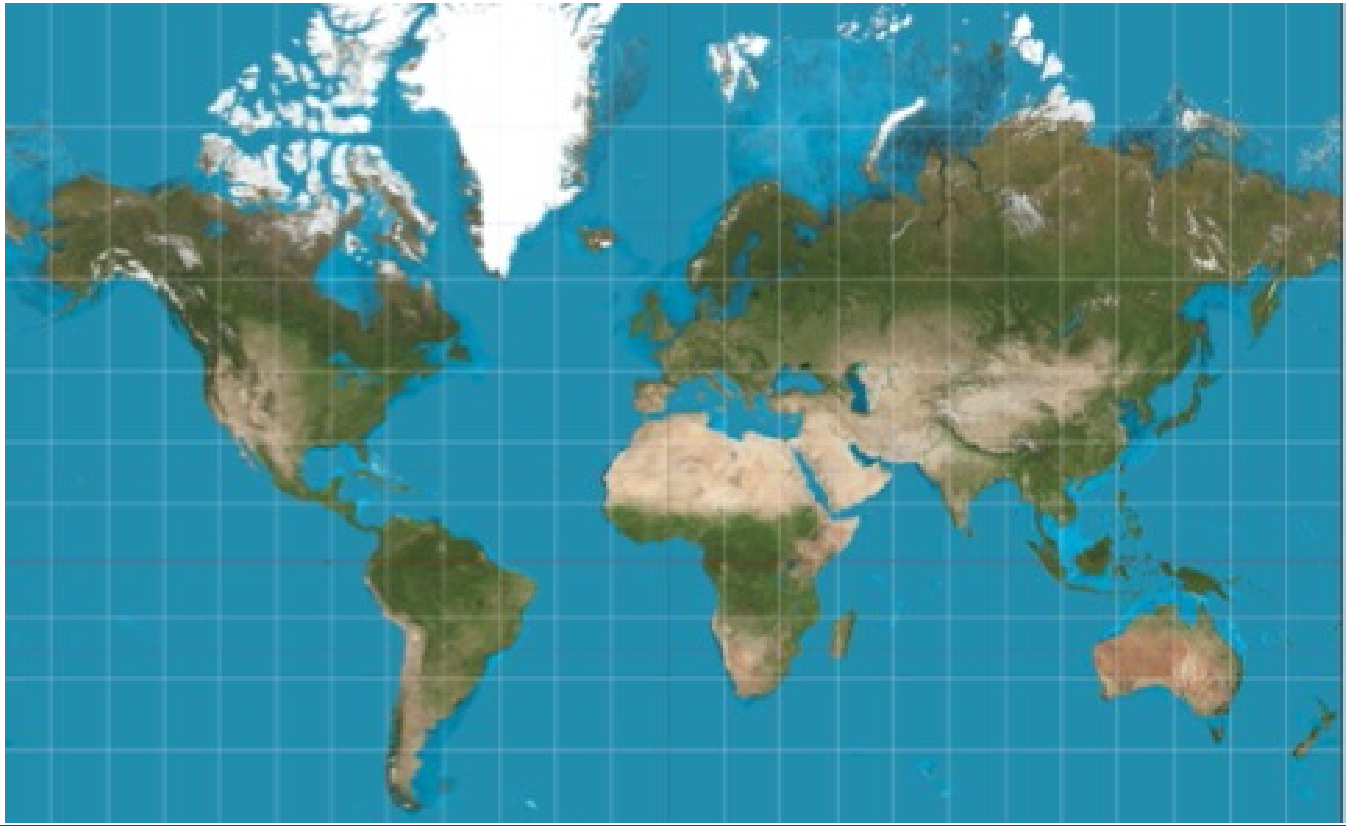
Overview of Superconducting Magnet Technologies

Soren Prestemon

Lawrence Berkeley National Laboratory

Outline

- Introduction and motivation
- Driving considerations
- Advances in superconductors
- Magnet design concepts for high field
- Diagnostics - techniques and applications
- Status and future directions
- Conclusions



Physics motivation and strategic planning

- The physics drivers for a future High Energy Physics colliders are well documented by community planning, e.g.
  - US "Snowmass" process
  - European Strategy for Particle Physics

P5 recommendation 24:

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

Last US "P5" report ~2014

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.

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."

From 2022 Snowmass Summer Study closeout

Accelerator Frontier "Message"

Snowmass 2021

On R&D: We have an ongoing R&D program aimed at fundamental beam physics and long-term accelerator concepts and technologies (RF, magnets, beam physics, advanced concepts, targets & sources, etc):

- All these items have broad applicability across future accelerators with ideas generated by Universities and labs
- R&D is key to enable facilities for neutrinos, rare processes and colliders

Physics motivation and strategic planning

- The physics drivers for a future High Energy Physics colliders are well documented by community planning, e.g.
  - US "Snowmass" process
  - European Strategy for Particle Physics

P5 recommendation 24:

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

HEPAP Accelerator R&D Subpane

Recommendation 5b. Form a focused U.S. high- that is coordinated with global design studies for a collider. The over-arching goal is a large improvem

Recommendation 5c. Aggressively pursue the de suitable for use in a very high-energy proton-proto

Recommendation 5d. Establish and execute a hi conducting (HTS) material and magnet developme milestones to demonstrate the feasibility of cost-e using HTS.

Recommendation 5e. Engage industry and manu disciplines to explore techniques to both decrease the overall reliability of next-generation supercond

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

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 ics community should ramp up its efforts / accelerator technologies, in -field superconducting magnets, rature superconductors." der consideration include high-field rature superconductors, plasma n and other high-gradient accelerating on beams, energy revovery linacs."

nature

Explore content ⌄ About th ... n with us ⌄ Subscribe

nature

First impressions coming out of Snowmass!

NEWS | 08 August 2022

Particle physicists want to build the world's first muon collider

The accelerator would smash together this heavier version of the electron and, researchers hope, discover new particles.

Elizabeth Gibney

s Summer Study closeout

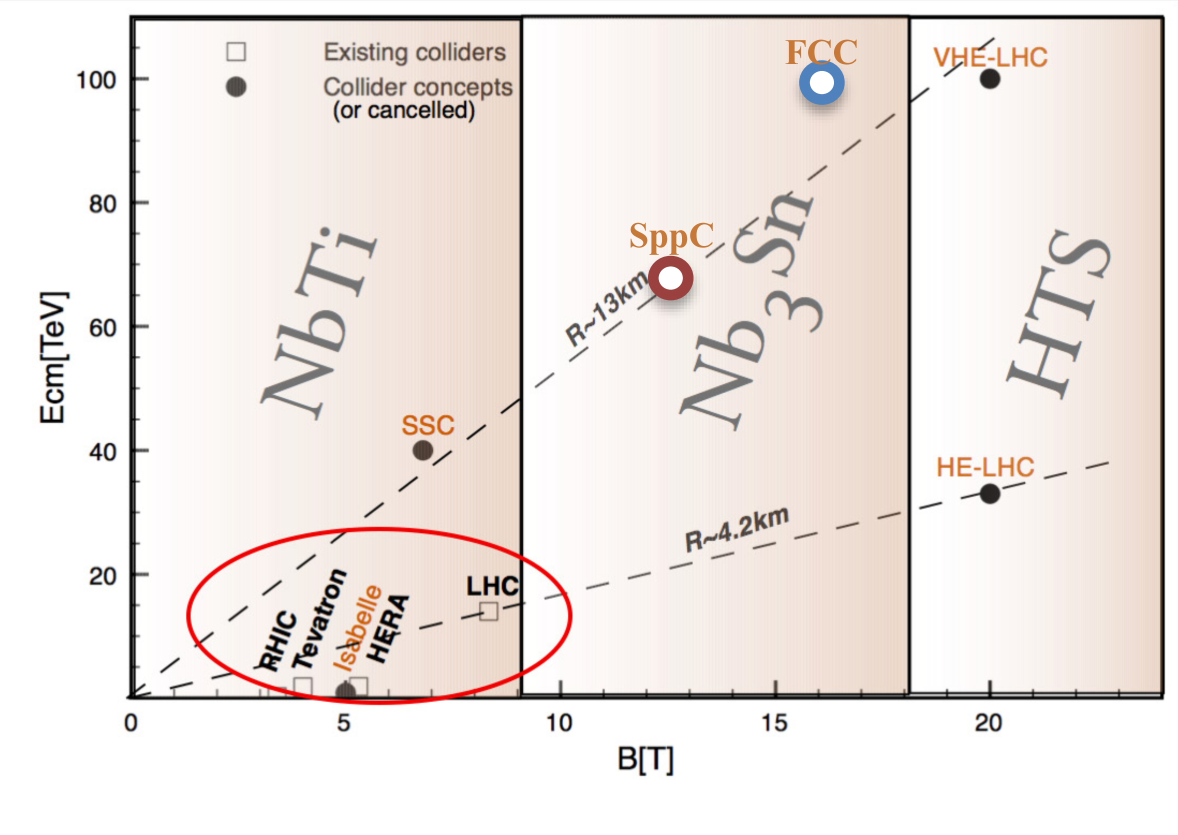
ator Frontier "Message"

ave an ongoing R&D program aimed at am physics and long-term accelerator chnologies (RF, magnets, beam physics, epts, targets & sources, etc):

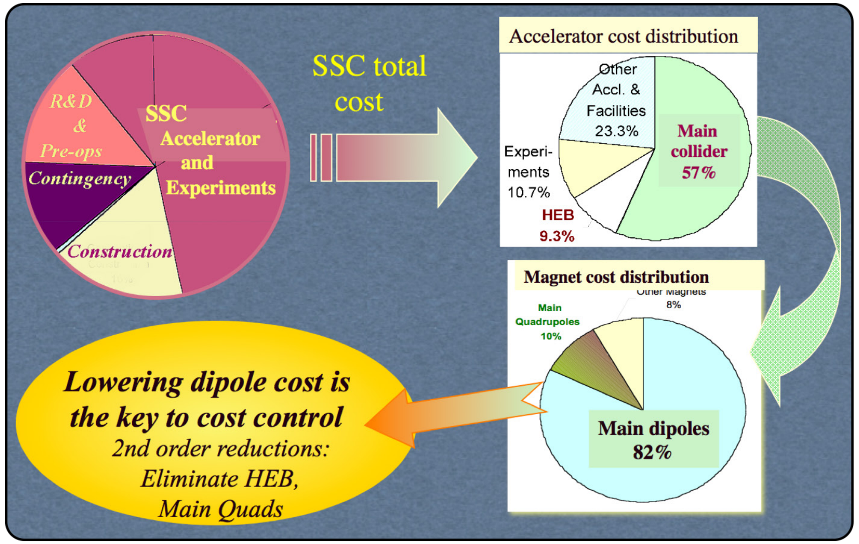
s have broad applicability across future with ideas generated by Universities and labs

- R&D is key to enable facilities for neutrinos, rare processes and colliders

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



Cost/performance is the critical metric

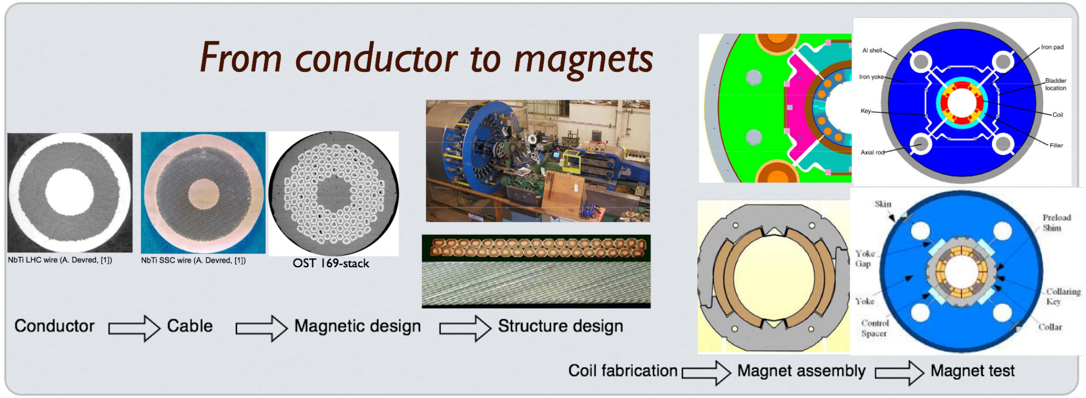


Barletta

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

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

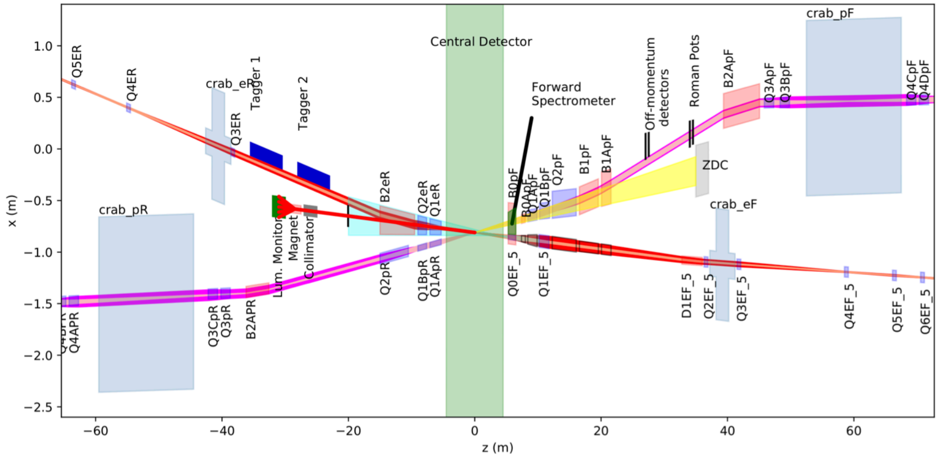
*L. Rossi, "TOE" talk



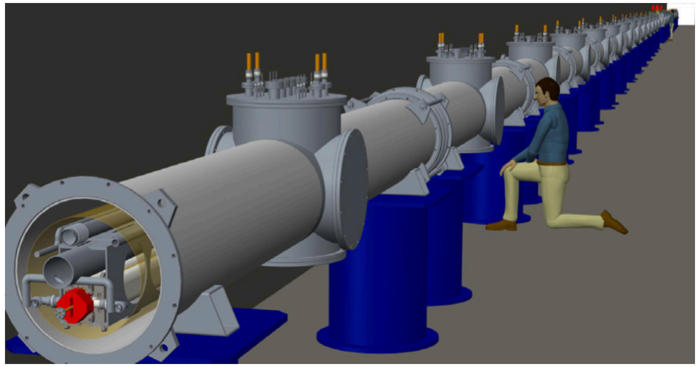
Dominant cost drivers for a pp collider: Magnets and tunnel

Advanced superconducting magnets impact DOE-SC more broadly

- Critical to Nuclear Physics:
  - EIC – complex interaction region magnets
  - FRIB – high power ECR sources
  - JLAB – central to 12GeV Upgrade
- Critical to Basic Energy Sciences
  - Novel end station magnets
  - Superconducting undulators
- Central to Fusion Tokamaks and Stellarators
  - Particularly for compact Tokamaks

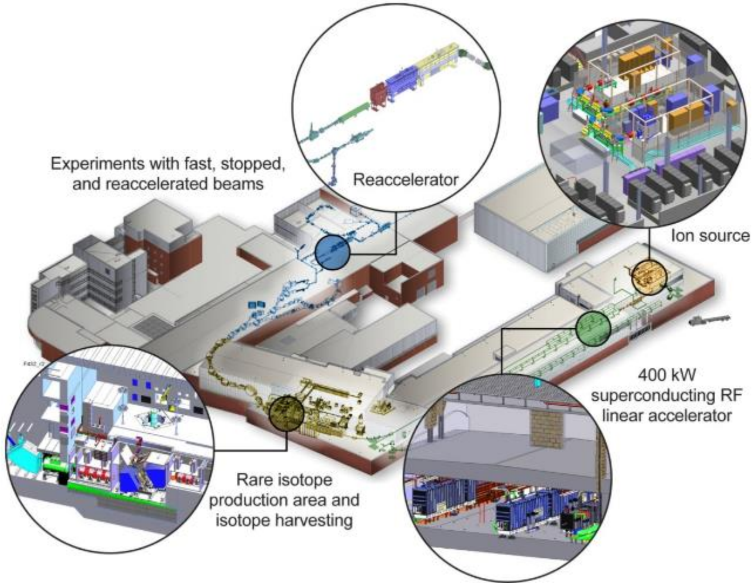


H. Witte et al., IPAC 2021, doi:10.18429



P. Emma et al., Proceedings of FEL2014

Zhang & Calvi, Supercond. Sci. Technol. 35 (2022)



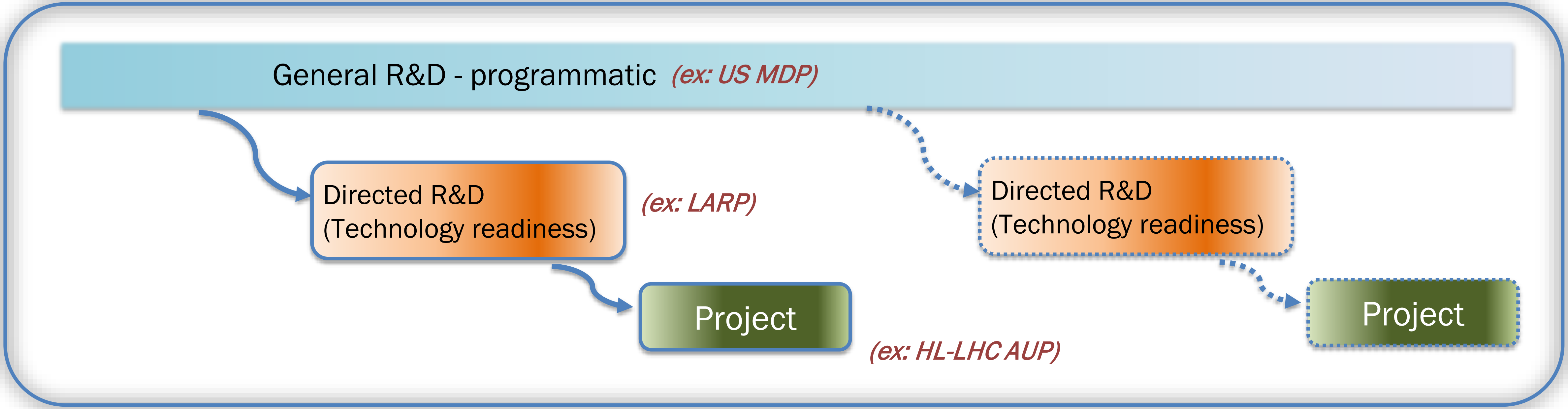
J. Wei et al., this conference!

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

- DOE created the US Magnet Development Program (MDP) in ~2016
- Europe has completed the High Field Magnet Program Roadmap (HFM) *New!*

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

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



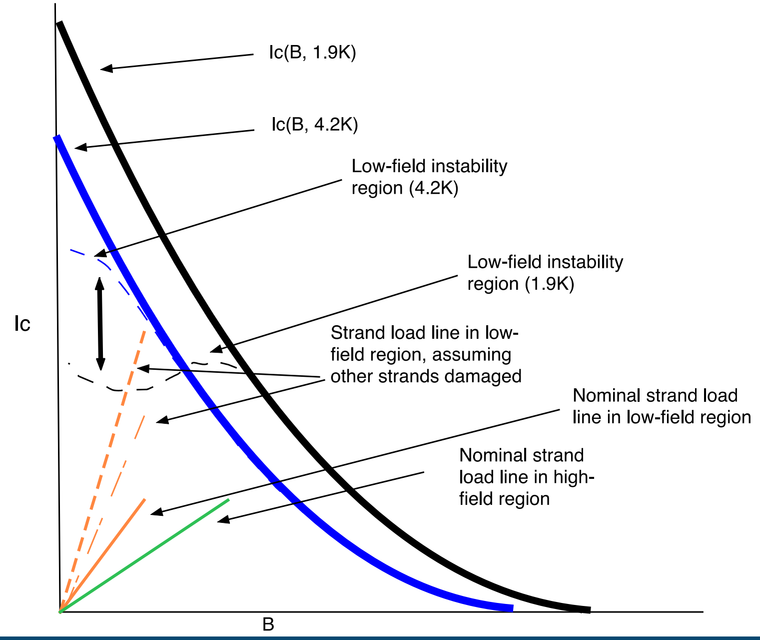
The US DOE approach balances long-range R&D and project preparation

Key challenges for high field magnets and associated superconductors

- Challenge 1: Mechanics of magnets and superconductors
  - Superconductors in accelerator magnets are subjected to complex stress and strain states
    - Stem from magnet fabrication processes, differential thermal contractions during cooldown, and Lorentz forces during operation
    - Wind-and-react approaches introduce additional constraints on materials and processes
  - The conductor properties are intimately affected by strain
    - Nb_3Sn, REBCO, and Bi2212 are particularly strain-sensitive
      - ***Irreversible*** regime needs to be avoided for accelerator application => impacts specs
      - Reversible element needs to be considered in design for high-field magnets

- Challenge 2: Improving conductor transport performance – with caveats…
  - Higher J_{eng} => higher efficiency => reduces conductor volume => reduces magnet size

    => *may* translate into lower cost and/or more operating margin
    - Caveats (Nb_3Sn):
      - Flux jump instabilities => need to reduce subelement diameter along with improved J_c
    - Caveats (Nb_3Sn, HTS):
      - Magnet protection must address J_{Cu} during quench and extract energy to limit hot-spot
      - Higher J_{eng} translates into higher stresses => magnet design needs to address mechanics



Key challenges for high field magnets and associated superconductors

- Challenge 3: Diagnosing and characterizing magnet and conductor performance
  - Magnet:
    - In-situ measurements of stress/strain provide critical feedback to magnet design
    - Magnetic field measurements (multipoles, including at ends)
  - Conductor:
    - Ic, RRR are (of course) critical
    - Microstructure and insight into failure mechanisms are extremely valuable

- Challenge 4: Accelerating the conductor-magnet feedback loop
  - The time-constants for magnet design-fabrication-test, and for conductor development, are long:
    - New high field accelerator magnet designs take years to bring to fruition
    - Development of new conductor architectures can easily take 5-10 years

    =>To expedite the feedback loop we implement subscale and mirror magnet configurations

    => Are there new paradigms that can expedite conductor development?

  - A steady flow of conductor procurements is essential:
    - Provides continuity to industry to maintain and develop processes and to innovate
    - Provides timely conductor for magnet fabrication and testing

Integrated programs share common themes, but unique perspectives

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:

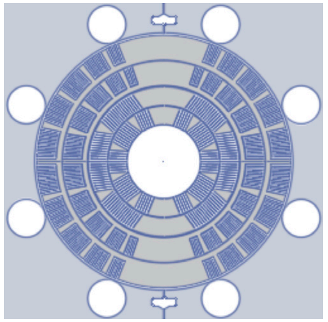
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

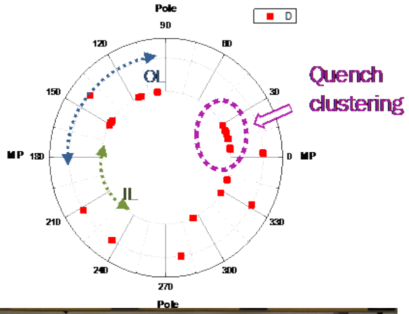
GOAL 4:

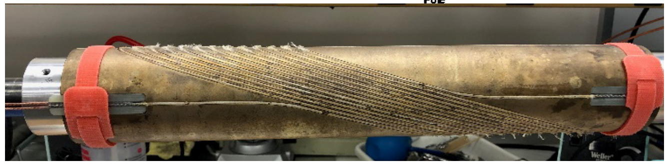
Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

Strategic directions for the update plan:

- *Probing stress management structures*
- *Hybrid HTS/LTS designs*
- *Understanding and impacting the disturbance-spectrum*
- *Advancing both LTS and HTS conductors, optimized for HEP applications*







Integrated programs share common themes, but unique perspectives

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:

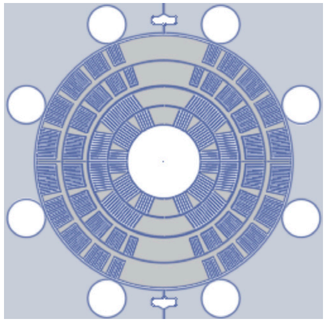
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

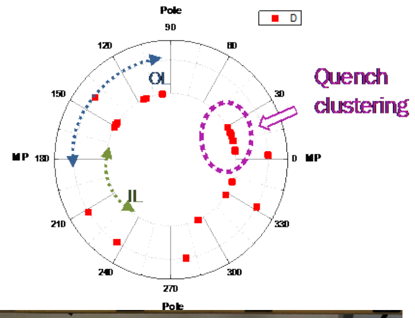
GOAL 4:

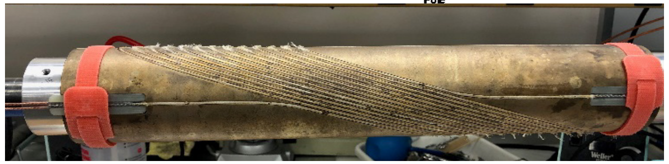
Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

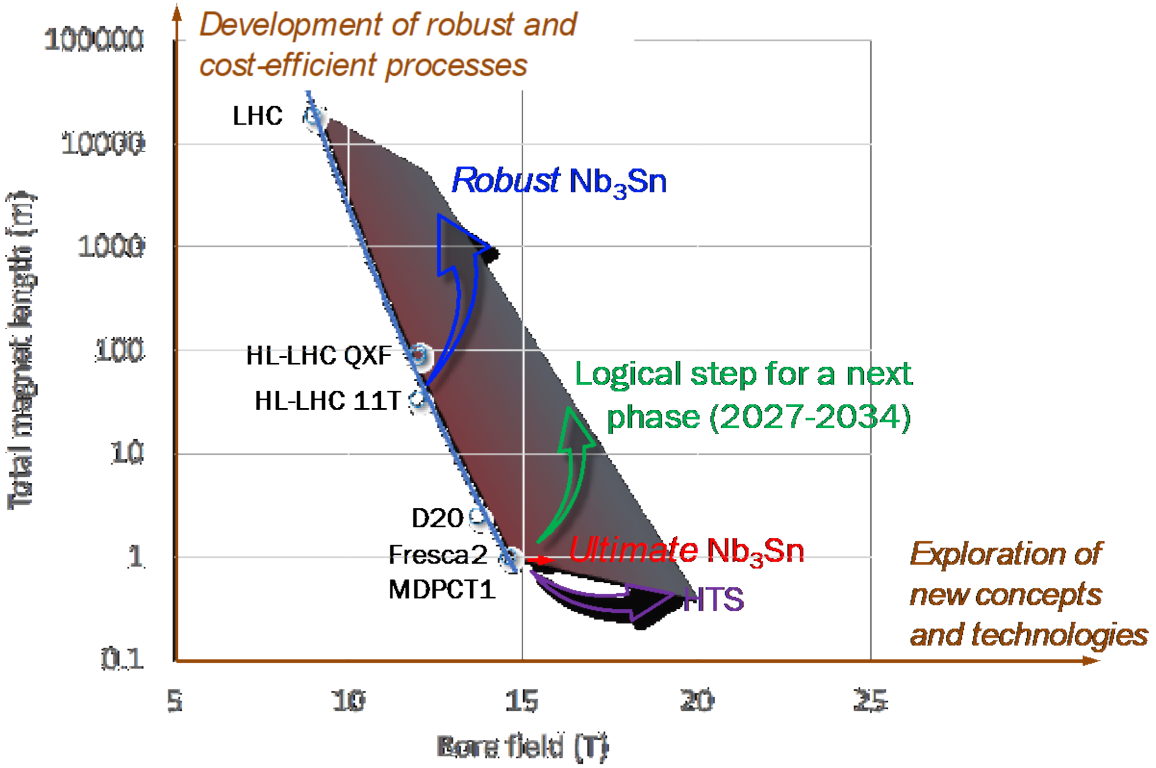
Strategic directions for the update plan:

- *Probing stress management structures*
- *Hybrid HTS/LTS designs*
- *Understanding and impacting the disturbance-spectrum*
- *Advancing both LTS and HTS conductors, optimized for HEP applications*









Courtesy Luca Bottura

Integrated programs share common themes, but unique perspectives

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:

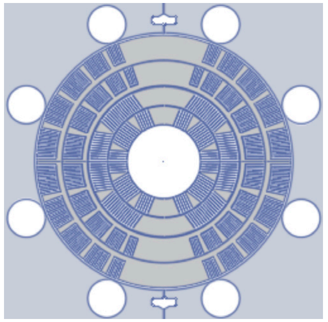
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

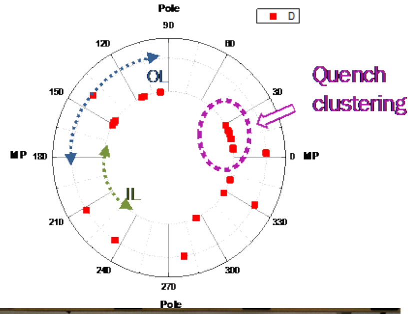
GOAL 4:

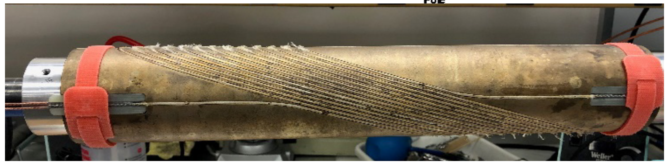
Pursue Nb_3Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

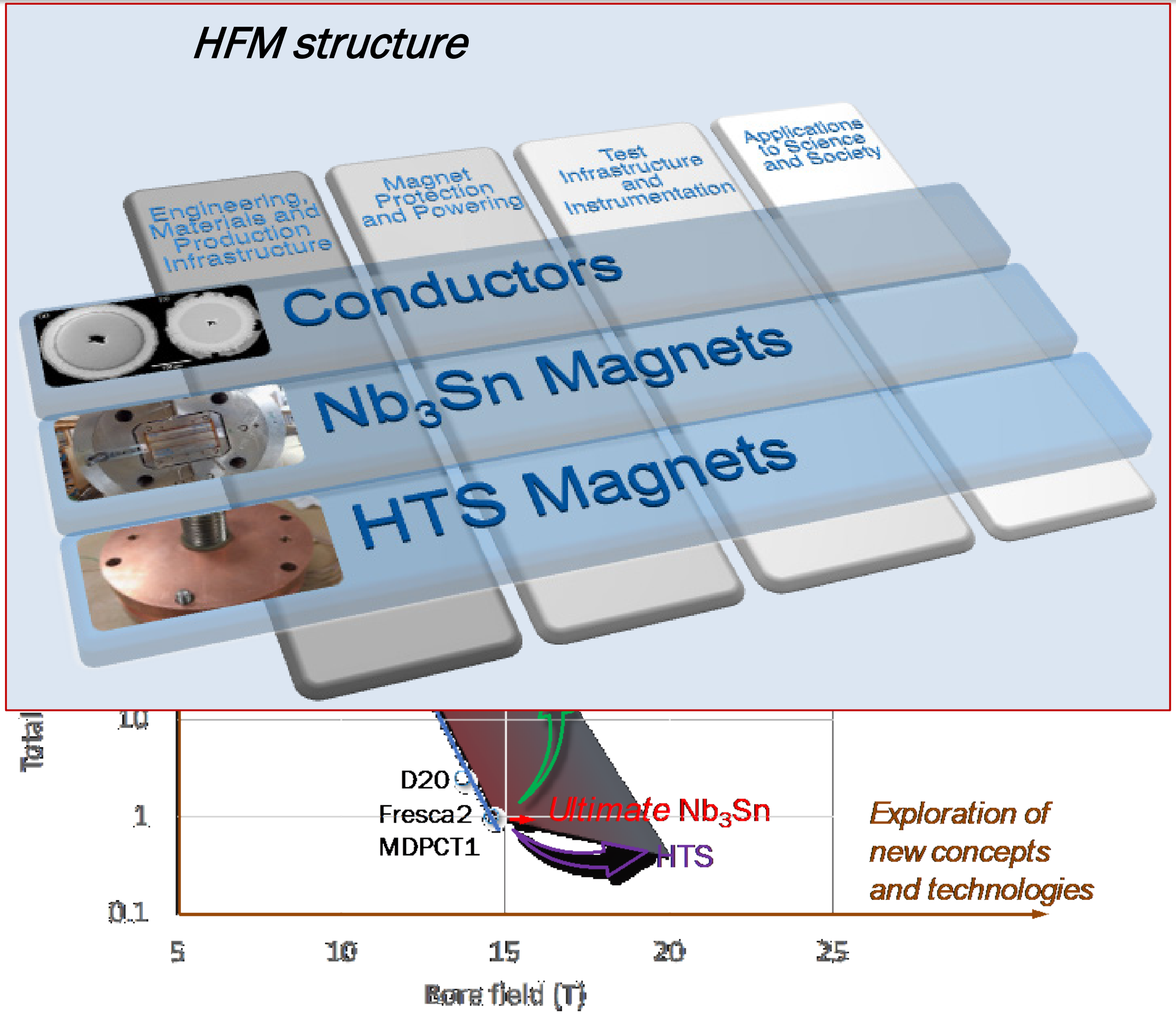
Strategic directions for the update plan:

- *Probing stress management structures*
- *Hybrid HTS/LTS designs*
- *Understanding and impacting the disturbance-spectrum*
- *Advancing both LTS and HTS conductors, optimized for HEP applications*









Courtesy Luca Bottura

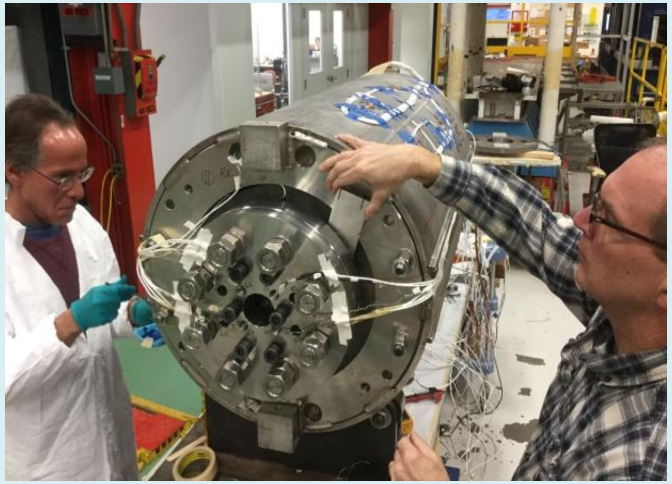
US MDP Program strategy & goals: driving questions re: performance

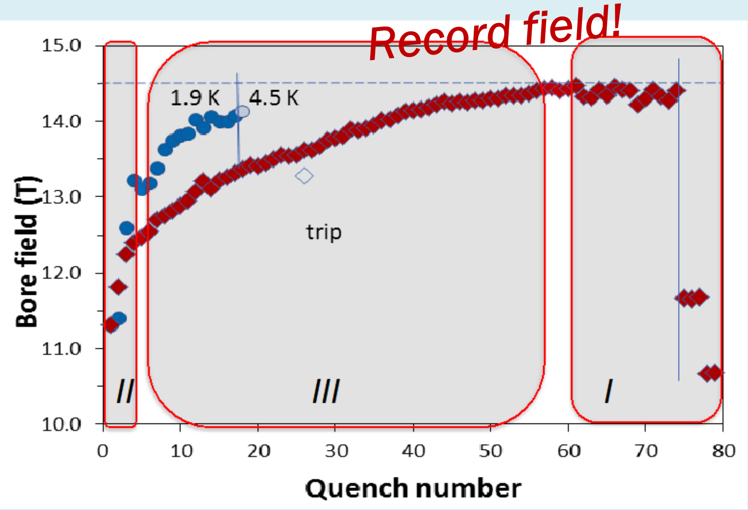
U.S. MAGNET DEVELOPMENT PROGRAM

- Ultimate Performance of Magnets
  - What is the nature of accelerator magnet training? Can we reduce or eliminate it?
  - How do we best define operating margin for Nb_3Sn and HTS accelerator magnets, and to what degree can and should it be minimized?
  - Can we control the disturbance spectrum and engineer a magnet response to reduce operating margin and enhance reliable performance?
  - What are the mechanical limits and possible stress-management approaches for Nb_3Sn, HTS, and 20 T hybrid LTS/HTS magnets, and do they have defined mechanical limits?
  - Do hybrid designs benefit from the best features of LTS and HTS, or inherit the difficulties of both material technologies?

Example: MDP 4-layer, 60mm bore cosine-theta magnet led by FNAL

A. Zlobin et al., DOI:10.1109/TASC.2021.3057571





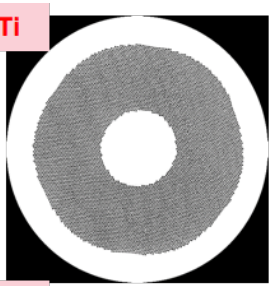
[I]: Highest priority issue: ***degradation*** Mechanisms; design mitigation

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

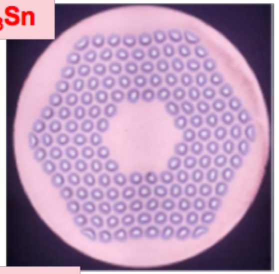
[III]: Third priority: ***Training rate***

Magnets start with the superconductor – “low” and “high” temperature

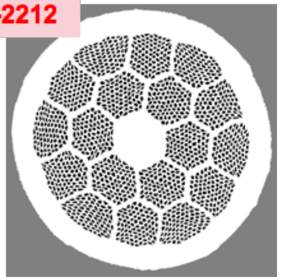
Nb-Ti

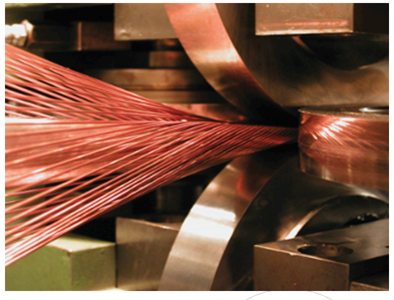


Nb_3Sn

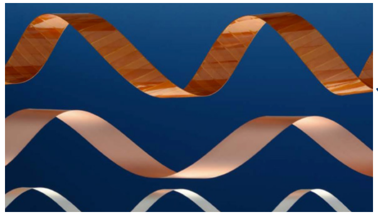


Bi-2212

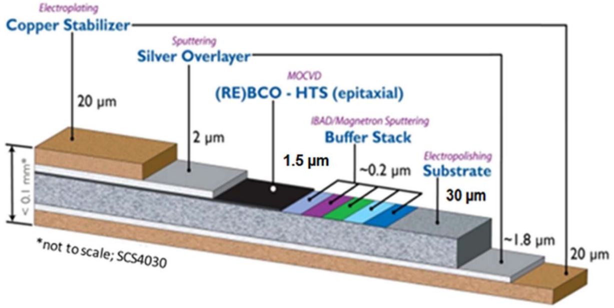


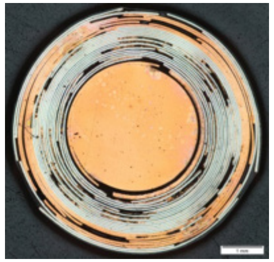


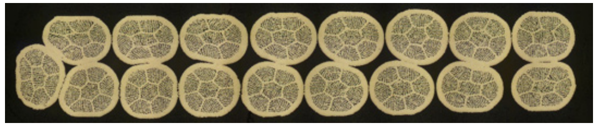
REBCO



SuperPower Inc

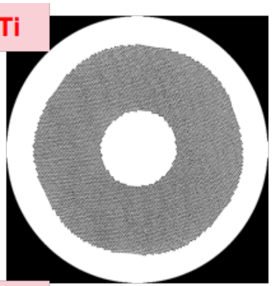




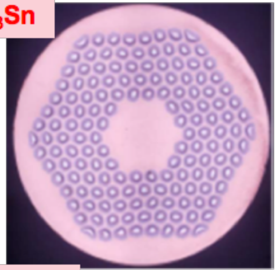


Magnets start with the superconductor – "low" and "high" temperature

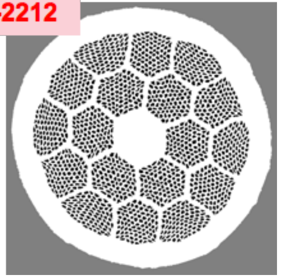
Nb-Ti

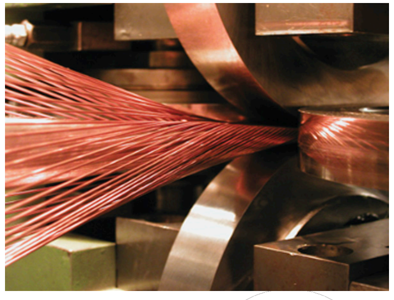


Nb_3Sn

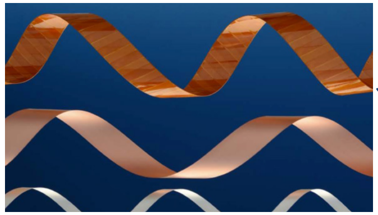


Bi-2212

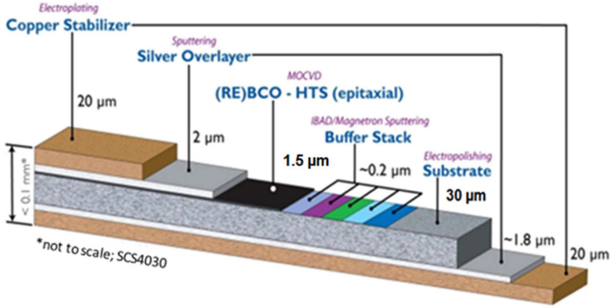


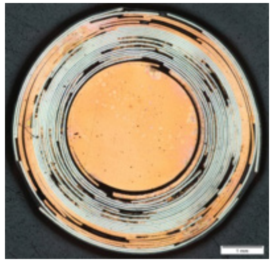


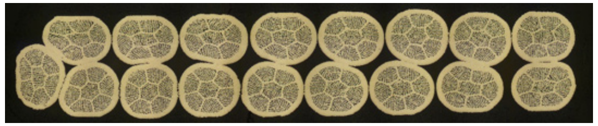
REBCO



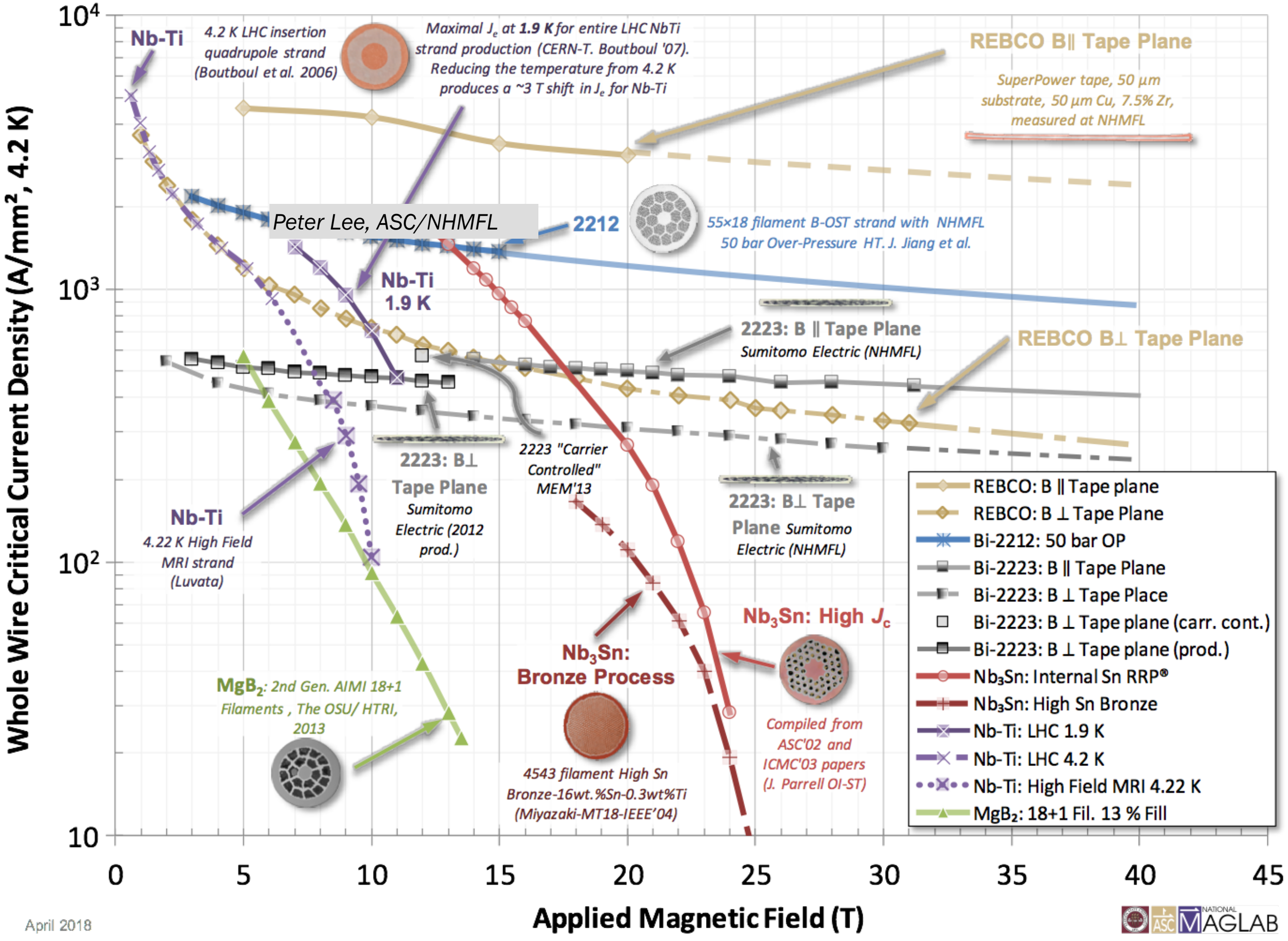
SuperPower Inc







Peter Lee, ASC/NHMFL

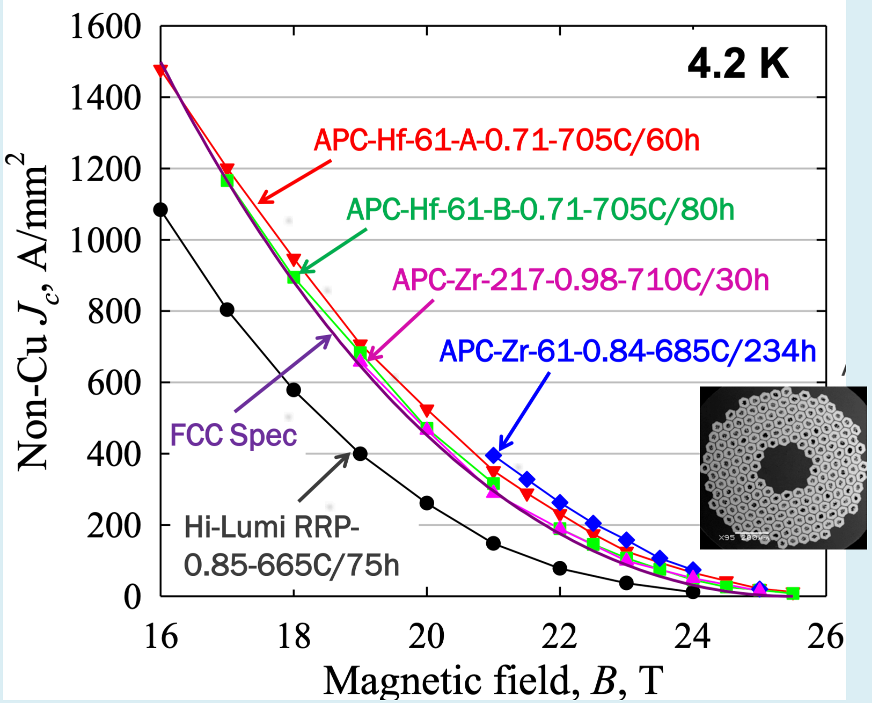


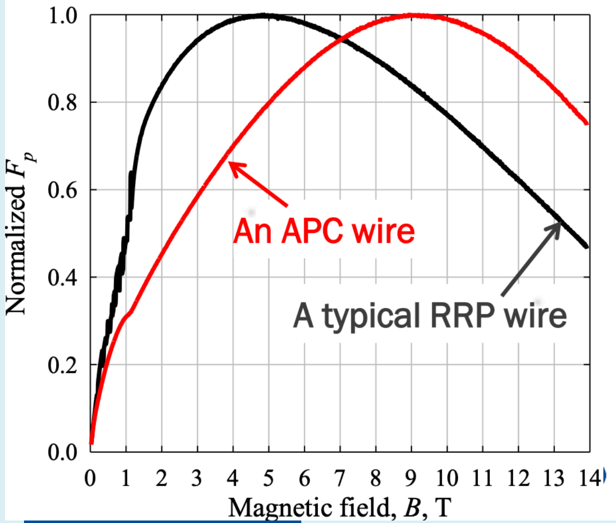
Significant advances in Nb_3Sn by introducing new pinning sites

U.S. MAGNET DEVELOPMENT PROGRAM

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

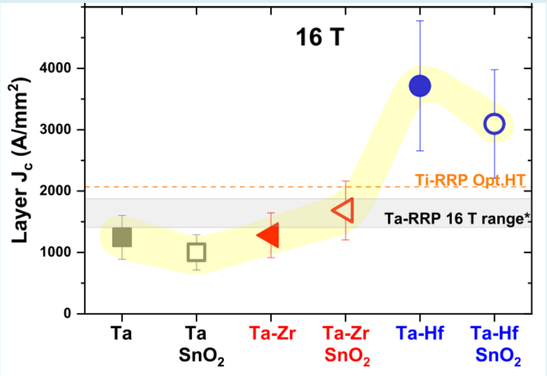
X. Xu, SoftA Workshop, CERN, 2021
See also Xu et al., J. AlloyCompd.857,158270(2021)





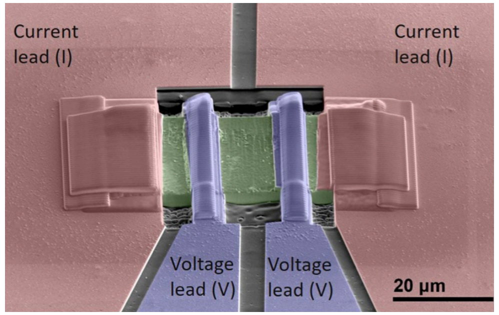
Fermilab

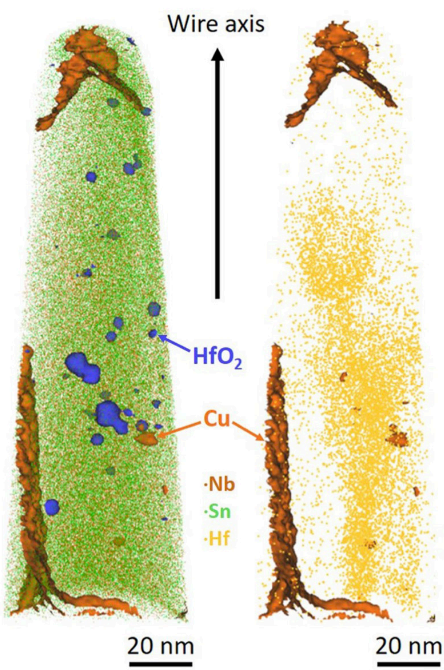
Hyper Tech Research, Inc.



S. Balachandran et al 2019 SUST 32

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

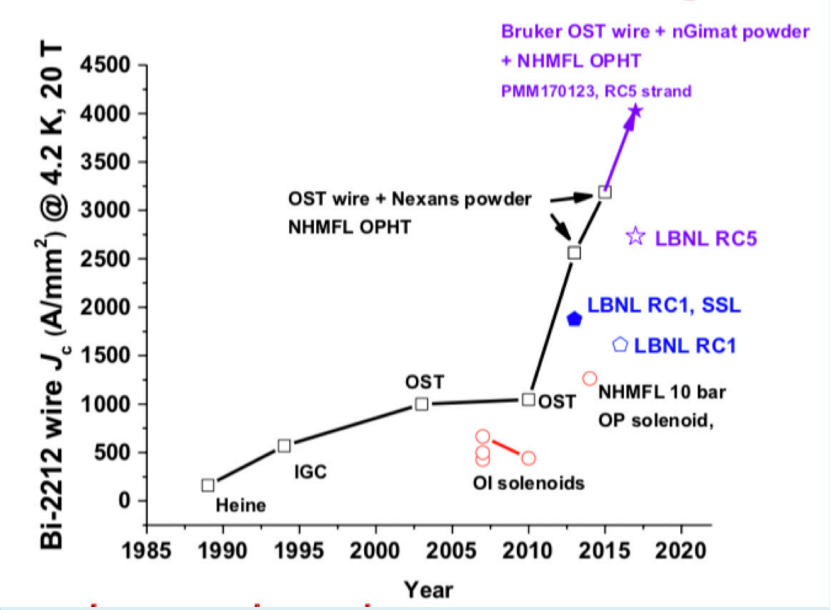


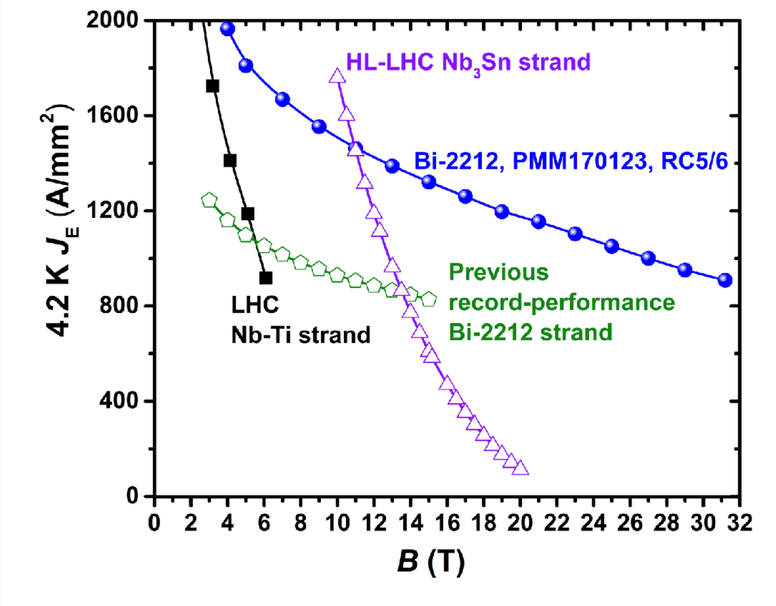


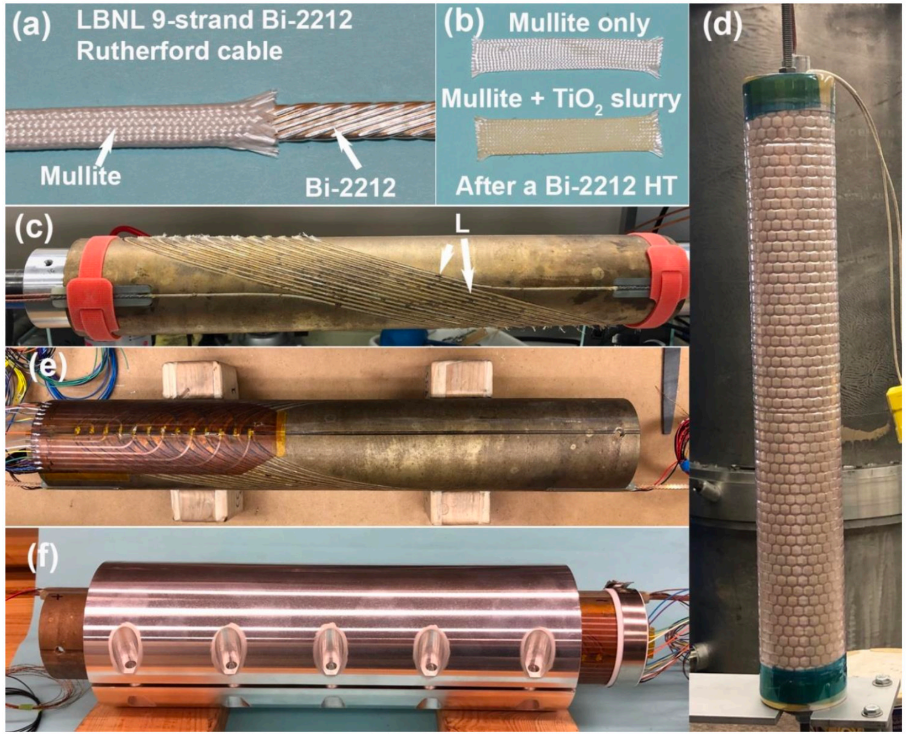
The HTS material Bi2212 has made dramatic strides

U.S. MAGNET DEVELOPMENT PROGRAM

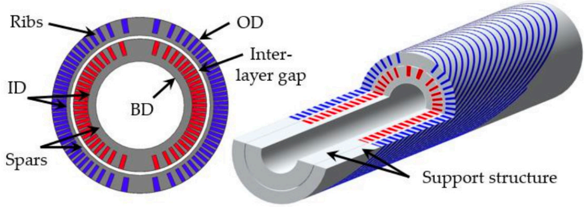
- Round isotropic wire
- Requires challenging heat treatment
- MDP working towards hybrid magnet test

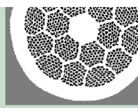






Shen & Fajardo, Instruments 2020



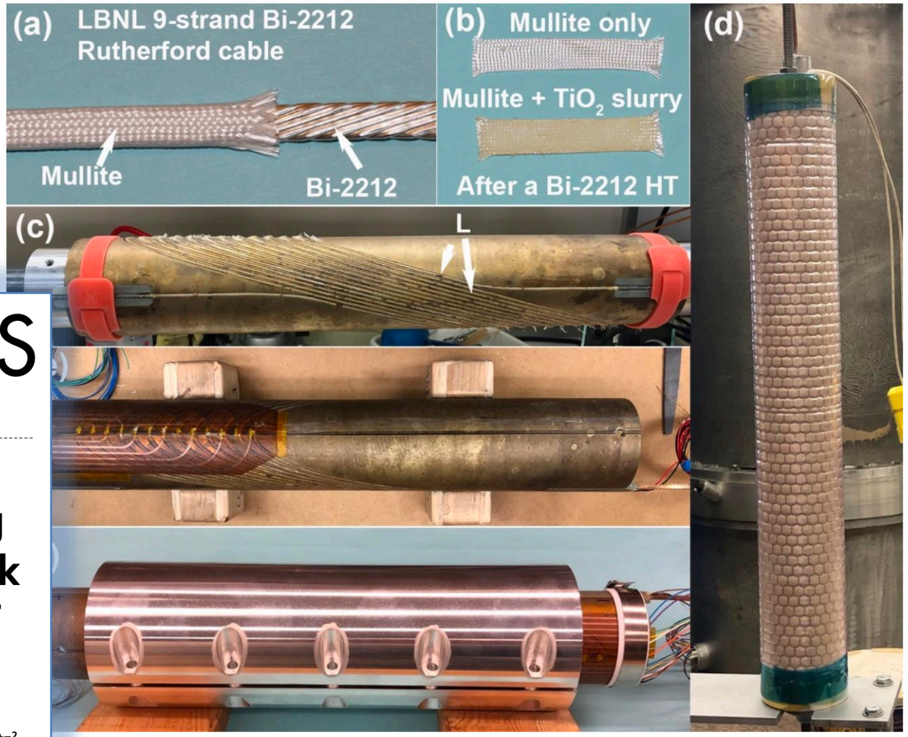


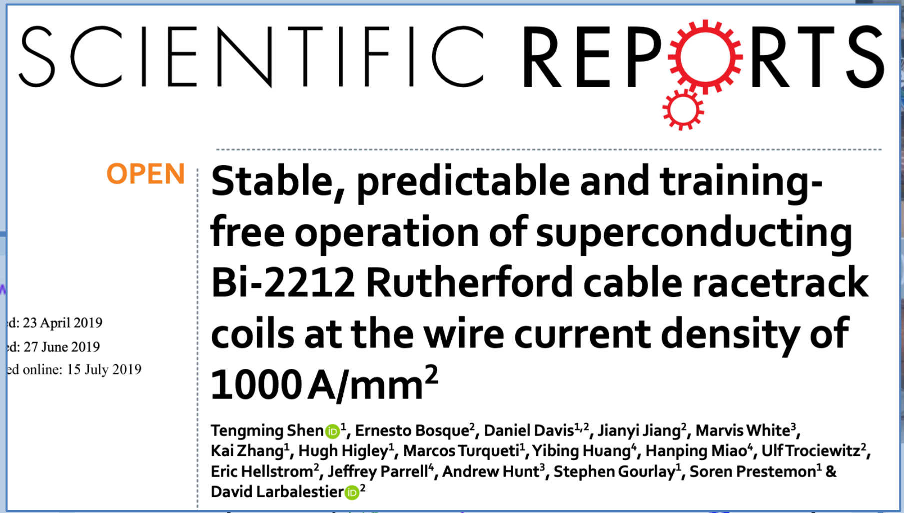
nGimat
NATIONAL MAGLAB
BRUKER
BERKELEY LAB

The HTS material Bi2212 has made dramatic strides

U.S. MAGNET DEVELOPMENT PROGRAM

- Round isotropic wire
- Requires challenging heat treatment
- MDP working towards hybrid magnet test



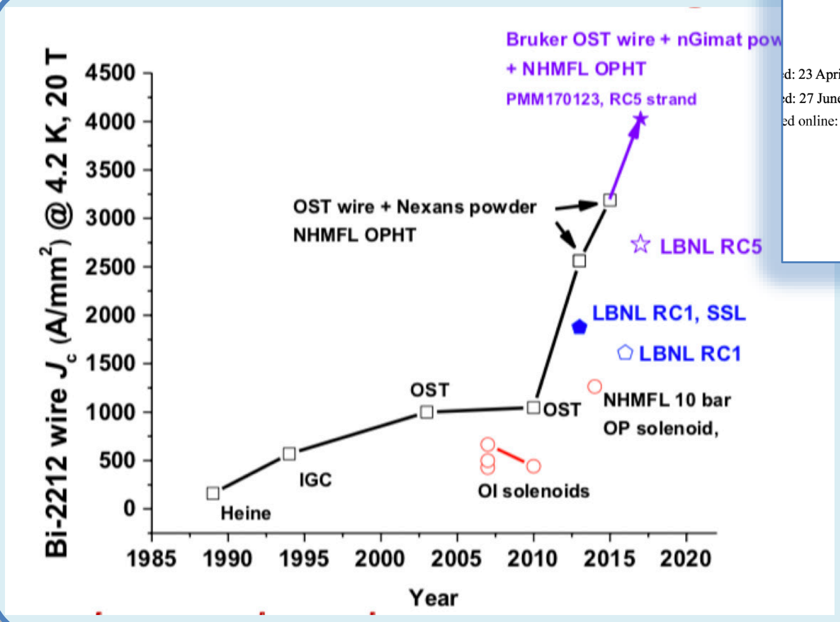

SCIENTIFIC REPORTS

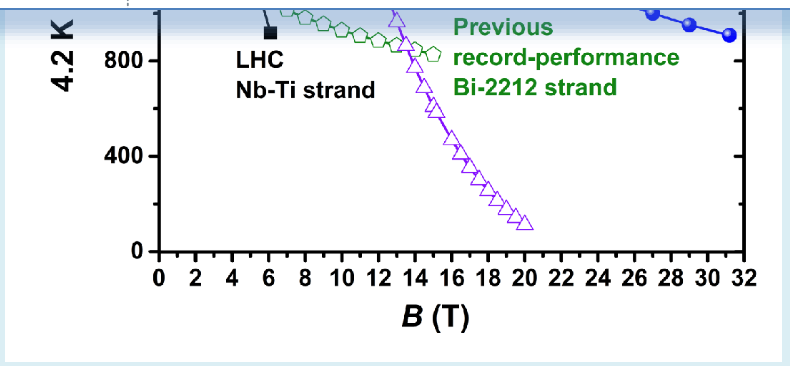
OPEN

d: 23 April 2019
d: 27 June 2019
d online: 15 July 2019

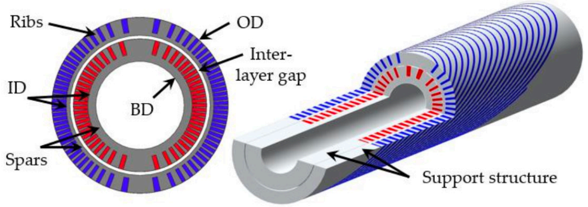
Stable, predictable and training-free operation of superconducting Bi-2212 Rutherford cable racetrack coils at the wire current density of 1000 A/mm²

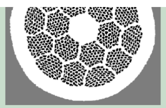
Tengming Shen[1], Ernesto Bosque[2], Daniel Davis[1,2], Jianyi Jiang[2], Marvis White[3], Kai Zhang[1], Hugh Higley[1], Marcos Turqueti[1], Yibing Huang[4], Hanping Miao[4], Ulf Trociewitz[2], Eric Hellstrom[2], Jeffrey Parrell[4], Andrew Hunt[3], Stephen Gourlay[1], Soren Prestemon[1] & David Larbalestier[2]





Shen & Fajardo, Instruments 2020

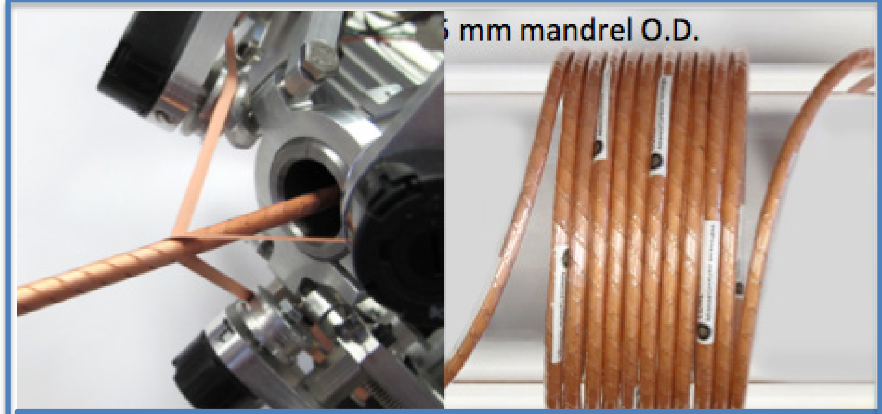




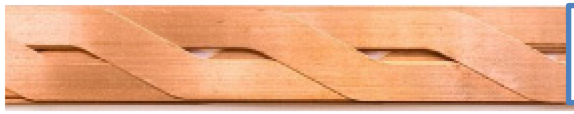
nGimat
NATIONAL MAGLAB
BRUKER
BERKELEY LAB

HTS material REBCO has broad appeal, significant growth

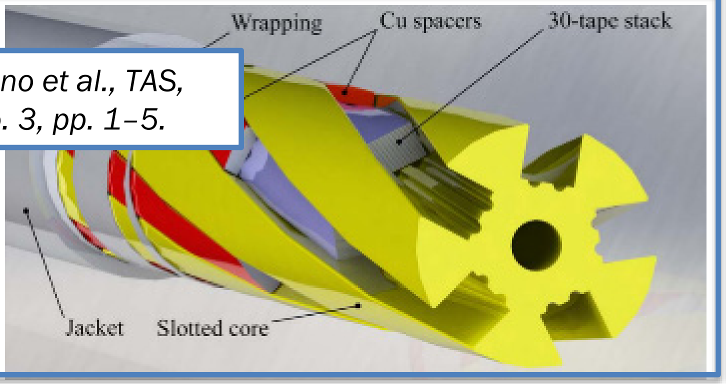
- Produced in tape form, no reaction needed
- Many international suppliers
  - A few scaling up production significantly to meet demand from fusion
  - Potential for significant cost reduction, but not manifesting yet
- Anisotropic properties
  - Ic, mech., magnetic
- Cable architectures being explored/developed
  - HEP, FES
  - Does current sharing make REBCO cables tolerant of flaws?



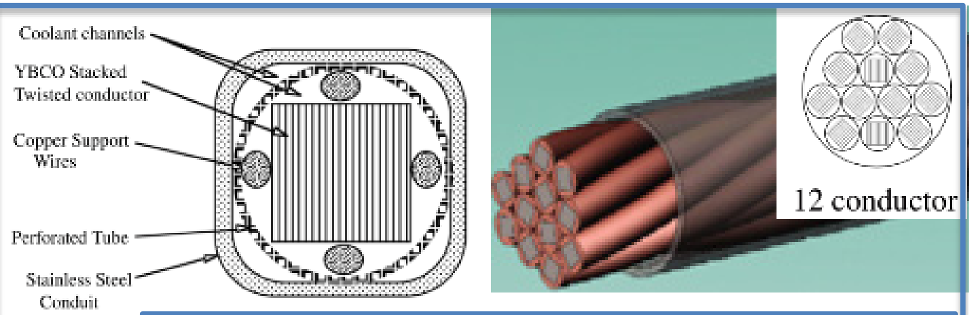
D. van der Laan, Advanced Conductor Technologies LLC



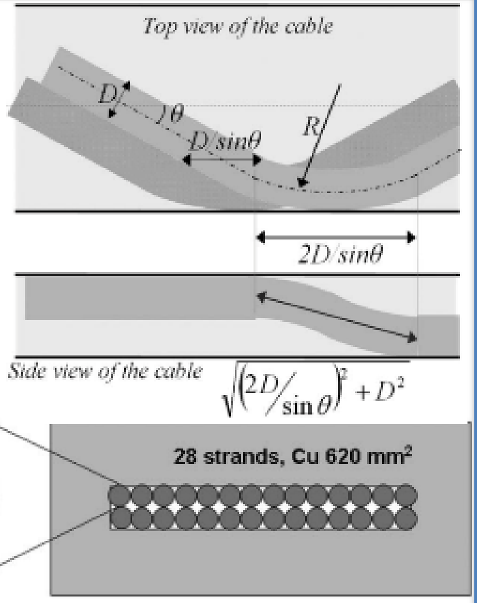
W. Goldacker et al., TAS 17 3396–401



G. Celentano et al., TAS, vol. 24, no. 3, pp. 1–5.



M. Takayasu, L. Chiesa, L. Bromberg, and J. V. Minervini, SUST, vol. 25, no. 1, Jan. 2012.



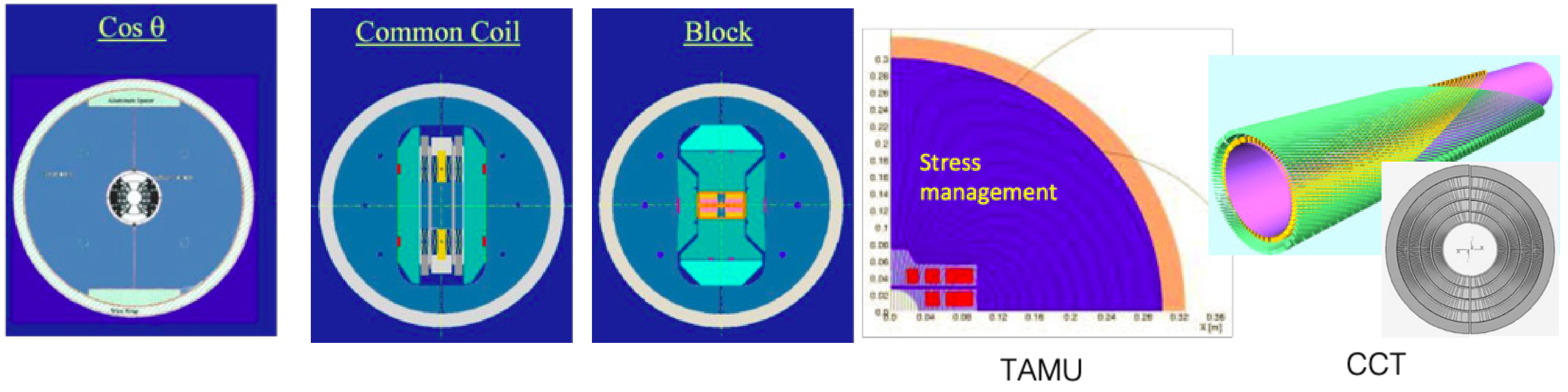
D. Uglietti, R. Wesche, and P. Bruzzone, TAS, vol. 24, no. 3, pp. 1–4.

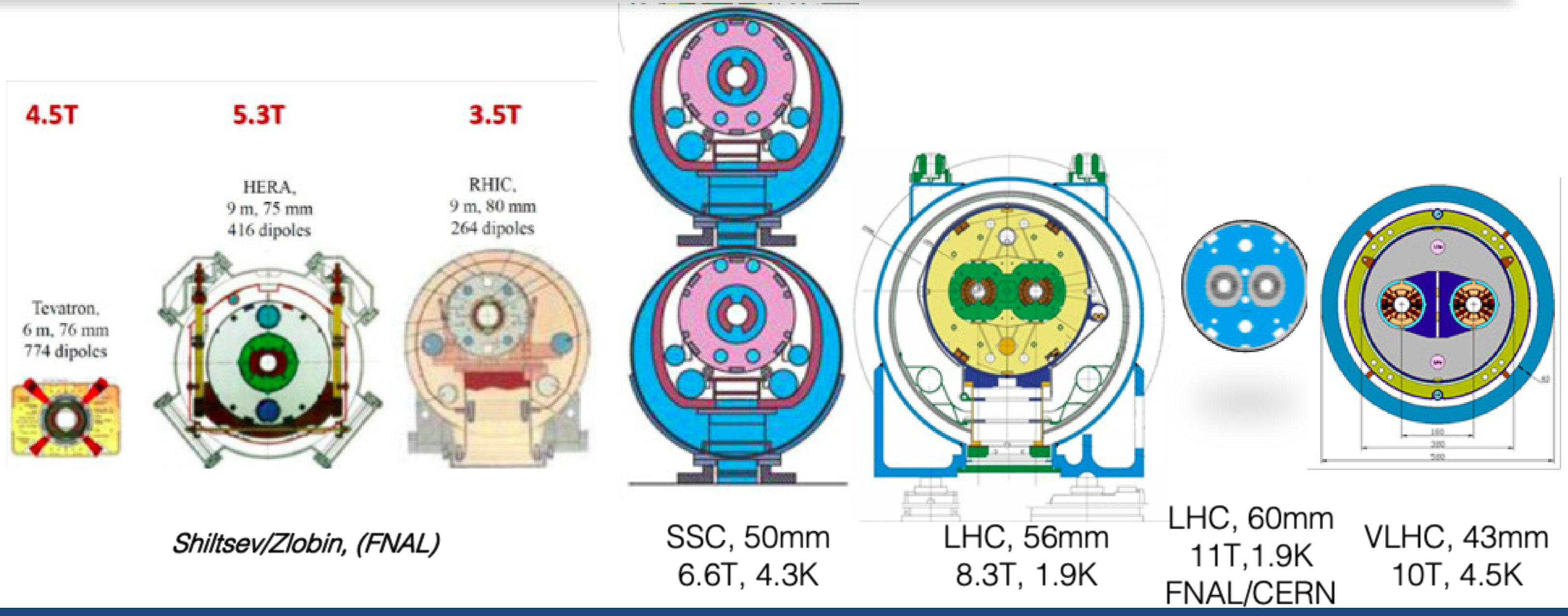
The "magnet zoo" in colliders are (to-date) all based on Cos(t) designs

U.S. MAGNET DEVELOPMENT PROGRAM

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

- At high field and/or large bore, "managing" stress through judicious force interception will be required





Stress-managed structures avoid force accumulation - at the expense of more interfaces

U.S. MAGNET DEVELOPMENT PROGRAM

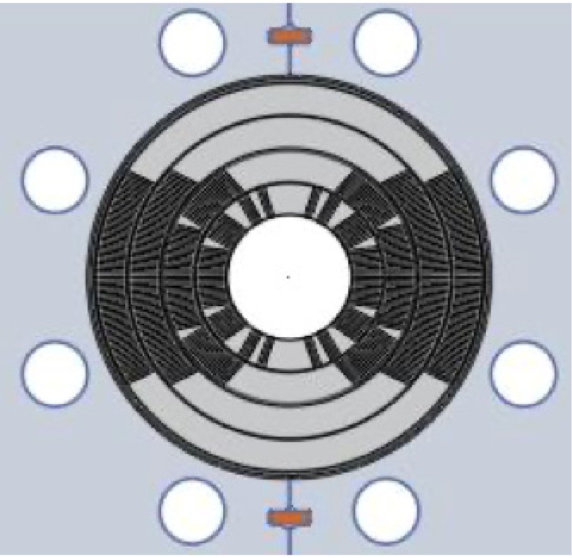
- ***Interception of azimuthal forces*** holds promise to enable high-field and large-bore dipoles – break the traditional scaling of stress with bore and field
- Use new design concepts as opportunity to introduce ***cost-effective fabrication processes***

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

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

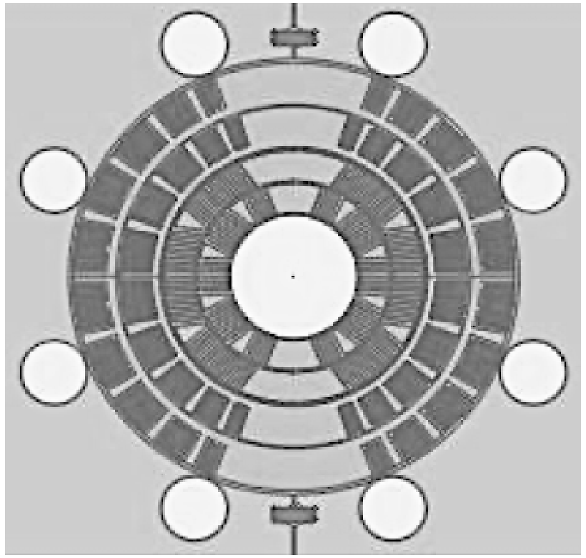
"Traditional" Cos-theta

- Midplane stress due to azimuthal force accumulation



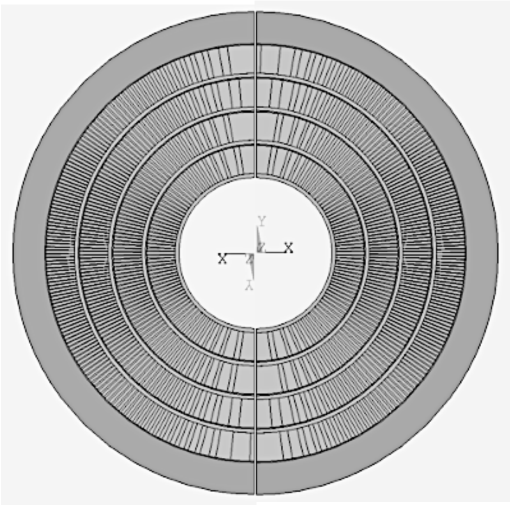
"Stress-managed" Cos-theta

- Groups of turns, azimuthal forces intercepted by support



"Canted" Cos-theta

- Every turn has azimuthal forces intercepted by support



For very high field magnets, a "hybrid" HTS/LTS approach is most efficient

U.S. MAGNET DEVELOPMENT PROGRAM

- Design studies underway to explore 20+T dipole concepts
  - Optimal use of superconductor
  - Comparative study
  - Identify research directions

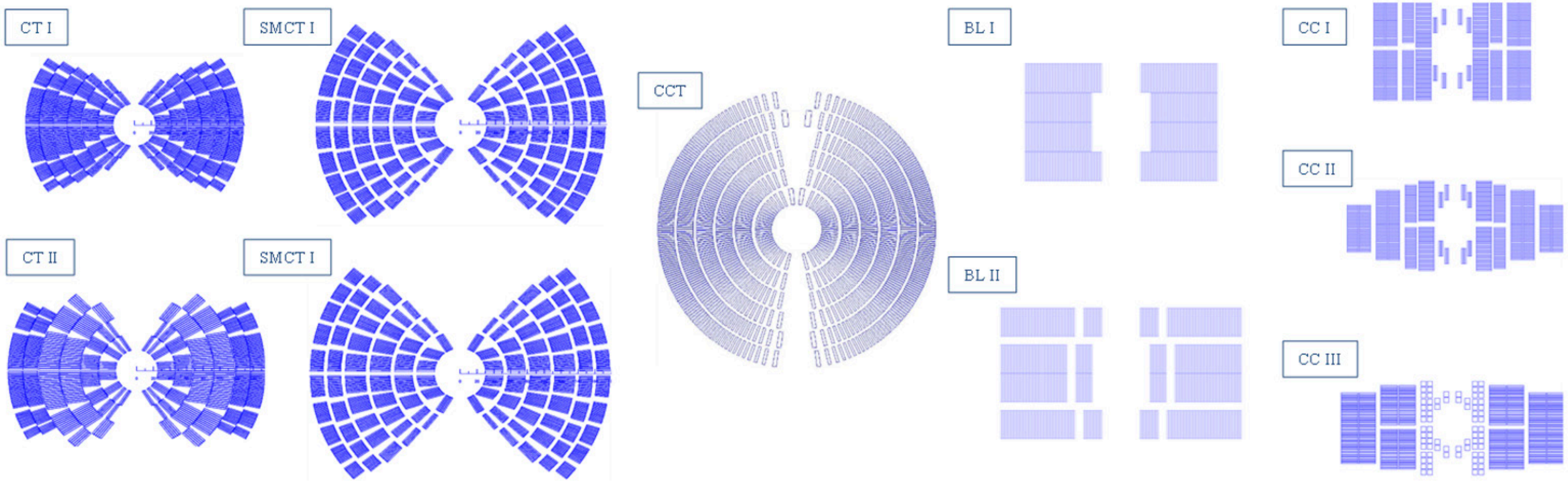


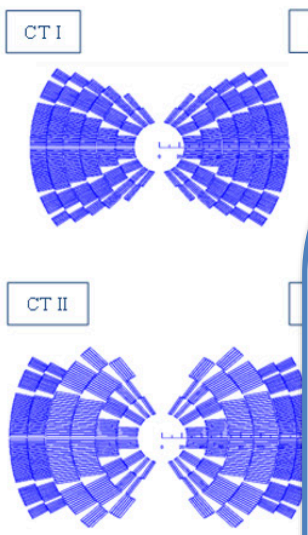
Fig. 6. Cross-sections of 20 T hybrid dipole coils. The designs use consistent conductor properties, but are at different stages of the analysis in terms of field quality, mechanics, and quench protection: *therefore, they are not comparable among them.* From left two right: Cos-theta (CT) design, with 4 (top) and 2 (bottom) layer Bi2212 coils; Stress management Cos-theta (SMCT) design, with 4 (top) and 2 (bottom) layers Bi2212 coils; Canted Cos-theta (CCT) design, with 4-layer Bi2212 coil; Block (BL) design, with and without stress management; Common Coil (CC) design, with Bi2212 (top, with 3 external Nb_3Sn layers, and center, with 5 external Nb_3Sn layers) and REBCO CORC coils (bottom, with 4 external Nb_3Sn layers). For all the CC designs, only one aperture is shown.

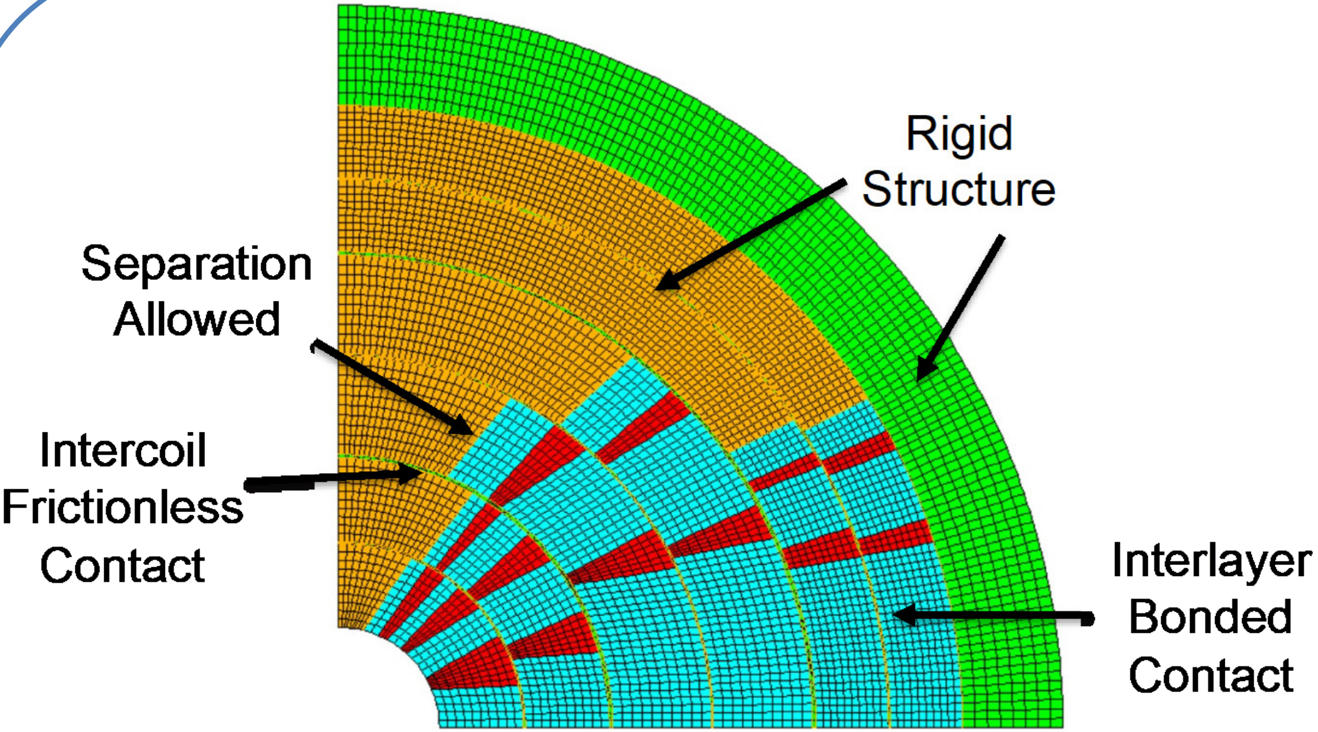
See Snowmass whitepaper *"A Strategic Approach to Advance Magnet Technology for Next Generation Colliders"* arXiv:2203.13985

For very high field magnets, a "hybrid" HTS/LTS approach is most efficient

U.S. MAGNET DEVELOPMENT PROGRAM

- Design studies underway to explore 20+T dipole concepts
  - Optimal use of superconductor
  - Comparative study
  - Identify research directions





Example: "stress-managed Cos(t)" concept, inner 2 coils bi2212; analysis underway to find solutions within conductor degradation limits

See Snowmass whitepaper *"A Strategic Approach to Advance Magnet Technology for Next Generation Colliders"* *arXiv:2203.13985*

Magnet modeling & diagnostics are developing rapidly – key to advancing technology

- “Eyes and ears” on conductor and magnet behavior
  - Guide R&D
  - Critical for magnet protection, operation
- Advances on many fronts:
  - Fiberoptics, acoustics, quench antennae;
  - Modeling, AI/ML, HPC
  - Cryogenic electronics
  - Conductor and cable QC, magnet monitoring

IDSM01 First Workshop on Instrumentation and Diagnostics for Superconducting Magnets

Berkeley, California, USA *24-26 April 2019*

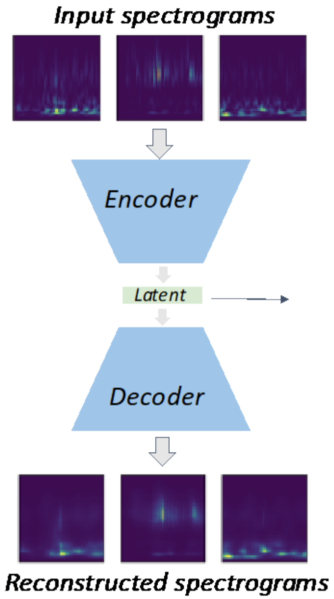
The superconducting magnet community is pushing boundaries of magnet systems operating closer than ever to the stress and current limits of technical superconductors. Obtaining such high performance heavily relies on diagnostic instrumentation and data analysis. We are witnessing a broad effort in developing novel techniques for magnet diagnostics geared towards solving long-standing problems such as training, determining quench origins, and identifying quench-driving factors.

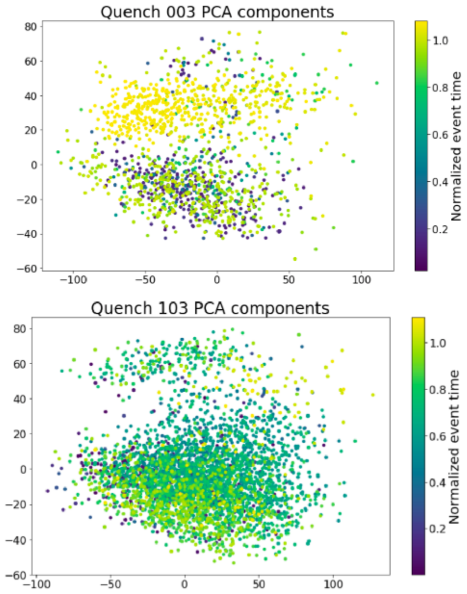
The First Workshop on Instrumentation and Diagnostics for Superconducting Magnets (IDSM01) is aimed at defining a common strategy in diagnostics, and establish a platform for exchanging and circulating new ideas. While focusing on instrumentation and diagnostics, we also welcome contributions on forward-looking, disruptive concepts and ideas relevant to superconducting magnets and their applications.

Machine Learning

Goal: Use unsupervised learning to investigate physics (cracking vs. stick-slip) in magnet quench dataset

Stretch goal: Develop method to predict the quench in real-time





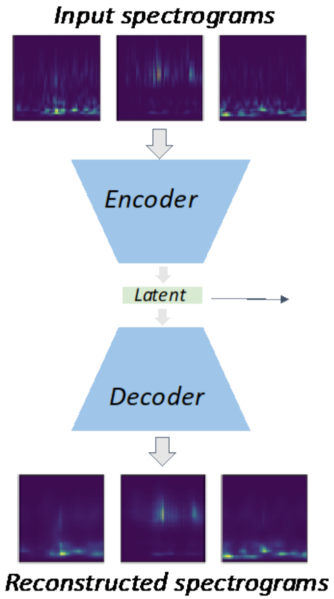
A sampling of diagnostics developments – driven by MDP needs, but with broad impact to magnet technology

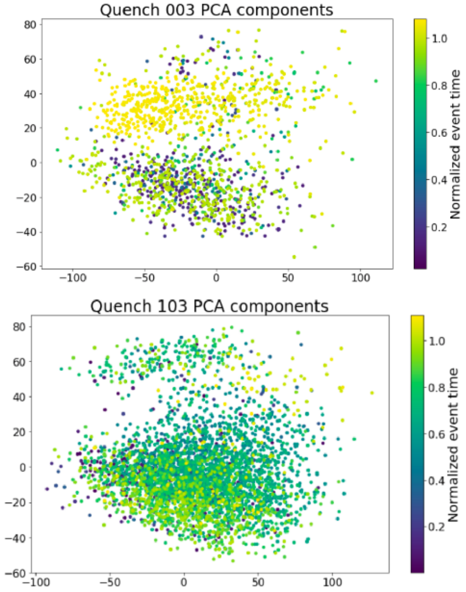
U.S. MAGNET DEVELOPMENT PROGRAM

Machine Learning

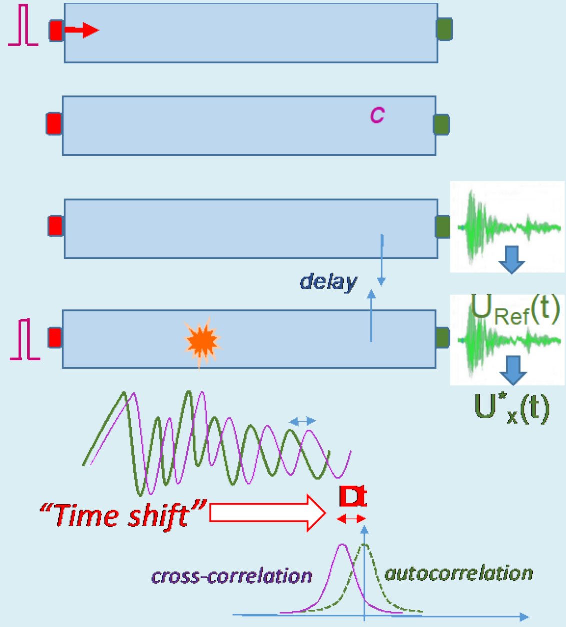
Goal: Use unsupervised learning to investigate physics (cracking vs. stick-slip) in magnet quench dataset

Stretch goal: Develop method to predict the quench in real-time

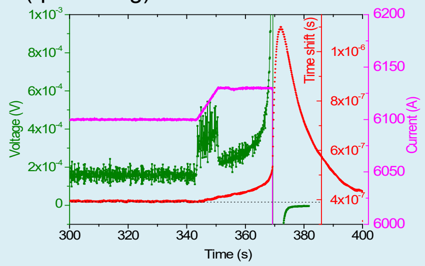




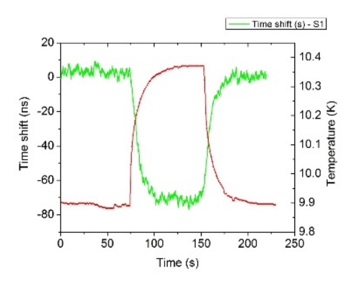
Active acoustics



Experiment at 4.2 K. Current ramp stopped at 6100 A (stable) and then increased by 30 A (quenching)



Acoustic thermometry



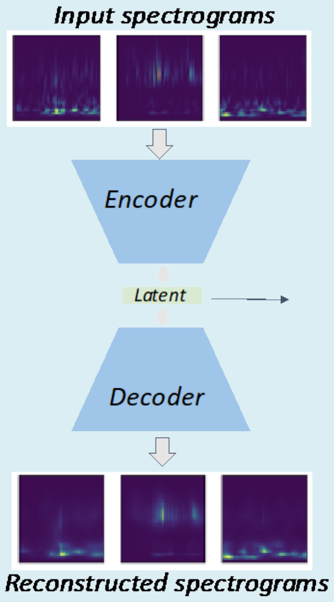
A sampling of diagnostics developments – driven by MDP needs, but with broad impact to magnet technology

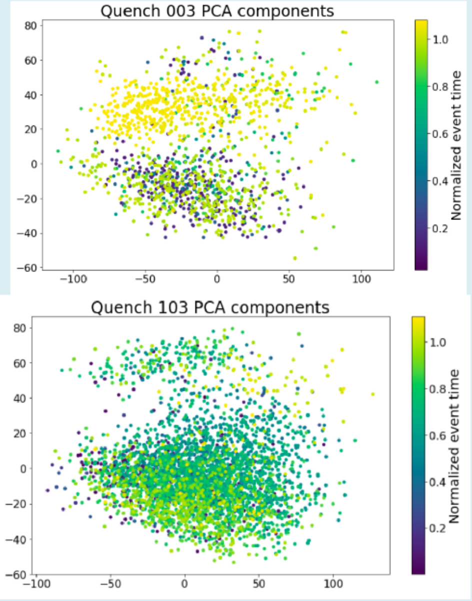
U.S. MAGNET DEVELOPMENT PROGRAM

Machine Learning

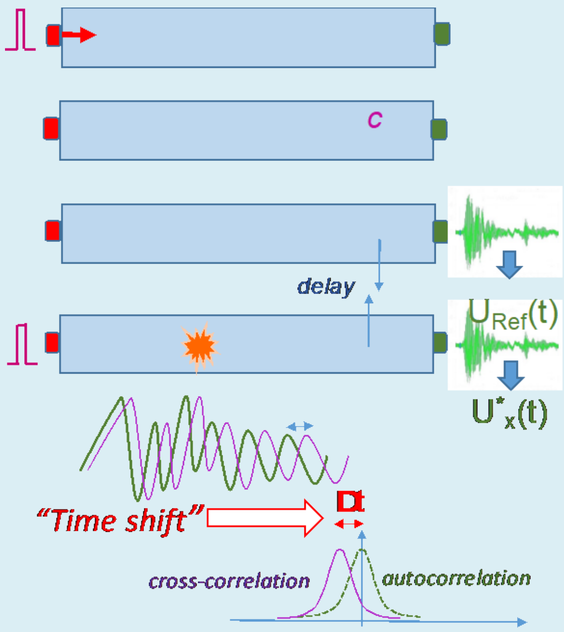
Goal: Use unsupervised learning to investigate physics (cracking vs. stick-slip) in magnet quench dataset

Stretch goal: Develop method to predict the quench in real-time

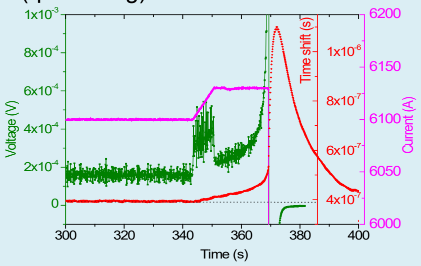




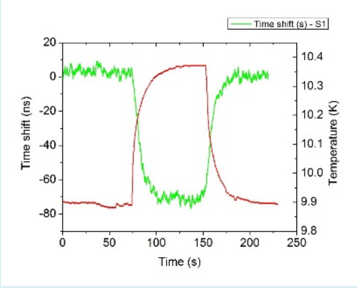
Active acoustics

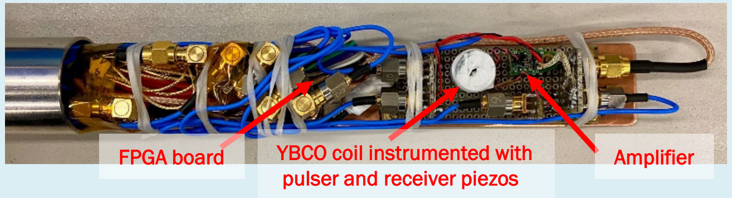


Experiment at 4.2 K. Current ramp stopped at 6100 A (stable) and then increased by 30 A (quenching)

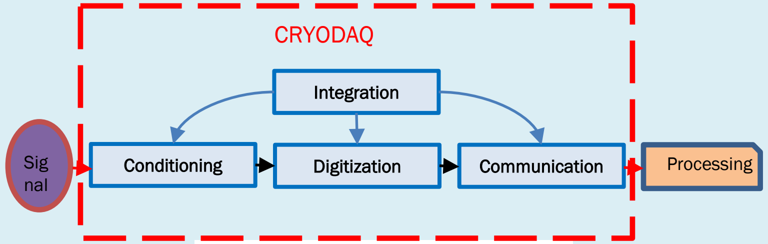


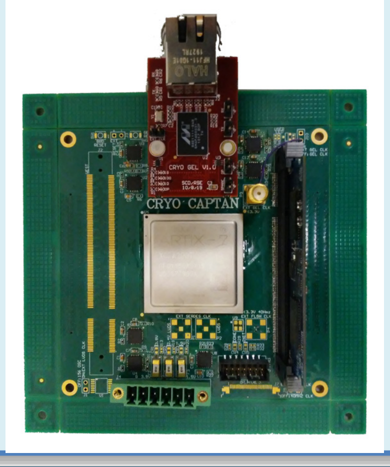
Acoustic thermometry





First successful cryogenic (LHe) test of an FPGA digitizer with analog front end





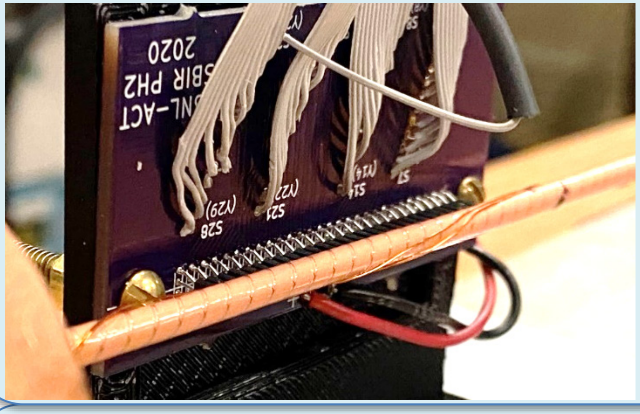
Technical progress on current distribution, quench detection for REBCO magnets

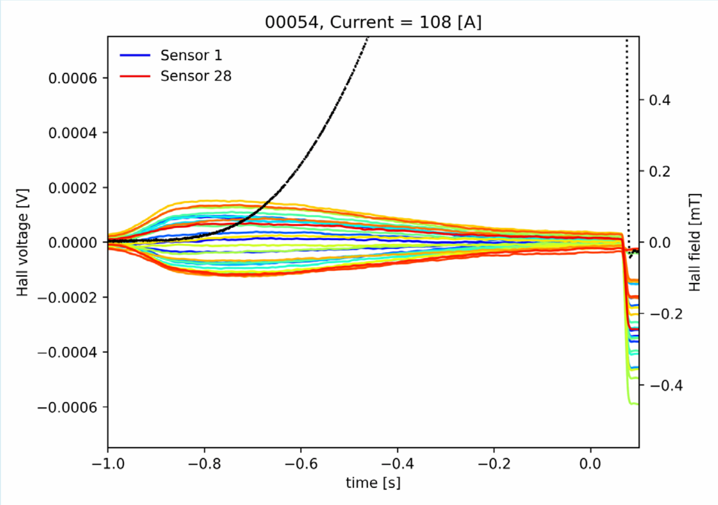
SBIR PH II with ACT

J D Weiss et al 2020 SUST 33

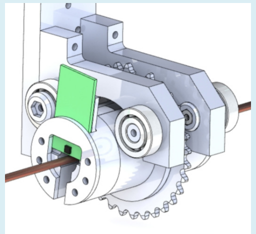
Quench detection for CORC® cables using Hall sensors

We have built a new type of axial-filed Hall sensor arrays and demonstrated robust detection of quenching

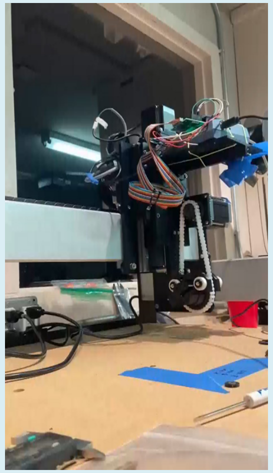


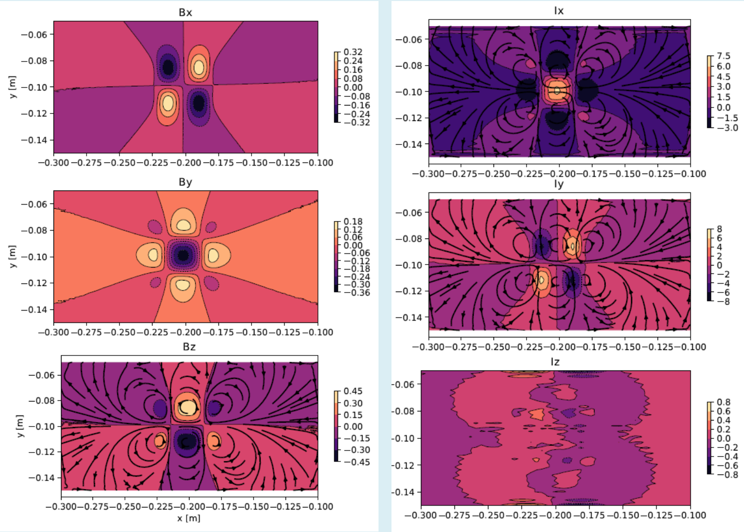


R. Teyber et al., DOI: 10.1109/TMAG.2021.3092527



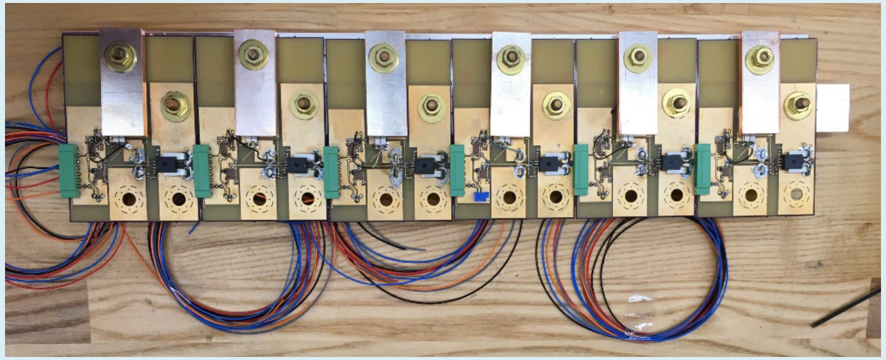
Developing a Hall probe scanner to measure 3D field distribution around a CORC® conductor and recover corresponding current distribution using inversion of Biot-Savart law.





Collaboration with ASC/NHMFL/FSU

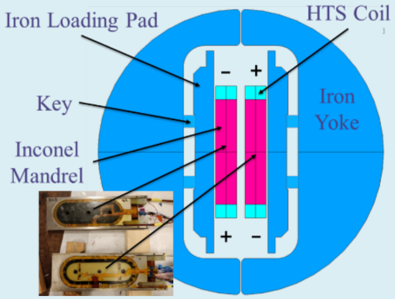
Unique setup to independently power and apply arbitrary ramping profiles to ReBCO conductors in the CORC® and tape stacks and monitor current flow using large-scale Hall sensor array.



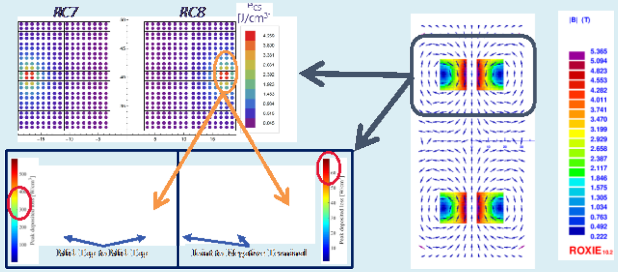
Wide array of modeling advances underway to support diagnostics feedback and to optimize magnet systems

U.S. MAGNET DEVELOPMENT PROGRAM

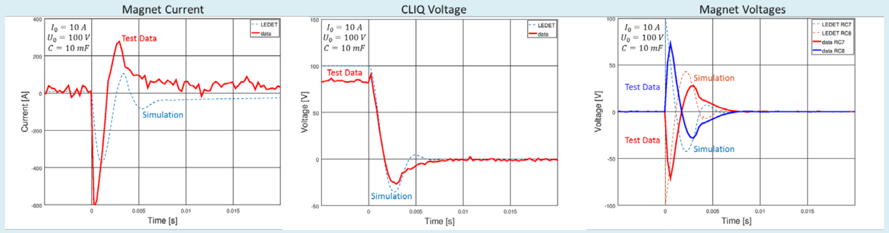
Magnet Protection



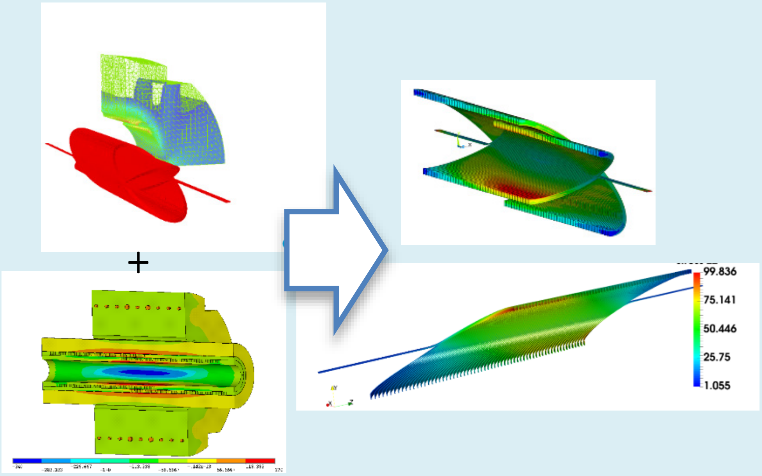
CLIQ optimized through simulation

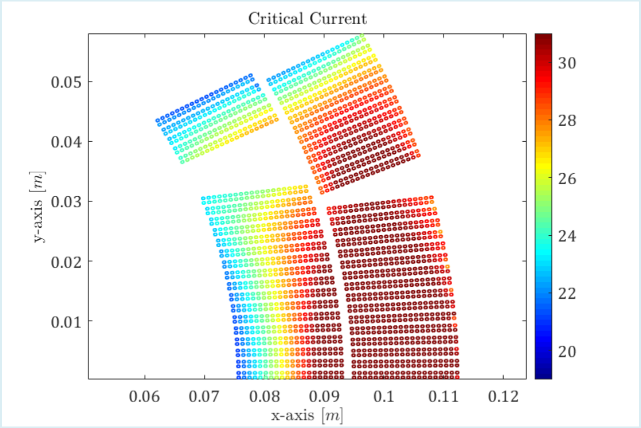


First test of CLIQ on Bi-2212 common coil, 77 K: comparing simulation and measurement

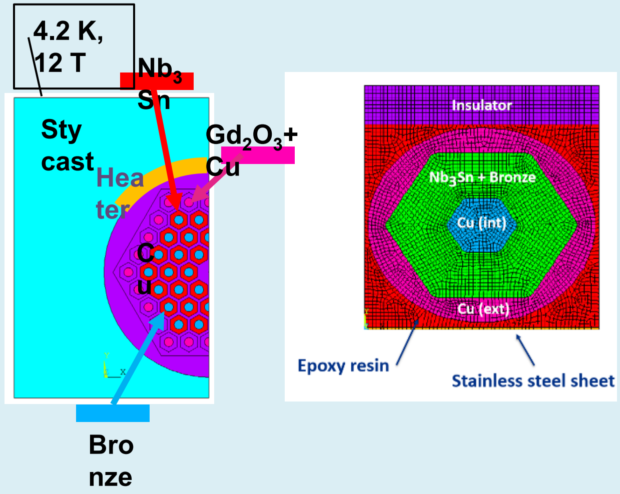


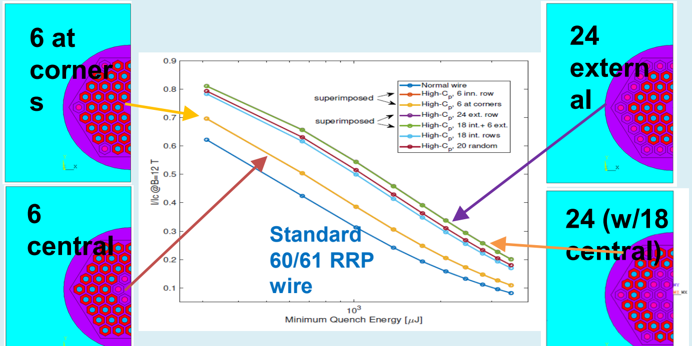
Strain impact on operation





Mechanics and thermal processes in conductors





"Heat diffusion in Nb_3Sn strands", E. Barzi, to be published.

Current focus areas and key challenges

- Can ***stress-management*** provide a viable means of accessing high-field and/or large bore dipole magnets without risk of conductor degradation?

- Can ***hybrid LTS/HTS*** magnets deliver on the promise of efficient high-field dipoles
  - Will they inherit the "best of both" or the "worst of both"

- Advance HTS magnet technology to a respectable level of maturity
  => ***make it "real"***

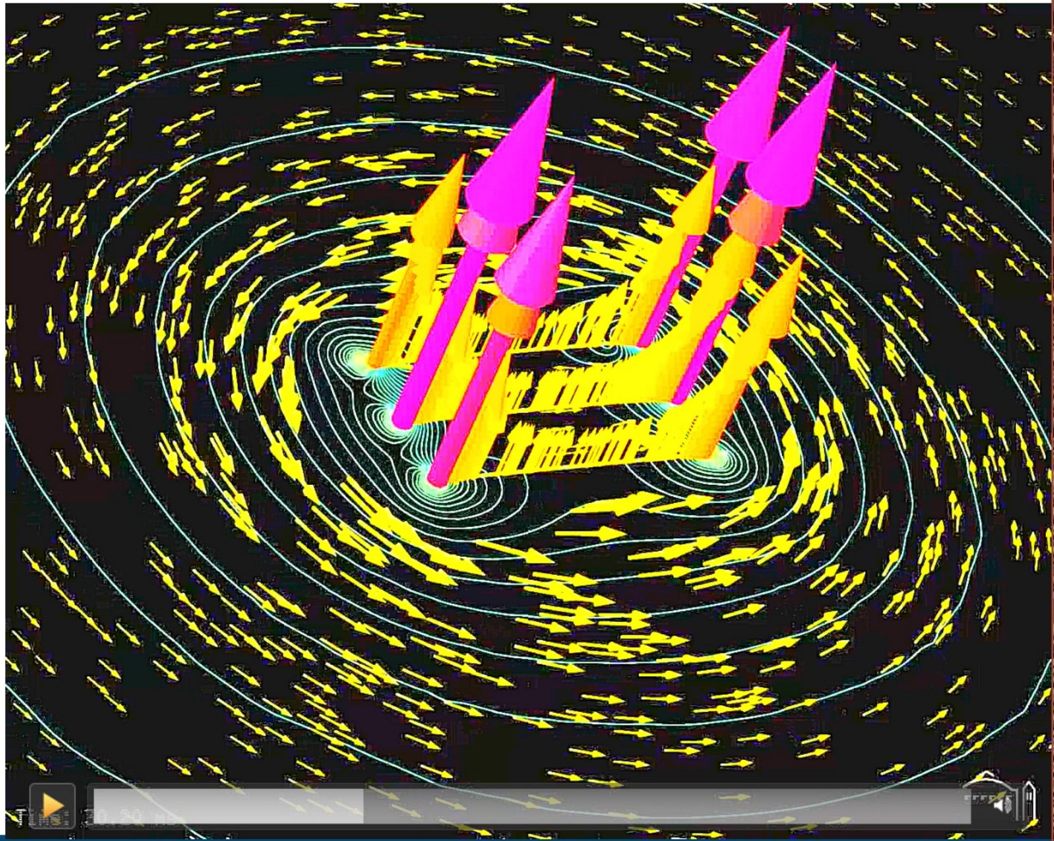
- Advance diagnostics and modeling to further enhance our insight into magnet performance and issues

- Overcome the advanced Nb_3Sn architecture issues and mature them to industrial levels

- Provide a ***substantial and timely quantity of conductor*** for magnet research and feedback to conductor development

Current focus areas and key challenges

- Can ***stress-management*** provide a viable means of accessing high-field and/or large bore dipole magnets without risk of conductor degradation?
- Can ***hybrid LTS/HTS*** magnets deliver on the promise of efficient high-field dipoles
  - Will they inherit the "best of both" or the "worst of both"
- Advance HTS magnet technology to a respectable level of maturity => ***make it "real"***
- Advance diagnostics and modeling to further enhance our insight into magnet performance and issues
- Overcome the advanced Nb_3Sn architecture issues and mature them to industrial levels
- Provide a ***substantial and timely quantity of conductor*** for magnet research and feedback to conductor development



Plans and Roadmaps are well advanced globally

- US MDP – *well established (arXiv:2011.09539)*
- European HFM – ***roadmap established*** *(arXiv:2201.07895)*
- Japan efforts at KEK - *coordinated with CERN and MDP*
- China efforts led by IHEP – *progressing well*

New!

UGA Université Grenoble Alpes
CERN
ETH zürich
PAUL SCHERRER INSTITUT PSI
EPFL
BRUKER
irig
NÉEL institut
G2E lab
UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES
ICMAB INSTITUT DE CIÈNCIA DE MATERIALS DE BARCELONA
EXCELENCIA SEVERO OCHOA
université PARIS-SACLAY
cnrs
Grenoble INP
LNCMI
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

BERKELEY LAB
Fermilab
Brookhaven National Laboratory
ASC
NATIONAL HIGH MAGNETIC FIELD LABORATORY
BRUKER
nGimat
OHIO STATE
ENGI·Mat NANO ENGINEERED MATERIALS
Advanced Conductor Technologies www.advancedconductor.com
AMPeers
SuperPower Inc. A Furukawa Company


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!

KYOTO UNIVERSITY
TOHOKU UNIVERSITY
KOBELCO
JASTEC SUPERCONDUCTOR
TOKAI UNIVERSITY
KEK Inter-University Research Institute Corporation High Energy Accelerator Research Organization

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

Summary

- The High Energy Physics community has clearly indicated the science potential associated with a future circular colliders that probes significantly higher energies

=> The onus is on the magnet community to determine what is possible and what is feasible in terms of field strength

There is a concerted effort around the world to integrate teams of specialists and facilities to most efficiently, effectively, and rapidly advance magnet technology

There is also strong interest in collaborating – nationally and internationally - where strengths and capabilities are deemed complementary or can serve to accelerate R&D

We are at a critical period, where innovation and progress in magnet technology is essential to enable new science

We welcome the challenge while recognizing the responsibility!