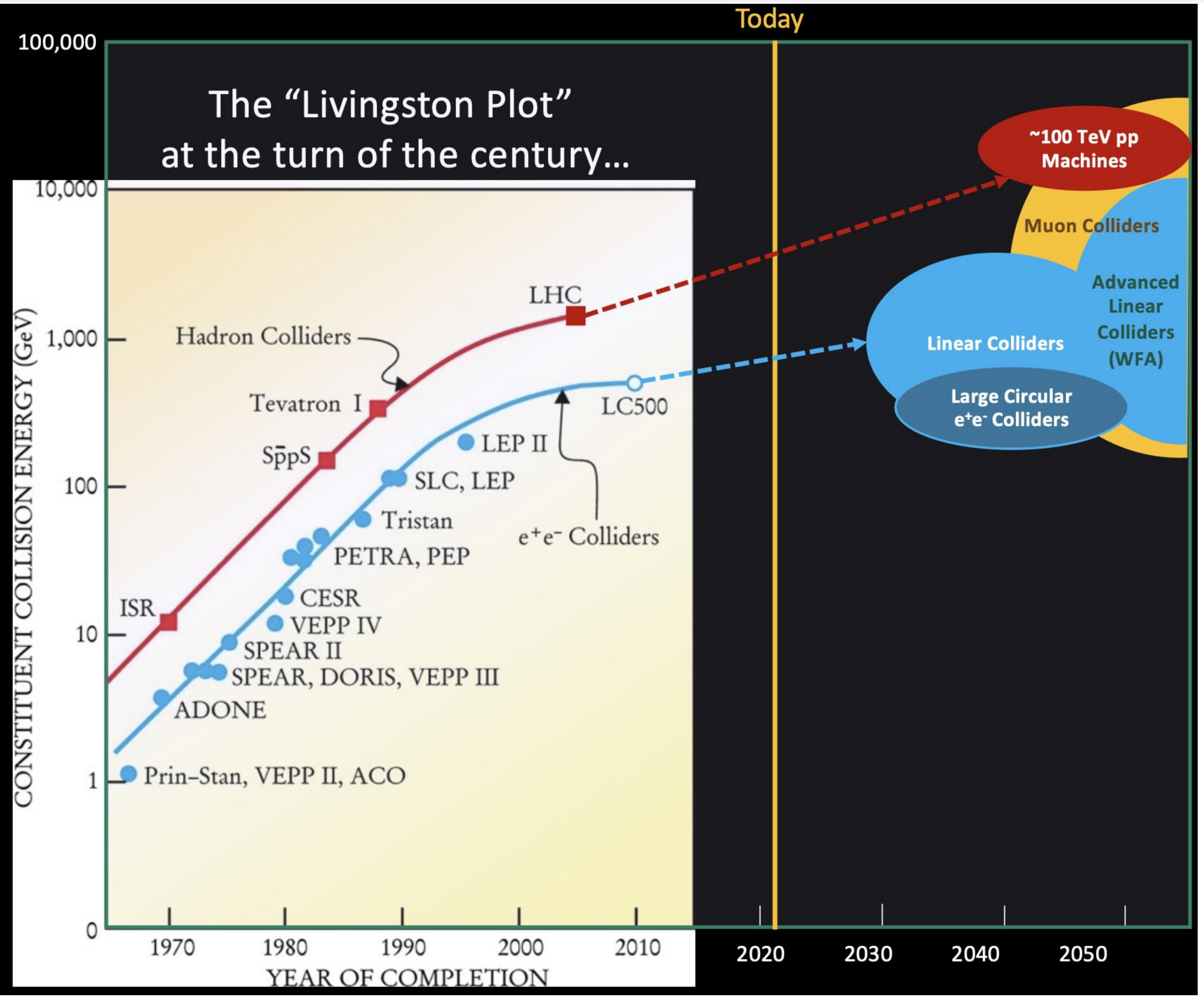
U.S. MAGNET DEVELOPMENT PROGRAM

The US Magnet Development Program

Soren Prestemon
US Magnet Development Program
Lawrence Berkeley National Laboratory

Magnet technology drives the cost and reach of a future collider



M. Palmer, MT21

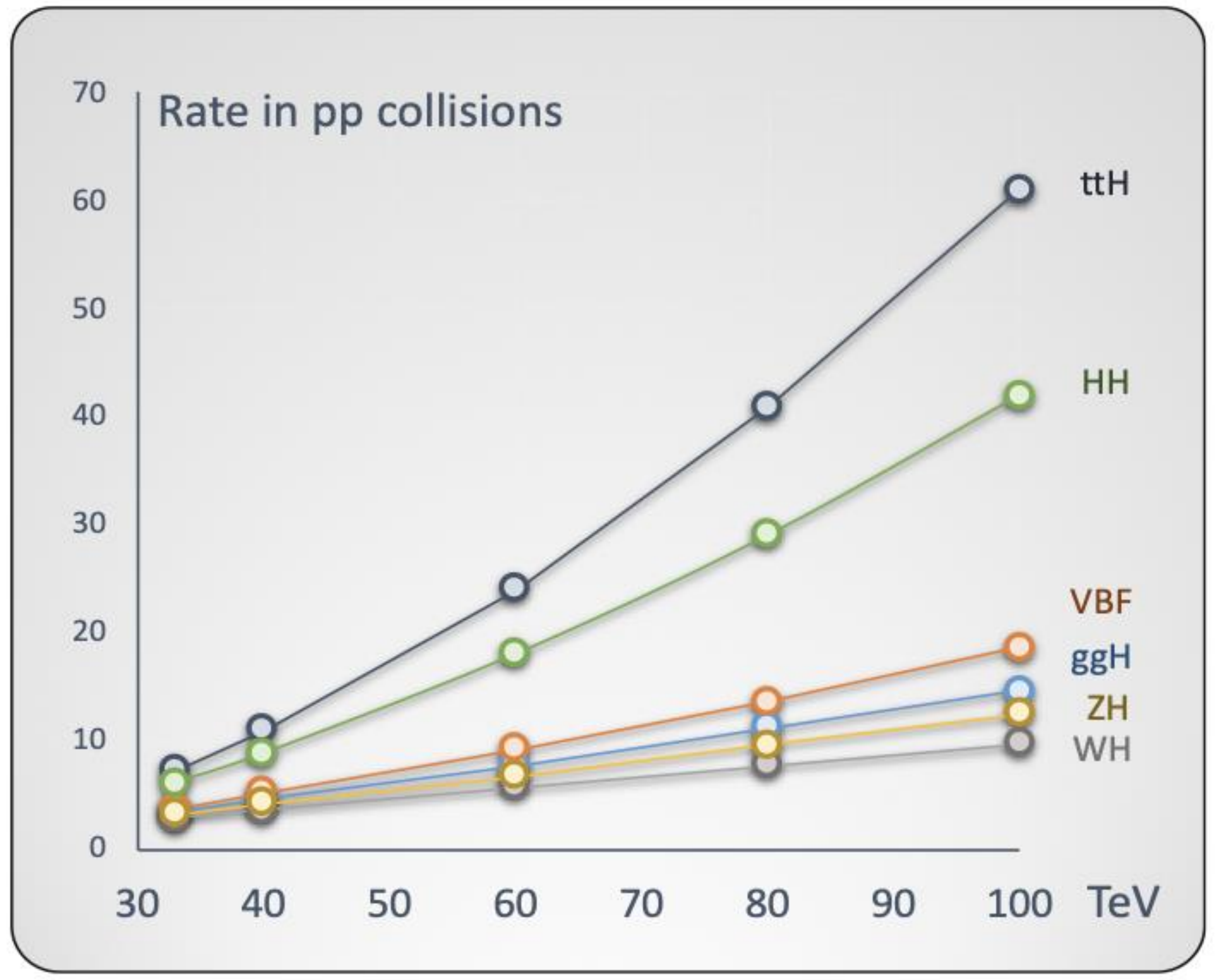


Figure 2: Higgs production cross sections versus collision energies normalized to the 14 TeV rates.

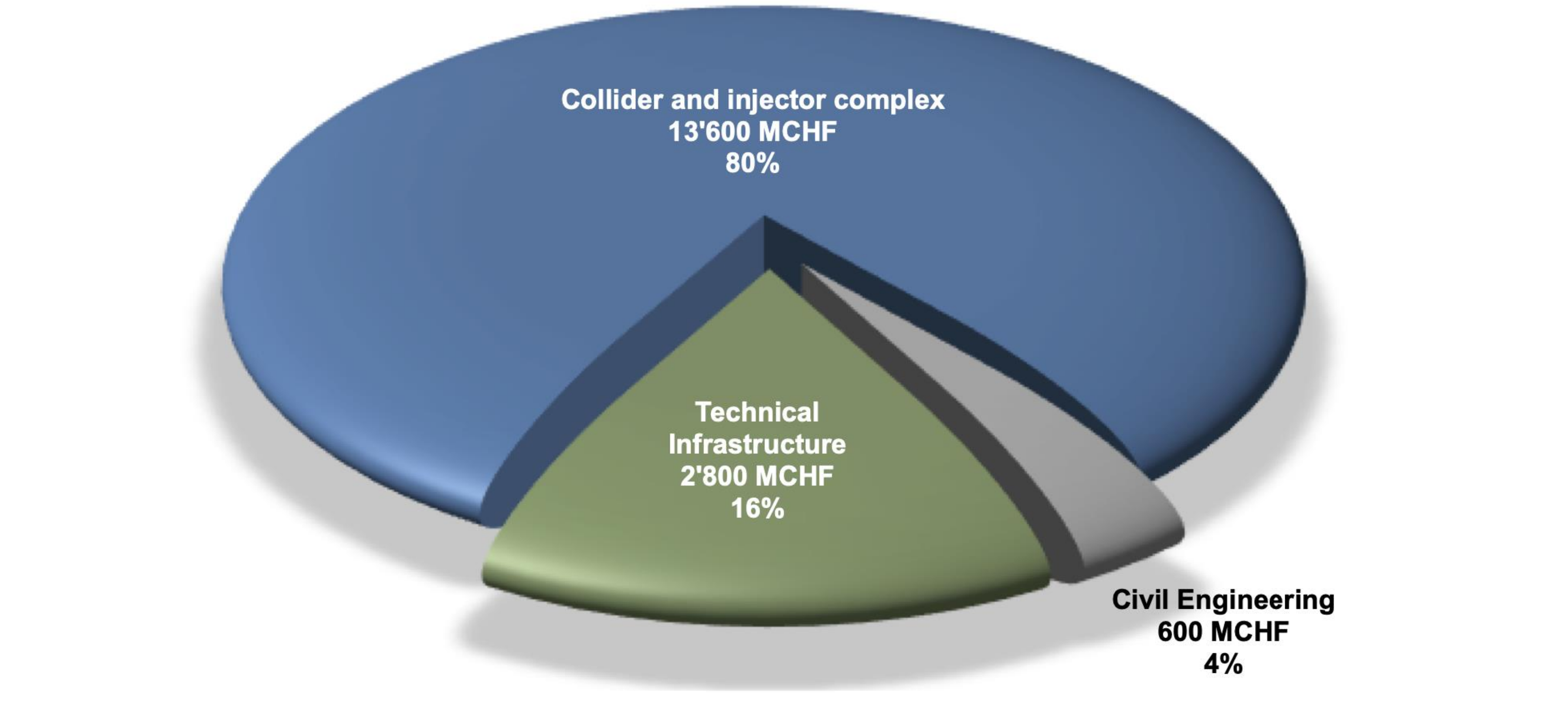


Figure 7: FCC-hh capital cost per project domain as a combined project, if FCC-hh is built after FCC-ee.

Note: The magnets are estimated to be ~70% of the Collider & Injector complex cost

Source: Future Circular Collider - European Strategy Update Documents, 2019, CERN-ACC-2019-0005

Physics reach is driven by magnet technology

Dominant cost drivers for energy frontier colliders: <u>Magnets</u> and tunnel

The US Magnet Development Program (MDP) Vision and Goals

- ***Maintain and strengthen US Leadership*** in high-field accelerator magnet technology for future colliders

- **Focus on the *four primary goals* identified in the the original MDP Plan**
  - **Explore the performance limits of Nb_3Sn accelerator magnets, with a focus on minimizing the required operating margin and significantly reducing or eliminating training**
  - **Develop and demonstrate an HTS accelerator magnet with a self-field of 5T or greater, compatible with operation in a hybrid HTS/LTS magnet for fields beyond 16T**
  - **Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction**
  - **Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets**

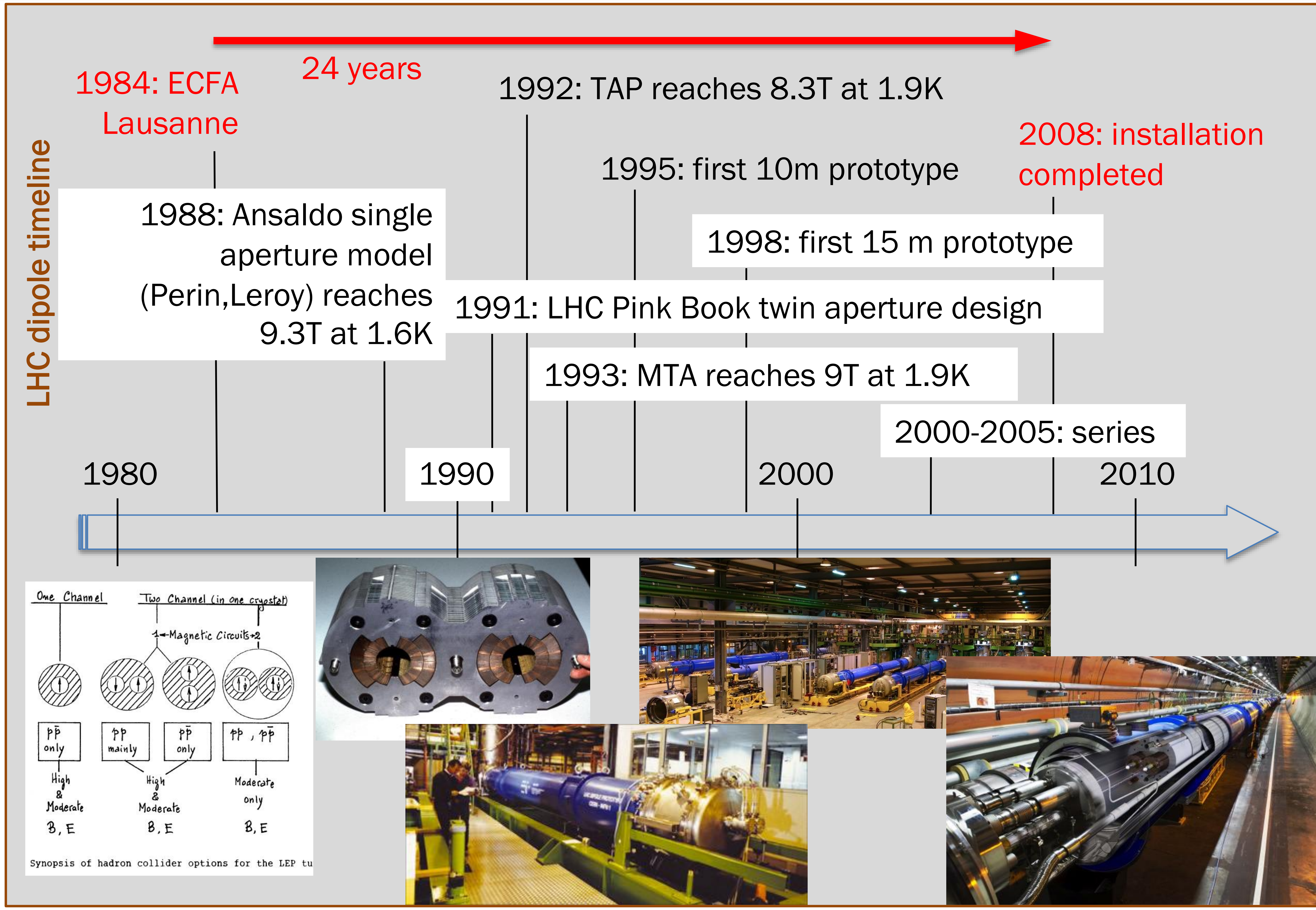
- **Further *develop and integrate the teams* across the partner laboratories and Universities for maximum value and effectiveness to the program**

- **Identify and *nurture cross-cutting / synergistic activities* with other programs to more rapidly advance progress towards our goals**

A look at the timeline from the LHC itself

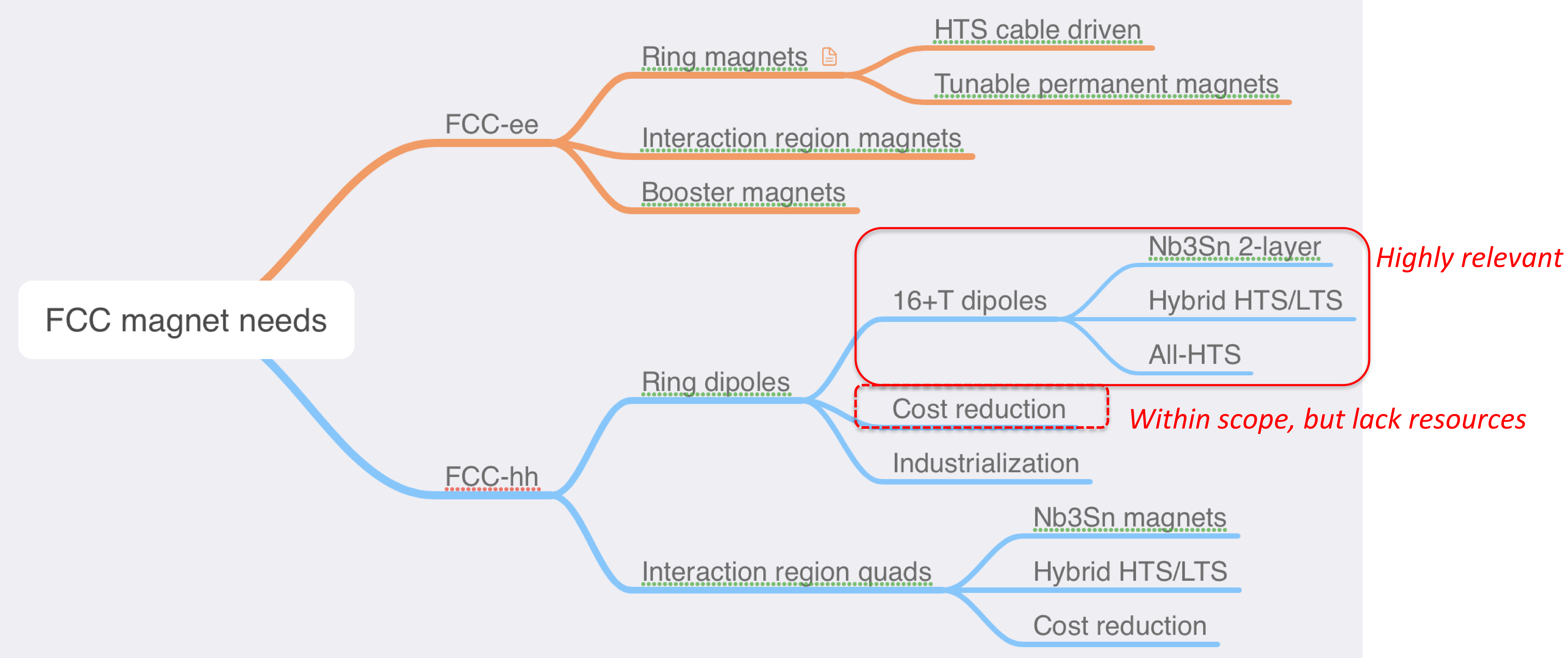
- **The path to next generation magnet technology for a collider is complex:**
  - Need R&D to probe concepts, develop and understand potential
  - Need robust industrial suppliers of conductor
  - Need to ready a given technology for a project
  - Need to develop industrial partners for magnet production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

MDP is highly relevant to the FCC-hh

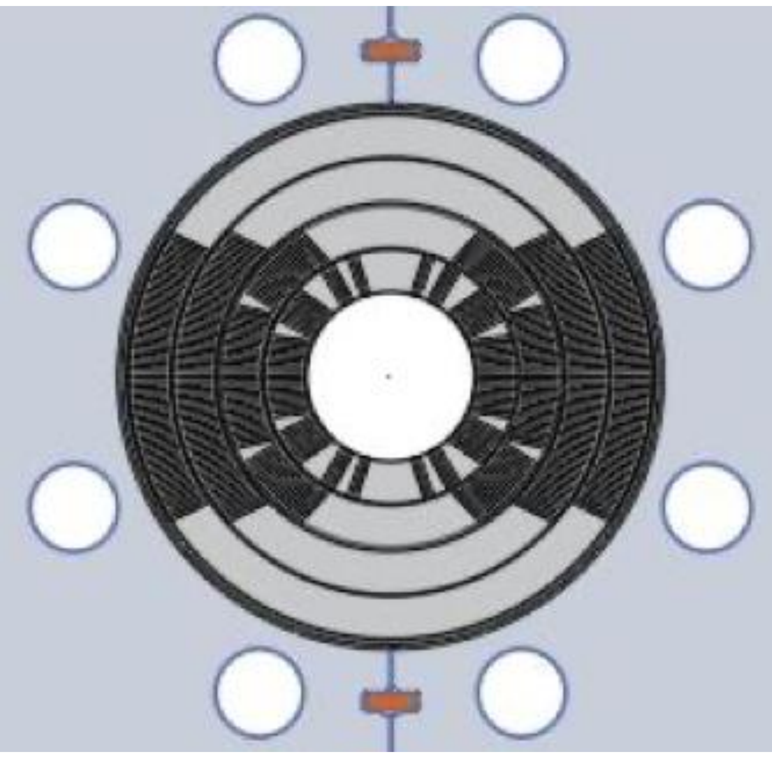


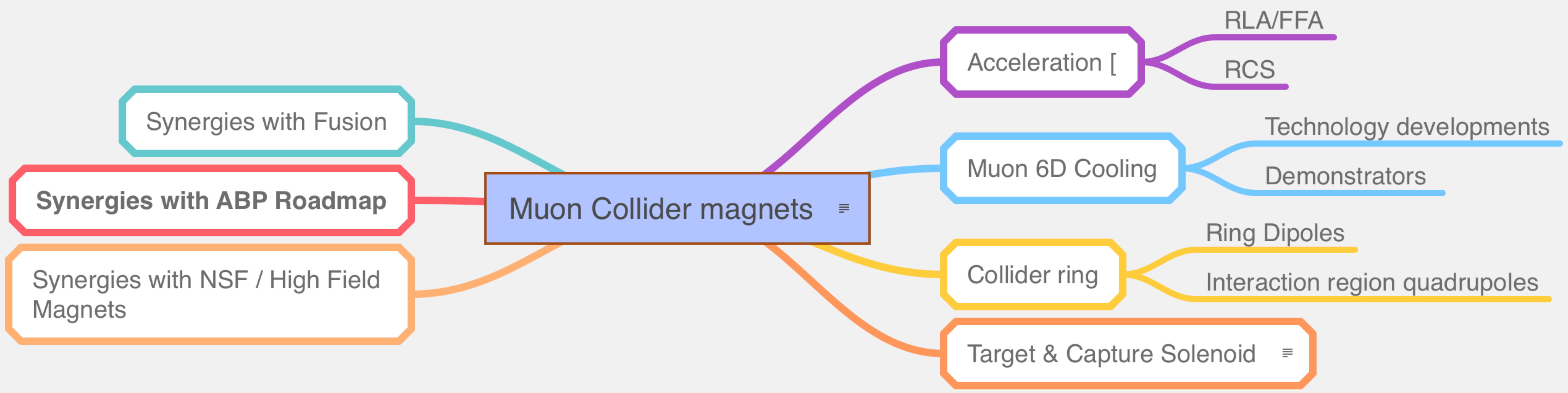
Both the FCC and the muon collider depend on advances in accelerator magnet technology

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

"Traditional" Cos-theta

- Midplane stress due to azimuthal force accumulation



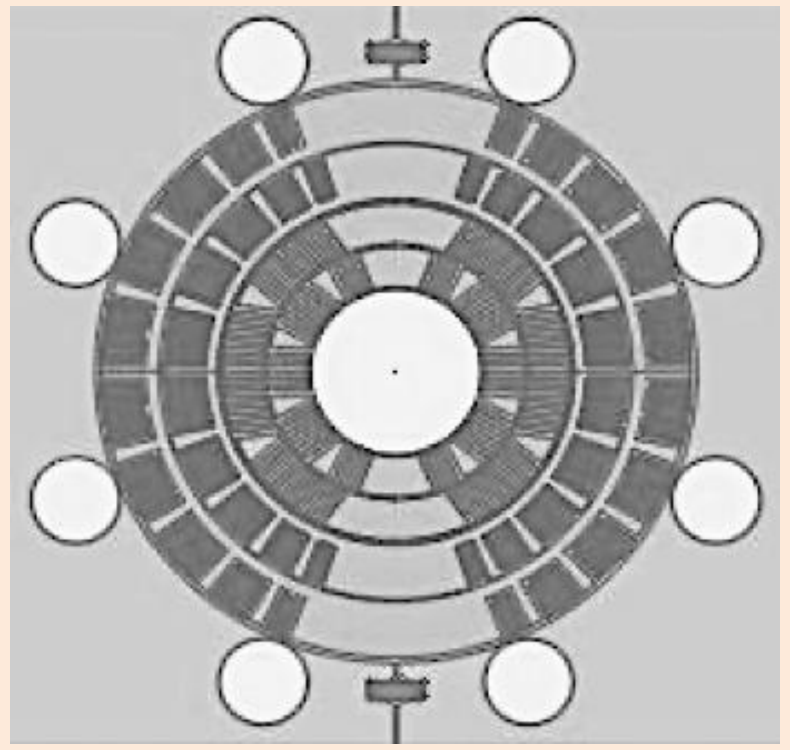


The magnet development scope described in the Snowmass whitepapers addresses FCC-hh and Muon collider needs
=> *Will require significant investments to advance to the level needed to build the next machine!*

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

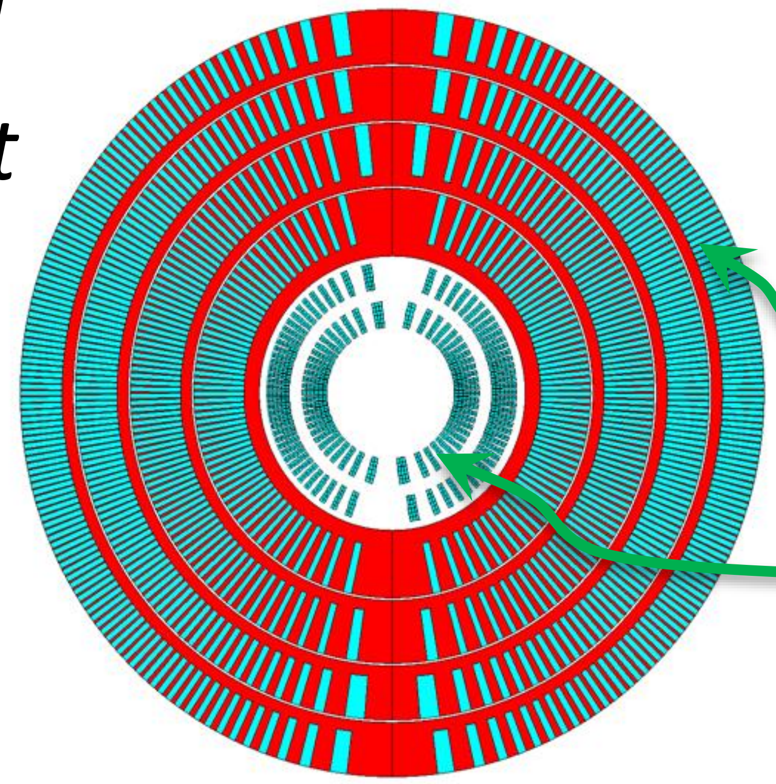
"Stress-managed" Cos-theta

- Groups of turns, azimuthal forces intercepted by support



MDP stress-managed hybrid magnets under development

- Critical for strain sensitive Nb_3Sn and HTS conductors



Serves as good candidate for muon collider ring dipole

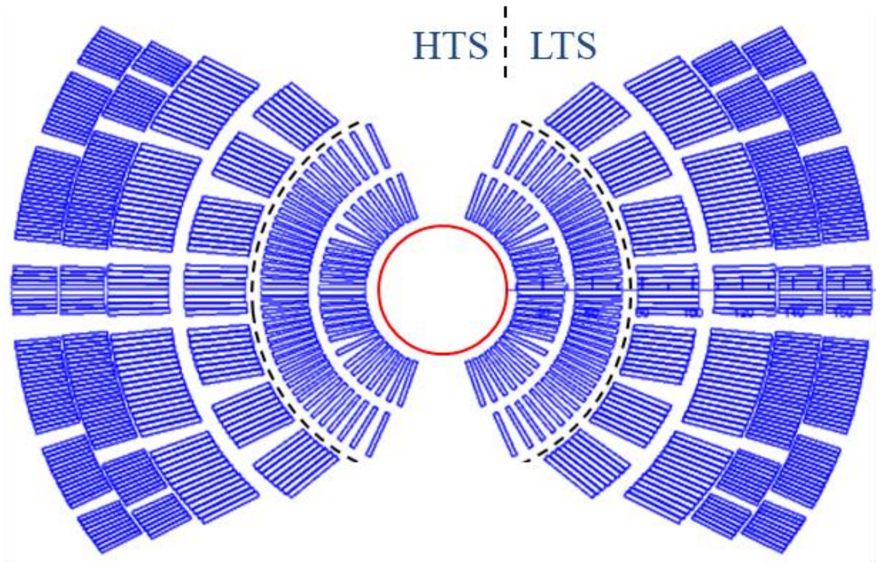
Nb_3Sn outsert

HTS insert

HTS vs LTS superconductors & magnets – some key distinctions

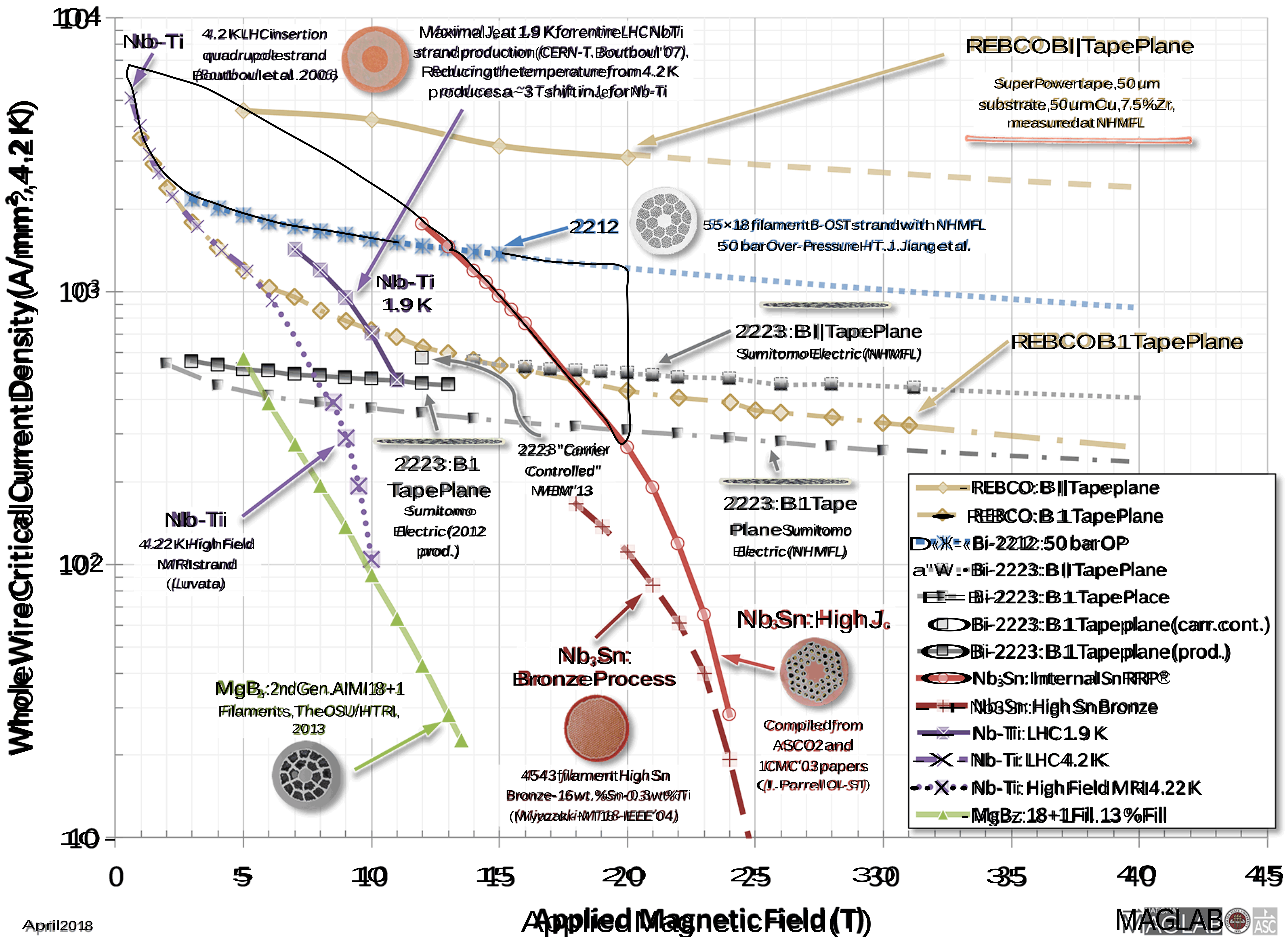
- HTS materials outperform LTS at higher field, but under-perform at low field

=> hybrid magnets are most efficient



MDP 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 Nb_3Sn and HTS accelerator magnets?
- What are the mechanical limits and possible stress management approaches for Nb_3Sn and 20 T LTS/HTS magnets?
- What are the limitations on means to safely protect Nb_3Sn and HTS magnets?

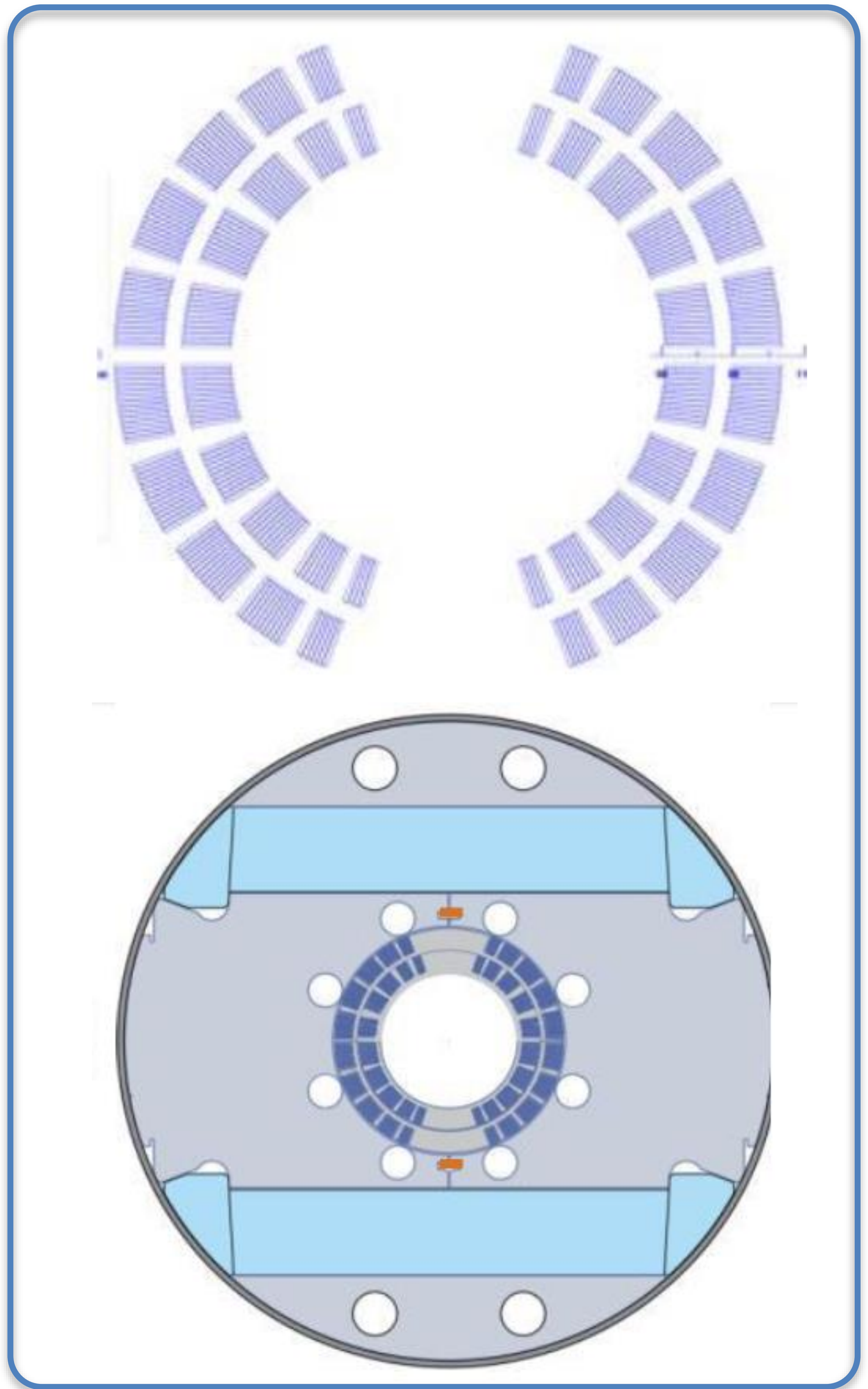


A priority now is to build the Nb_3Sn outserts

- **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

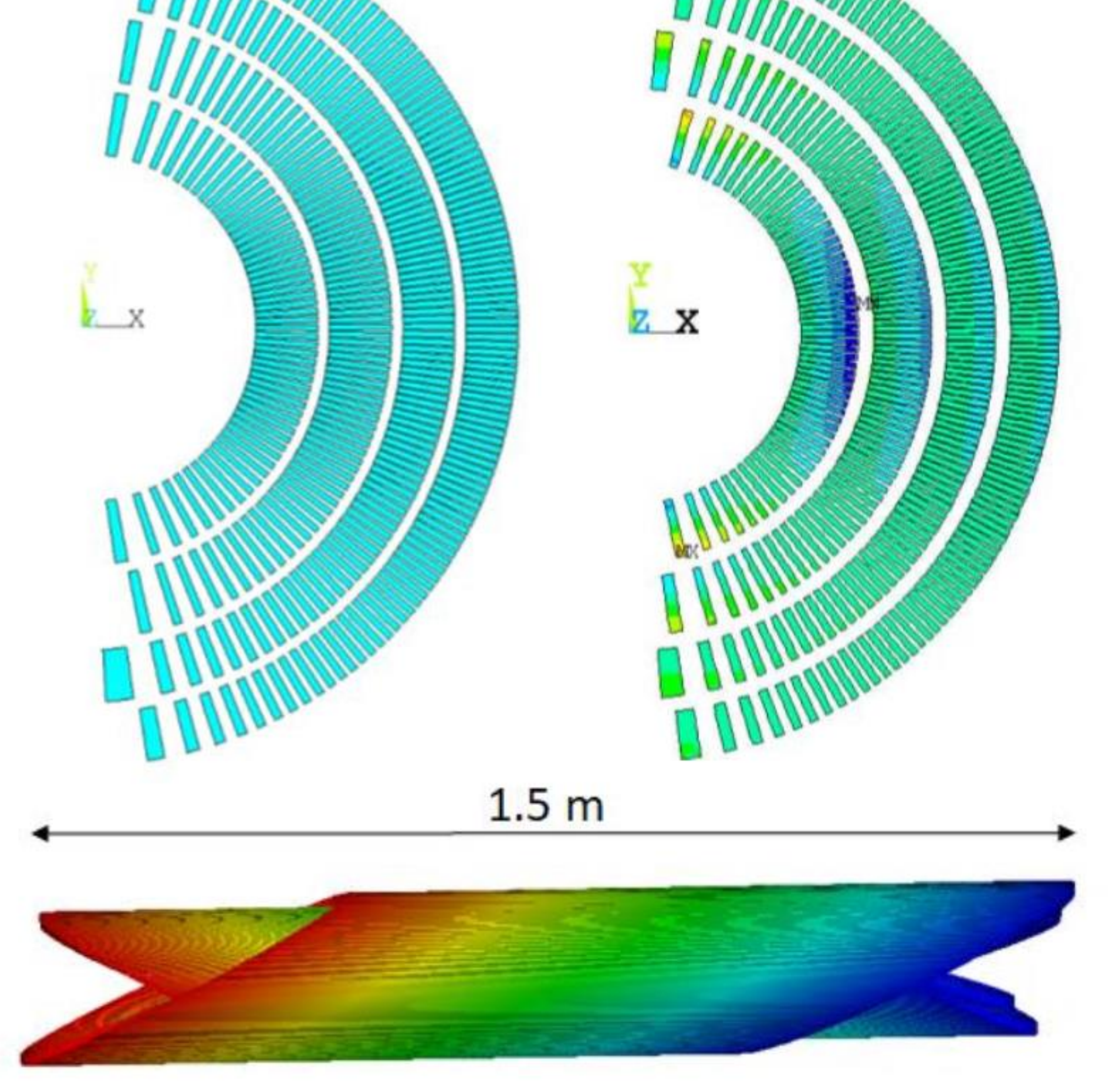
These are two variants on stress-management
- CCT is a "limiting case" of maximal SM
- SMCT is a more efficient design

SMCT



CCT

30+ % current margin at target fields of 12 T, 4.2 K and 13 T, 1.9 K



Design efforts now leading to hardware and first testing

FNAL mirror test of SMCT imminent

Practice winding of CCT6 underway

HTS superconducting magnets behave differently

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

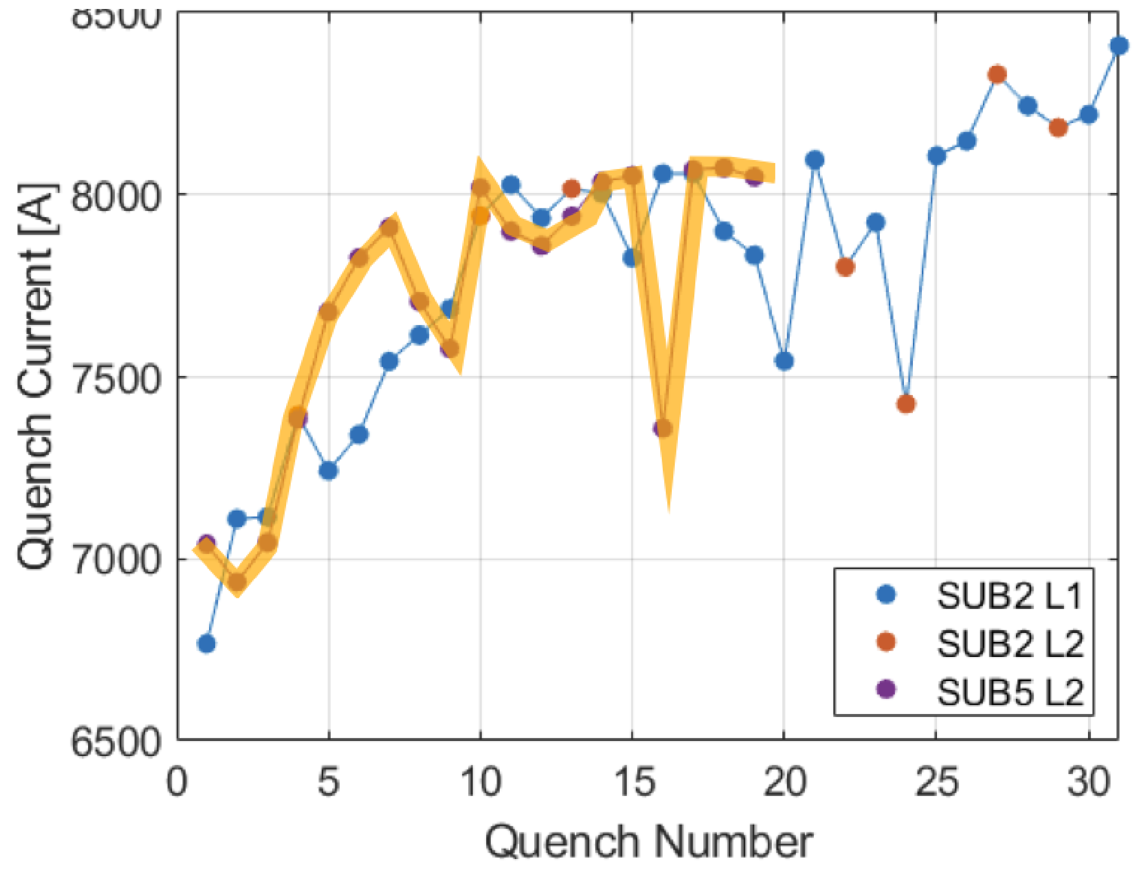
Can we contemplate a new paradigm for HTS?

- 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 !?

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

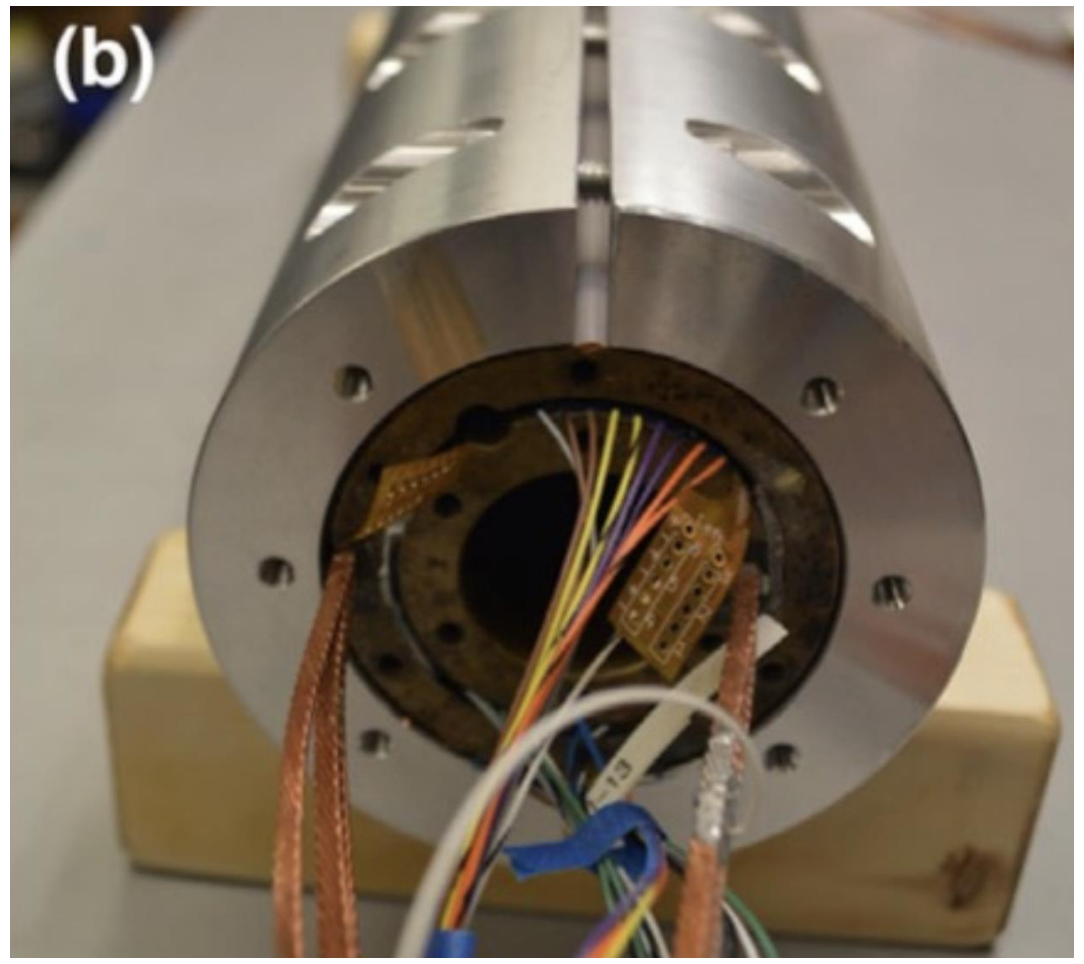
1st Nb_3Sn CCT coil impregnated with wax

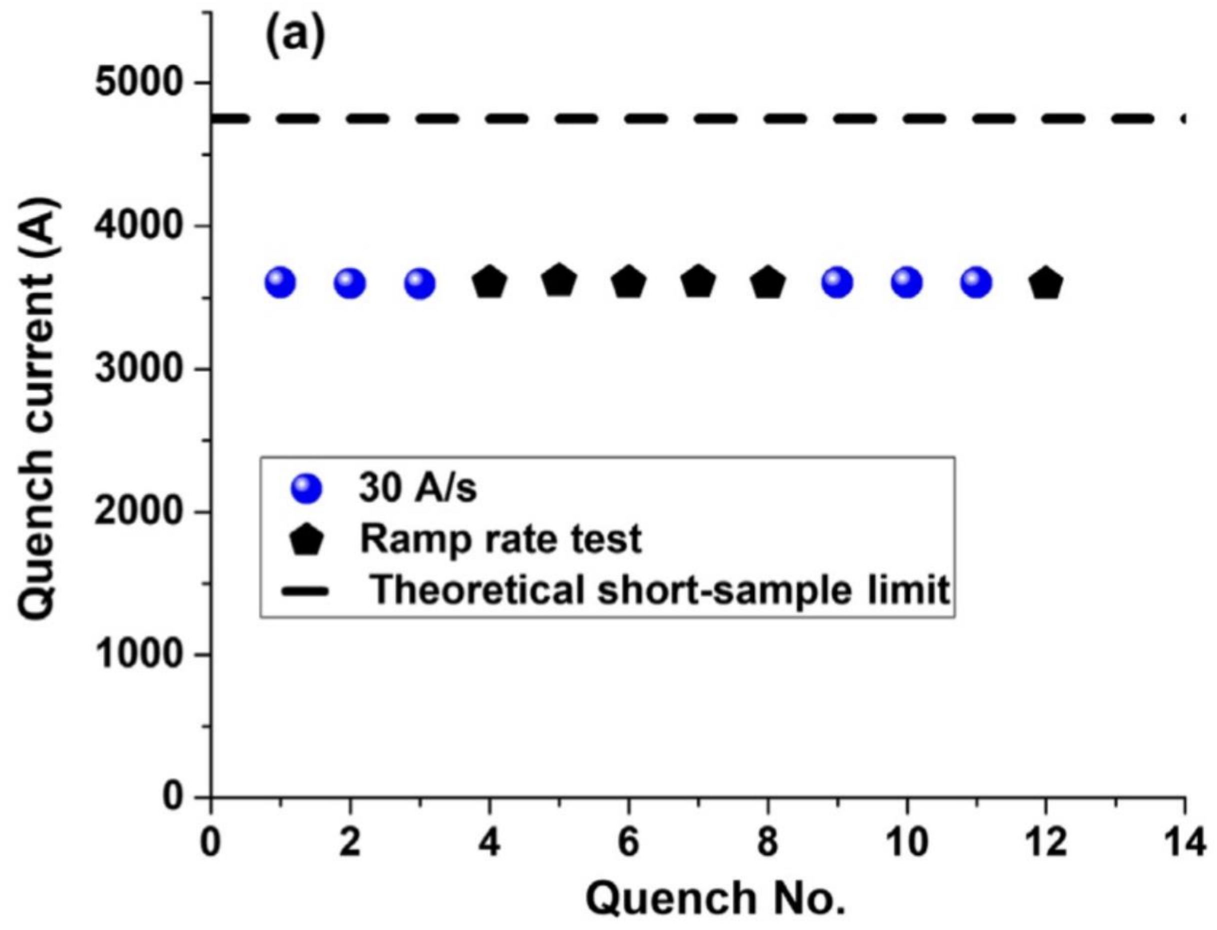


⇒ no quench of inner wax coil!

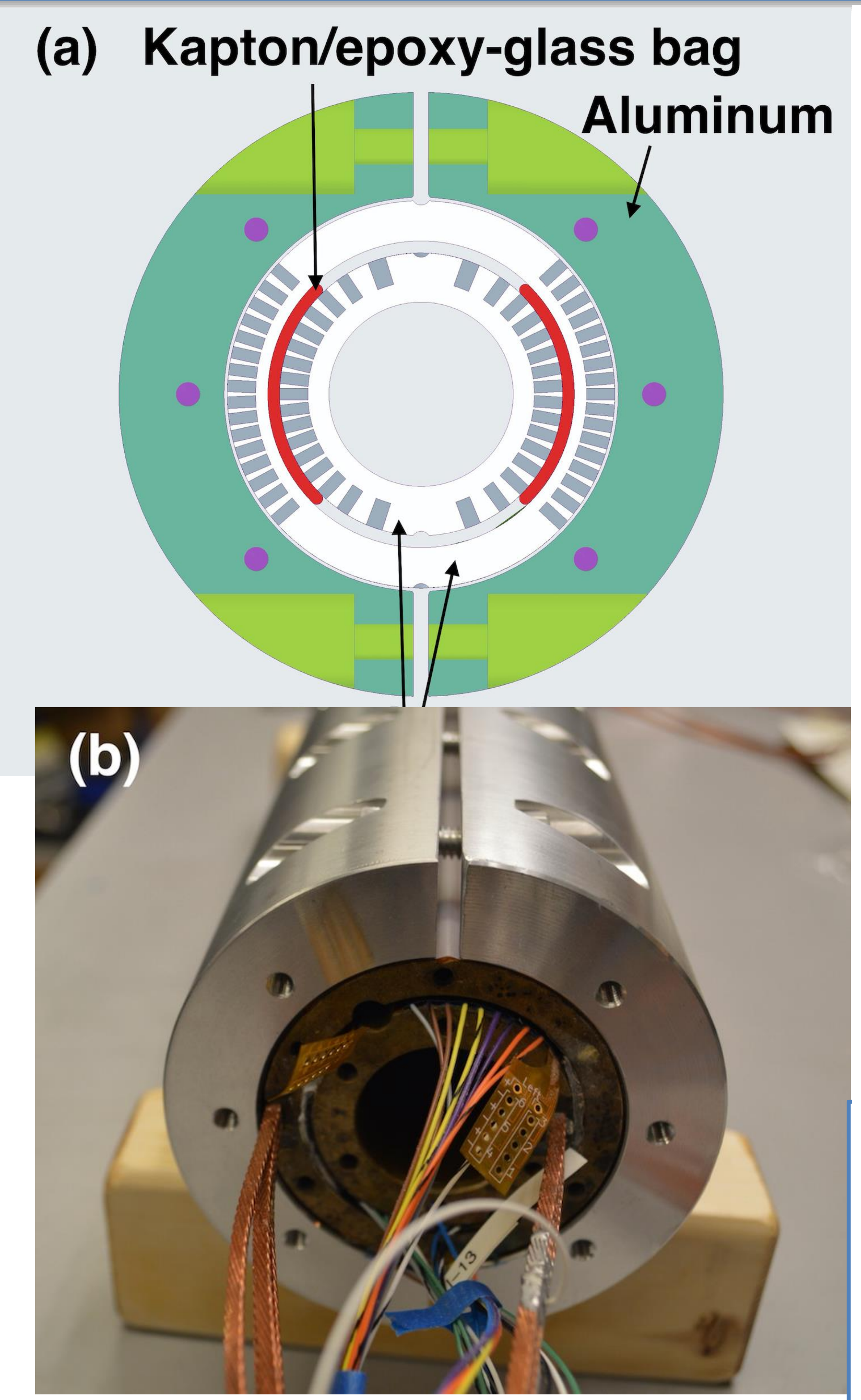
- All quenches were in outer coil

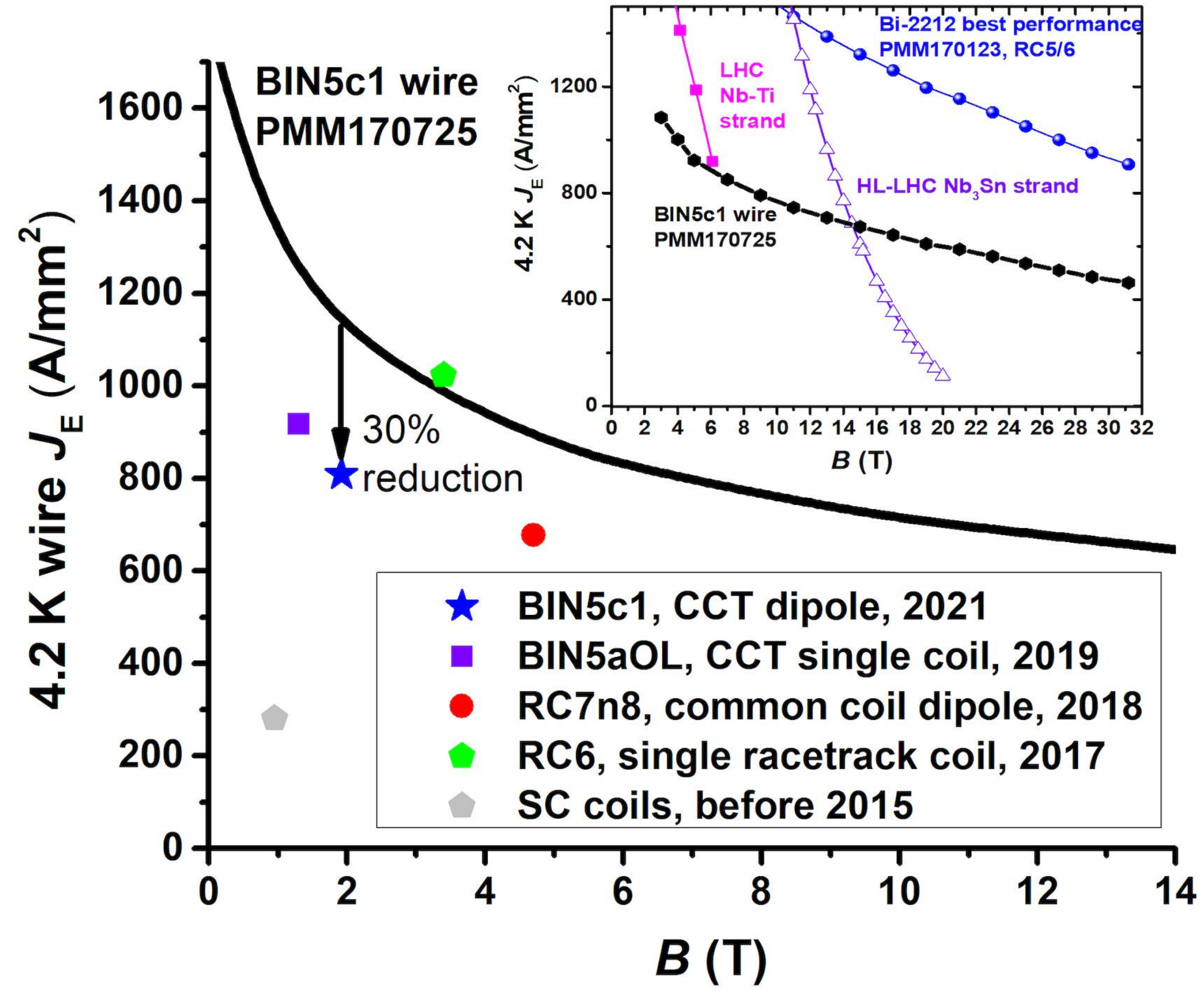
*Motivated by “Box” results: Daly et al 2022 SUST **35** 055014*





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

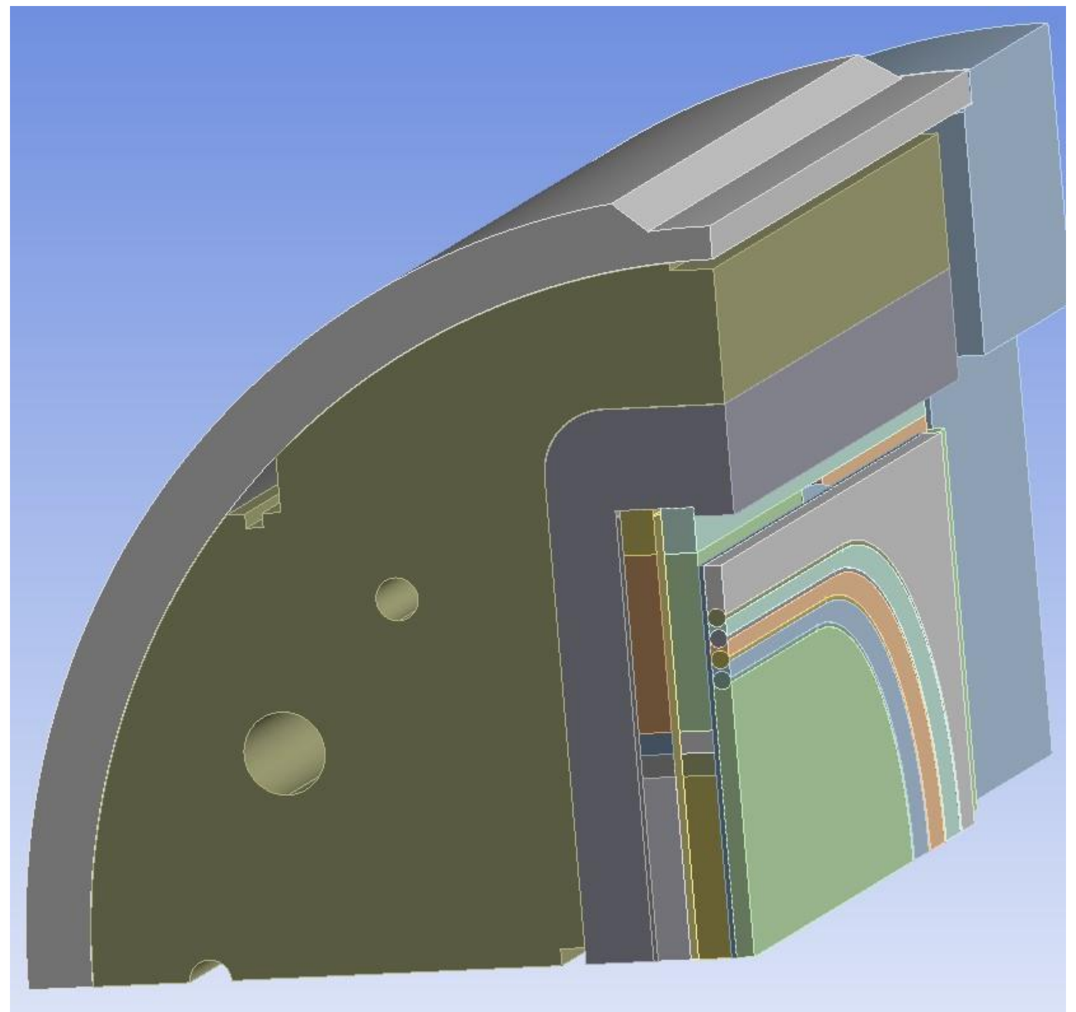
3 coils at FSU, ready

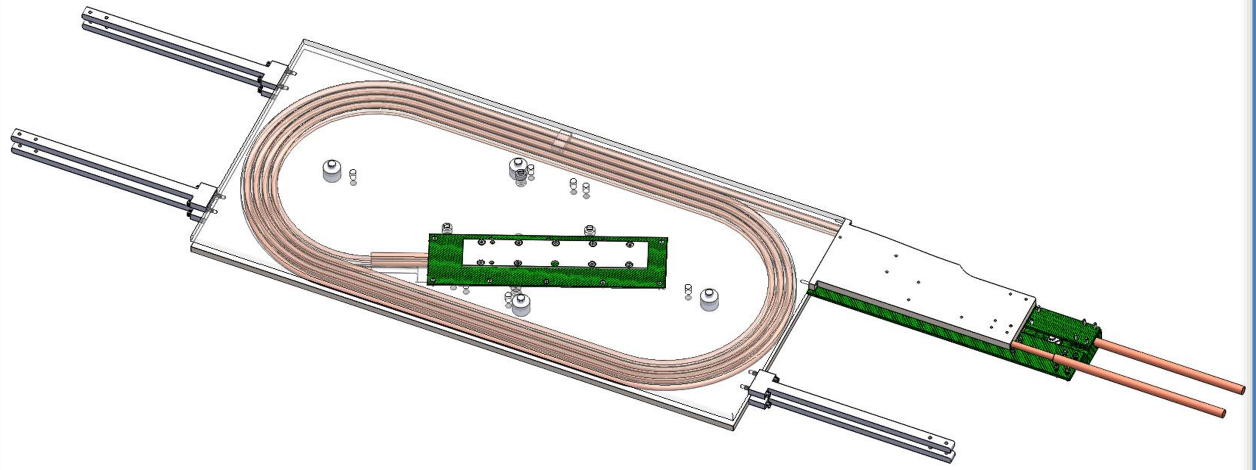
CCT6-Bi-CCT2

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

REBCO makes steady progress – focus on CORC® & STAR®

Test CORC in-field at BNL

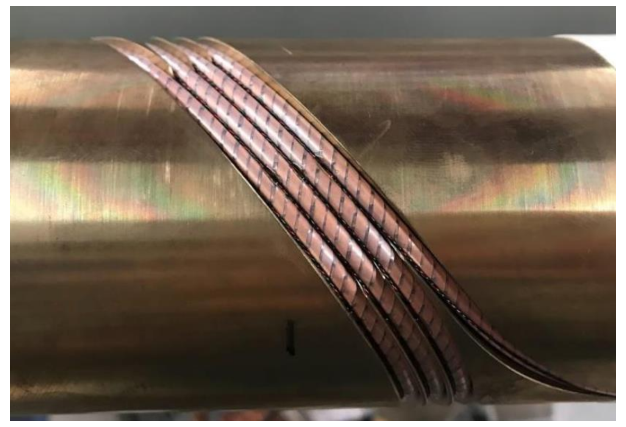


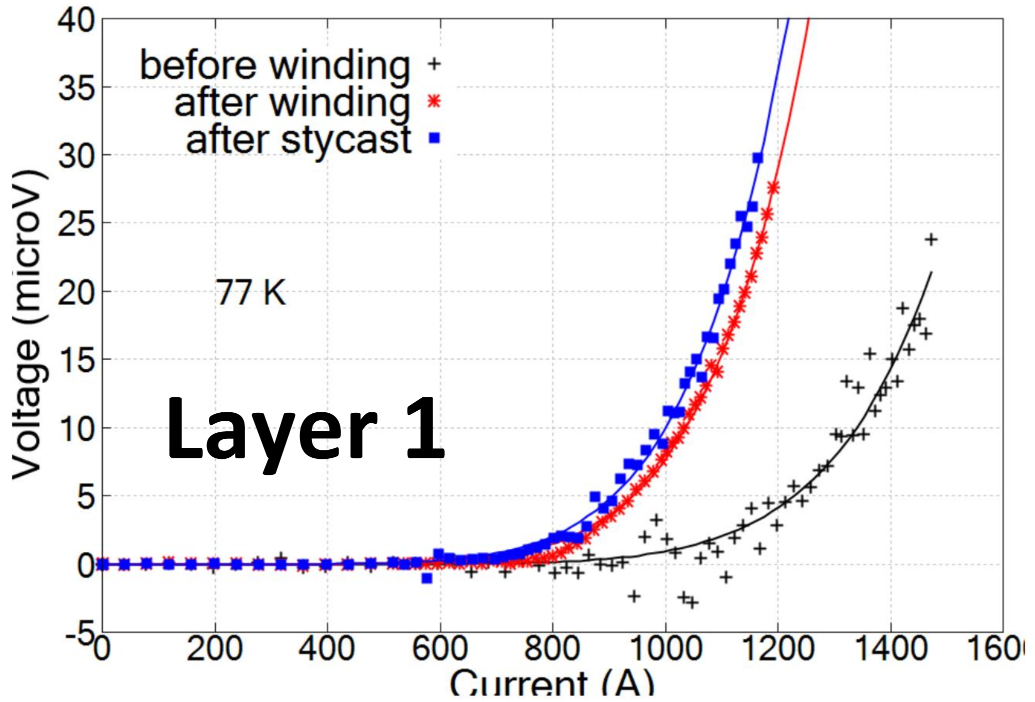


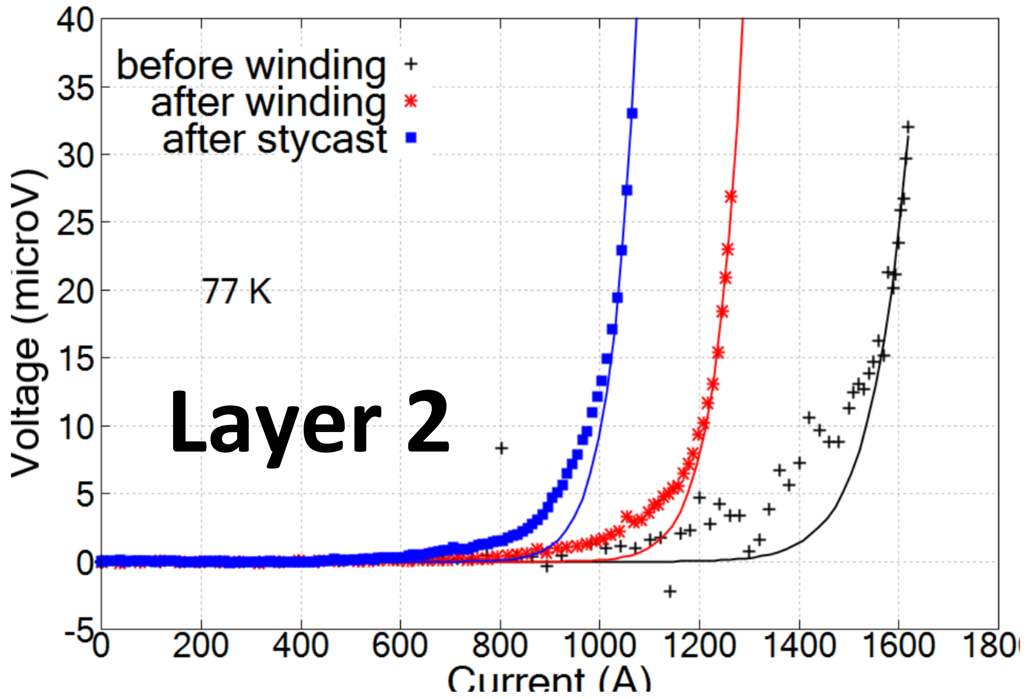
C3 – next deliverable

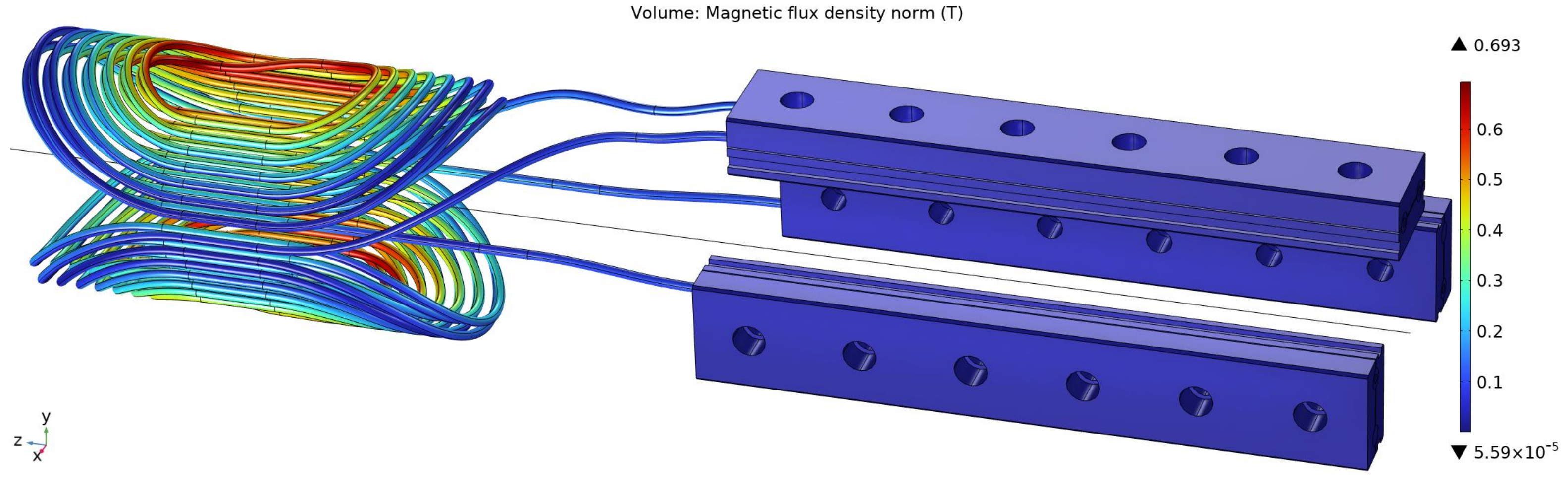
- Generate 5 T
- 6-layer CCT using CORC® wires
- Tapes in-hand, cable underway

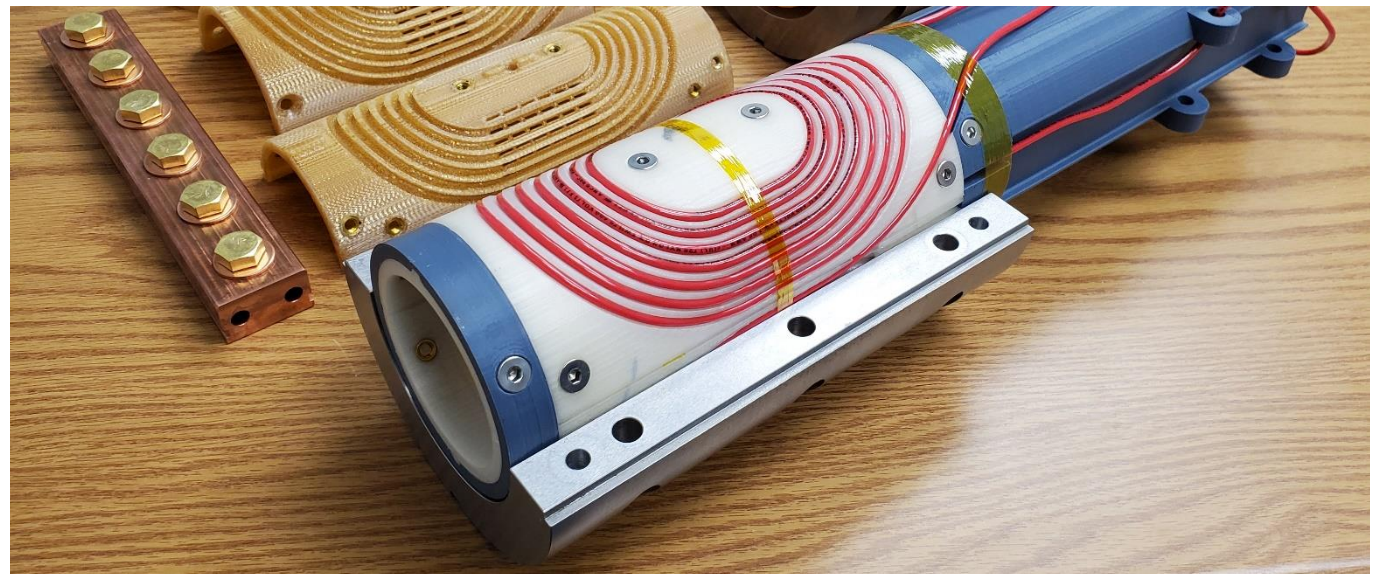
3-turn practice windings are done for each layer





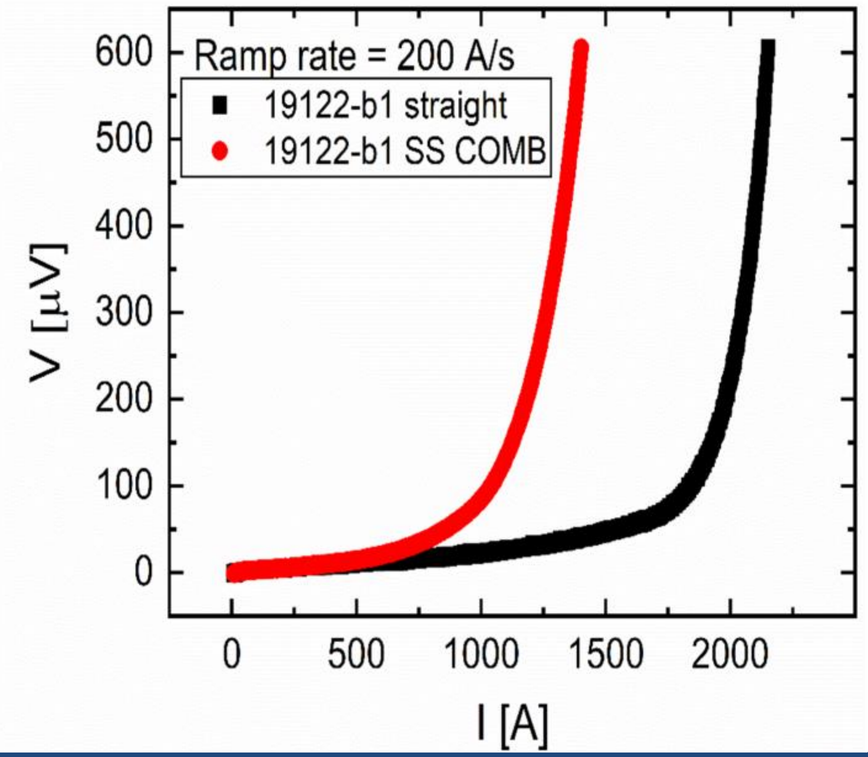




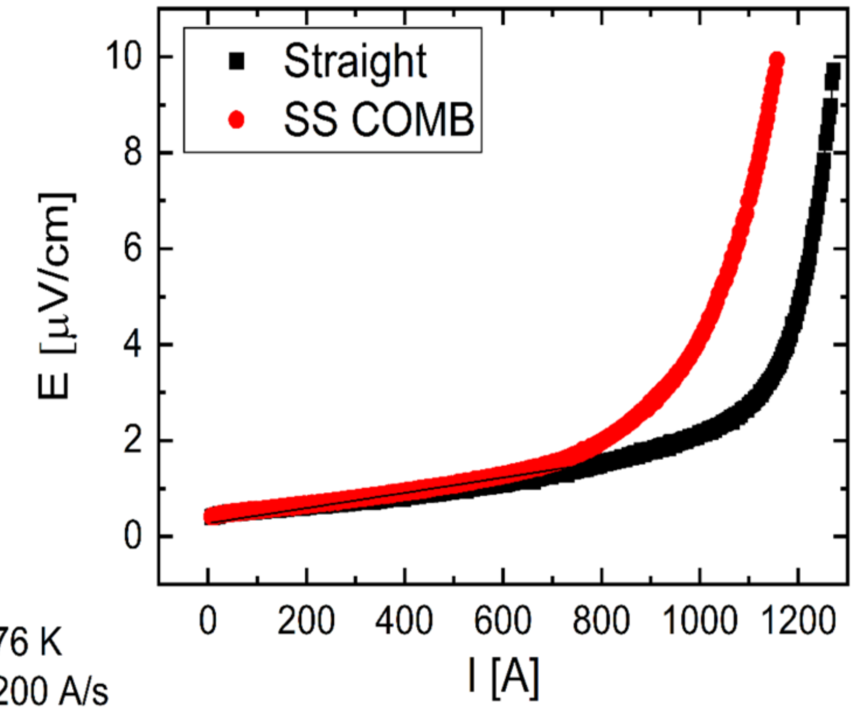


"COMB" design advancing as a test platform

"Early" CORC



Improved CORC

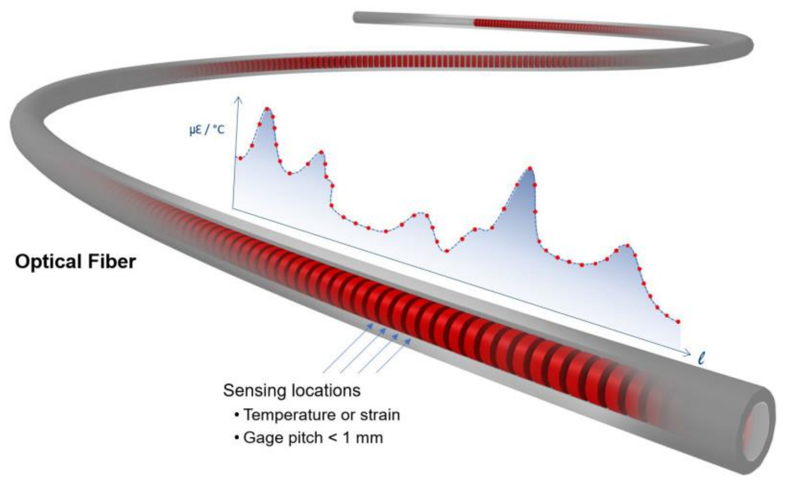


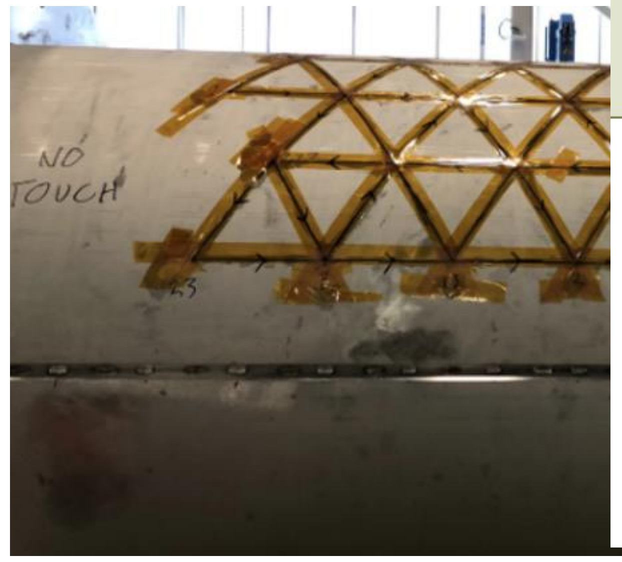
76 K
200 A/s

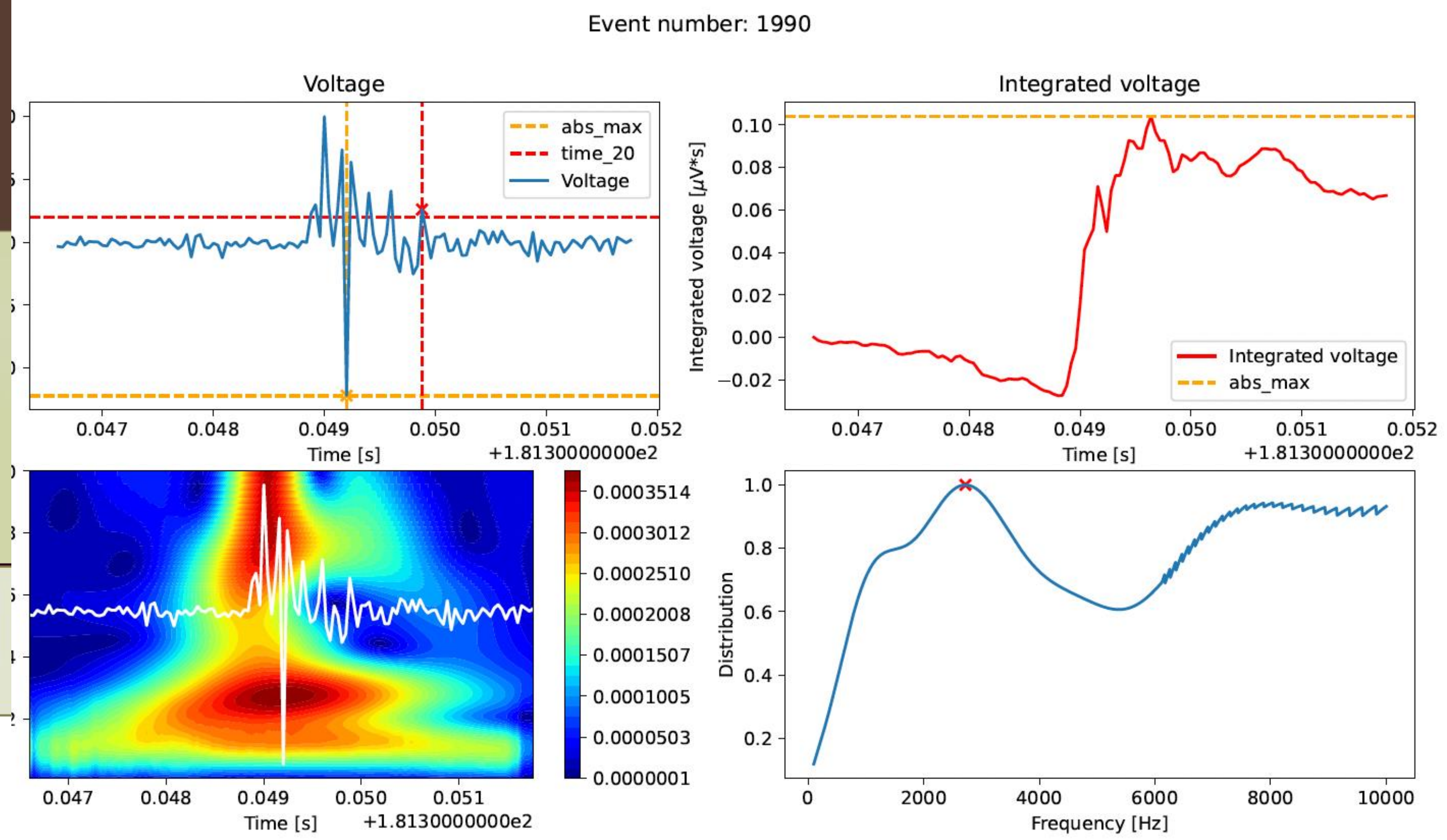
Diagnostics are central to advance magnet technology

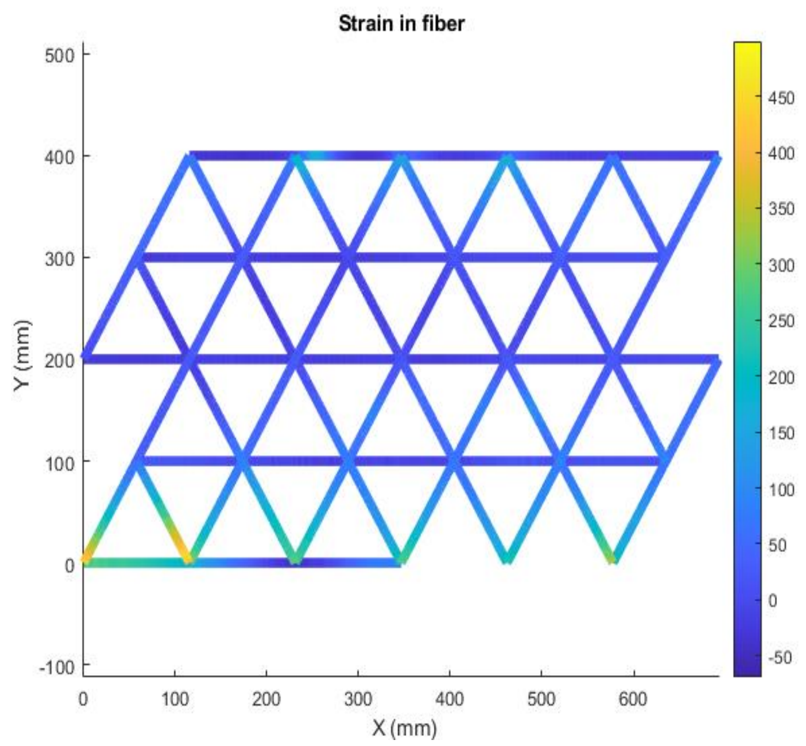
M. Baldini, S. Krave

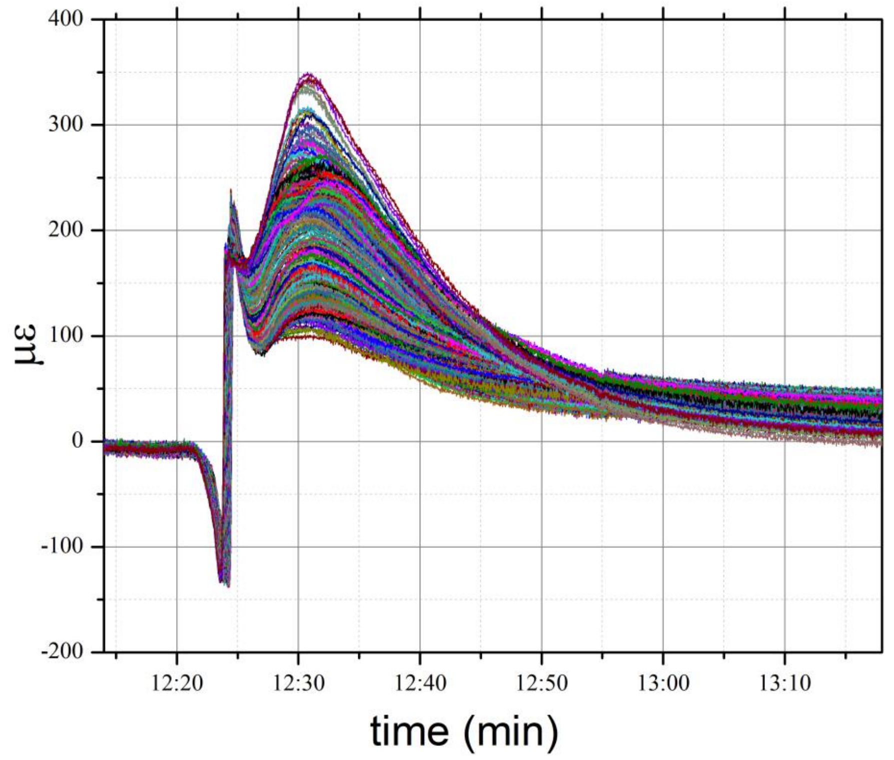
Rayleigh backscatter fiber optics f
area-level strain monitoring

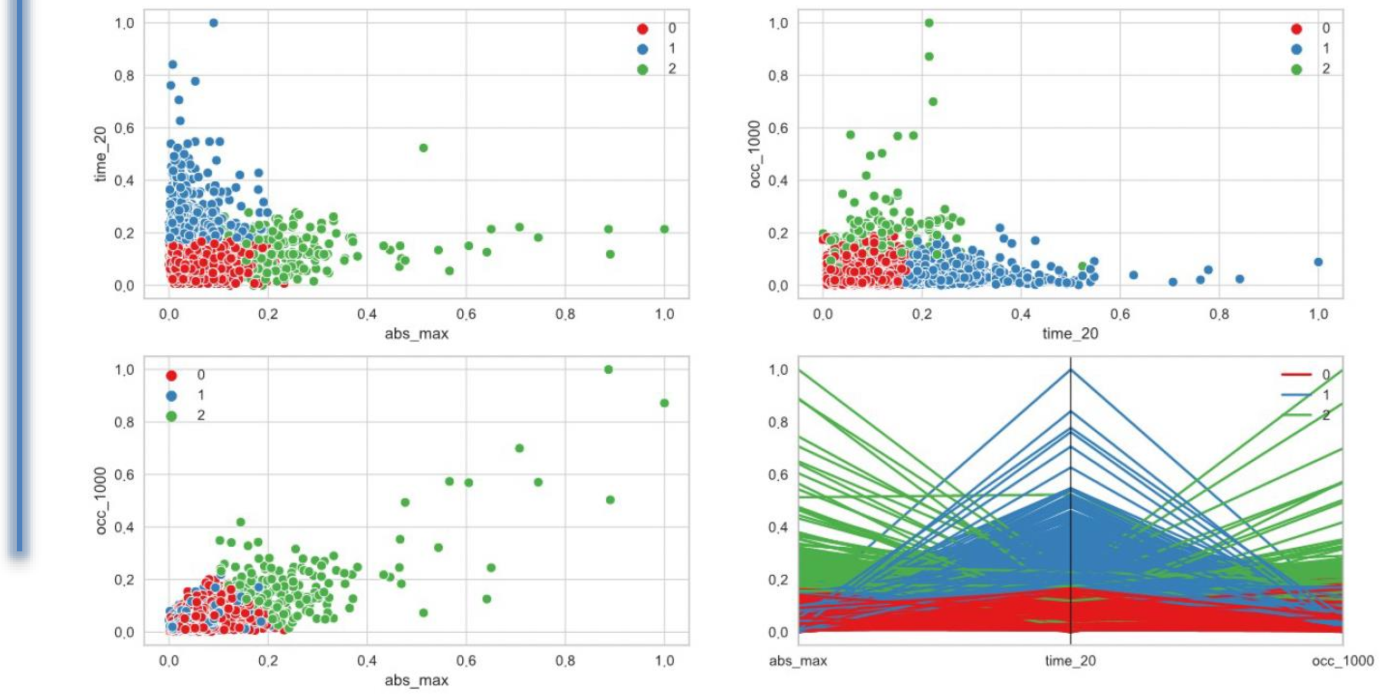






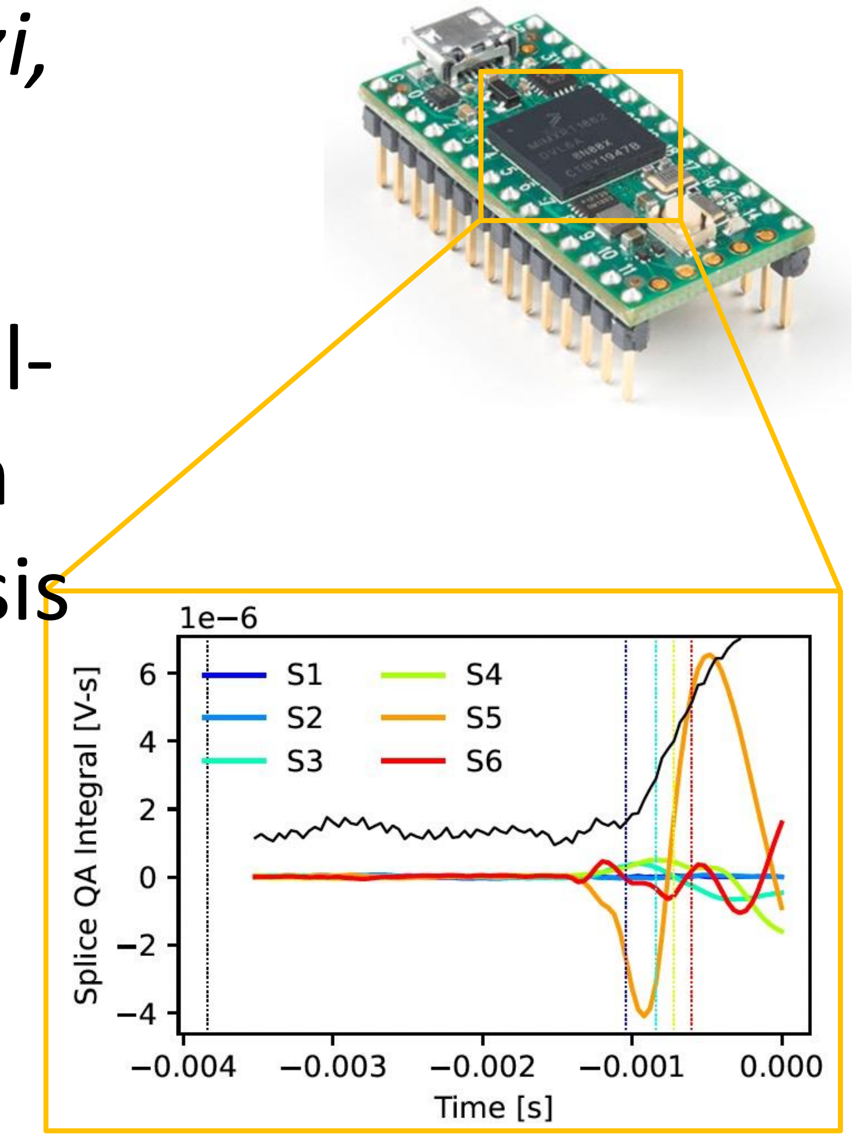




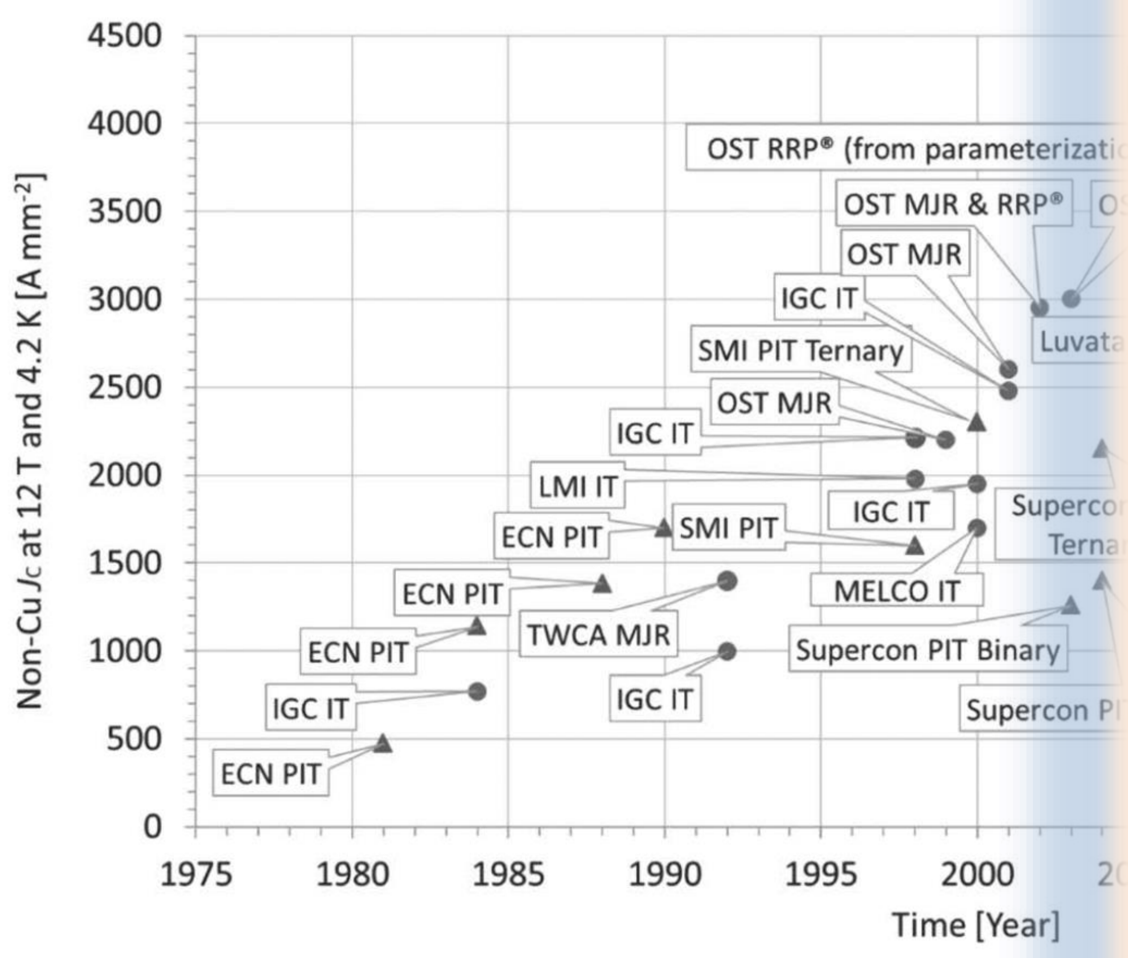


Plebani, E. Barzi, Teyber

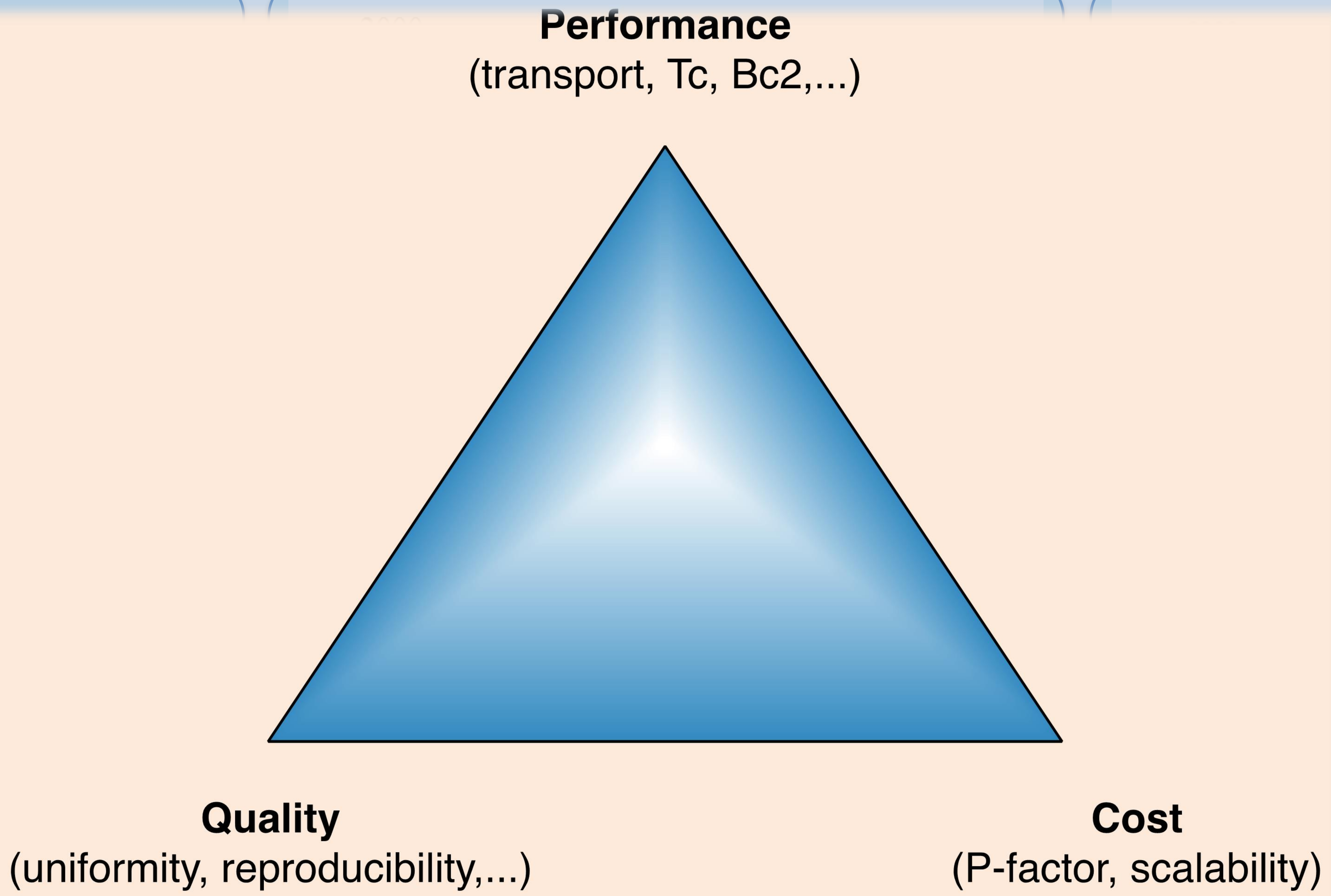
Towards real-time quench signal analysis

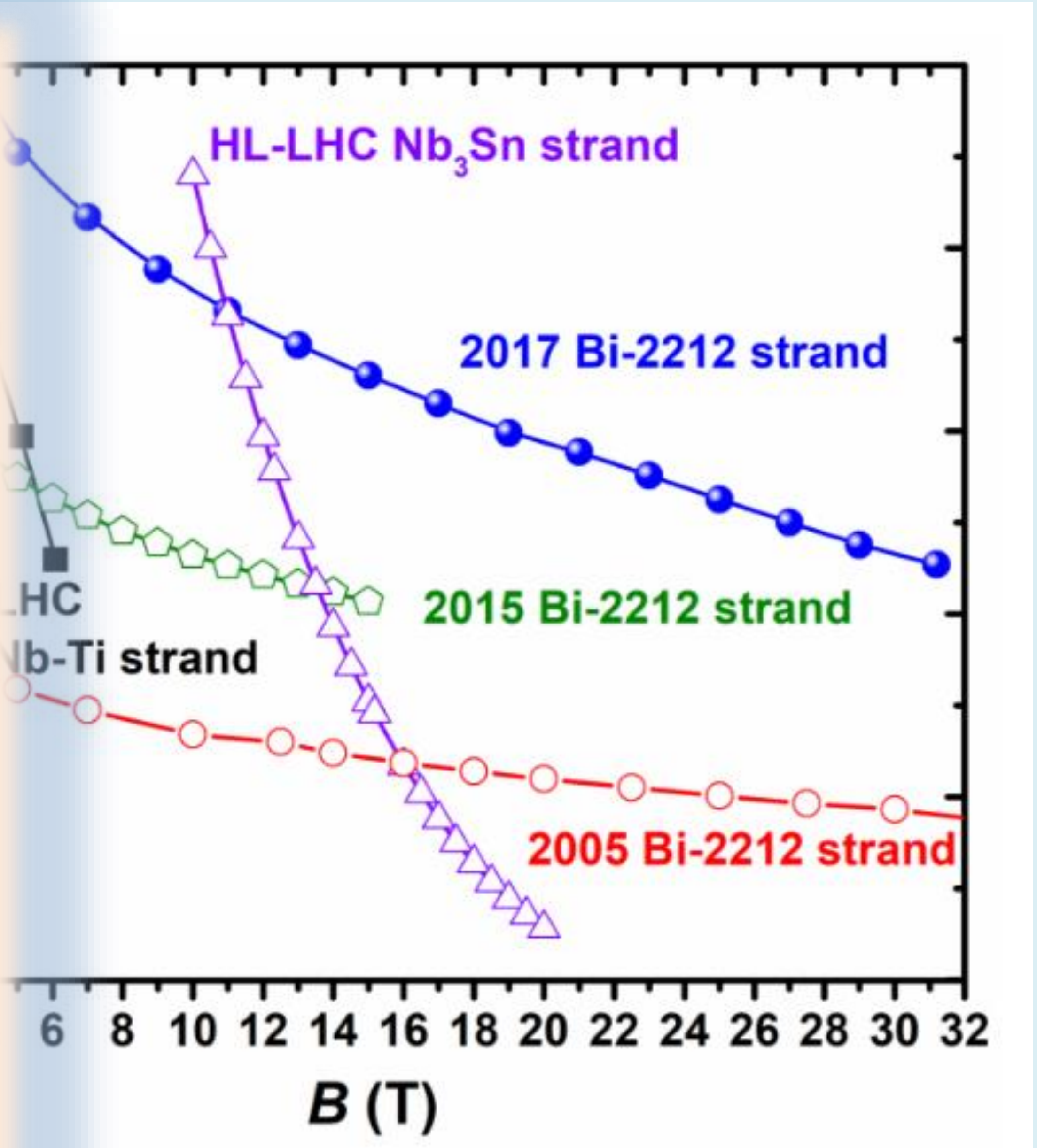


Superconductor advances are heavily driven by OHEP magnet developments, needs, and focused and consistent investments



I. Pong, Handbook of Supercon
Chapter E3.8





Fajardo, Instruments, 2020

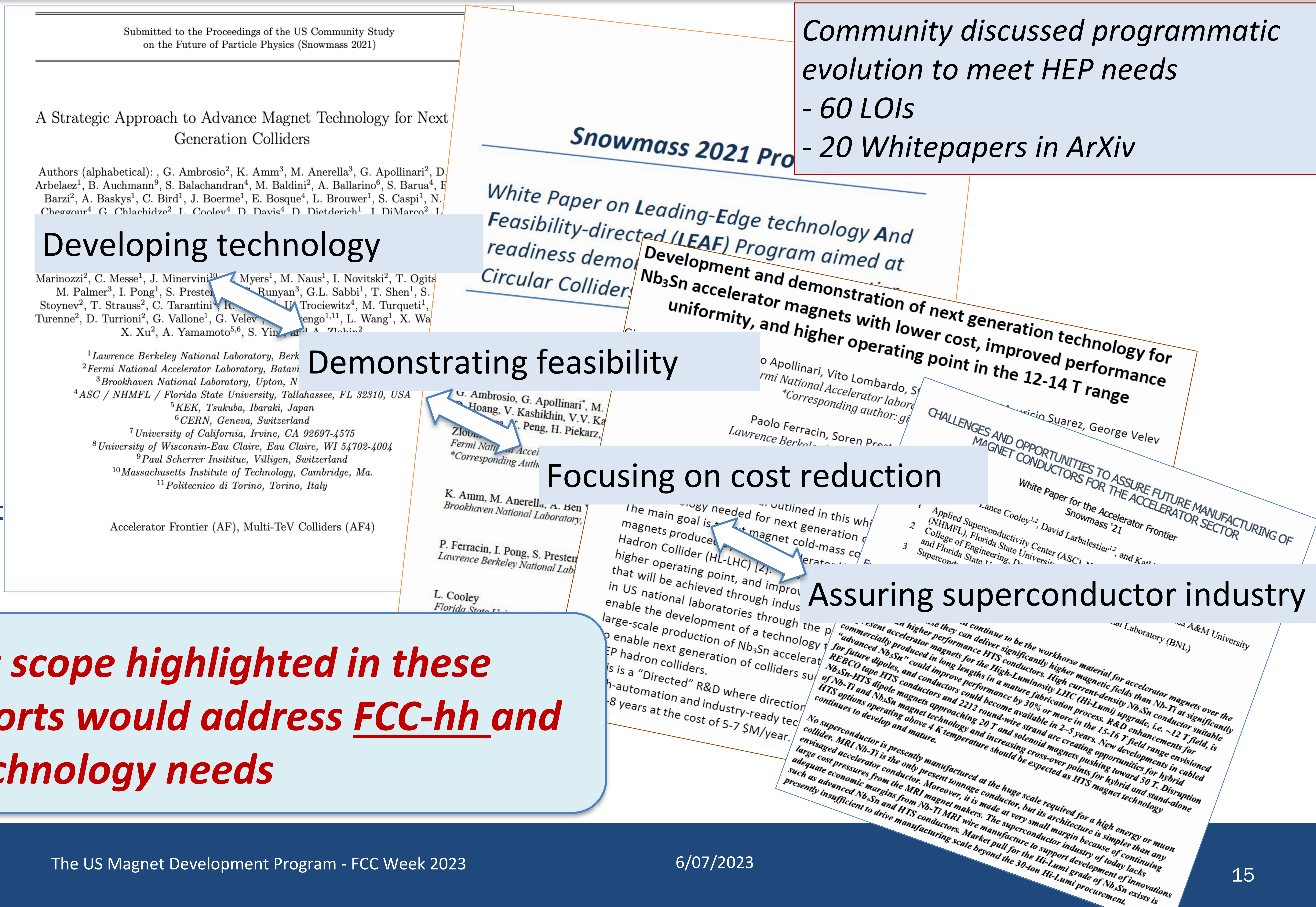
A longstanding history of
public/private partnershi
performance of superconductors

Bi2212 as a magnet-ready
rature superconductor

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

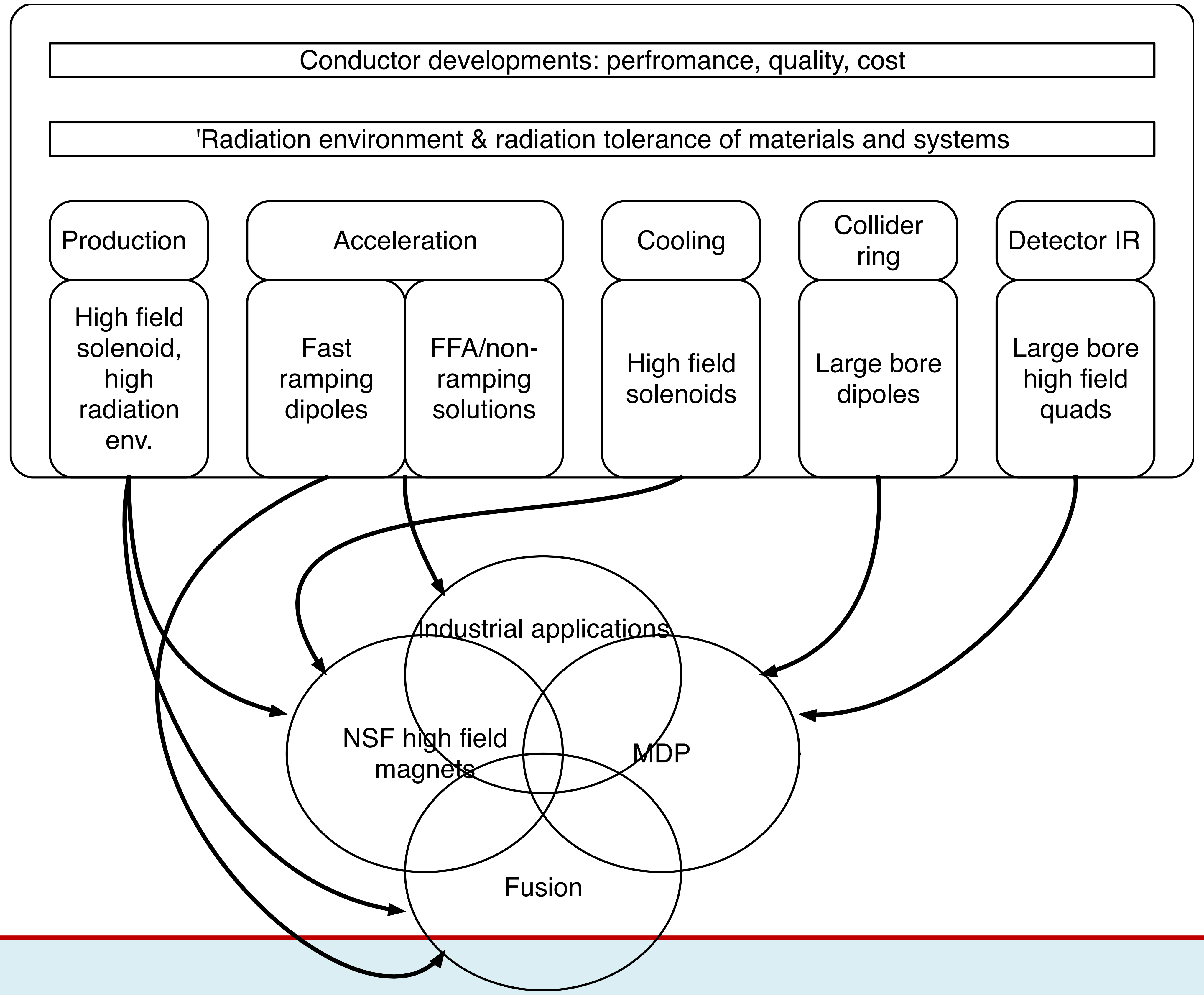
- The MDP has been very effective in organizing and focusing a multi-lab team on accelerator magnet R&D
  - International leadership, record dipole magnet, advances in HTS magnet technology,…
  - Reviewed positively by OHEP
- The AUP team is delivering state of the art magnets for HiLumi
  - As the project 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

There are synergies in magnet technology that can be exploited across the FCC, muon collider, as well as other offices – FES, ARDAP



Muon collider system	Synergies with other end users: Future HEP Facilities	Fusion	NSF (High DC Fields)	Synergies with programs: US-MDP	ARDAP/Industry
Collider Dipoles					
IR Quads					
Target Solenoid					
Cooling Channel Solenoids					
High Ramp Rate for RCS					

FCC-ee	Synergies with other end users: Future Colliders	Fusion	NSF (High DC Fields)	Synergies with programs: US-MDP	ARDAP/Industry
IR quadrupoles					
Collider dipoles					
Booster magnets					
FCC-hh					
Collider Dipoles					
IR Quads					

Legend

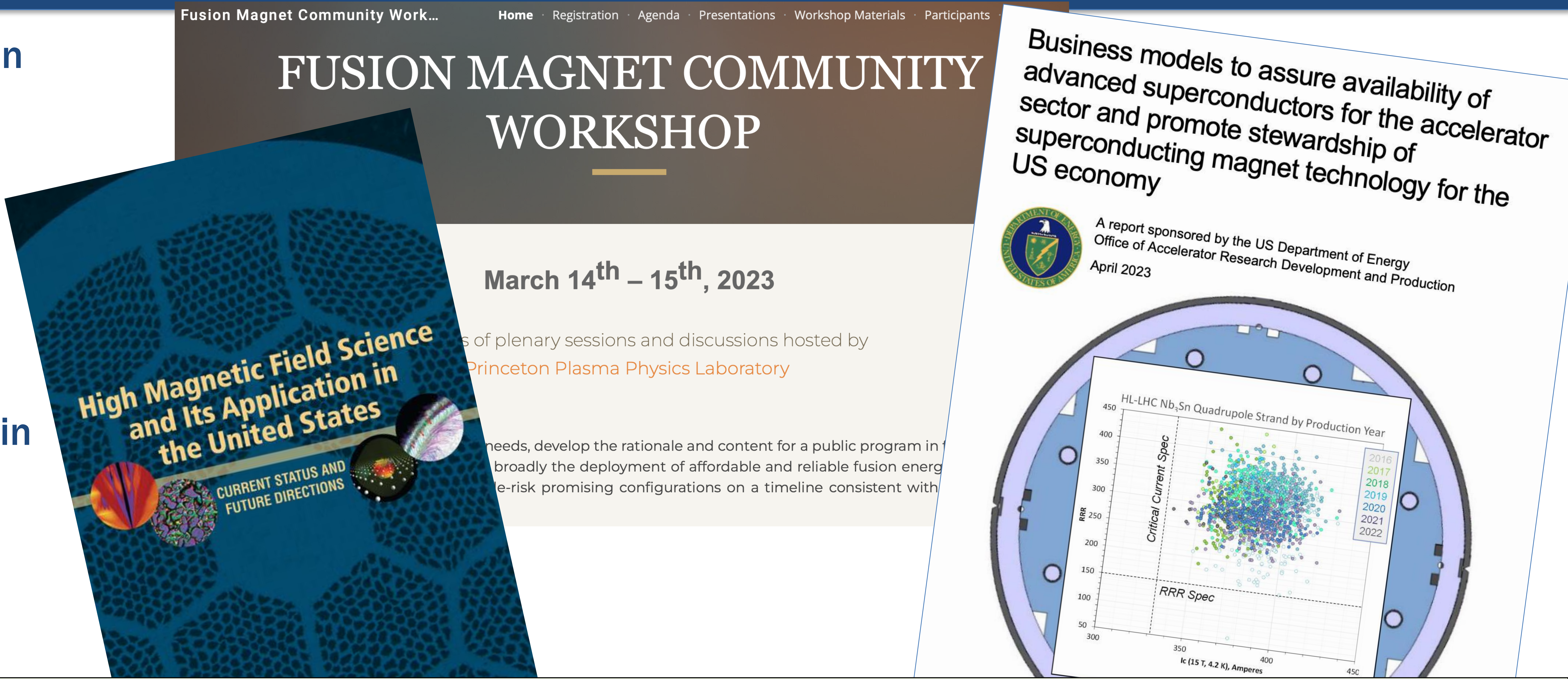
Strong synergy	
Some synergy	
Current focus	
Synergistic	
Potentially supportive	

An ***enhanced magnet research portfolio***, focusing on the most critical magnet development needs for a Hadron collider and a Muon collider, and ***fully leveraging synergies with other DOE and NSF programs***, will be the most effective way to ***aggressively prepare for the next collider***

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

- The High Energy Physics community has clearly indicated the science potential associated with a future colliders that probe significantly higher energies
- There is a concerted effort around the world to integrate teams of specialists and facilities to most efficiently, effectively, and rapidly advance magnet technology – for HEP, but also for FES!
- There is also strong interest in collaborating internationally, where strengths and capabilities are deemed complementary and can more rapidly advance the technology
- To aggressively prepare magnet technology for a hadron or muon collider, a significant increase in the magnet R&D effort is needed, fully leveraging synergistic activities, e.g. from FES and NSF

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

Physics motivation and strategic planning

- The physics drivers for a future hadron collider have been discussed and documented by community planning, e.g.
  - 2014 P5 & 2022 US "Snowmass" processes
  - 2020 Update of the European Strategy for Particle Physics

From 2020 ESPP:

"Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry"

"The particle physics community should ramp up its efforts focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors."

"The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy revovery linacs."

Last US "P5" report ~2014

P5 recommendation 24:

"Participate in global conceptual design studies and critical p
R&D for future very high-energy proton-proton colliders.
Continue to play a leadership role in superconducting magne
technology focused on the dual goals of increasing performa
and decreasing costs."

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.

Fabiola Gianotti (CERN), LHCP, 7 June 2021

CERN's implementation

Full exploitation of the physics potential of LHC and high-luminosity LHC (including HI, flavour, …)
→ CERN's highest priority in the short/medium term (→ see M. Lamont's talk)

Highest-priority next collider: e^+e^- Higgs factory
→ continued development of FCC-ee and CLIC technologies; support to ILC

Increased R&D on accelerator technologies: high-field superconducting magnets, high-gradient accelerating structures, plasma wakefield, muon colliders, ERL, etc.
→ see next slide

Investigation of the technical and financial feasibility of a future ≥ 100 TeV hadron collider at CERN, with e^+e^- Higgs and electroweak factory as a possible first stage.
→ see next slide

R&D efforts for accelerator magnet technology are becoming more structured

U.S. MAGNET DEVELOPMENT PROGRAM

- DOE created the US Magnet Development Program (MDP) in ~2016
- Europe has initiated the High Field Magnet Program (HFM)

https://arxiv.org/abs/2011.09539

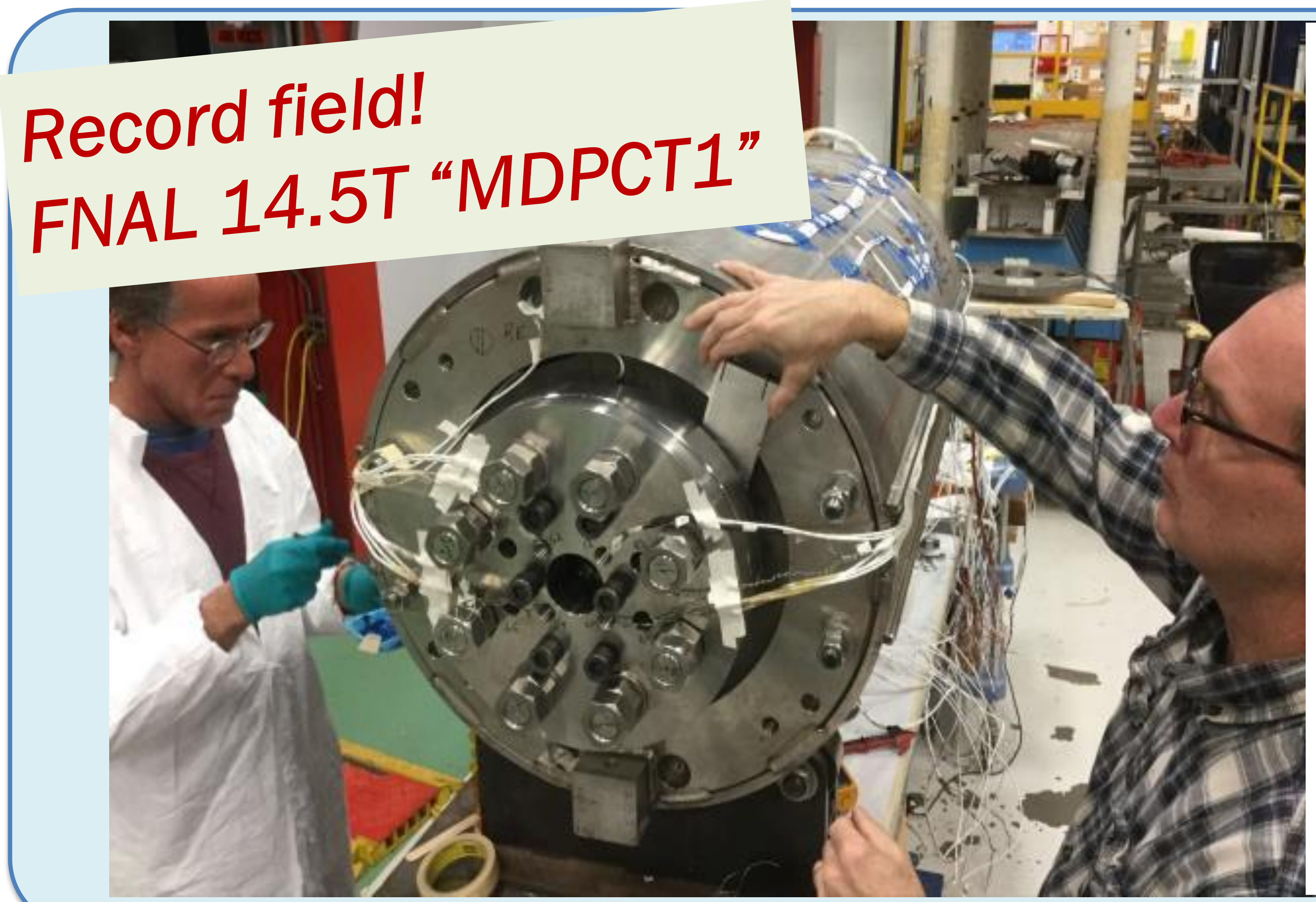
http://arxiv.org/abs/2201.07895

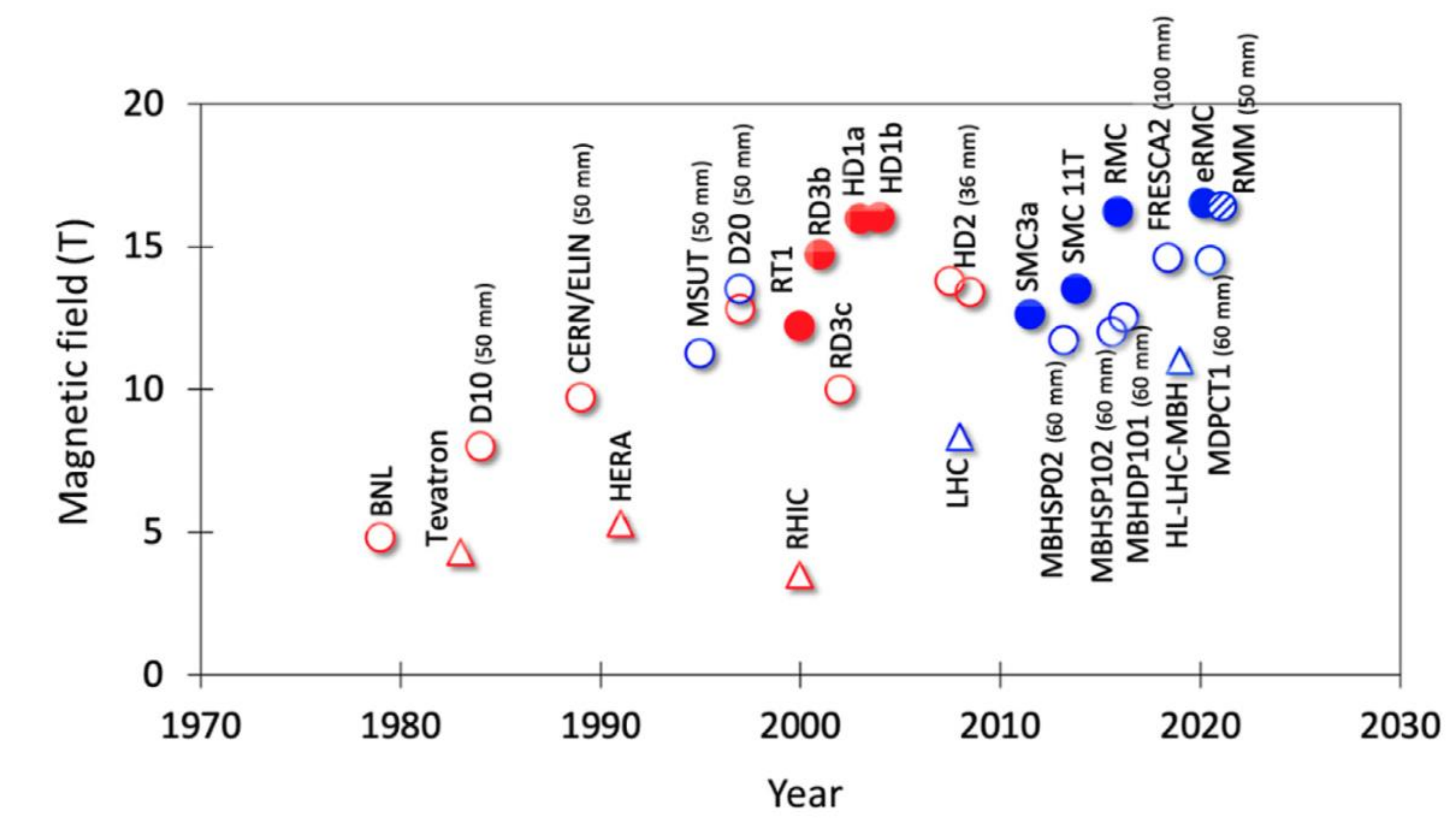
These are **significant programs**, derived from ~decadal community planning processes

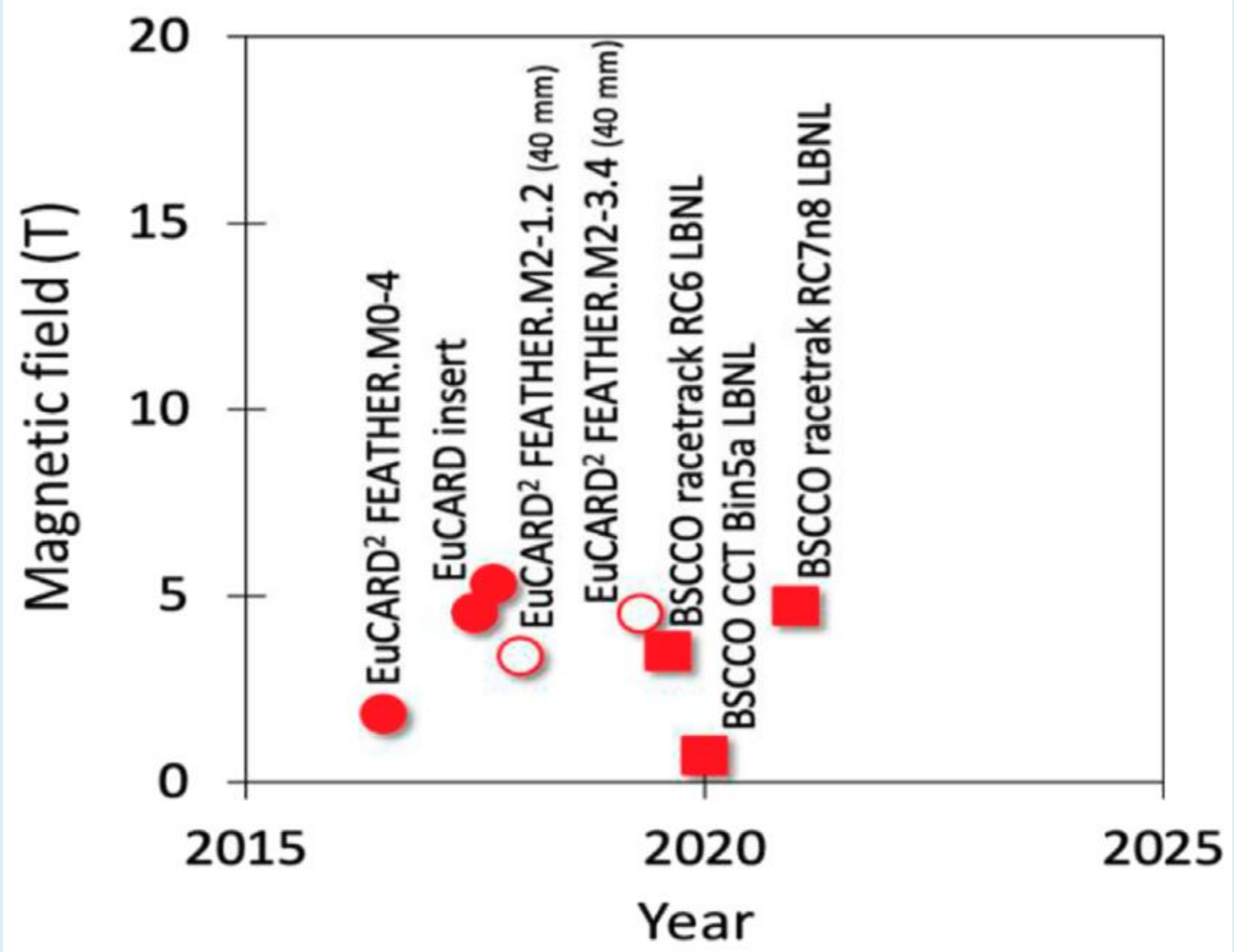
=> Strive to coordinate efforts to more rapidly advance technology development

We are poised to break new ground with hybrid LTS/HTS magnets in the coming years

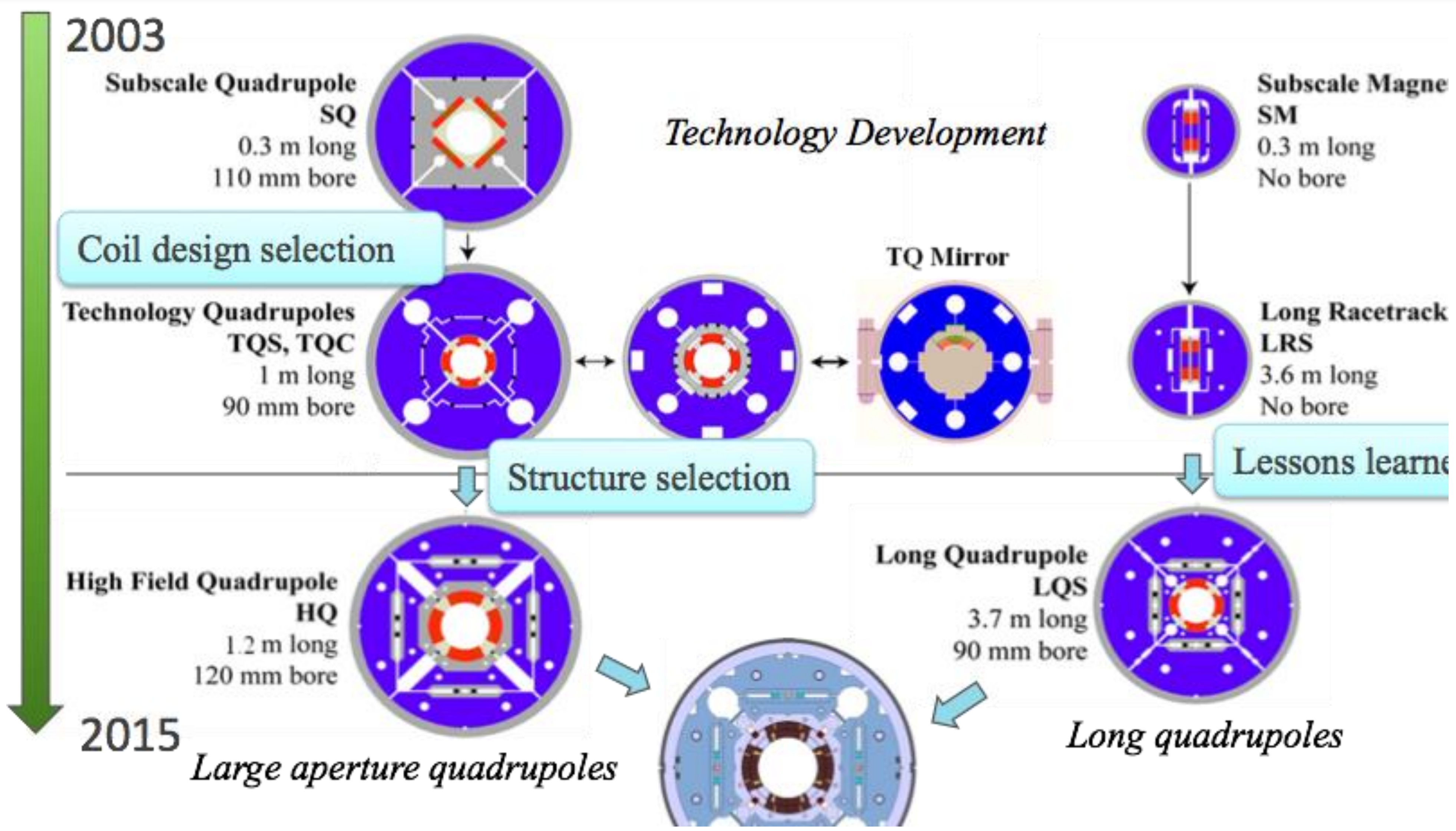
Bottura, Prestemon, Rossi, & Zlobin, Front. Phys., 12 October 2022

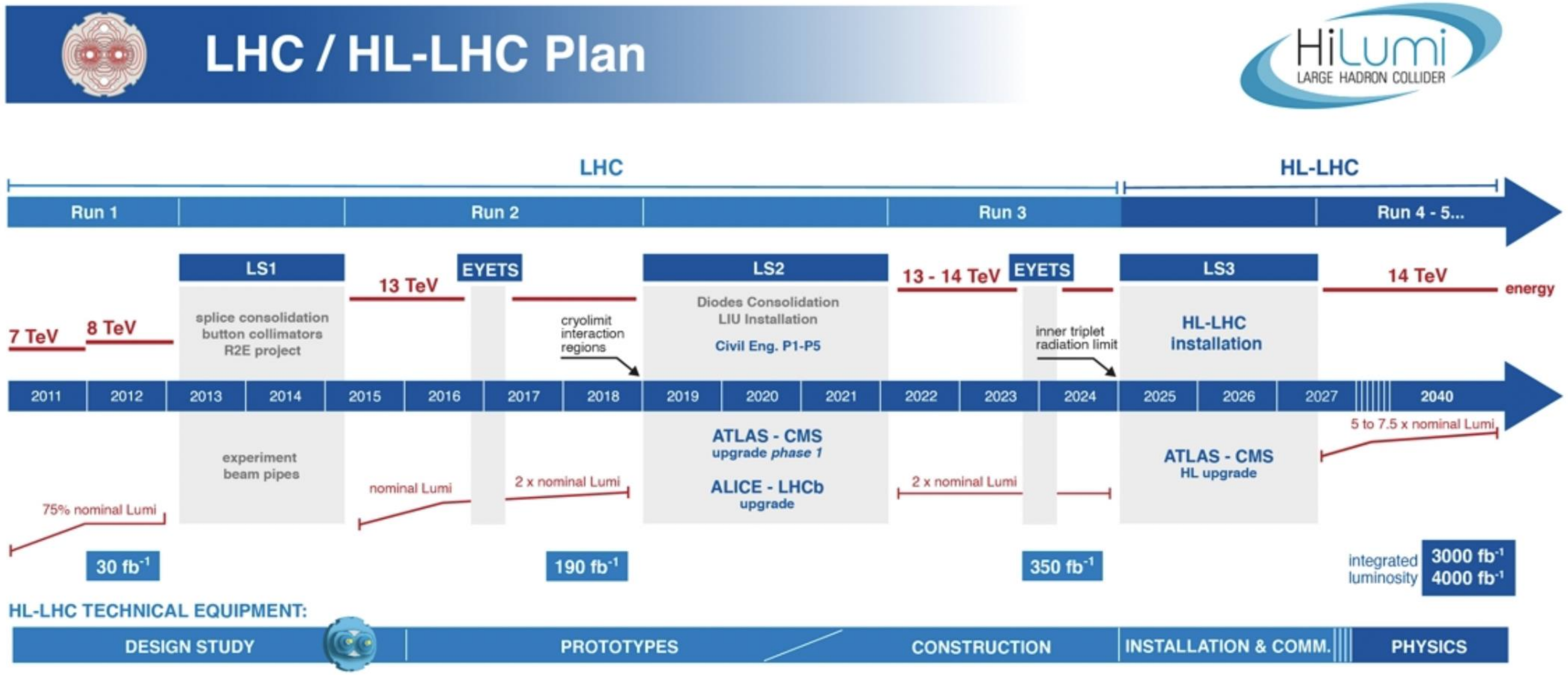


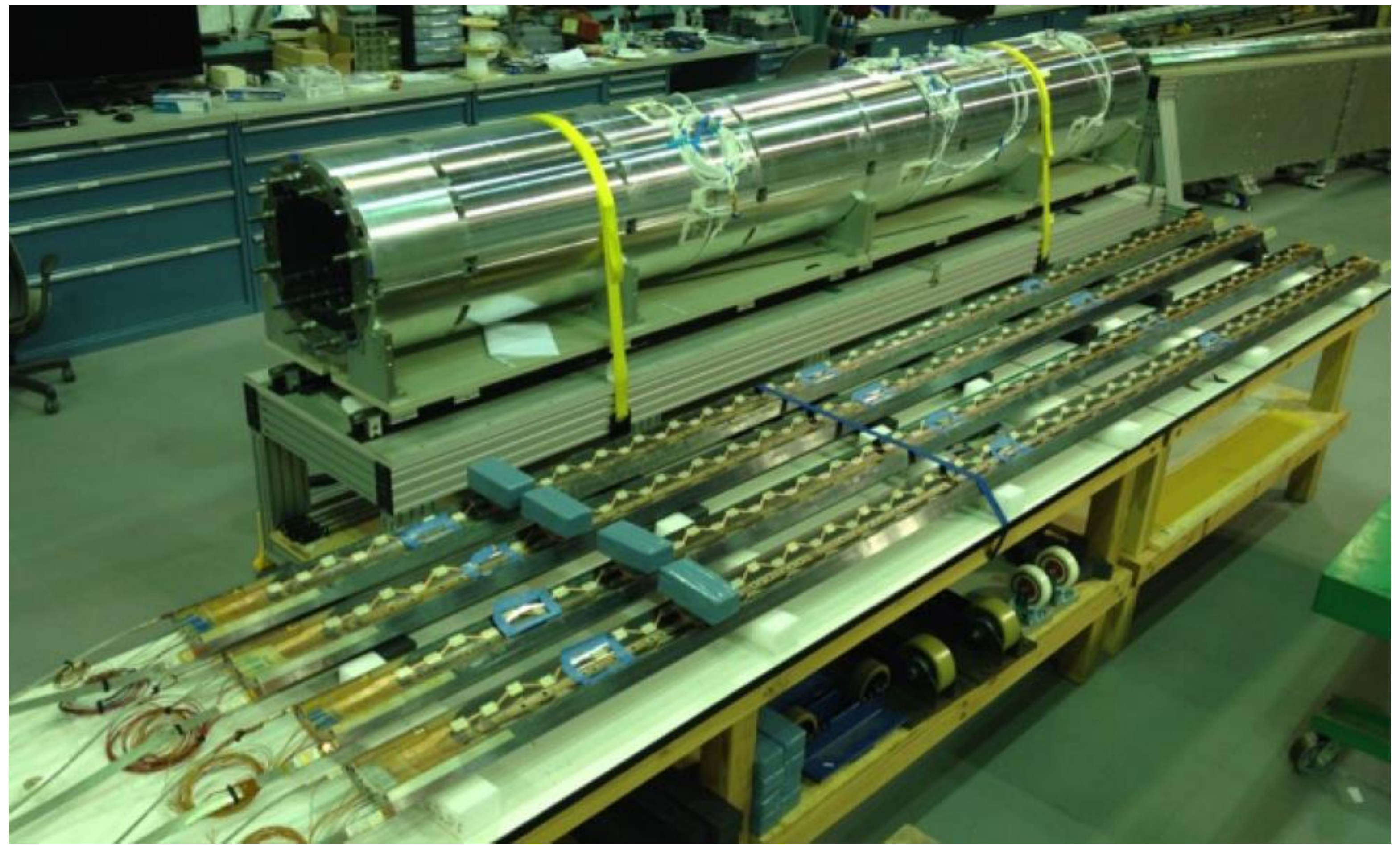




Nb3Sn accelerator magnet technology is - *for the 1st time* - being installed in a collider







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***

U.S. MAGNET DEVELOPMENT PROGRAM

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***

2020 Updated Roadmaps

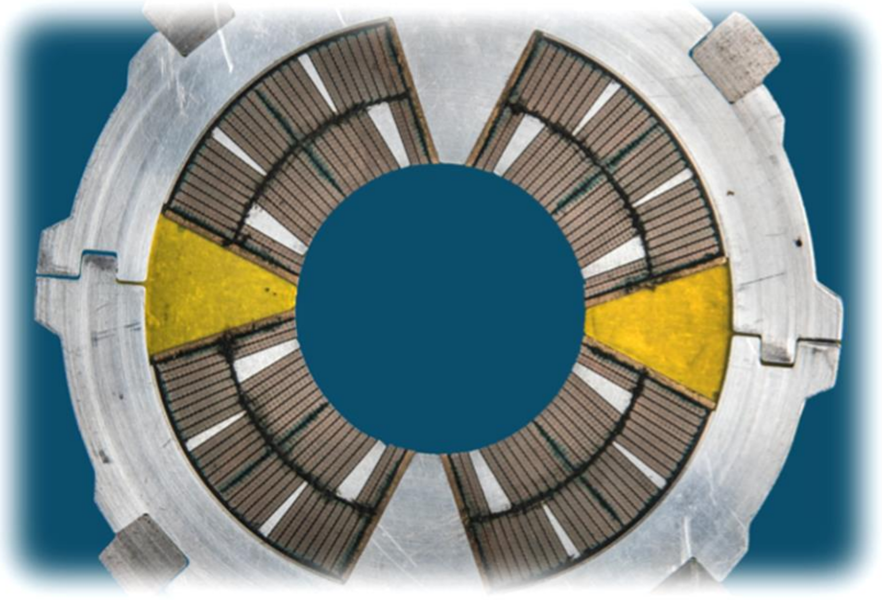
The 2020 Updated Roadmaps for the US Magnet Development Program

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!

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