U.S. MAGNET
DEVELOPMENT
PROGRAM

U.S. DEPARTMENT OF
ENERGY
Office of Science

Advances in superconducting magnet technology for future colliders

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Berkeley Center for Magnet Technology

FRIB – APES Seminar

BERKELEY LAB
Bringing Science Solutions to the World

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Outline

- The roles of superconductivity in accelerators
- Introduction to superconductivity and modern superconductors
- Overview of accelerator magnets and associated technology
- Current state of the art
- Primary research directions and examples of current progress
- Perspective on future directions, progress and science impact

From first cyclotron…

…to the LHC

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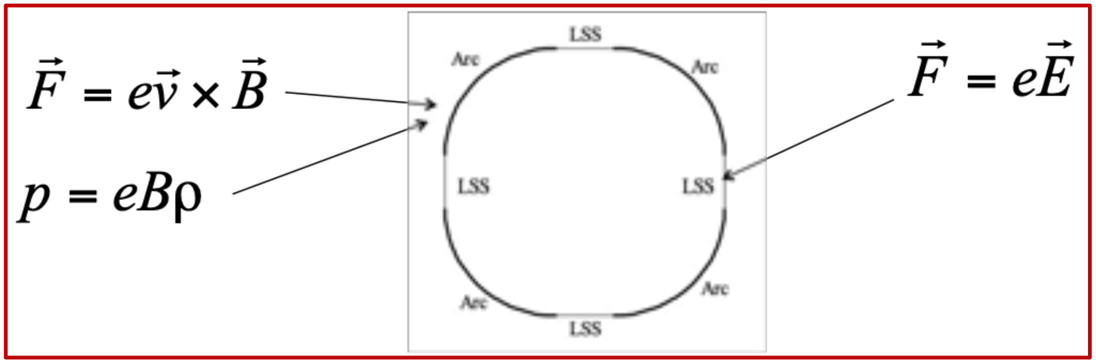
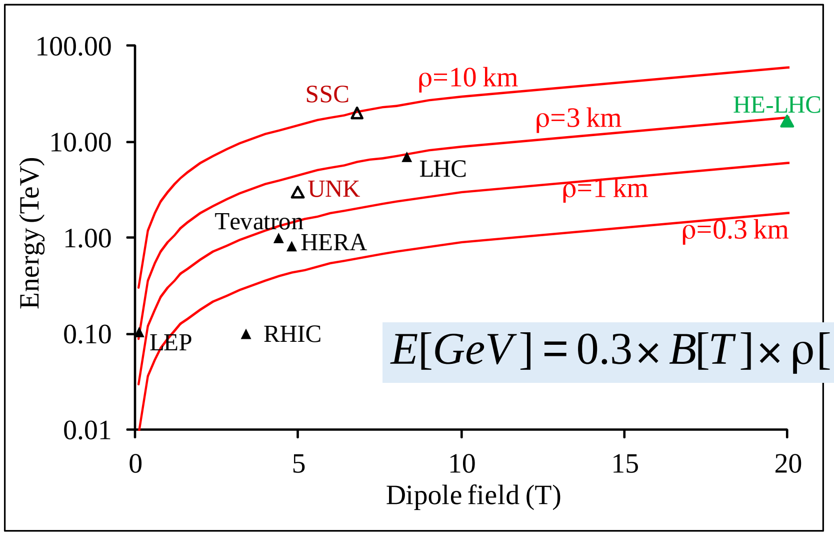
The role of superconductivity in accelerators

- Magnets serve as the ***optics*** for relativistic charged particles
  - Fields>~2T require superconducting technology
  - For given radius: p~B


$$\vec{F} = e\vec{v} \times \vec{B}$$

$$p = eB\rho$$

$$\vec{F} = e\vec{E}$$



$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$

*Superconductivity is also used in RF cavities to **accelerate** charged particles – not discussed here*

Reminder: basics of accelerator magnets

$$F(z) = A(z) + iV(z)$$

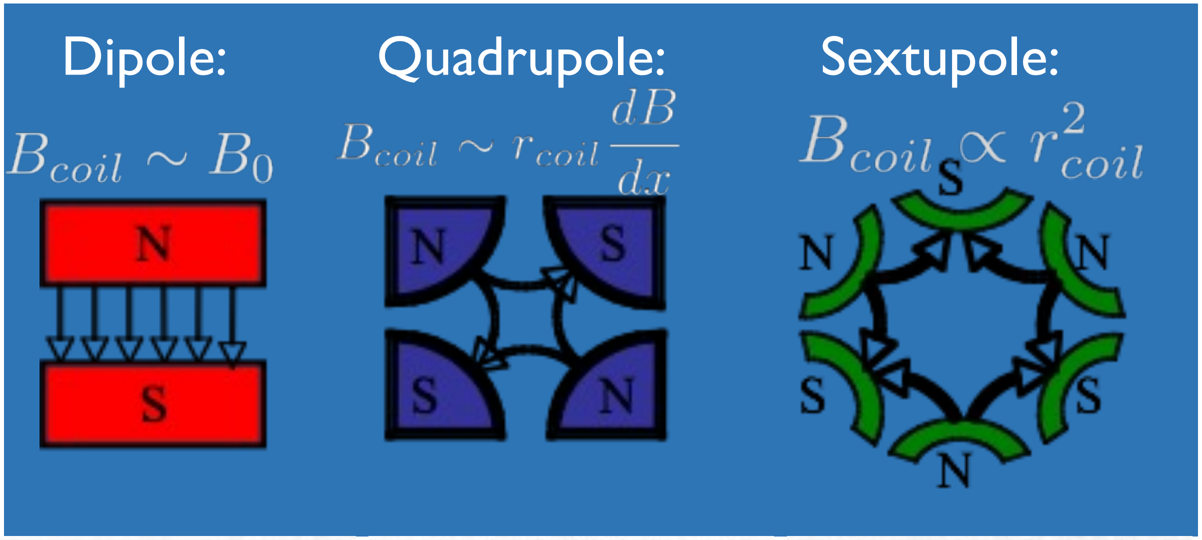
A: Vector potential
V: Scalar potential

$$B_x - iB_y = B^* = i\frac{dF}{dz} = i\frac{d}{dz}\left(A + iV\right)$$

$$\boxed{\vec{B} = \nabla\times\vec{A} \quad \left(\text{results from } \nabla\cdot\vec{B} = 0 \text{ and identity } \nabla\cdot\left(\nabla\times\vec{A}\right) = 0,\ \forall\vec{A}\right)}$$

$$\boxed{\vec{B} = -\nabla V \quad \left(\text{results from } \nabla\times\vec{B} = 0 \text{ and identity } \nabla\times\left(\nabla V\right) = 0,\ \forall V\right)}$$

$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty}(b_n + ia_n)\left(\frac{x+iy}{R_{ref}}\right)^{n-1}$$



Dipole:

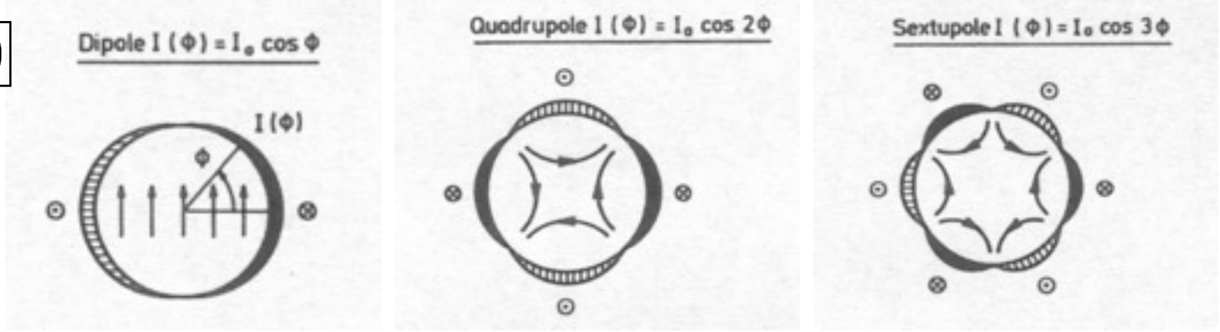
$B_{coil} \sim B_0$

Quadrupole:

$B_{coil} \sim r_{coil}\frac{dB}{dx}$

Sextupole:

$B_{coil} \propto r^2_{coil}$

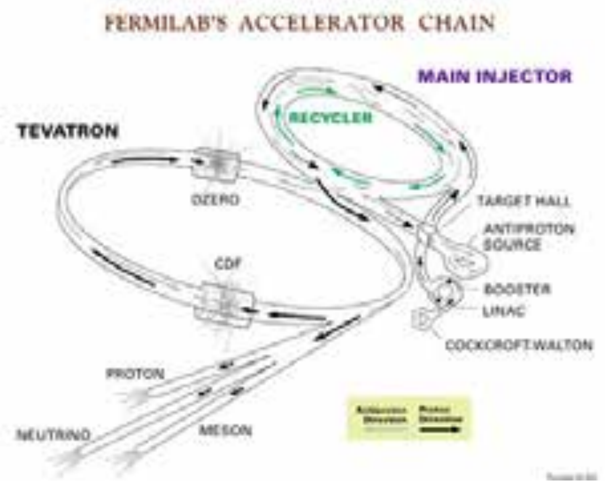


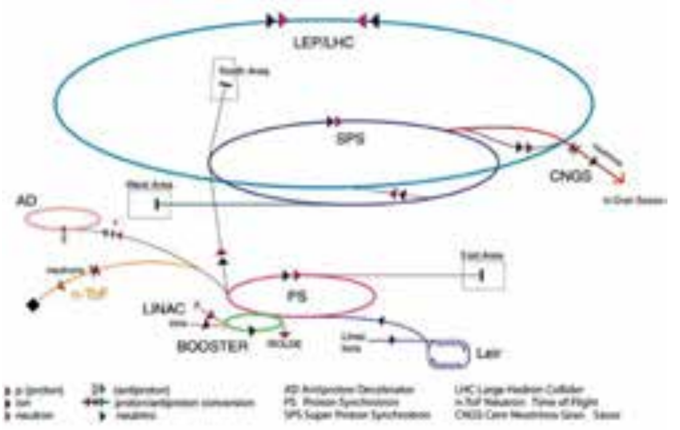
Dipole $I(\Phi) = I_0 \cos\Phi$

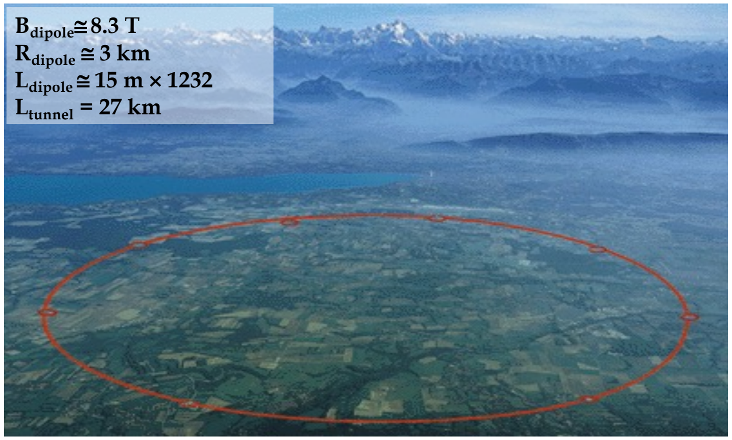
Quadrupole $I(\Phi) = I_0 \cos 2\Phi$

Sextupole $I(\Phi) = I_0 \cos 3\Phi$

Superconductivity enabled all modern colliders







$B_{dipole} \cong 8.3$ T
$R_{dipole} \cong 3$ km
$L_{dipole} \cong 15$ m × 1232
$L_{tunnel} = 27$ km

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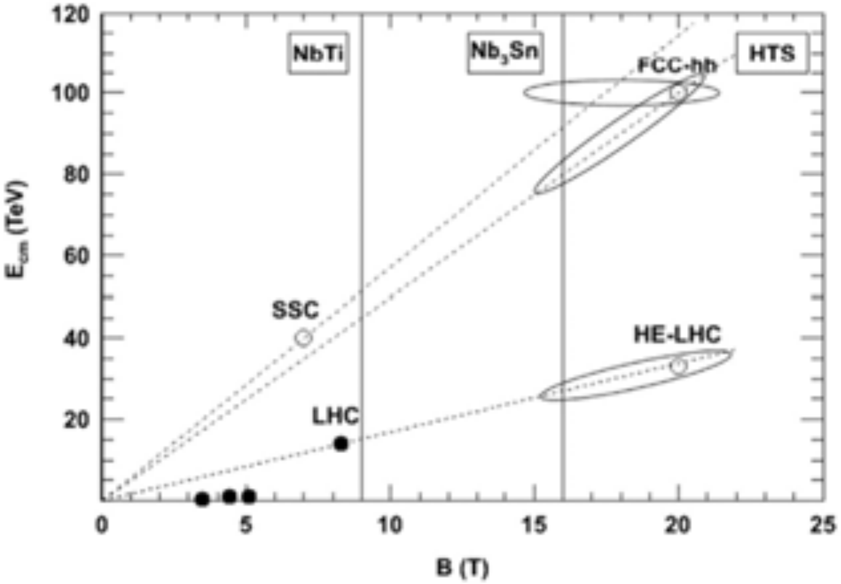
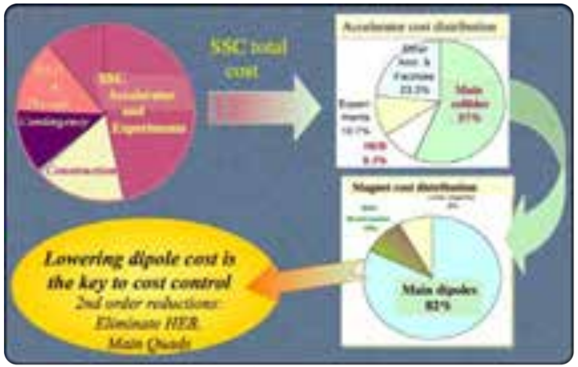
Superconductors and superconducting magnets drive the energy reach of colliders



Barletta et al., NIMS A, vol. 764, no. C, pp. 352–368, Nov. 2014

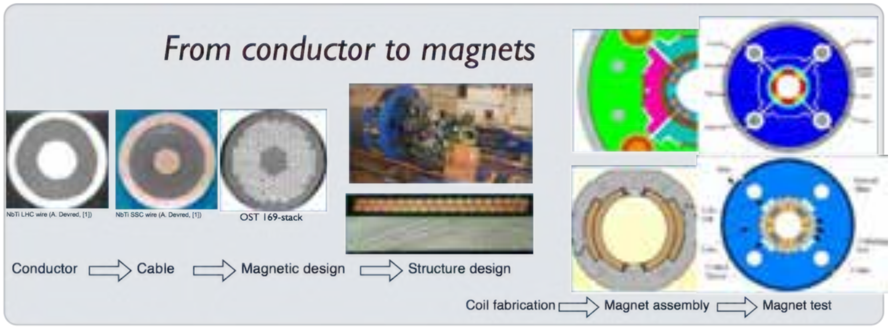


Barletta

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

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

**L. Rossi, "TOE" talk*



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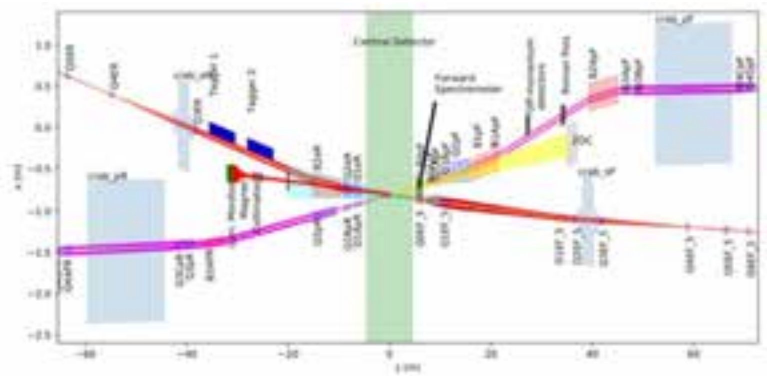
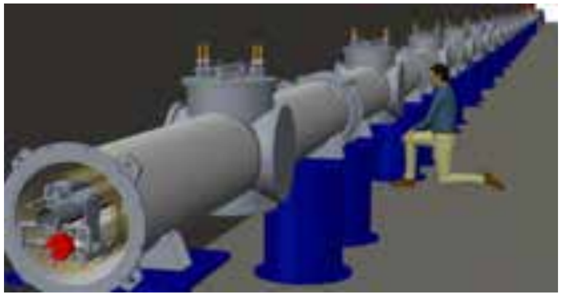
Advanced superconducting magnets impact DOE-SC more broadly

- 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

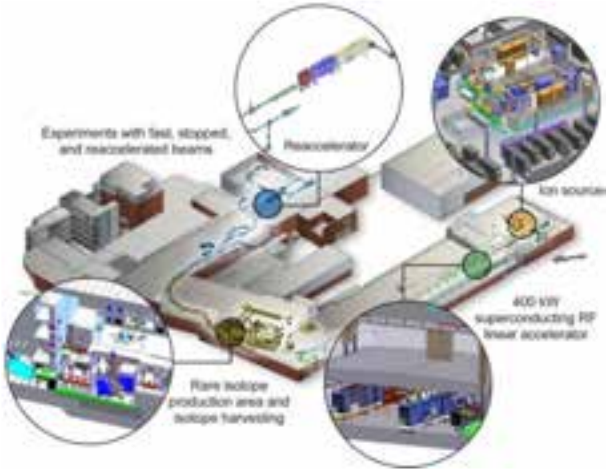


H. Witte et al., IPAC 2021, doi:10.18429



P. Emma et al., Proceedings of FEL2014

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



J. Wei et al.

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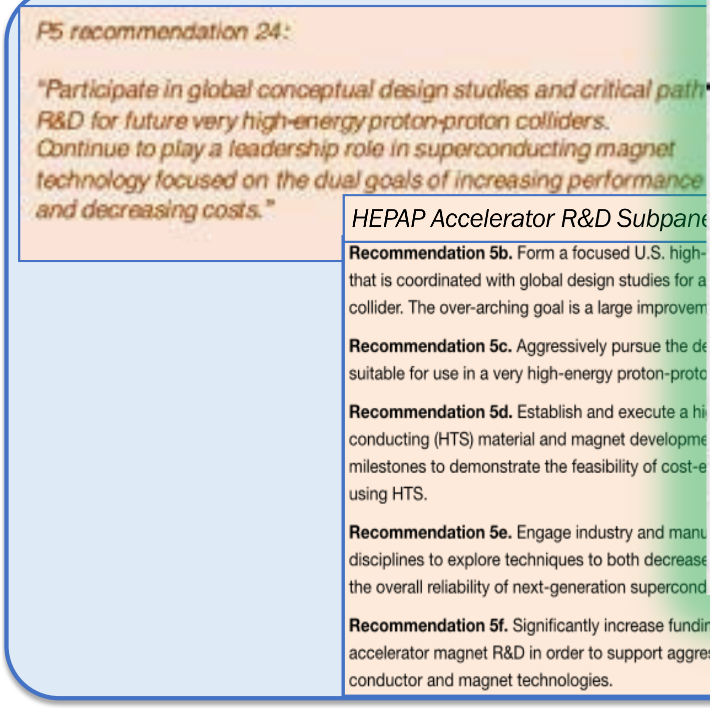
Physics motivation and strategic planning

- The physics drivers for a future High Energy Physics colliders are well documented by community planning, e.g.
    - o US “Snowmass” process
    - o 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.

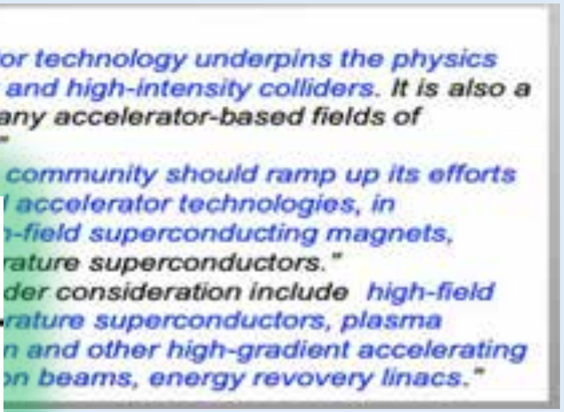
First impressions coming out of Snowmass!

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



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
l 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.”

ss 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,
pts, 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

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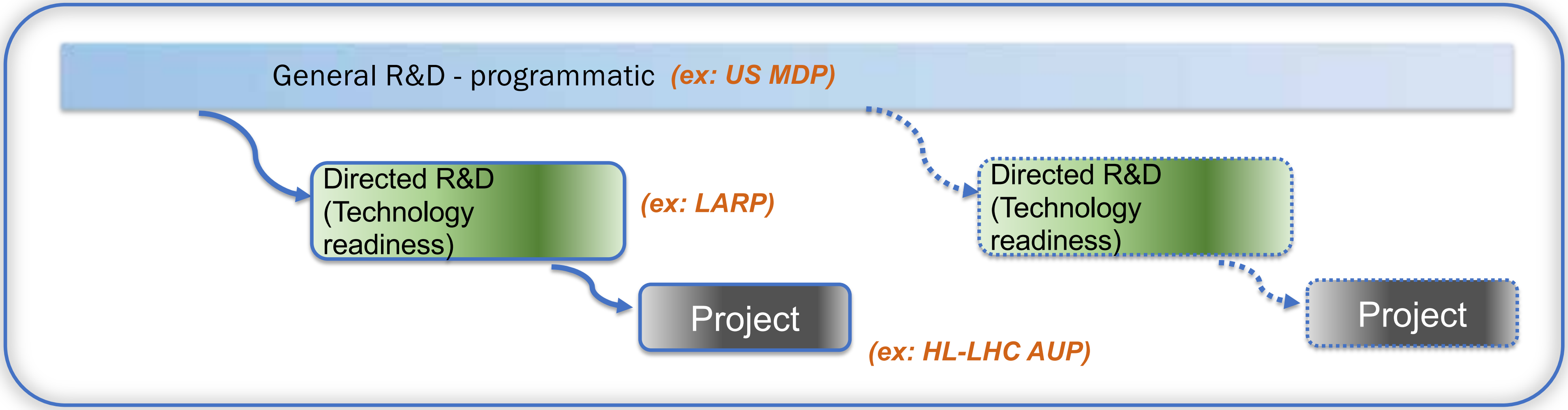
R&D efforts for accelerator magnet technology are becoming more structured

- 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



General R&D - programmatic *(ex: US MDP)*

Directed R&D (Technology readiness)

(ex: LARP)

Project

(ex: HL-LHC AUP)

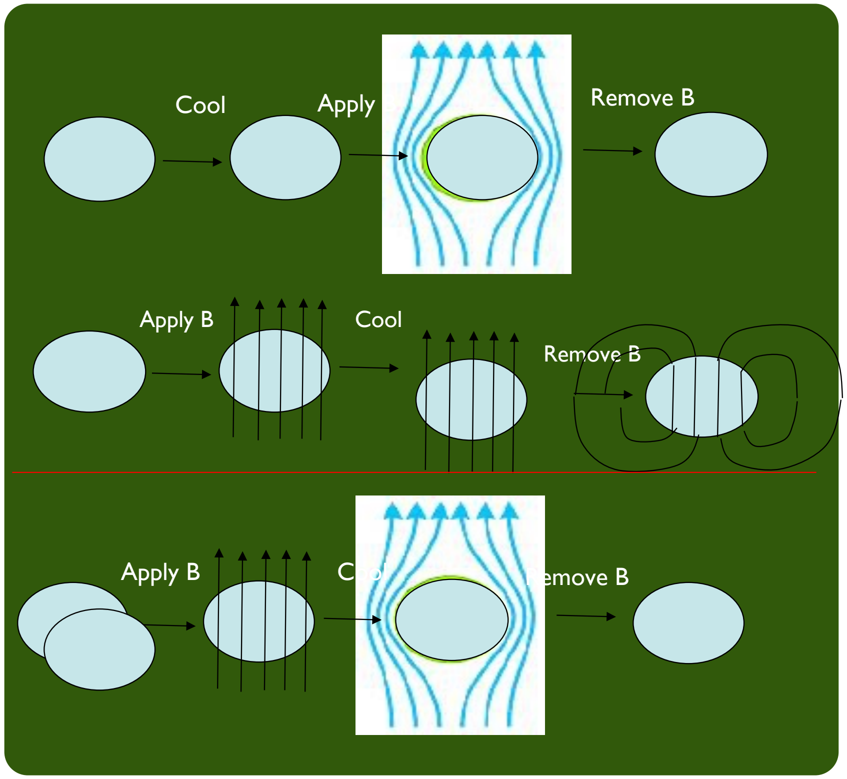
Directed R&D (Technology readiness)

Project

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

Diamagnetic behavior of superconductors

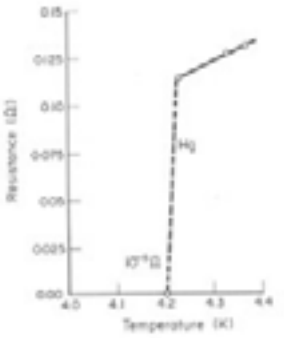
- What differentiates a “perfect” conductor from a diamagnetic material?



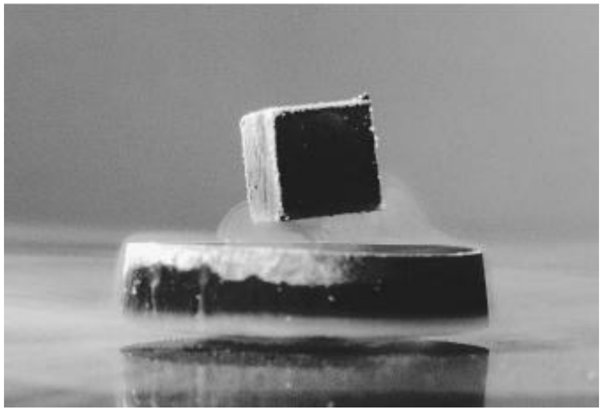
A perfect conductor apposes any change to the existing

magnetic state

Superconductors exhibit diamagnetic behavior: flux is always expulsed - Meissner effect

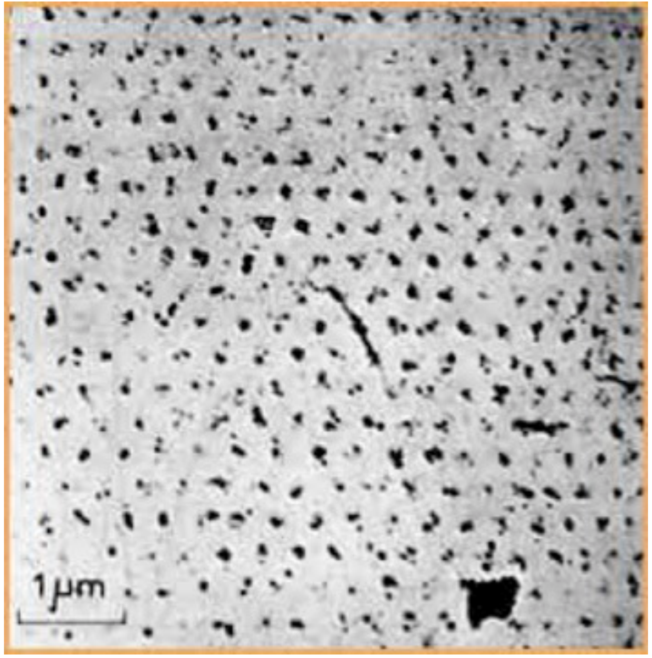


Kamerlingh Onnes,
Nobel Prize 1913



Type I vs Type II superconductors

First photograph of vortex lattice, U. Essmann and H. Trauble, Max-Planck Institute, Stuttgart, Physics Letters 24A, 526 (1967)



- **Type I superconductors** are characterized by the Meissner effect, i.e. flux is fully expulsed through the existence of supercurrents over a distance λ_L.

- **Type II superconductors** find it energetically favorable to allow flux to enter via normal zones of fixed flux quanta: "fluxoids" or vortices.
  - The fluxoids or flux lines are vortices of normal material of size ~$\pi\xi^2$ "surrounded" by supercurrents shielding the superconducting material.

Only Type II superconductors are relevant for ”transport”, e.g. for magnets

- The Lorentz force acting on a fluxoid will, in the absence of pinning, result in motion of the fluxoid
- Fluxoid motion generates a potential gradient (i.e. voltage) and hence heating

Flux pinning

- Fluxoids can be pinned by a wide variety of material defects
    - Inclusions
        - Under certain conditions, small inclusions of appropriate materials can serve as pinning site locations; this suggests tailoring the material artificially through manufacturing
    - Lattice dislocations / grain boundaries
        - These are known to be primary pinning sites. Superconductor materials for wires are severely work hardened so as to maximize the number and distribution of grain boundaries.
    - Precipitation of other material phases
        - In NbTi, mild heat treatment can lead to the precipitation of an a-phase Ti-rich alloy that provides excellent pinning strength.

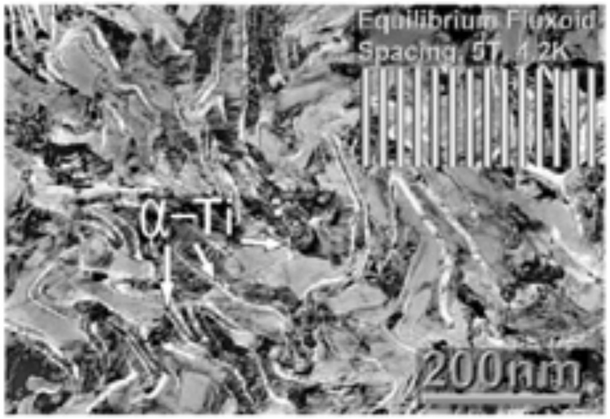
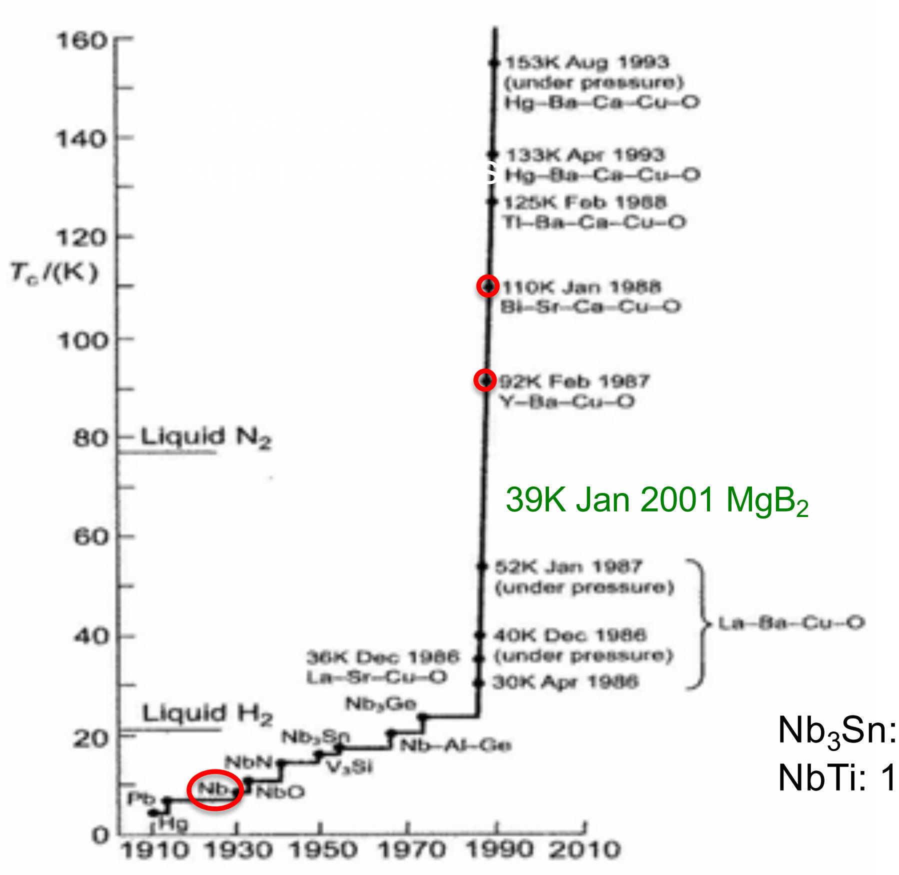


Fig. 1: Microstructure of a NbTi filament (Courtesy of P.J. Lee, University of Wisconsin at Madison)

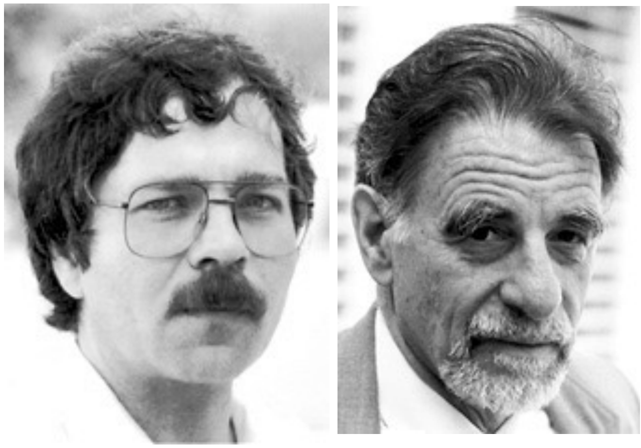
Fig. 4: Microstructure of a Nb_3Sn filament (Courtesy of C. Verwaerde, Alstom/MSA)

Many superconductors – few industrialized



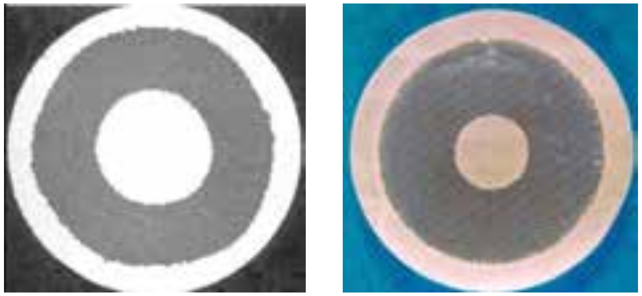
Nb_3Sn: 1954
NbTi: 1962 => first wire in 1964

Discovery of HTS (copper-oxides)

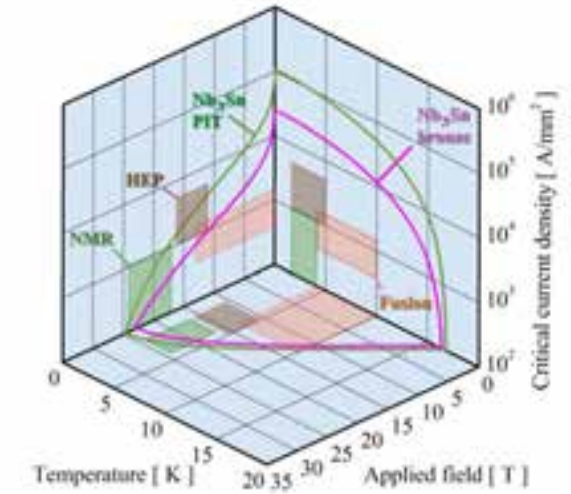


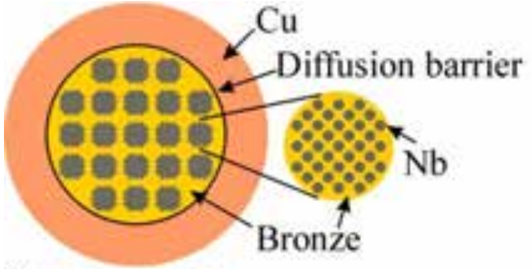
George Bednorz and Alexander Muller
Nobel prize for Physics (1987)

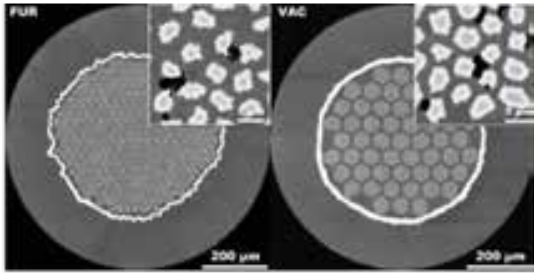
Practical (LTS) superconductors for magnets



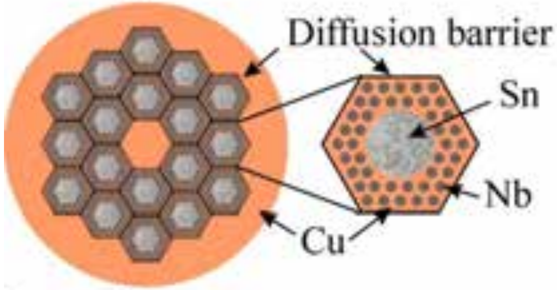
LHC and SSC NbTi wires

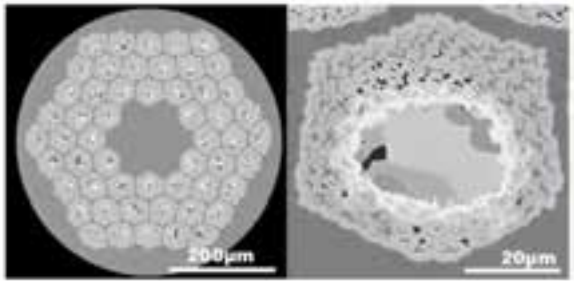






“Bronze process” Nb_3Sn wires



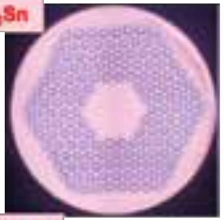


“Internal Tin” Nb_3Sn wires (e.g. RRP)

Magnets start with the superconductor – LTS & HTS

Nb-Ti

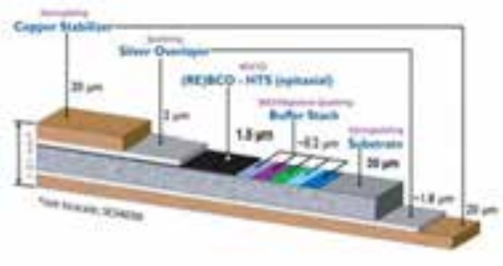
Nb$_3$Sn



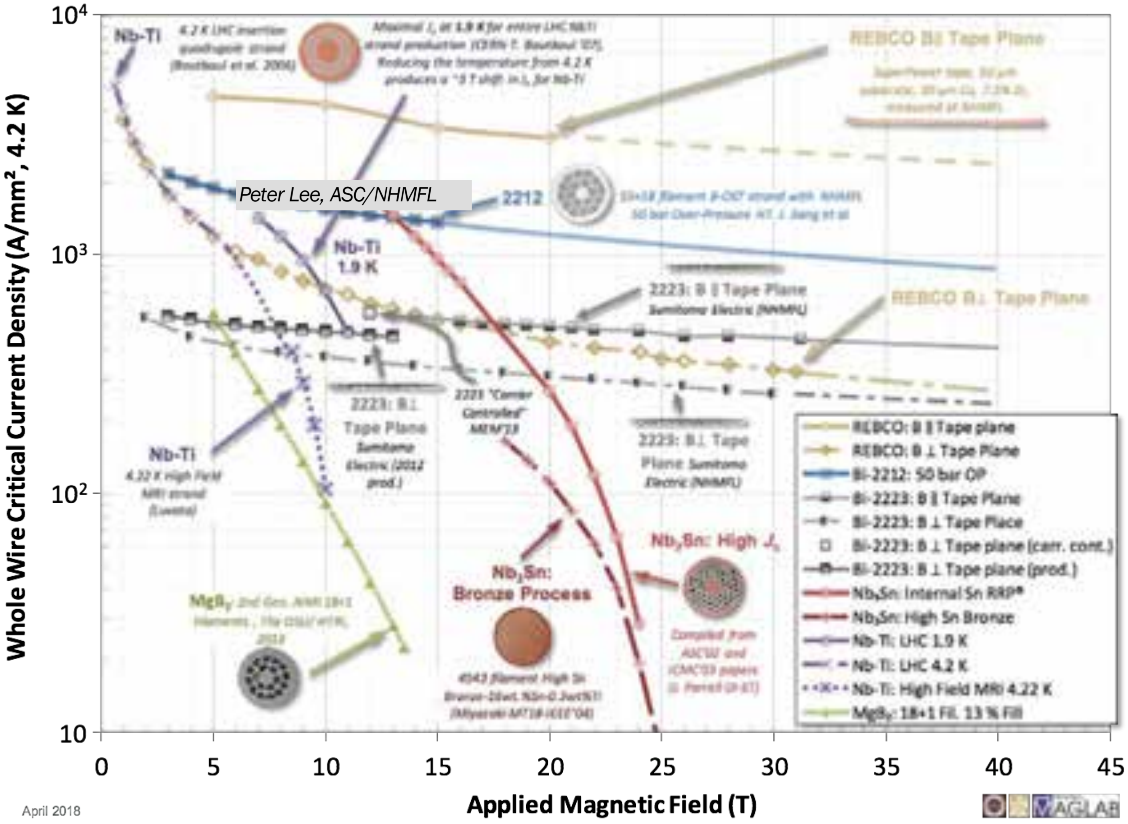
Bi-2212

REBCO

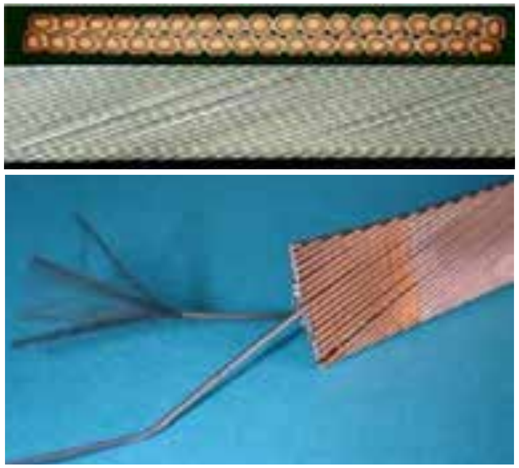
SuperPower Inc

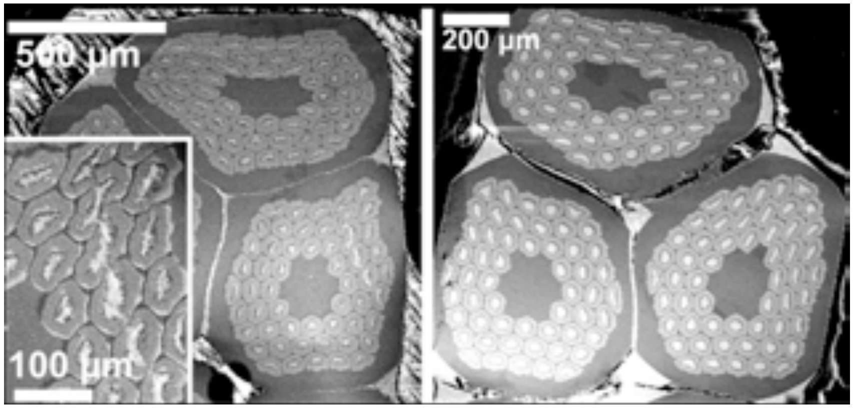


Peter Lee, ASC/NHMFL



Increasing conductor current – Rutherford cables





Bad edge def.

Good edge def.

Add core to dramatically reduce transverse coupling, while maintaining decent Ra for current sharing

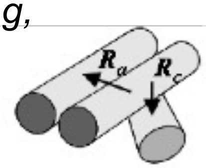
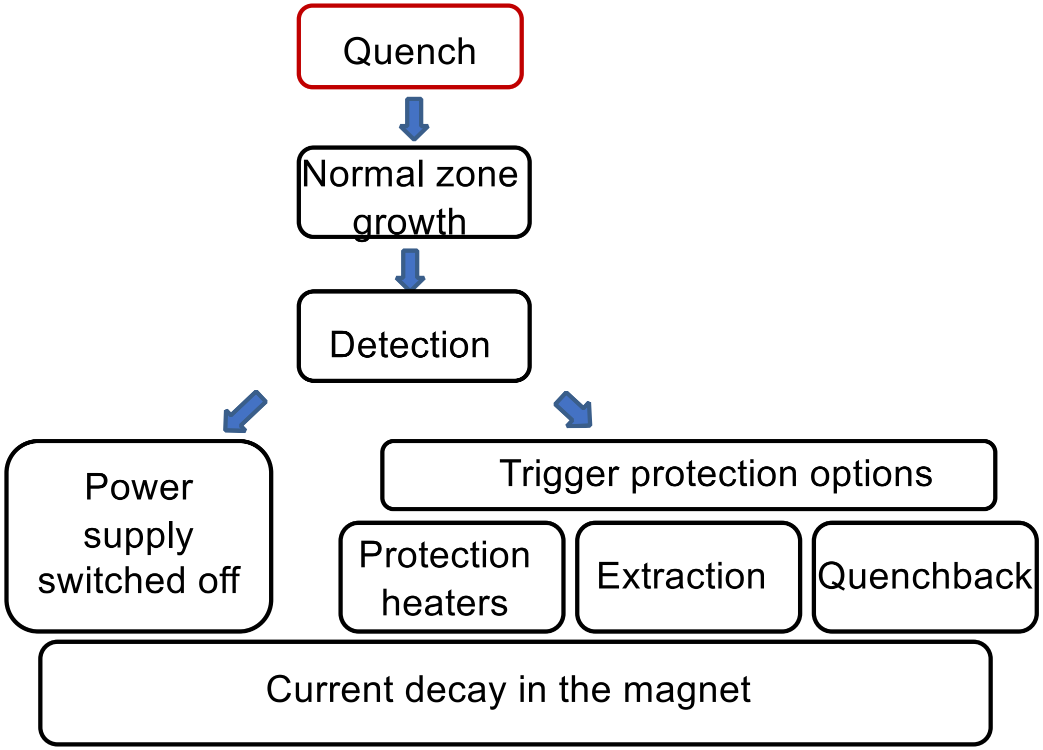


Fig. 18. Crossover resistance R_c and adjacent resistance R_a.

Protecting magnets drives conductor and cable design



Quench

Normal zone growth

Detection

Power supply switched off

Trigger protection options

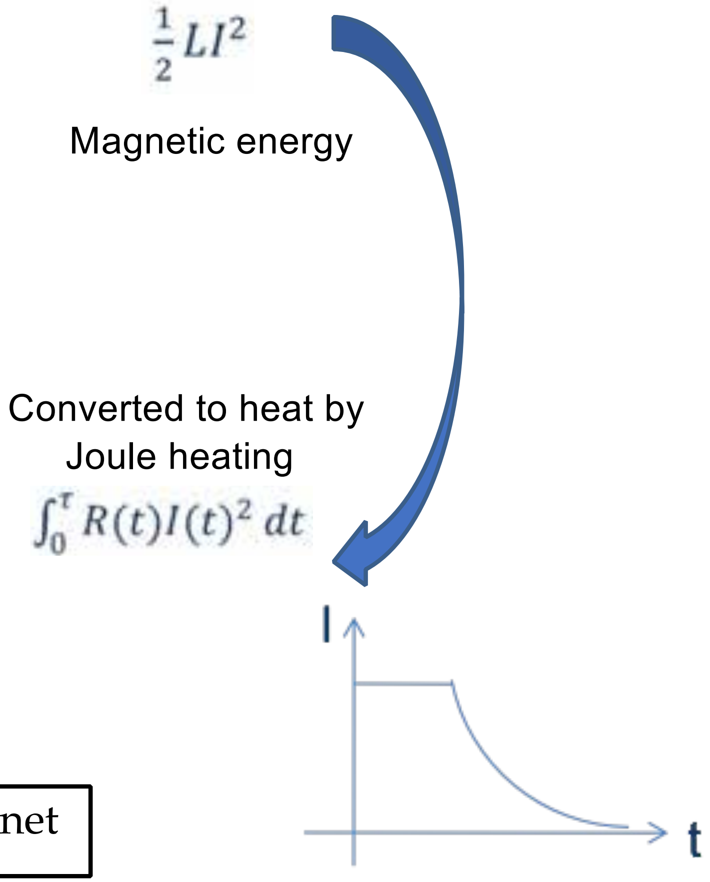
Protection heaters

Extraction

Quenchback

Current decay in the magnet

The faster this chain happens the safer is the magnet



$\frac{1}{2}LI^2$

Magnetic energy

Converted to heat by Joule heating

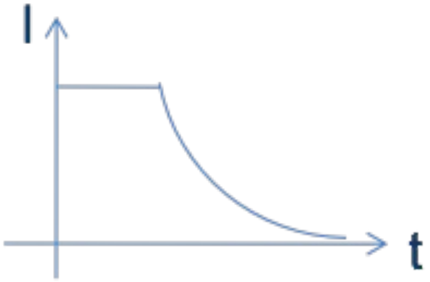
$\int_0^\tau R(t)I(t)^2\,dt$

Current decay/Hot spot correlation: the MIITs

- Basic energy conservation
  - Energy deposited by Joule heating inducing an increase in temperature based on the specific heat of the materials

$$\gamma C_p(T)dT = \rho J(t)^2 dt$$

  - With the assumptions that:
    - Joule heating only produced by stabilizer (Cu)
    - Heat capacity of conductor and insulation
    - Adiabatic condition: no longitudinal heat transfer



$$A_{tot}\sum_k \gamma_k v_k C_{p,k}(T)dT = \frac{\rho_{Cu}(T,B)}{A_{Cu}} I(t)^2 dt$$

$$\boxed{10^6 MIITs = \int_0^\infty I(t)^2 dt = A_{tot}A_{Cu}\int_{T_0}^{T_{max}} \frac{\sum_k \gamma_k v_k C_{p,k}}{\rho_{Cu}(T,B)} dT}$$

By evaluating the MIITs from the current decay, we obtain an estimate of the hot spot temperature T_{max}

Overview of Accelerator Magnets to-date

- All magnets in accelerators to-date have used…
  - a Cos-theta coil layout (of different flavors)
  - NbTi (HiLumi will be first application of Nb_3Sn in accelerators)
  - "Collar" approach to provide prestress
  - Iron laminations – facilitate fabrication, cost, performance

Tevatron

HERA

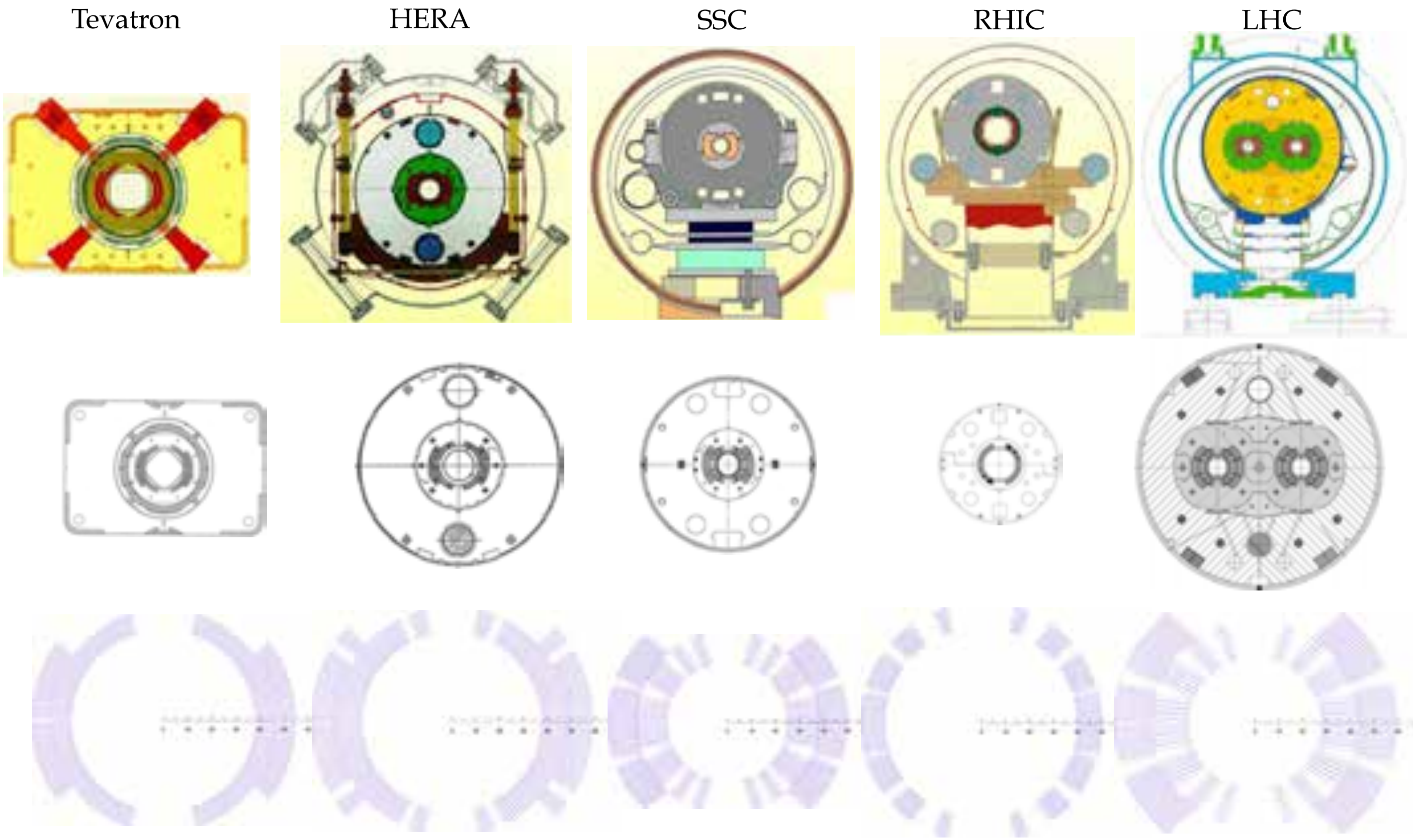
SSC

RHIC

LHC

Not in scale

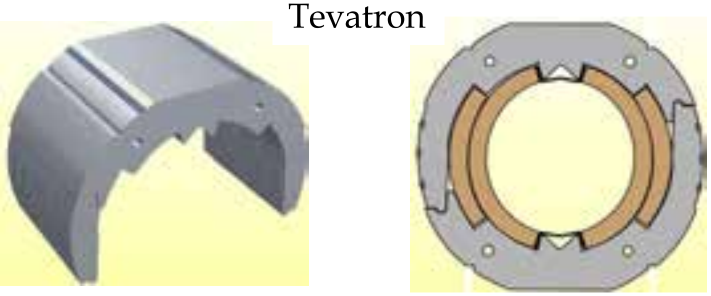
Overview of accelerator dipole magnets



Support structures typically feature ”Collars”

- Collars were implemented for the first time in the Tevatron dipoles.
    - they have been used in all but one (RHIC) accelerator magnet and in most R&D magnets
- They are composed of stainless-steel or aluminum laminations, typically few mm thick.
- By clamping the coils, the collars provide
    - coil pre-stressing;
    - rigid support against e.m. forces (it can be self-supporting or not);
    - precise cavity (tolerance ~20 μm).

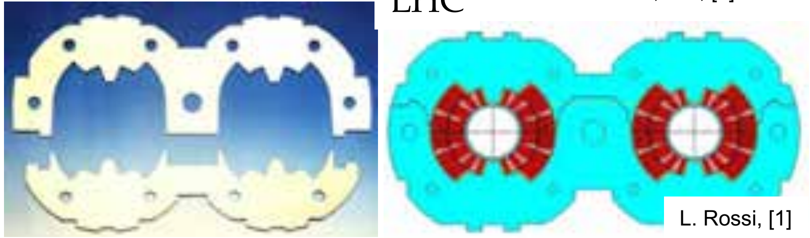
Tevatron



SSC

MJB Plus, Inc., [2]

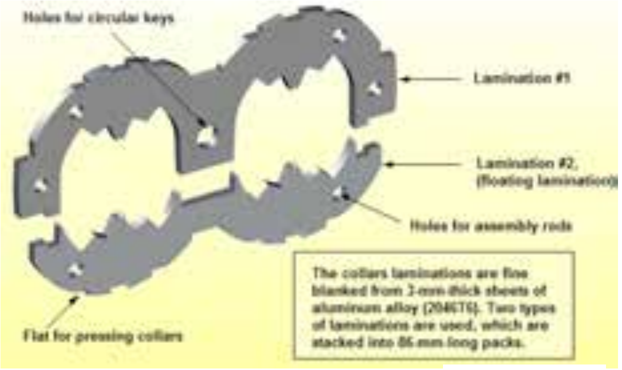
LHC



L. Rossi, [1]

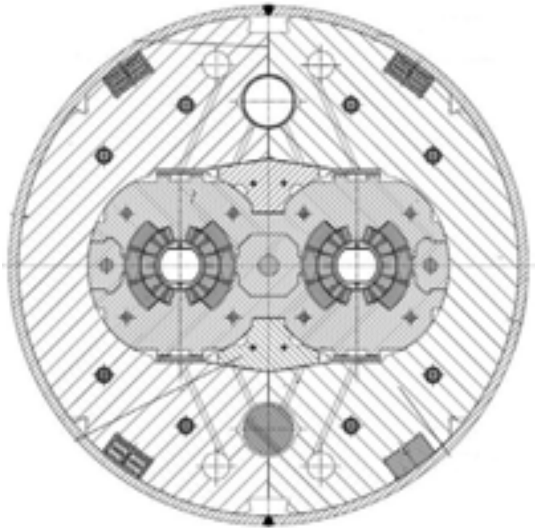
The LHC main dipole as an example

- Two-in-one configuration
  - Both beam pipes are contained within one cold mass
- Stainless steel collars are locked by three full-length rods.
- Magnetic insert
  - It transfers vertical force from the yoke to the collared coils
  - It improves field quality
- Iron yoke vertically split
  - At the end of the welding operation the yoke gap is closed
- Stainless steel shell halves are welded around the yoke to provide He containment, a 9 mm sagitta, and to increase rigidity.



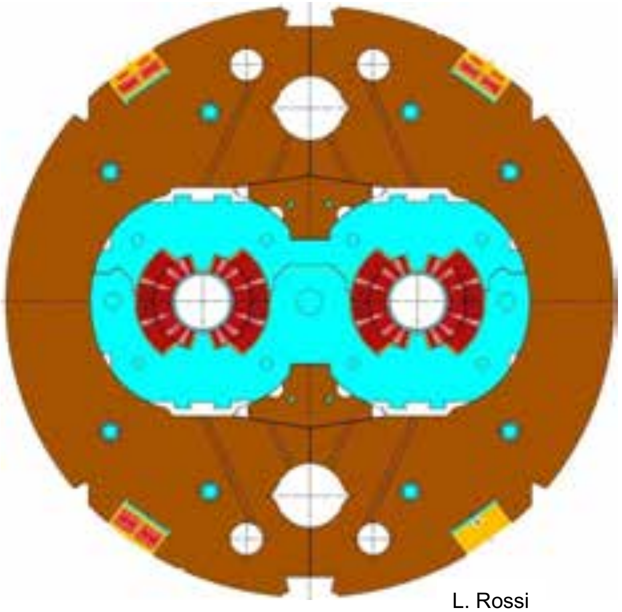
The collars laminations are fine blanked from 3-mm-thick sheets of aluminum alloy (2046T6). Two types of laminations are used, which are stacked into 86-mm-long packs.

MJB Plus, Inc



The Iron yoke also serves multiple functions

- As the collars, iron yoke are made in laminations (several mm thick), with a packing factor > 95%.
- Magnetic function
  - o The yoke contains and enhances the magnetic field.
- Structural function
  - o Except for the cases where the collars are self supporting (i.e. like in Tevatron and HERA dipoles), the yoke is in tight contact with the collar. Therefore, it contributes to increase the rigidity of the coil support structure and limit radial displacement.
- Holes are included in the yoke design for
  - o Correction of saturation effect
  - o Cooling channel
  - o Assembly features
  - o Electrical bus

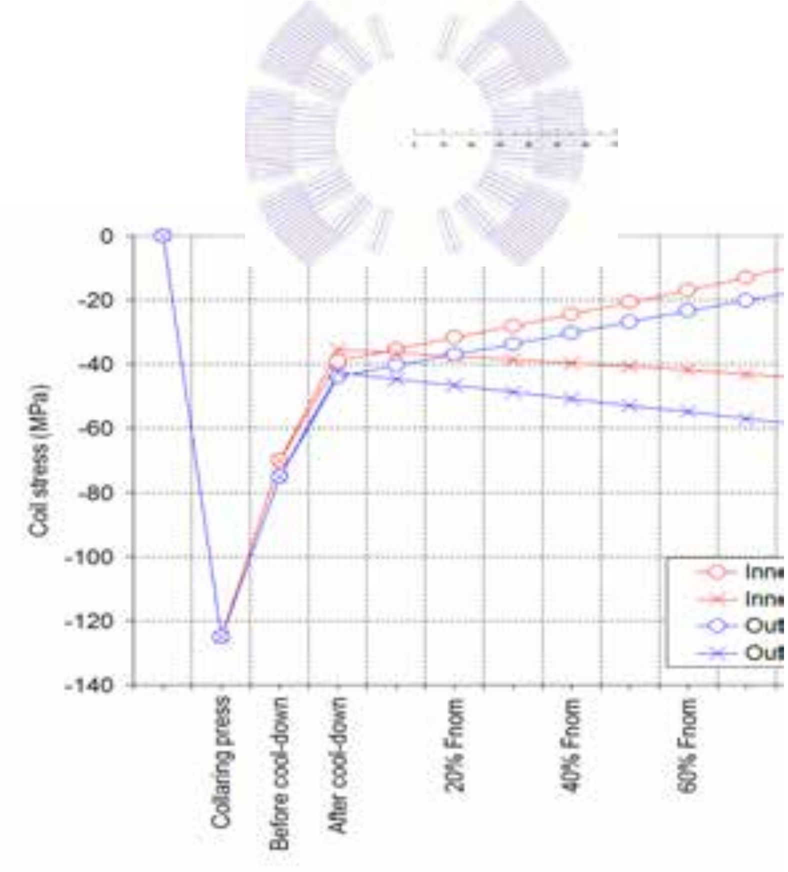


L. Rossi

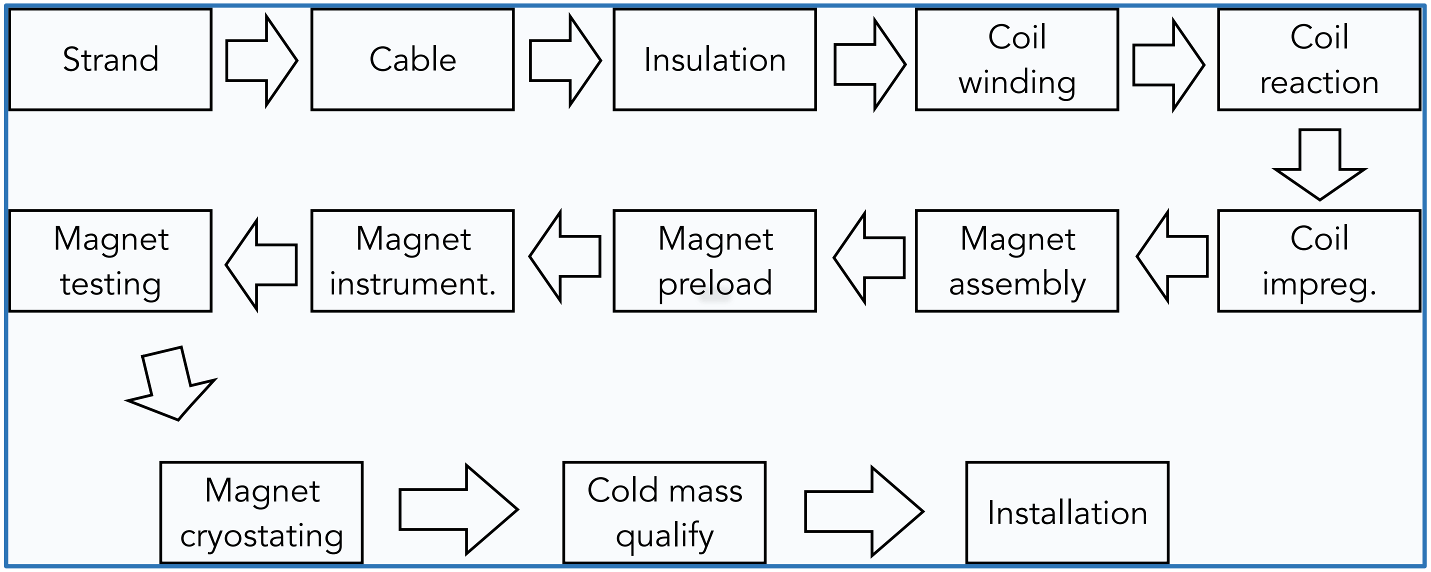
Example: LHC main dipole

- Coil stress evolution
    - After cool-down the coil is pre-compressed to about 40 MPa.
    - Pre-stress is lost during assembly and cool-down.

- By computing the coil response in an infinitely rigid structure, it appears that the coil pole remains (almost) always in contact with the collar during excitation.



An example process flow in Nb_3Sn high-field magnets



Strand → Cable → Insulation → Coil winding → Coil reaction → Coil impreg. → Magnet assembly → Magnet preload → Magnet instrument. → Magnet testing → Magnet cryostating → Cold mass qualify → Installation

Every element has requirements and QC; in every step examples of issues exist!
*Start to end time not a **critical parameter <u>if</u> the process flow is reliable***

In the early 2000's the "shell-based", "bladder and key" structure was developed to address strain-sensitivity of Nb_3Sn

- Example from "HD3" – a block-style dipole that reached 13.4T at 4.4K

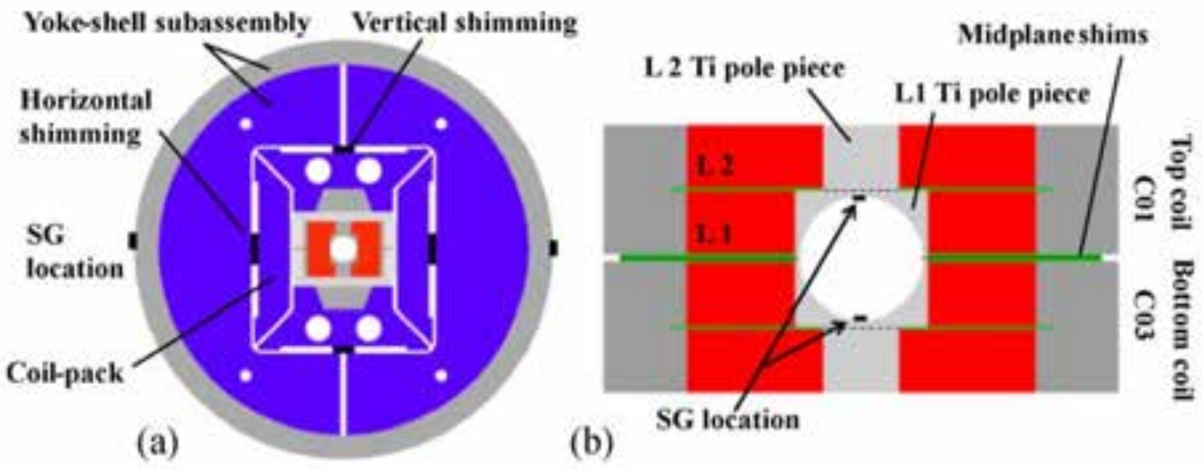
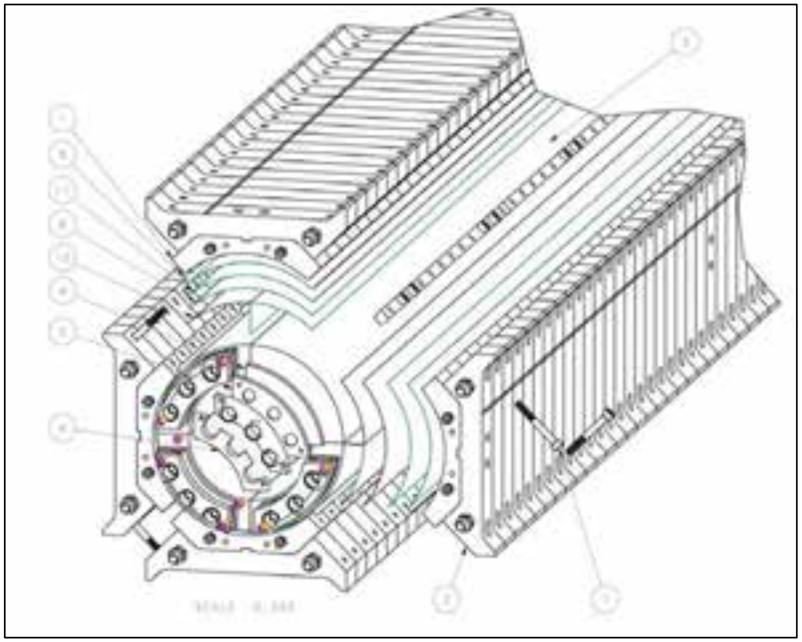
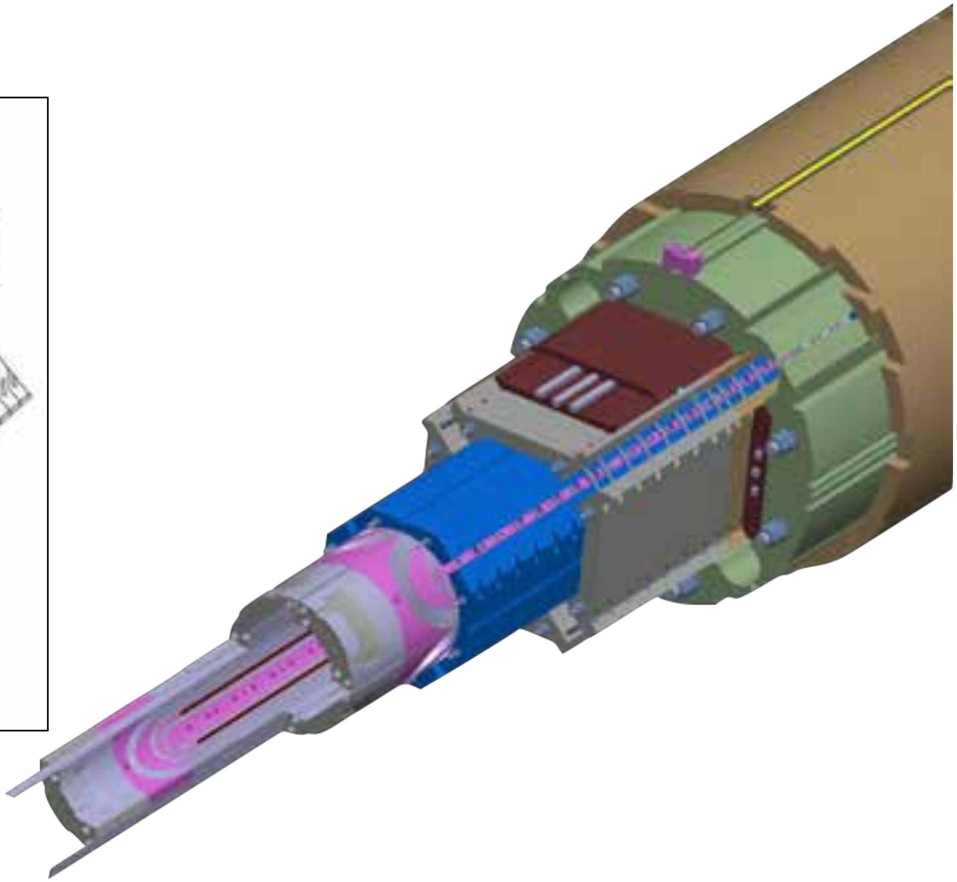


Fig. 1. (a) HD3 magnet cross-section. (b) HD3a coils cross-section showing layer 1 (L1) and 2 (L2), midplane shims and strain gauges location.

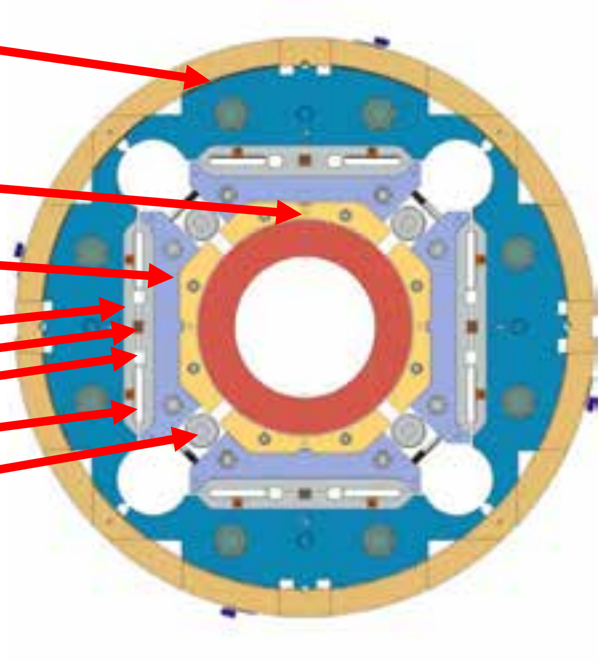
Felice et al., TAS, vol. 23, no. 3, June 2013

Another example: exploded views of the HL-LHC AUP MQXFA magnet structure





Primary MQXFA Structure Subassemblies

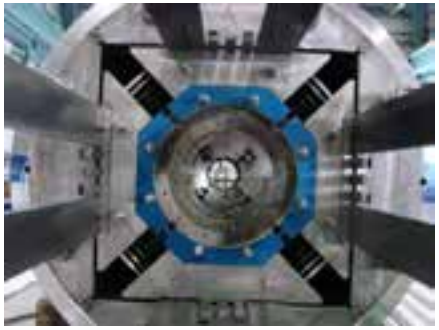


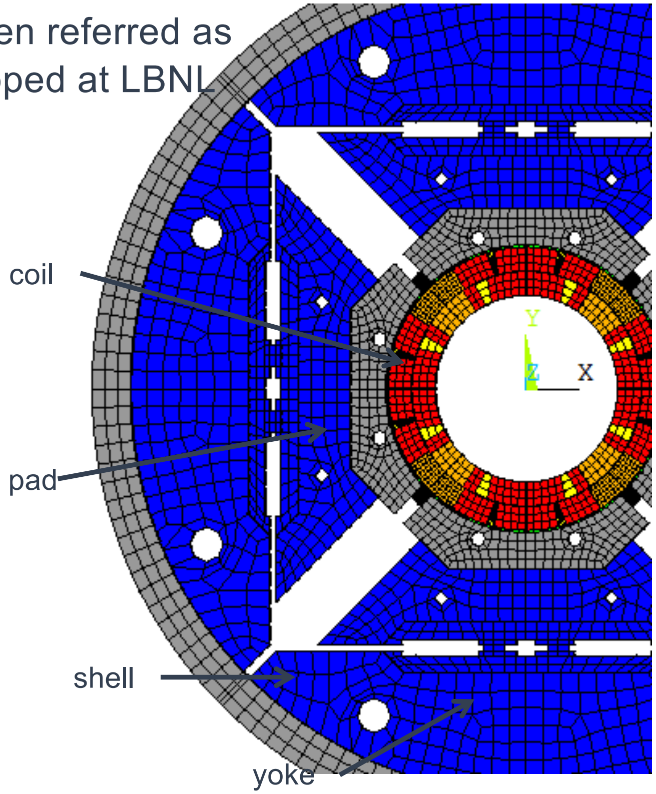
- Shell-Yoke Structure
  - Half-length subassemblies
  - Joined shell-yoke subassembly, full-length
- Coilpack
  - Coil pack subassembly
    - Load pad stacks
  - Collar pack subassembly
    - Collar stacks
    - Instrumented and GPI wrapped coils
- Master Key packages
  - Alignment keys
  - Load keys
  - Bladders
- Axial load
  - Axial rods, [end plates, wire guides]
- Splice Connection box
- Magnet support ring
  - Instrumentation connector skirt

Shell –based support structure concept Shown here on HQ

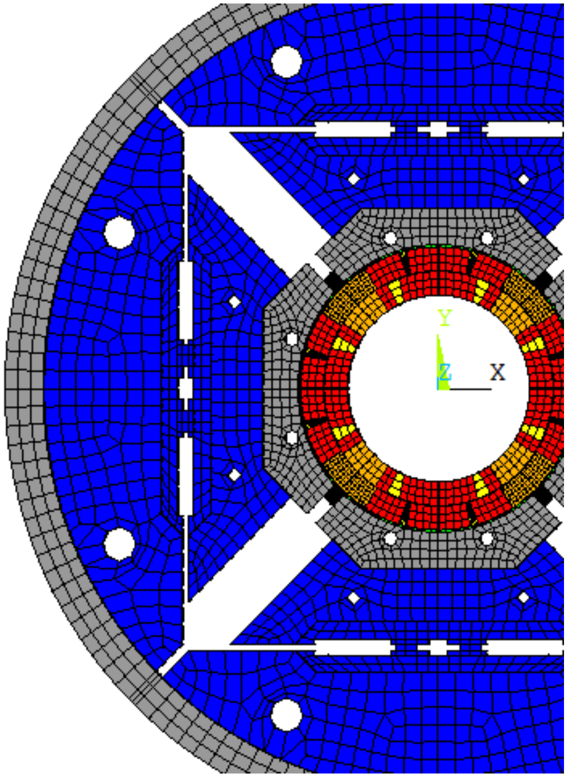
- Shell-based support structure often referred as “bladder and keys” structure developed at LBNL for strain sensitive material

Slides by Helene Felice

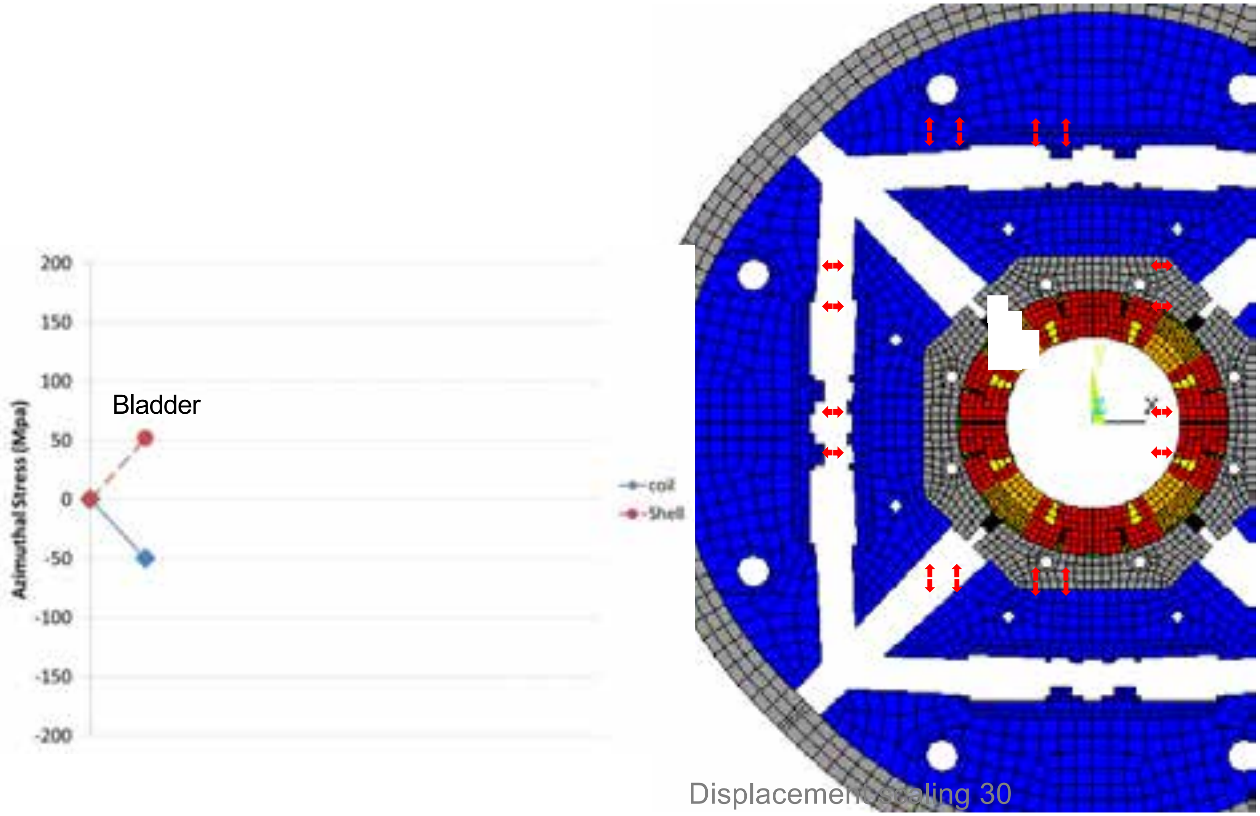




Shell-based support structure concept

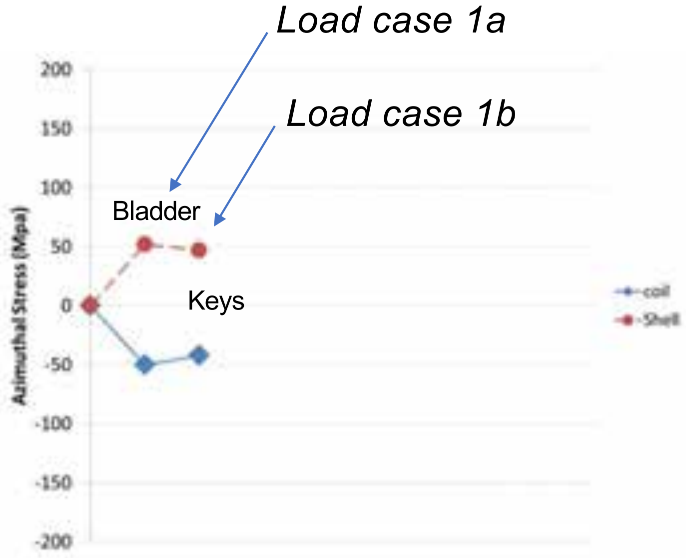


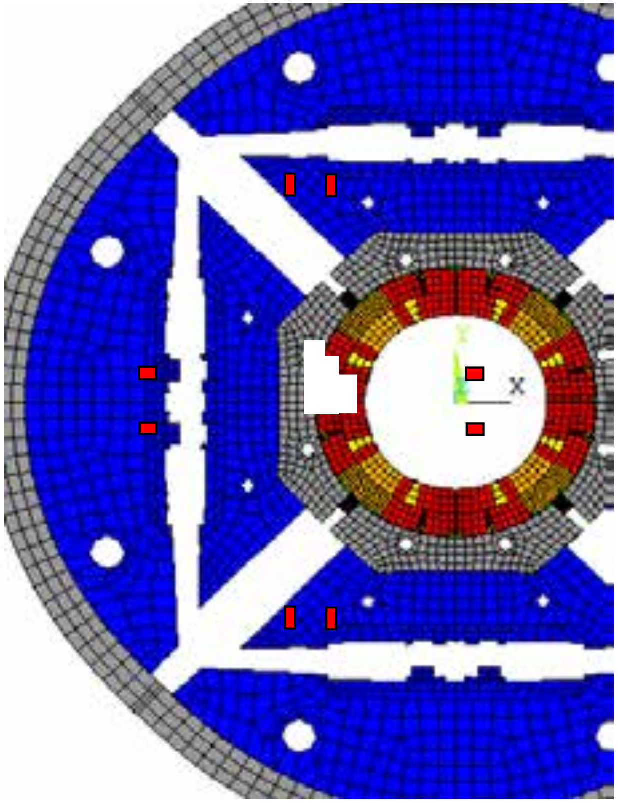
Shell-based support structure concept



Displacement scaling 30

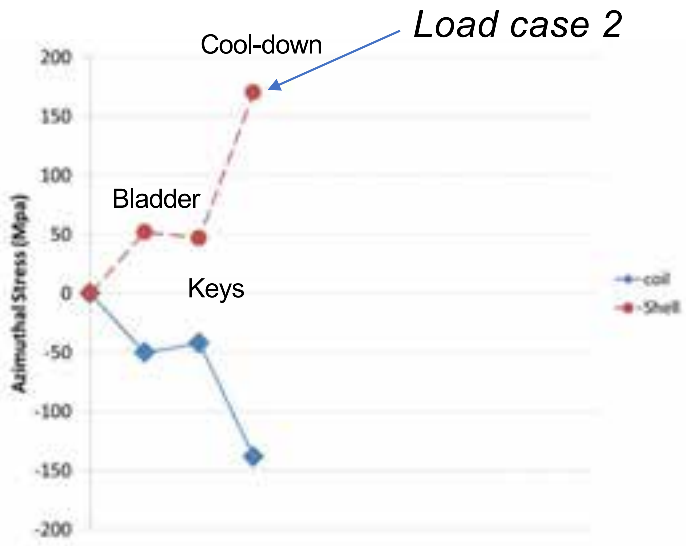
Shell-based support structure concept





Displacement scaling 30

Shell-based support structure concept

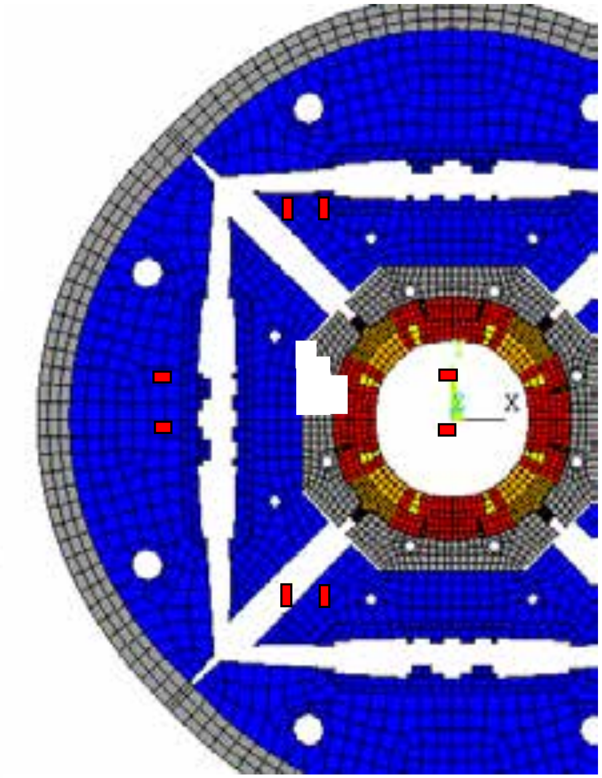


Load case 2

Cool-down

Bladder

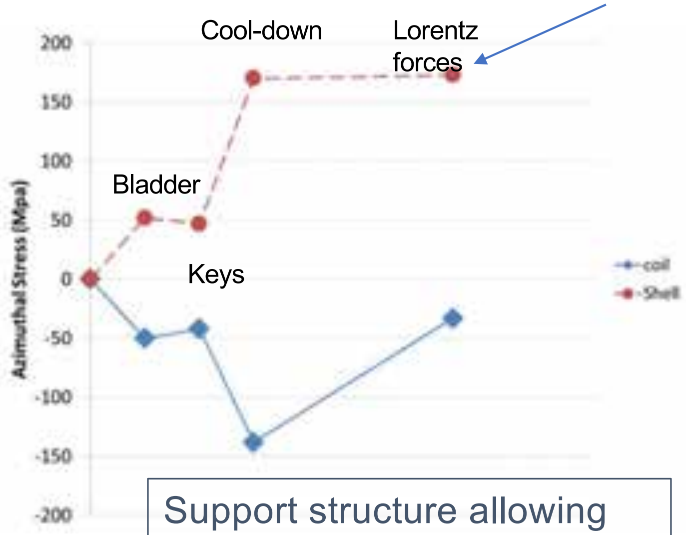
Keys



Displacement scaling 30

Shell-based support structure concept

Load case 3

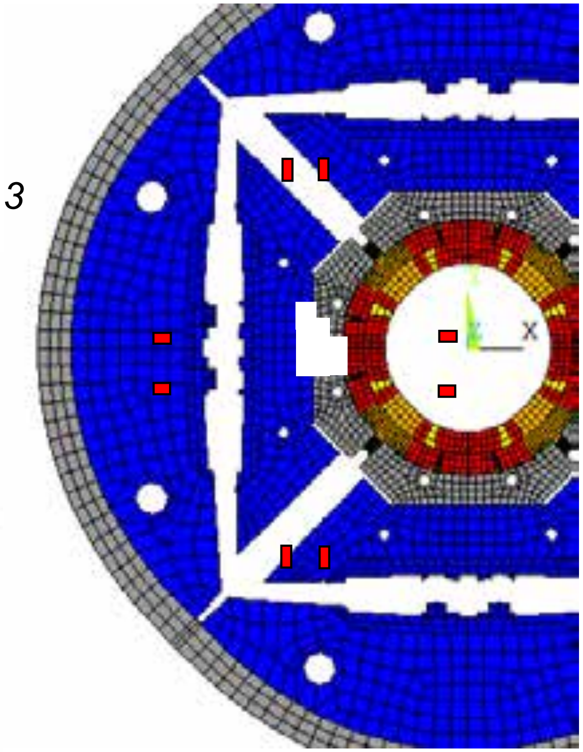


Cool-down

Lorentz forces

Bladder

Keys

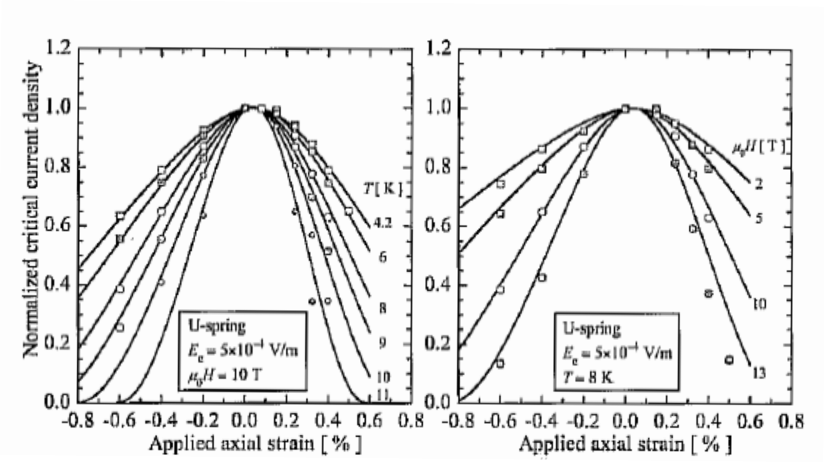


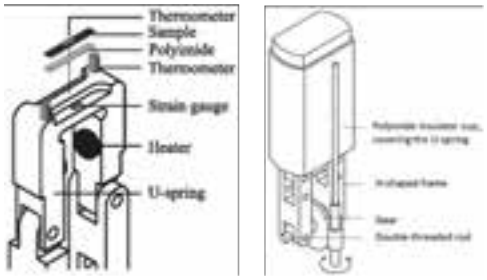
Support structure allowing fine tuning of the pre-stress

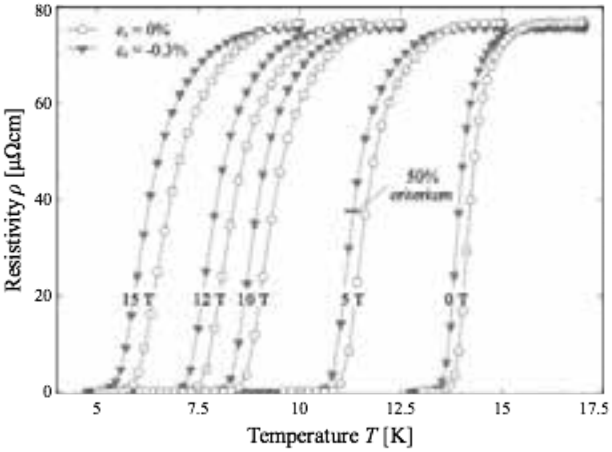
Displacement scaling 30

Key challenges for high field magnets and associated superconductors

- Challenge 1: Mechanics of magnets and superconductors
  - o 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
  - o 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







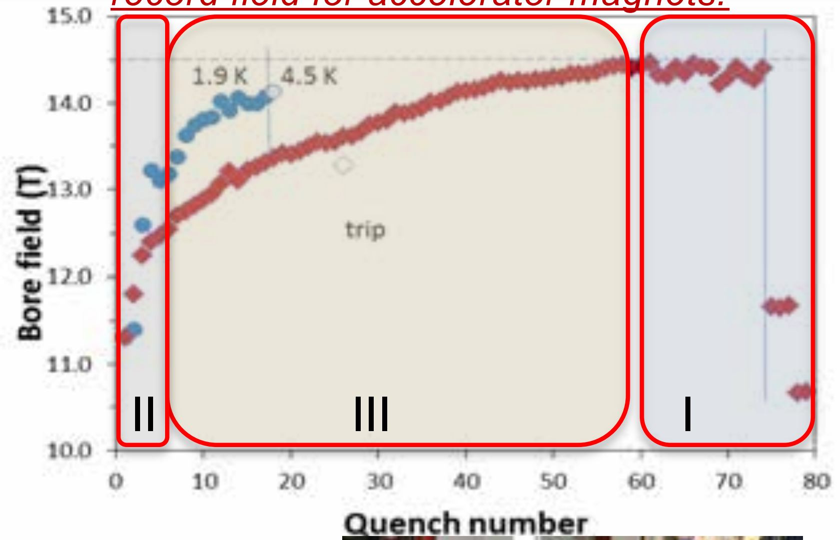
The MDPCT1 test motivates critical elements of our MDP Research Plan

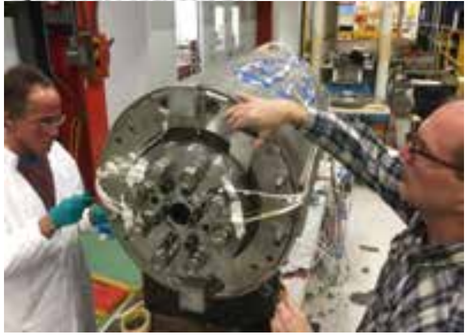
[I]: Highest priority issue: ***degradation*** mechanisms; design mitigation

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

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

B_{max}=14.5 T @1.9K – *the new world record field for accelerator magnets!*





- **Our updated roadmaps include a focus on “stress-management”:**
  - **Strives to mitigate the usual scaling of coil stress with field and aperture**
- **Unfortunate consequence:**
  - **More interfaces and shear-stress considerations**

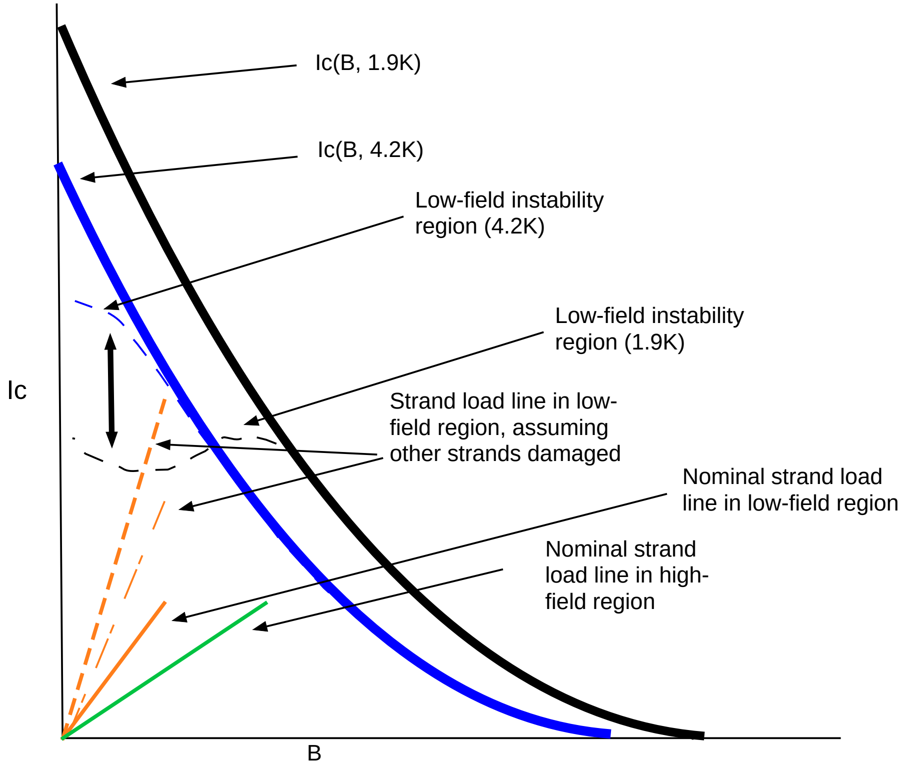
$$B \propto wJ_0 \implies \sigma_\theta \propto J_O B r$$

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

Key challenges for high field magnets and associated superconductors

- 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

U.S. MAGNET
DEVELOPMENT
PROGRAM

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:

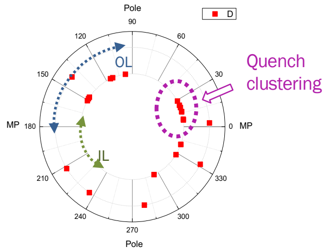
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

GOAL 4:

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

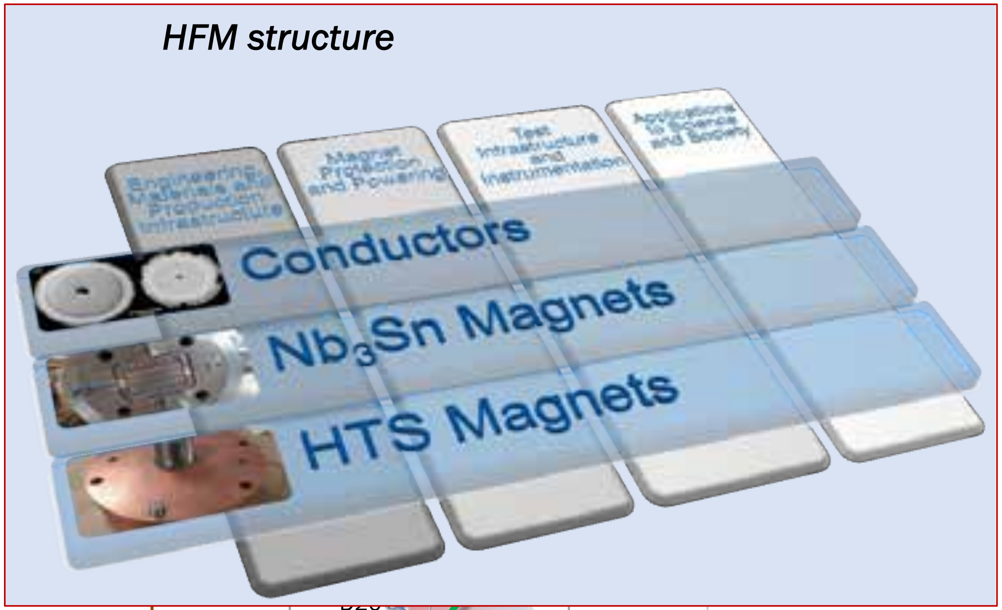
Strategic directions for the update plan:

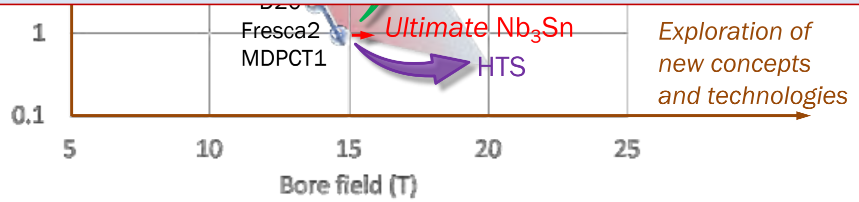
- *Probing stress management structures*
- *Hybrid HTS/LTS designs*
- *Understanding and impacting the disturbance-spectrum*
- *Advancing both LTS and HTS conductors, optimized for HEP applications*



Quench clustering

HFM structure





Exploration of new concepts and technologies

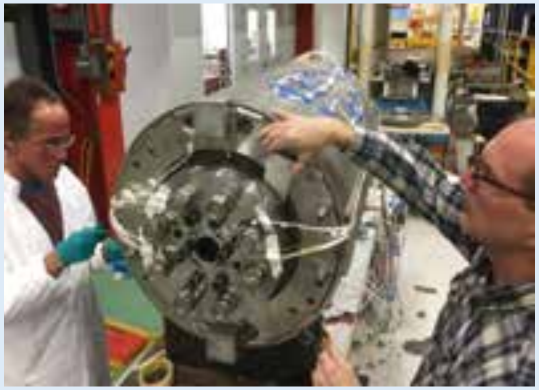
Courtesy Luca Bottura

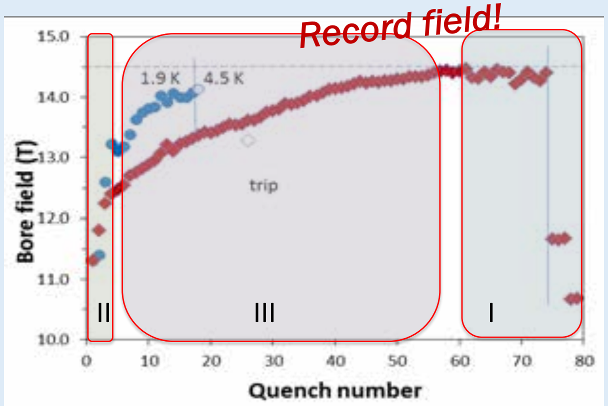
US MDP Program strategy & goals: driving questions re: performance

- 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***

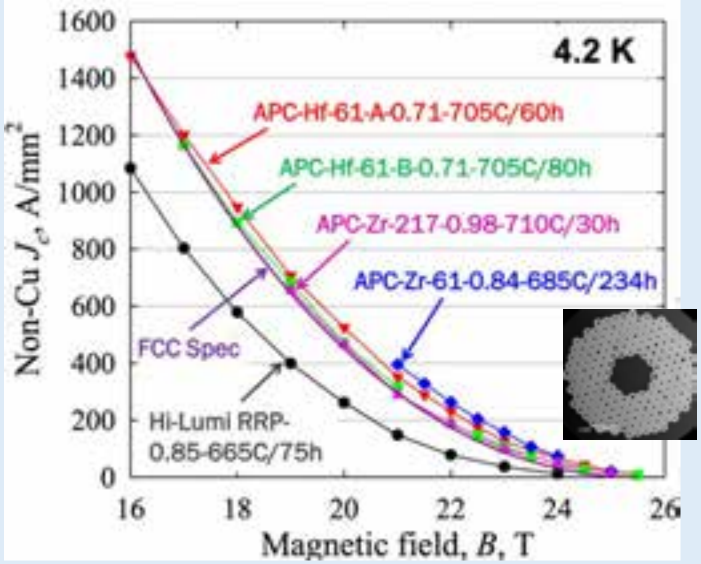
[III]: Third priority: ***Training rate***

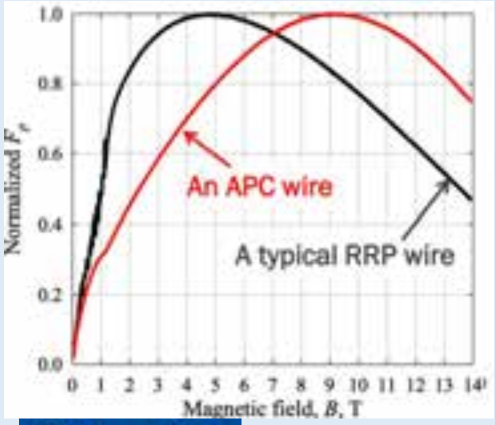
U.S. MAGNET DEVELOPMENT PROGRAM

Significant advances in Nb_3Sn by introducing new pinning sites

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

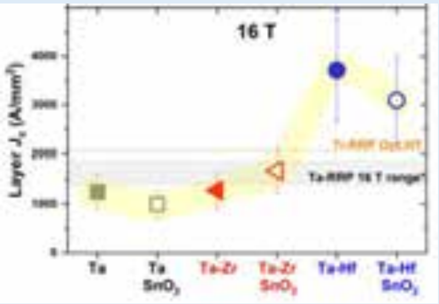
X. Xu, SoftA Workshop, CERN, 2021
See also Xu et al., J. AlloyCompd.857,158270(2021)





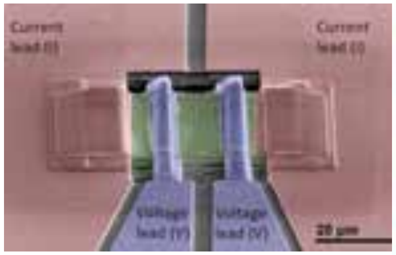
Fermilab

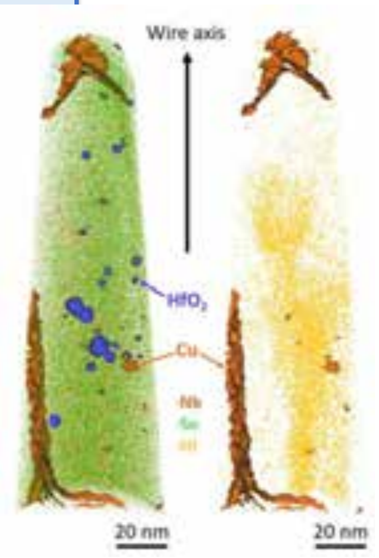
Hyper Tech Research, Inc.



S. Balachandran et al 2019 SUST 32

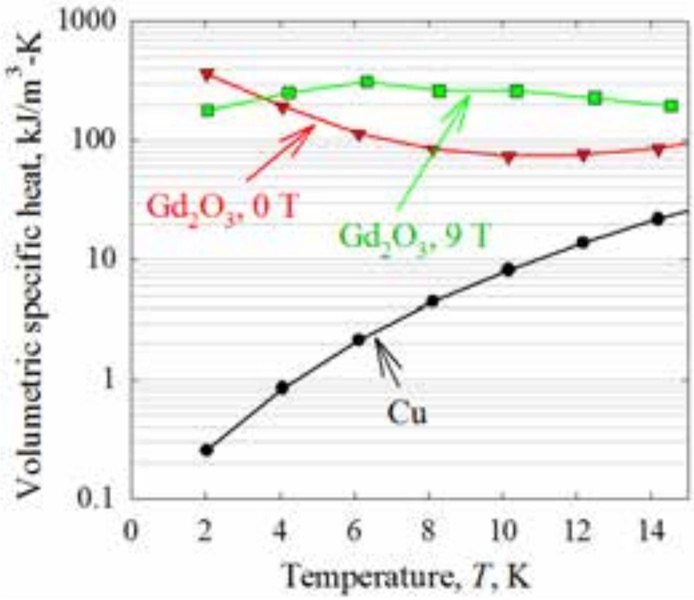
Tarantini et al., Nature Scientific Reports, (2021) 11:17845

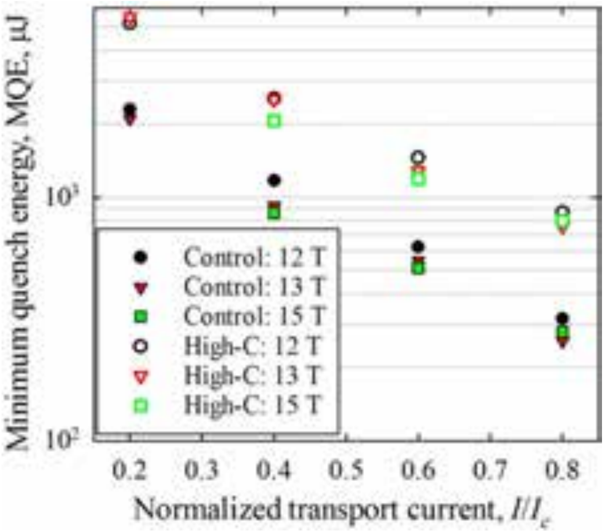




Increasing local heat capacity to absorb random/anomalous thermal disturbances

- Concept being investigated within MDP: doping conductor with Gd_2O_3
  - Significant enhancement of MQE
  - Next step: demonstrate impact on training

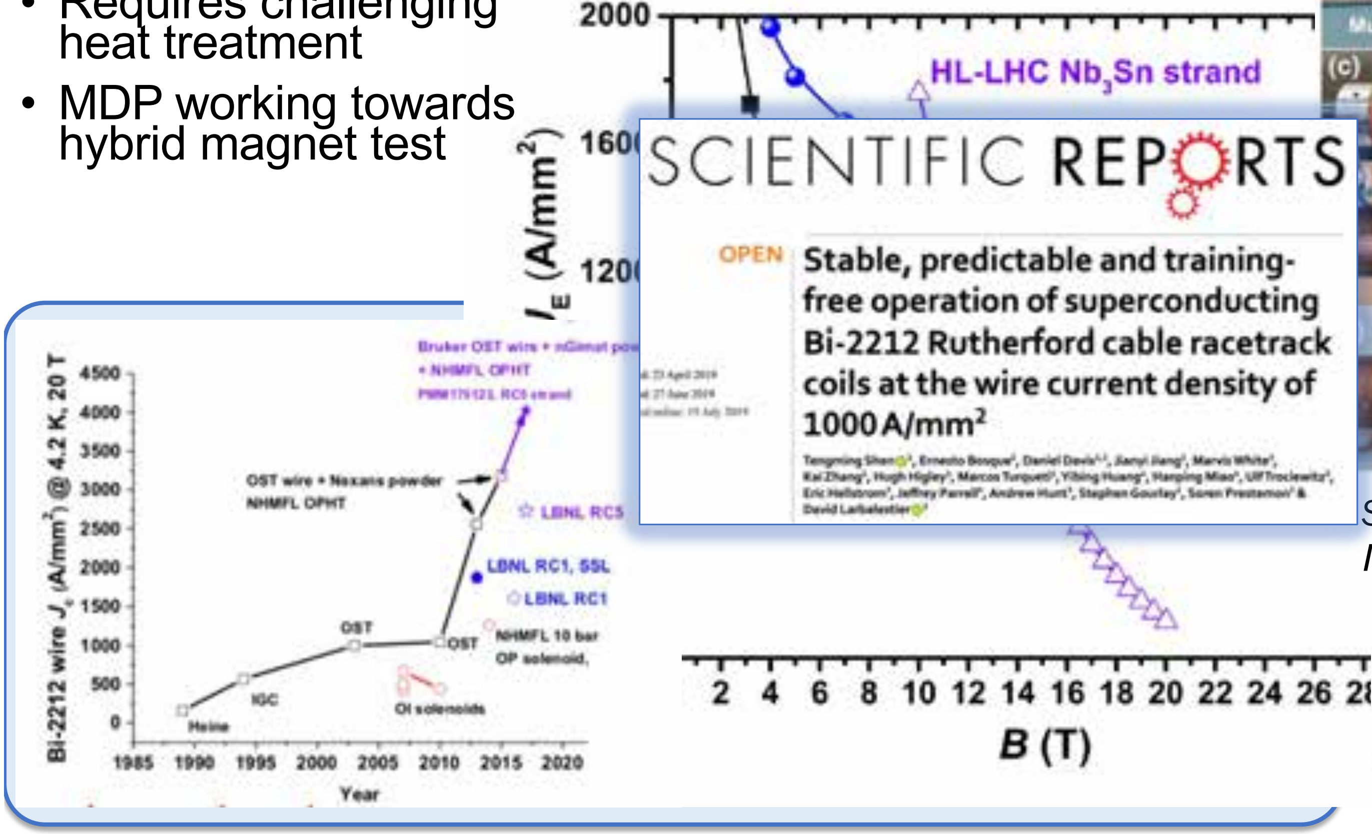




“Nb_3Sn conductors with artificial pinning centers (APC) and high specific heat”, Xingchen Xu, Workshop on Advanced Superconducting Materials and Magnets, KEK, Jan 21-23 2019

The HTS material **Bi2212** has made dramatic strides

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

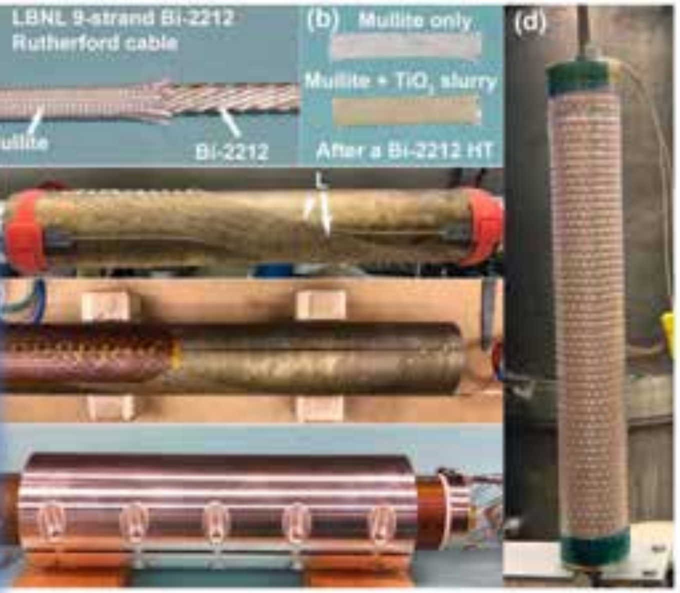


SCIENTIFIC REPORTS

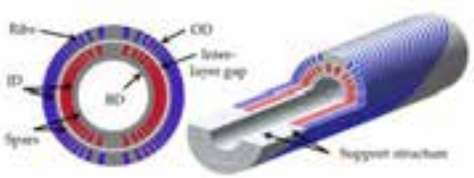
OPEN

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



Shen & Fajardo, Instruments 2020



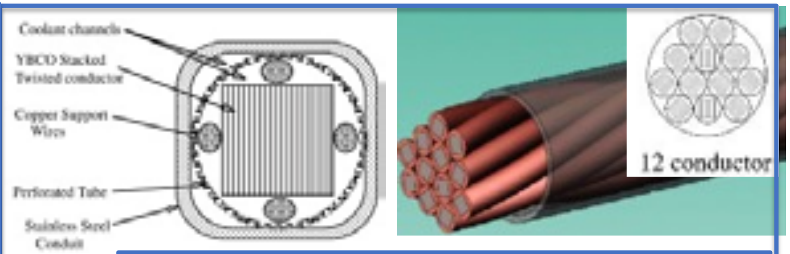
nGimat
MAGLAB
BRUKER
BERKELEY LAB

BCMT
BERKELEY CENTER FOR MAGNET TECHNOLOGY

HTS **REBCO** has broad appeal, significant growth

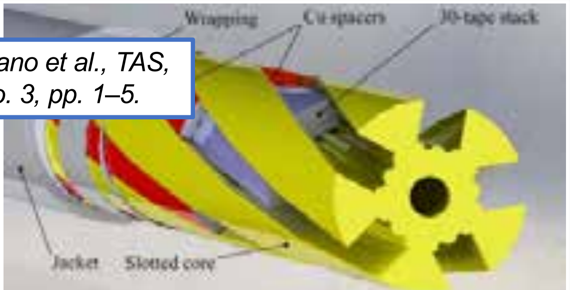
- Produced in tape form***:***
  - ***no reaction needed***
- Many international suppliers
  - A few scaling up production significantly to meet demand from fusion
  - Potential for significant cost reduction, but not manifesting yet
- Anisotropic properties
  - Ic, mech., magnetic
- Cable architectures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

D. van der Laan, Advanced Conductor Technologies LLC



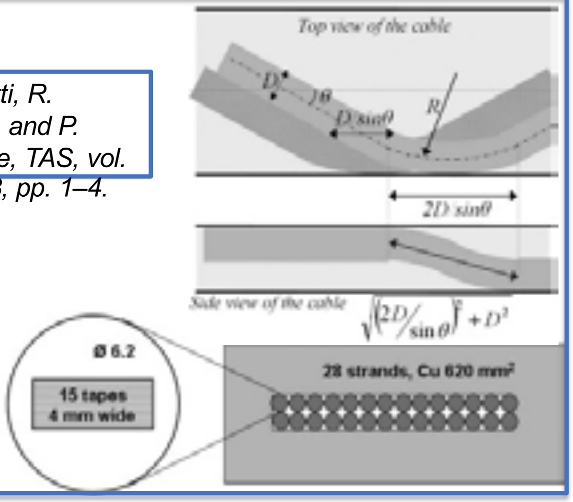
M. Takayasu, L. Chiesa, L. Bromberg, and J. V. Minervini, SUST, vol. 25, no. 1, Jan. 2012.

W. Goldacker et al., TAS 17 3396–401



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

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



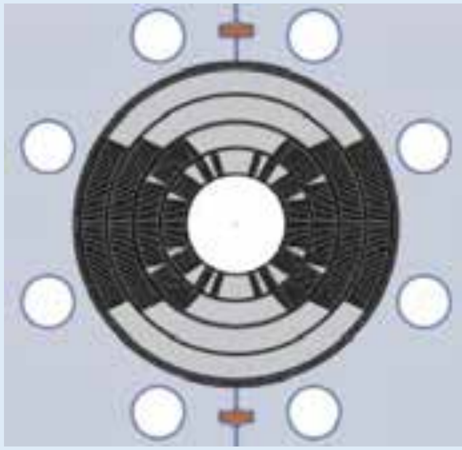
Stress-managed structures avoid force accumulation - at the expense of more interfaces

- ***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***

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

“Traditional” Cos-theta

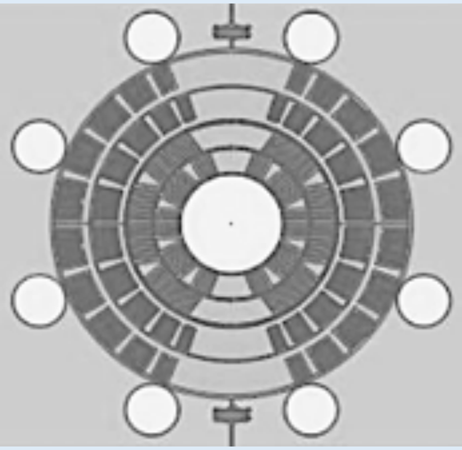
- Midplane stress due to azimuthal force accumulation



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

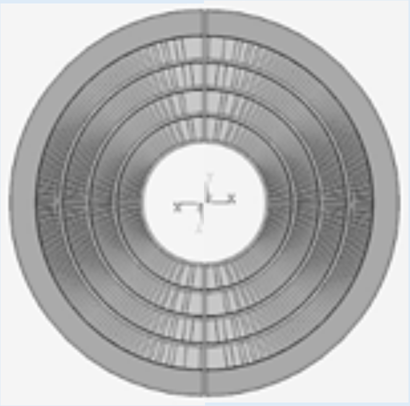
“Stress-managed” Cos-theta

- Groups of turns, azimuthal forces intercepted by support



“Canted” Cos-theta

- Every turn has azimuthal forces intercepted by support



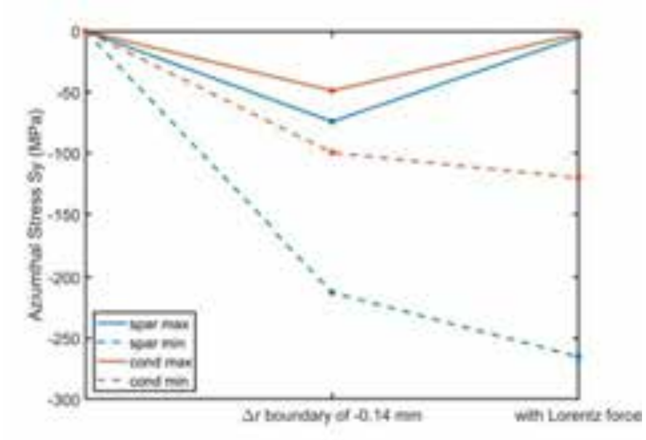
U.S. MAGNET DEVELOPMENT PROGRAM

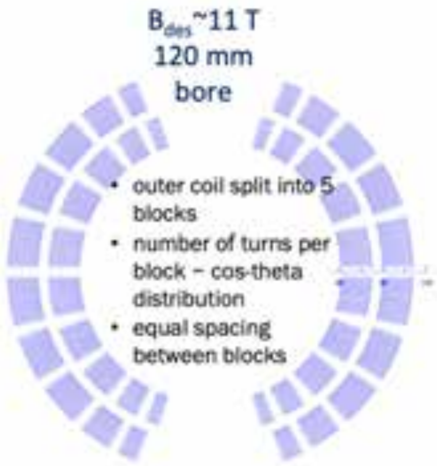
MDP stress management concepts target high fields and large bores for hybrid magnet needs

Canted Cosine-theta

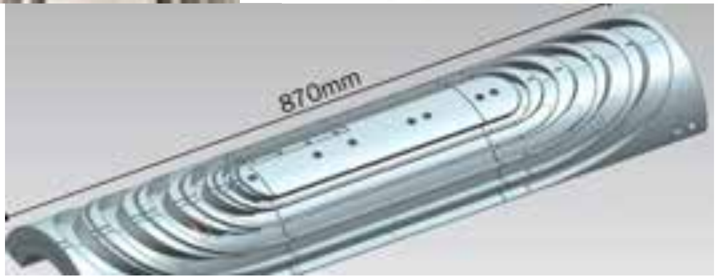
Share utility structure
Shared modeling approaches
Similar instrumentation approaches to be used
Same aperture for HTS inserts

Stress-managed Cosine-theta





- outer coil split into 5 blocks
- number of turns per block – cos-theta distribution
- equal spacing between blocks



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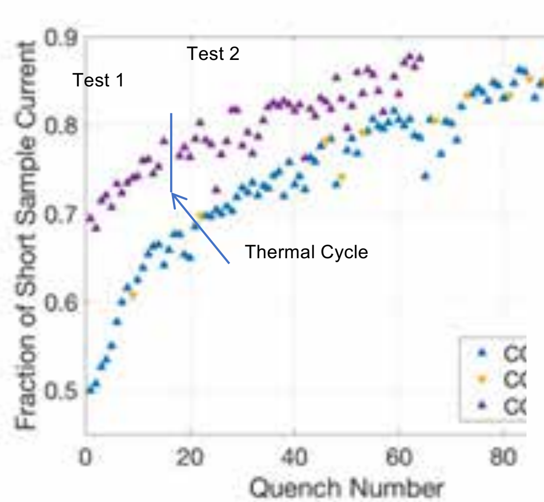
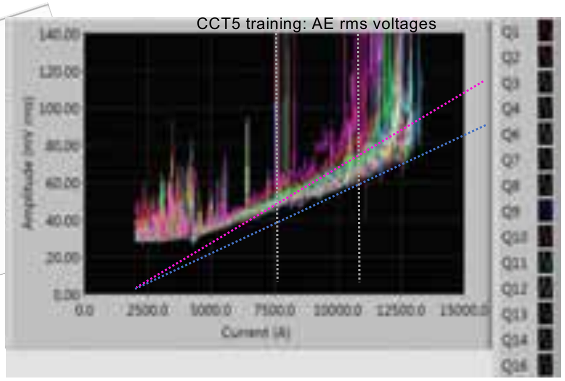
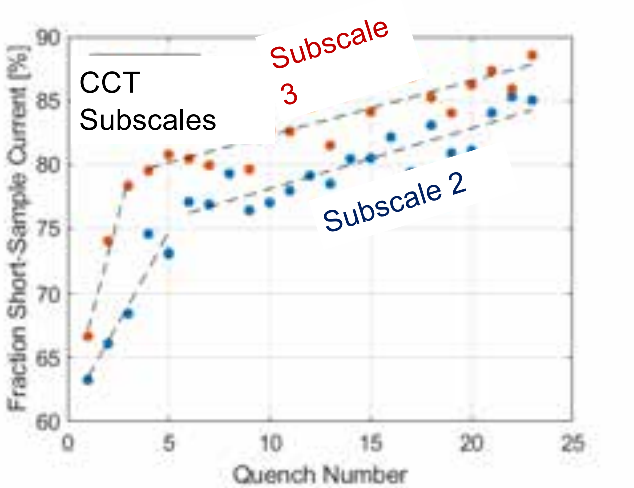
Canted Cosine Theta efforts are focused on subscale versions to probe training mechanisms and their mitigation

Quench Current Relative to SSL

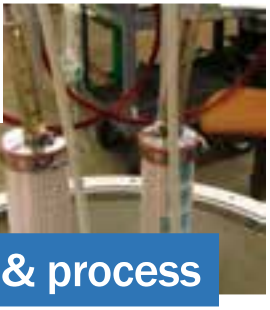


Acoustic Sensor Localization





Coil Winding with Vtap Flag



Potting Tooling & process

Impregnated Coil

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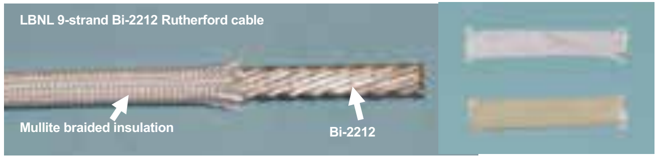
Bi2212 magnet technology is developing rapidly, and we are preparing infrastructure for hybrid magnet development

1. Insulation for minimizing electric shorts



3. After reaction and before VPI – nearly no deformation; still many leakages.

Overall – easy winding and robust fabrication
- No electrical shorts after winding, VPI, and tests.
- VPI using vacuum bag techniques established for CCT Nb_3Sn.

5. After VPI (NHMFL mix 61), with voltage traces shown

2. OPHT in FSU DELTECH

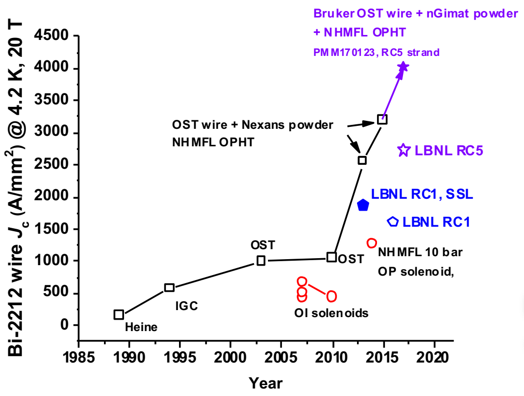
4. Getting ready for VPI

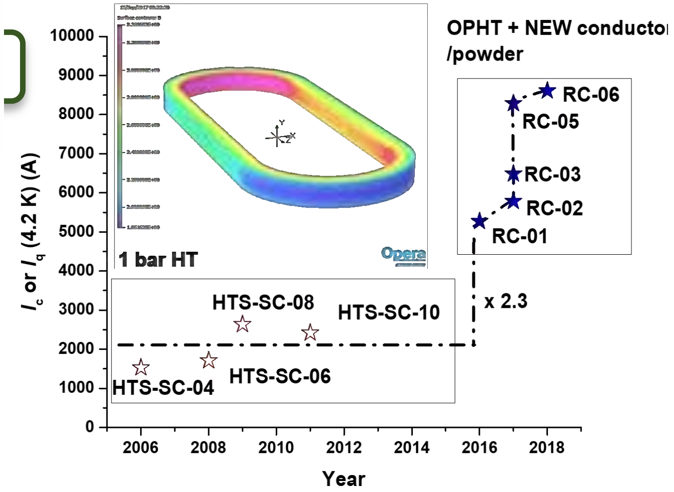
6. Getting inside a A

SCIENTIFIC REPORTS

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

4.7 T @ 5.7 kA





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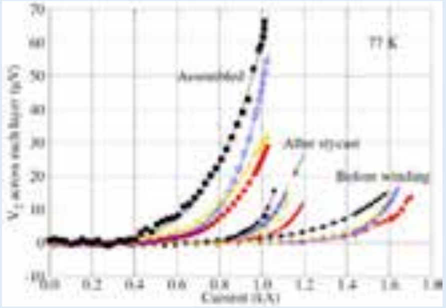
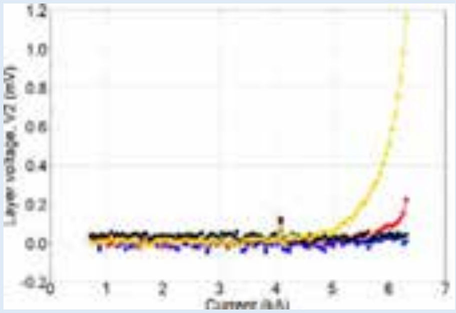
REBCO accelerator magnet technology is progressing in close coordination with industry

- ACT fabricated a record length of 100 m 30-tape CORC® wire for “C2”, consuming 6 km of SuperPower tapes with 30-μm thick substrate



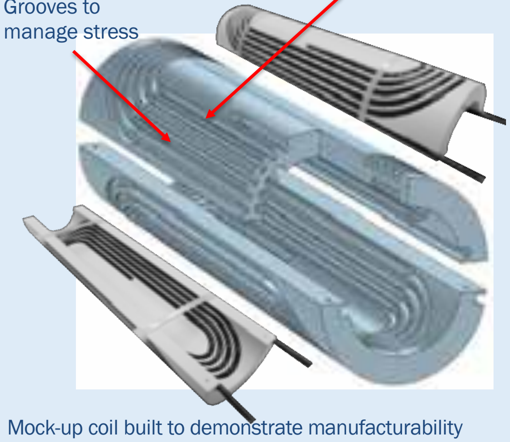


Advanced Conductor Technologies
www.advancedconductor.com

SuperPower Inc.
A Furukawa Company

“C3” will use tapes with 30 μm thick substrate
ID 70 mm, OD approaching 160 mm, ***produce 5T***

Alternative concept under development – improved efficiency

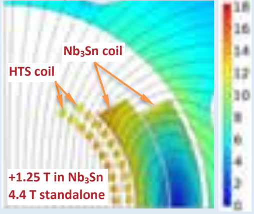


Straight section generates 100% transverse fields

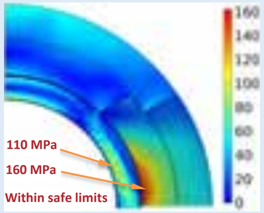
Grooves to manage stress

Mock-up coil built to demonstrate manufacturability

Magnetic field (T)



Equivalent stress (MPa)



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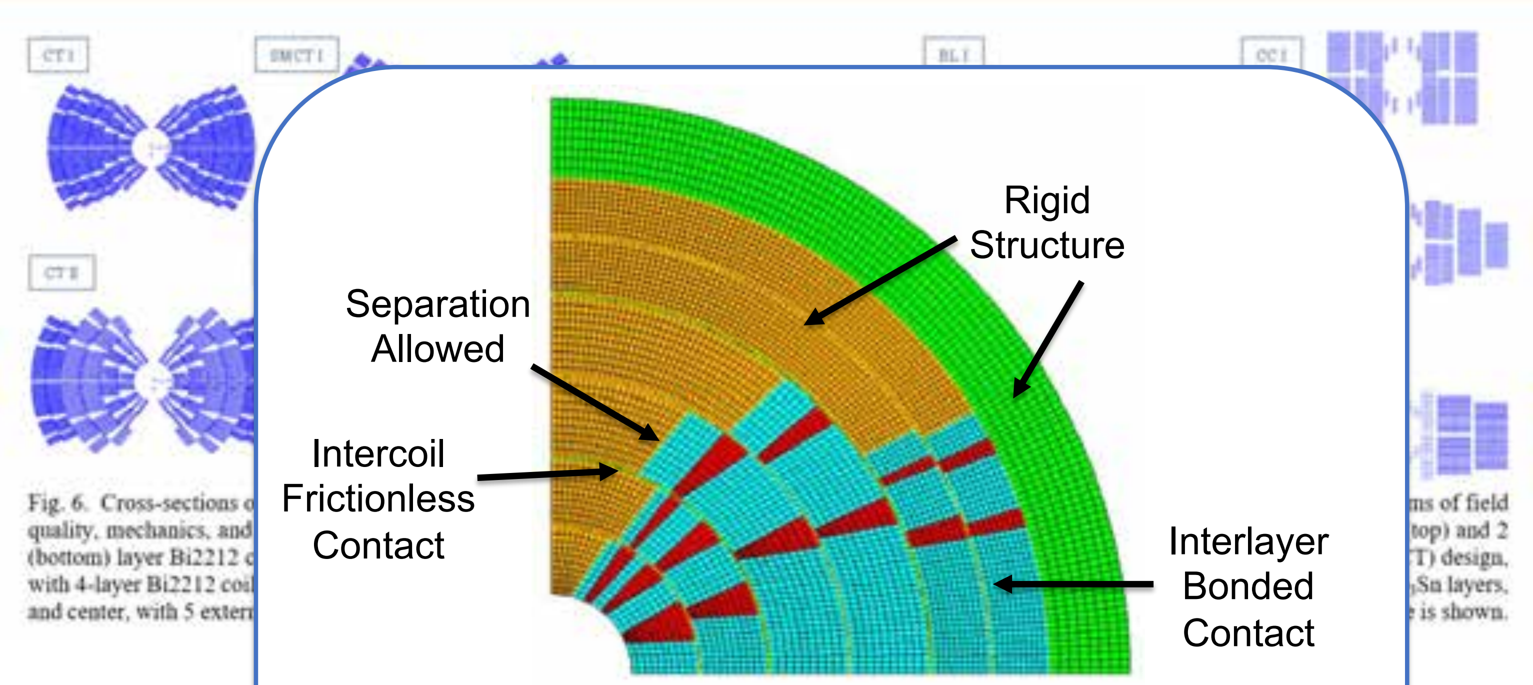
For very high field magnets, a “hybrid” HTS/LTS approach is most efficient

- 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.

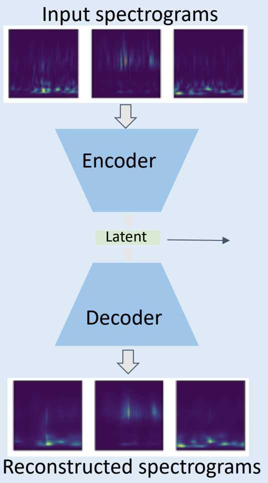
The First Workshop on Instrumentation and Diagnostics for Superconducting Magnets (IDSM01) is aimed at defining a common strategy in diagnostics, and establish a platform for exchanging and circulating new ideas. While focusing on instrumentation and diagnostics, we also welcome contributions on forward-looking,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

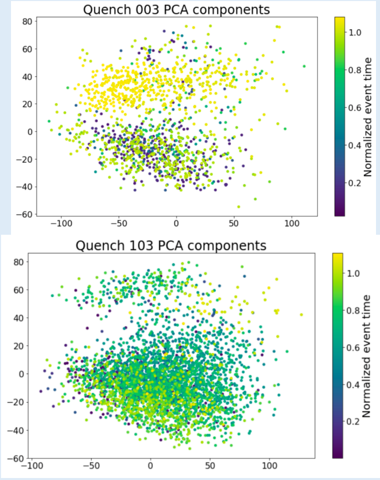
A sampling of diagnostics developments – driven by MDP needs, but with broad impact to magnet technology

Machine Learning

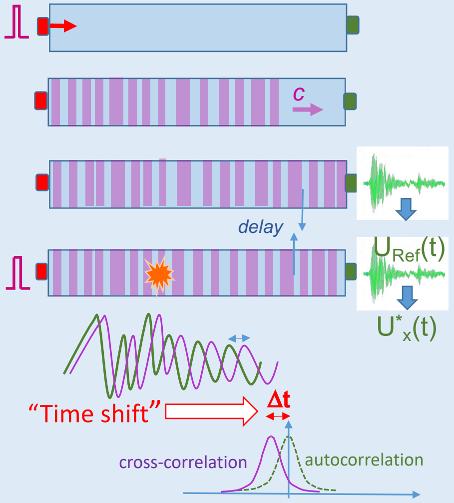
Goal: Use unsupervised learning to investigate physics (cracking vs. stick-slip) in magnet quench dataset

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

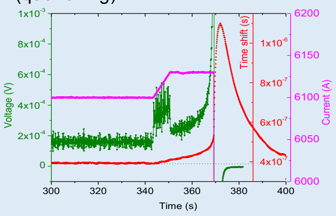




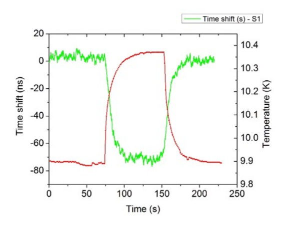
Active acoustics



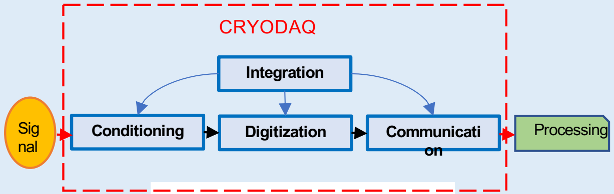
Experiment at 4.2 K. Current ramp stopped at 6100 A (stable) and then increased by 30 A (quenching)



Acoustic thermometry



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



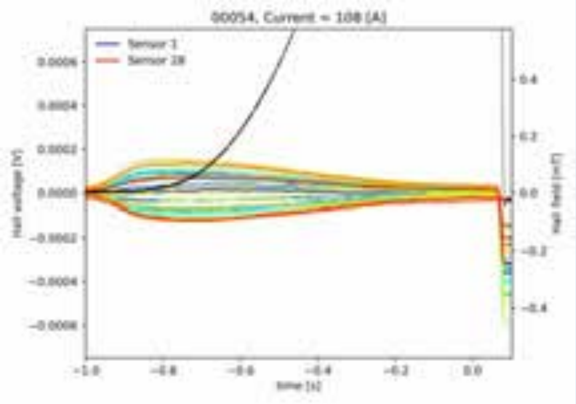
Technical progress on current distribution, quench detection for REBCO magnets

SBIR PH II with ACT

Quench detection for CORC® cables using Hall sensors

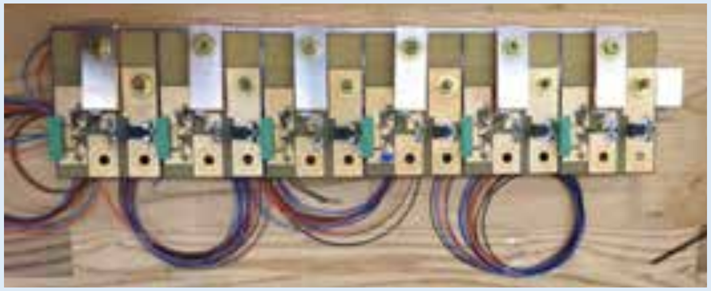
We have built a new type of axial-filed Hall sensor arrays and demonstrated robust detection of quenching

J D Weiss et al 2020 SUST 33



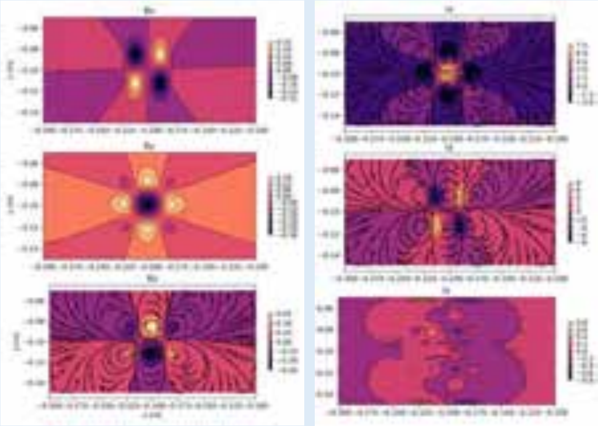
Collaboration with ASC/NHMFL/FSU

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.



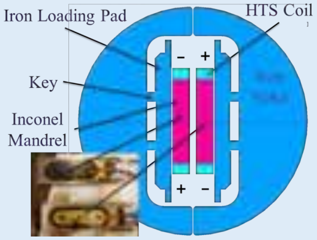
R. Teyber et al., DOI: 10.1109/TMAG.2021.3092527

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.

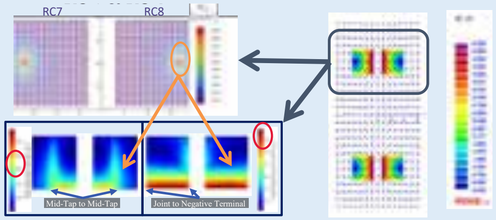


Wide array of modeling advances underway to support diagnostics feedback and to optimize magnet systems

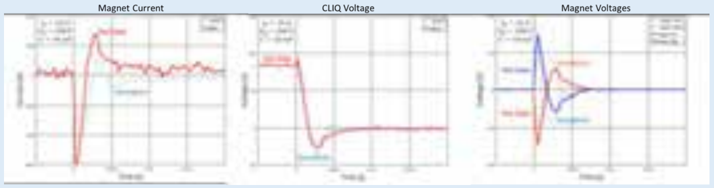
Magnet Protection



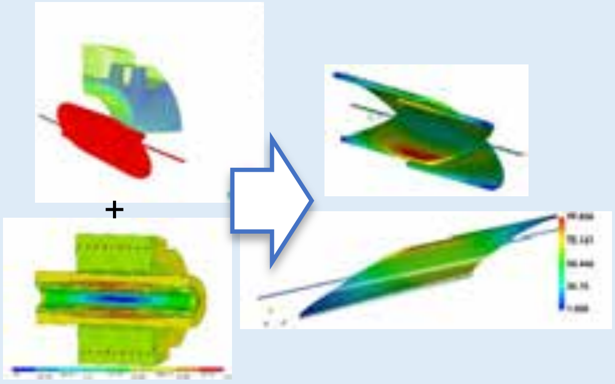
CLIQ optimized through simulation

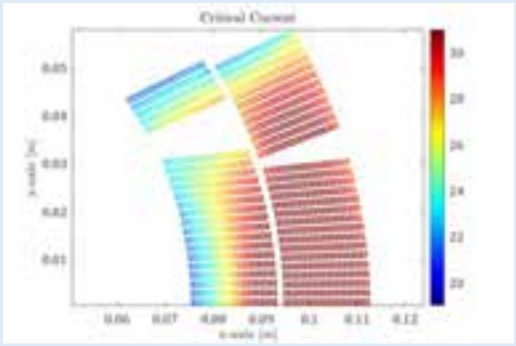


First test of CLIQ on Bi-2212 common coil, 77 K: comparing simulation and measurement

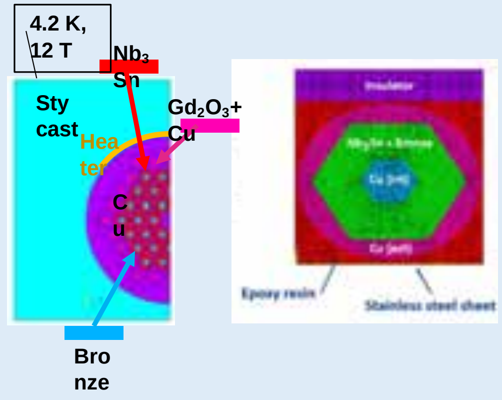


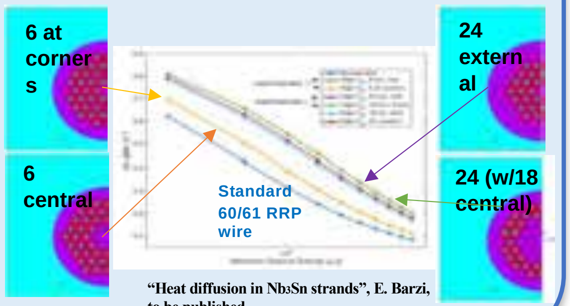
Strain impact on operation





Mechanics and thermal processes in conductors





“Heat diffusion in Nb3Sn strands”, E. Barzi, to be published.

The accelerator magnet R&D is managed through DOE-OHEPS Magnet Development Program

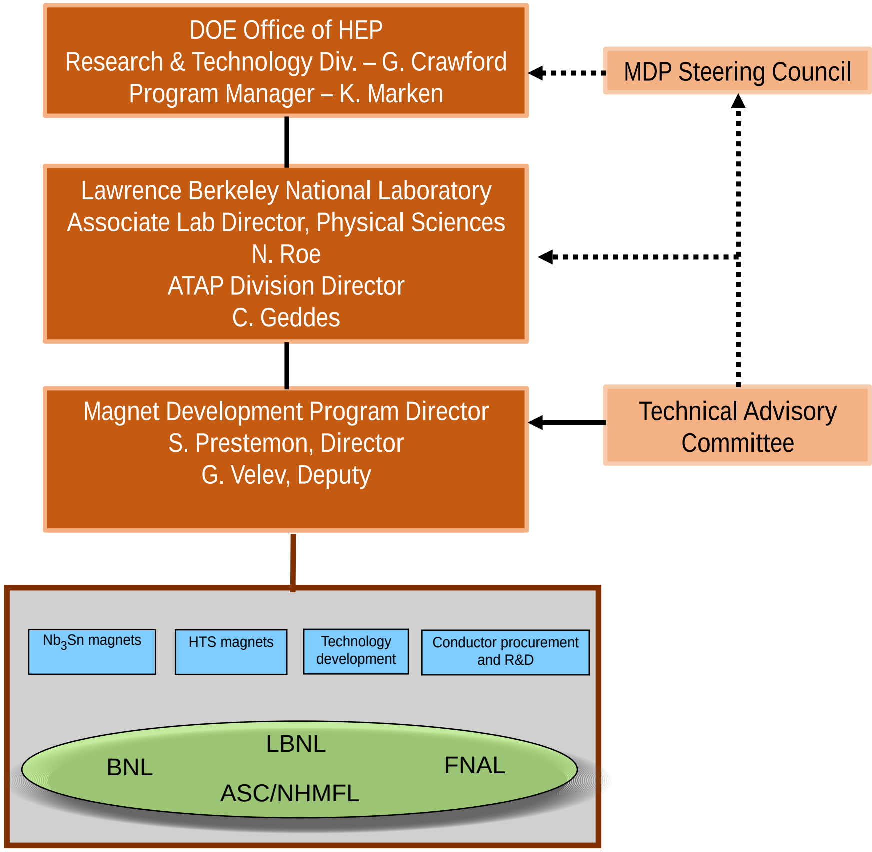
- The following slides summarize the MDP Roadmaps and structure

General management structure of the US MDP

- Integrates the teams from LBNL, FNAL, BNL and the ASC/NHMFL
- A “G7” Management Team meets weekly and provides oversight of the day-to-day progress of the MDP technical Areas
- Bi-weekly “General” meetings of the overall MDP
- Teams associated with technical Areas meet regularly
    - Report back at Bi-weekly General meetings on rotation

“G7” members

Kathleen Amm	BNL
Lance Cooley	ASC/NHMFL
Steve Gourlay	LBNL
David Larbalestier	ASC/NHMFL
Soren Prestemon	LBNL
George Velev	FNAL
Sasha Zlobin	FNAL



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

MDP Steering Council

Lawrence Berkeley National Laboratory
Associate Lab Director, Physical Sciences
N. Roe
ATAP Division Director
C. Geddes

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

Technical Advisory Committee

Nb_3Sn magnets
HTS magnets
Technology development
Conductor procurement and R&D

LBNL
BNL
FNAL
ASC/NHMFL

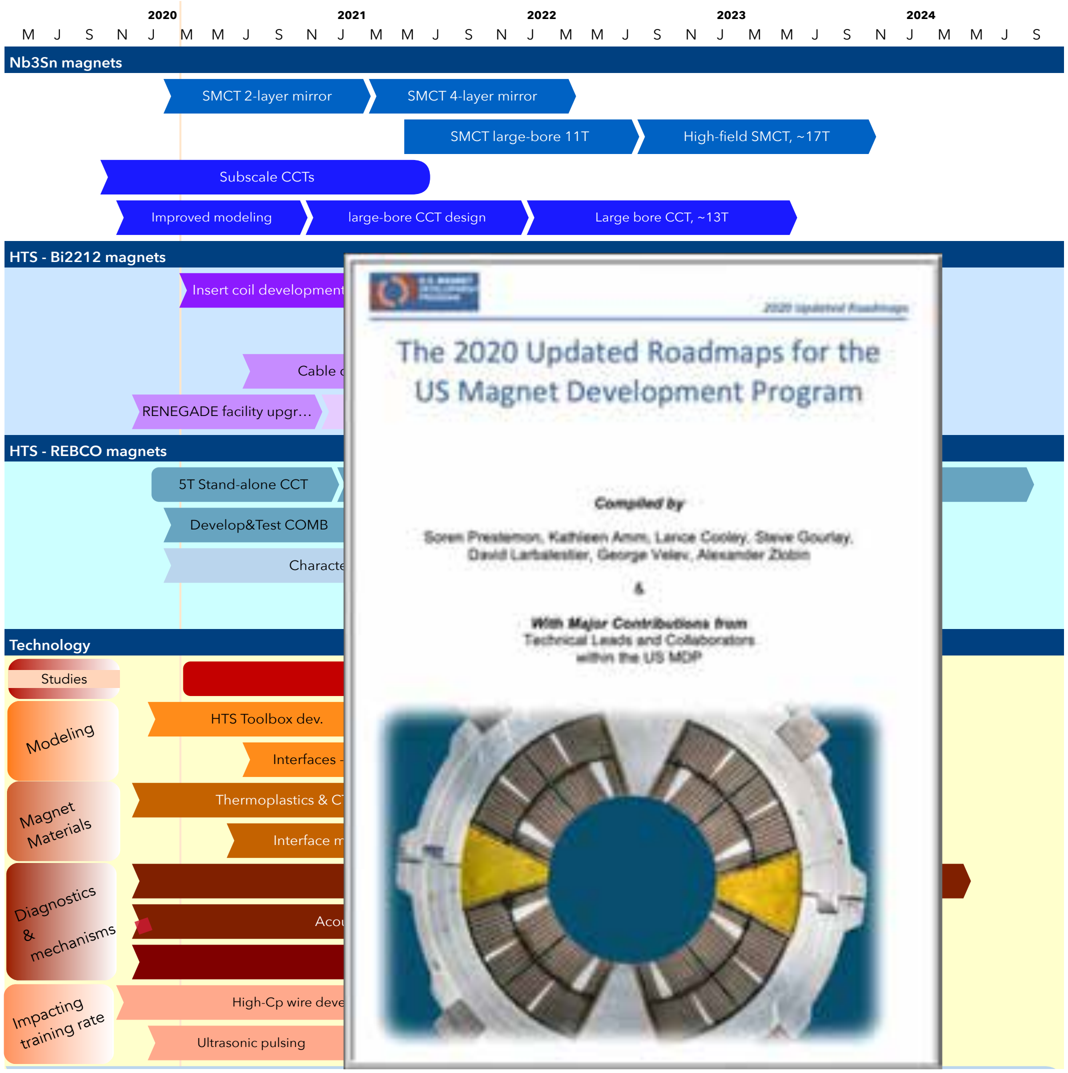
Program roadmap for the 2020-2024 period

- Strategic directions for the (2020) updated plan:
  - o Probing stress management structures
  - o Hybrid HTS/LTS designs
  - o Understanding and impacting the disturbance-spectrum
  - o Advancing both LTS and HTS conductors, optimized for HEP applications

We also introduced a new technology element

20T Hybrid Magnet Design & Comparative Analysis,

=> designed to prepare for future milestones and directions



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

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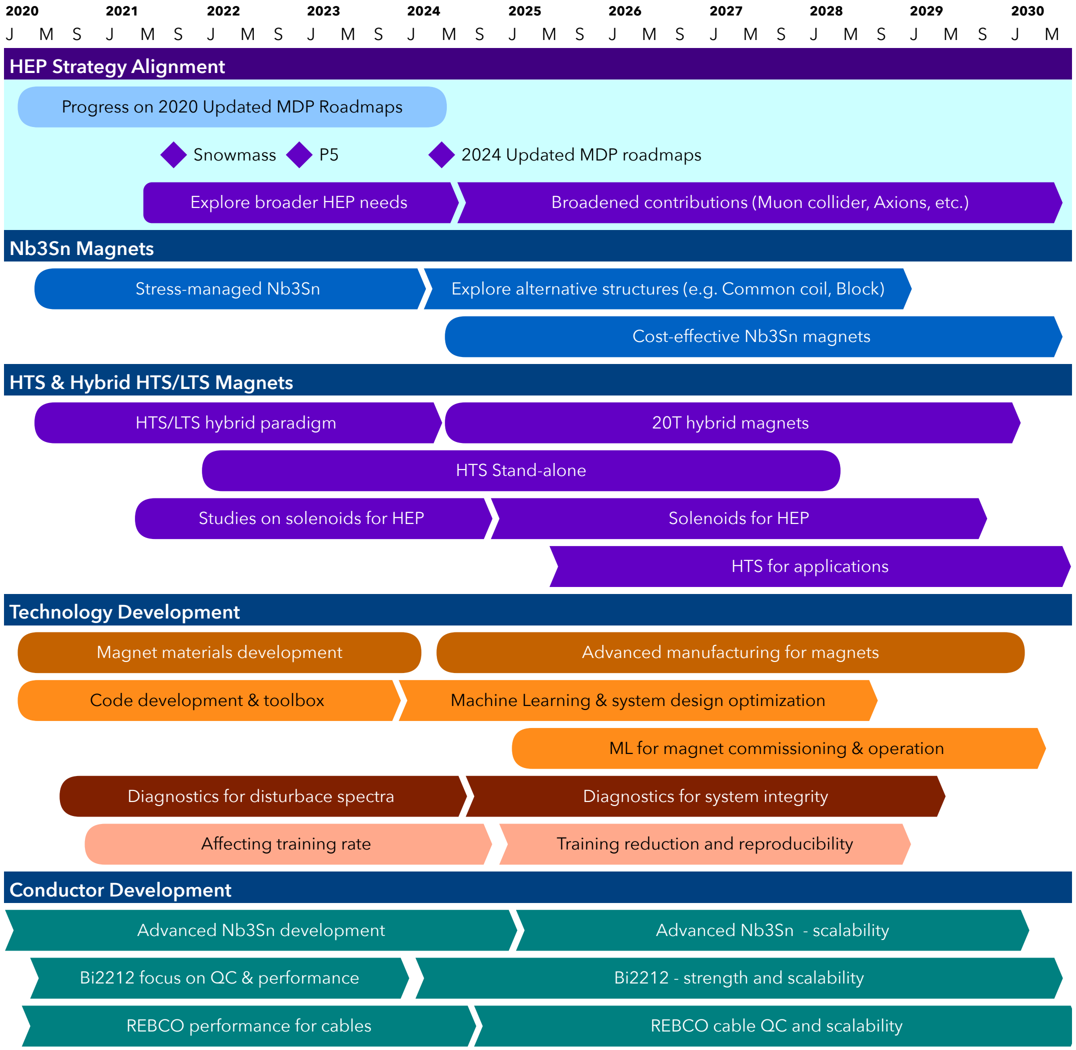
Ten-year roadmap

- A 10-year high-level roadmap recognizes the Snowmass process and possible program adjustments

- Significant synergies with other programs
  - o NHMFL development of high field solenoid technologies
  - o Fusion development of high-field HTS-based Tokamaks
  - o The DOE HEP and FES offices are investing now in a High Field Cable Test Facility
  - o We are working with DOE’s ARDAP to identify means to strengthen US industrial/laboratory ecosystem in superconductors and magnets



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Summary of 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