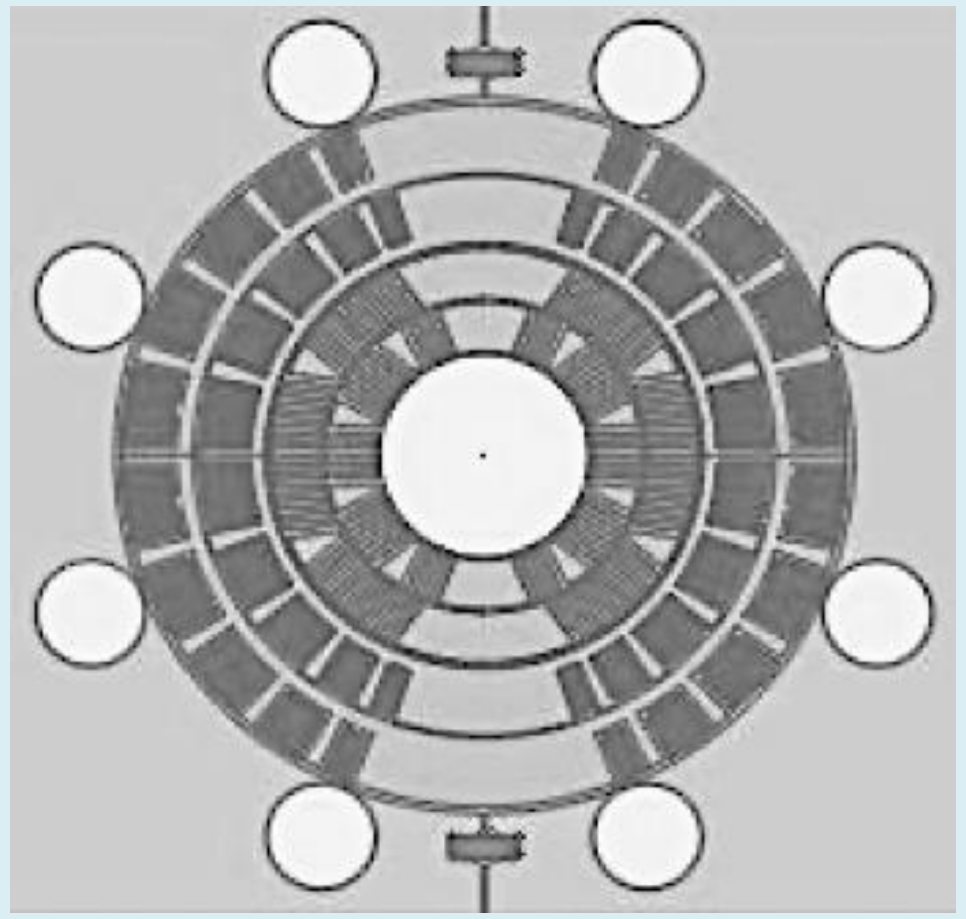
- Midplane stress due to azimuthal force accumulation



$$\sigma_{\theta,SM} \propto J_0 B \sim F_p$$

"Stress-managed" Cos-theta

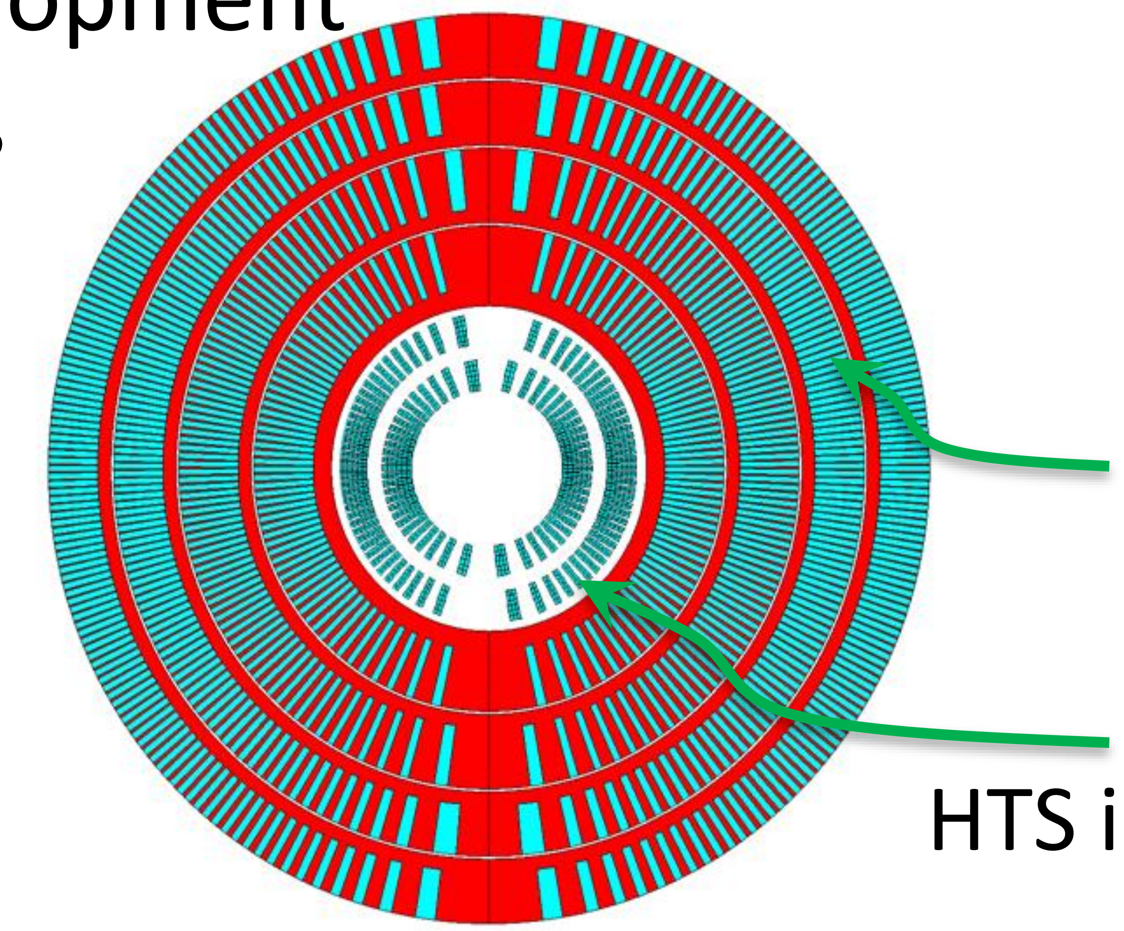
- Groups of turns, azimuthal forces intercepted by support



MDP stress-managed hybrid magnets are under development

- Critical for strain sensitive Nb_3Sn & HTS conductors
- Characterized by significant interfaces

These "stress-managed" structures may enable combined function high-field accelerator magnets, which are subject to complex force distributions



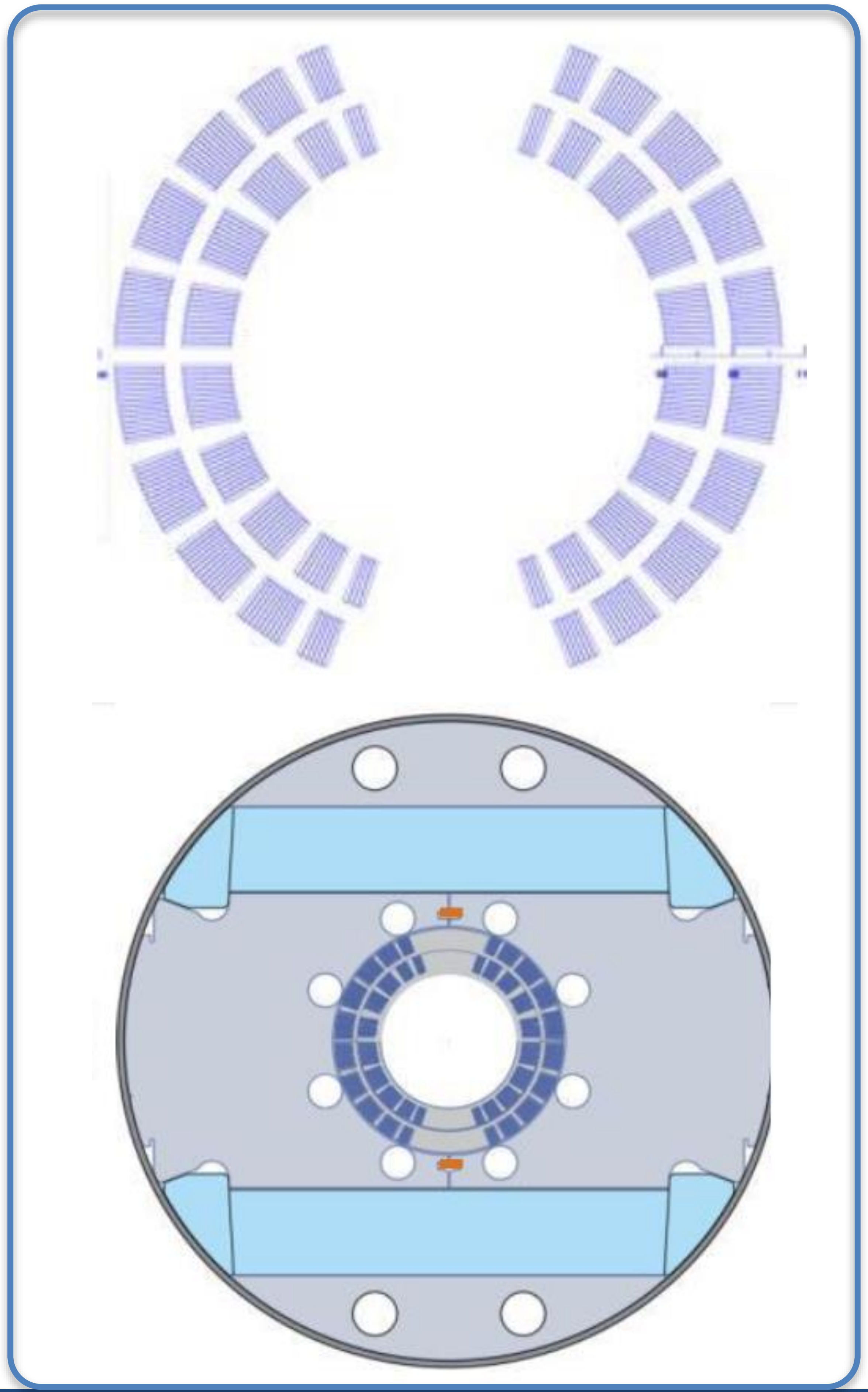
Serves as good candidate for muon collider ring dipole

A priority now is to build the Nb_3Sn outserts

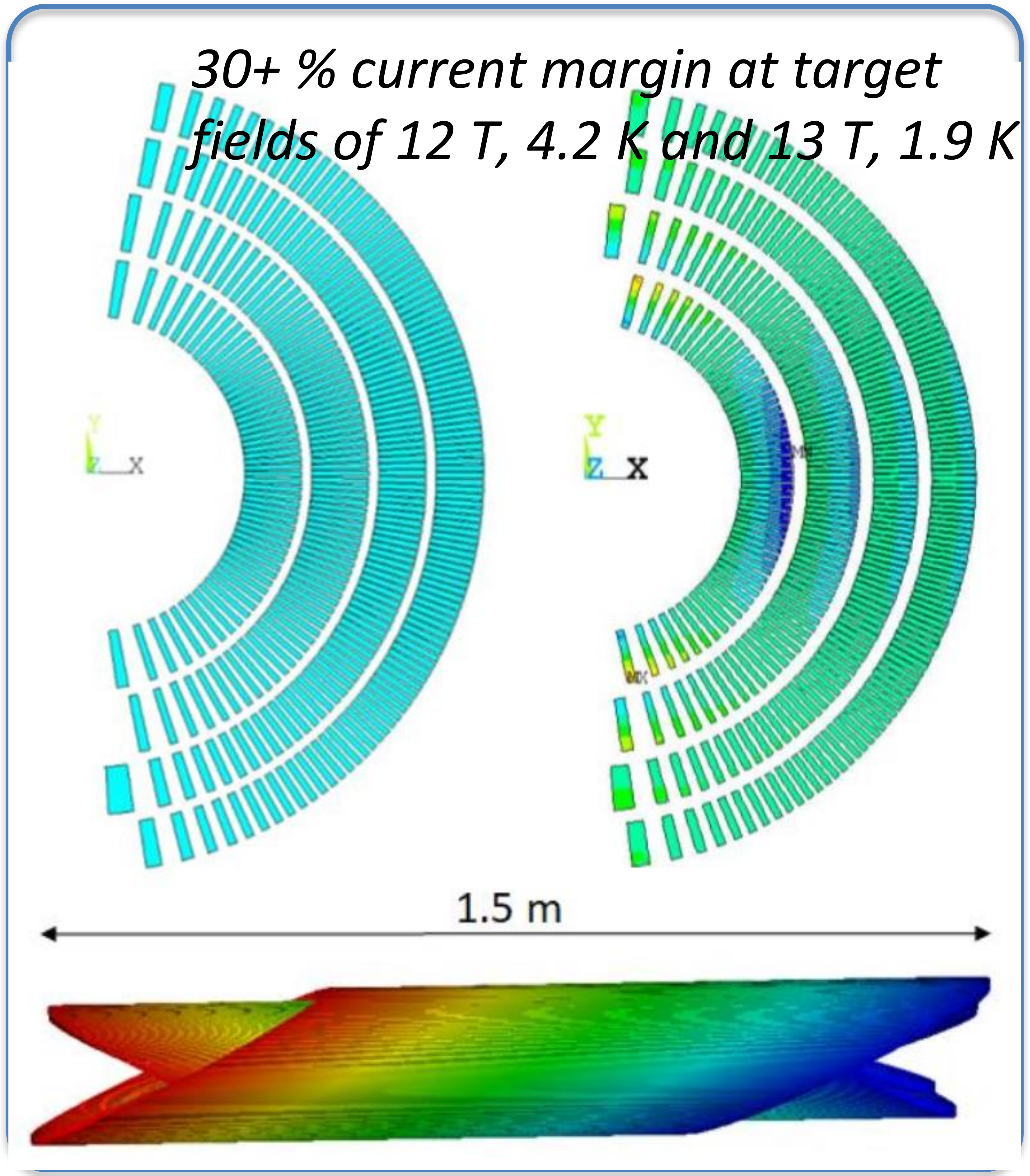
- Canted Cosine theta:
  - 4 layers
    - Bore field of 12 T / 13 T for standalone operation
    - Bore diameter: 120 mm
- Stress-managed Cosine Theta:
  - 2 layers
    - Bore field of 11 T
    - Bore diameter: 120mm

These are two variants on stress-management
- CCT is a "limiting case" of maximal SM
- SMCT is a more efficient design

SMCT

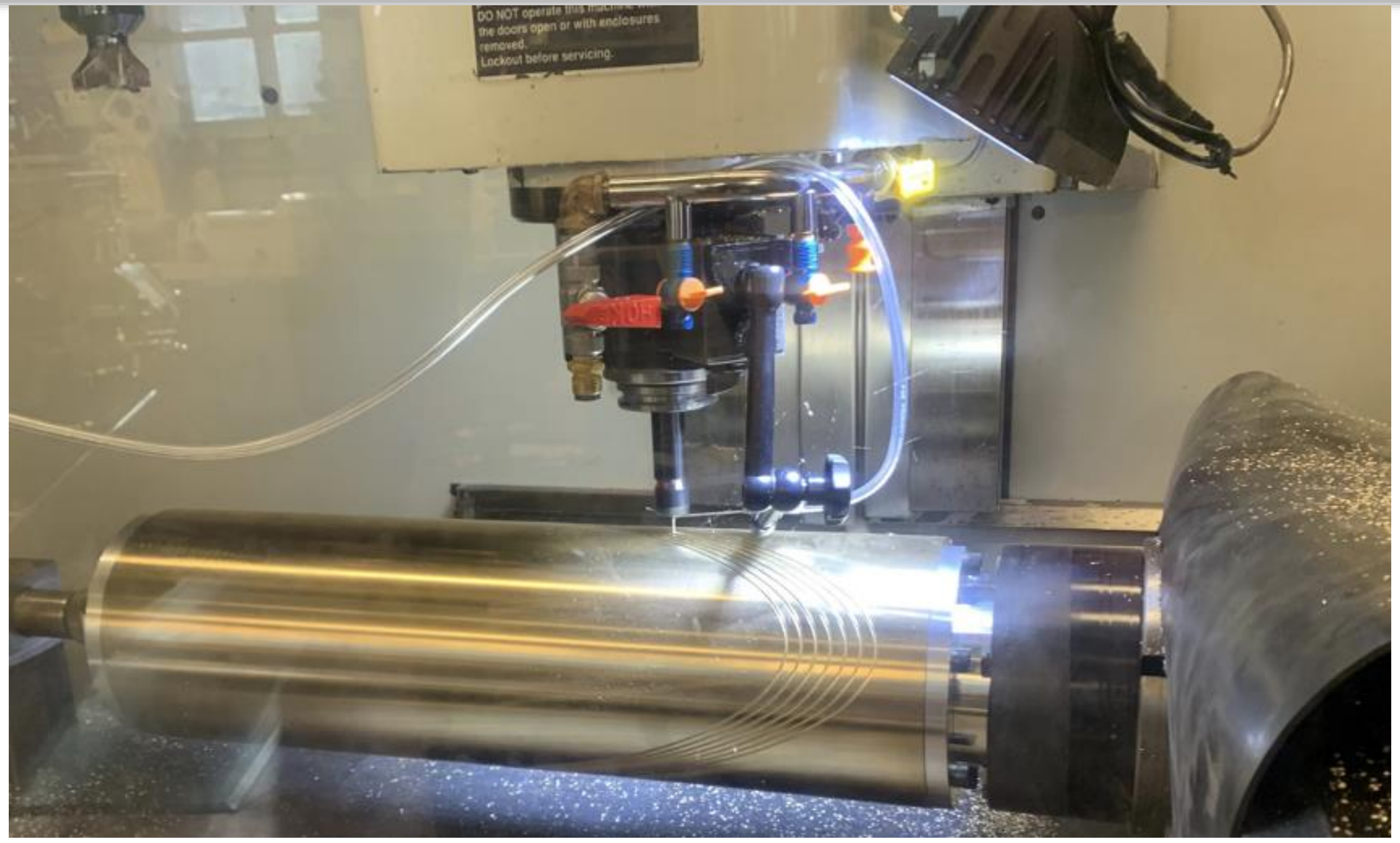


CCT



Design efforts now leading to hardware and first testing

FNAL mirror test of SMCT – successfully trained!
– now proceeding with thermal cycle

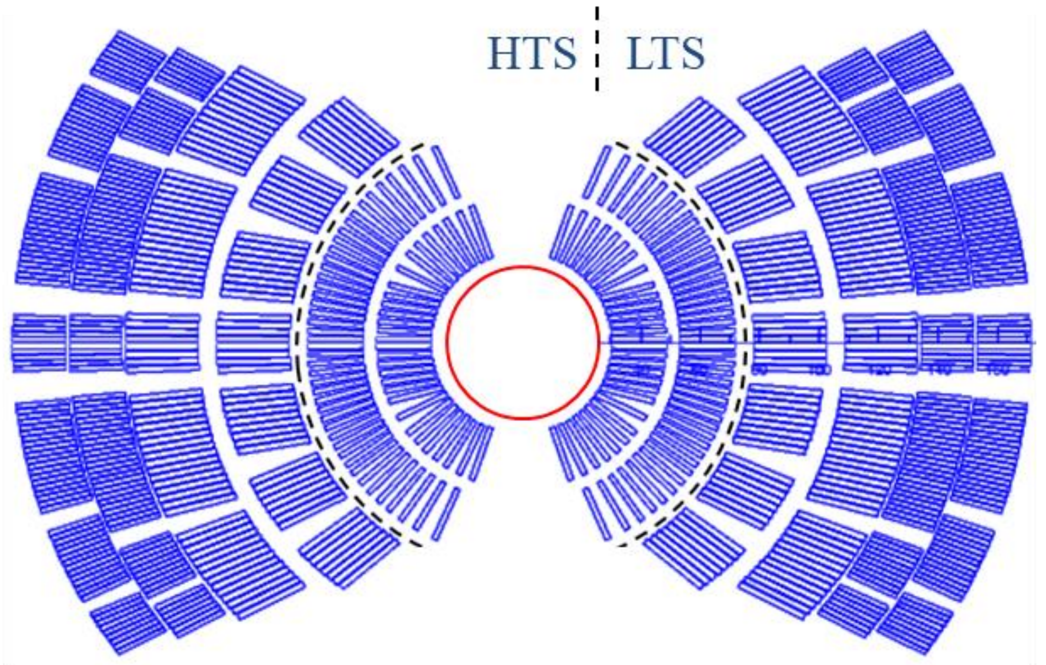


Practice winding of CCT6 underway

HTS vs LTS superconductors & magnets – some key distinctions

- **HTS materials outperform LTS at higher field, but under-perform at low field**

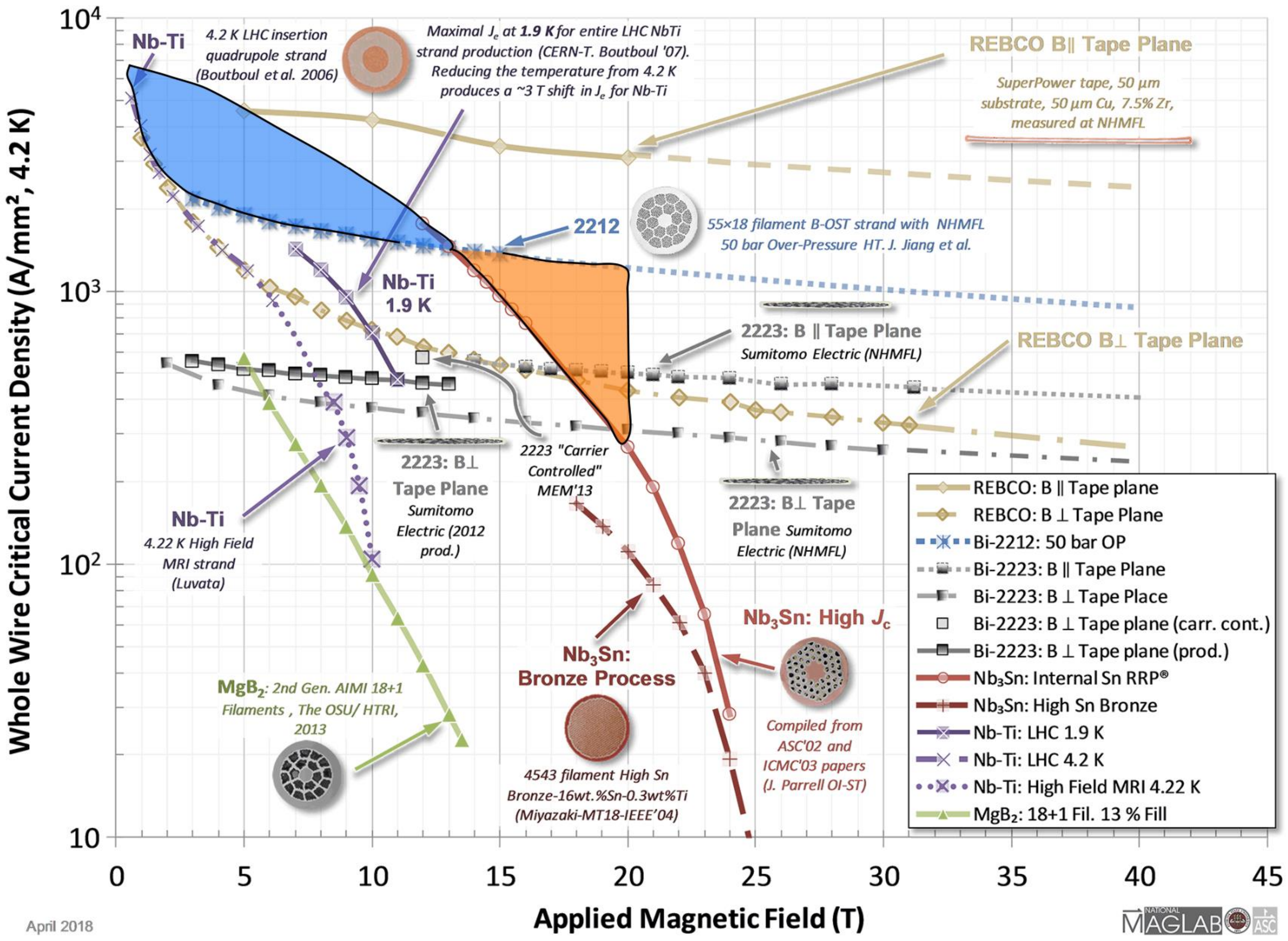
=> hybrid magnets are most efficient



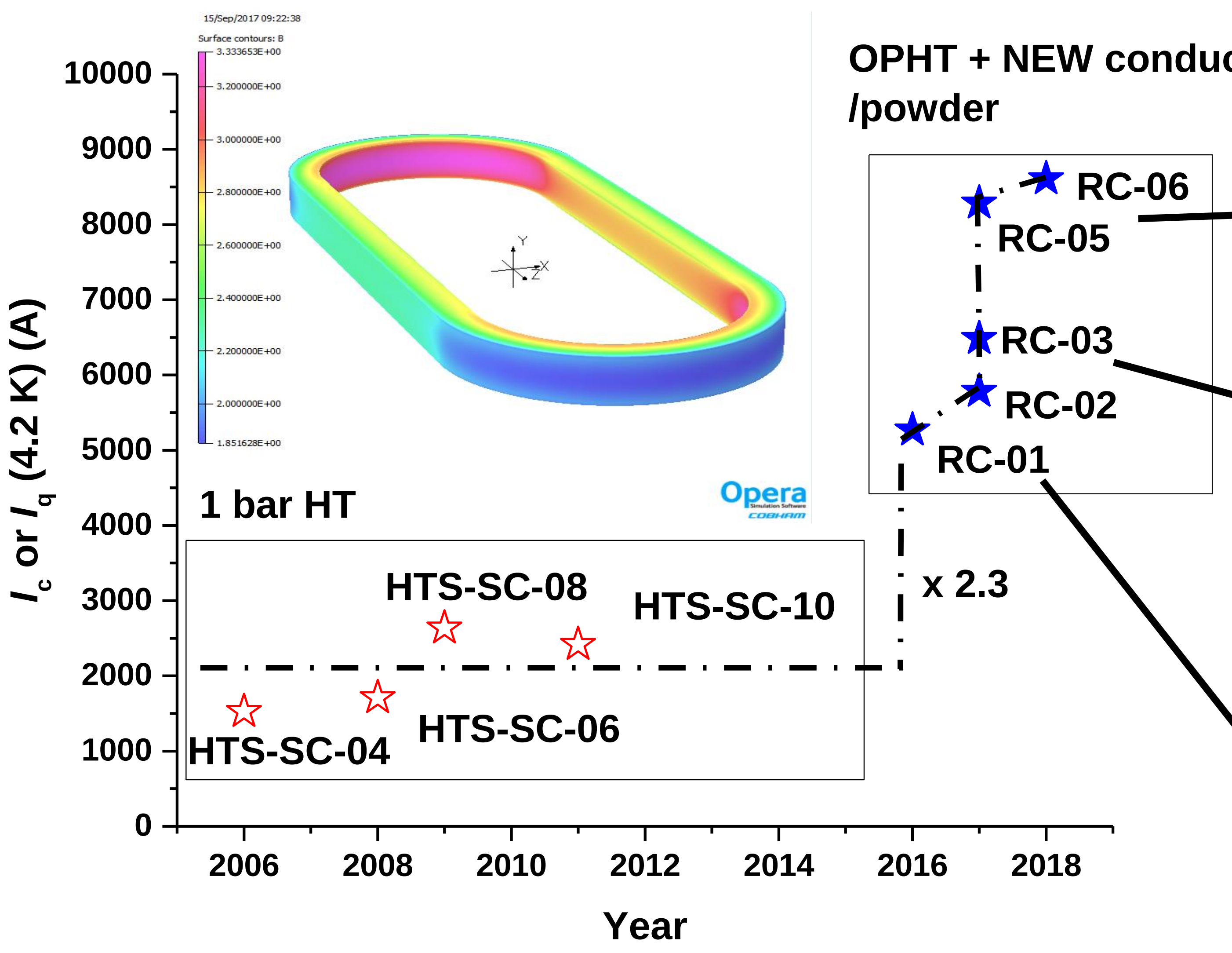
MDP HTS research is currently focused on Bi2212 and REBCO

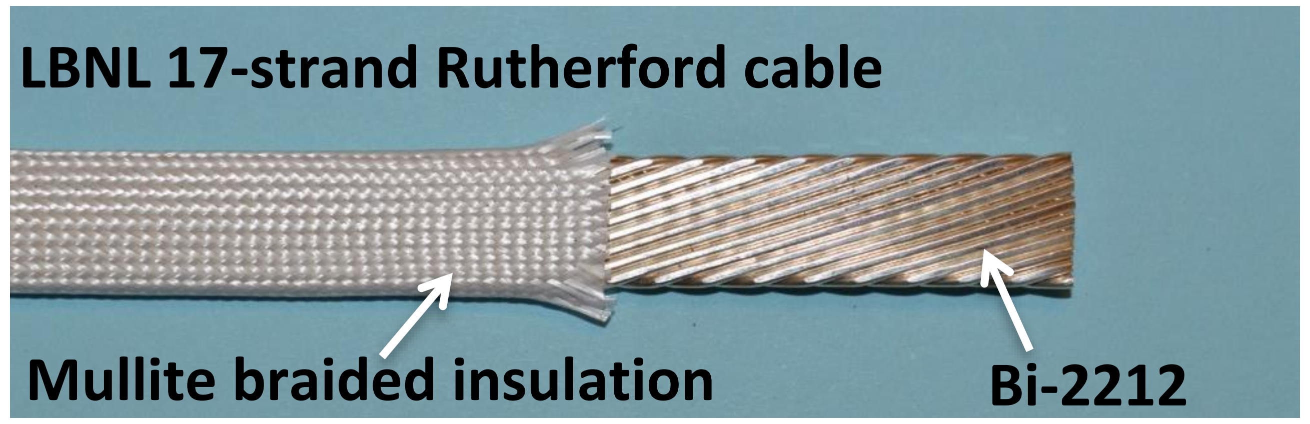
MDP seeks to address questions such as:

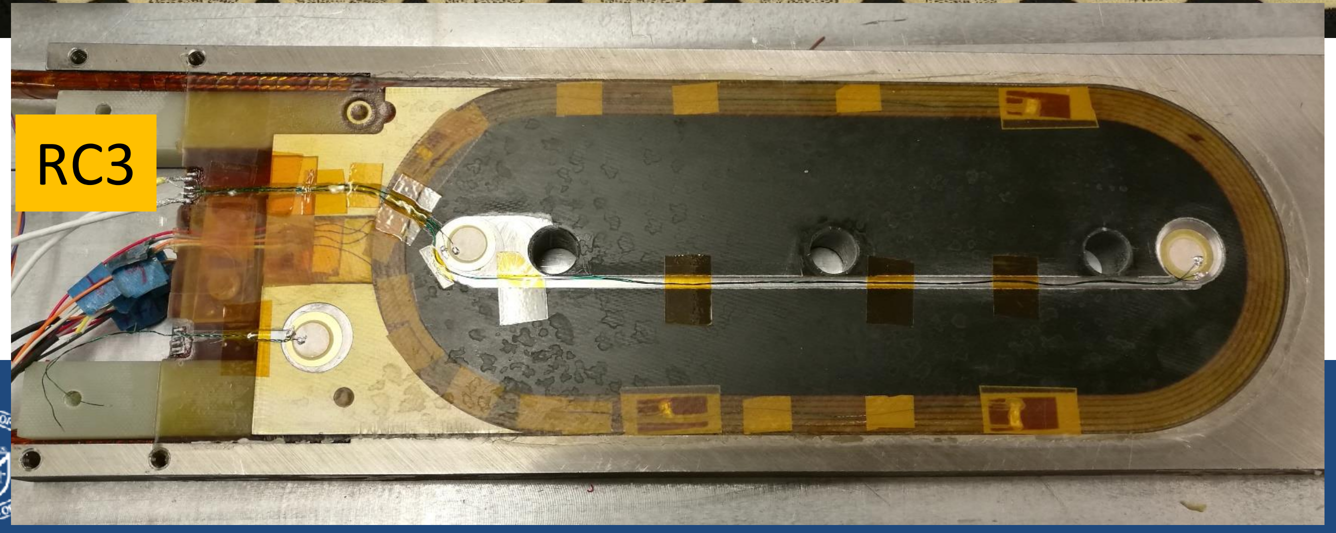
- What is the nature of accelerator magnet training? Can we reduce or eliminate it?
- What are the drivers and required operation margin for Nb3Sn and HTS accelerator magnets?
- What are the mechanical limits and possible stress management approaches for Nb3Sn and 20 T LTS/HTS magnets?
- What are the limitations on means to safely protect Nb_3Sn and HTS magnets?

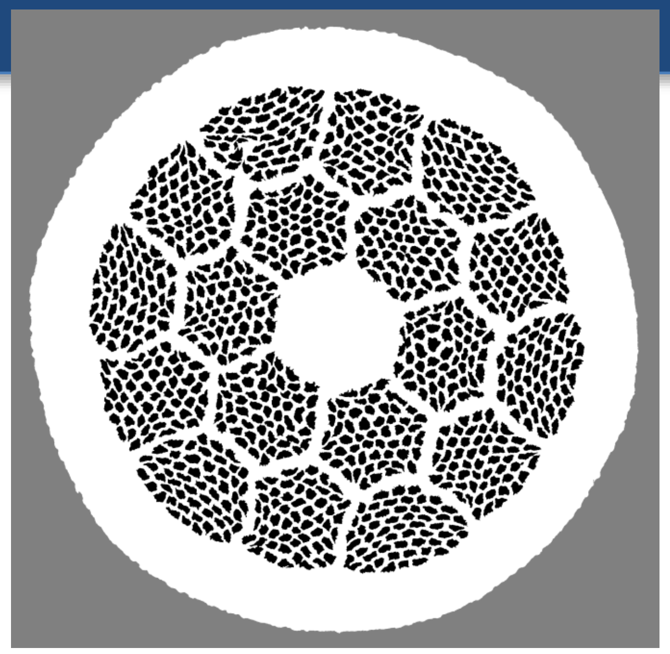


Bi-2212 wires => Rutherford cables => racetrack coils to verify heat treatment, materials compatibility, insulation, cable parameters

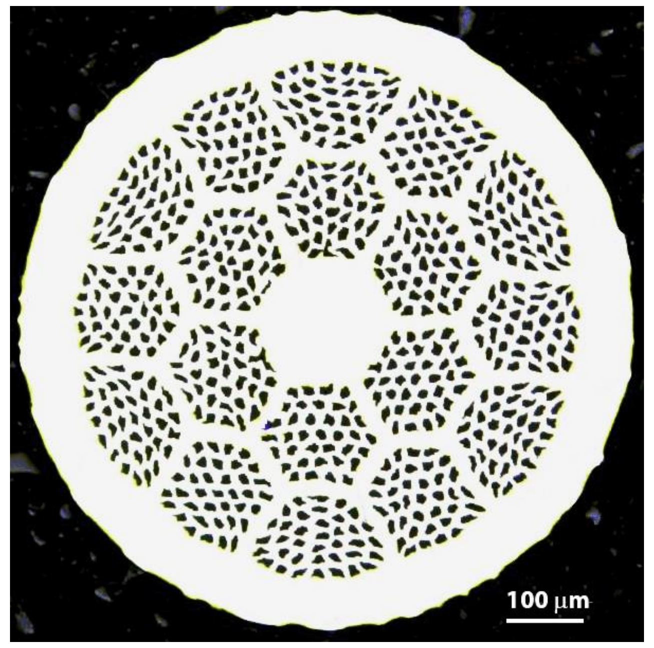




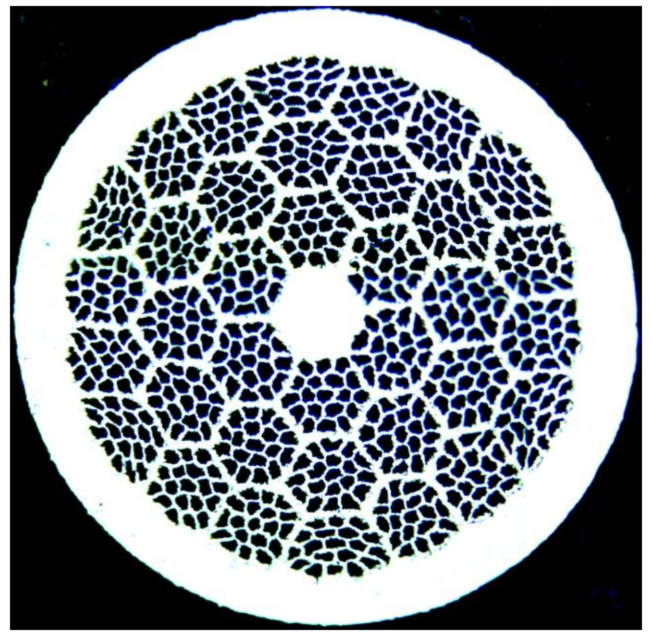




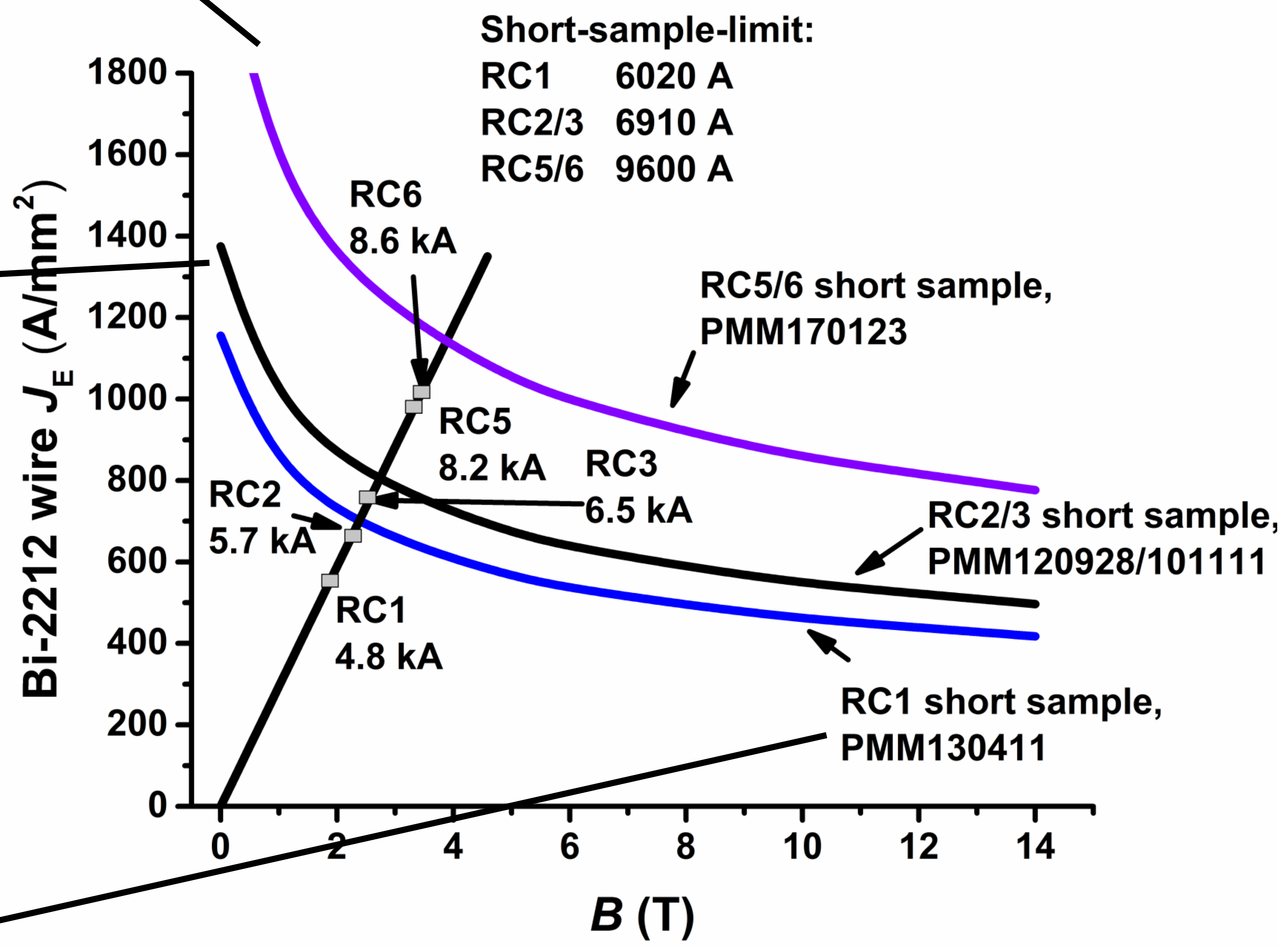
PMM170123, 55x18, nGimat power LXB-52



PMM101111, 36x18, Nexans powder 77

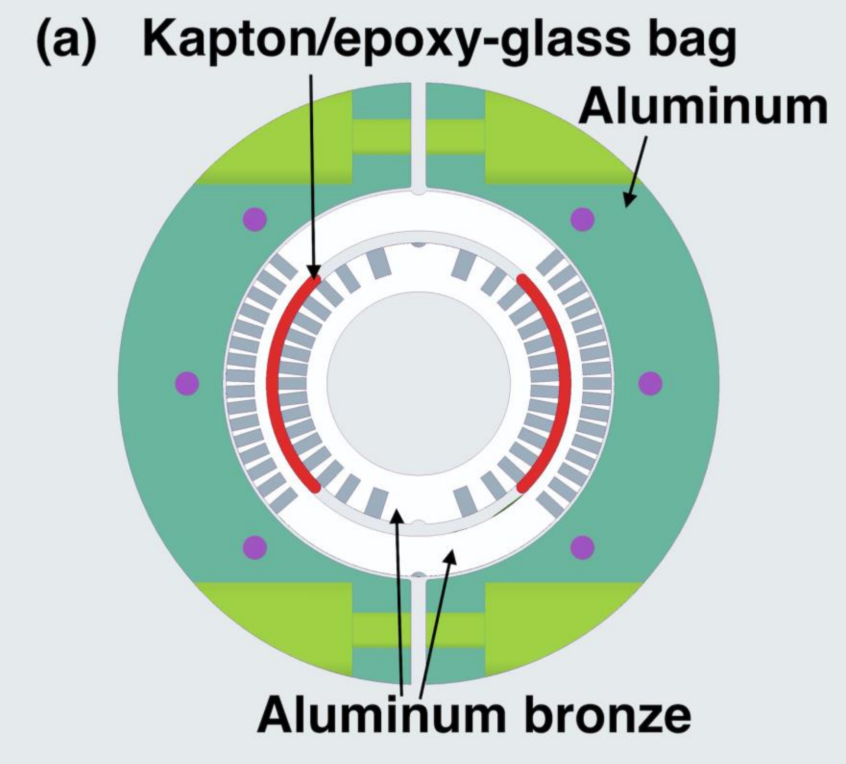


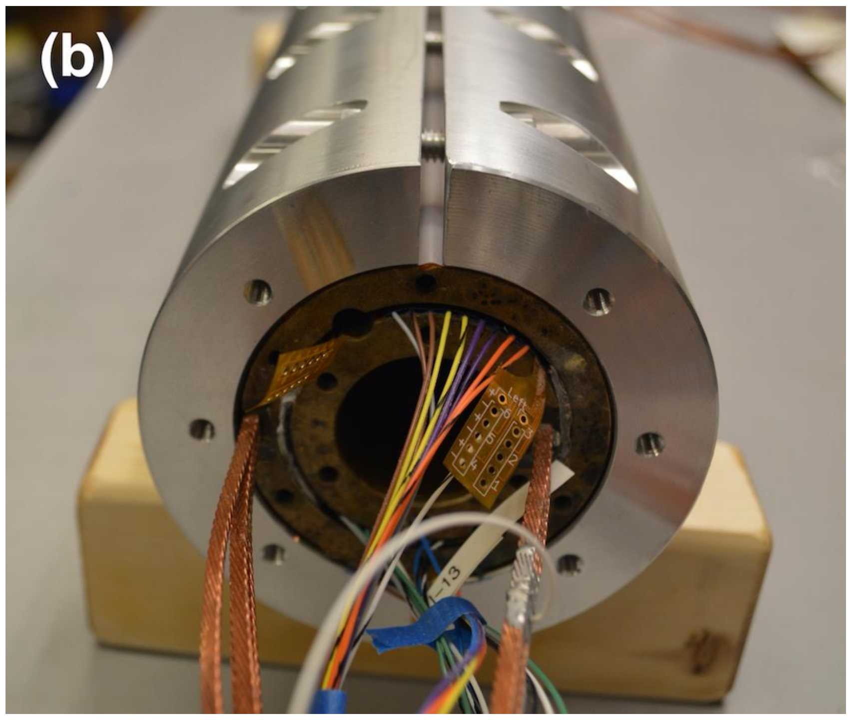
PMM130411, 19x36, Nexans powder 77

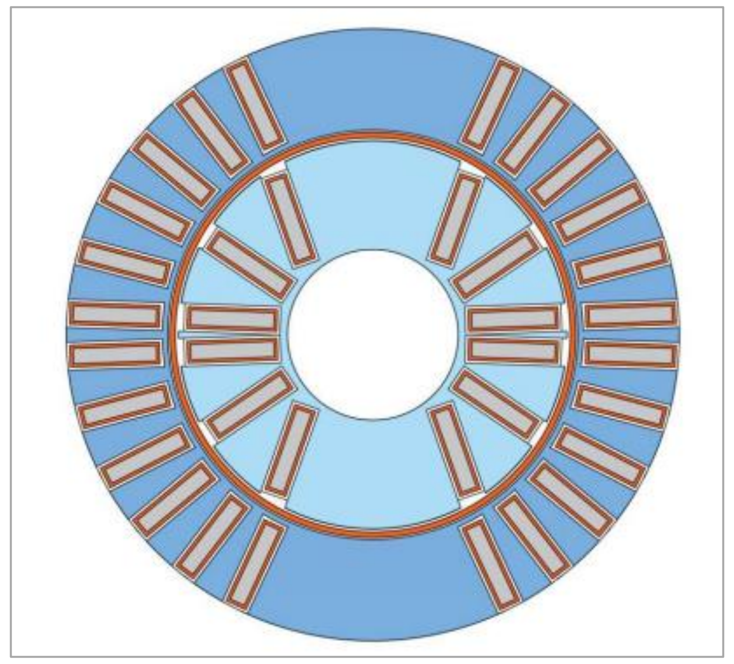


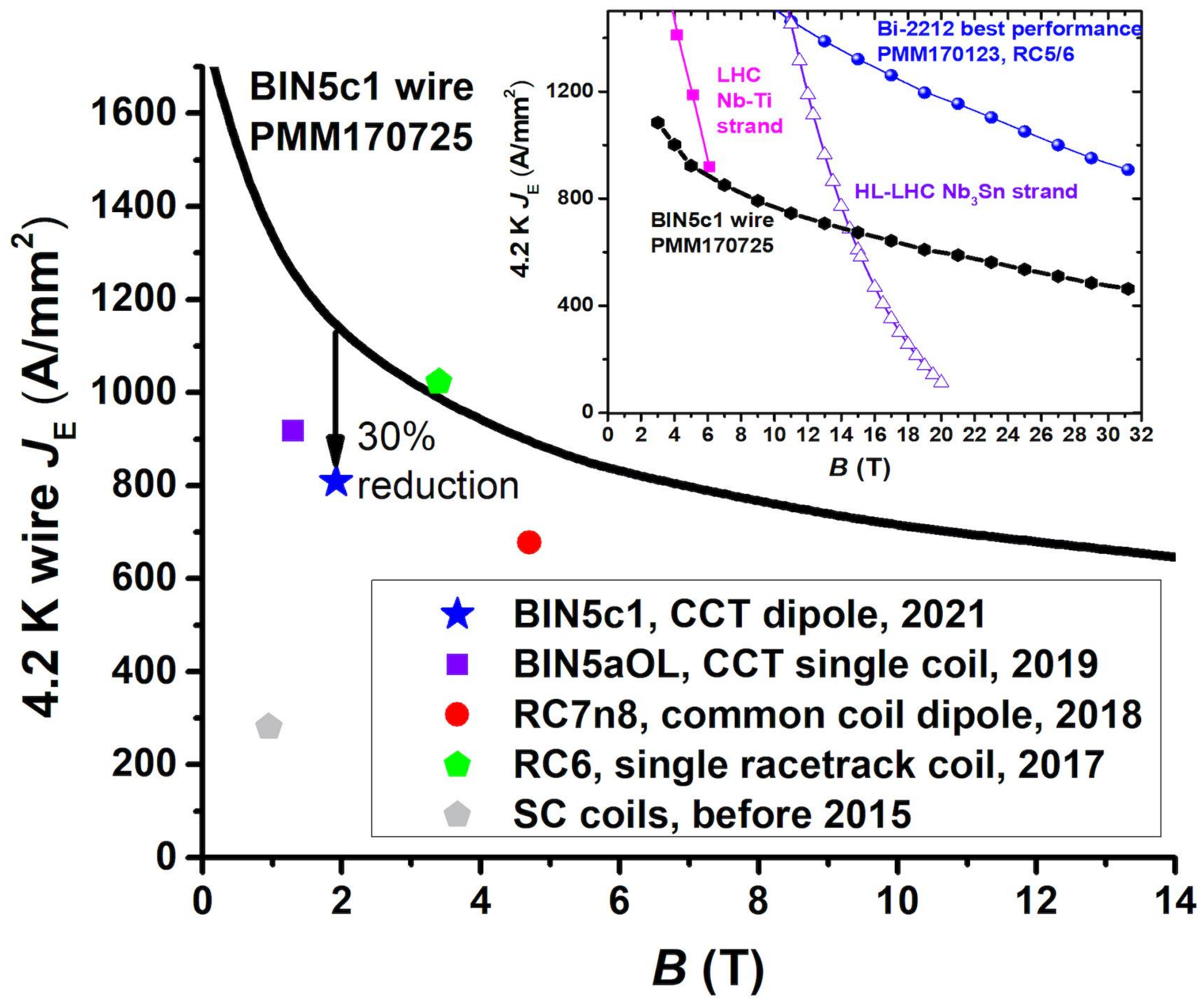
Jiang et al., TAS, Vol. 33, No. 5, August 2023
Shen et al., Scientific Reports Vol. 9, Art. No.: 10170 (2019)
Zhang et al Supercond. Sci. Technol. 31 105009 (2018)

Bi2212 shows strong promise – being readied for hybrids









IOP Publishing | Superconductor Science and Technology
Supercond. Sci. Technol. 34 (2021) 024001 (11pp) | https://doi.org/10.1088/1361-6668/abc73d

First demonstration of high current canted-cosine-theta coils with Bi-2212 Rutherford cables

L Garcia Fajardo[1], T Shen[2], X Wang[2], C Myers[2,3], D Arbelaez[1], E Bosque[4], L Brouwer[2], S Caspi[1], L English[4], S Gourlay[2], A Hafalia[1], M Martchevskii[2], I Pong[2] and S Prestemon[1]

CCT6-Bi-CCT1

- ID 40mm
- OD 95mm
- SSL 5T
- 17-strand
- 0.8mm diameter

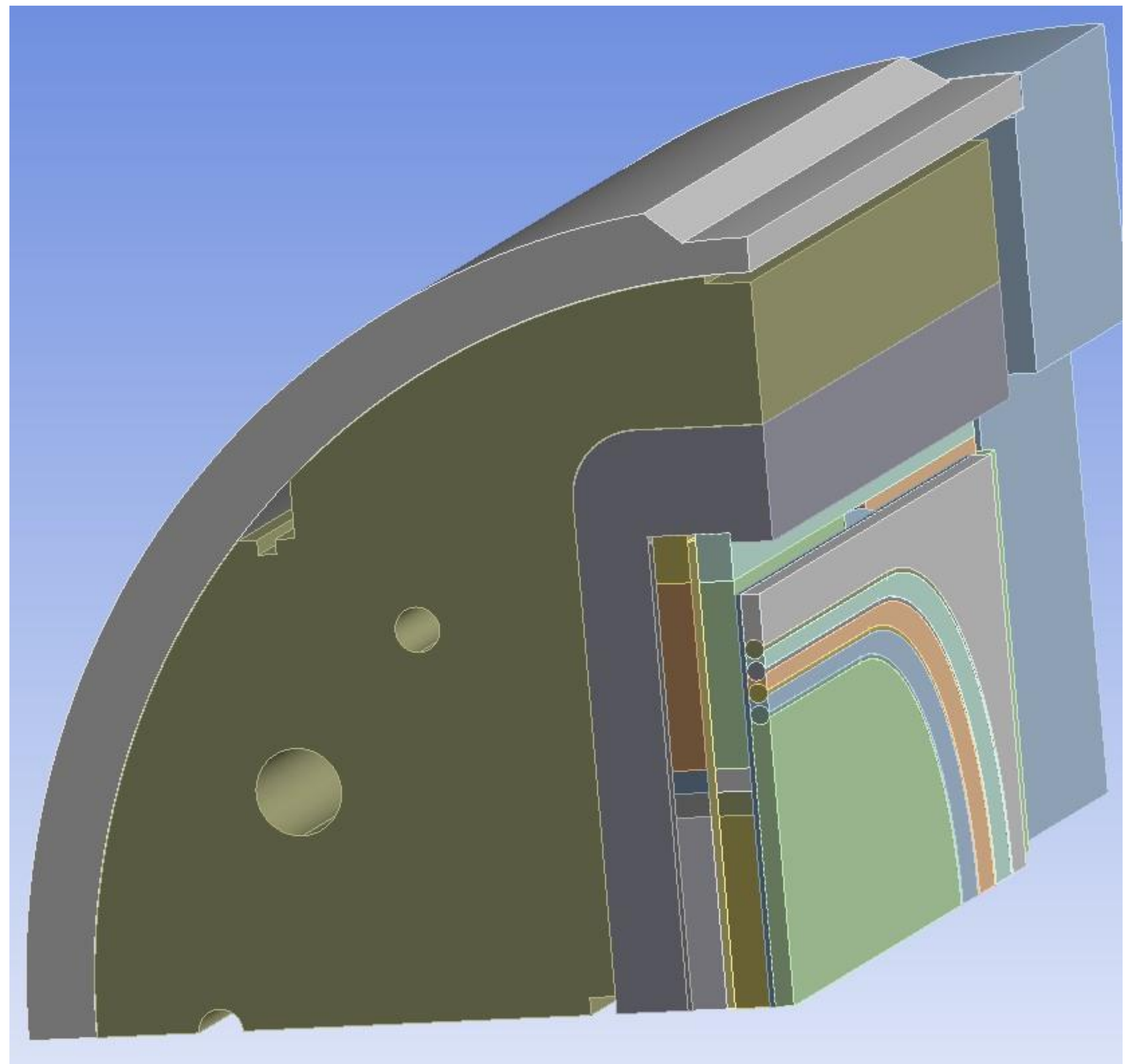
3 coils at FSU, ready f

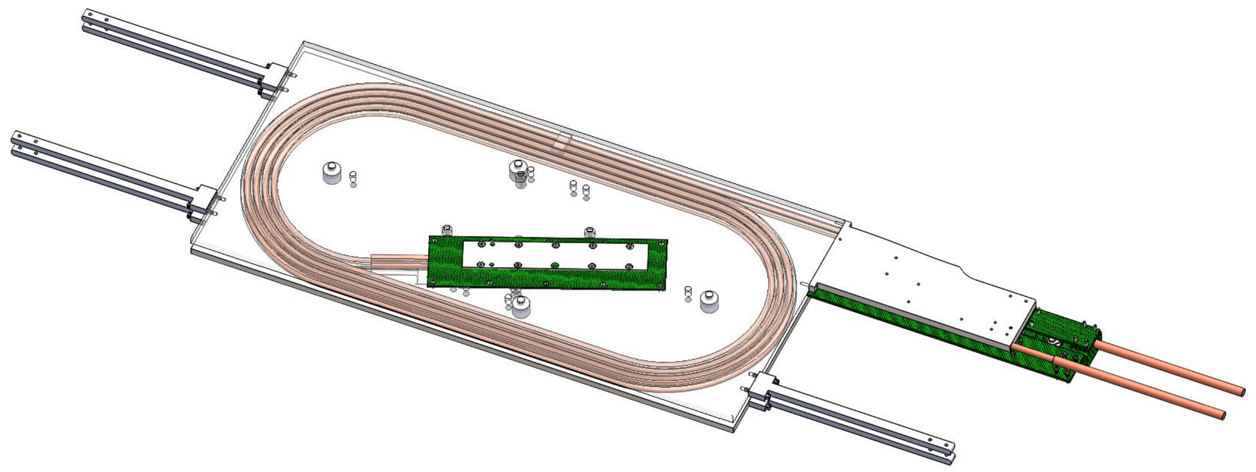
CCT6-Bi-CCT2

- ID 40mm
- OD 115mm
- SSL 6.8T
- 23-strand
- 1.0mm diameter

REBCO makes steady progress – MDP focuses on CORC® & STAR®

Test CORC in-field at BNL in the common-coil test facility

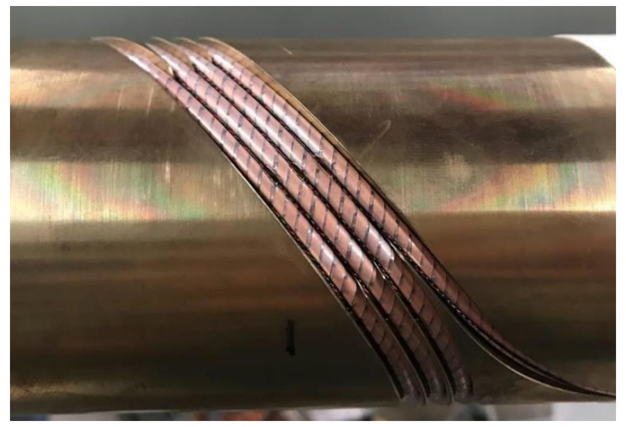


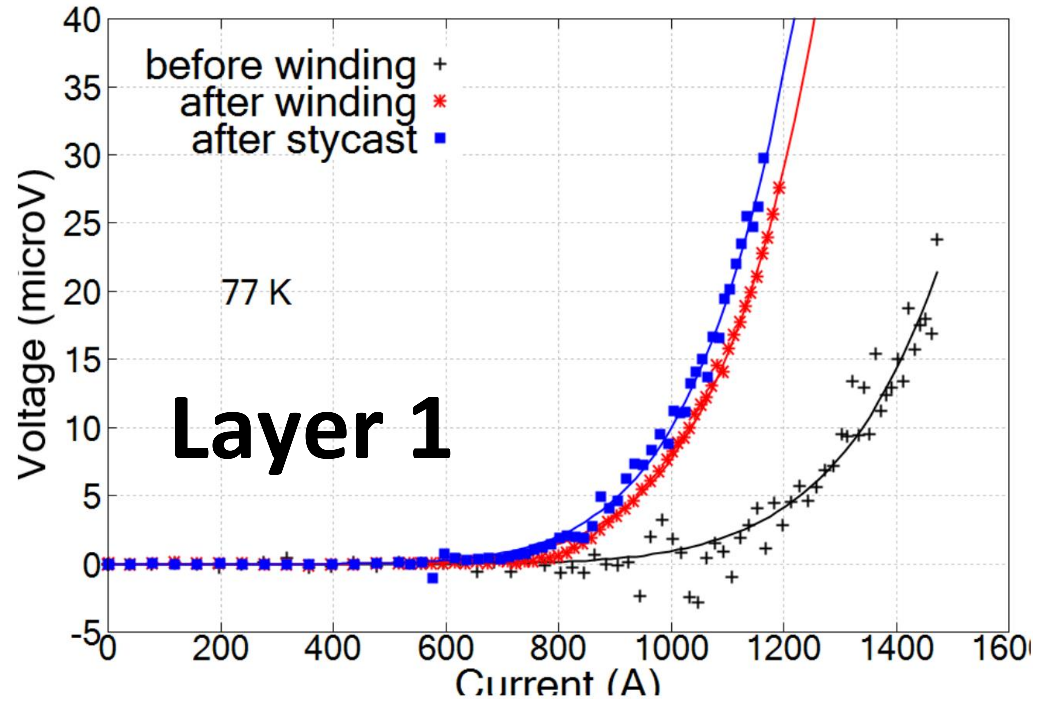


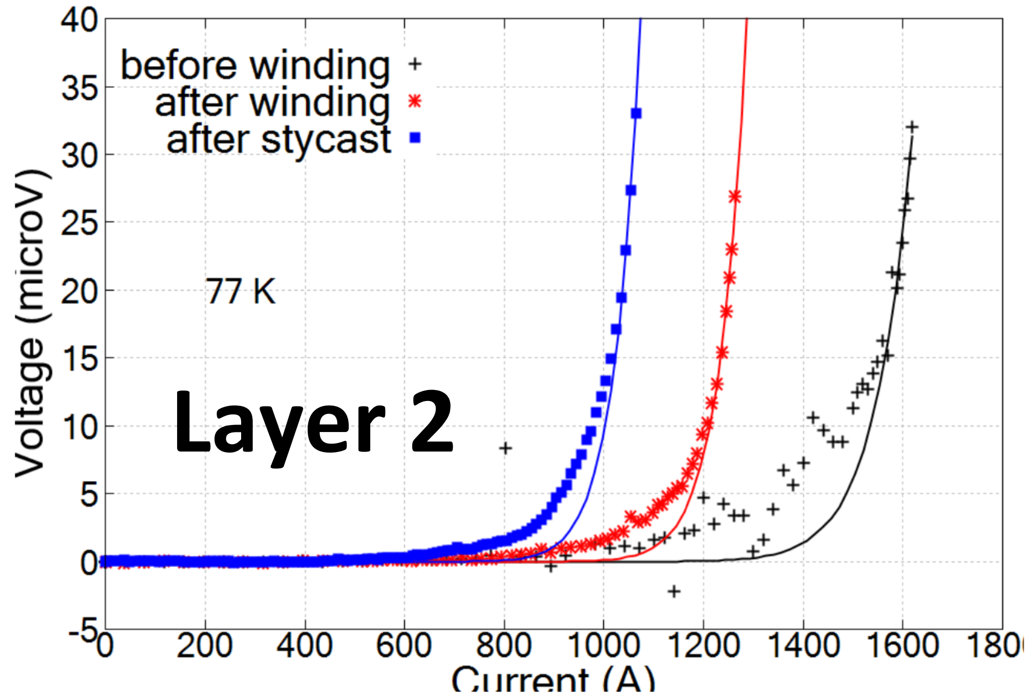
Next deliverable – "C3"

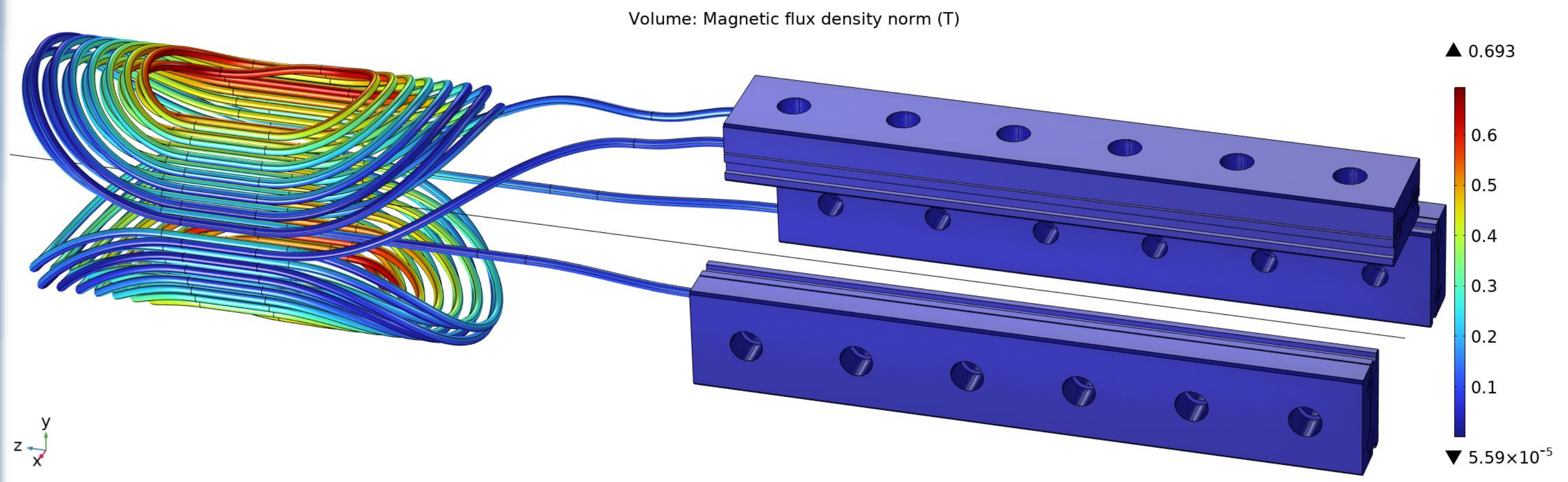
- Generate 5 T
- 6-layer CCT using CORC® wires
- Tapes in-hand, cable underway

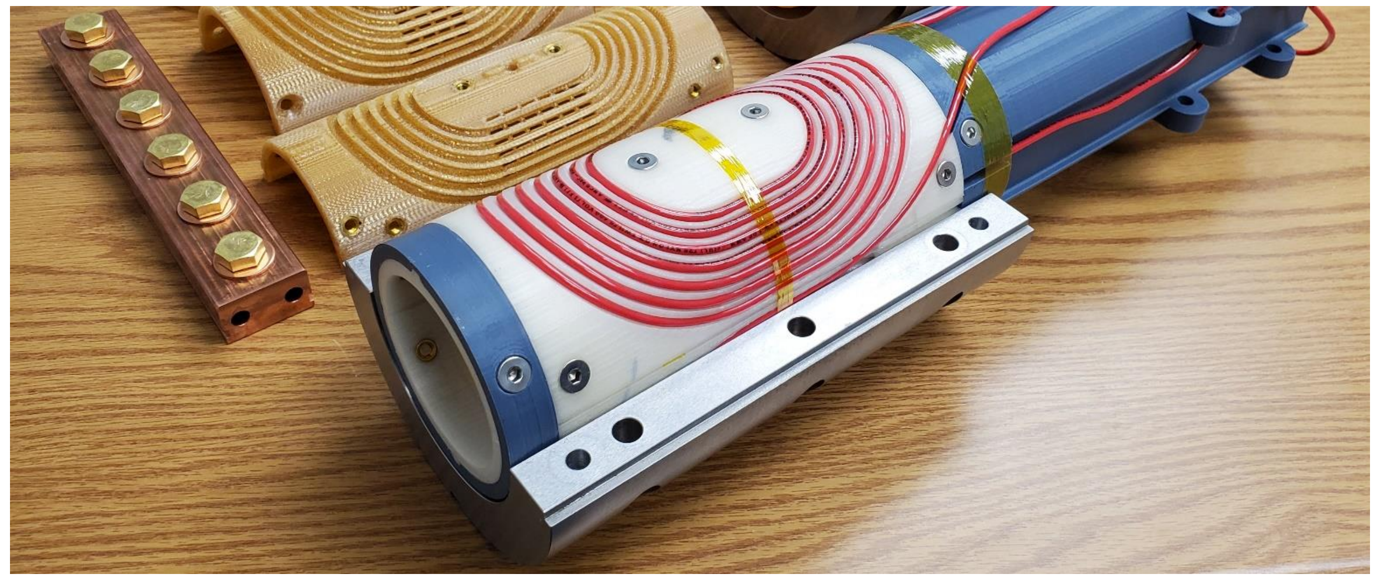
3-turn practice windings are done for each layer





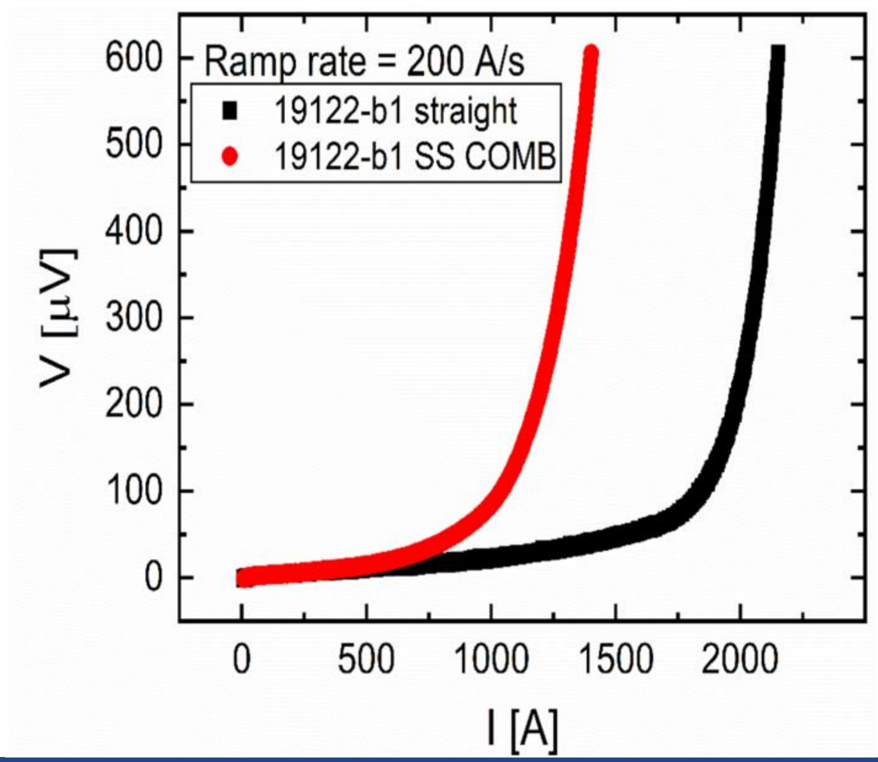




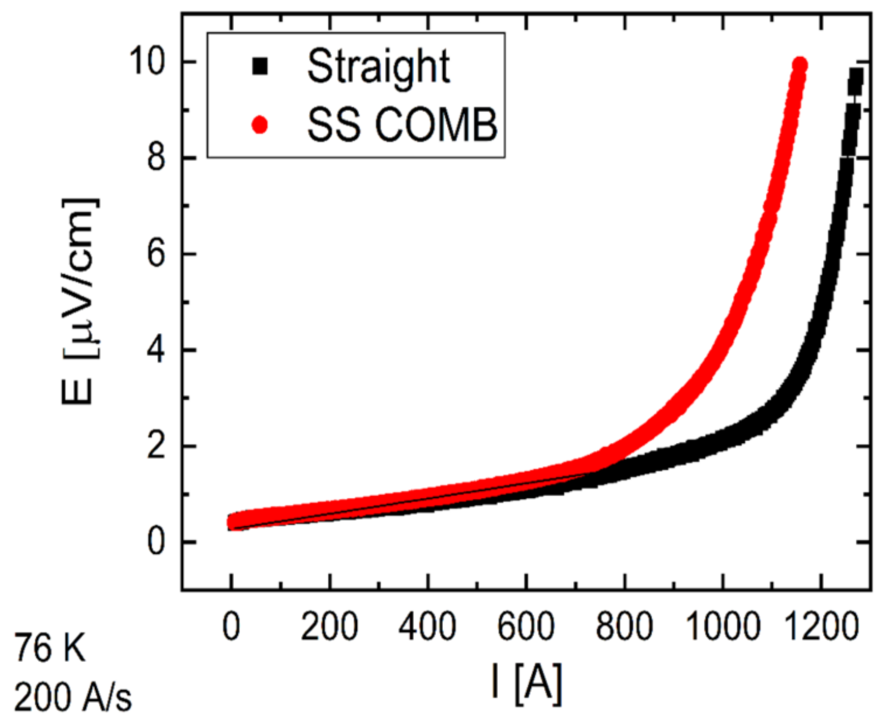


"COMB" design advancing as a test platform

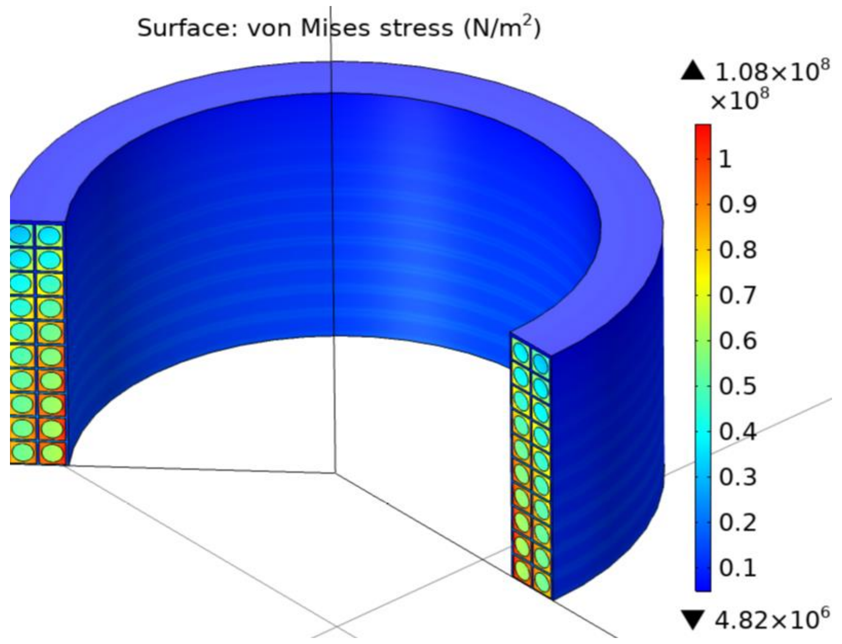
"Early" CORC



Improved CORC

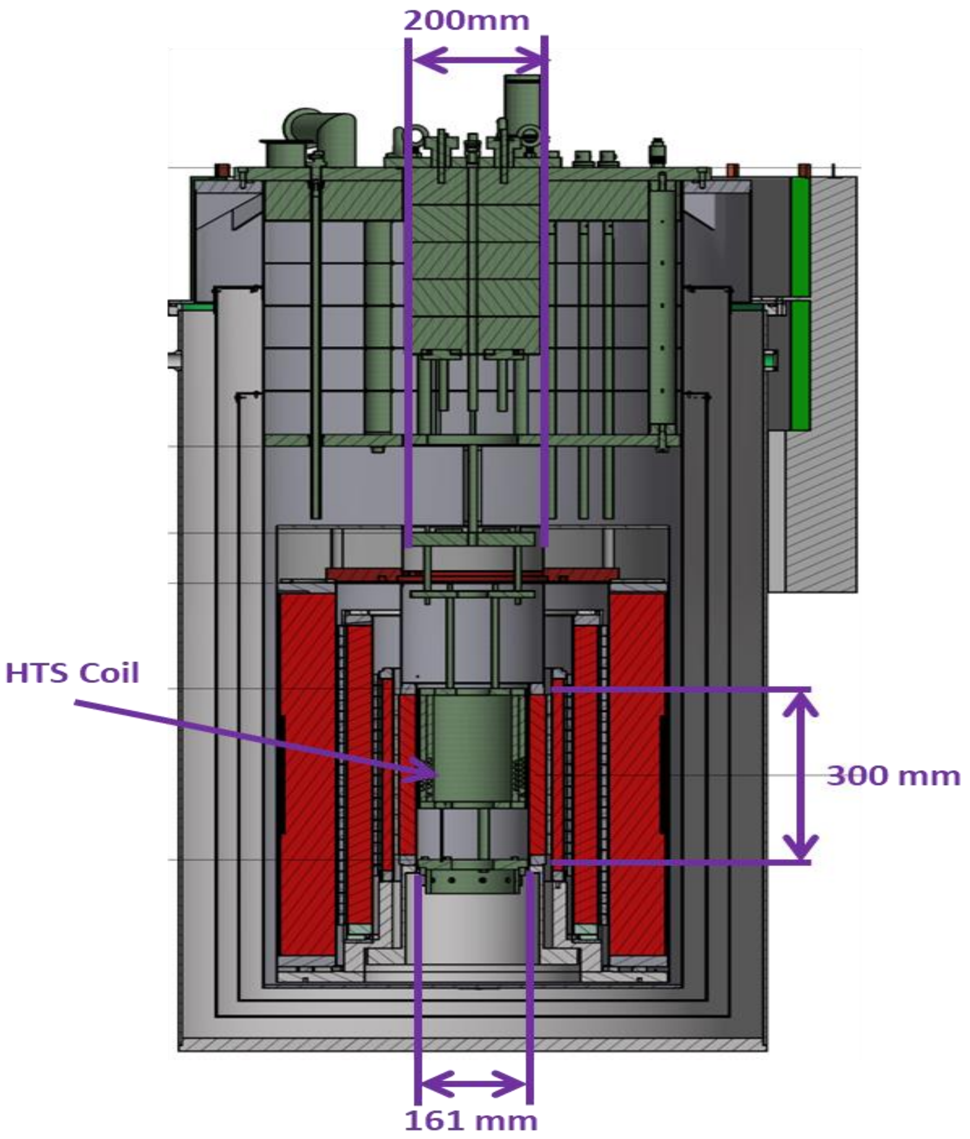


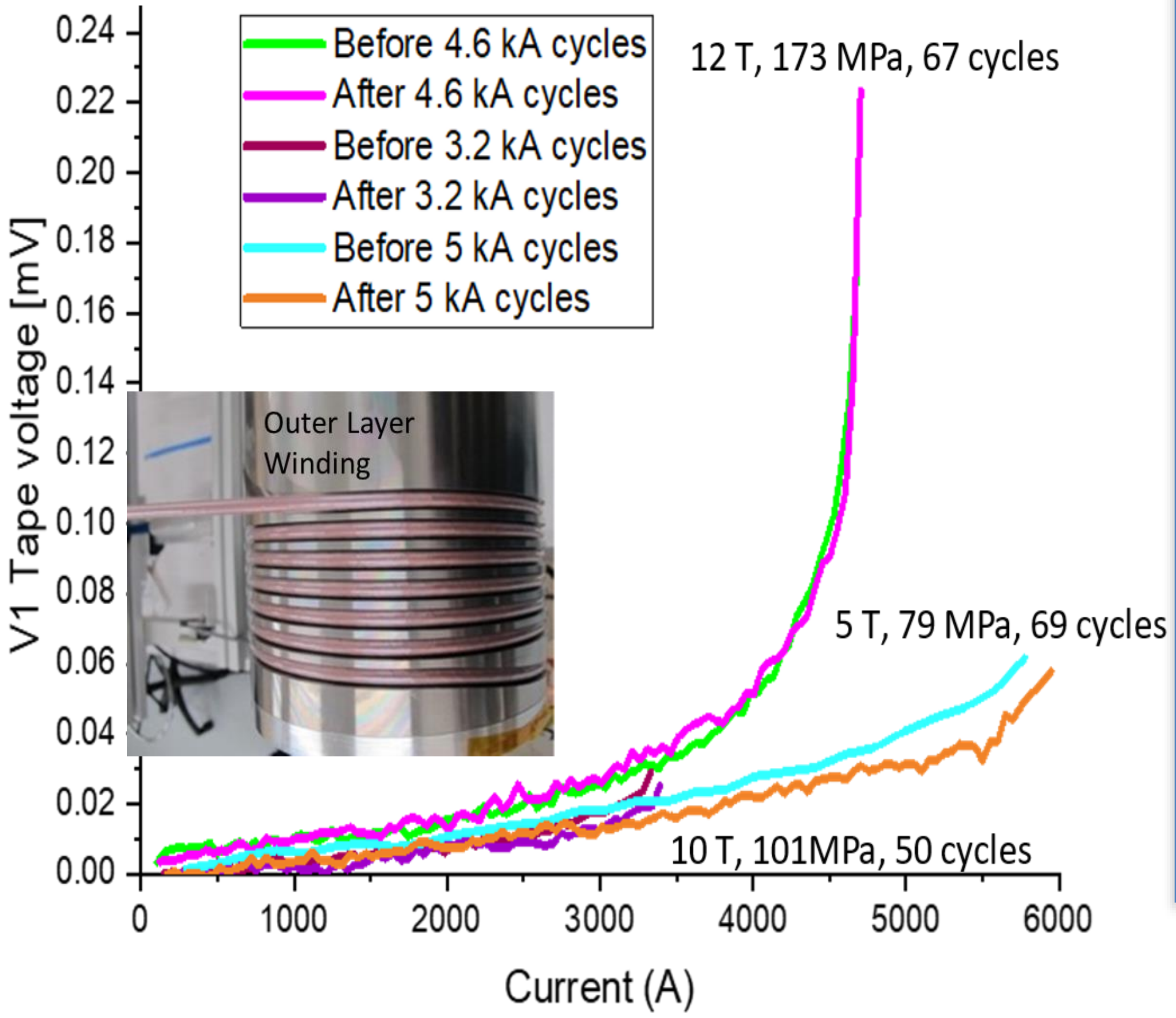
Strong synergies with Fusion REBCO research are leveraged



- No sign of degradation seen in high field & low-cycle fatigue testing - IC>80% sum of tapes
- Demonstrate feasibility of direct dry wound (non-VPI) coil design

A two layer Cable Model Coil to test for cyclic degradation





DOE Offices of HEP & FES jointly funding a large-bore cable test facility

- Will provide 15T dipole field over 750mm good-field, 1.9-50K on-sample
- Cryostat will enable testing of high-field hybrid magnets
- Being located at FNAL

HFVMTF Cable Test Facility: First Workshop on User Interfaces

Registration

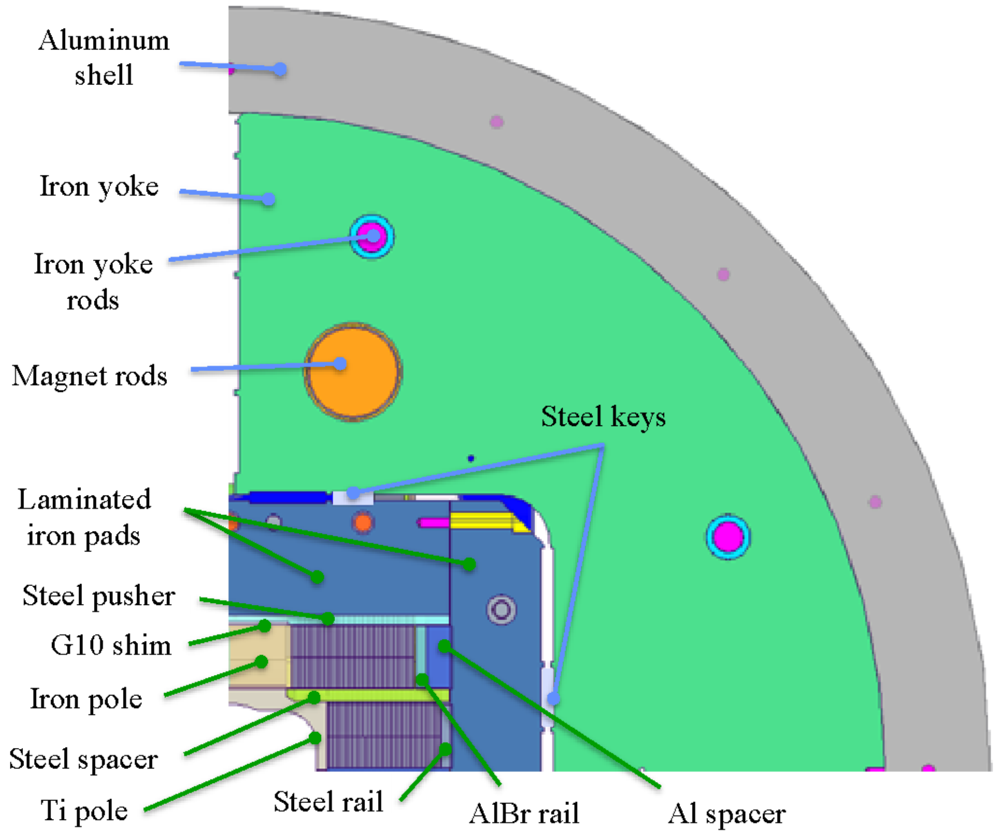
Event Registration

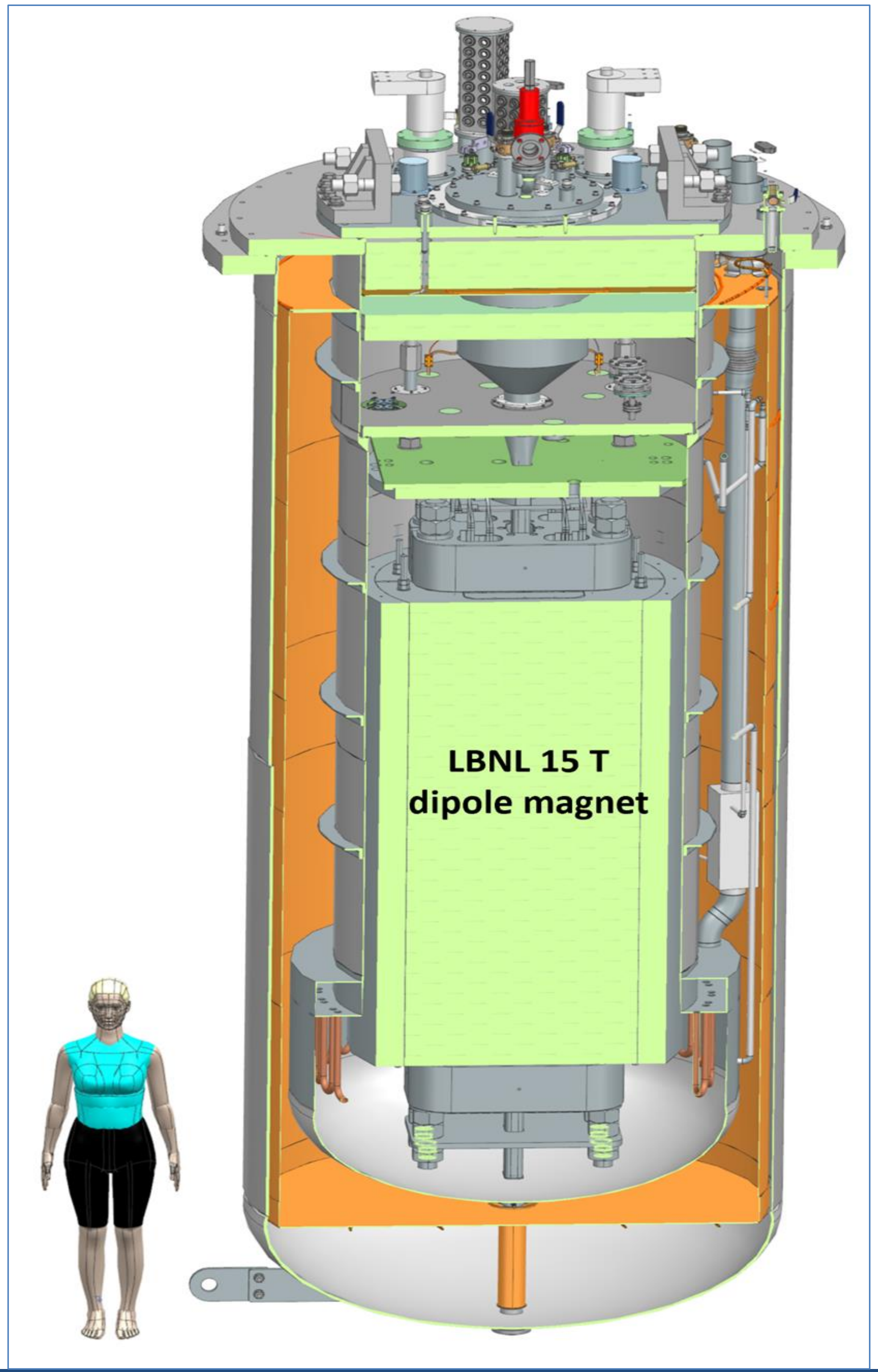
Contact info
velev@fnal.gov,denise2@fnal.gov

Fermi National Accelerator Laboratory and Lawrence Berkeley National Laboratory are together building a new High Field Vertical Magnet Test Facility (HFVMTF) for testing high-temperature superconducting cables in a high magnetic dipole field. The HFVMTF is jointly funded by the US DOE Office of Science's Fusion Energy Sciences and High Energy Physics programs. HFVMTF will serve both communities as a superconducting cable test facility in high magnetic fields and in a wide range of temperatures.

The purpose of the first workshop is to establish connections between prospective users and the facility design team. The primary goal will be to receive users' feedback on facility specifications, mainly the sample holder and instrumentation interfaces, as well as on operating ranges for the samples in the test well.

The workshop will take place on half-days via Zoom on November 21-22.



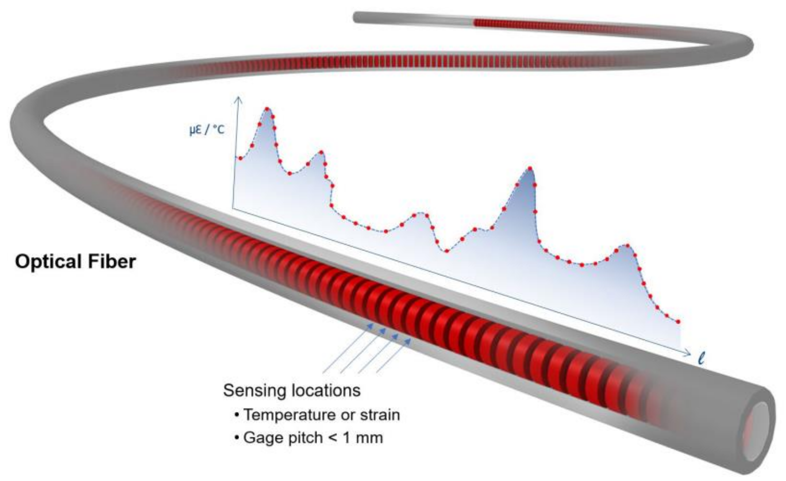


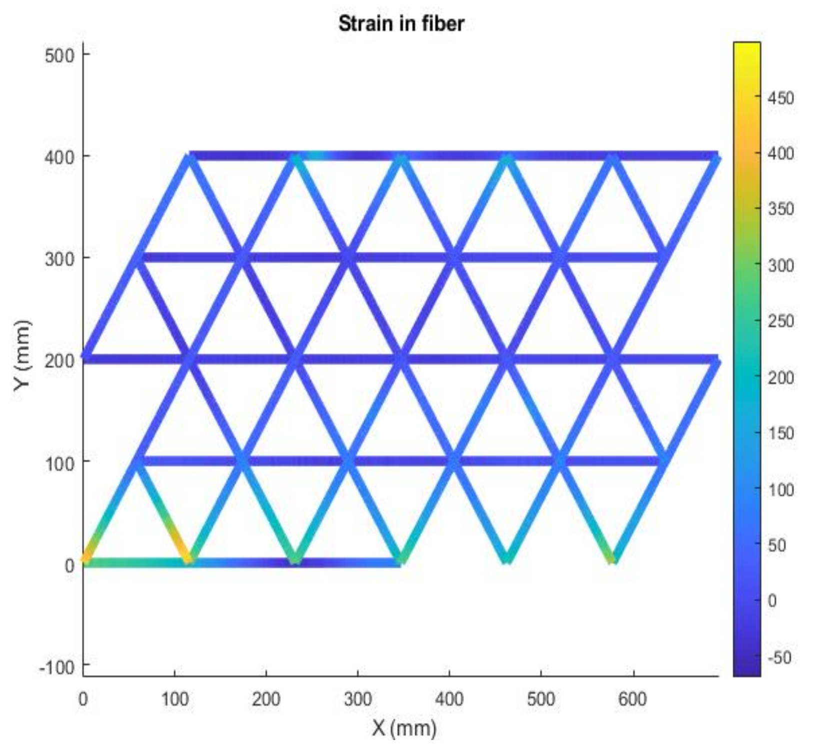
U.S. MAGNET DEVELOPMENT PROGRAM

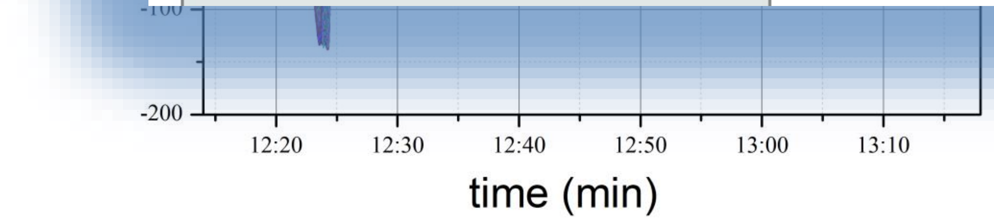
Diagnostics are central to advance magnet technology

M. Baldini, S. Krave

Rayleigh backscatter fib[…]
for area-level strain mon[…]








4th Superconducting Magnet Test Facilities Workshop & 2nd Workshop on Instrumentation and Diagnostics for Superconducting Magnets

Apr 24 – 28, 2023
Hotel Ariston, Paestum (SA), Italy
Europe/Rome timezone

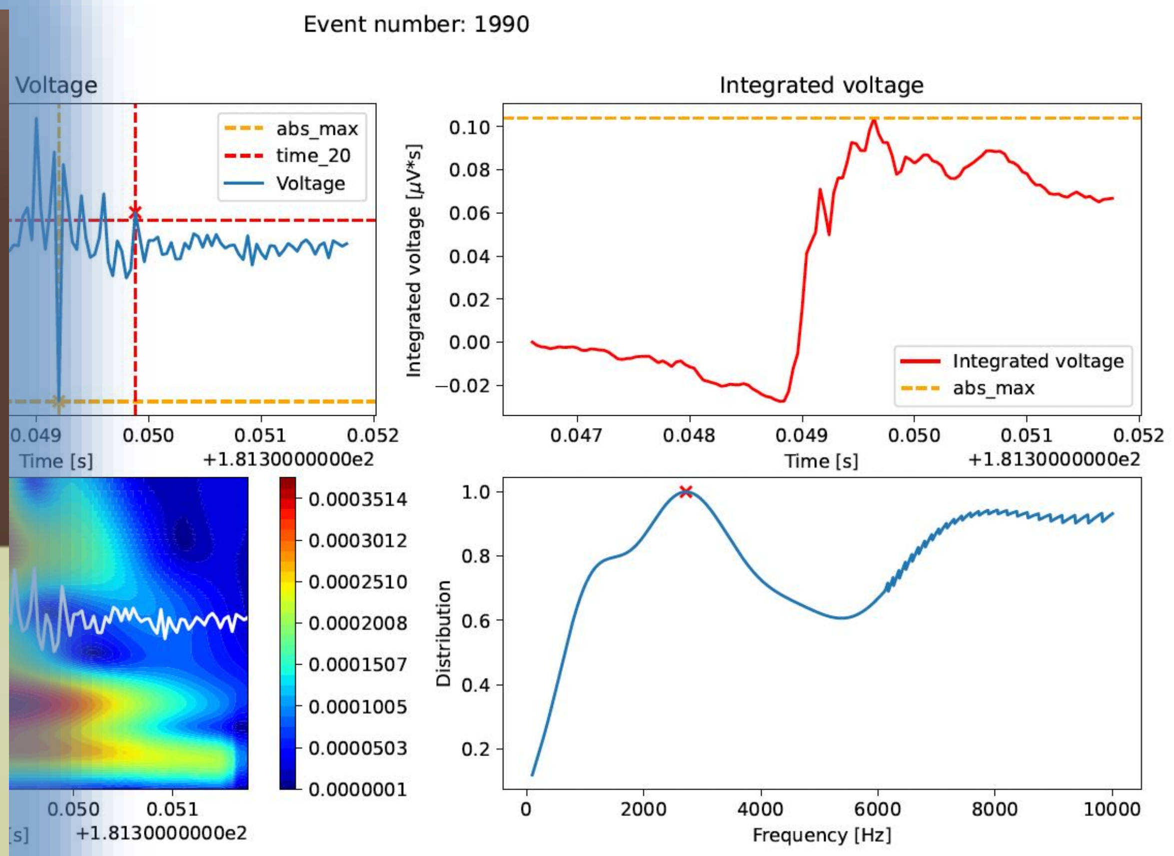
Enter your search term

Introduction
Scientific Program
Venue and Booking
Tourism and sightseen in the area
Timetable

Introduction

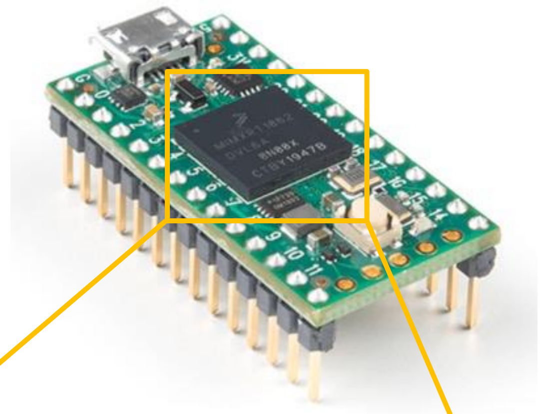
Following difficult years of pandemics, the ***Superconducting Magnet Test Facility Workshop*** *(SMTF) is back! I would like to announce that the next workshop is being organised and proposed for spring 2023.*

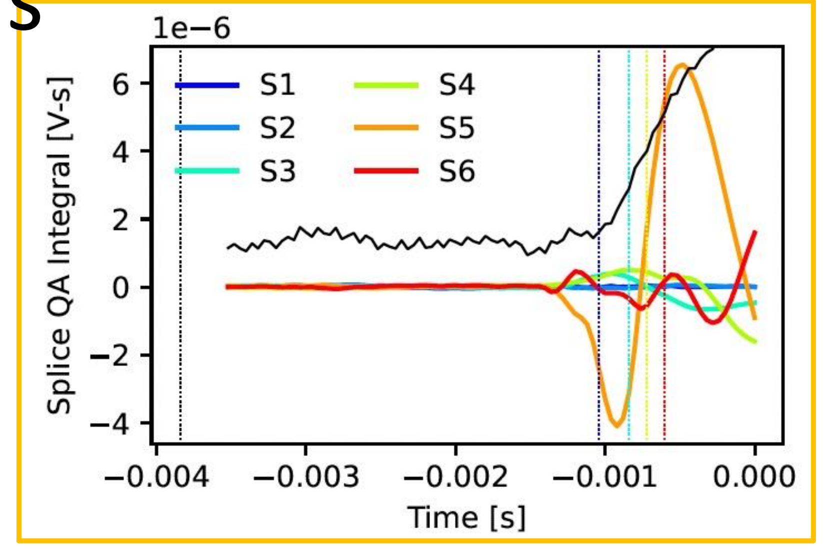
For this new edition, we would like to propose a joint event with the ***Instrumentation and Diagnostics for Superconducting Magnets Workshop*** *(IDSM), which had been initiated in 2019 by M. Marchevsky and G. Willering. The two workshops will be held close to INFN, University of Salerno (IT).*

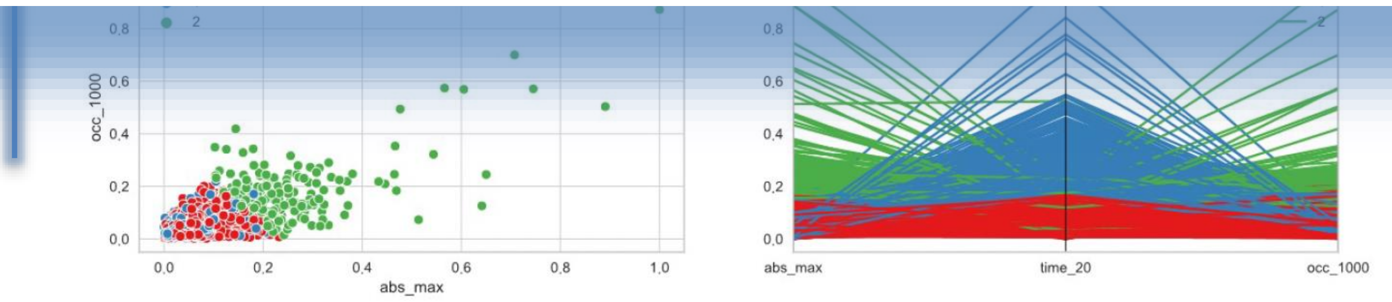


[…]i, E. Barzi,

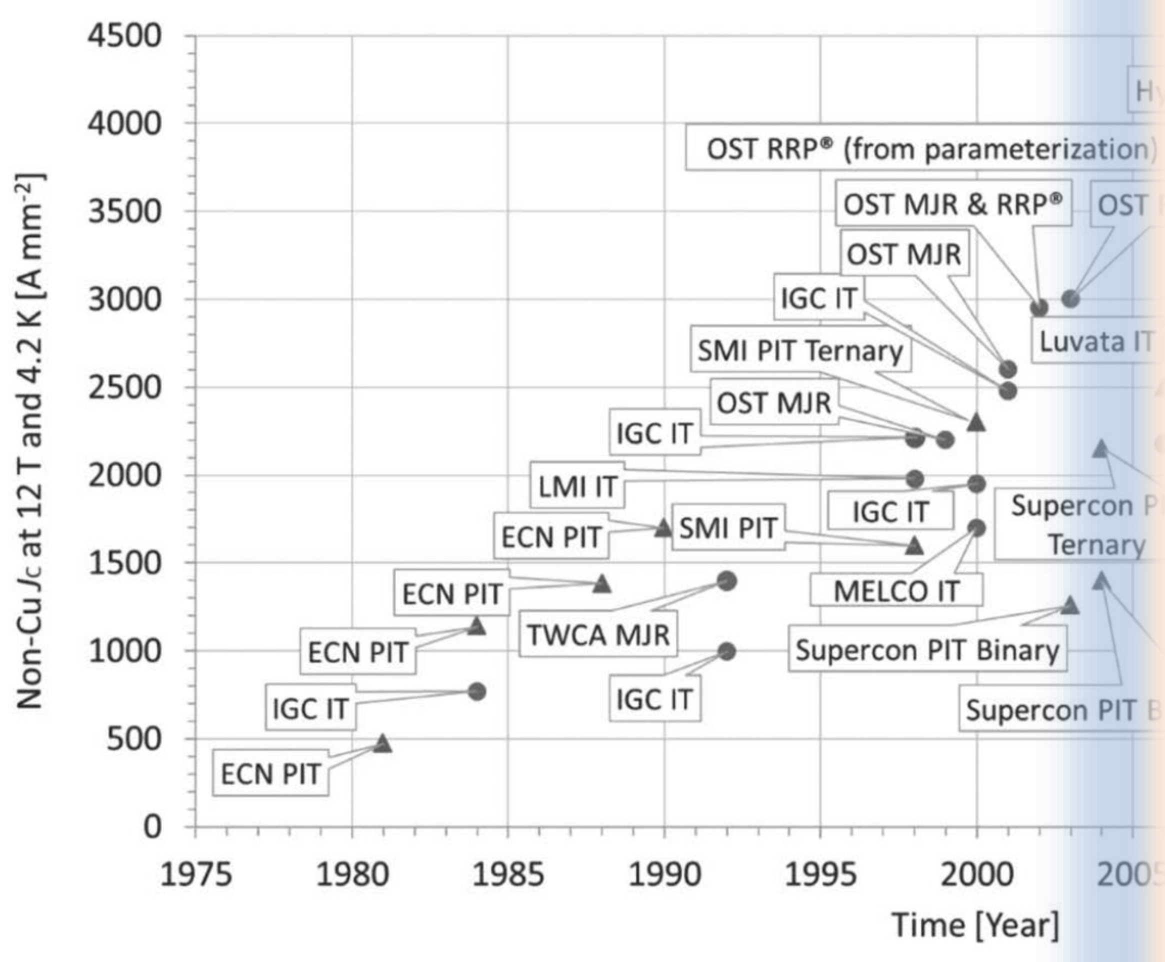
[…]ards real-
[…]e quench
[…]al analysis





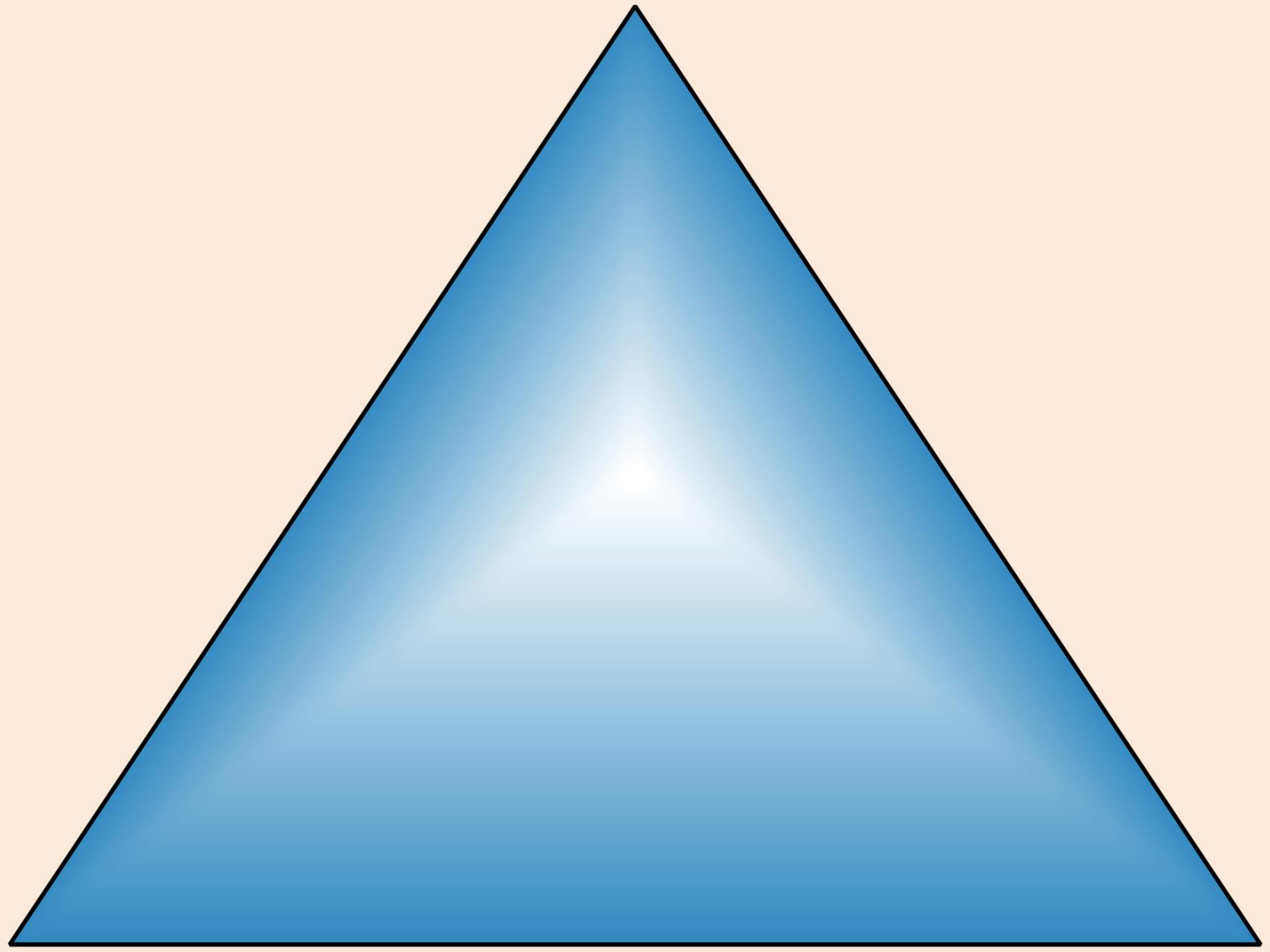


Superconductor advances are heavily driven by OHEP magnet developments, needs, and focused and consistent investments



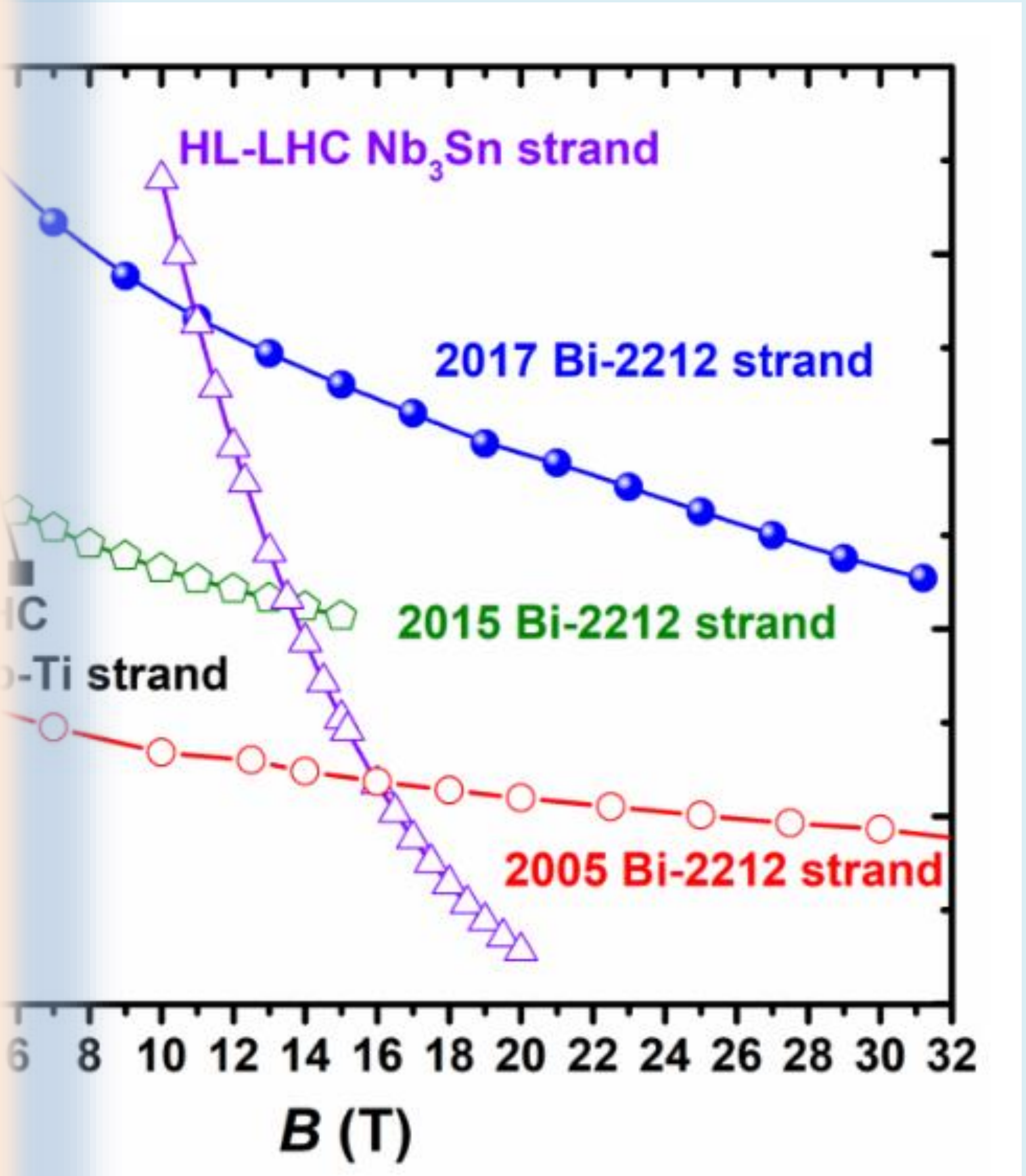
I. Pong, Handbook of Supercond
Chapter E3.8

Performance
(transport, Tc, Bc2,...)



Quality
(uniformity, reproducibility,...)

Cost
(P-factor, scalability)



ajardo, Instruments, 2020

A longstanding history of public/private partnership driving performance of superconductors

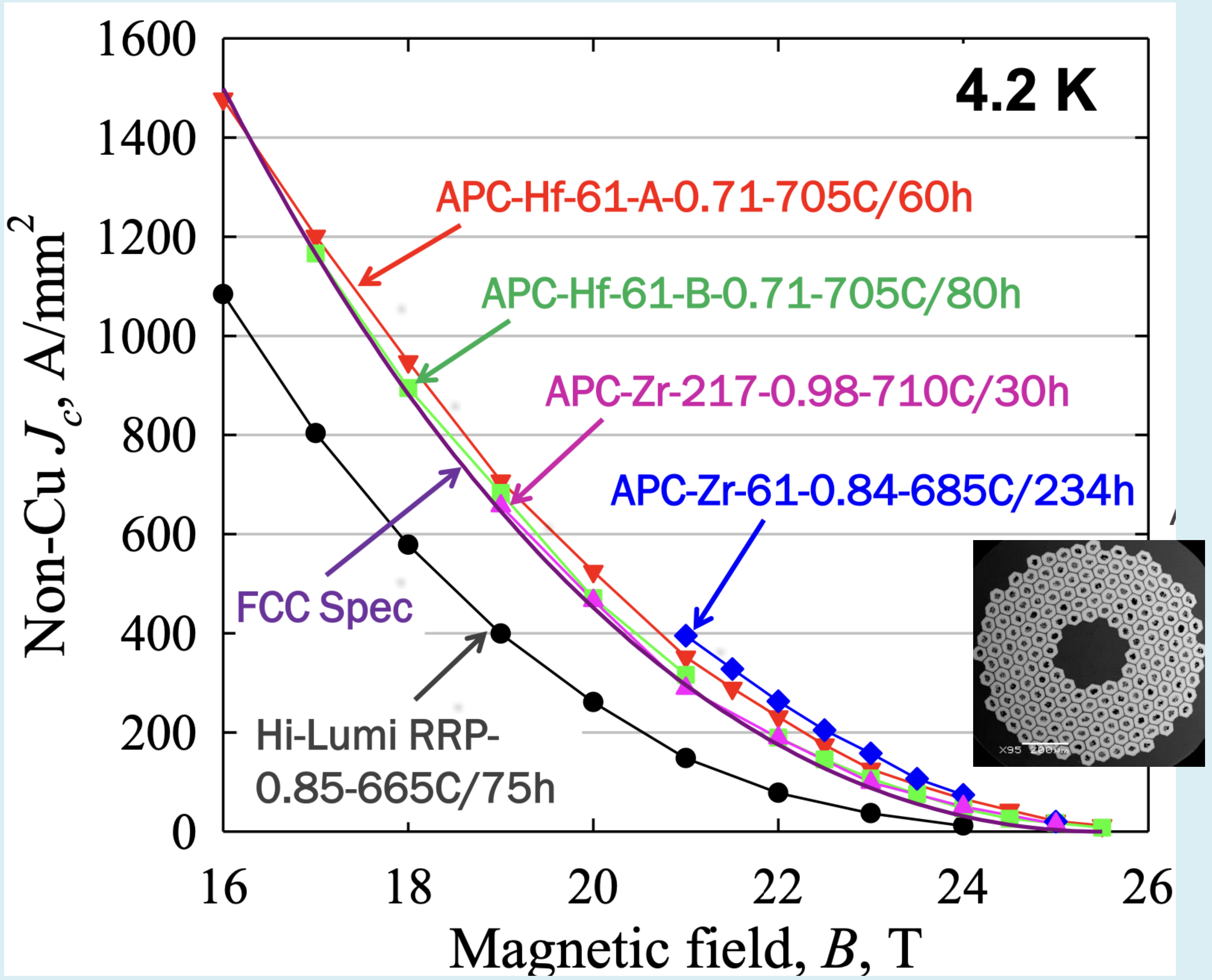
generation Nb3Sn superconductor

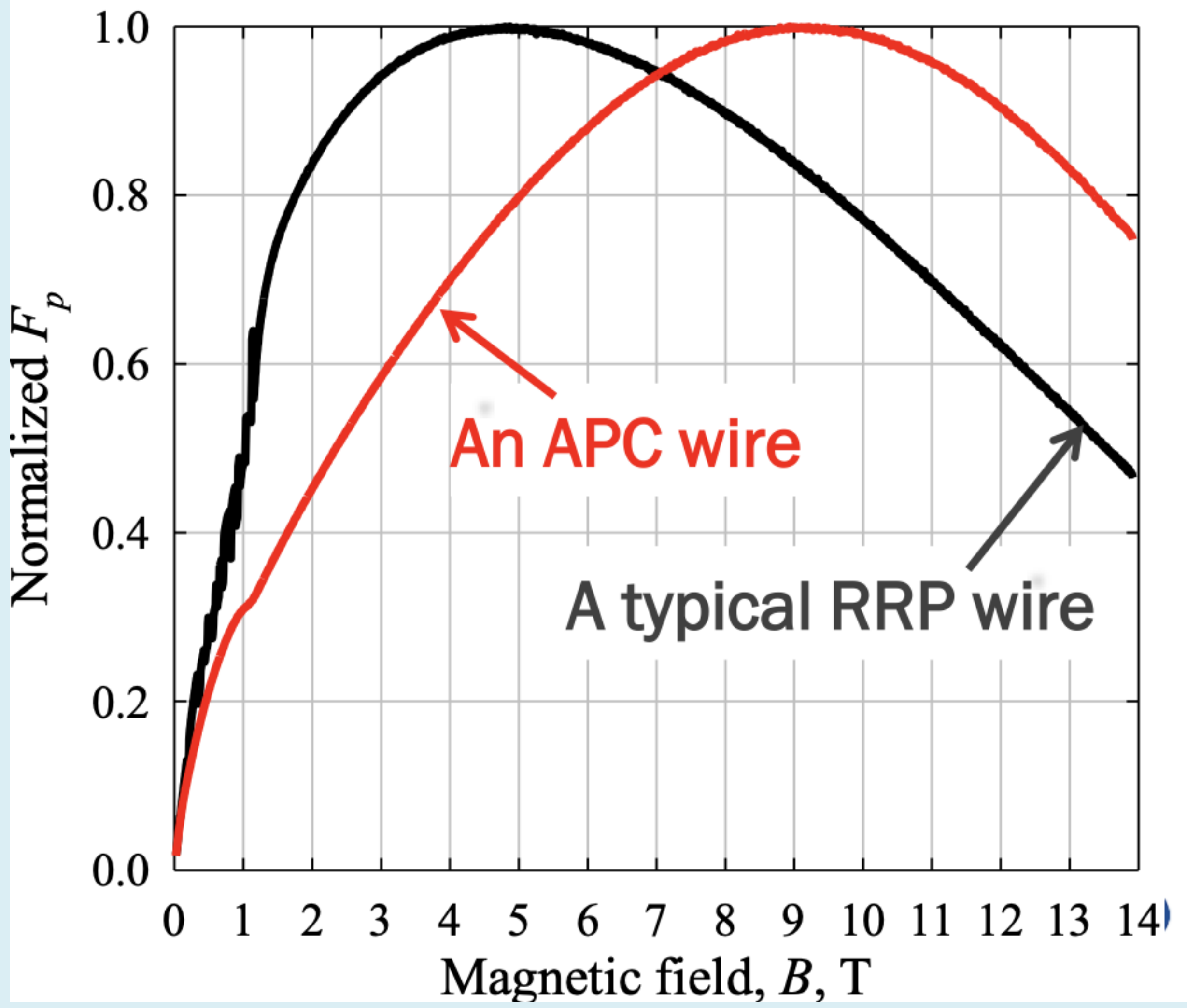
Bi2212 as a magnet-ready high temperature superconductor

Significant advances in Nb_3Sn performance by introducing new pinning sites

- Path to "FCC spec" wires exists
  - o Powder-in-tube" approach advancing
  - o Also exploring Hf doping in "internal Tin" approach

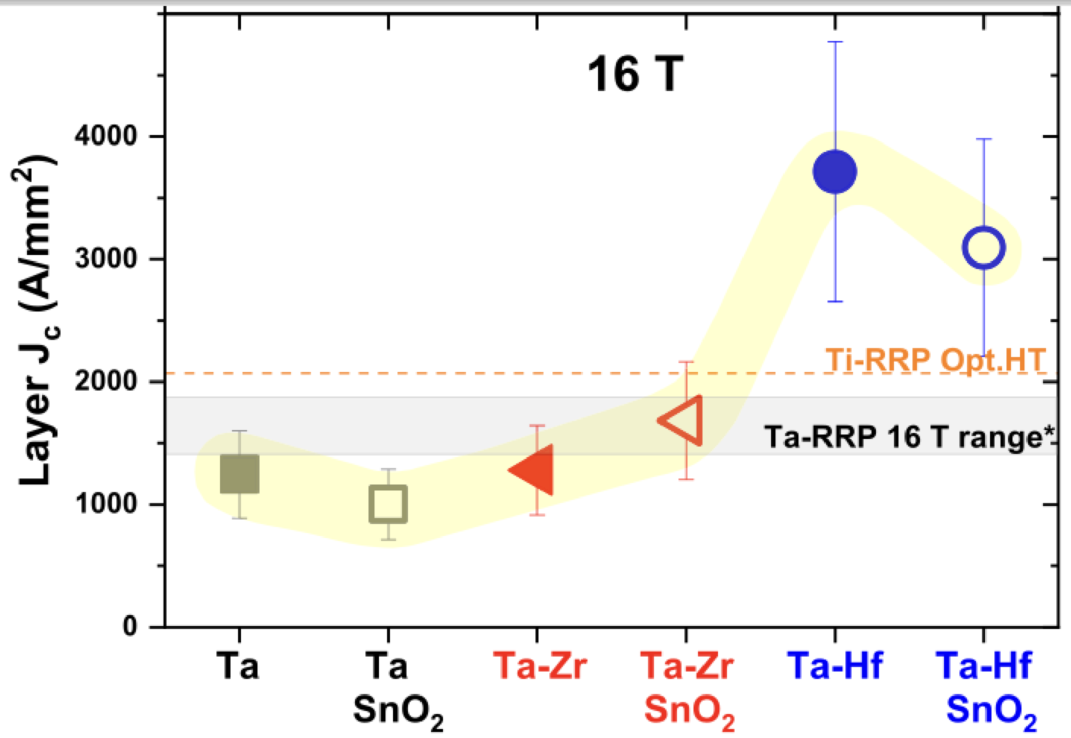
X. Xu, SoftA Workshop, CERN, 2021
See also Xu et al., J. AlloyCompd.857,158270(2021)





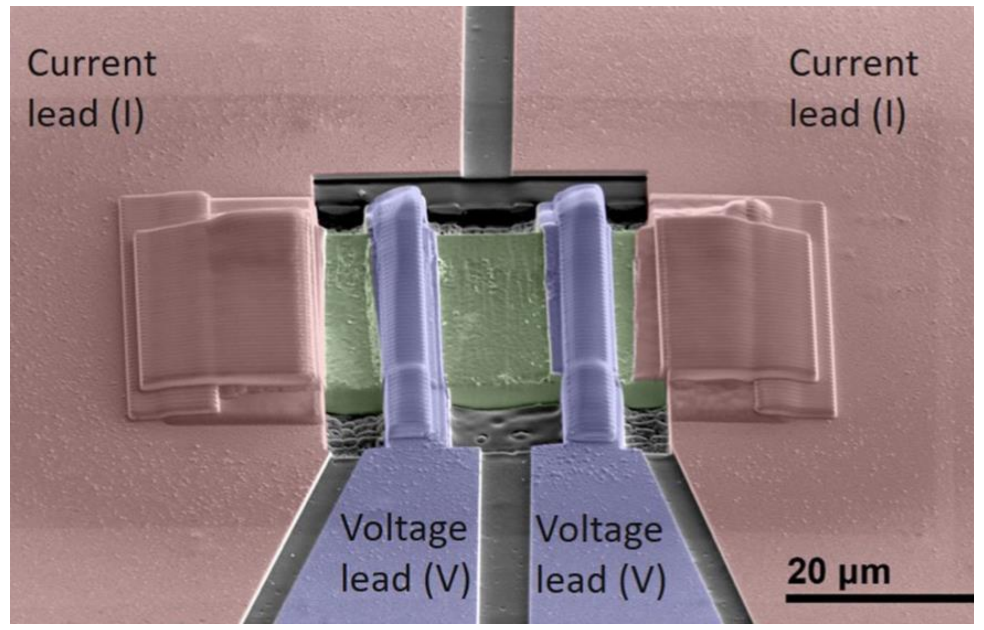
Fermilab

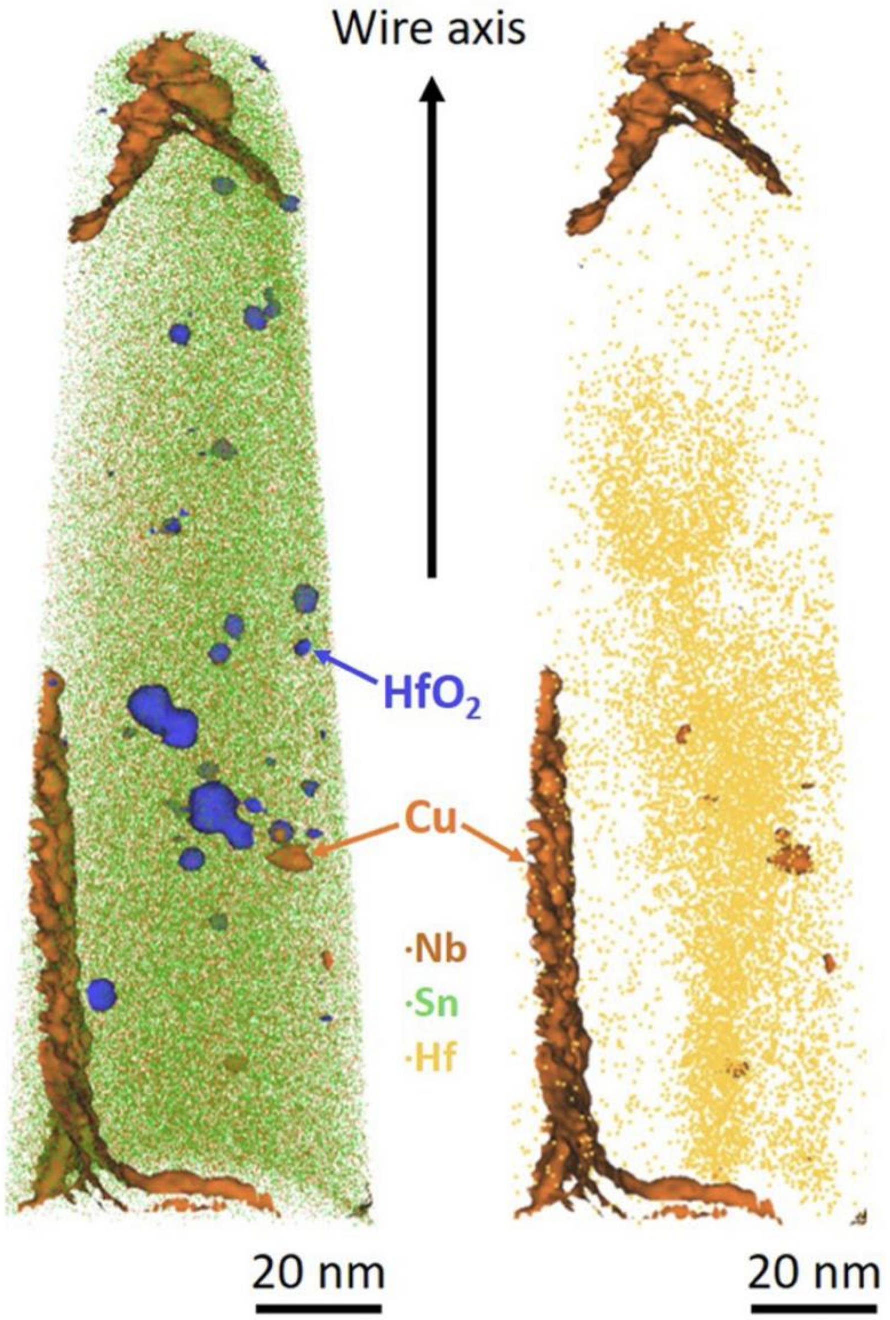
Hyper Tech Research, Inc.



S. Balachandran et al 2019 SUST 32

Tarantini et al., Nature Scientific Reports, (2021) 11:17845





L.Wheatley PhD student U of Oxford

New paradigms: quench-free HTS magnet designs?

Traditional superconducting magnet design ensures magnet can survive quenches

Motivation:

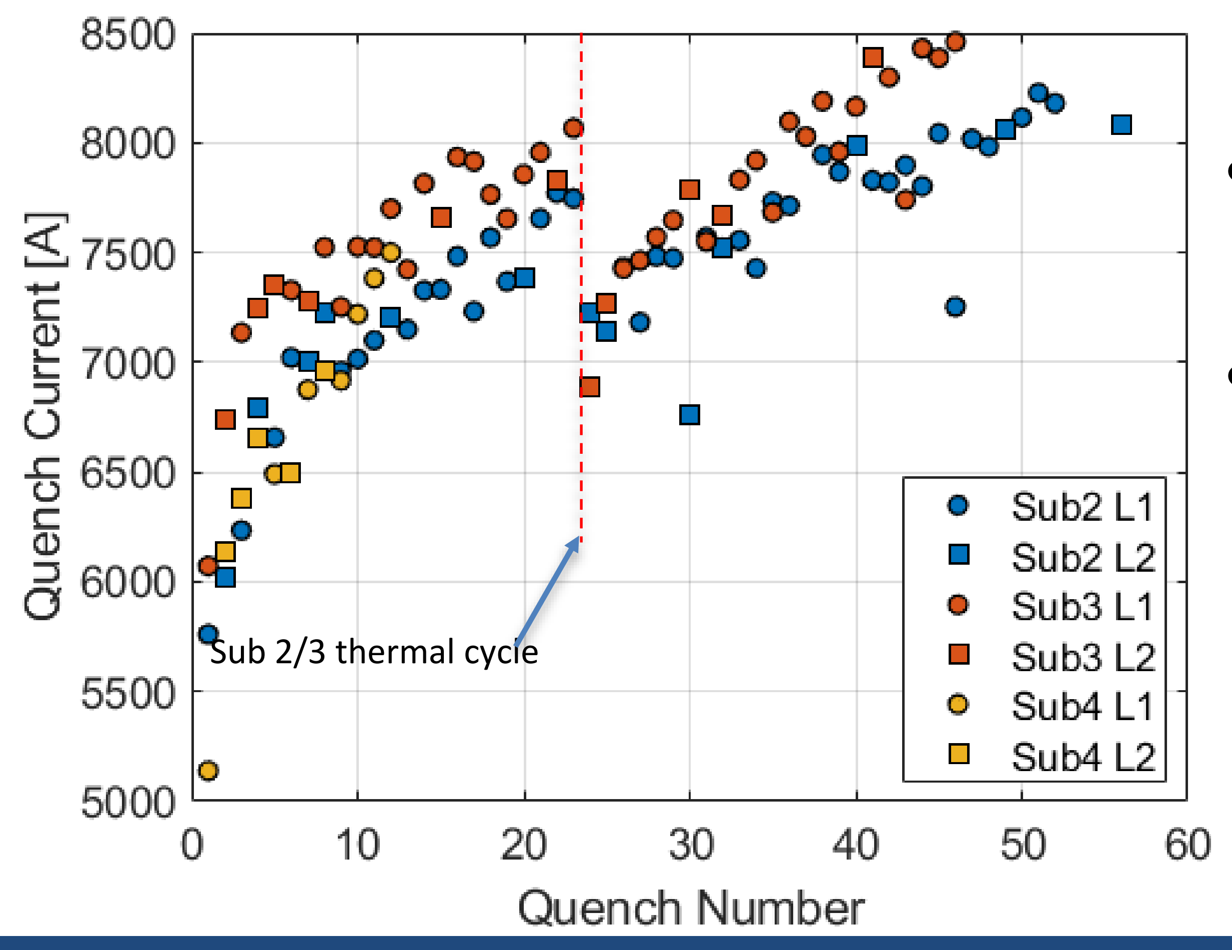
- spontaneous quenches => lack of reliable precursor, not controllable
- Training => potential for improved performance after quenching

Can we contemplate a new paradigm for HTS?

- Higher MQE => not (?) susceptible to spontaneous quenches => no “random” behavior
- So far no indication that HTS magnets exhibit training => no performance enhancement

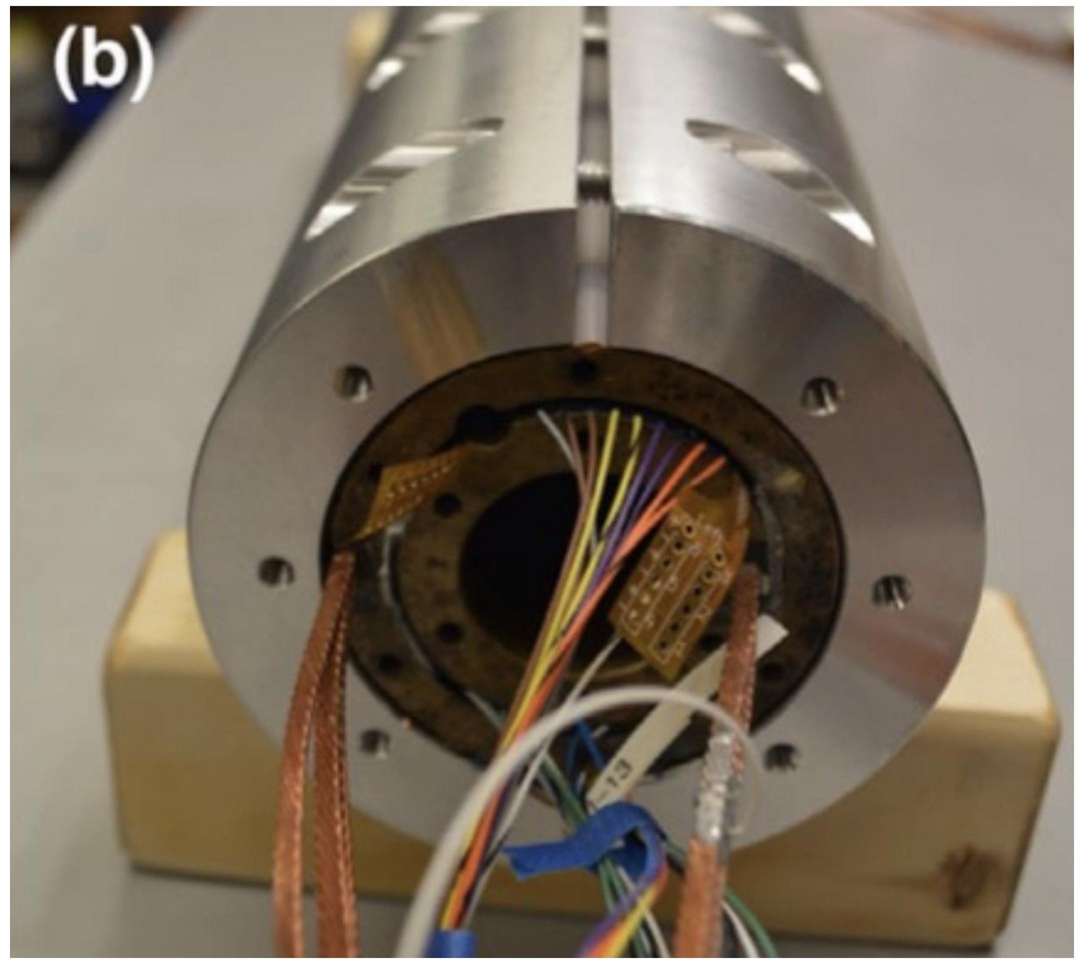
Design to eliminate run-away quenching !?

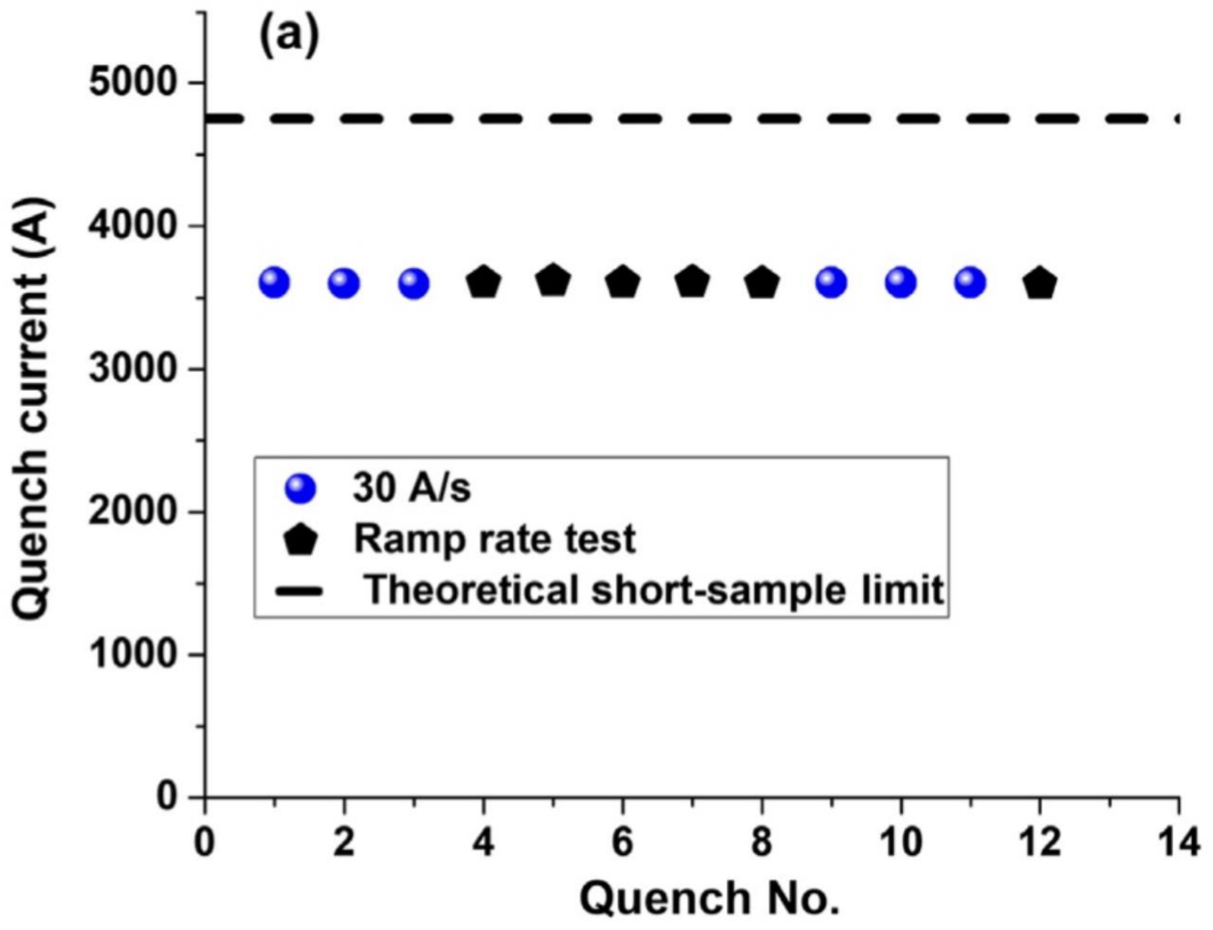
“Typical” Nb_3Sn CCT magnet training



- “Rapid” training to ~75% short-sample, then rate changes
- “Fair” memory after thermal cycle

T. Shen et al., PHYS. REV. ACCEL. BEAMS 25, 122401 (2022)





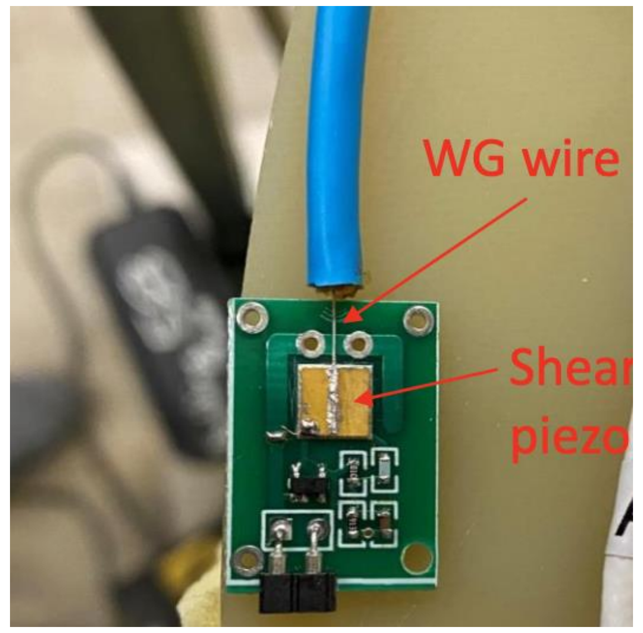
New paradigms – Active/dynamic local powering of magnets for safety, field quality, etc?

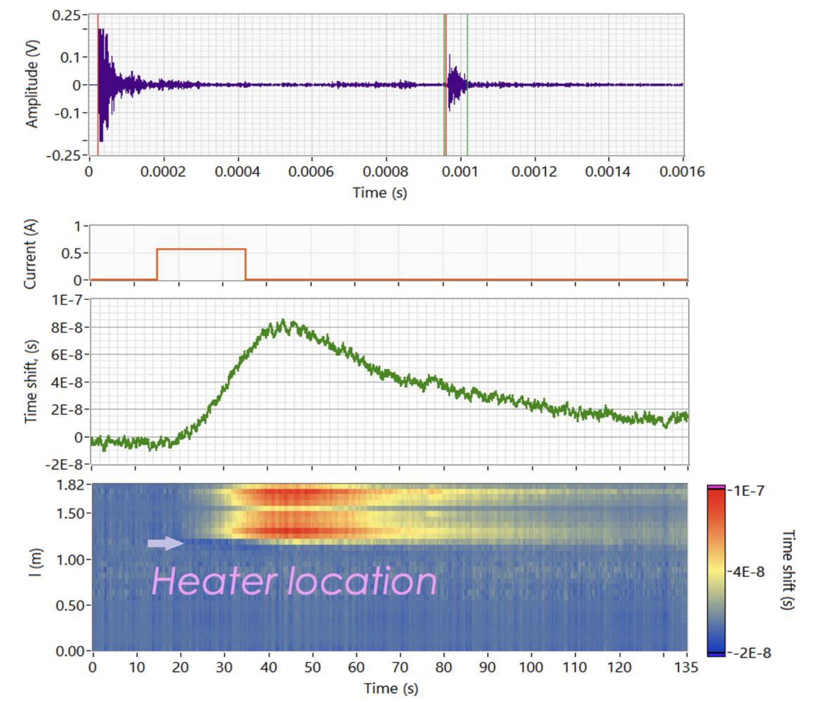
- High bandwidth diagnostics coupled to in-situ FPGA data analysis
- Multiple "physics-independent" diagnostics - analyzed and cross-corelated
- AI/ML utilized to weed out irrelevant data, identify critical events/behavior

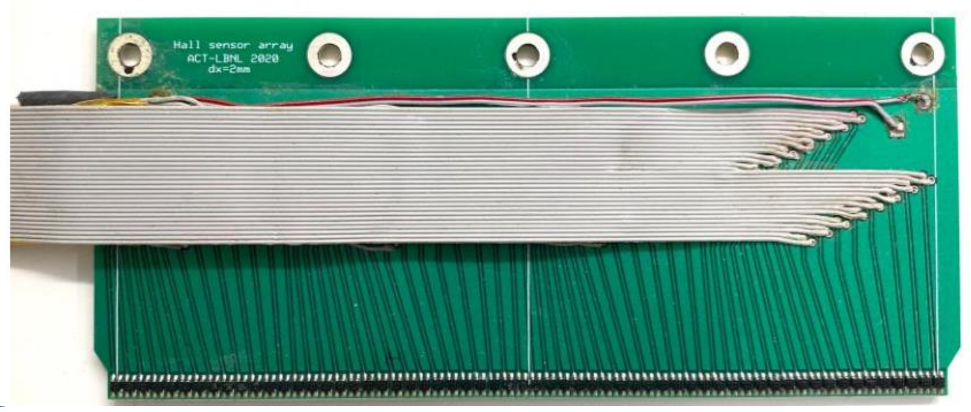
- Most data acquisition, analysis, decision-making occurring "below the header"
  - o Only digital data sent "out", e.g. via redundant fiberoptics (non-conductive)
- Stored diagnostics data monitored/analyzed for system integrity check
  - o Modeling coupled to diagnostics => digital twin corelates cause and effect

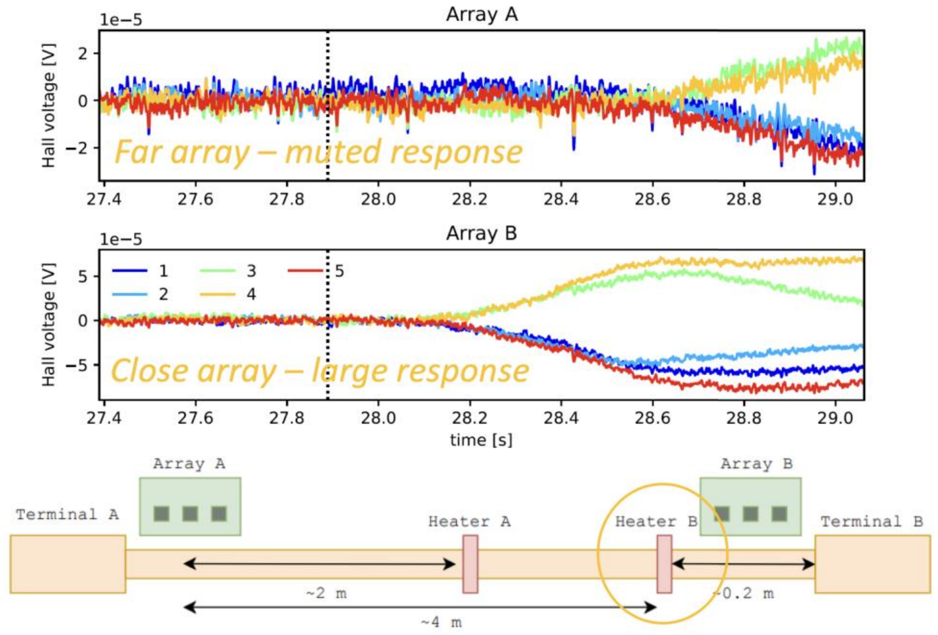
- Cryo-power electronics (MOSFETS, IGBTs, etc) developed to actively control/route power => become integral to magnet protection

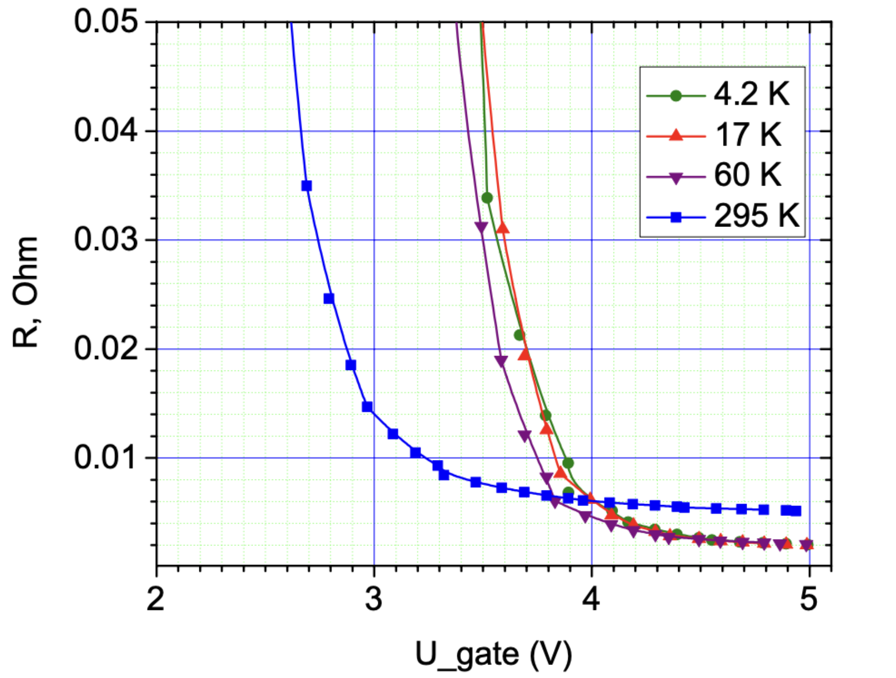
- *Key to enable HTS "Quench-free" paradigm*

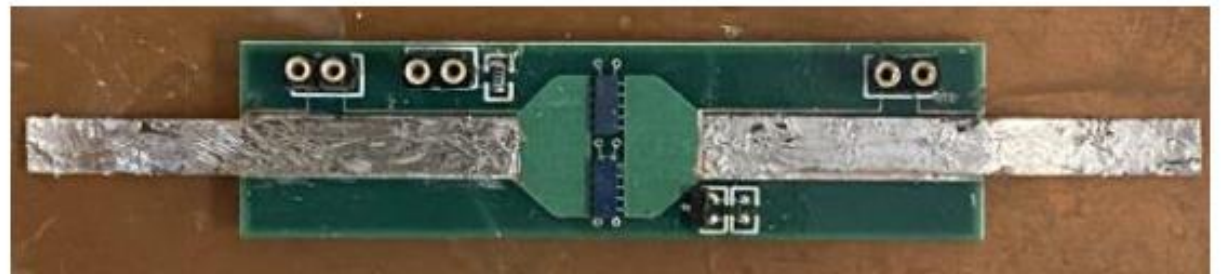










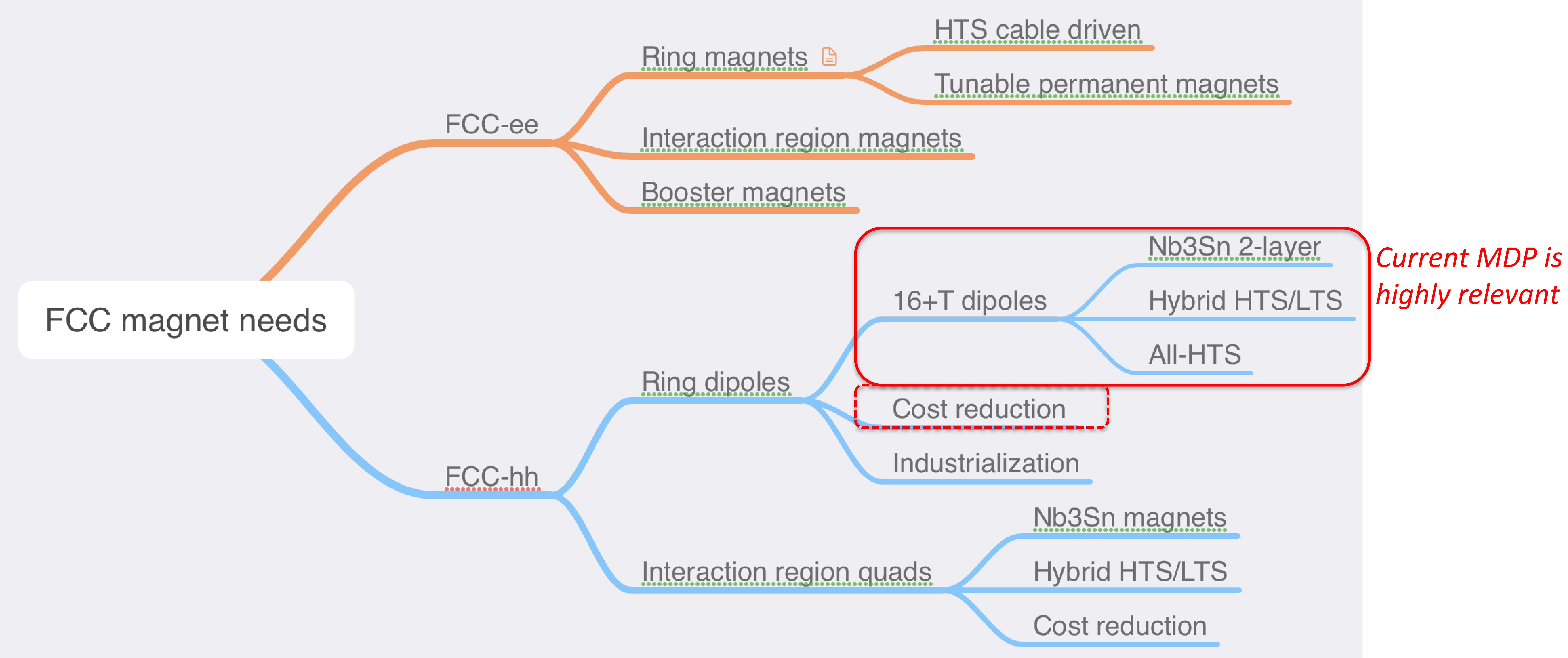


New paradigms: Liquid hydrogen cooled collider?

- **Hydrogen has critical advantages:**
  - Plentiful => not supply limited
  - Carnot + liquefaction efficiency => dramatic improvement in ”wall-plug efficiency”
  - Strong investments from other societal uses => cost, storage/shipping evolving rapidly
- **But there are concerns/issues:**
  - Safety => highly combustible in presence of oxygen
  - Materials compatibility => some restrictions due to embrittlement/corrosion
  - Limits superconductor option => only REBCO maintains significant transport current at 20K

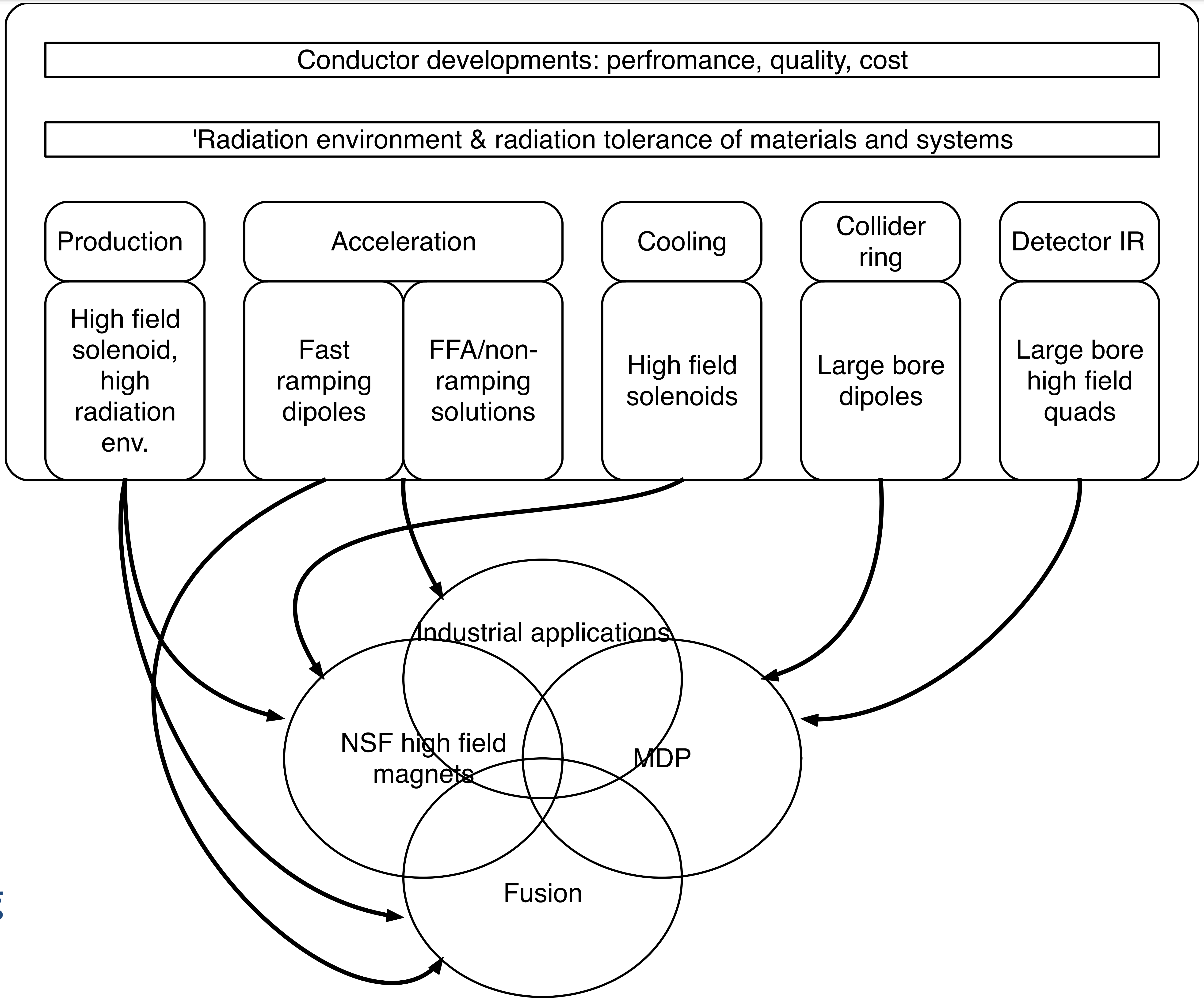
Sustainability will be a driving consideration in any future international physics experiment - our community needs to make a strong, dedicated effort to explore liquid hydrogen for future colliders

The US MDP currently pursues research addressing a– critical – subset of the magnet needs for a future FCC hadron collider



A muon collider will require critical advances in magnet technology – ripe for synergies with other applications

- **Radiation is a major consideration:**
  - Study tradeoff in aperture/bore+shielding vs magnet radiation hardness
  - Further advance understanding of radiation hardness of superconductors and magnet materials
- **Rapid acceleration is critical:**
  - Study fixed-field booster options where applicable
  - Further investigate high dB/dt magnet concepts
  - Evaluate acceleration (particularly low-energy) schemes in an integrated approach
- **Large thermal loads** suggest higher-temperature operation
  - Explore all-HTS option
  - Explore facility and operational cost models
- **Leverage strong synergies with fusion and High-Field magnets** (e.g. condensed matter):
  - Fastest development path for very challenging target and cooling magnets

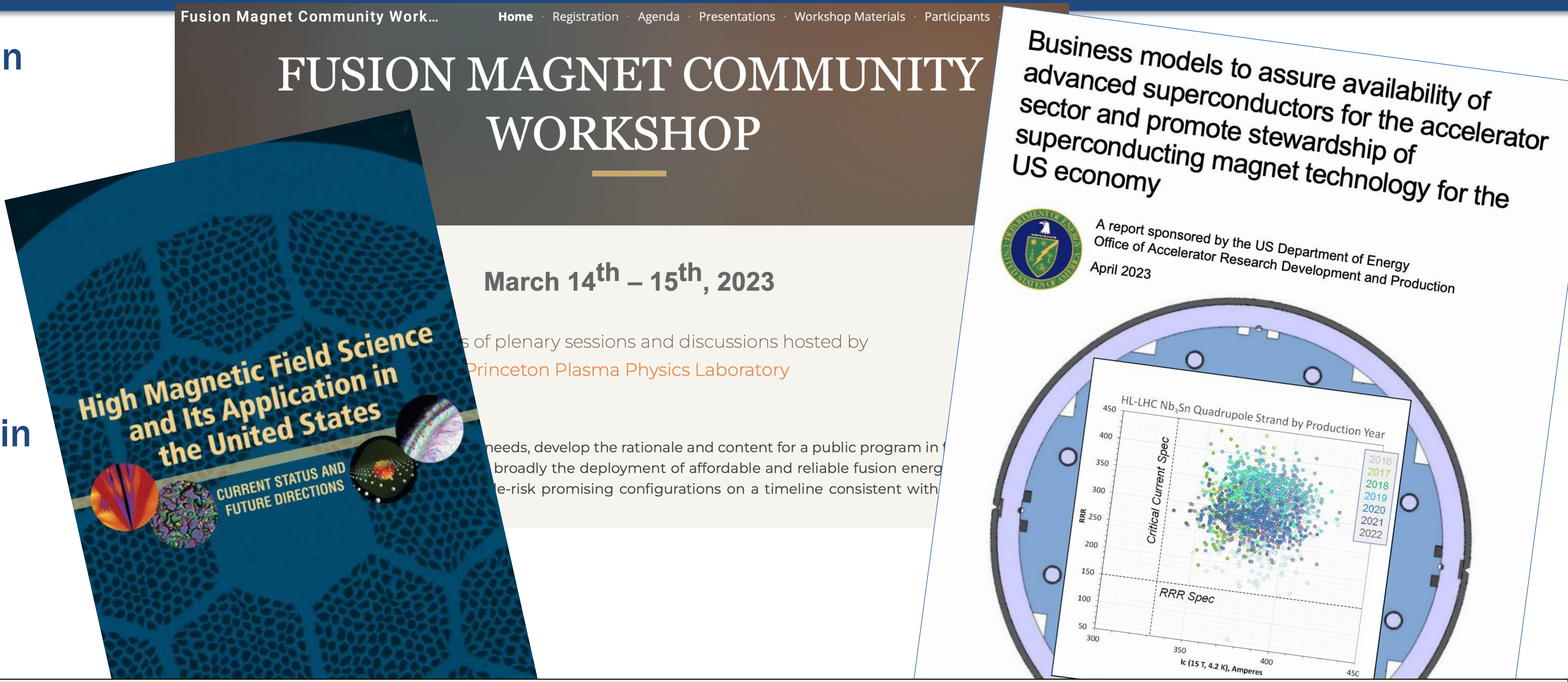


We are actively engaged in identifying and leveraging synergistic activities to the benefit of HEP

- Active participation in planning efforts
  - for HEP, but also across many synergistic agencies

- Strong participation in public-private partnerships

New!



The **National Academies of Sciences, Engineering, and Medicine** is undertaking a forward-looking study to examine
(1) the status of domestic and international high magnetic field science and technology;
(2) current and future science disciplines that have critical needs for new capabilities that could only be enabled by high magnetic fields;
(3) gaps in current high magnetic field science, technology, and infrastructure that could help address critical needs.

Summary

We are at a critical period, where innovation and progress in magnet technology is essential to enable the next generation of colliders – the opportunity and challenge is shared with Fusion and other applications!

Magnet and Conductor Plans & Roadmaps are well-advanced globally

- US MDP – ***well established***
- European HFM – ***recently established***
- Japan efforts at KEK - coordinated with CERN and MDP
- China efforts led by IHEP – ***progressing well***

U.S. MAGNET DEVELOPMENT PROGRAM

2020 Updated Roadmaps

The 2020 Updated Roadmaps for the US Magnet Development Program

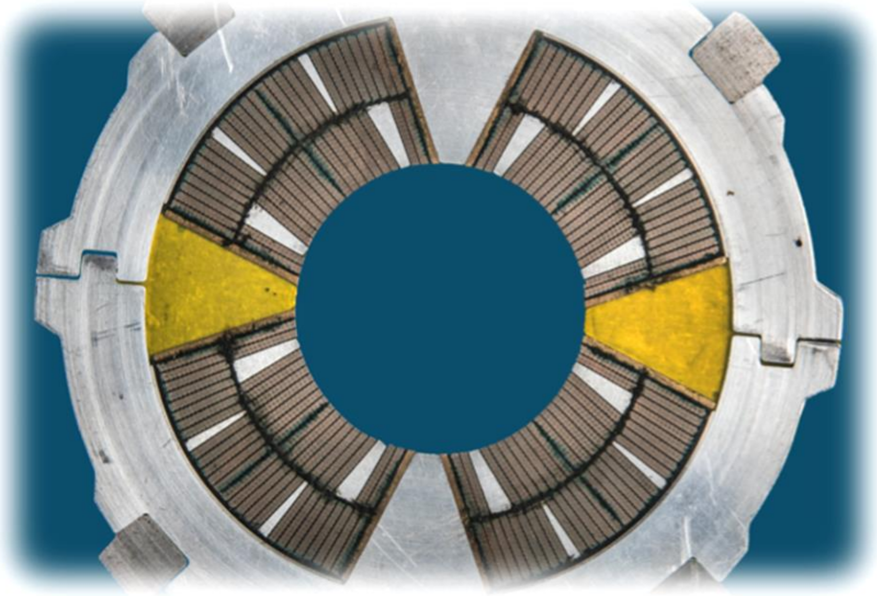
Compiled by

Soren Prestemon, Kathleen Amm, Lance Cooley, Steve Gourlay, David Larbalestier, George Velev, Alexander Zlobin

&

With Major Contributions from

Technical Leads and Collaborators within the US MDP



This is ***not*** a comprehensive list of collaborators… our community is broad and diverse!

中国科学院电工研究所
Institute of Electrical Engineering, CAS

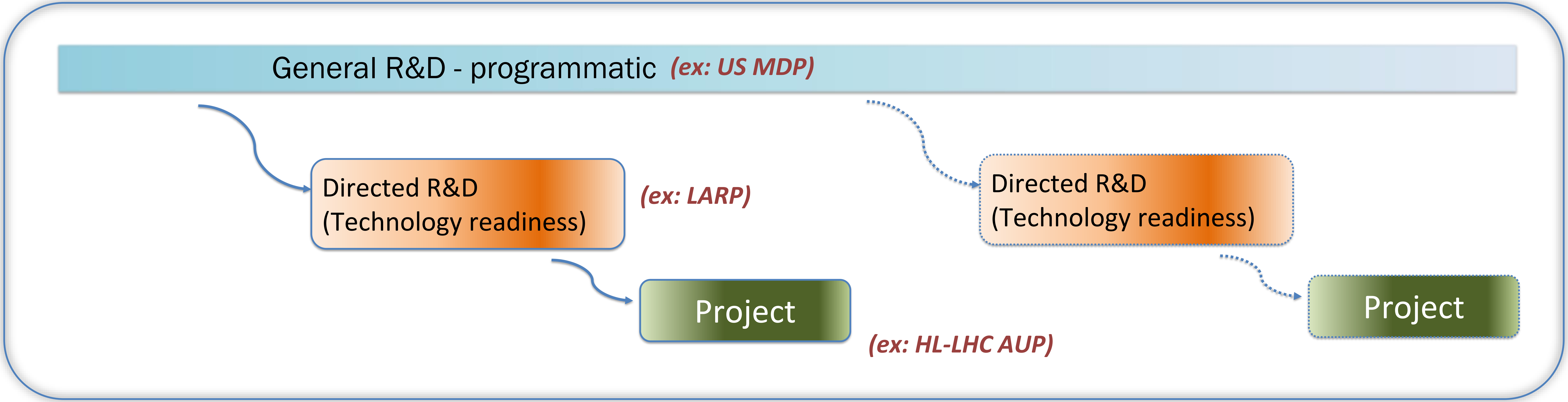
中国科学院高能物理研究所
Institute of High Energy Physics, CAS

Updated US MDP Roadmaps have been published https://arxiv.org/abs/2011.09539

DOE-OHEP has an excellent record of developing advanced technology

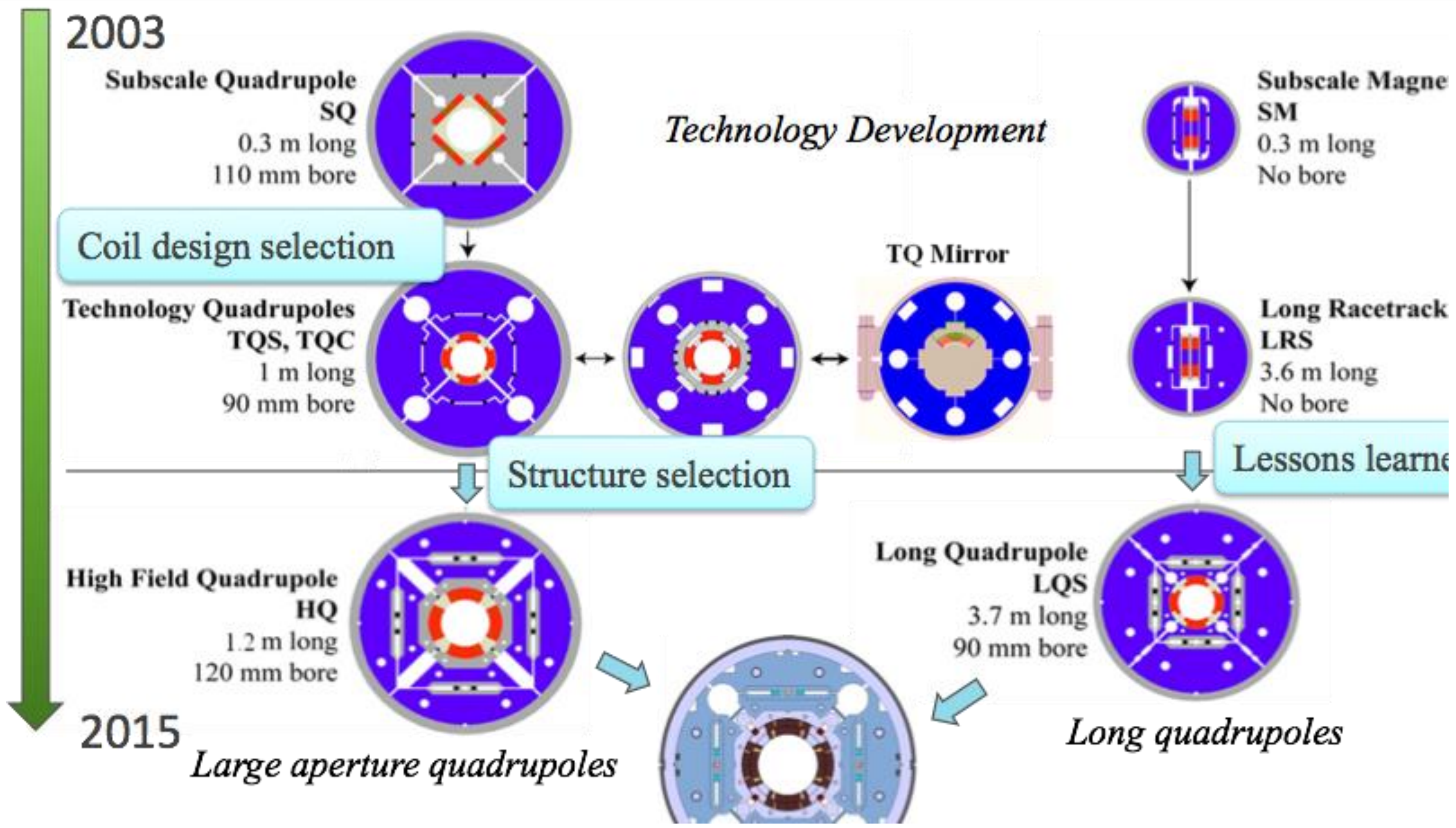
- **Long term investments in general accelerator R&D set the stage for dedicated readiness programs, which in turn enable successful delivery of advanced technology for colliders**

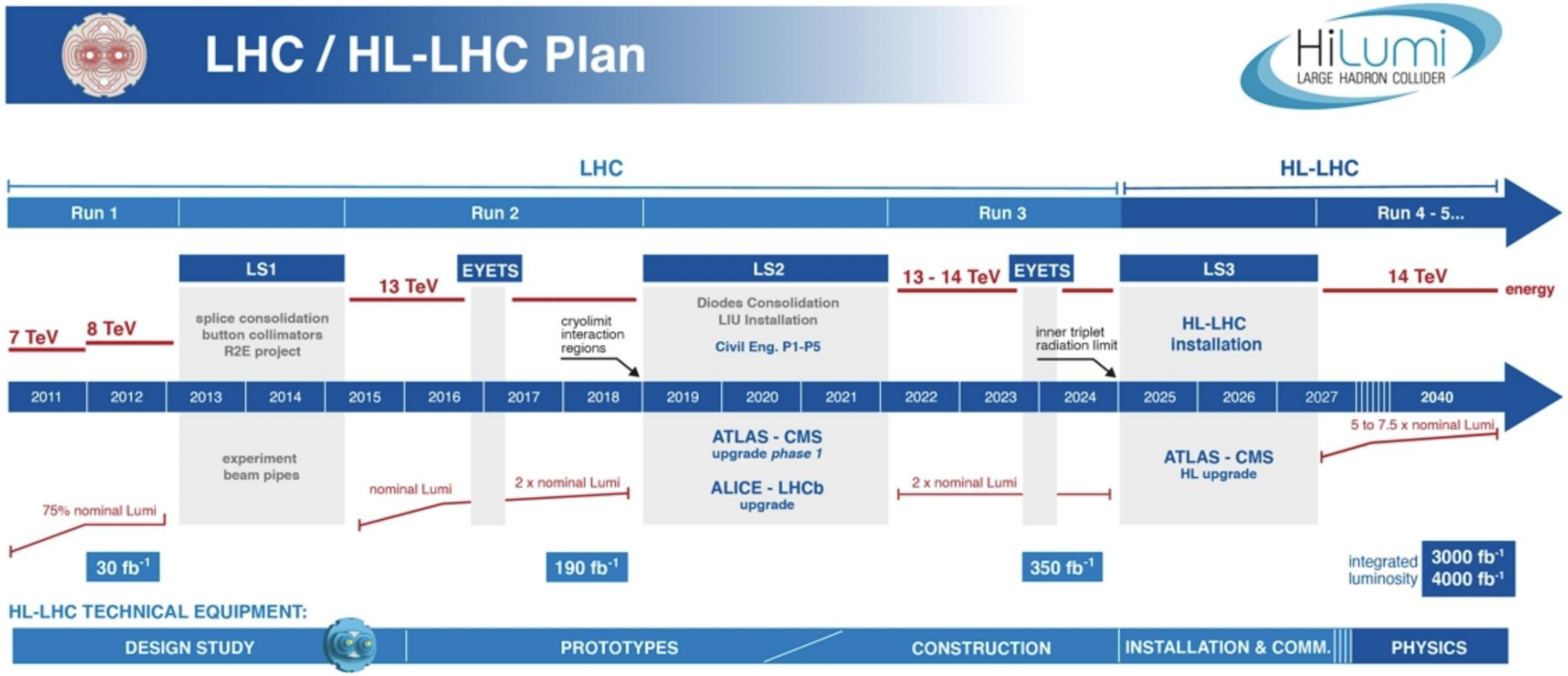
The programs strive to coordinate efforts to more rapidly advance technology development

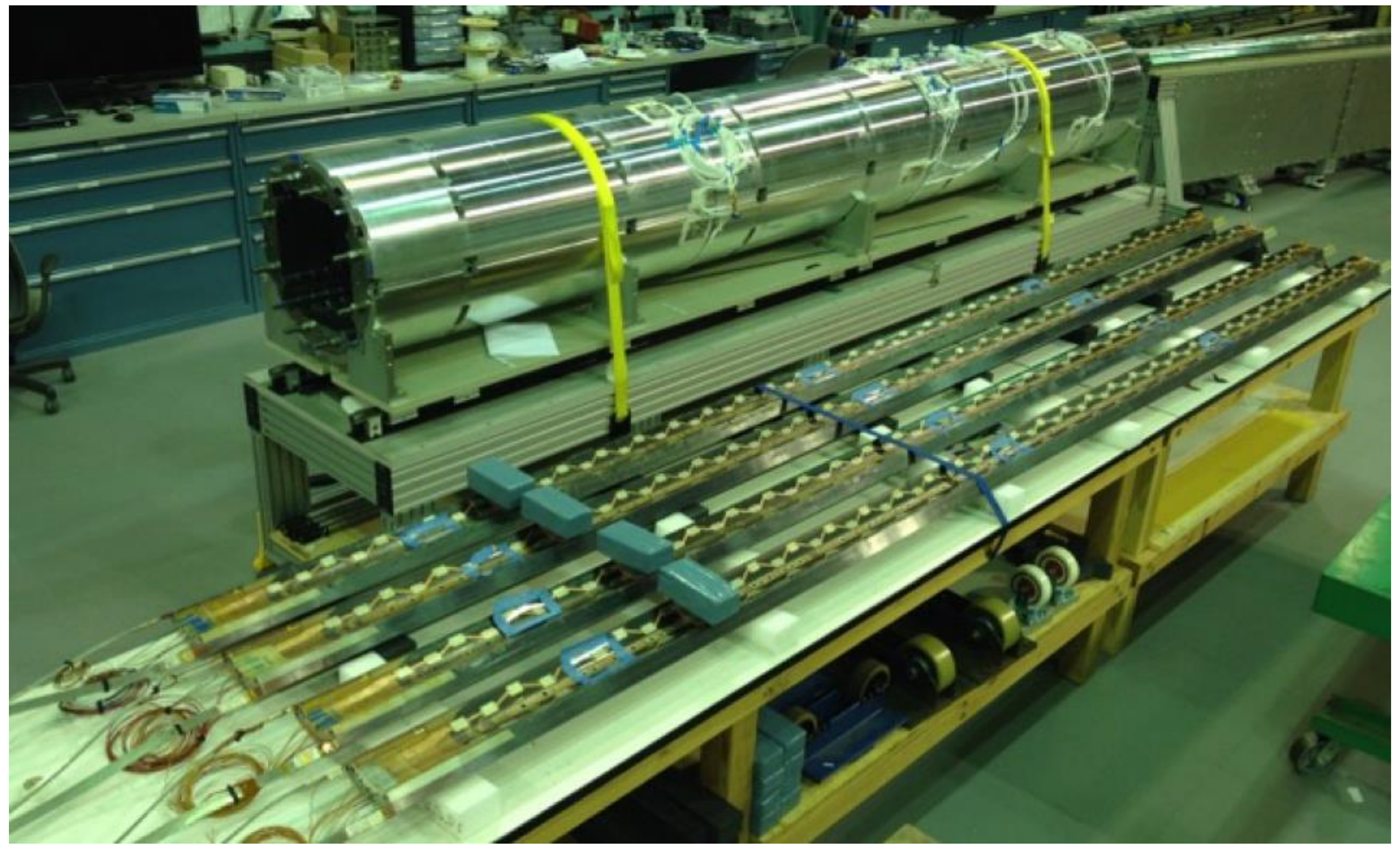


The US DOE approach balances long-range R&D and project preparation

Nb3Sn accelerator magnet technology is - *for the 1st time* - being installed in a collider







HiLumi magnet production is arguably "boutique production"

- First implementation of Nb_3Sn superconductor in a collider
- What are the risks and benefits of full-scale industrial production of Nb_3Sn magnets?
- What elements of the design are "robust", and what elements generate risk/performance limitations?

⇒ ***There is significant value-engineering that can be performed***

European High Field Magnet (HFM) program: plans are in place – teams active and engaged

U.S. MAGNET DEVELOPMENT PROGRAM

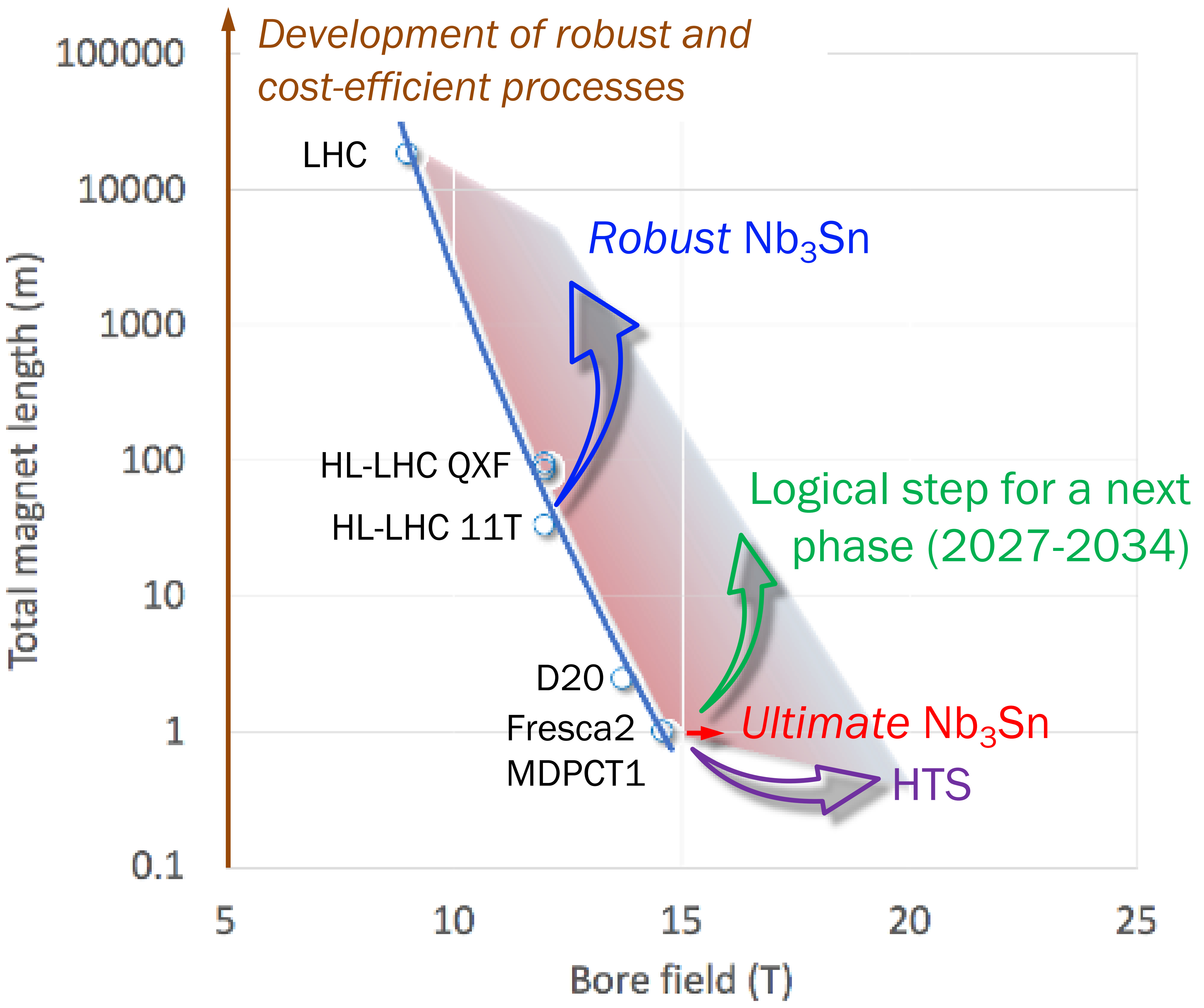
- **The EU Accelerator R&D Roadmap identifies main objectives for the High Field Magnet Programme:**
  - **OBJECTIVE 1:**

    Design and demonstrate a full-size Nb3Sn accelerator magnet to proof the maturity of the most advanced technologies today, based on the HL-LHC design, i.e., 12 T magnets, and applying all the lessons learned from the US LHC Accelerator Research programme (LARP), the US High-Luminosity LHC Accelerator Upgrade project (AUP) and the HL-LHC project
  - **OBJECTIVE 2:**

    Explore the limitations of the LTS state-of-the-art technology and push Nb3Sn magnet technology to its practical limits in terms of ultimate performance, towards the 16 T target targeted by the FCC-hh
  - **OBJECTIVE 3:**

    Explore the capabilities and limitations of state-of-the-art HTS and magnet technology based on these superconductors. Demonstrate the suitability of HTS

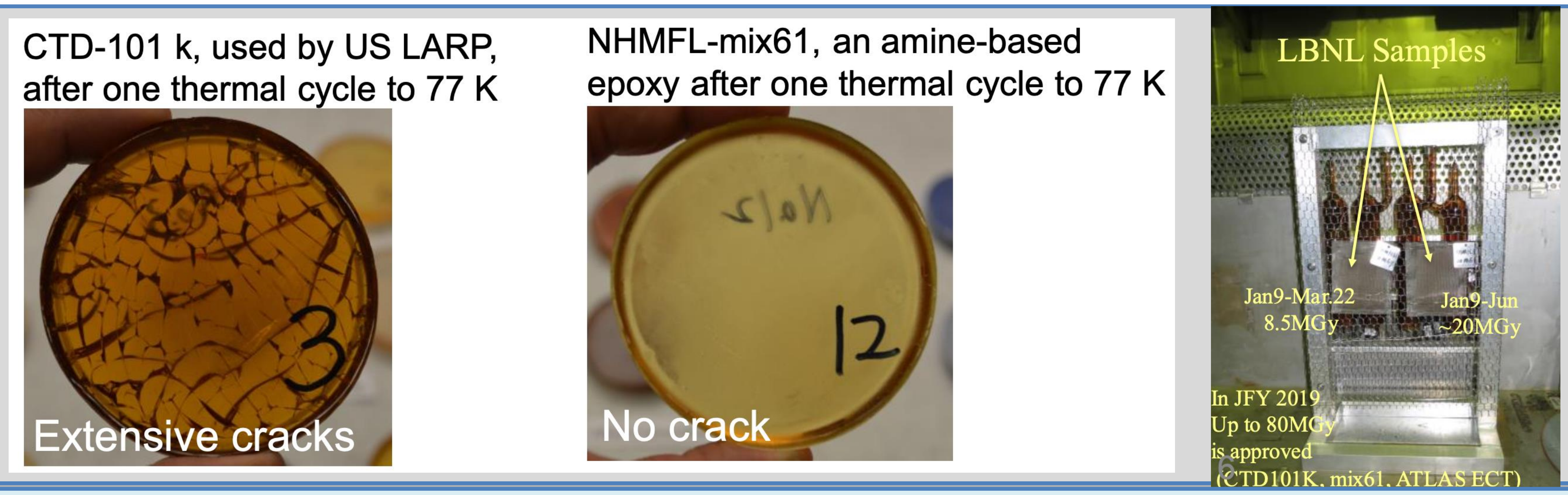
Create a European Research Network involving CERN and National Labs



U.S. MAGNET DEVELOPMENT PROGRAM

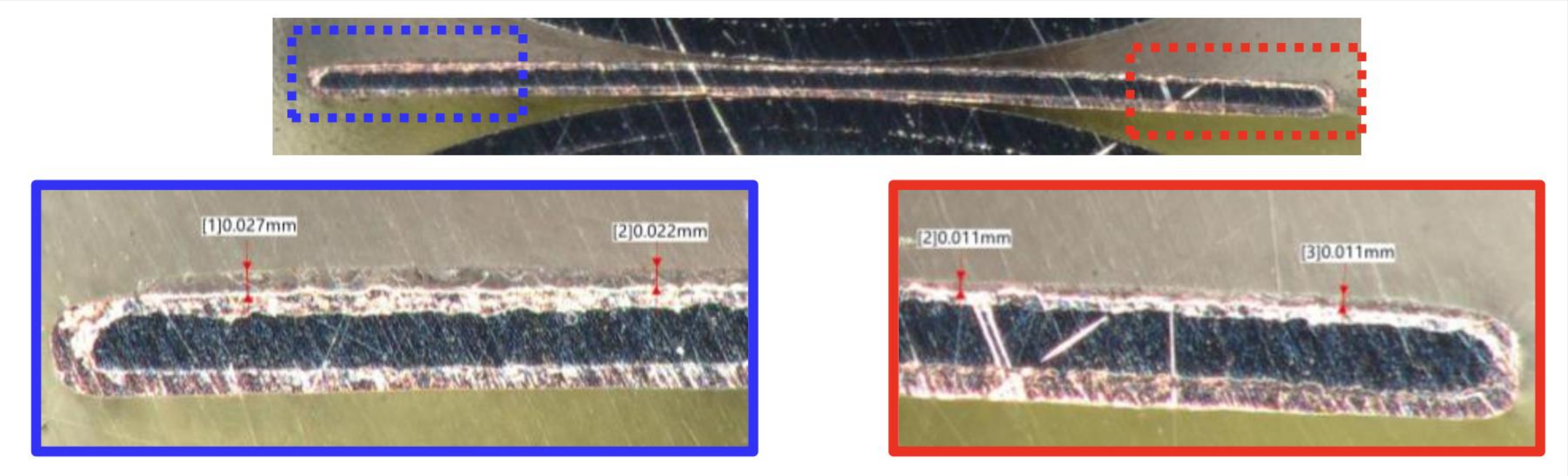
KEK plans and progress – magnet technology examples

- **Task1: HTS magnet technologies for high-radiation environment**
- **Task 2: Stability, quench protection, and magnet safety**
- **Task 3: Measuring and modeling AC loss and field quality of HTS accelerator magnets**
- **Task 4: HTS/LTS high field hybrid accelerator dipole technology**



Radiation impacts on magnet materials

Development of inorganic insulation technology



Strong links with DOE-OHEP strategy

U.S. DEPARTMENT OF ENERGY | Office of Science

The US-Japan High Energy Physics Program