U.S. MAGNET DEVELOPMENT PROGRAM

US Magnet Development Program and synergies with FCC-hh

FCC Week 2024

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For the US MDP Team

Outline

- The US Magnet Development Program: current themes
- Key messages from the US P5 report
- Current MDP focus areas
- Areas of synergistic research
- Future ideas that are being discussed
- Plans for P5 alignment

BERKELEY LAB
Brookhaven National Laboratory
Fermilab
ASC

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Central themes / focus of current 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 (Nb3Sn, 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!*

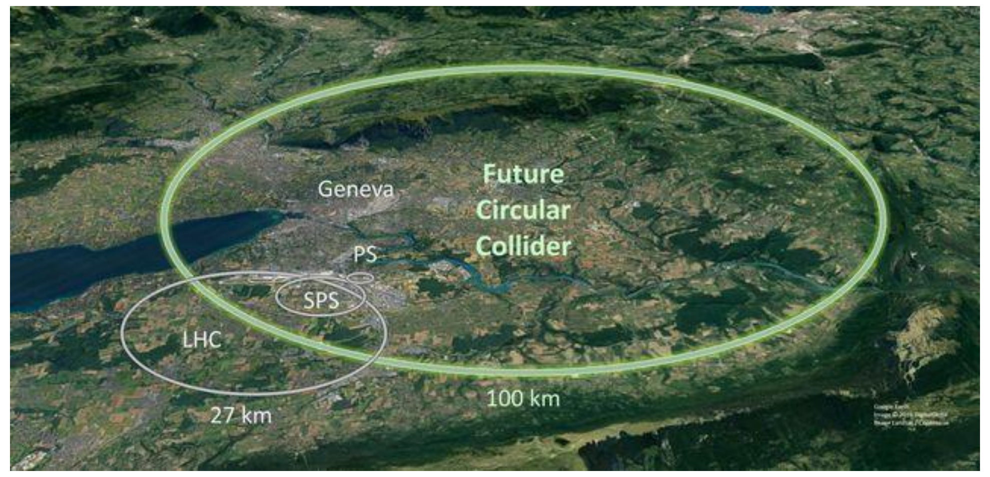
The P5 report had a clear message – 10 TeV pCM colliders!

- Precision studies of the Higgs self-interaction and searches for possible new spin-less particles related to the Higgs require much larger energies per fundamental particle (parton) interaction than previously considered: ***on the order of 10 TeV or more.***

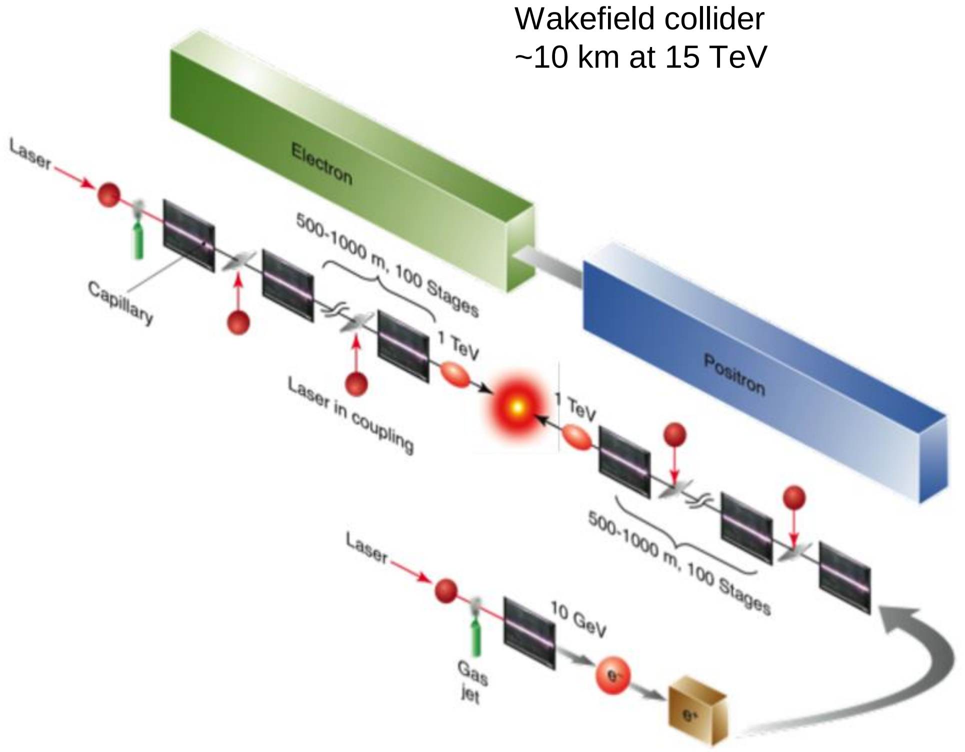
- Theoretical and experimental studies indicate that a comprehensive study of the electroweak scale requires colliders with ***energy of at least 10 TeV pCM***, larger than previously assumed.

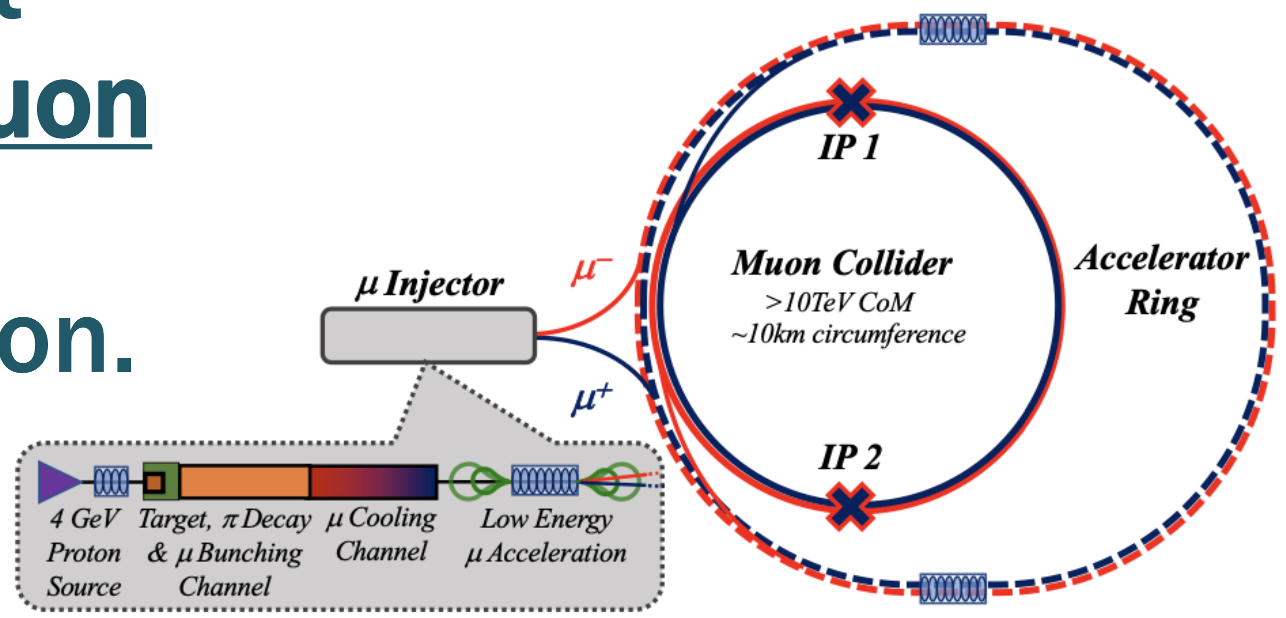
- Revealing the secrets of the Higgs boson, characterizing WIMP dark matter, and searching for direct evidence of new particles ultimately requires access to the electroweak scale provided by ***a collider with pCM energy of 10 TeV.***

- ***We do not yet have a technology capable of building a 10 TeV pCM energy machine, but the case for one is clear.*** Extensive R&D is required to develop cost-effective options. Possibilities include **proton beams with high-field magnets, muon beams that require rapid capture and acceleration of muons within their short lifetime**, and conceivably electron and positron beams with wakefield acceleration. All three approaches have the potential to revolutionize the field.



Wakefield collider
~10 km at 15 TeV

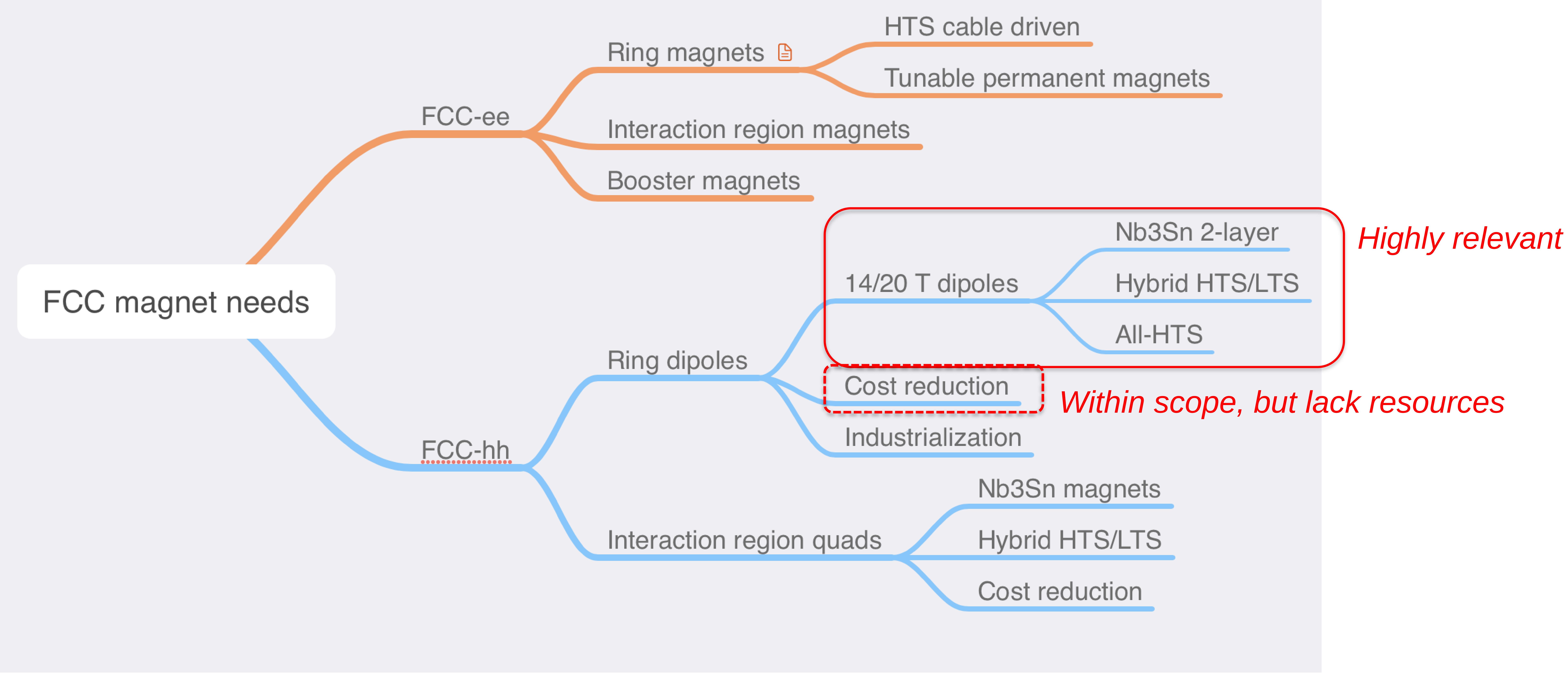




The P5 report provides critical guidance for the US MDP

- All options for a 10 TeV pCM collider are new technologies under development ***and R&D is required before we can embark on building a new collider.***
- Recommendation 4: Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. ***This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs*** that chart a realistic path to a 10 TeV pCM collider.
- ***Expand the General Accelerator R&D (GARD) program*** within HEP, including stewardship
- ***Conduct R&D efforts to define and enable new projects*** in the next decade
- This is why we recommend pursuing ***revolutionary R&D in areas such as high- field magnets***, a multi-megawatt proton driver, wakefield accelerator technology, and muon cooling (Recommendation 4a).
- We note that there are many ***synergies between muon and proton colliders, especially in the area of development of high-field magnets.*** R&D efforts in the next 5-year timescale will define the scope of test facilities for later in the decade, paving the way for initiating demonstrator facilities within a 10-year timescale (Recommendation 6).

MDP research is highly relevant to the FCC-hh



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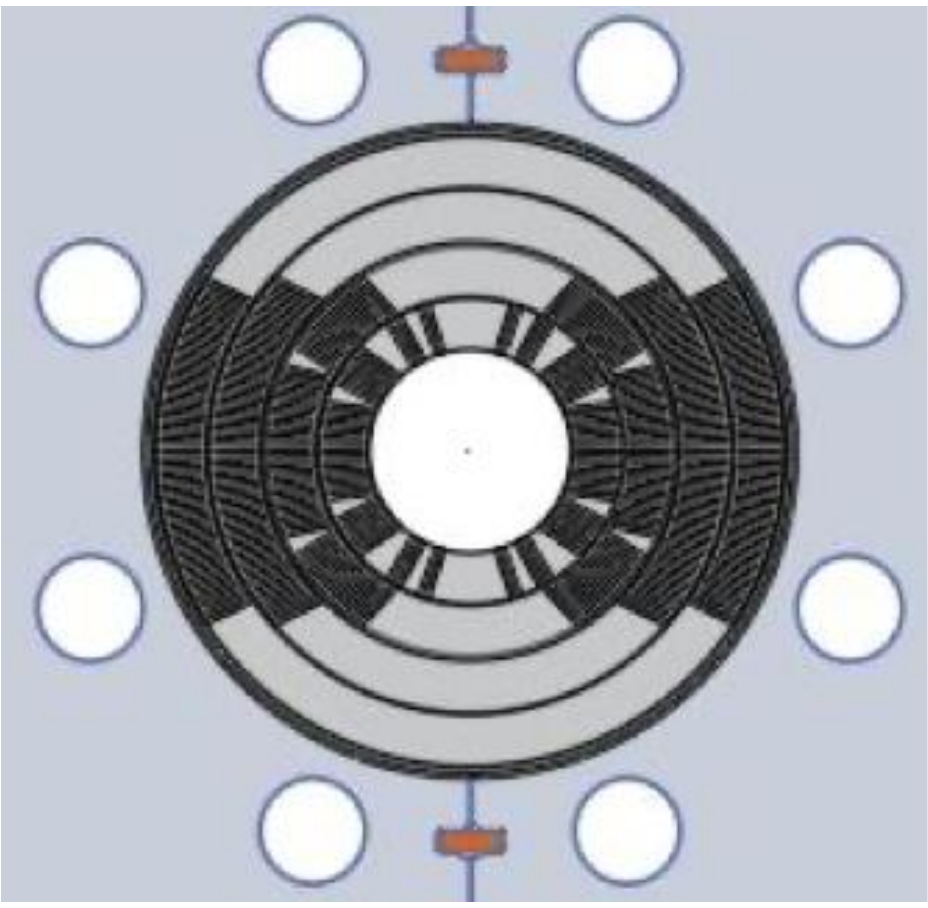
Managing mechanical stresses is key to higher fields – MDP is exploring stress-managed structures

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

"Traditional" Cos-theta

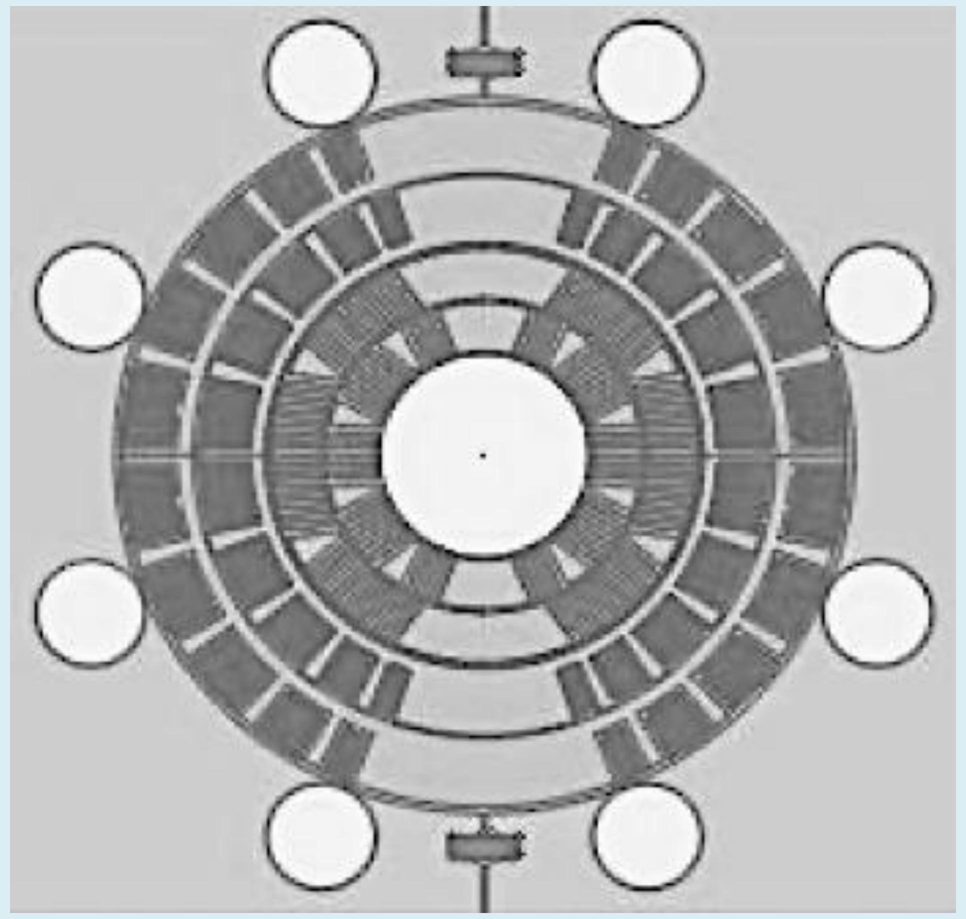
- Midplane stress due to azimuthal force accumulation



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

"Stress-managed" Cos-theta

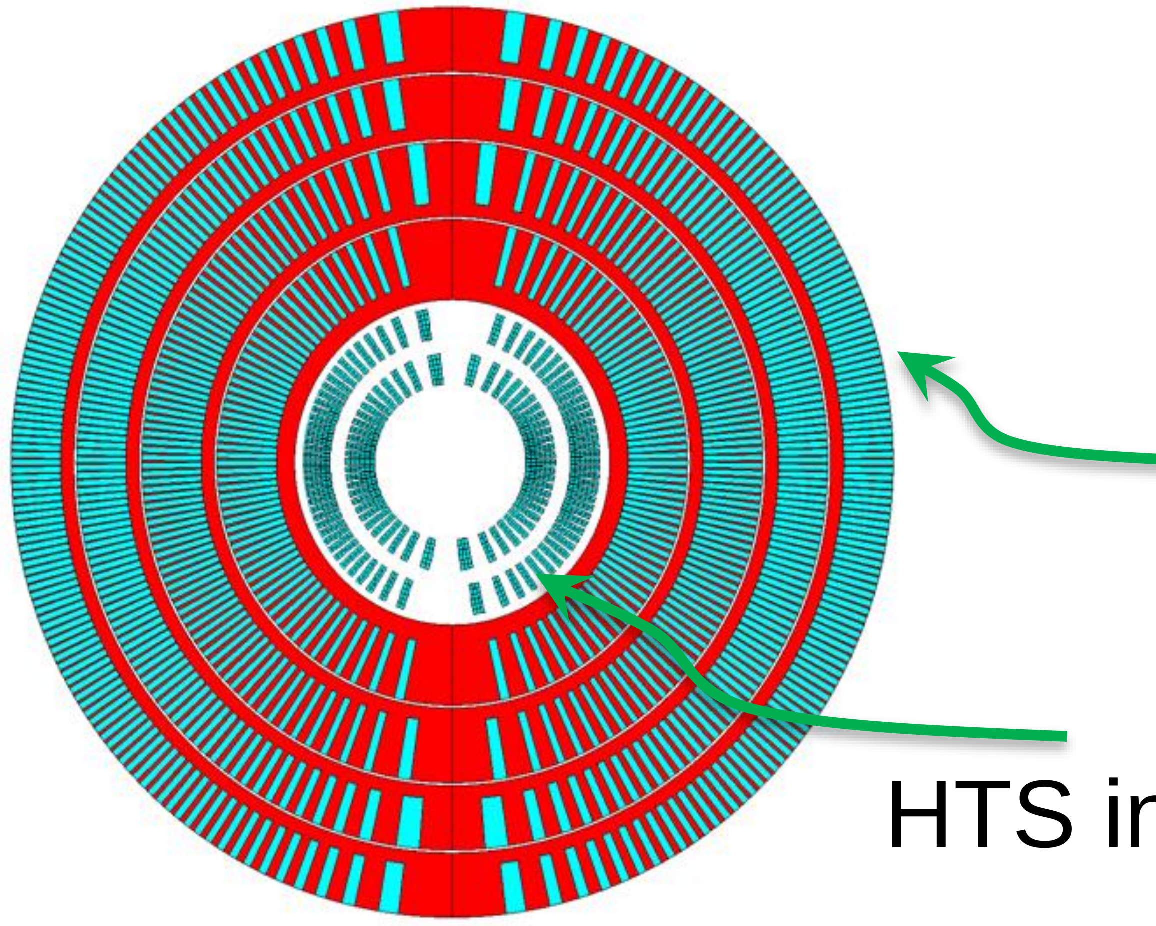
- Groups of turns, azimuthal forces intercepted by support



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

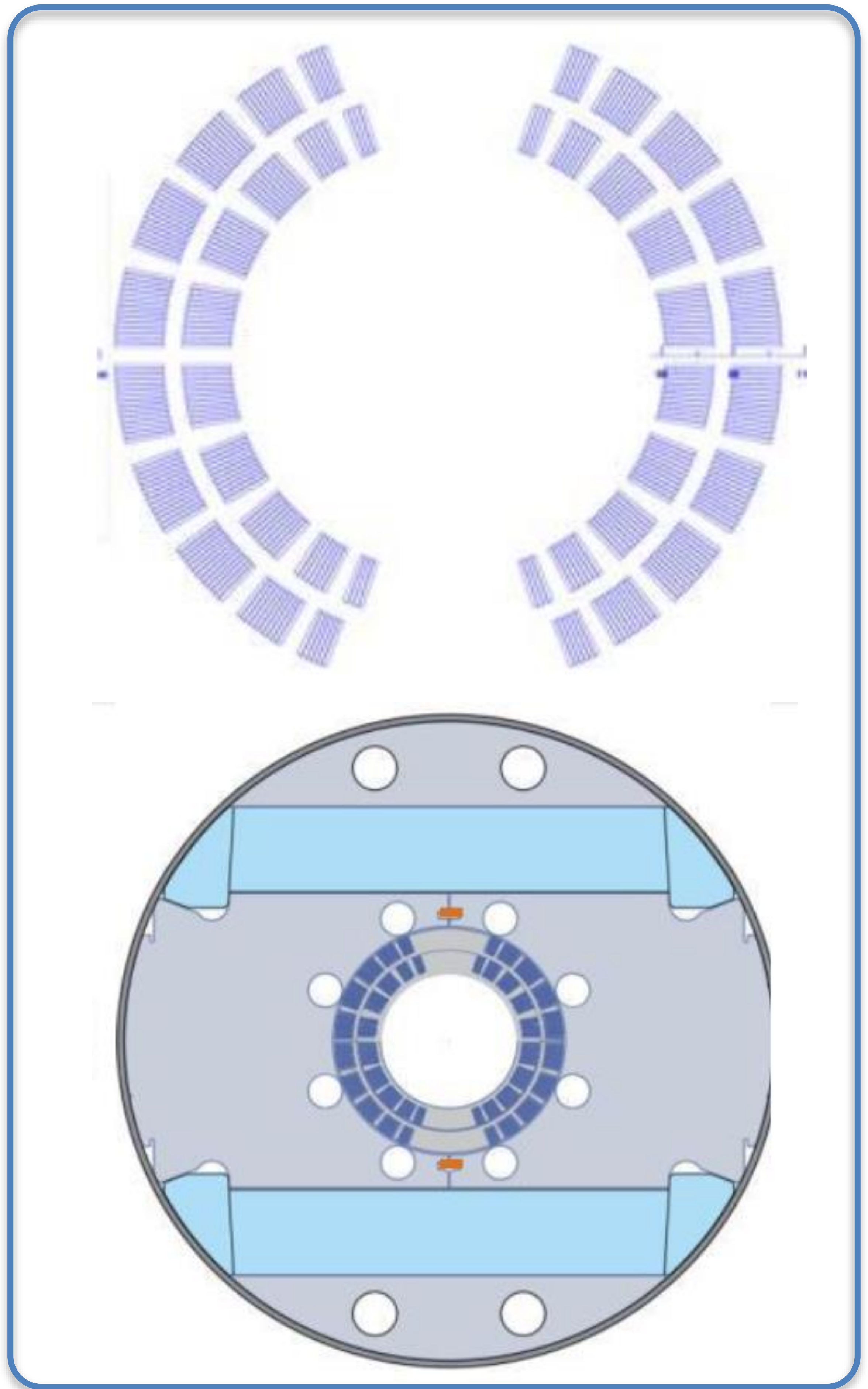


A priority now is to build high field Nb_3Sn stress managed magnets – serve as "outserts" for hybrid magnets

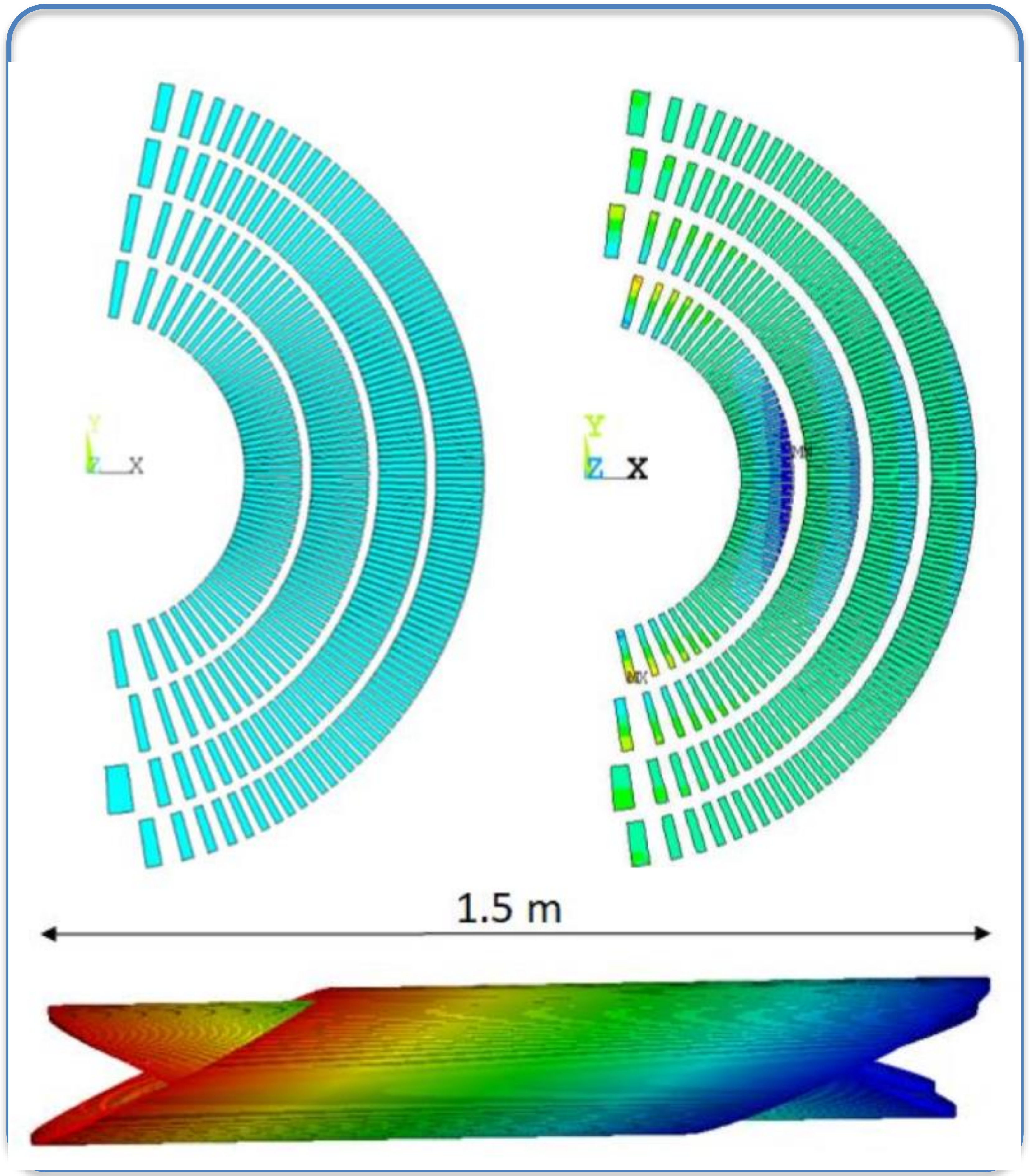
- **Canted Cosine theta:**
  - o 4 layers
    - Bore field of 12 T / 13 T for standalone operation
    - Bore diameter: 120 mm
- **Stress-managed Cosine Theta:**
  - o 2 layers
    - Bore field of 11 T
    - Bore diameter: 120mm

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

SMCT



CCT



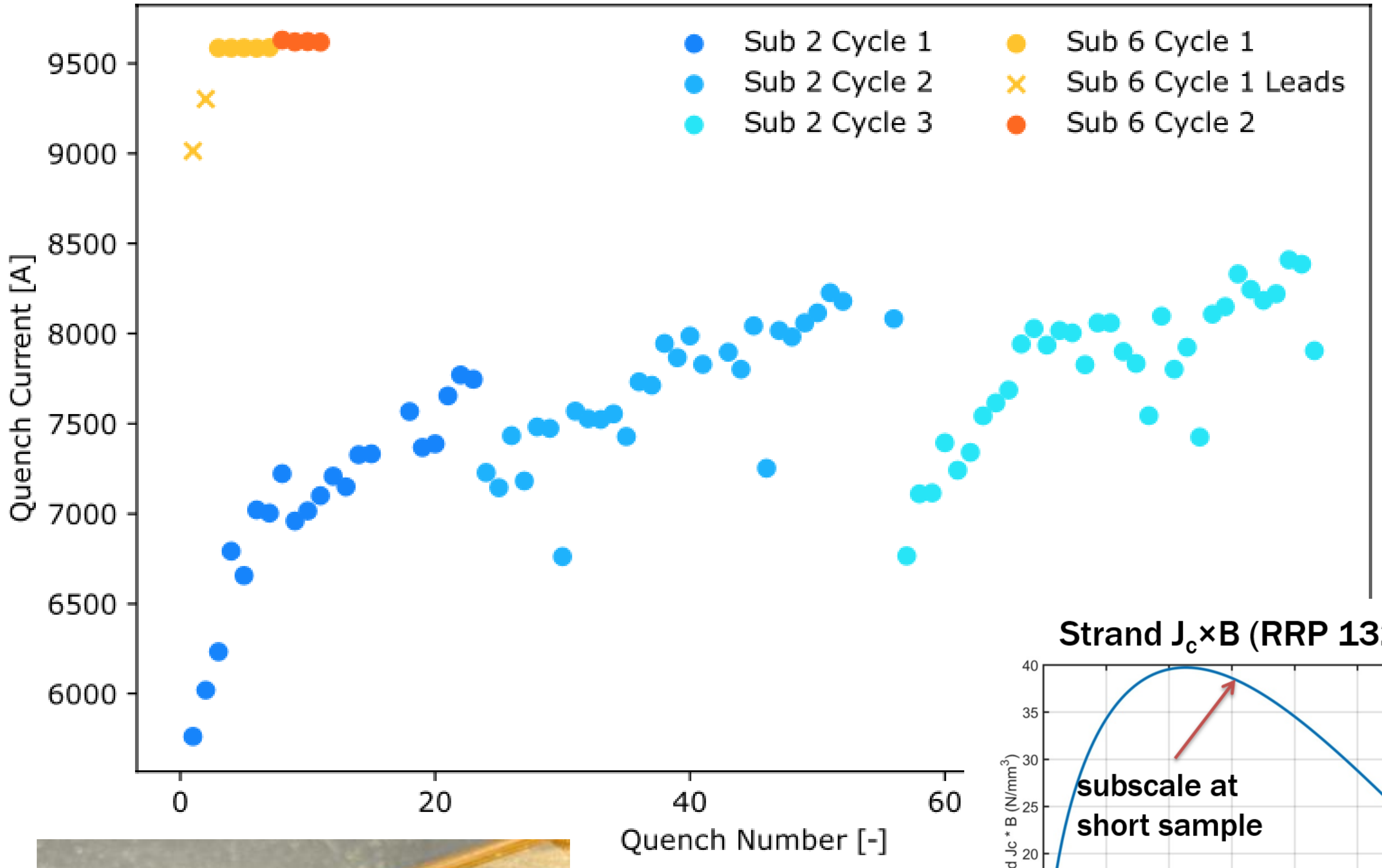
Subscale magnets are used to evaluate impregnation materials – the return of Paraffin Wax!

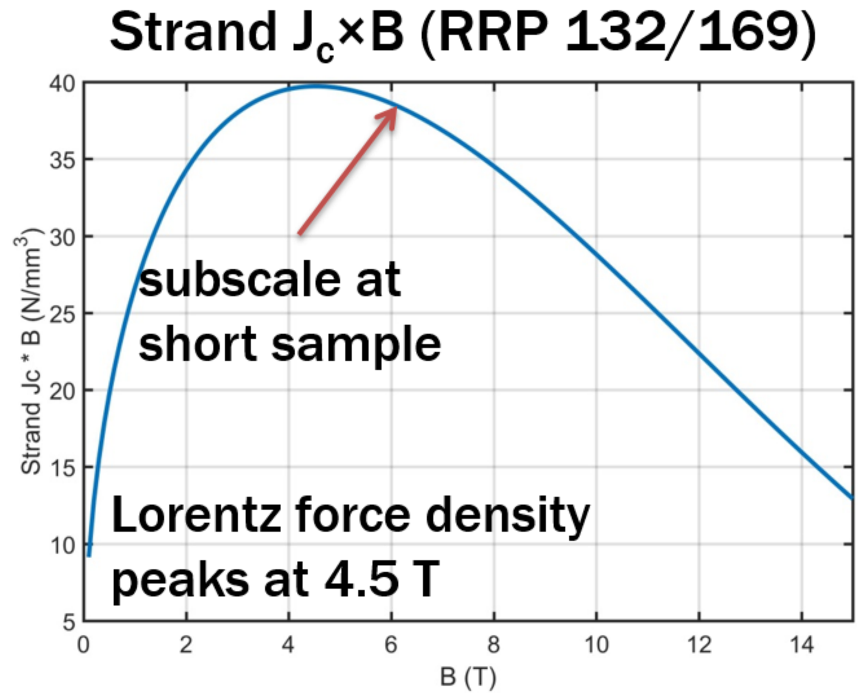
- A subscale CCT (CCT_sub_6) was built with two coils, both impregnated with Paraffin wax
- **Dramatic impact on training and margin**
  - o Only two "training" quenches, located in leads
  - o Highly reproducible quench current (~9500A)
  - o Held field (no quench) for 7 minute hold at I_q-30A
  - o Thermal cycle showed no degradation
- Excellent example of international collaboration
  - o Motivating studies using PSI "BOX" test platform
    - Data indicated wax reduced/eliminated training

    Daly et al 2022 ,SUST 35 055014

- Recent tests using Telene (on a different "platform") also suggest dramatic reduction/elimination of training
  - o Collaboration between FNAL, ANL and NIMS

E. Barzi *et al* 2024 *Supercond. Sci. Technol.* **37** 045008





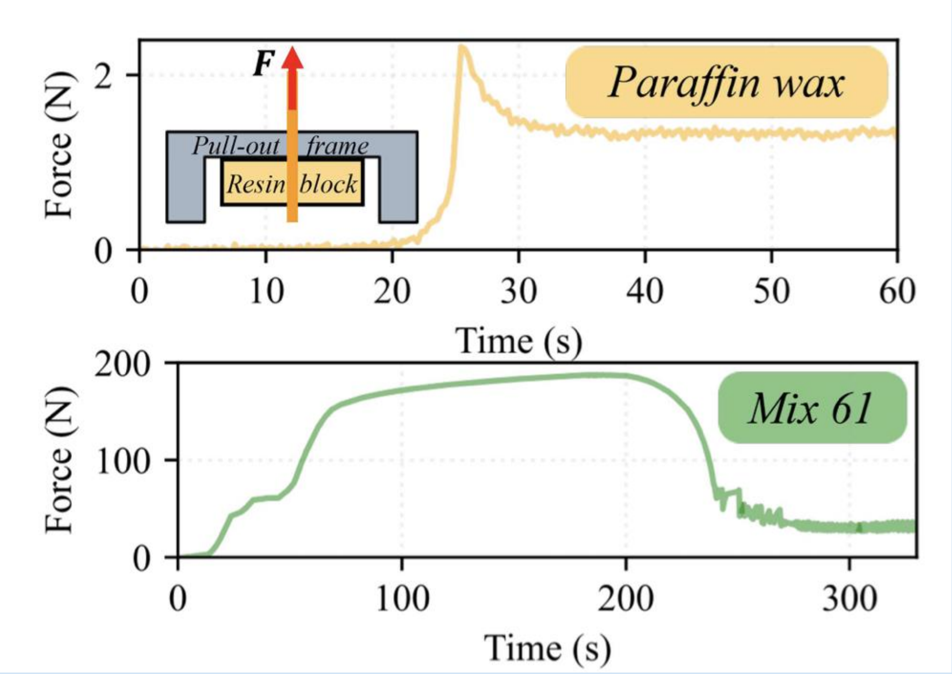
D Arbelaez et al., SUST 37 065015, 2024

Eliminating training and the need for significant operating margin is the ultimate challenge for Nb_3Sn magnets

- **MDP is addressing training & margin on multiple fronts:**
  - **Exploring disturbance spectra sources and distributions**
  - **Detailed analysis/modeling of interfaces**
  - **Exploring impregnation alternatives**
  - **Exploring high heat-capacity conductors**

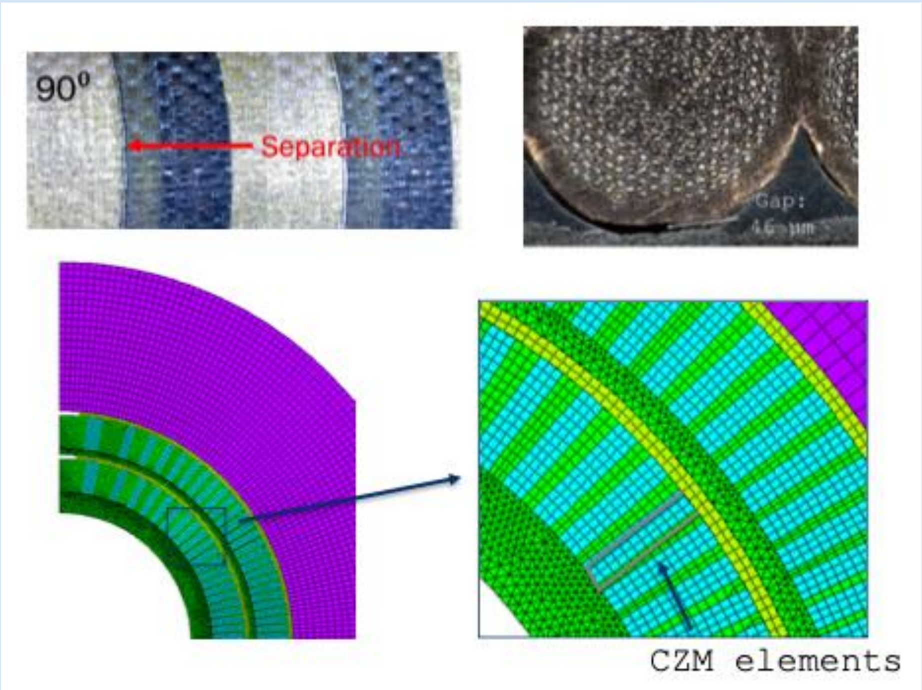
Next steps:
- Test with “filled-wax”
- Then test in high-field stress regime
- Then apply to record Nb3Sn magnet

Characterizing ***interfaces***

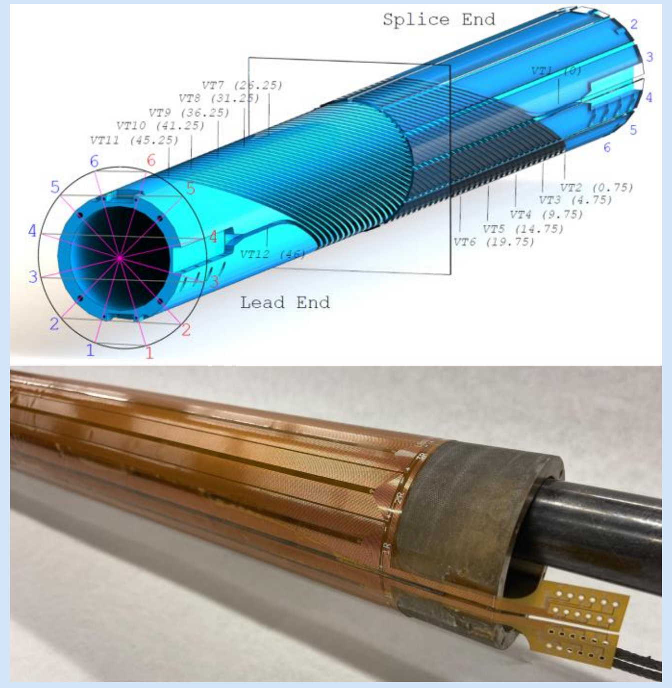


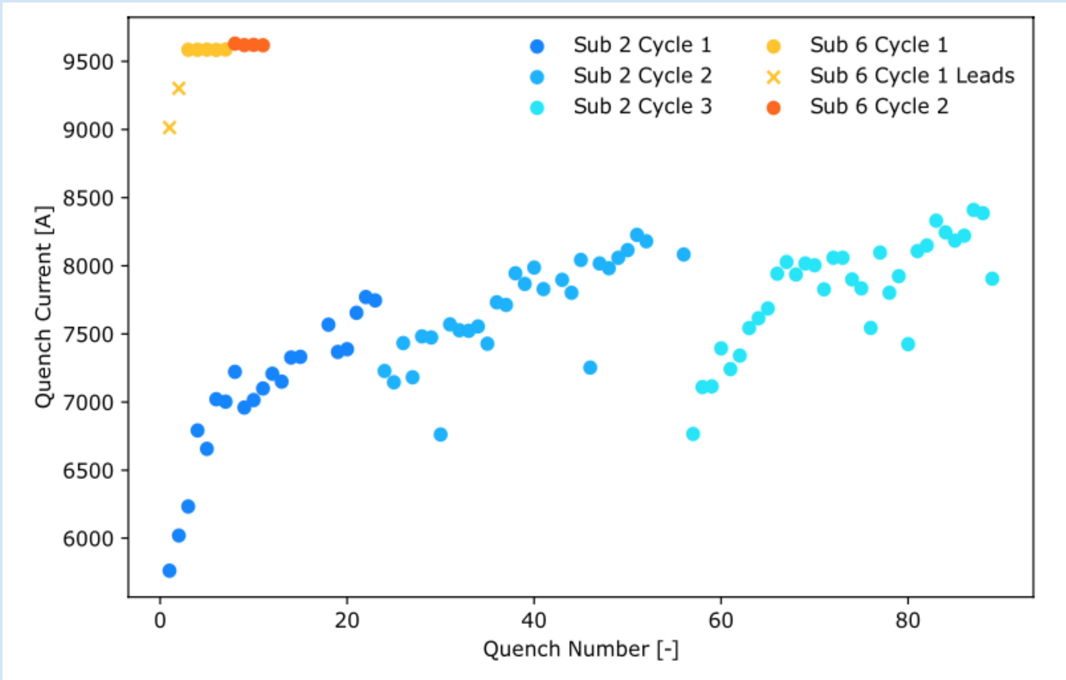
J. L. R. Fernández et al., IEEE Transactions on Applied Superconductivity, vol. 34, no. 5, pp. 1-5, Aug. 2024

Model progressive failure under operation => predict training



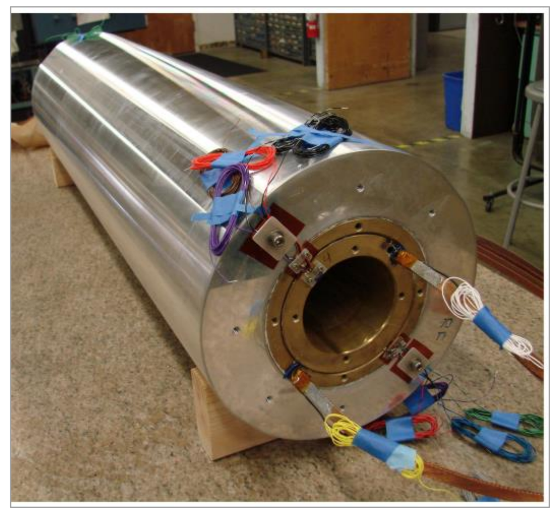
Subscale platform demonstrates ***training-free magnets***

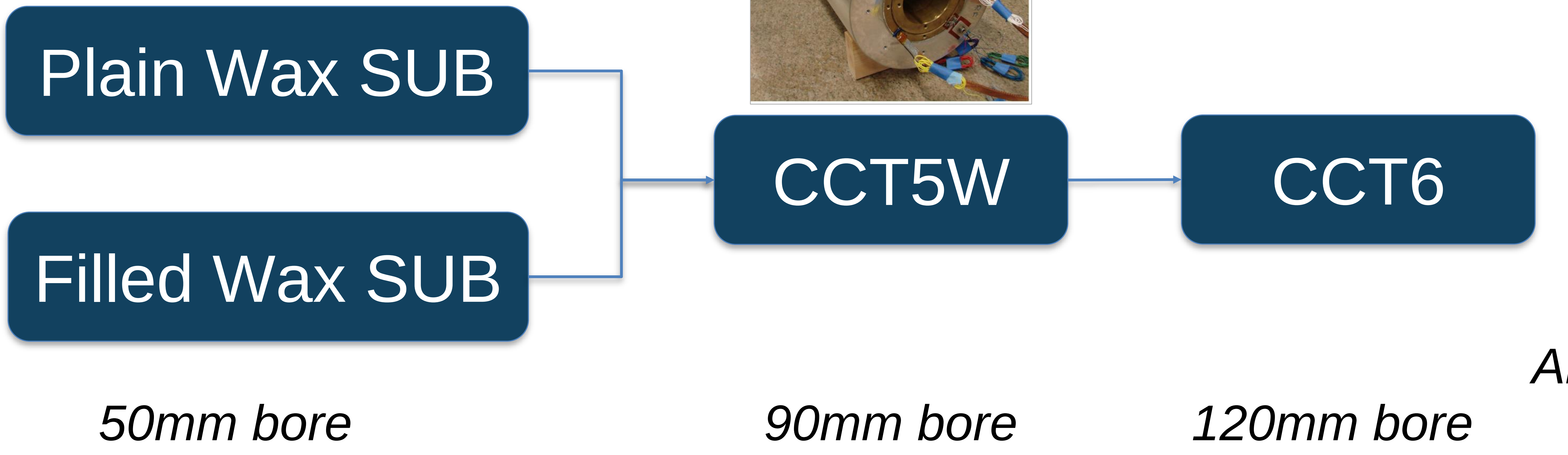




CCT5-W (Wax Impregnated) – validating training reduction without degradation

- Desire to operate close to the conductor limit with minimal training for CCT6
- Wax subscale has been completed without training
- Currently working on filled wax subscale magnet
- Wax-impregnated CCT5 @10T (CCT5-W) as a stepping stone towards CCT6
  - Average radial stress of CCT5 at 10 T is representative of CCT6 at ~12 T





Stress on Turn from Lorentz Force

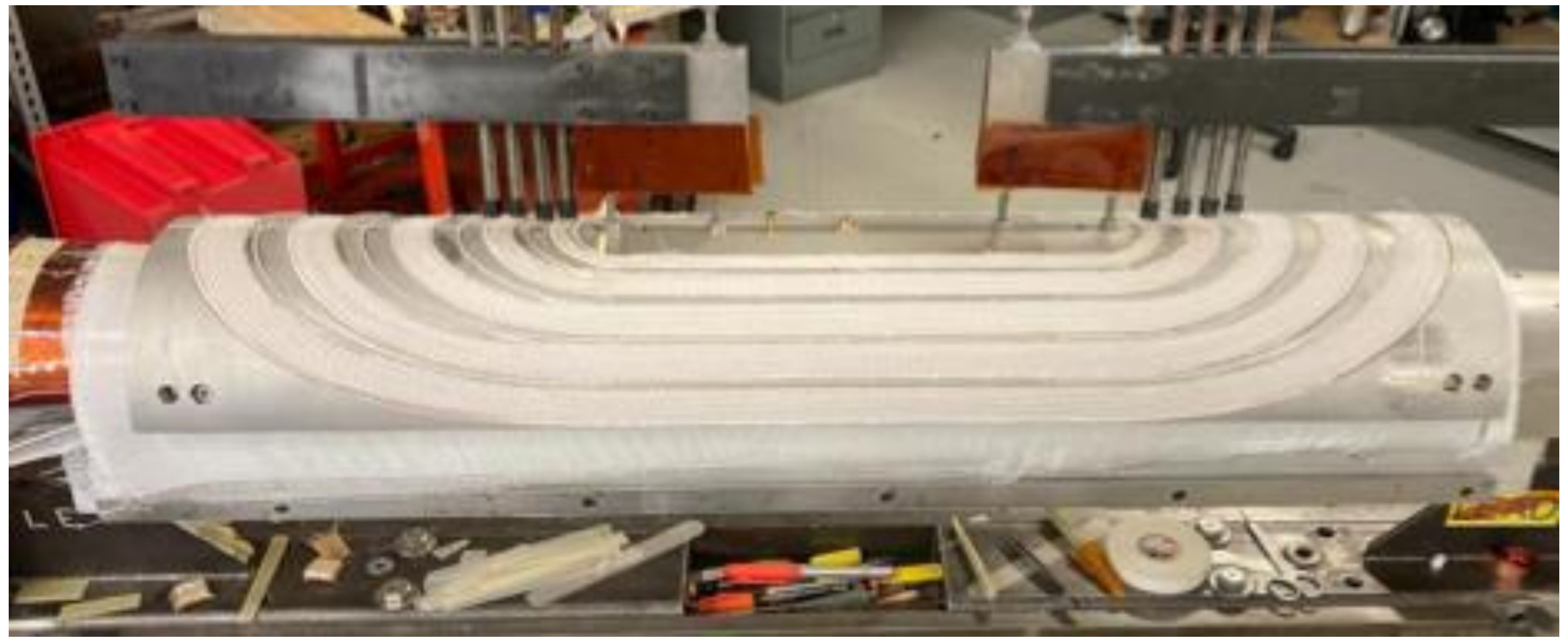
			2D FE - Magn	
Magnet	**Current**	**Field**	**srr_em**	**stt_em**
	kA	T	MPa	MPa
Subscale	9.5	5.3	15	10
CCT5	17.8	**10.0**	**71**	3
CCT6	10.67	**12**	**85**	5
CCT6	14.22	16	152	9

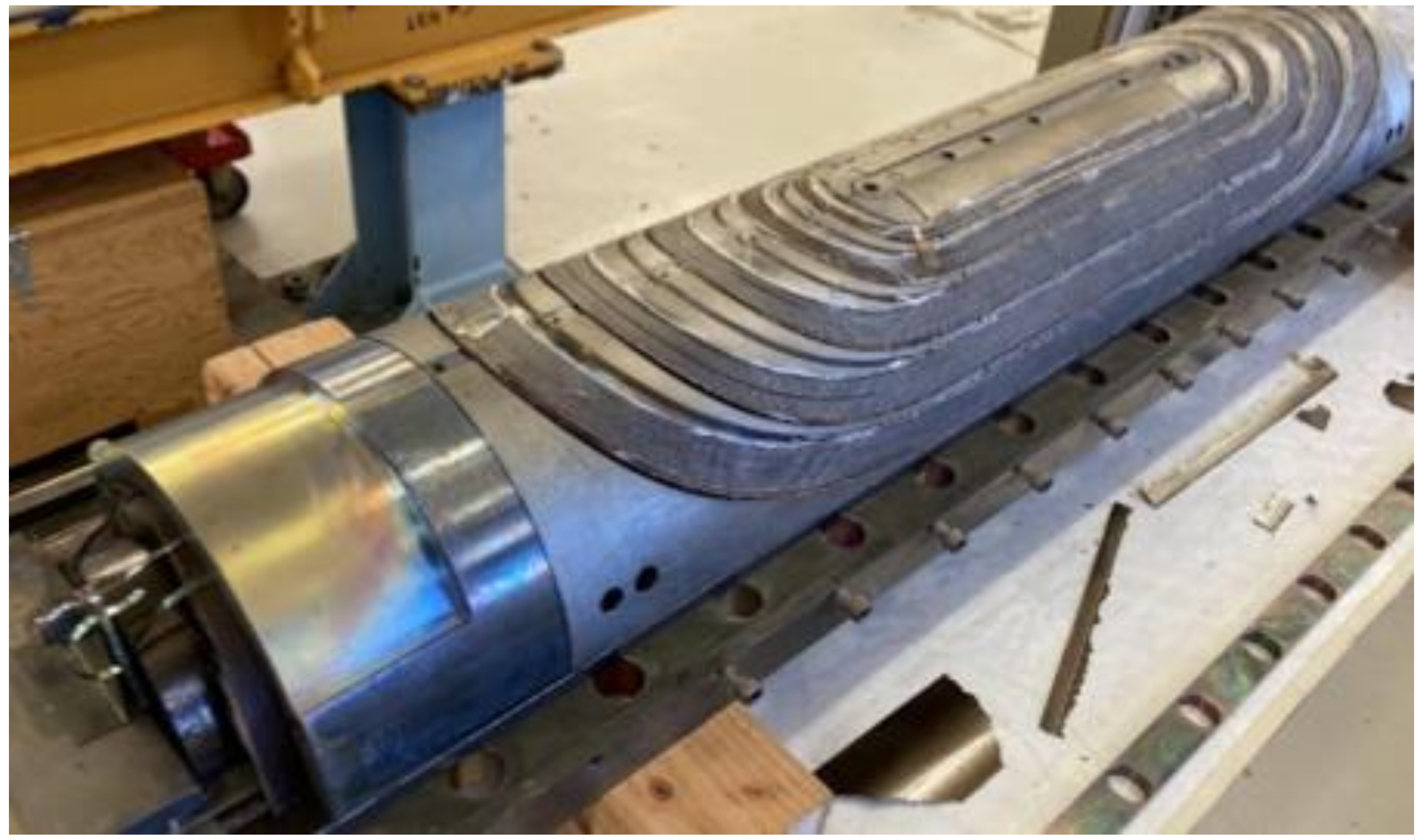
Analysis performed by G. Vallone and M. Juchno

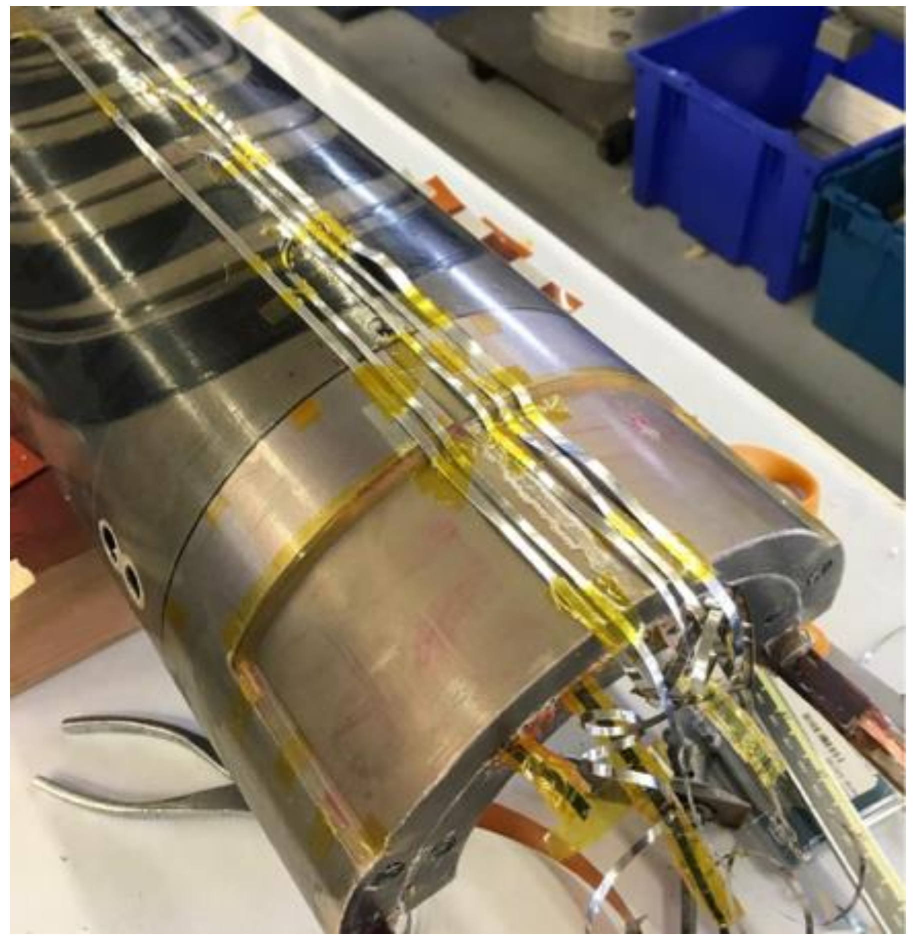
Strong progress on the Stress—managed Cos-theta (SMCT)

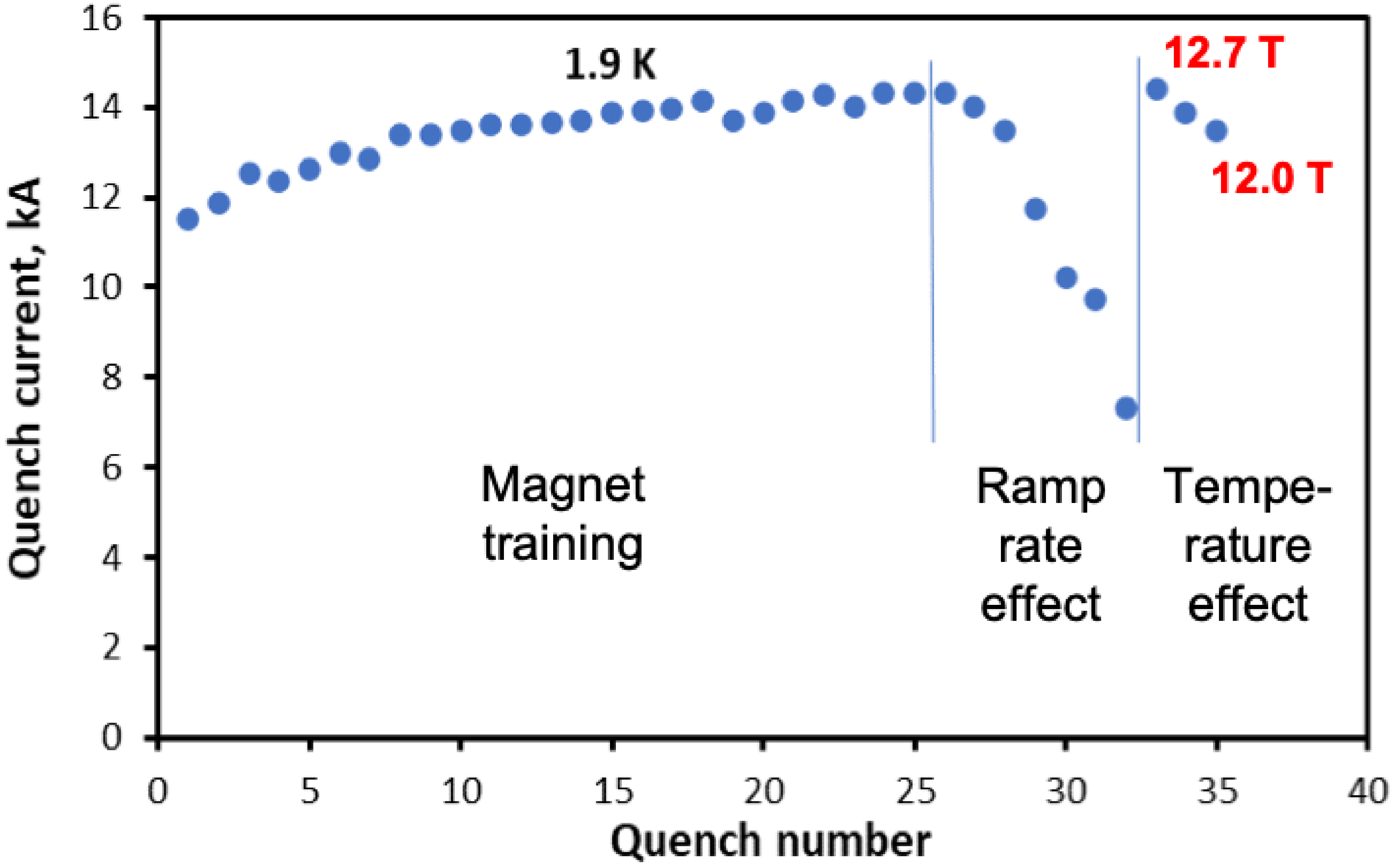
- Mirror coil fabricated and tested
  - **Solid Initial training** to B_{max}=12.7T
  - Indication reached conductor limit (~90% SS)

- Assembled magnet included inner 2 layers from 15T
  - Recently wired in series and tested – results pending

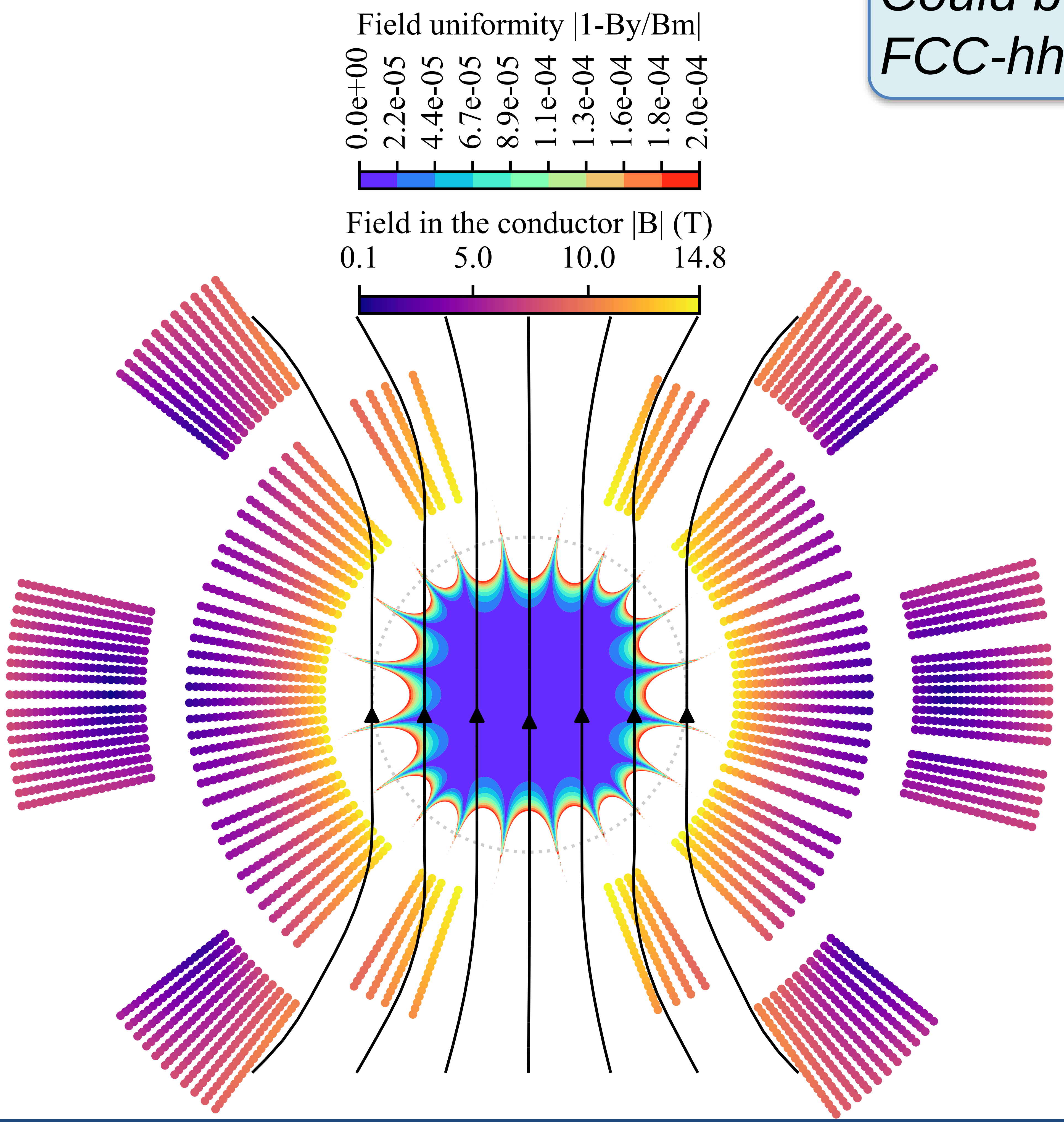








The "Uni-layer" concept leverages strengths of both CCT and SMCT – may enable efficient 2-layer Nb_3Sn 14 T dipole



Could be the seed for an outstanding FCC-hh magnet candidate!

Not currently within MDP

Fernández, J. L. R., & Ferracin, P. (2023). Uni-layer magnets: a new concept for LTS and HTS based superconducting magnets. *Superconductor Science and Technology*, *36*(5), 055003.

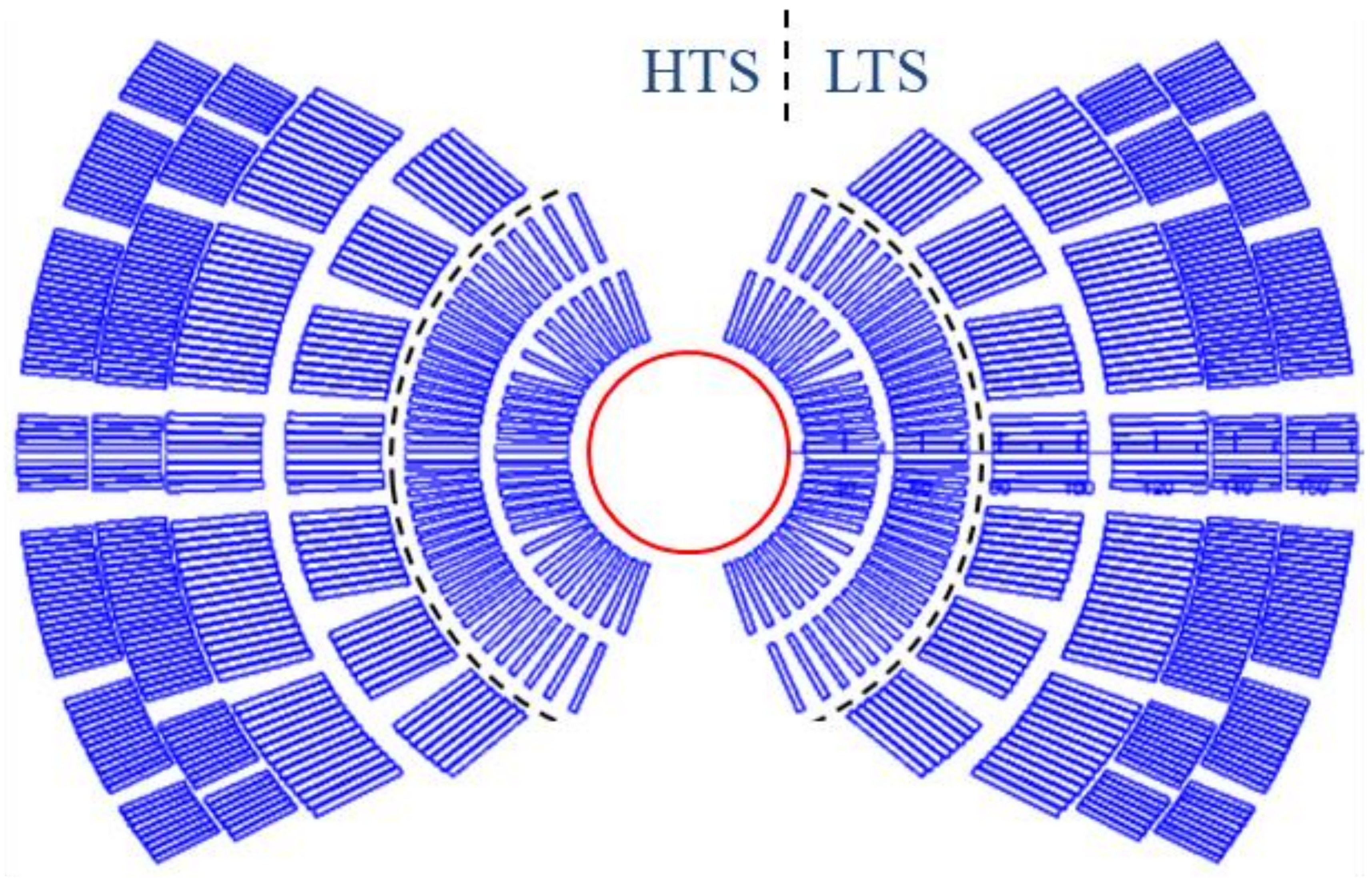
Calculated performance ***without iron***

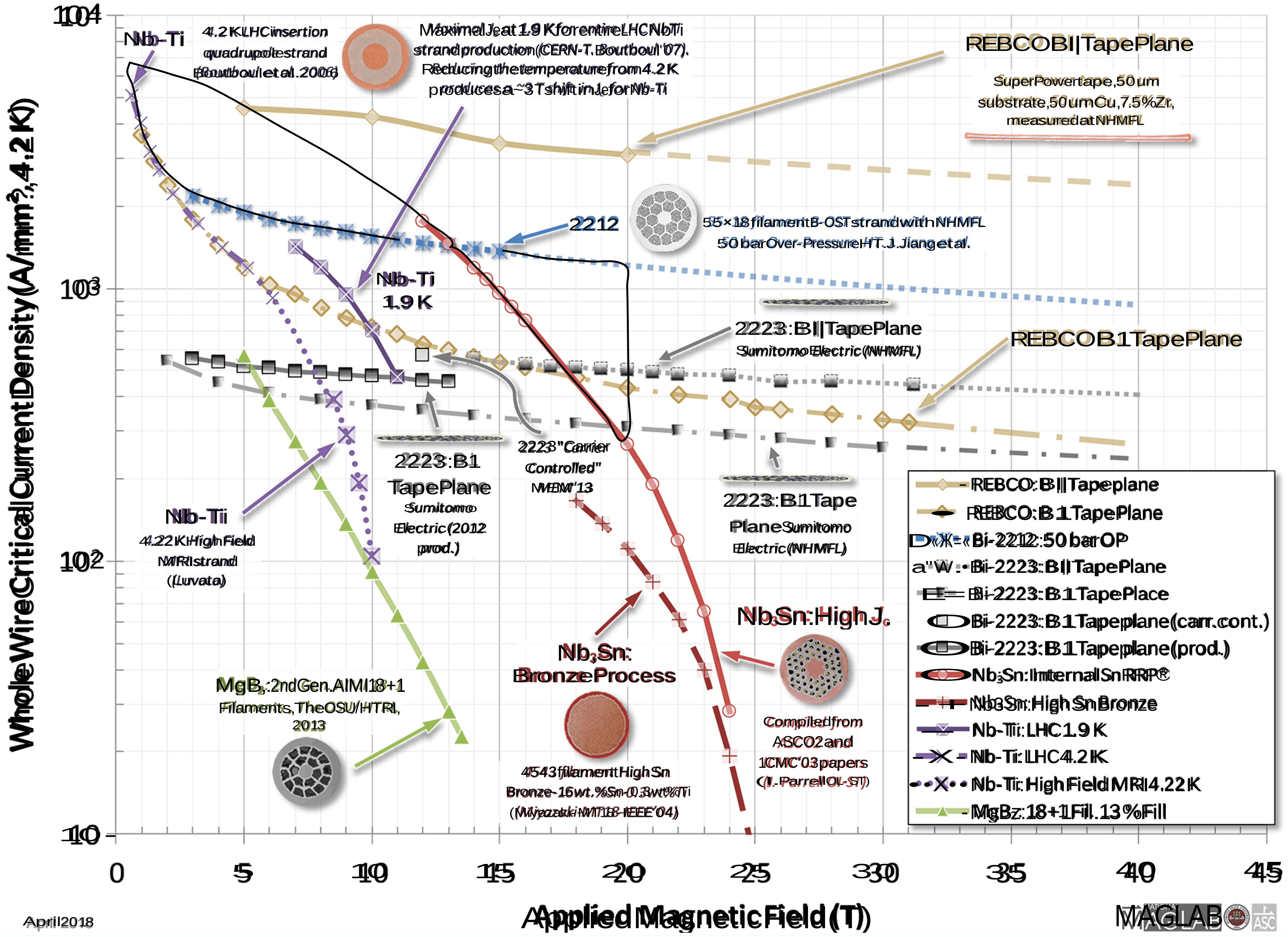
	Nb_3Sn magnet parameters
Conductor	Nb_3Sn Rutherford cable (LD1 cable, 22 mm wide)
Configuration	Duo-uni-layer (i.e. 2 layers)
Bore field (T)	14
Conductor peak field (T)	14.8
Conductor current (kA)	**29**
Aperture (mm)	50
Field quality @ 2/3 of aperture for n>1 (units)	$b_n < 1$
Magnet load-line (%) with **no Iron** contribution	**93 (1.9 K), 103 (4.2 K)**

Developing HTS accelerator magnet technology is a key component of MDP – hybrid HTS/LTS provides cost-effective path to high field

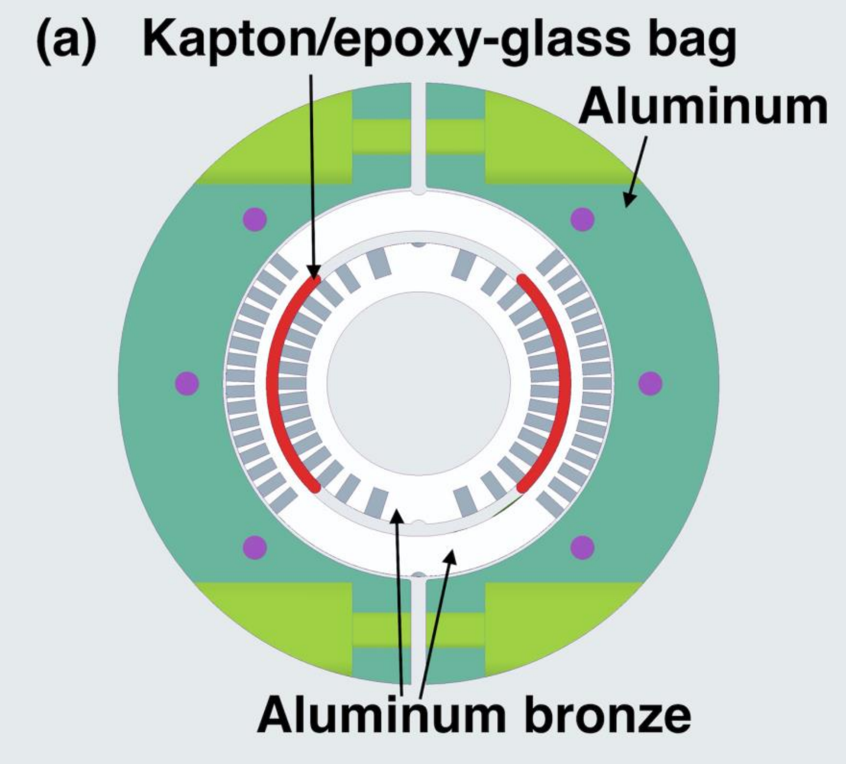
- HTS materials outperform LTS at higher field, but "under-perform" at low field
  - Motivates use of LTS "outsert", HTS "insert" as development tool for (expensive) HTS

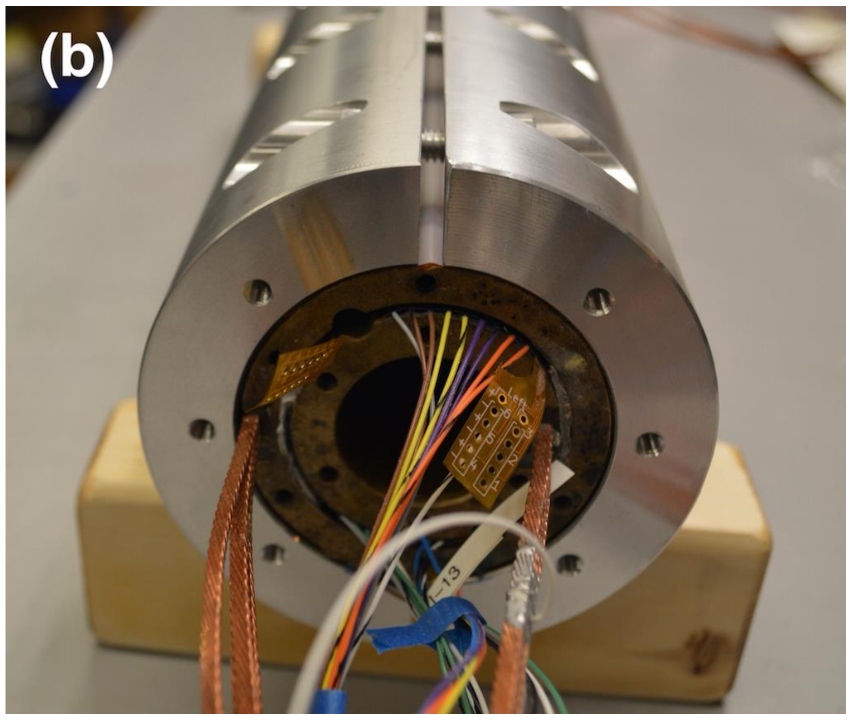
Example layout for a "stress-managed Cos-theta" hybrid magnet

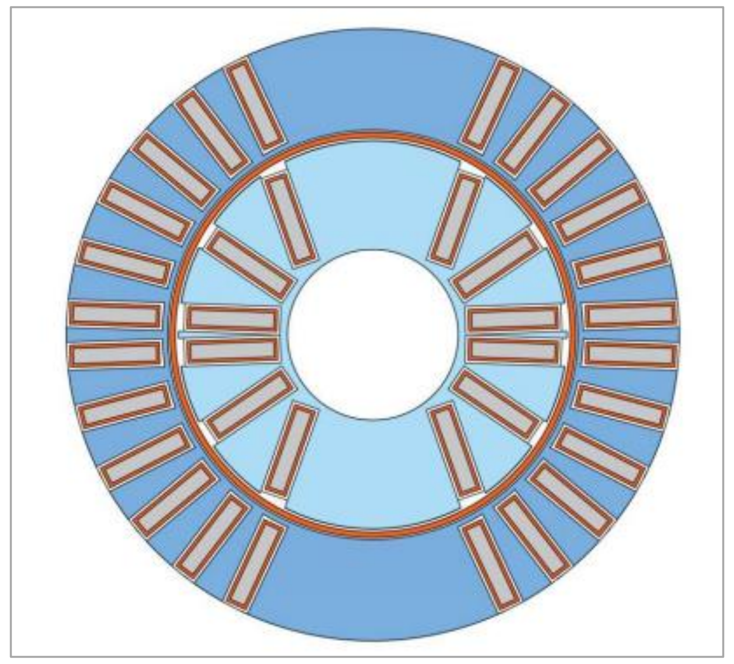


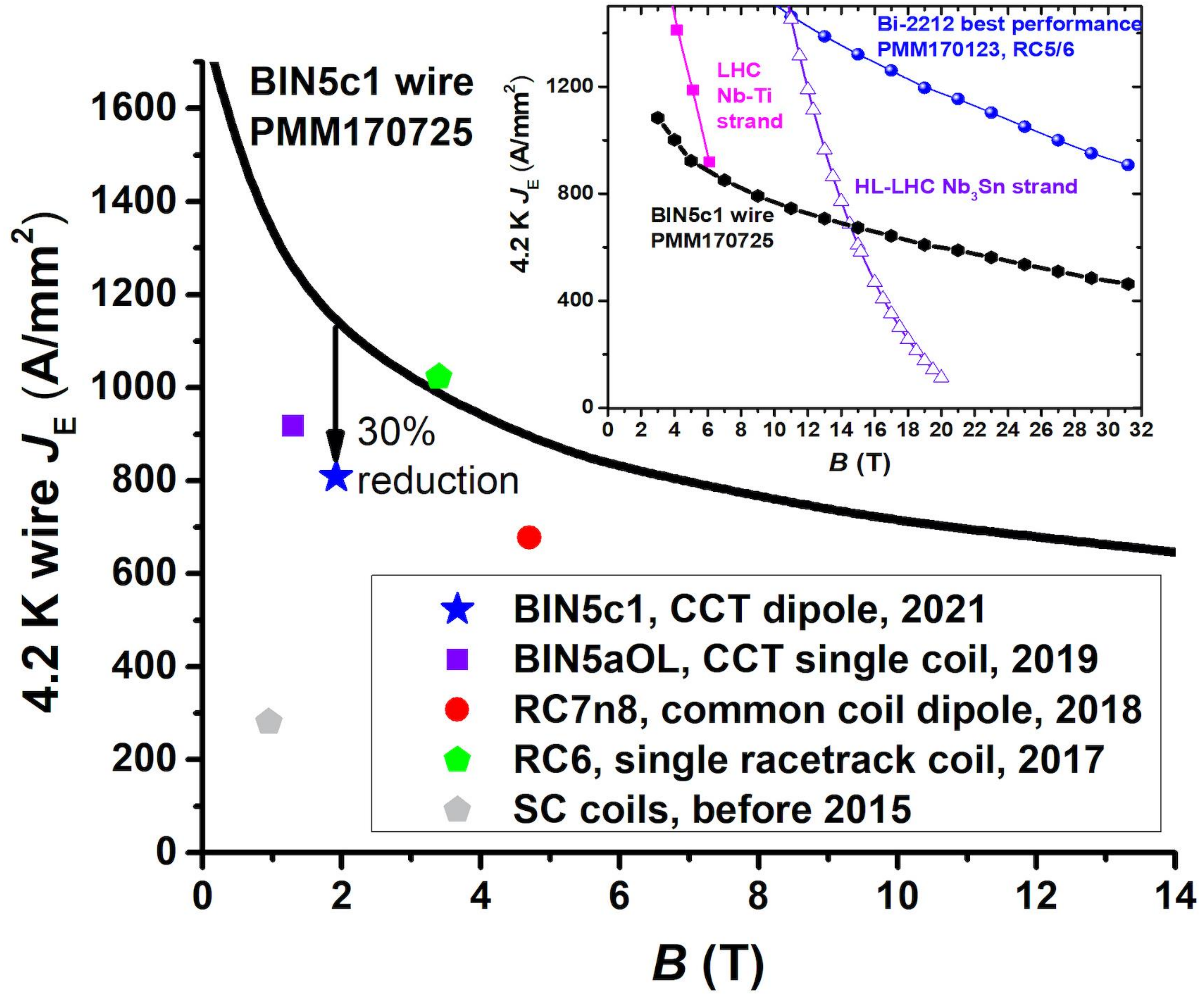


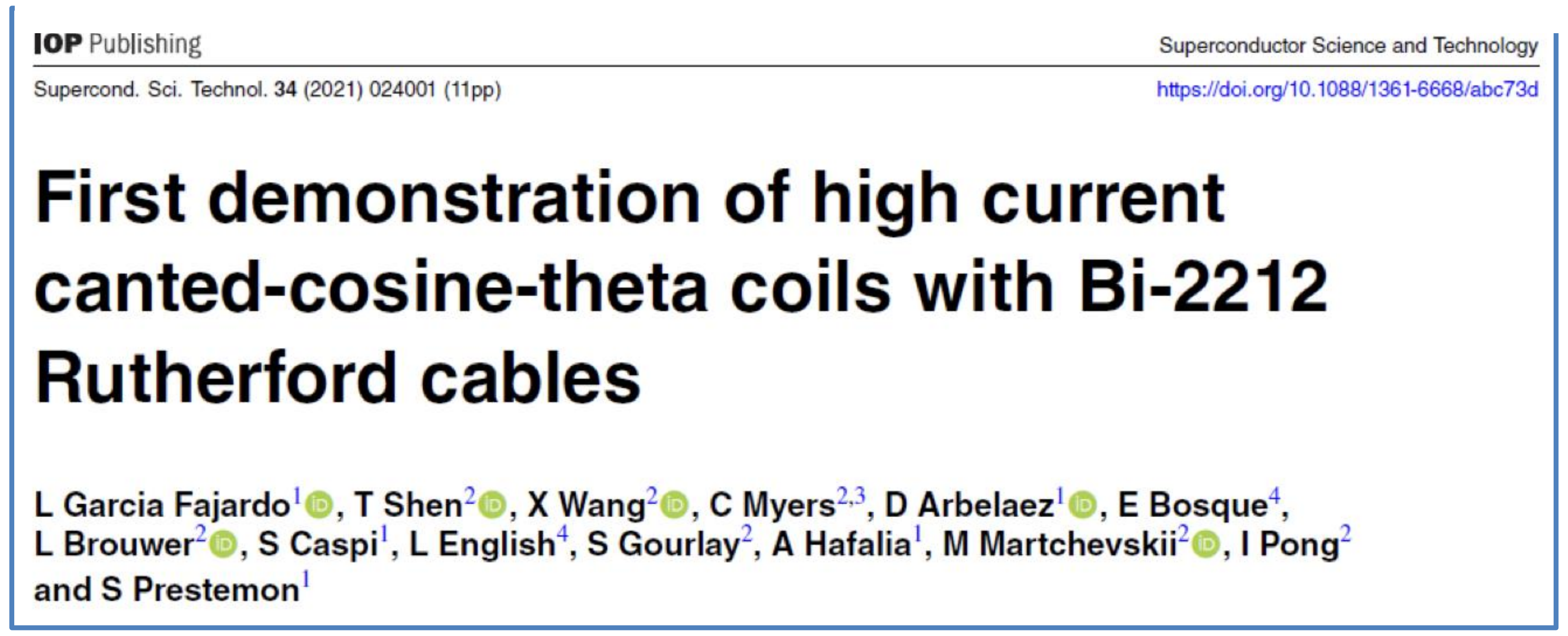
Bi2212 shows strong promise – being readied for hybrids










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

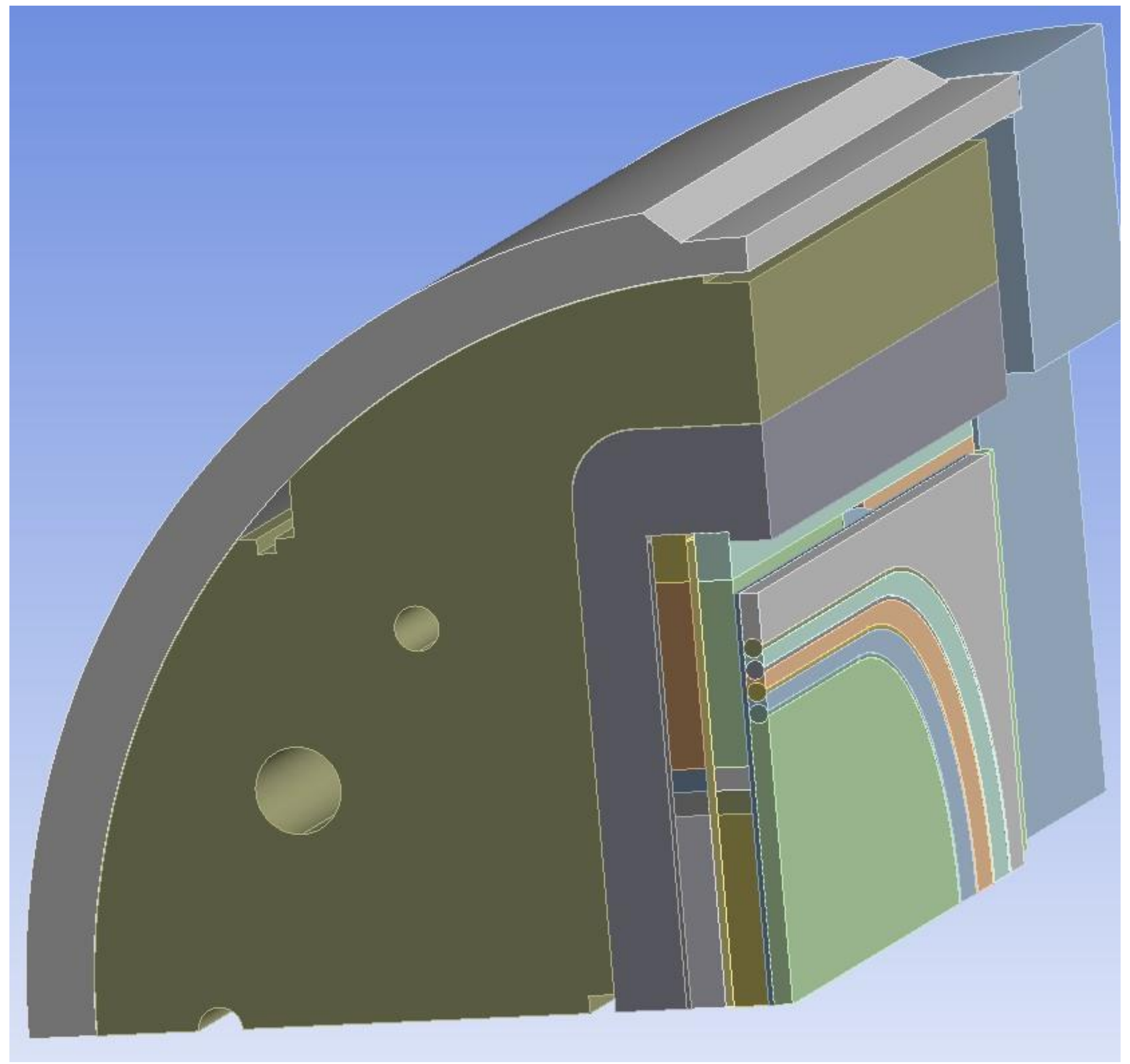
3 coils at FSU, ready f

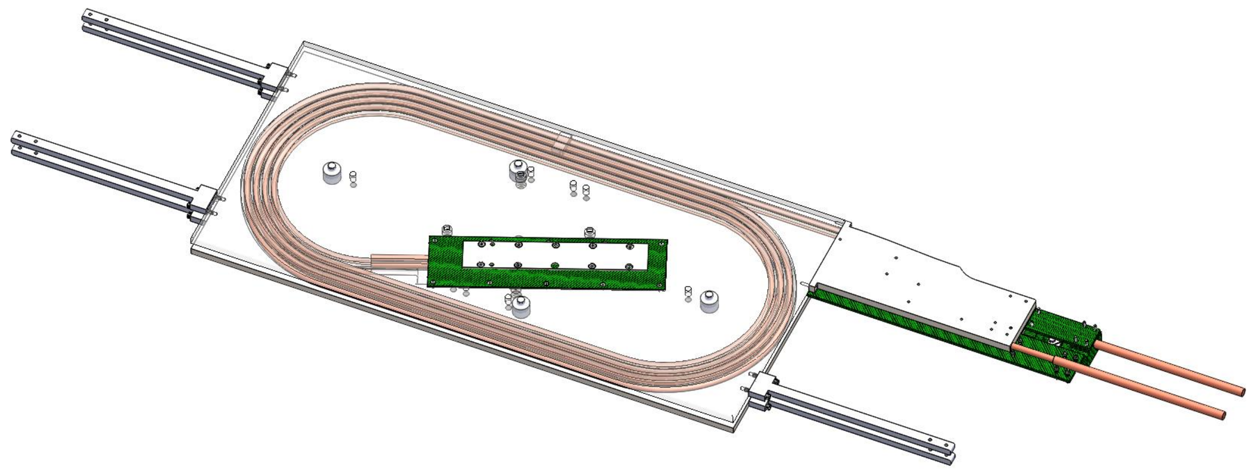
CCT6-Bi-CCT2

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

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

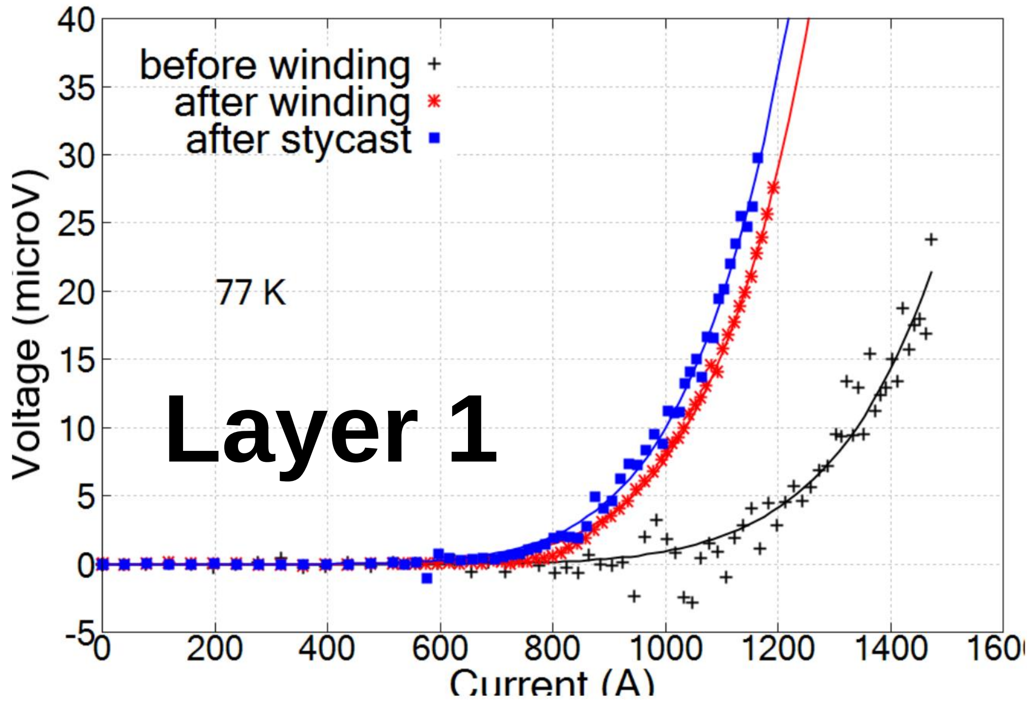
Test CORC in-field at BNL in the common-coil test facility

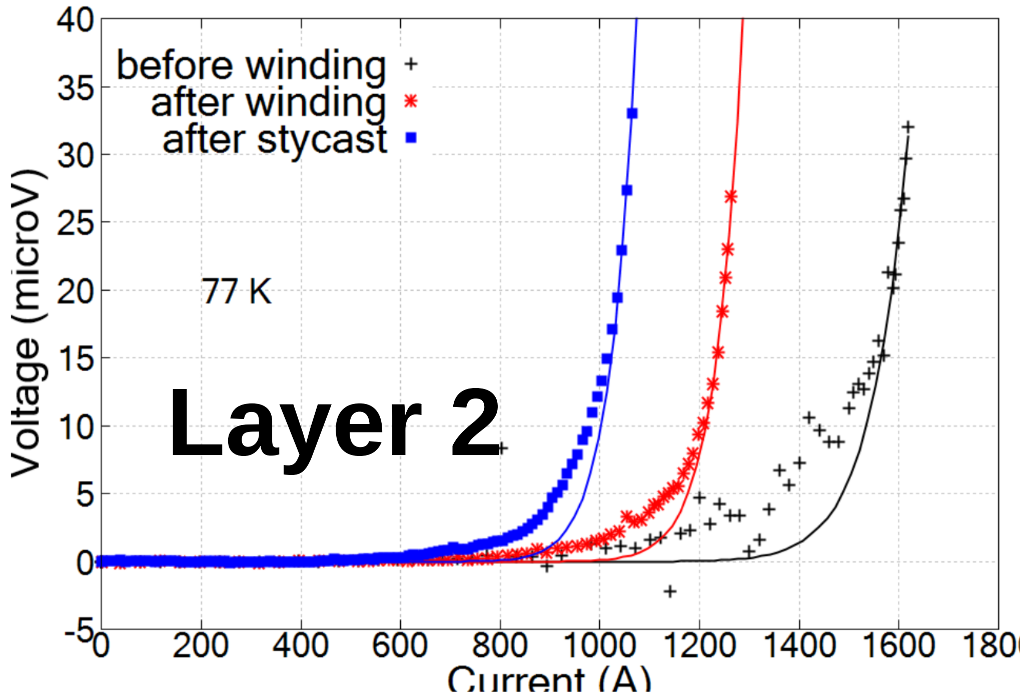




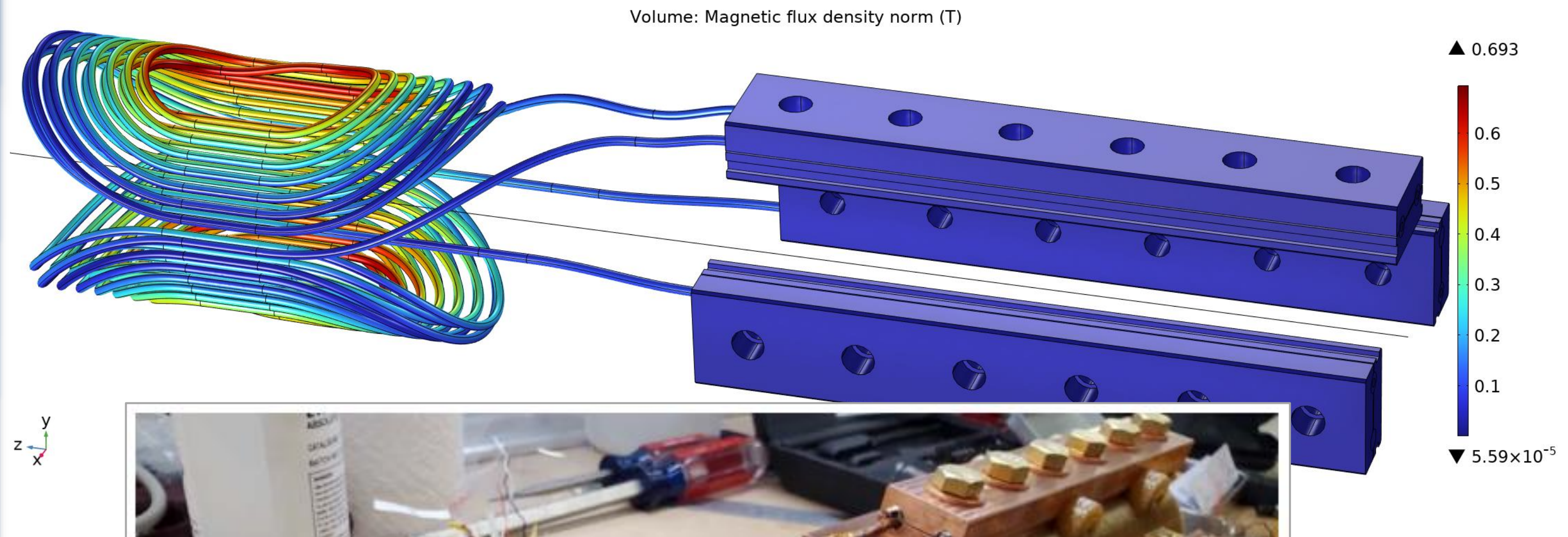
Next deliverable – "C3"

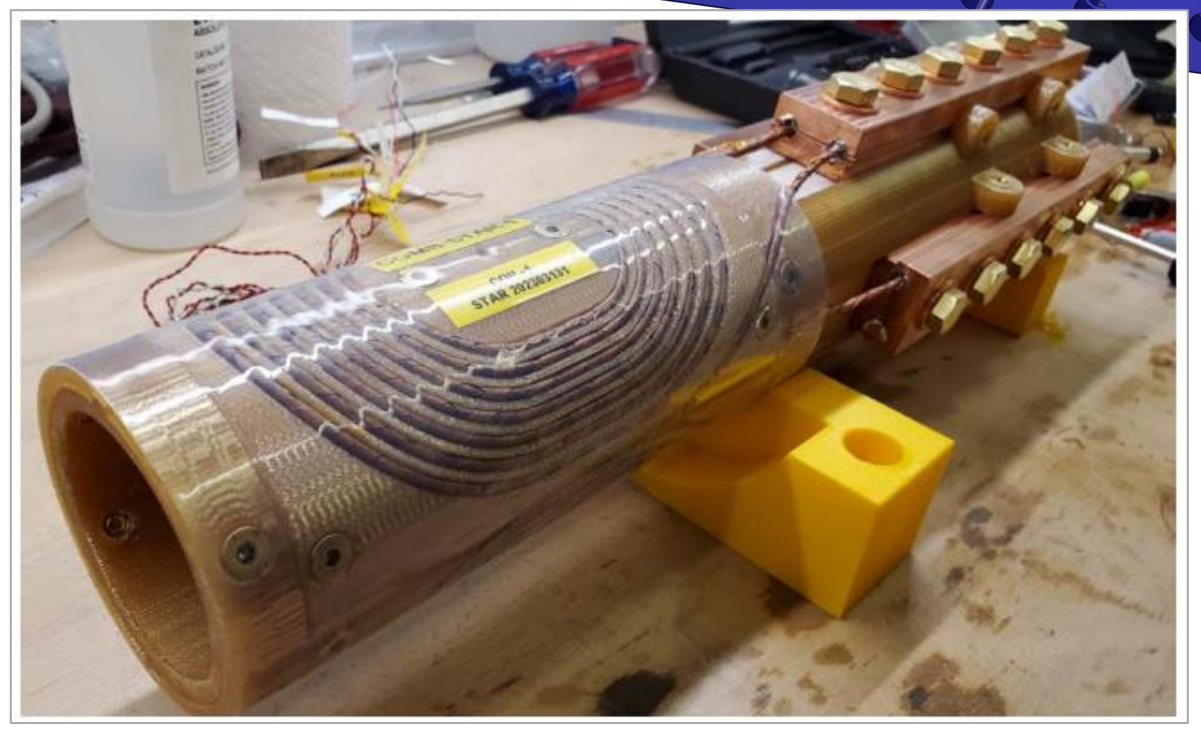
- Generate 5 T
- 6-layer CCT using CORC® wires
- Cable in-hand – winding ongoing





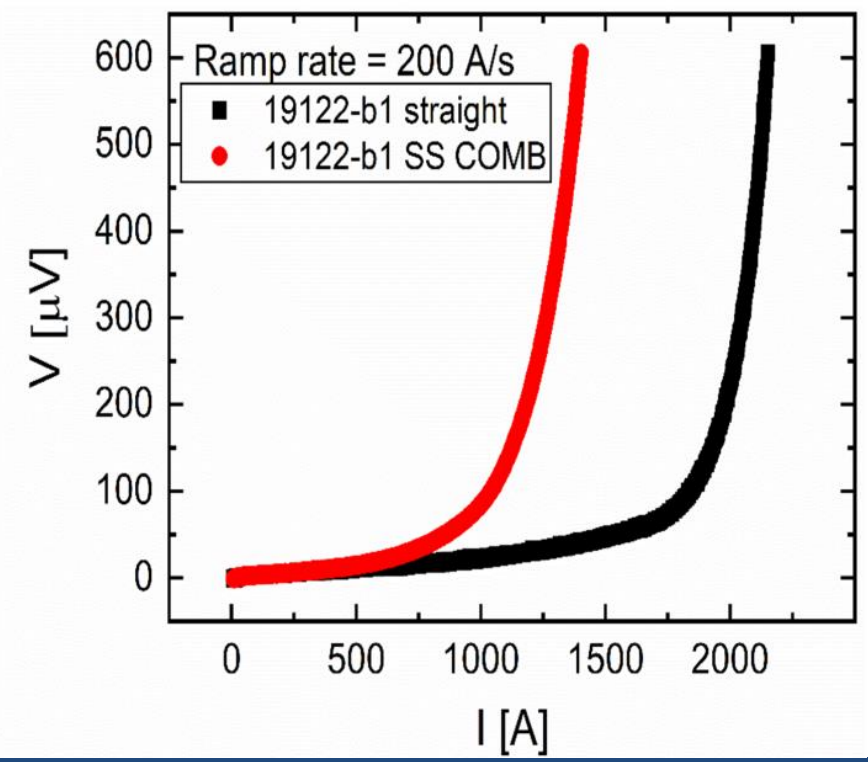
Results from 3-turn practice windings



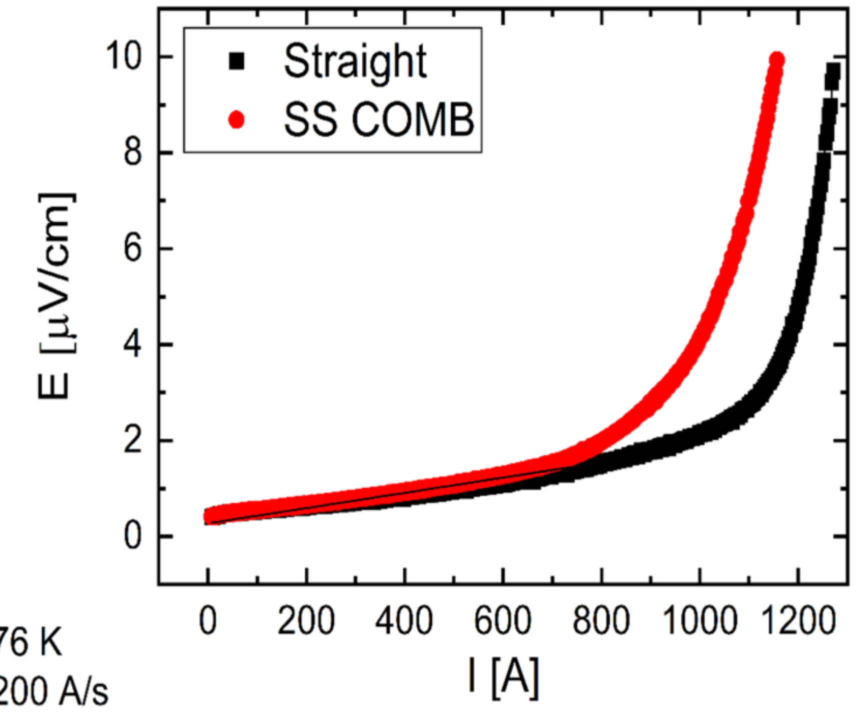


"COMB" design advancing as a test platform

"Early" CORC

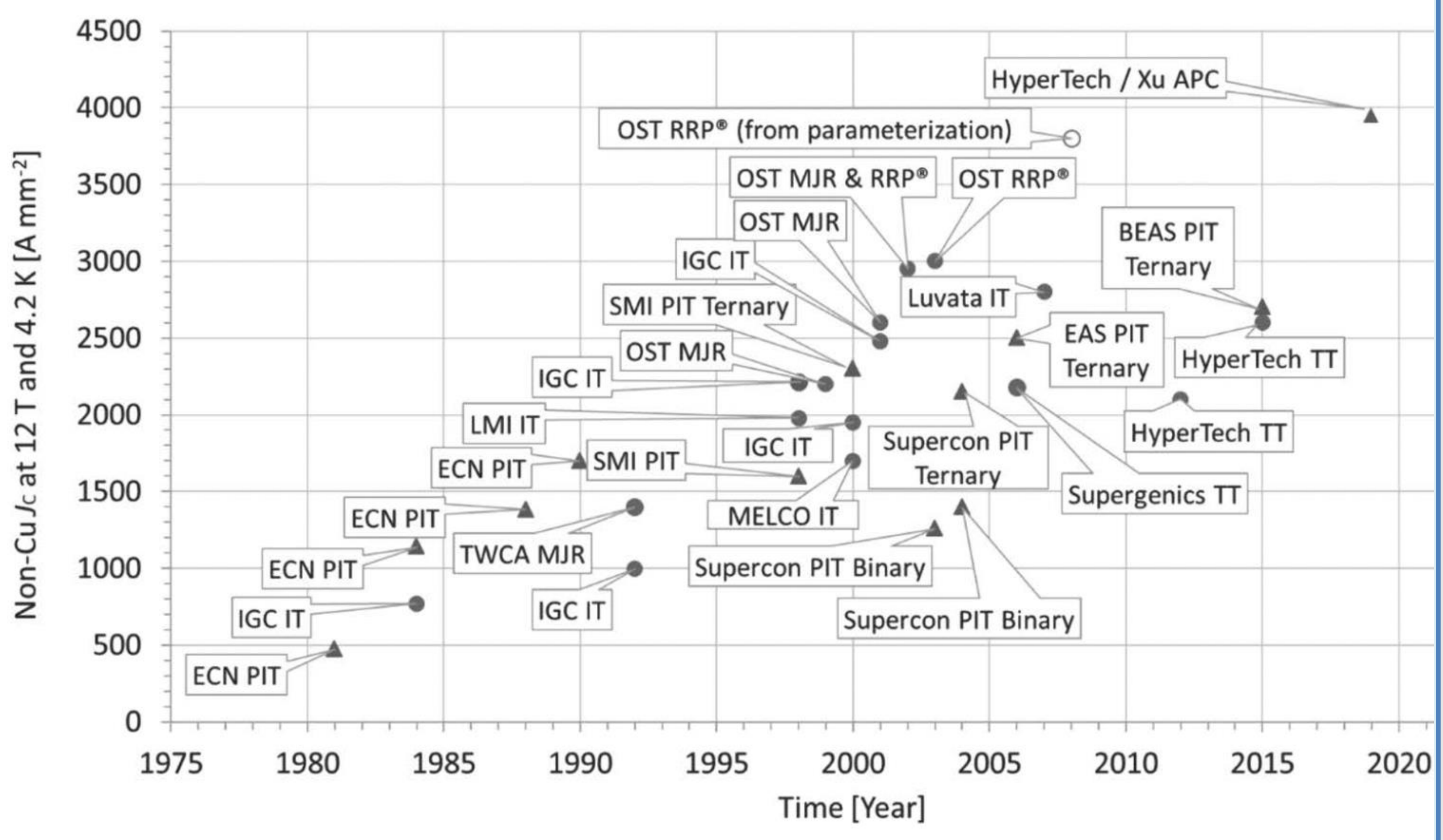


Improved CORC

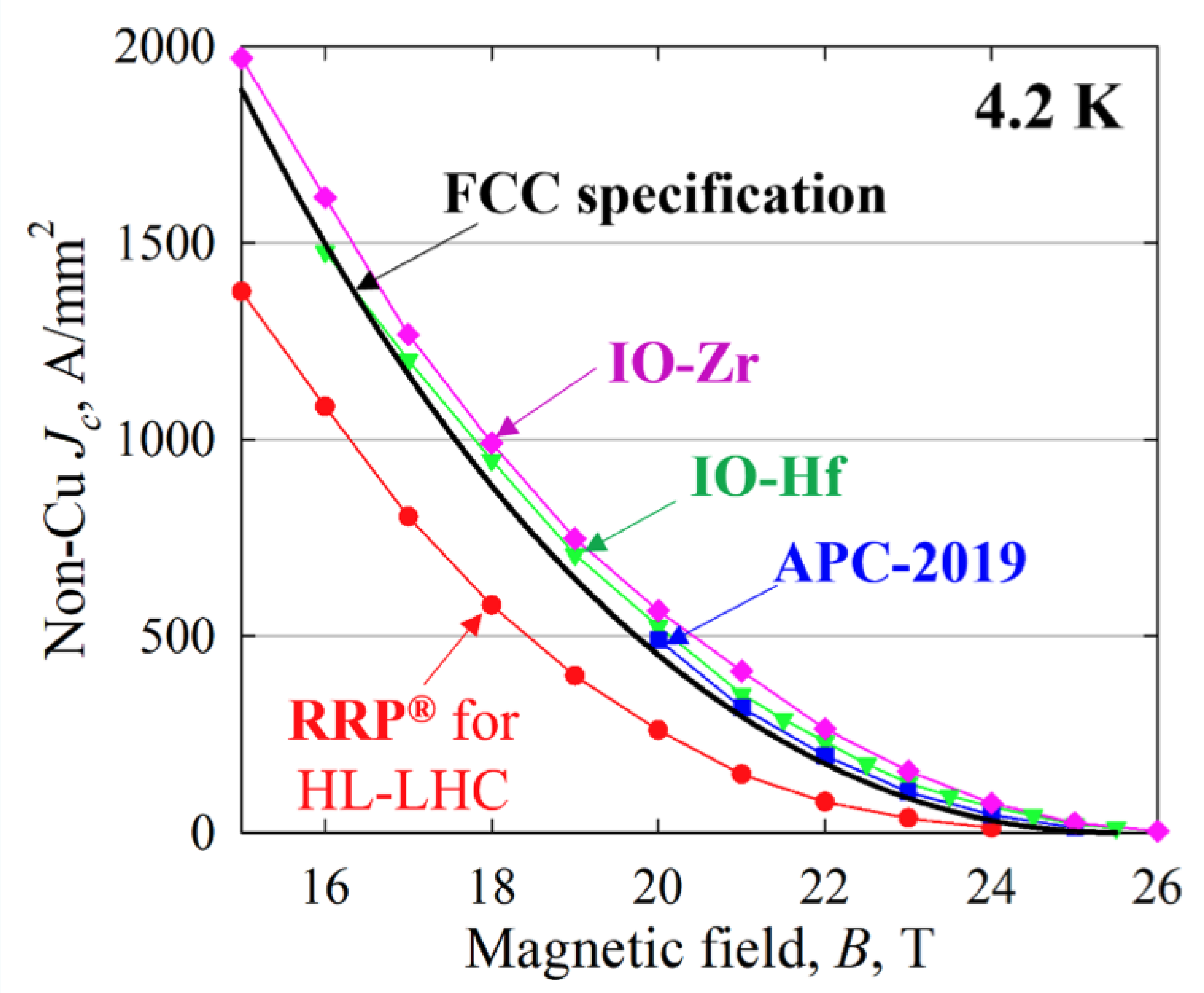


76 K
200 A/s

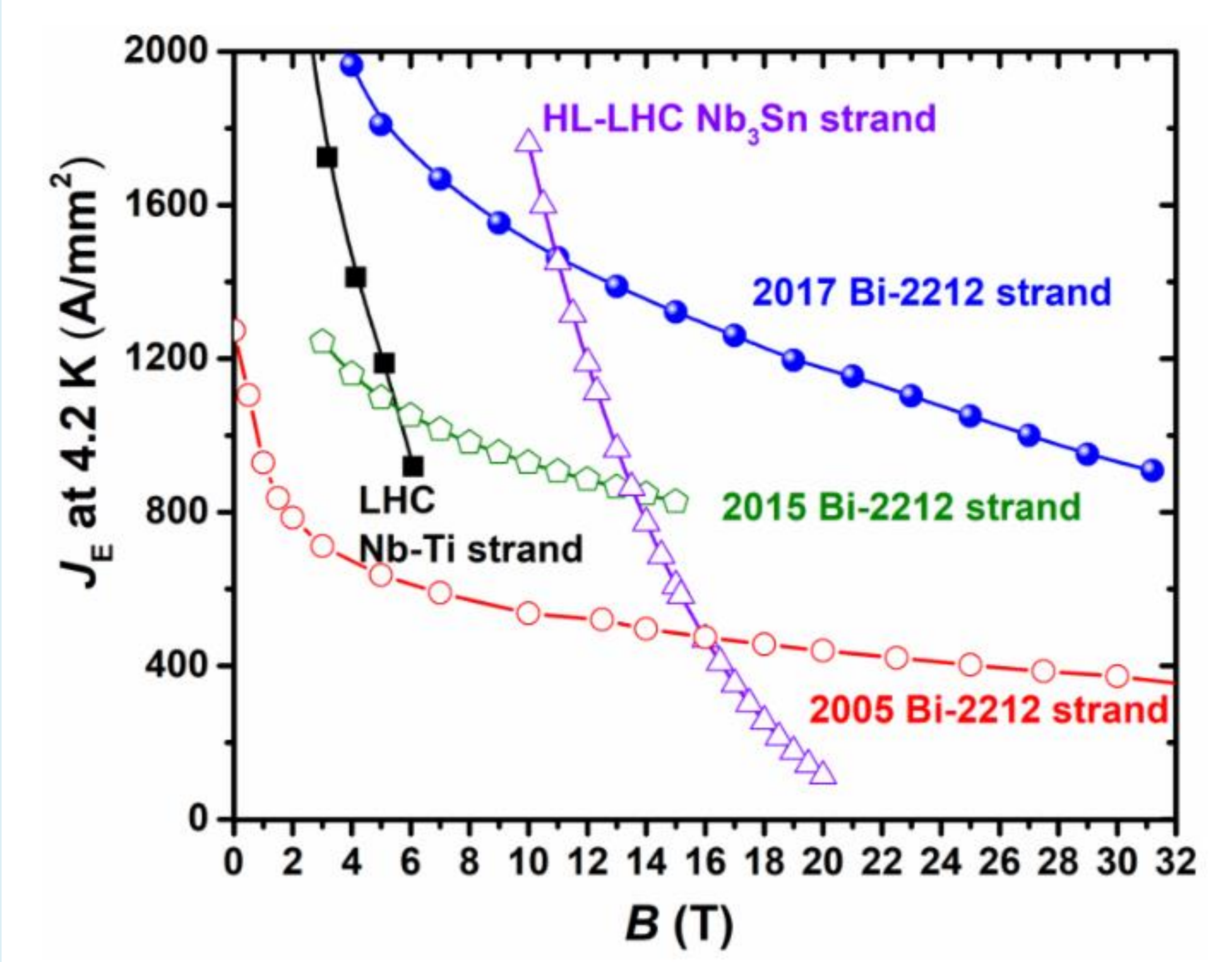
Superconductor advances are heavily driven by OHEP magnet developments, needs, and focused and consistent investments



I. Pong, Handbook of Superconductivity, Chapter E3.8



X Xu *et al* 2023 *Supercond. Sci. Technol.* **36** 035012



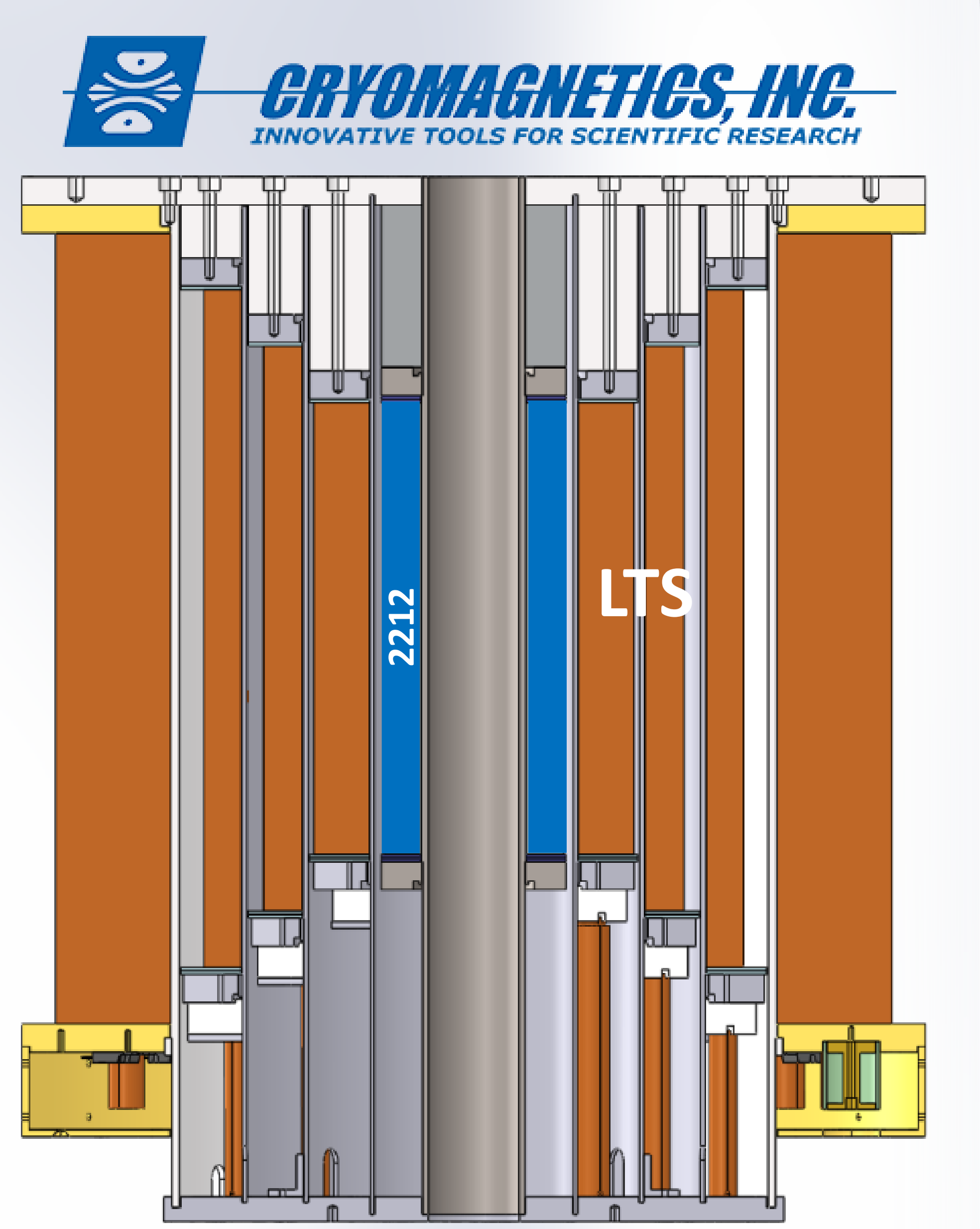
Shen & Fajardo, Instruments, 2020

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

Driving the development of the next generation Nb_3Sn superconductor

Advancing Bi2212 as a magnet-ready high temperature superconductor

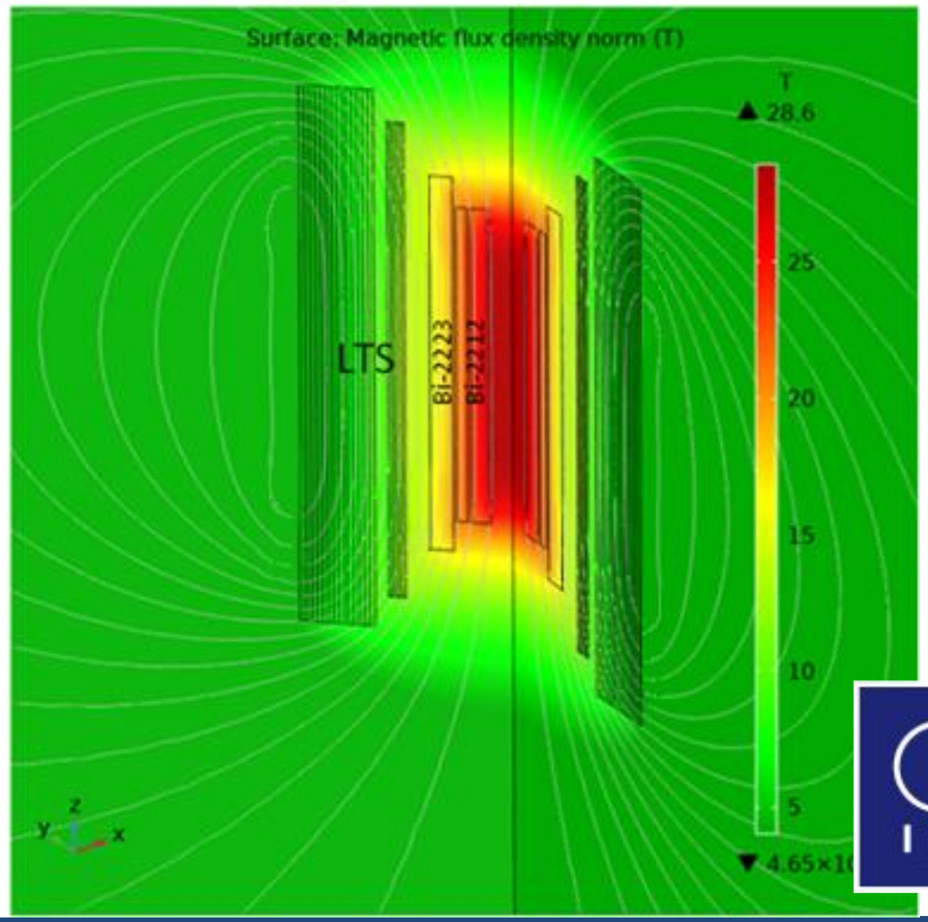
There are significant synergies to be leveraged to support Collider magnet development



ASC/NHMFL partnered with two magnet manufacturers, Cryomagnetics Inc. and Oxford Instruments

- Compact general science magnets in the 25 T range
- high homogeneity magnets >30 T
- Use substantial amount of Bi-2212

Bi-2212 and Bi-2223 Insert Coil Design for 28.2 T / 40 mm Bore UHF NMR Magnet System		
Bi-2212 Coil #1	a1; a2; z1; z2 [mm]	22.2; 40.5; -178.6; 178.6
	Turns	3920
	Field [T]	5.17
	wire length [km]	0.77
Bi-2212 Coil #2	a1; a2; z1; z2 [mm]	44.45; 55.3; -178.6; 178.6
	Turns	2240
	Field [T]	2.89
	wire length [km]	0.71
Bi-2223 Coil	a1; a2; z1; z2 [mm]	58.5; 81.4; -212.5; 212.5
	Turns	5767
	Field [T]	6.16
	wire length [km]	2.6
HTS Section Current [A]		380.5
Store Energy [MJ]		< 3 (~0.5 MJ in HTS)



OXFORD INSTRUMENTS

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

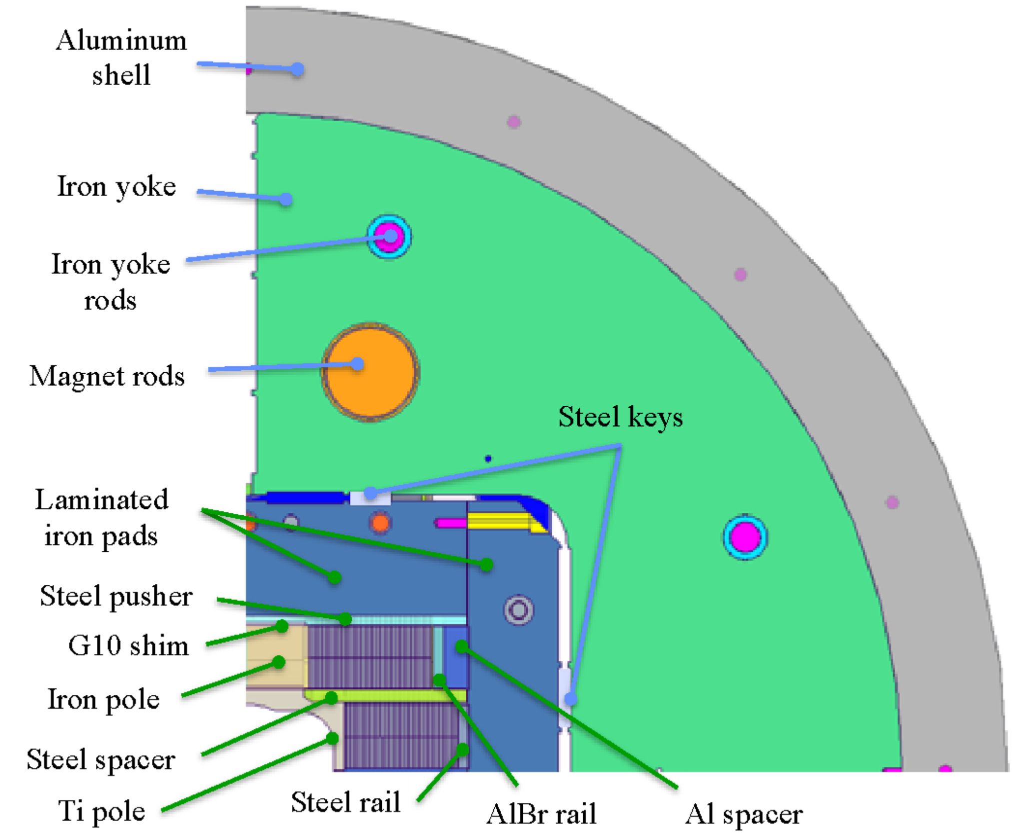
Event Registration

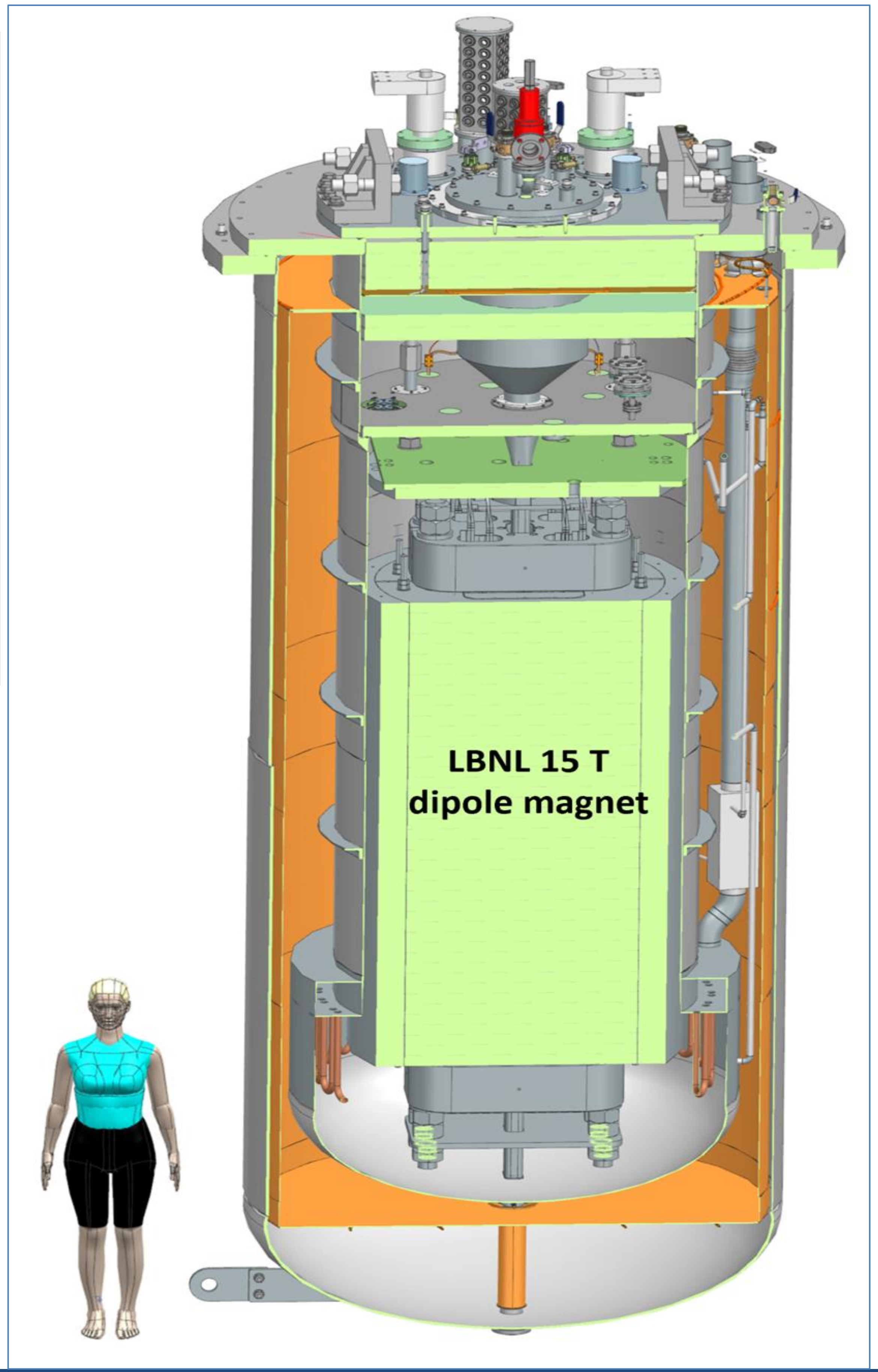
Contact info
velev@fnal.gov,denise2@fnal.gov

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.

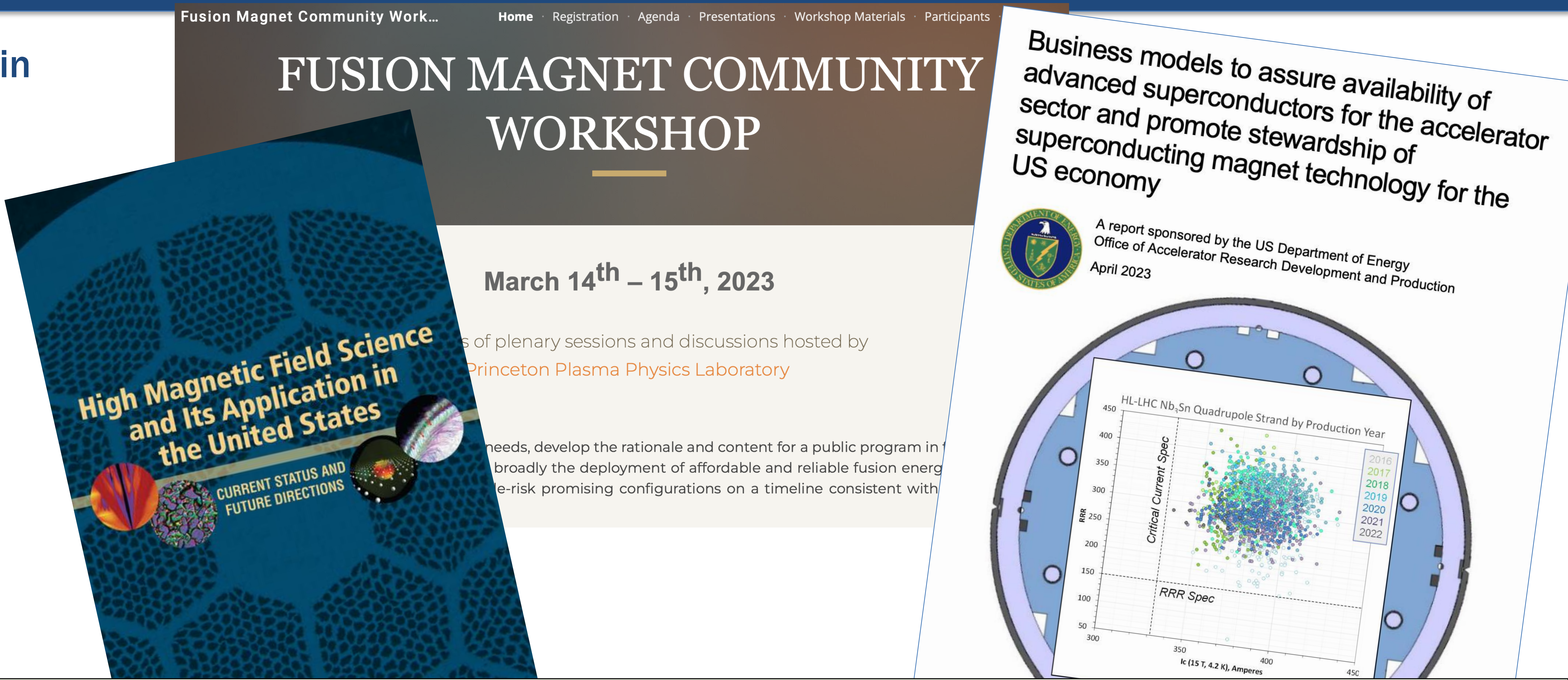




We are actively engaged in identifying and leveraging synergistic activities to the benefit of HEP

- 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 & 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.

New paradigms: quench-free HTS magnet designs?

Traditional superconducting magnet design ensures magnet can survive quenches

Motivation:

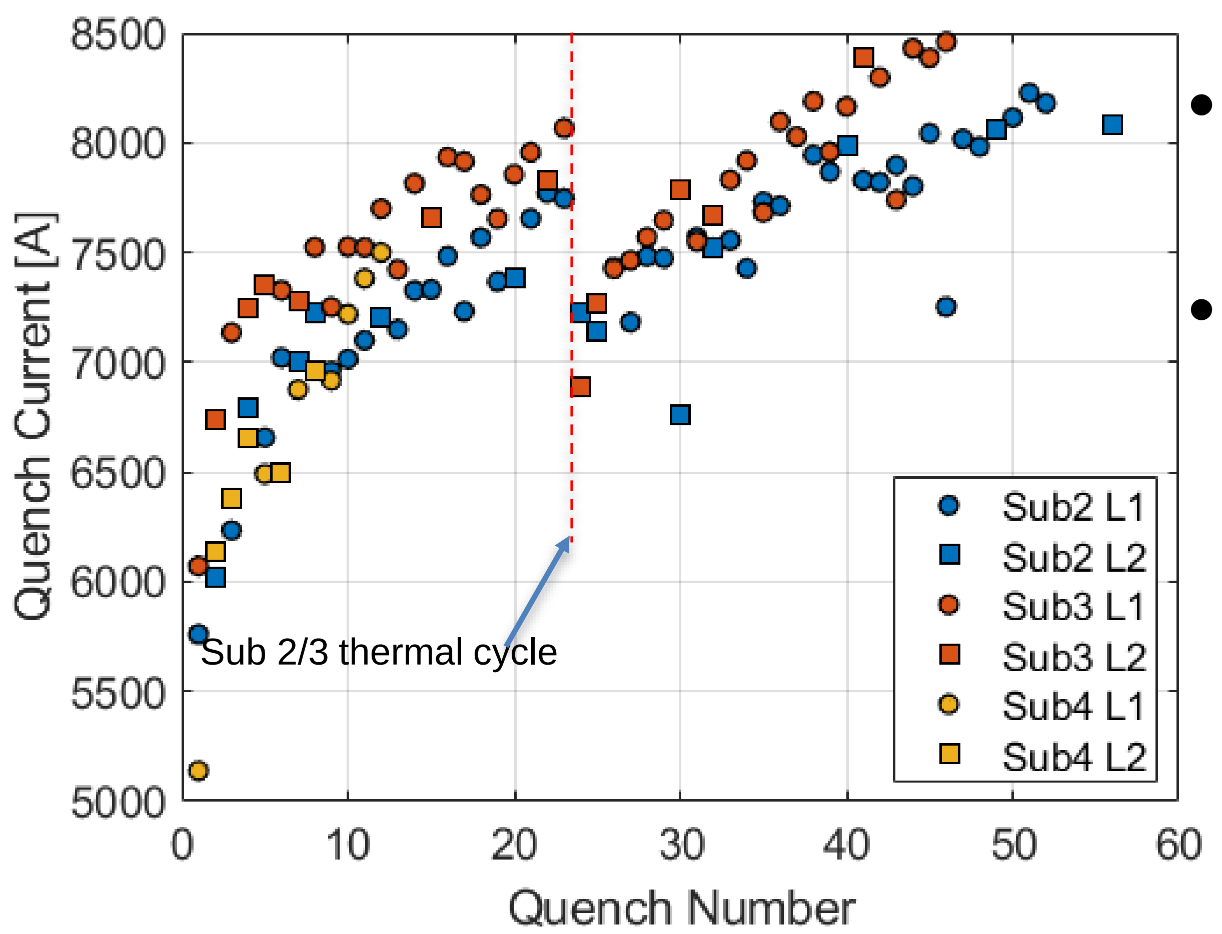
- spontaneous quenches => lack of reliable precursor, not controllable
- Training => potential for improved performance after quenching

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

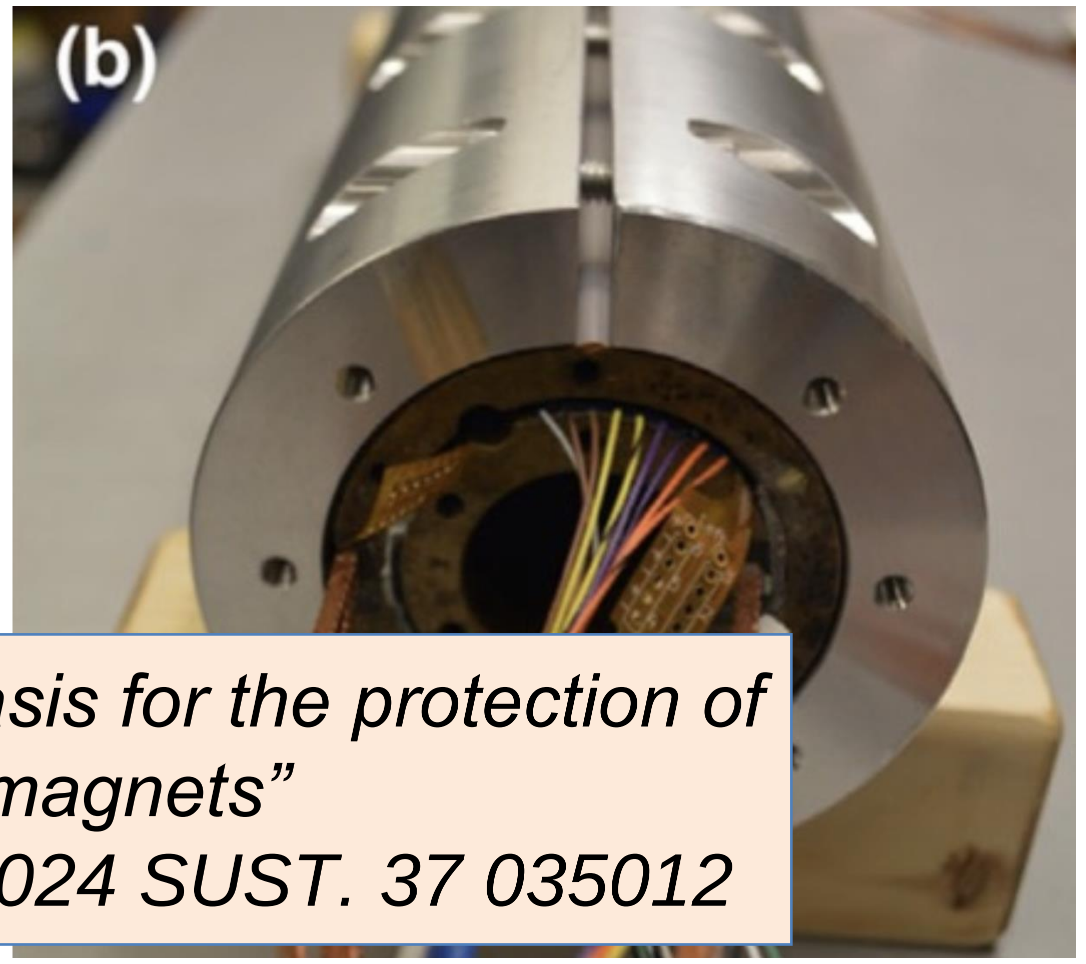
Design to eliminate run-away quenching !?

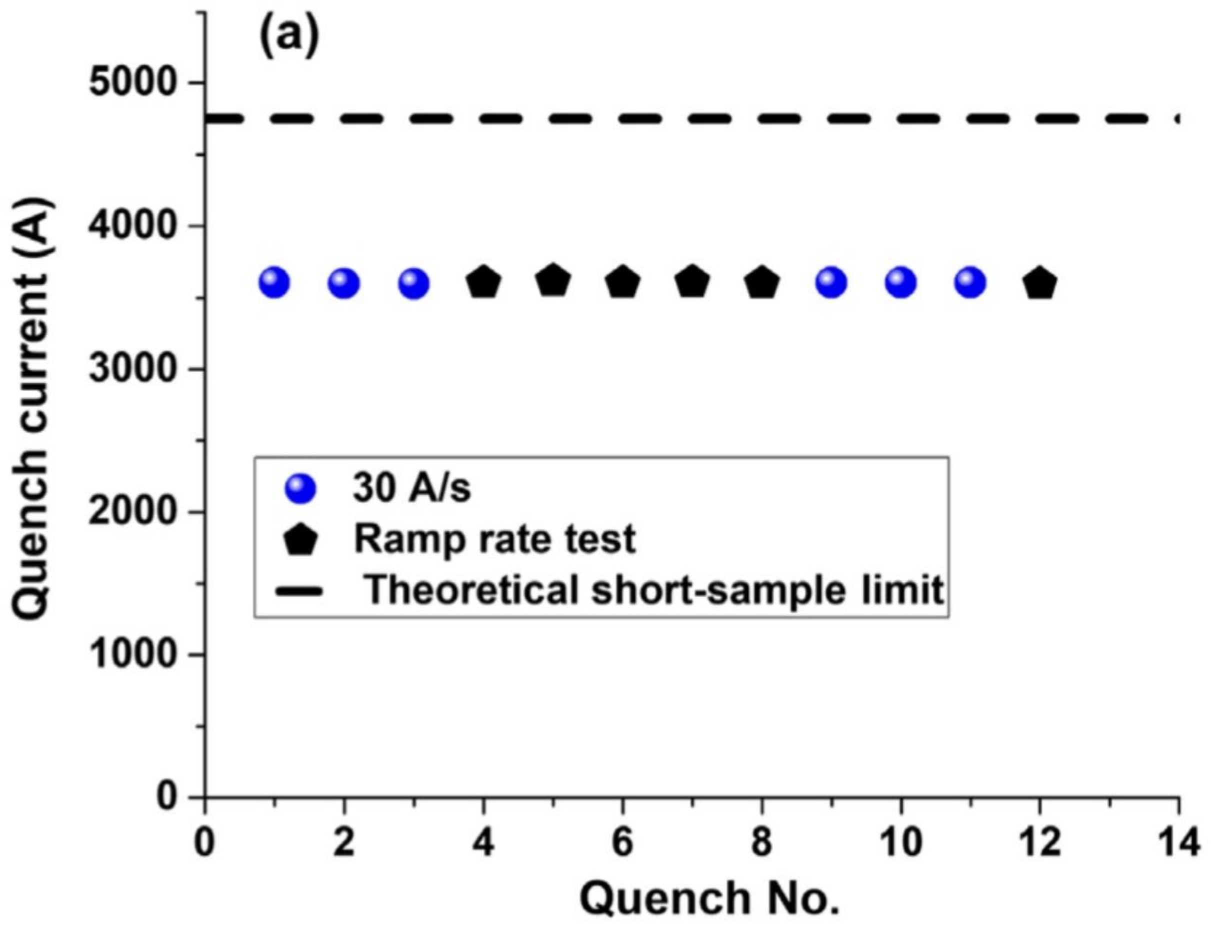
"Typical" Nb_3Sn CCT magnet training



- "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)





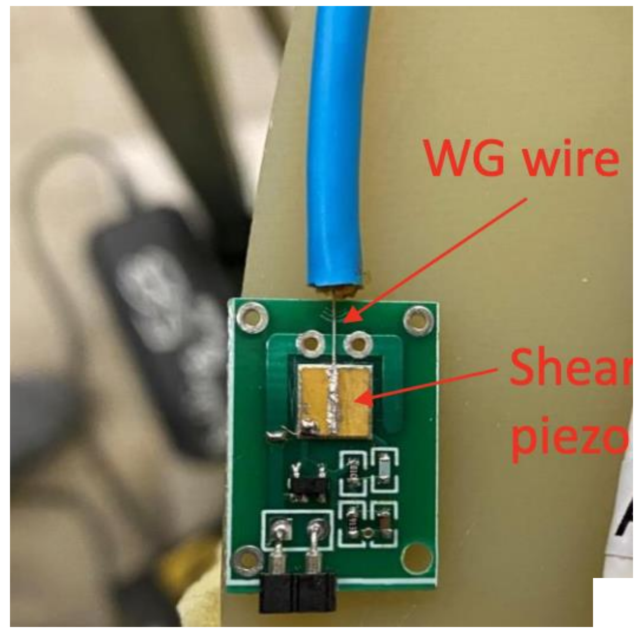
"Thermal runaway criterion as a basis for the protection of high-temperature superconductor magnets"
M Marchevsky and S Prestemon 2024 SUST. 37 035012

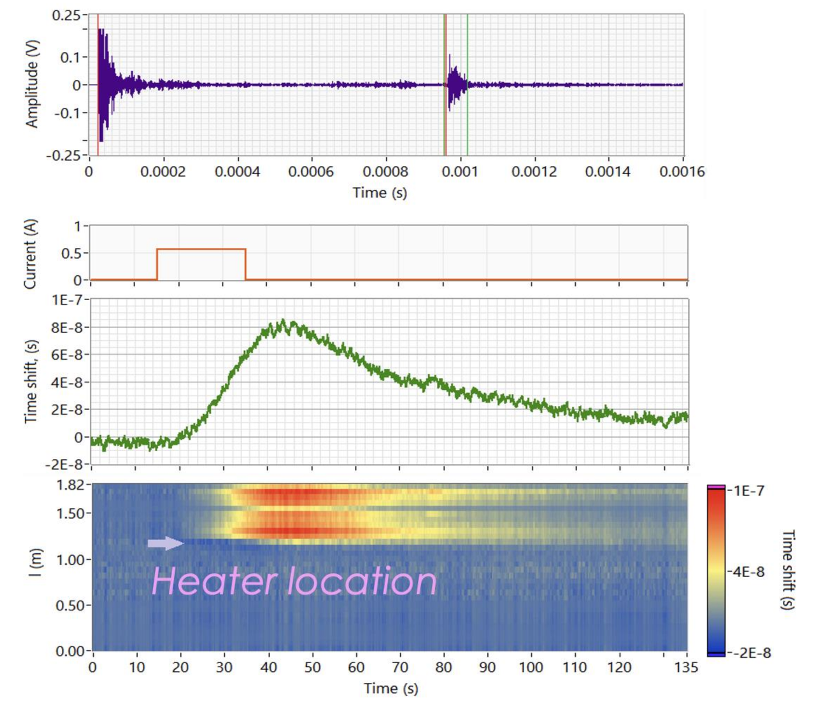
New paradigms – Active/dynamic local powering of magnets for safety, field quality, etc?

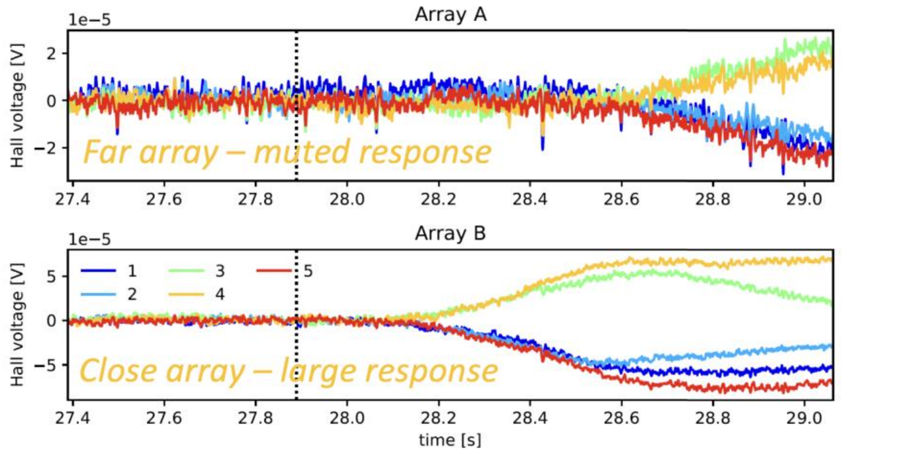
- High bandwidth diagnostics coupled to in-situ FPGA data analysis
- Multiple “physics-independent” diagnostics - analyzed & cross correlated
- AI/ML utilized to weed out irrelevant data, identify critical events/behavior

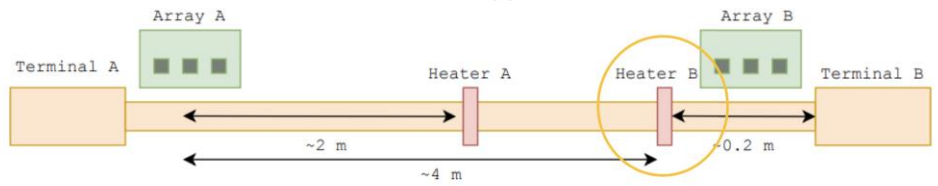
- Most data acquisition, analysis, decision-making ”below the header”
  - o Only digital data sent “out”, e.g. via redundant fiberoptics (non-conductive)
- Stored diagnostics data monitored/analyzed for system integrity checks
  - o Modeling coupled to diagnostics => digital twin corelates cause and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

- ***Key to enable HTS “Quench-free” paradigm***



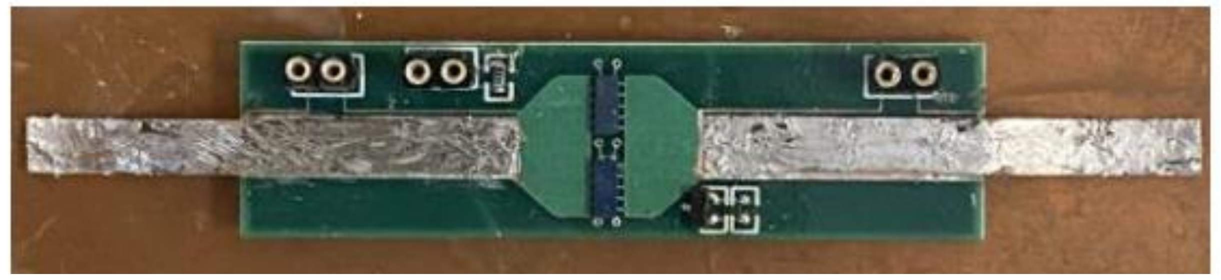


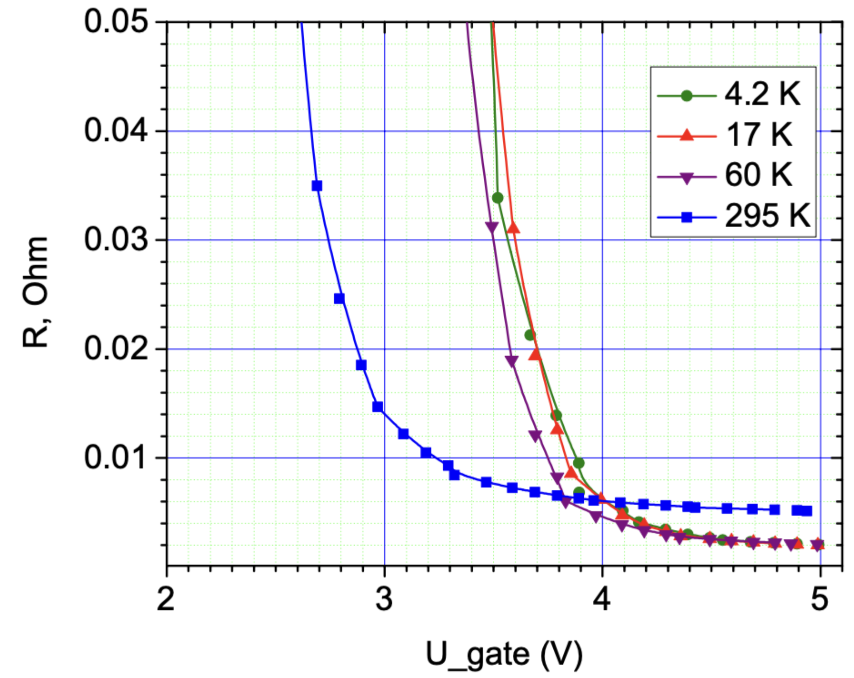




•Cryo-power electronics (MOSFETS, IGBTs, etc) developed to actively control/route power => become integral to magnet protection

Marchevsky and Prestemon, “Quench protection for high-temperature superconductor cables using active control of current distribution”, submitted to SUST





New paradigms: Liquid hydrogen cooled collider?

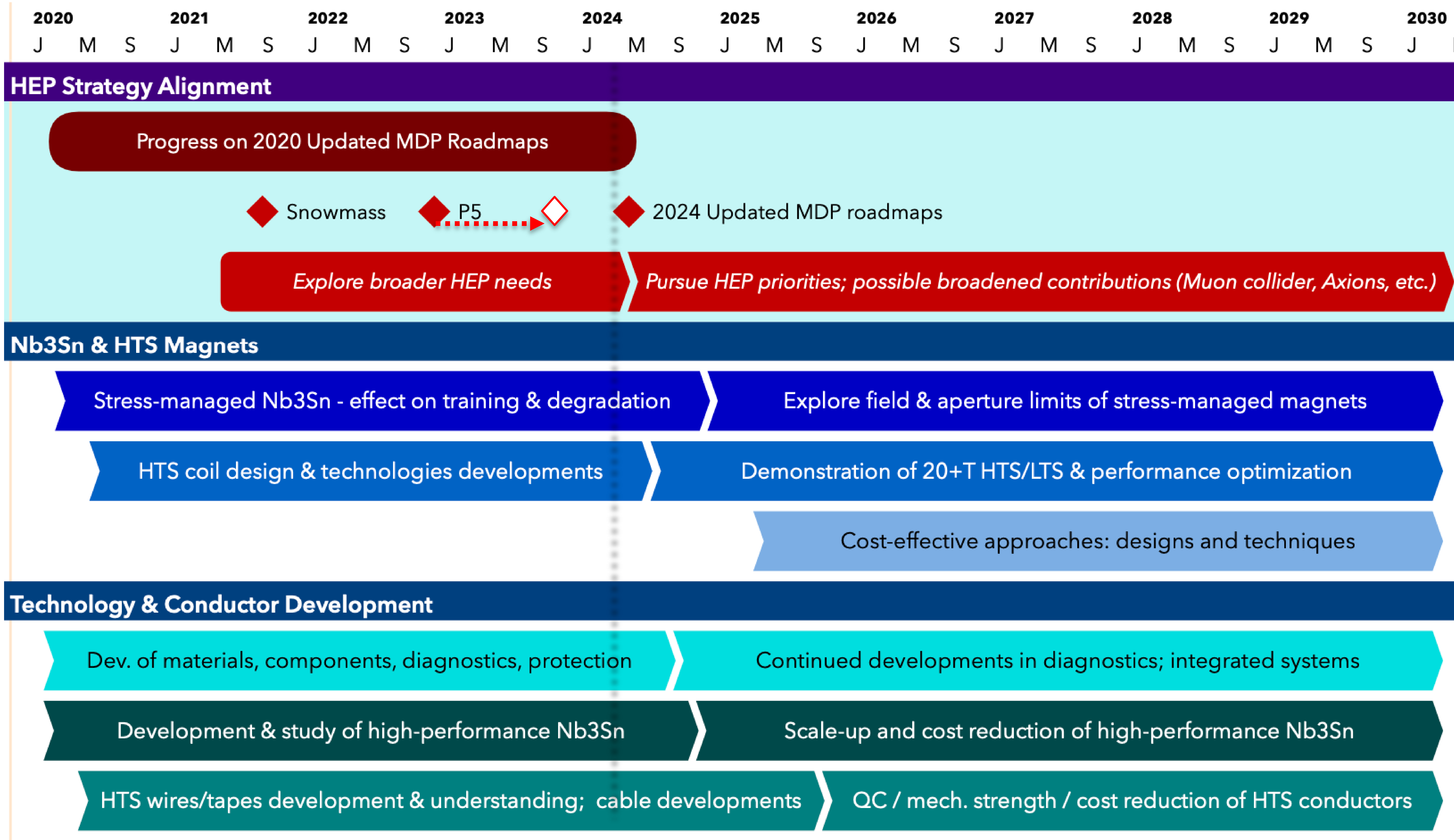
- **Hydrogen has critical advantages:**
  - Plentiful => not supply limited
  - Carnot + liquefaction efficiency => dramatic improvement in ”wall-plug efficiency”
  - Strong investments from other societal uses => cost, storage/shipping evolving rapidly
- **But there are concerns/issues:**
  - Safety => 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

US MDP 2020 roadmaps – long range – time for an update!

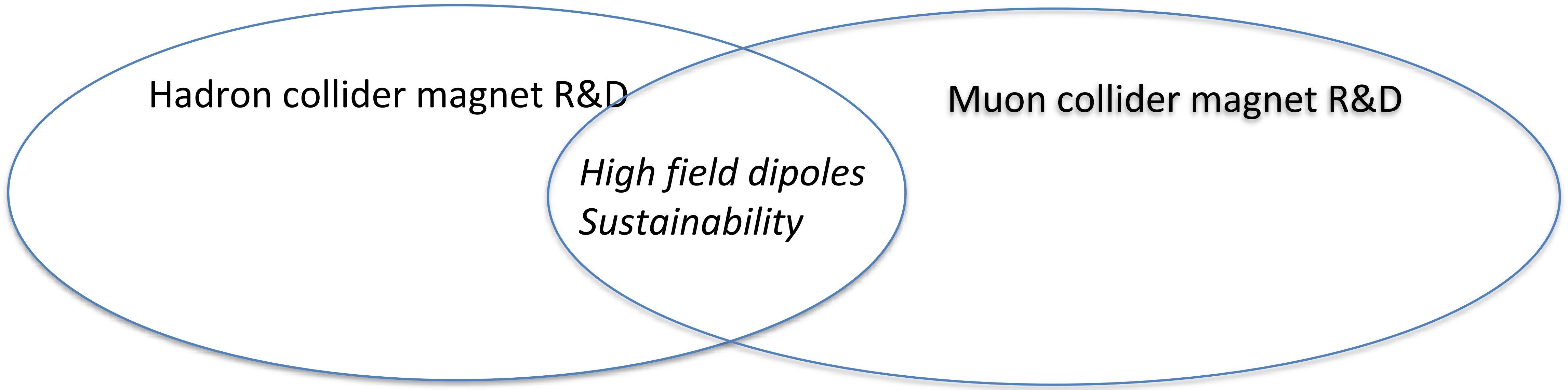
P5 guiding light:

- Clear "pull" from 10 pTeV collider science
  - most prominently Muon collider
- High-field remains a driving aspiration
  - Dictates hadron collider energy reach
  - Dictates muon collider luminosity



Following the 2023 P5 report, we are developing new aligned roadmaps that build on our progress while addressing the 10 pTeV challenge ahead

- **High-field Magnet R&D remains a central theme**
- **Stress-managed Nb_3Sn will become "workhorse" outserts to develop and test HTS in high field**
- **New / enhanced consideration of**
  - **Muon-collider relevant high field solenoid technology**
  - **Sustainability – cost of operation**



May	June	July	August	September	October	November
Data gathering: *P5*: - opportunities & priorties *Structure*: - what works well what can be improved		**Detailing structure** - identify Areas & priorities - identify milestones - timelines, resource needs		**Finalizing document & internal discussions**	**Review with HEP**	**Publish updated MDP Roadmap**

Summary

- MDP is performing research that is highly relevant to Hadron Colliders
  - The process of alignment of the program with the P5 will strengthen this

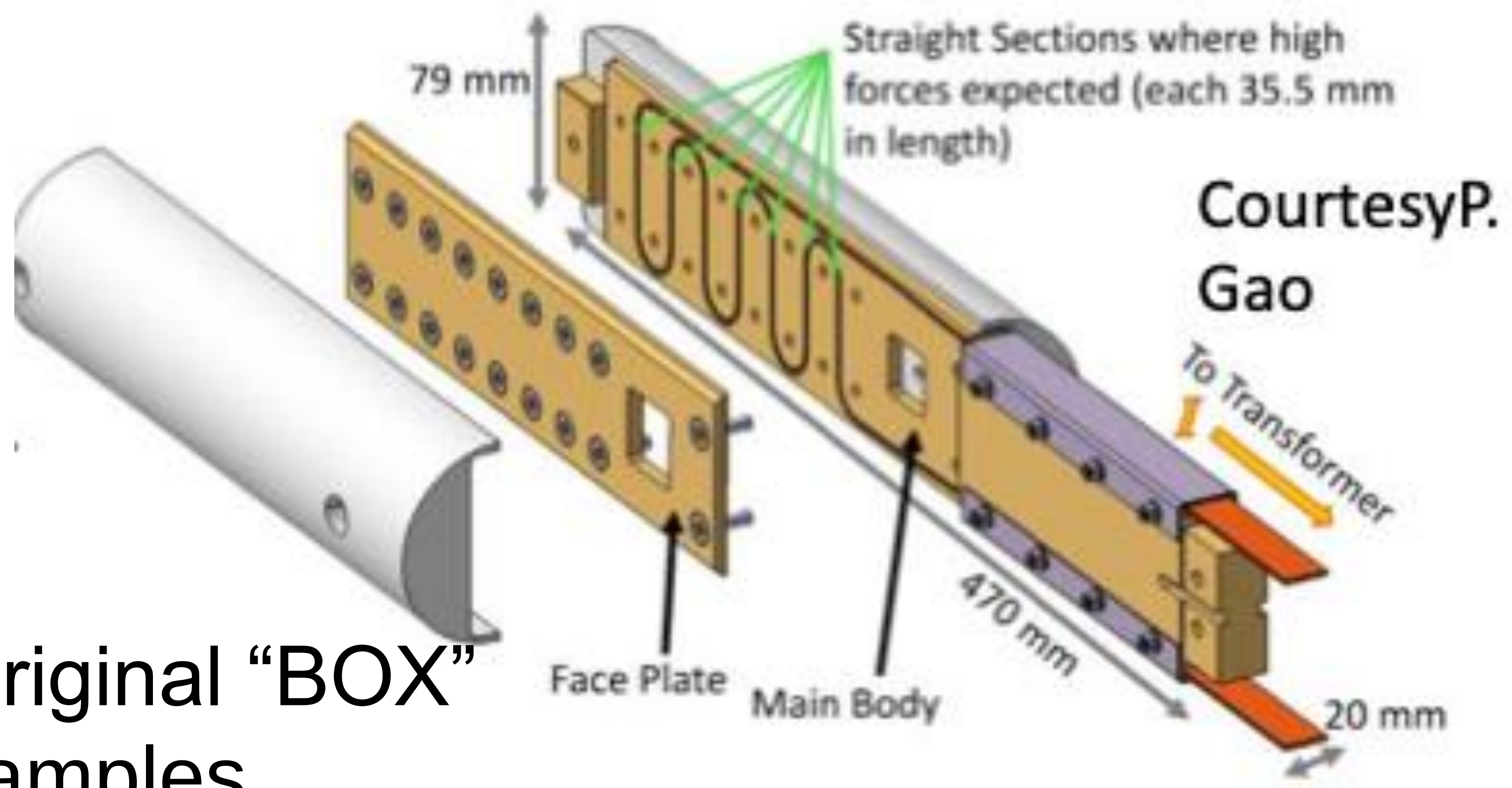
- R&D programs need further enhancement to meet the P5 challenge
  - ***More conductor in the pipeline is needed, and faster cycles of magnet development and test!***

- Leveraging synergies with Fusion, high field NMR, etc. will be critical

- International collaboration is vital to advance our research rapidly

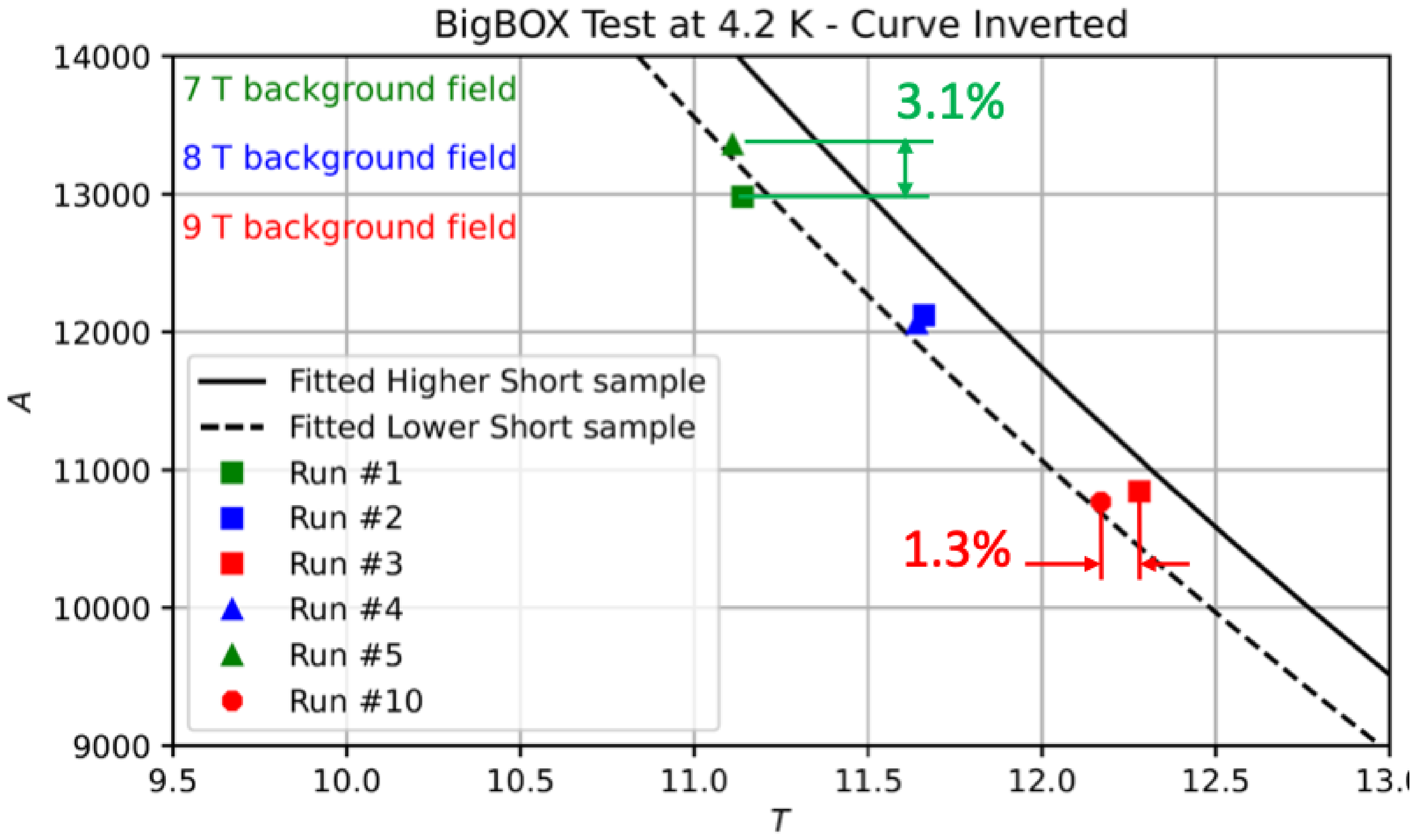
International collaboration supports MDP developments

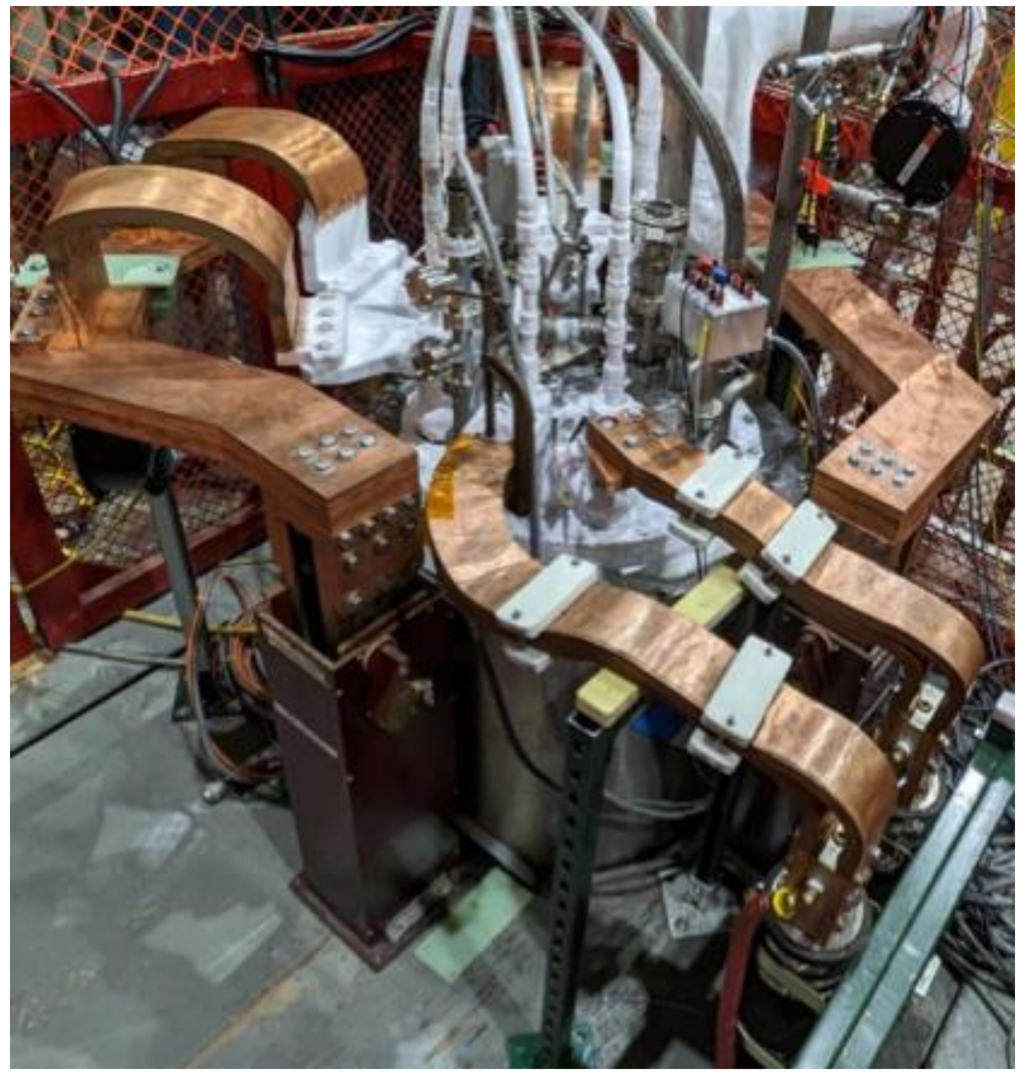
- PSI "BigBox" experiment designed to probe stress-management
  - **Leverages BNL 10T common-coil test facility**
  - Single-turn wax-impregnated sample (PSI & U. Twente)
  - Provides "knob" to vary transverse force on cable

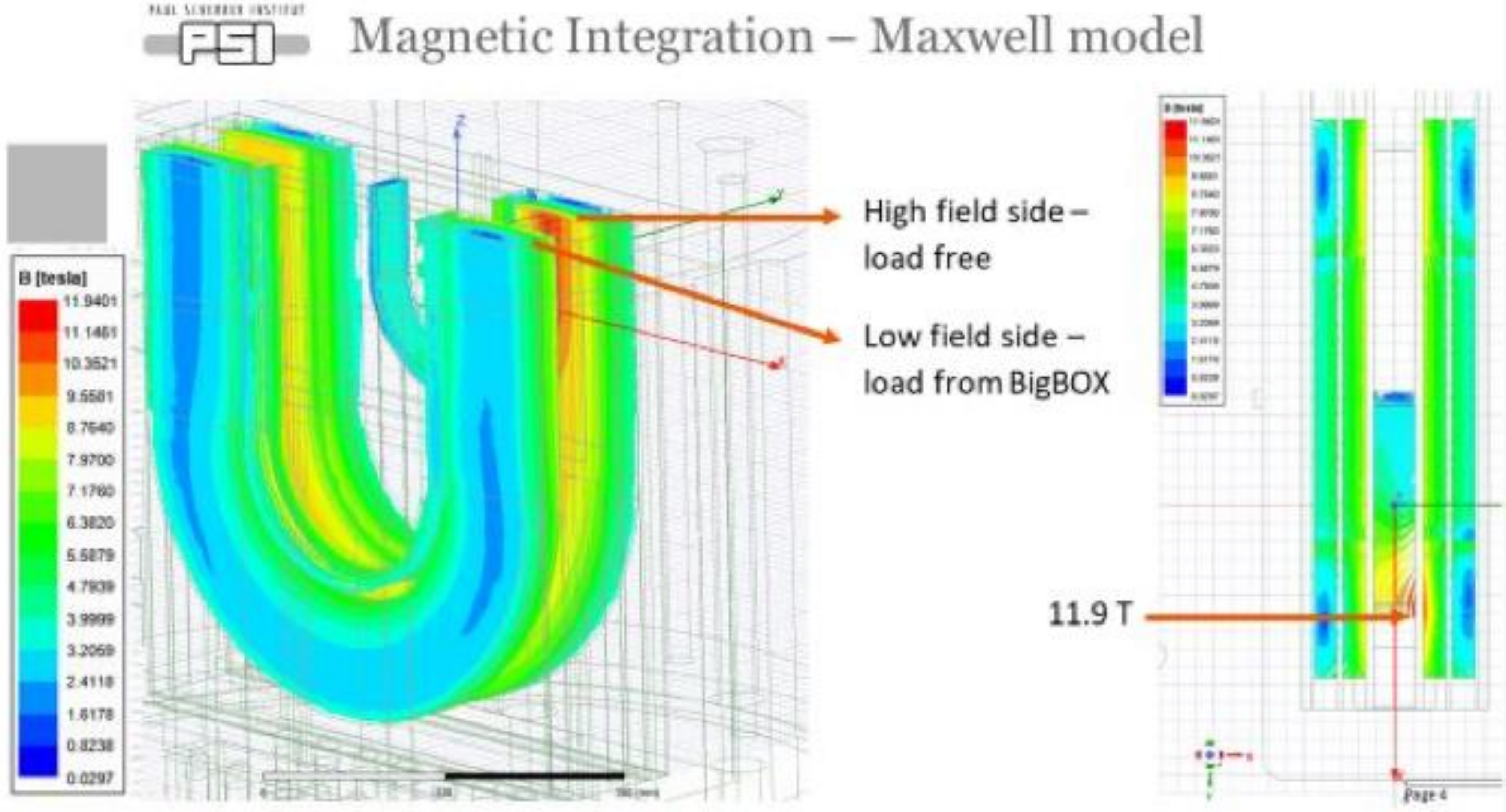


CourtesyP. Gao

Original "BOX" samples



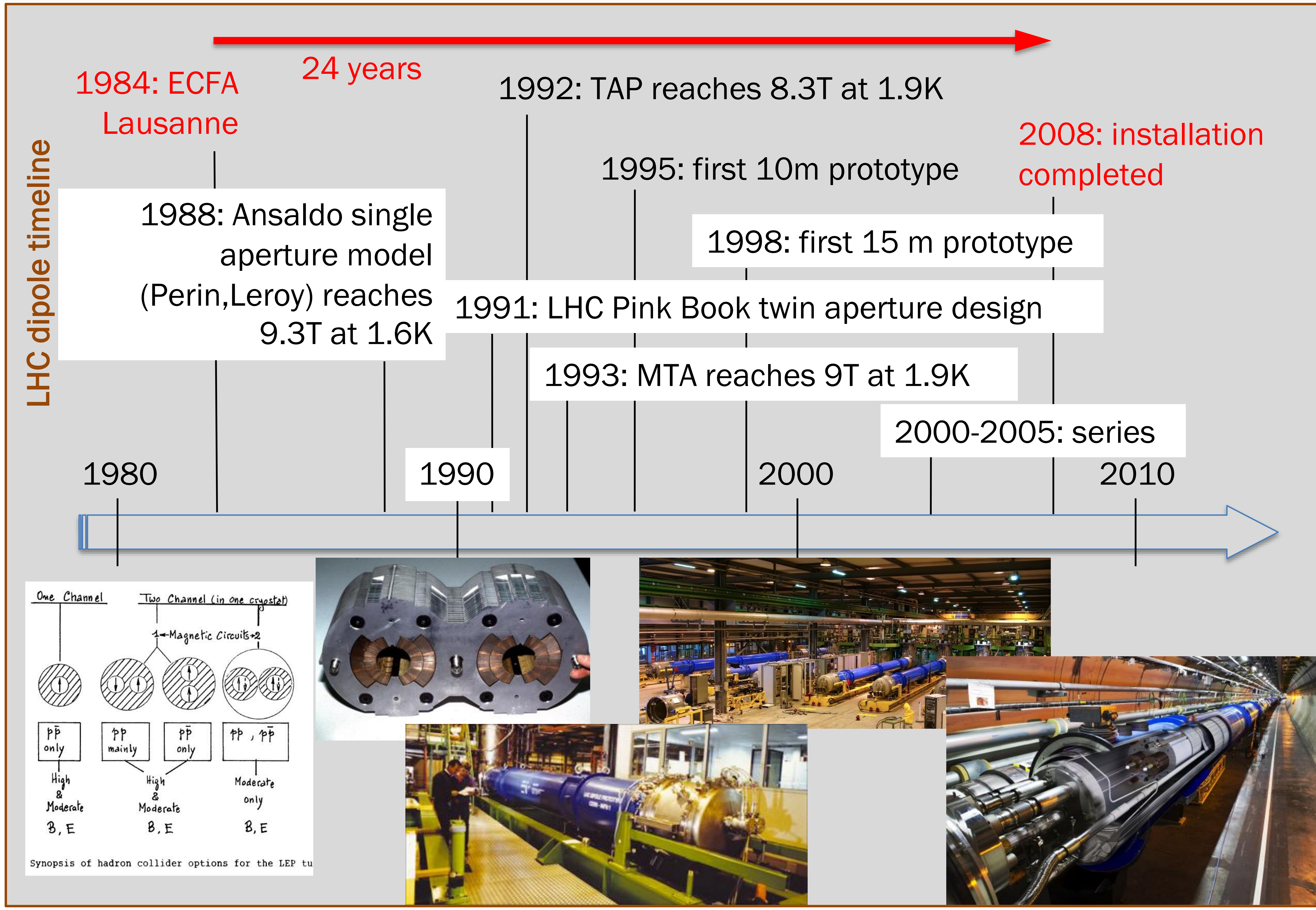




A look at the timeline from the LHC itself

- **The path to next generation magnet technology for a collider is complex:**
  - Need R&D to probe concepts, develop and understand potential
  - Need robust industrial suppliers of conductor
  - Need to ready a given technology for a project
  - Need to develop industrial partners for magnet production
  - And finally need to produce reliable, cost-effective magnets for the next collider

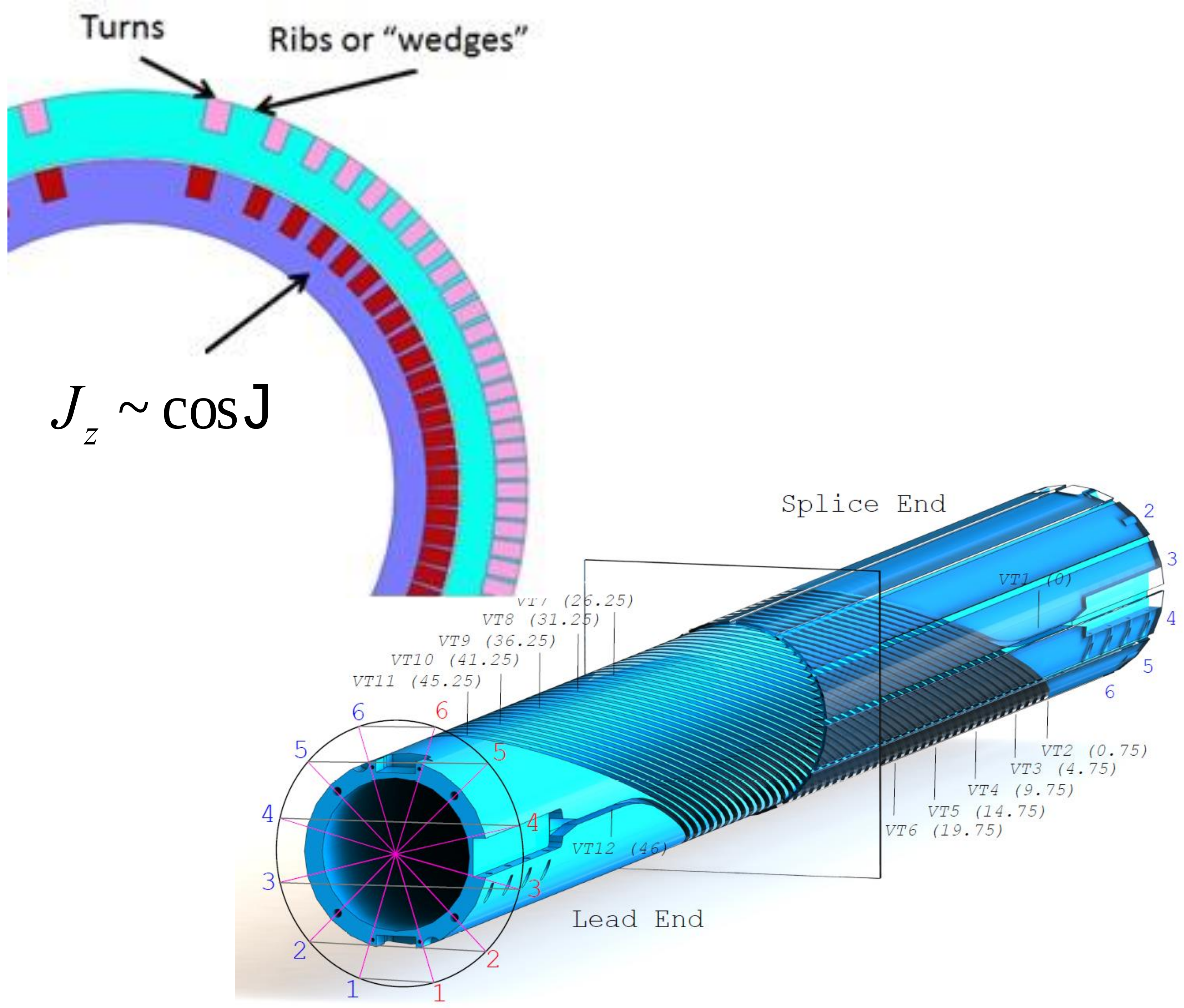
Requires a strong ecosystem of laboratory, University, and industrial partners

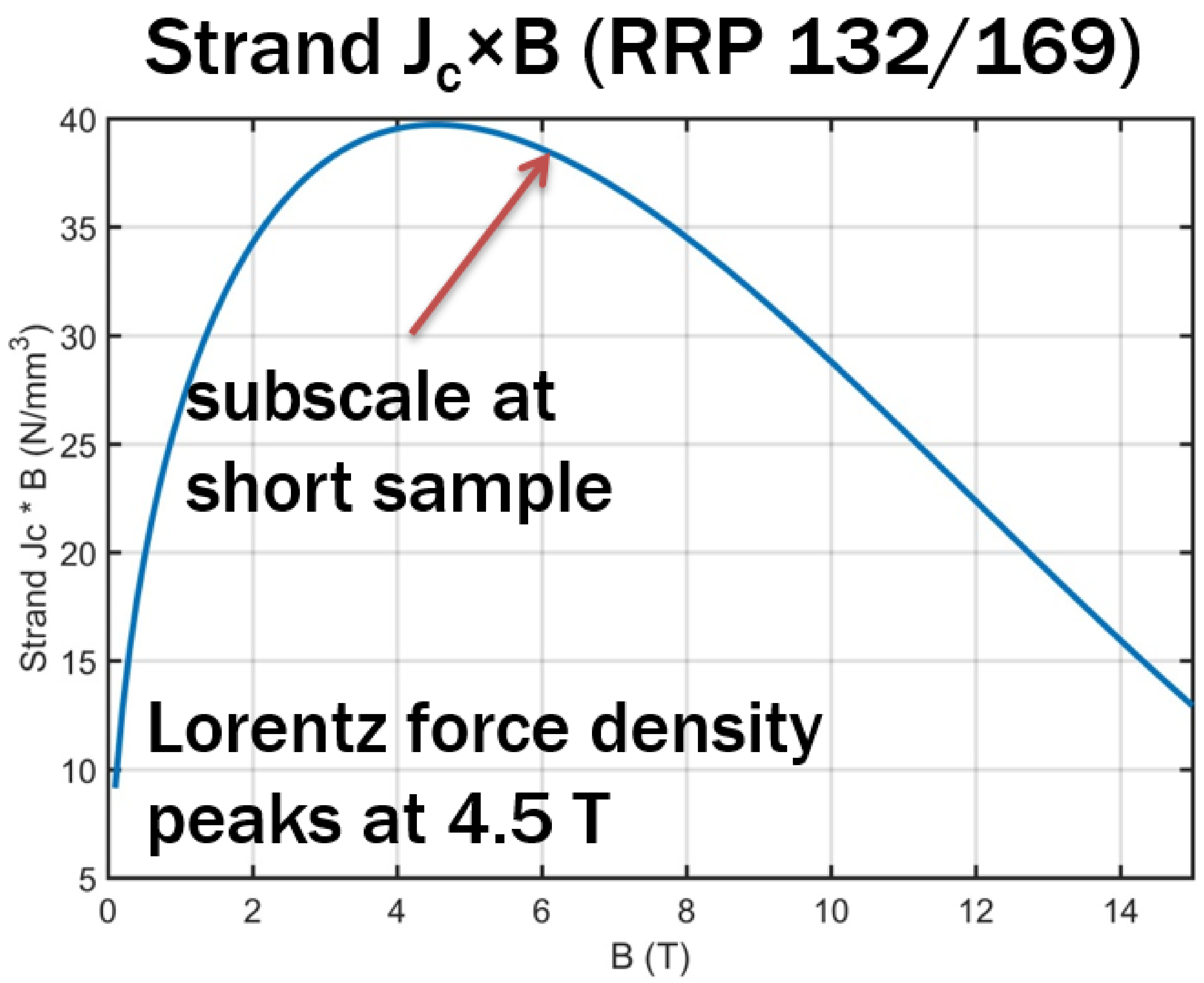


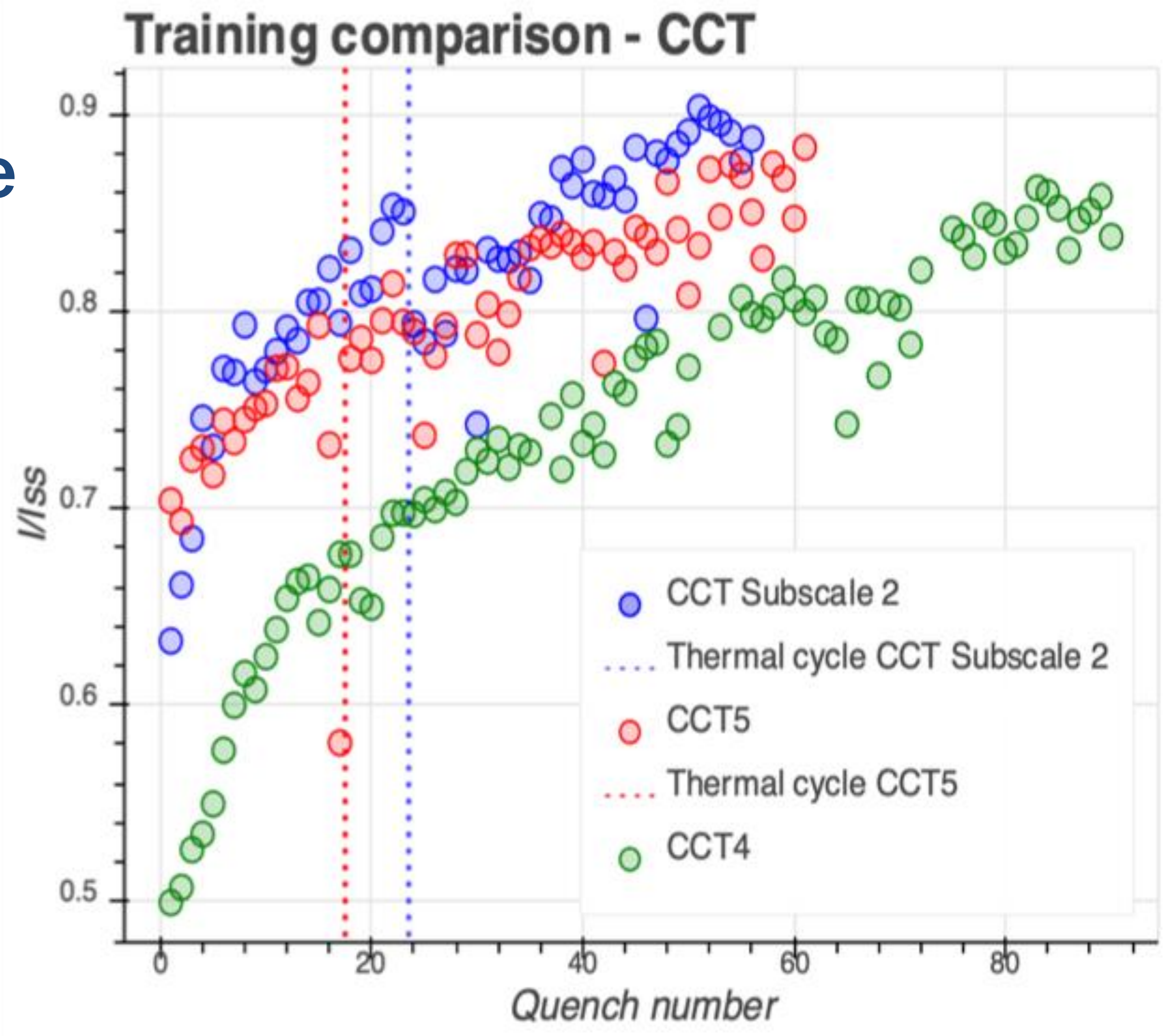
Courtesy Luca Bottura

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 6

U.S. MAGNET DEVELOPMENT PROGRAM

The US MDP strives to be open and collaborative

- We are a mature and vibrant integrated multi-lab research program focused on developing accelerator magnet technology for the next energy frontier collider
- This is an international endeavor, and we are eager to collaborate and join forces to rapidly advance the field
- High field accelerator magnets are essential for the next collider – the onus is on us to deliver!

We strive to…

- provide a clear vision for magnet development & conductor properties/performance we would like to see
- be open with our results and progress so others can benefit from our advances
- identify and benefit from the achievements and progress of others
- be good collaborators – we recognize the strengths and enthusiasm residing in the broader community!