U.S. MAGNET DEVELOPMENT PROGRAM

Nb_3Sn Accelerator Magnet Development in the US

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Director
US Magnet Development Program
Lawrence Berkeley National Laboratory

Outline

- Some history of Nb_3Sn accelerator magnet development in the US
  - DOE Laboratory efforts
  - NIST
  - University efforts
  - The DOE LHC Accelerator Research Program

- The US Magnet Development Program
  - How we are structured
  - Progress and current status

- Summary

Many DOE laboratories and Universities have been involved in Nb3Sn accelerator magnet technology development

- DOE labs:
  - LBNL, FNAL, BNL
- NIST
- Universities:
  - Texas A&M University
  - Ohio State (materials)
  - FSU/NHMFL (materials)

The DOE labs have been involved in Nb_3Sn technology for more than two decades

- *S. A. Gourlay, "High Field Magnet R&D in the USA," IEEE Trans. Appl. Supercond, vol. 14, no. 2, pp. 333–338, Jun. 2004.*
- *G. Apollinari, S. O. Prestemon, and A. V. Zlobin, "Progress with High-Field Superconducting Magnets for High-Energy Colliders," http://dx.doi.org/10.1146/annurev-nucl-102014-022128, Oct. 2015.*

- LBNL started working with Nb_3Sn in the early 1990's
  - D20 – Cos-theta configuration; tested in 1997, achieved 13.6T at 1.8K
  - RD2, then RD3b – common coil configuration, first proposed by BNL; Achieved 14.5T.
  - HD 1-3 – block designs (HD1 – 16T, HD2 – 13.74T, HD3 – 13.4T)
  - CCT 1-4 – Canted cosine-theta configuration (CCT4 9.14T)
- FNAL began working with Nb_3Sn in the late 1990's (E. Barzi and A. V. Zlobin, "15 Years of R&D on high field accelerator magnets at FNAL," NIMs-A, vol. 824, pp. 168–172, Jul. 2016)
  - VLHC design studies
  - HFDA series 1-6: Cosine theta configuration
  - HFDB-03 - Common coil configuration
  - MBHSP and MBHDP models: Cosine theta configuration
- BNL did some early work on Nb3Sn dipoles in the 1970's (W.B. Sampson et al., "Nb3Sn Dipole Magnets", IEEE Trans. Magnetics, vol. Mag-15, no. 1, pp. 117-118., Jan. 1979)
  - Restarted working on Nb_3Sn in early 2000's (R. Gupta et al., "Common coil magnet program at BNL," TAS, vol. 11, no. 1, pp. 2168–2171, Mar. 2001)
    - Common coil dipole DCC017 made using "React & Wind" technology

Early history of Nb_3Sn accelerator magnet technology in the US: Universities

- NIST:
  - Long history of materials characterization
- Texas A&M:
  - Significant effort toward stress management in high-field dipoles
- Ohio State
  - Significant expertise in strand and cable magnetization, instabilities, materials characterization
- Applied Superconductivity Center (U.W.=>FSU)
  - Long history of materials development – major leadership in conductor development
  - Played (and plays…) critical role in development of advanced Nb_3Sn

The LARP program has provided tremendous focus on bringing Nb_3Sn to real implementation for accelerators

- The LHC Accelerator Research Program
  - A major focus area at initiation was Nb_3Sn quadrupole development
  - Magnet team members: FNAL, LBNL, BNL
- Important understanding of the interdependence of conductor, cable, and magnets
  - Example: scale-up to 4m (LQ) highlighted importance of understanding Nb_3Sn conductor dimensional changes

The U.S. LHC Accelerator Research Program:

A Proposal

R. Kephart, M.J. Lamm, P. Limon, J. Marriner, T. Sen, J. Strait, A.V. Zlobin
Fermi National Accelerator Laboratory
Batavia, IL 60510

P. Cameron, A. Drees, W. Fischer, R. Gupta, M. Harrison, F. Pilat, S. Peggs
Brookhaven National Laboratory
Upton, NY 11973

W. Barletta, J. Byrd, P. Denes, M. Furman, S. Gourlay, A. Ratti, W. Turner
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

May 2003

=> “Handshake” from LARP to HL-LHC AUP currently underway

The US HEP Superconducting Magnet Programs are now integrated into the US Magnet Development Program

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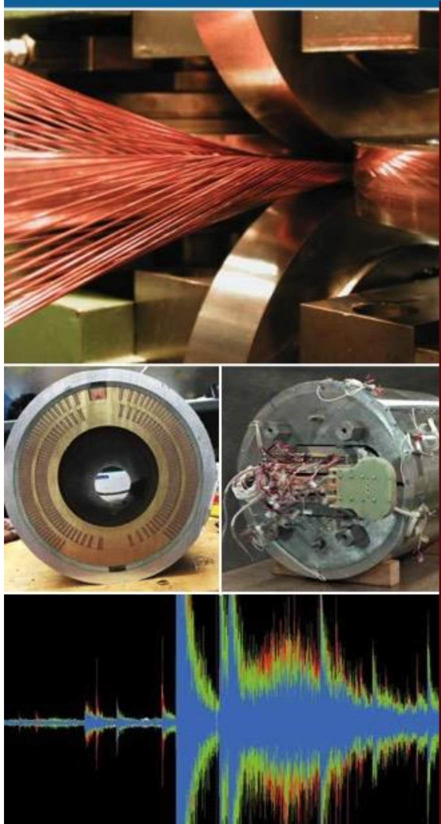
The U.S. Magnet Development Program Plan



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.

ns

ed U.S. high-field magnet R&D collaboration
studies for a very high-energy proton-proton
ge improvement in cost-performance.

A program for high-field accelerator magnet development funded by the DOE Office of High Energy Physics

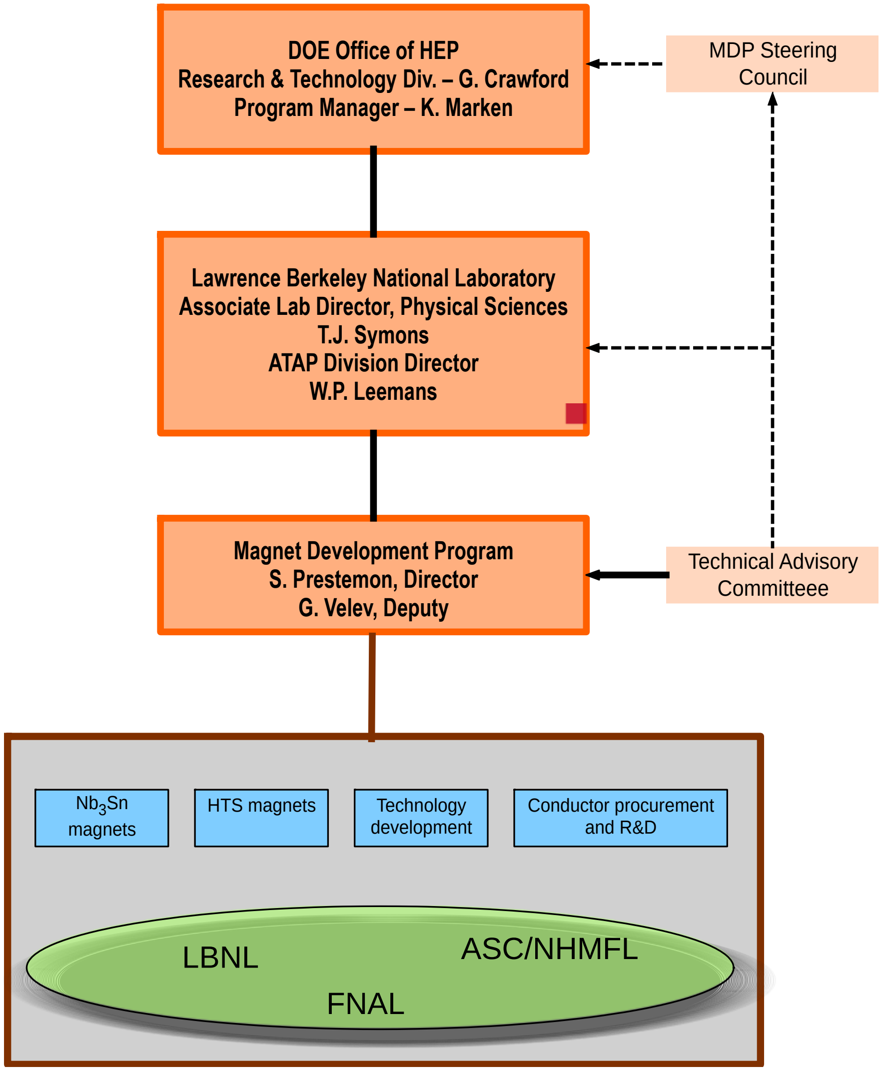
et development plan with appropriate
ility of cost-effective accelerator magnets

ce

try and manufacturing engineering
oth decrease the touch labor and increase
n superconducting accelerator magnets.

crease funding for superconducting
upport aggressive development of new

The management structure of the MDP is clearly defined and the program is fully functioning



Technical Advisory Committee
Andrew Lankford, UC Irvine – ***Chair***
Davide Tommasini, CERN
Akira Yamamoto, KEK
Joe Minervini, MIT
Giorgio Apollinari, FNAL (LARP/Hi-Lumi)
Mark Palmer, BNL

MDP Management Group
S. Prestemon, LBNL
G. Velev, FNAL
L. Cooley, FSU
S. Gourlay, LBNL
D. Larbalestier, FSU
A. Zlobin, FNAL

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Technical areas have leads who are responsible for coordination and planning

Magnets	Lead
Cosine-theta 4-layer	Sasha Zlobin
Canted Cosine theta	Diego Arbelaez
Bi2212 dipoles	Tengming Shen
REBCO dipoles	Xiaorong Wang
Cond Proc and R&D	**Lance Cooley**

→ Nb_3Sn

→ HTS

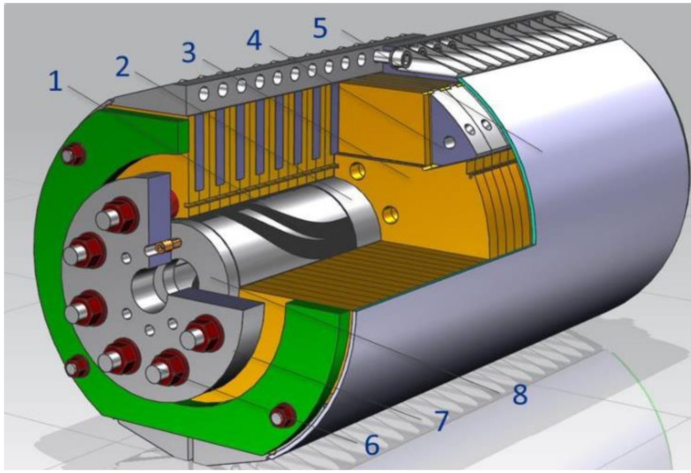
→ Conductor R&D

Technology area	LBNL lead	FNAL lead
Modeling & Simulation	Diego Arbelaez	Vadim Kashikhin
Training and diagnostics	Maxim Martchevsky	Stoyan Stoynev
Instrumentation and quench protection	Emmanuele Ravaioli	Thomas Strauss
Material studies – superconductor and structural materials properties	Ian Pong	Steve Krave

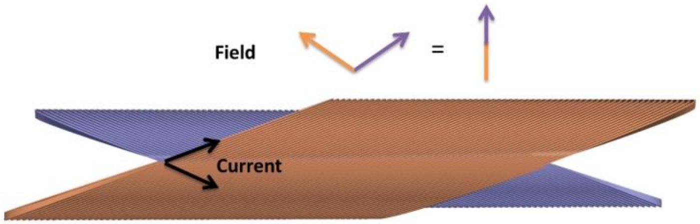
Technology development

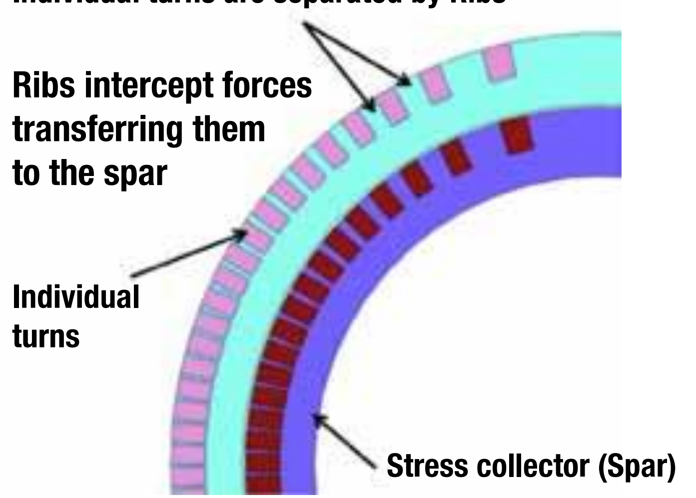
We have initiated a two-prong approach to high field dipoles to explore the limits of Nb_3Sn

- A reference design based on a 4-layer cosine-theta magnet utilizing high-performance Nb_3Sn



- A path to explore innovative designs
  - Starting with the canted cosine-theta (CCT), a different paradigm that integrates mechanical structure internally





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Overview of the Nb_3Sn Milestone Plan, Highlighting the Cos(θ) Reference Magnet Development and the Innovation Route with CCT

2016 | 2017 | 2018 | 2019

Push traditional Cos-theta technology to its limit with newest conductor and structure

Cos-theta 4 layer 15 T	Preload mods	15 T with improvements	4-layer 16 T Cos-theta
Leverage latest Nb_3Sn and Bladder and Key structure	Impact of preload on training		Optimized 16 T design as baseline

Develop innovative concept to address technology issues at high field...

CCT – 2-layer 10 T

1st model	Address conductor expansion	Address assembly issues	Test alternative materials	Focus on training	Focus on margin Prepare for HTS inserts	HTS insert training

...then demonstrate 16 T fields, and furthermore use for hybrid HTS-LTS dipoles

CCT – 4-layer 13 T model
- 1st model
- Improvements & reproducibility; possible element of future 16 T

CCT – 8-layer 16 T demonstration

CCT – 8-layer 15 T for hybrid
- HTS insert testing

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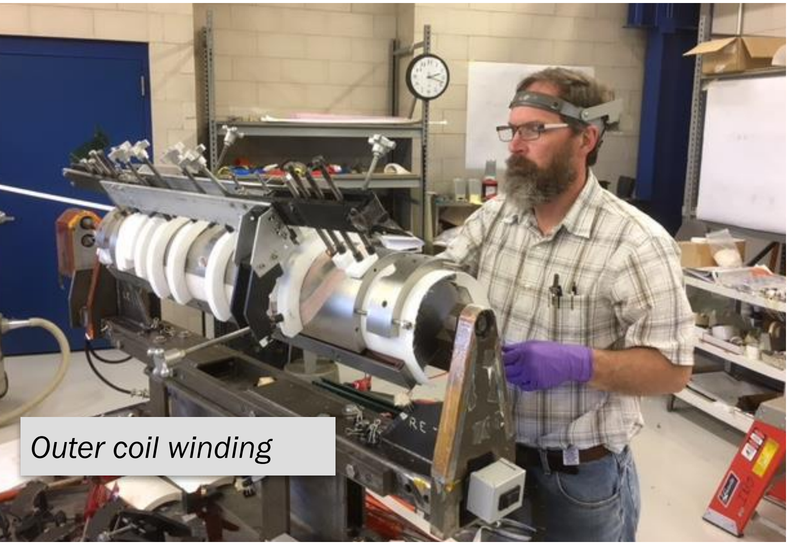
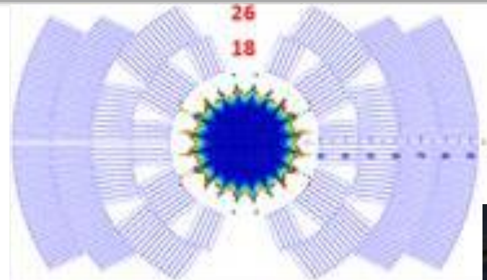
The Cosine-theta 4-layer magnet is proceeding well at FNAL, with 3 outer layer coils completed, mechanical model currently being tested



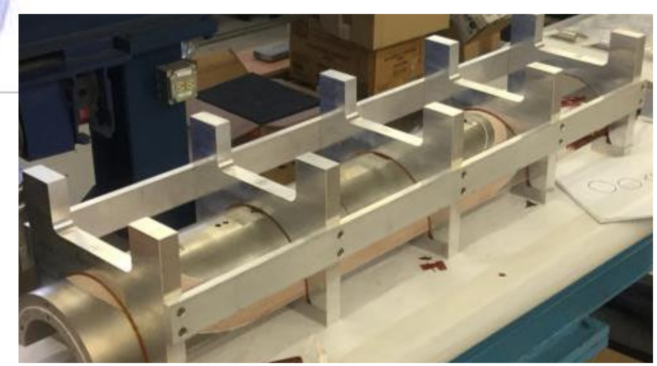
Outer coil winding



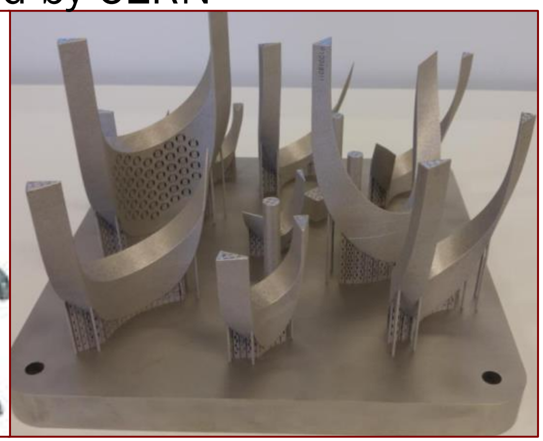
Novel coil layout addressing midplane stresses and field quality

Zlobin et al. MT25

Kokkinos et al. MT25



Coil parts provided by CERN



Traces by LBNL/FNAL

Committee:
Giorgio Ambrosio (FNAL, chair)
Jeffrey Brandt (FNAL)
Shlomo Caspi (LBNL)
Arup Ghosh (BNL)
Peter McIntyre (TAMU)
Alfred Nobrega (FNAL)

The CCT program is proceeding to systematically address technical issues

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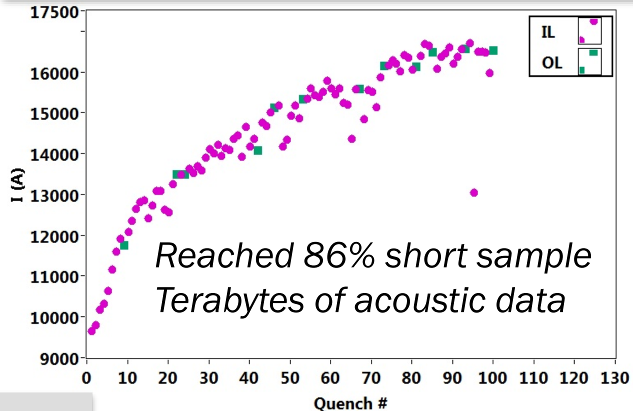
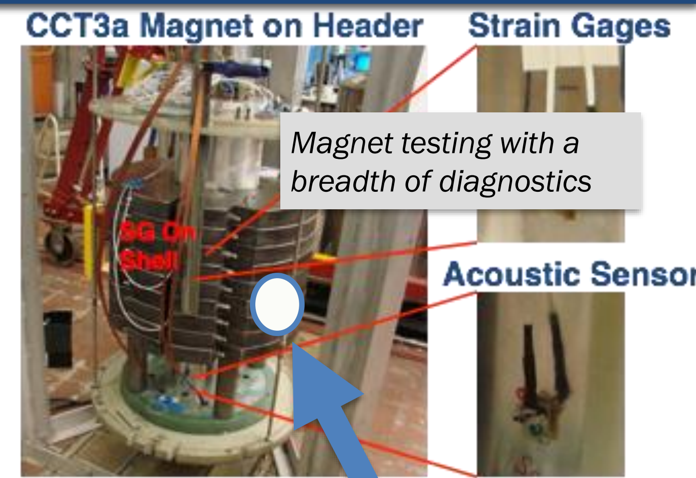
Arbelaez et al., MT25

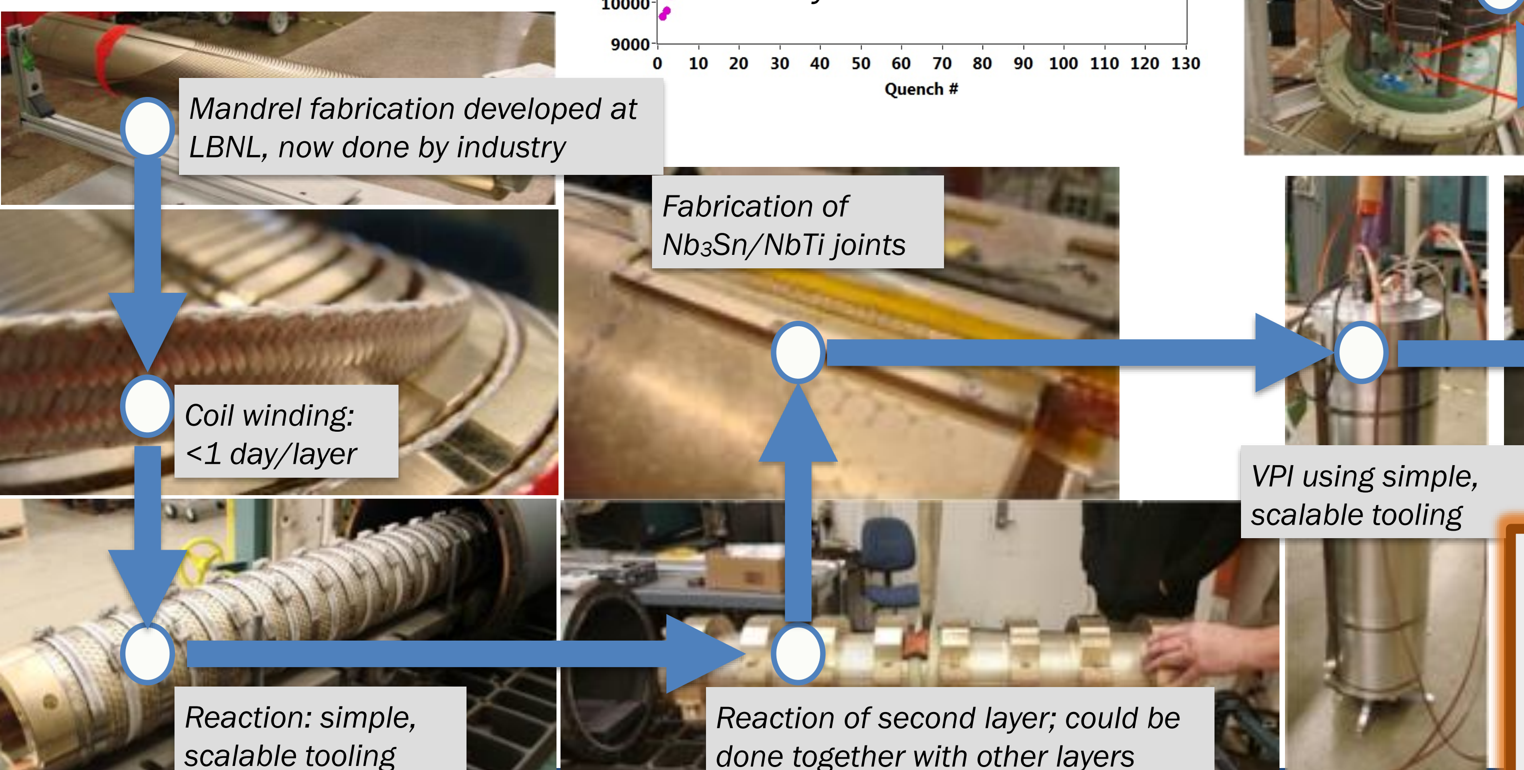
Marchevsky et al., MT25

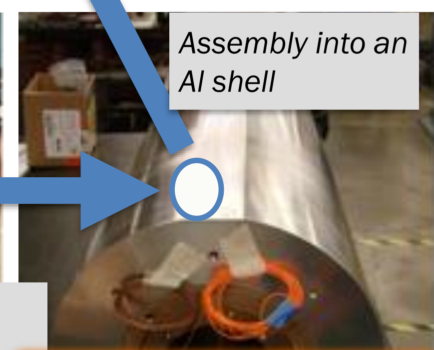
Brouwer et al., MT25

Auchmann et al., MT25









Review committee:

- Steve Virostek - Chair
- Helene Felice
- Shlomo Caspi
- Giorgio Ambrosio
- Sandor Feher

Overview of the HTS Milestone Plan, Highlighting the Bi-2212 Magnet Development and the REBCO Magnet Development

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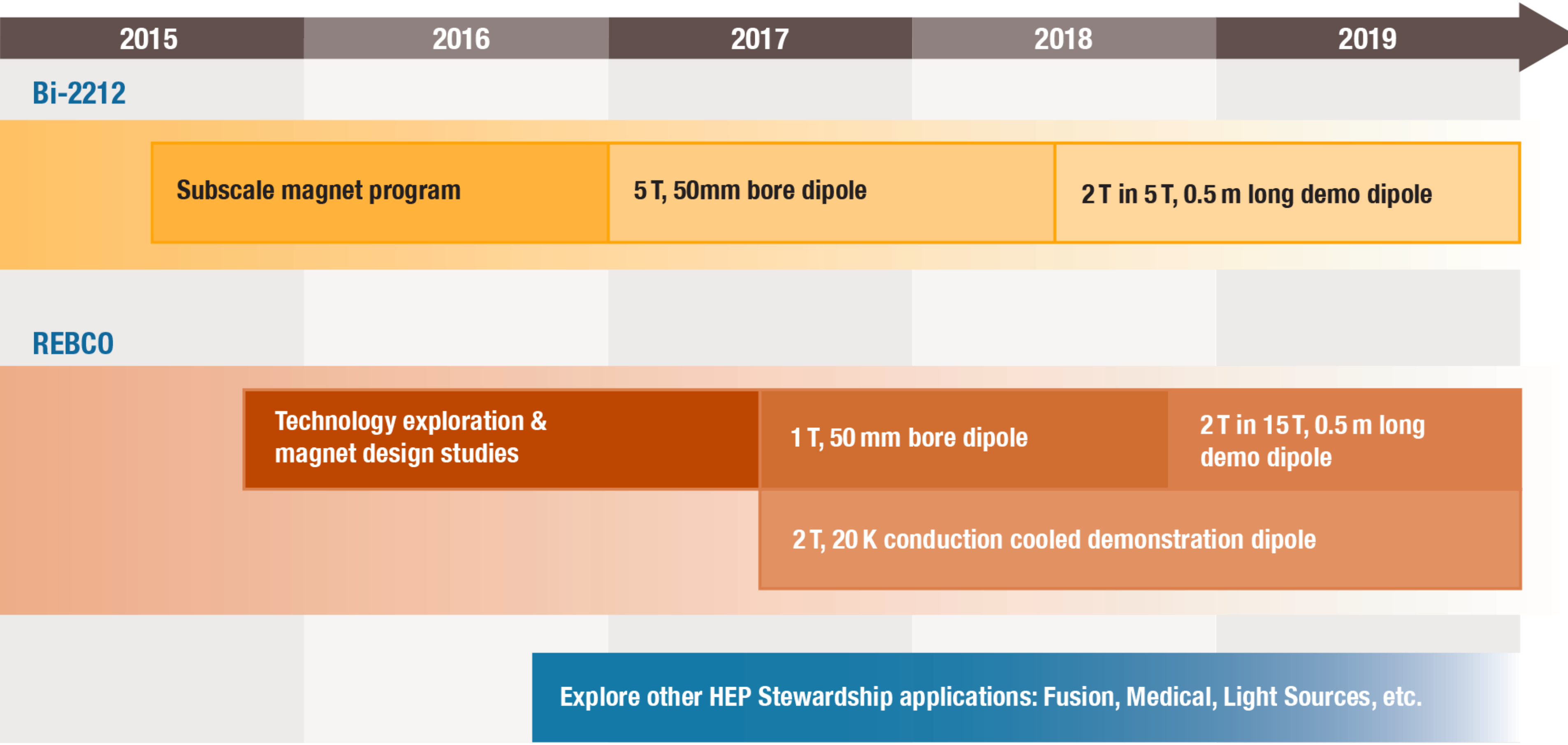
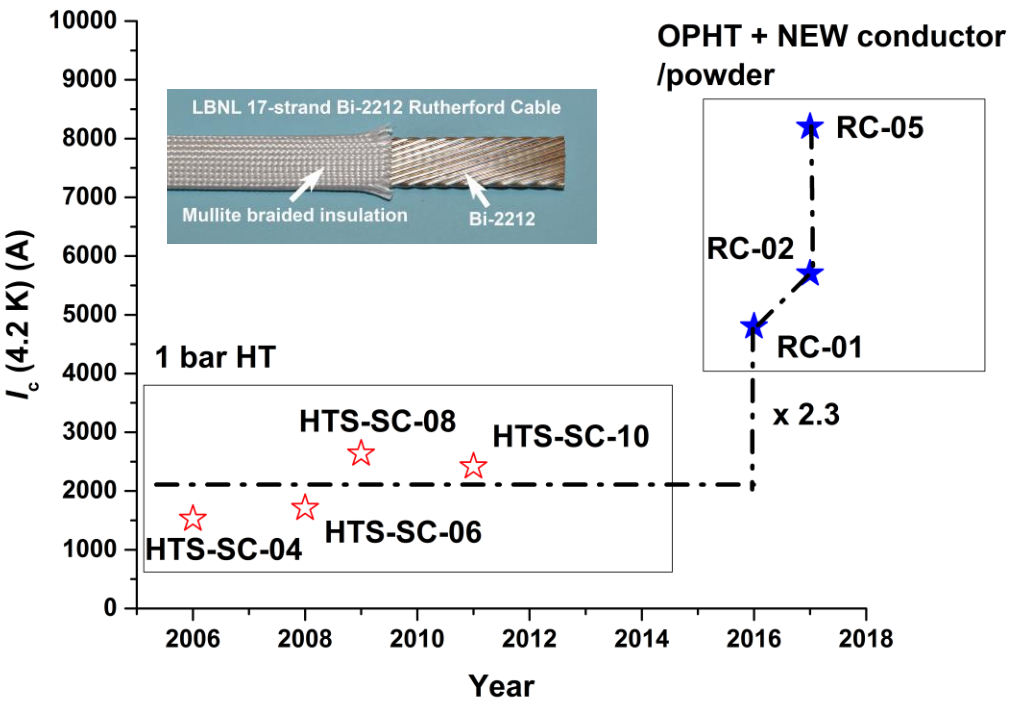
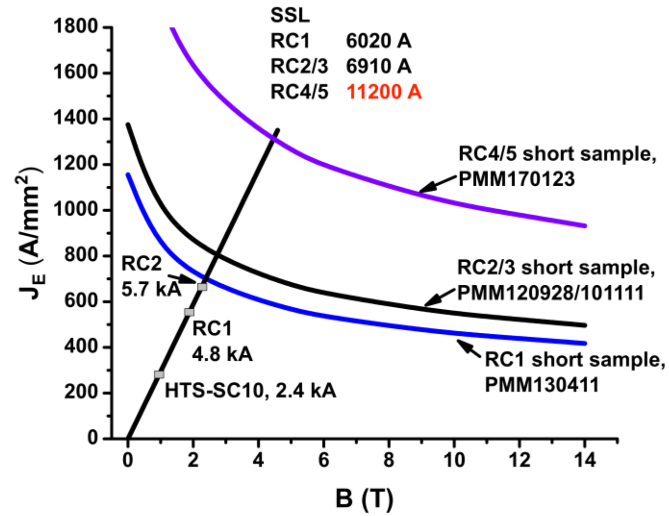


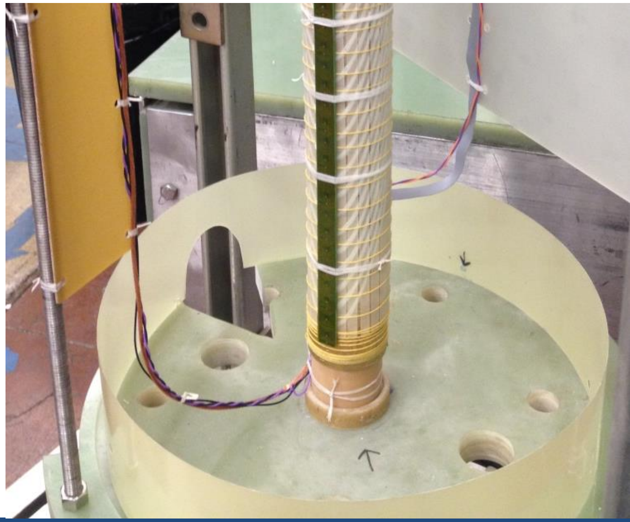
Significant progress on the Bi2212 HTS magnet front: Leveraging overpressure boost in magnet configurations

Bi2212 accelerator magnets:

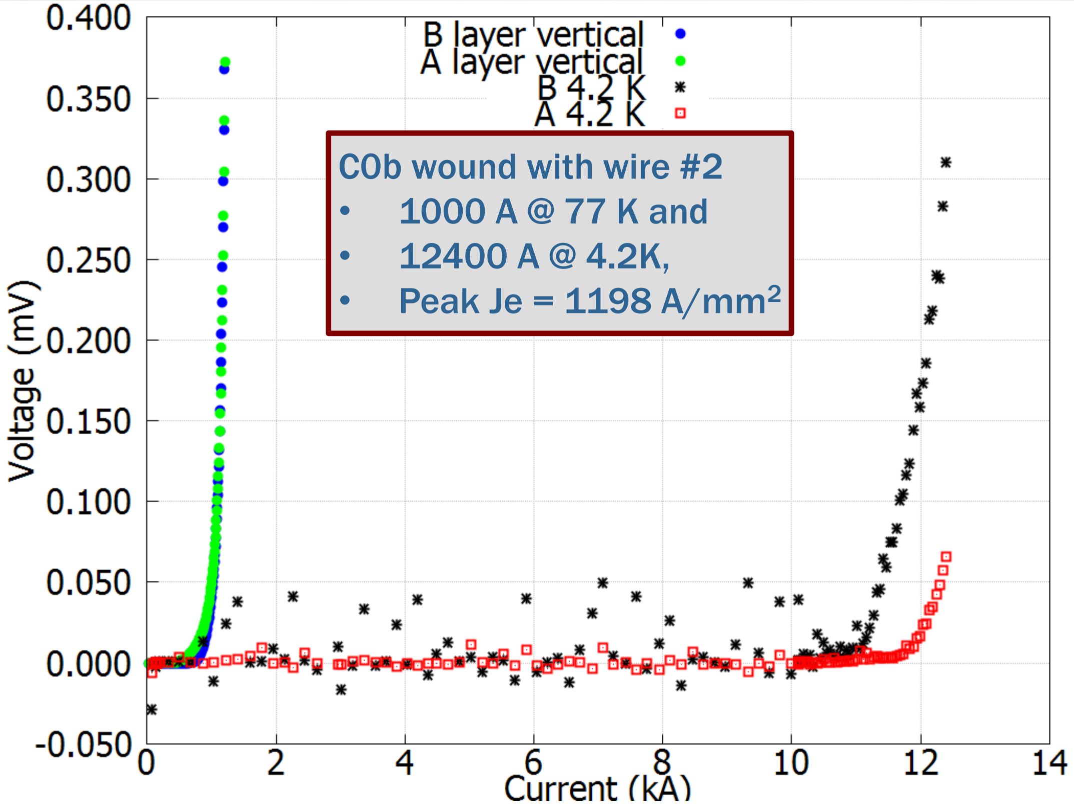
- Dramatic improvements in conductor properties in last couple of years
- Racetrack & CCT coils fabricated and pushed to their electrical, mechanical, and quench limits
- Solenoids teaching us much as well

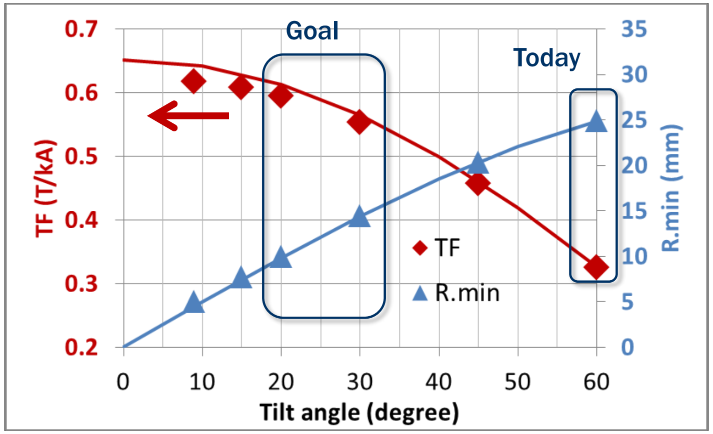






REBCO program developing quickly: conductor and cable characterization, magnet design and prototyping underway





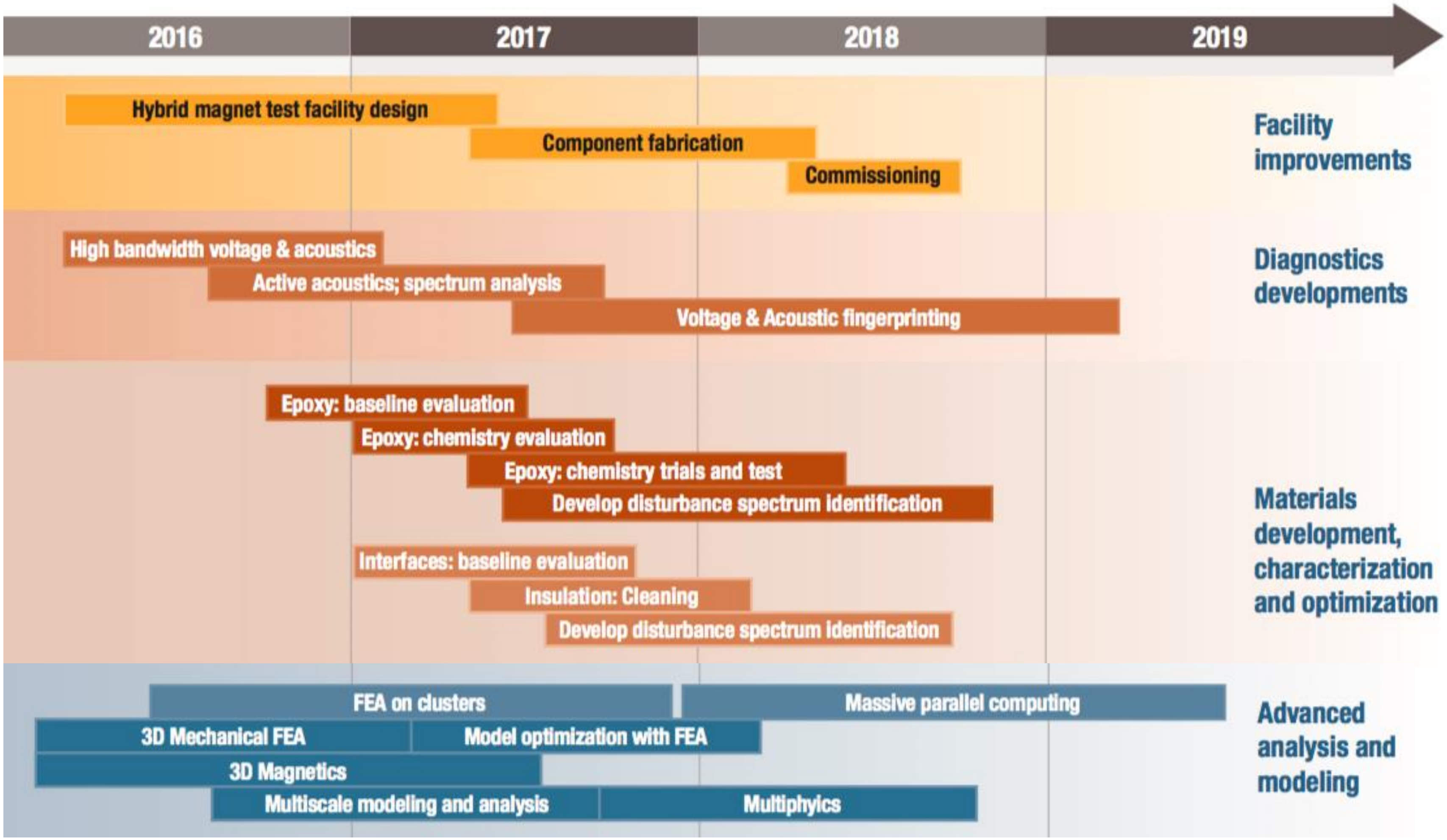
Backbone of the Program: Magnet Science and Development of Underpinning Technologies

Areas of focus:

- Training studies
- Modeling
- Diagnostics, quench detection, protection
- Develop infrastructure, e.g. insert testing
- New materials – insulation, impregnation and structural
- Design comparison and cost analysis to guide program

Improvements/advances from this part of the program are then integrated into the Nb_3Sn and HTS magnets

Overview of the Technology Development Milestone Plan, which Feeds the Nb_3Sn and HTS Magnet Program Elements



Numerous technology advances are essential to address the high field magnet challenge

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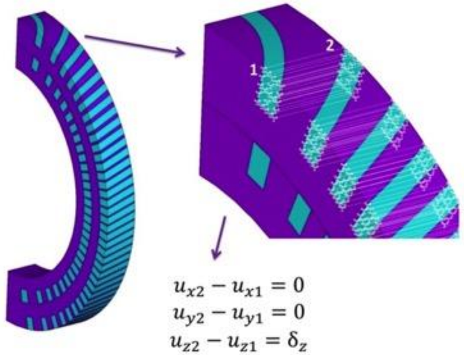
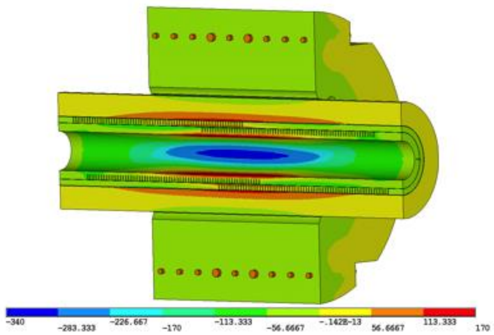
See Brouwer et al., MT25

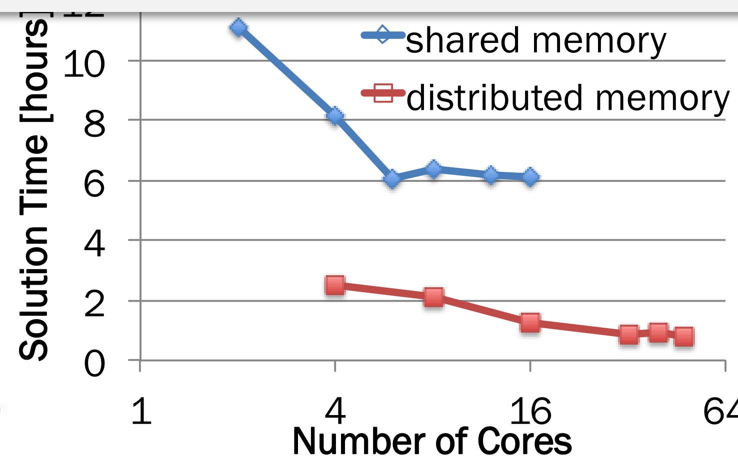
Full 3D simulations – utilizing the computing cluster Lawrencium at LBNL

Periodic Model

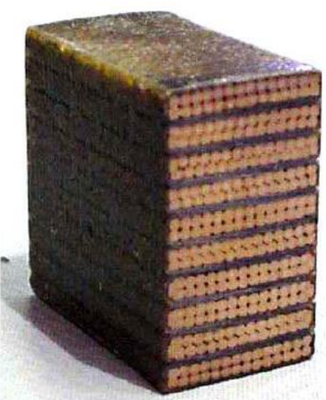


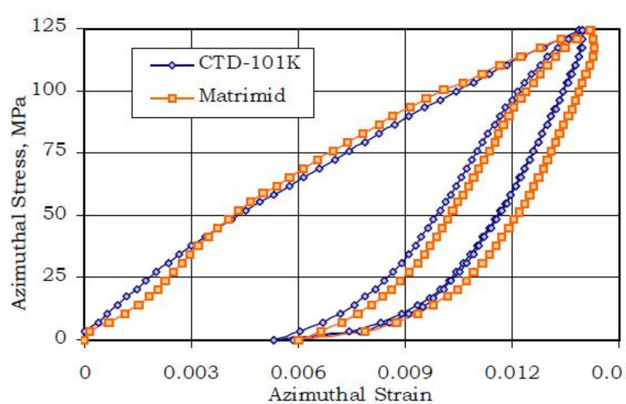
Full Model

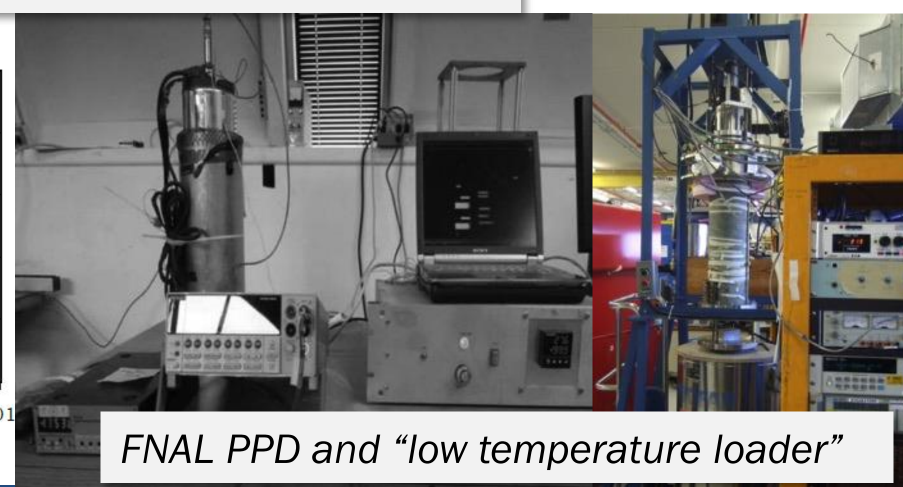




Ten-stack measurements provide critical materials properties







FNAL PPD and "low temperature loader"

Advanced diagnostics are providing new and critical insight into the mechanisms of training and magnet performance

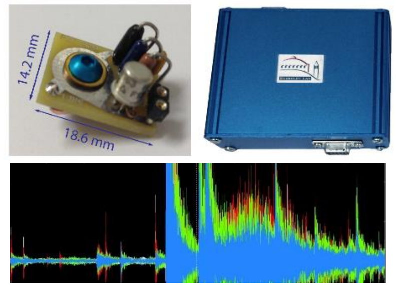
Marchevsky et al., MT25; EUCAS 17

Warm-bore quench antennas

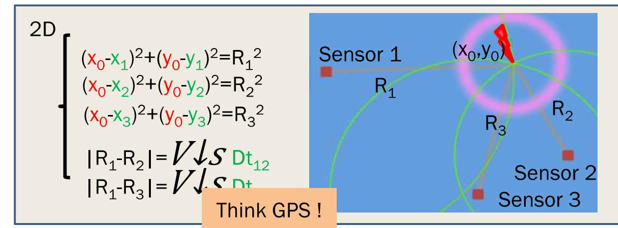
Senses <u>axial</u> gradient of the axial field

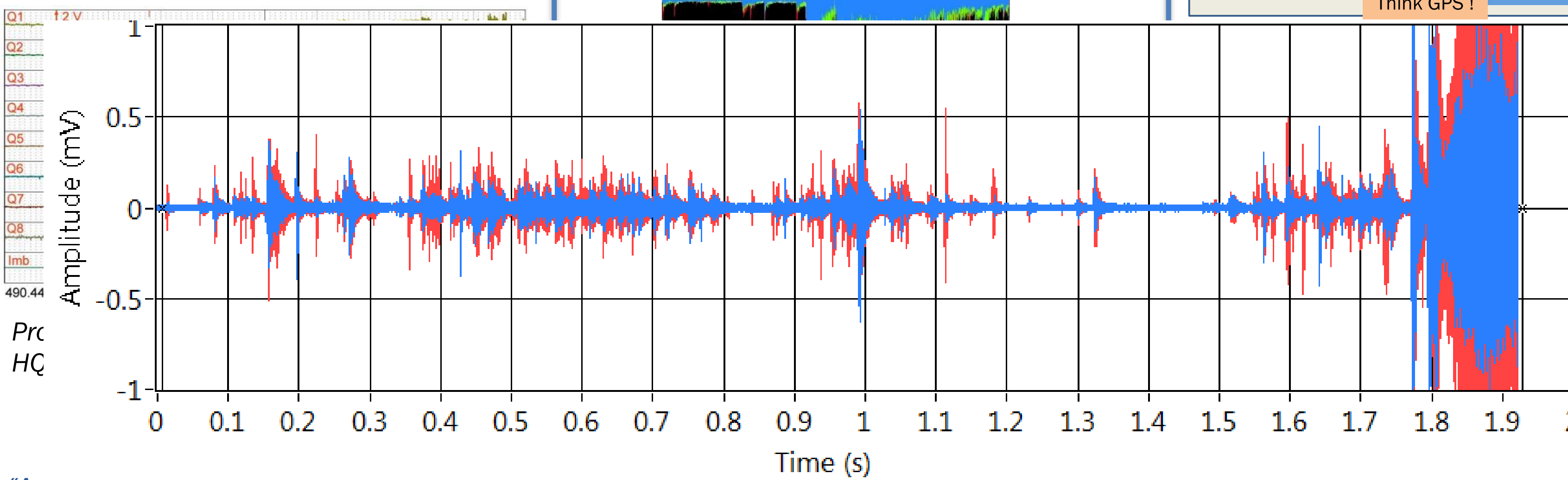
Acoustic emissions as detectors

(c)

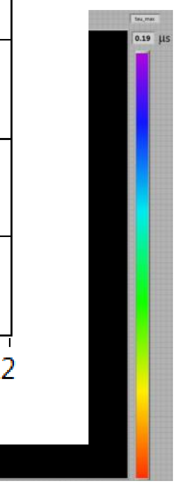


Acoustic emissions for localization





Pro
HQ



“Ax... Field Magnetic Quench Antenna for the Superconducting Accelerator Magnets”, M. Marchevsky, A. R. Hafalia, D. Cheng, S. Prestemon, G. Sabbi, H. Bajas, G. Chlachidze, IEEE Trans. Appl. Supercond. 25, 9500605 (2015), DOI: 10.1109/TASC.2014.2374536

Acoustic precursors to quenching (HD3 dipole) during current ramp

“Detecting mechanical vibrations in superconducting magnets for quench diagnostics", M. Marchevsky, X. Wang, G. Sabbi and S. Prestemon, *Proc. of the WAMSDO 2013 Workshop*, CERN, Geneva 2013.

Pre-quench mechanical event location in CCT3 triangulated using acoustic emission sensors (color map of arrival times)

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Superconducting Materials Procurement and R&D is Critical for Program Success

Sanabria et al., MT25

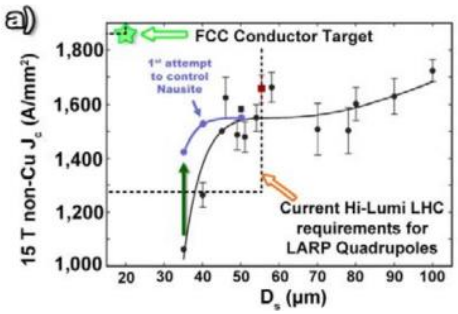
Lombardo et al., MT25

Lee et al., EUCAS
Tarantini et al., EUCAS

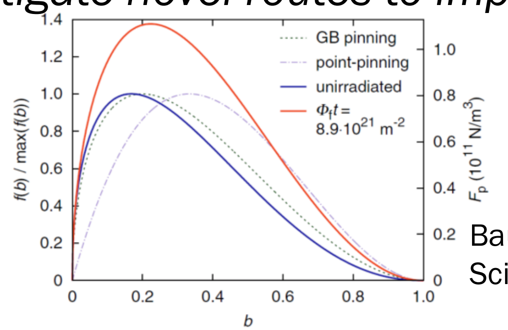
- **Push performance limits of Nb_3Sn and HTS conductors**
- **Performance of today's state of the art Nb_3Sn is the results of long term HEP investment in conductor R&D**

Nb_3Sn

Leverage existing wire/architecture…



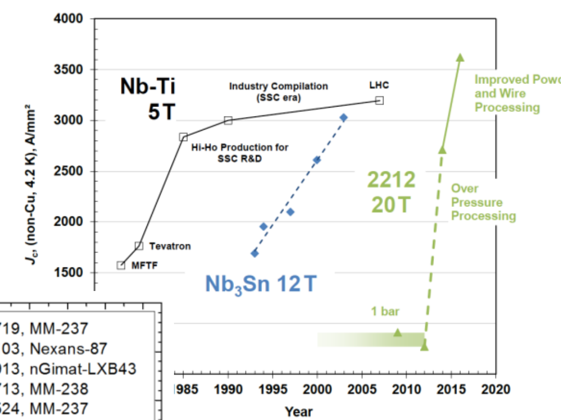
Investigate novel routes to improved pinning…

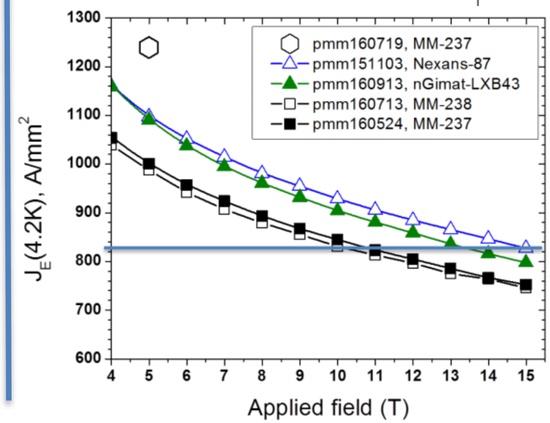


Baumgartner et al
Sci Rep 5 10236 (2015)

Bi2212

Impressive J_E improvements through OP processing and advances in powder…





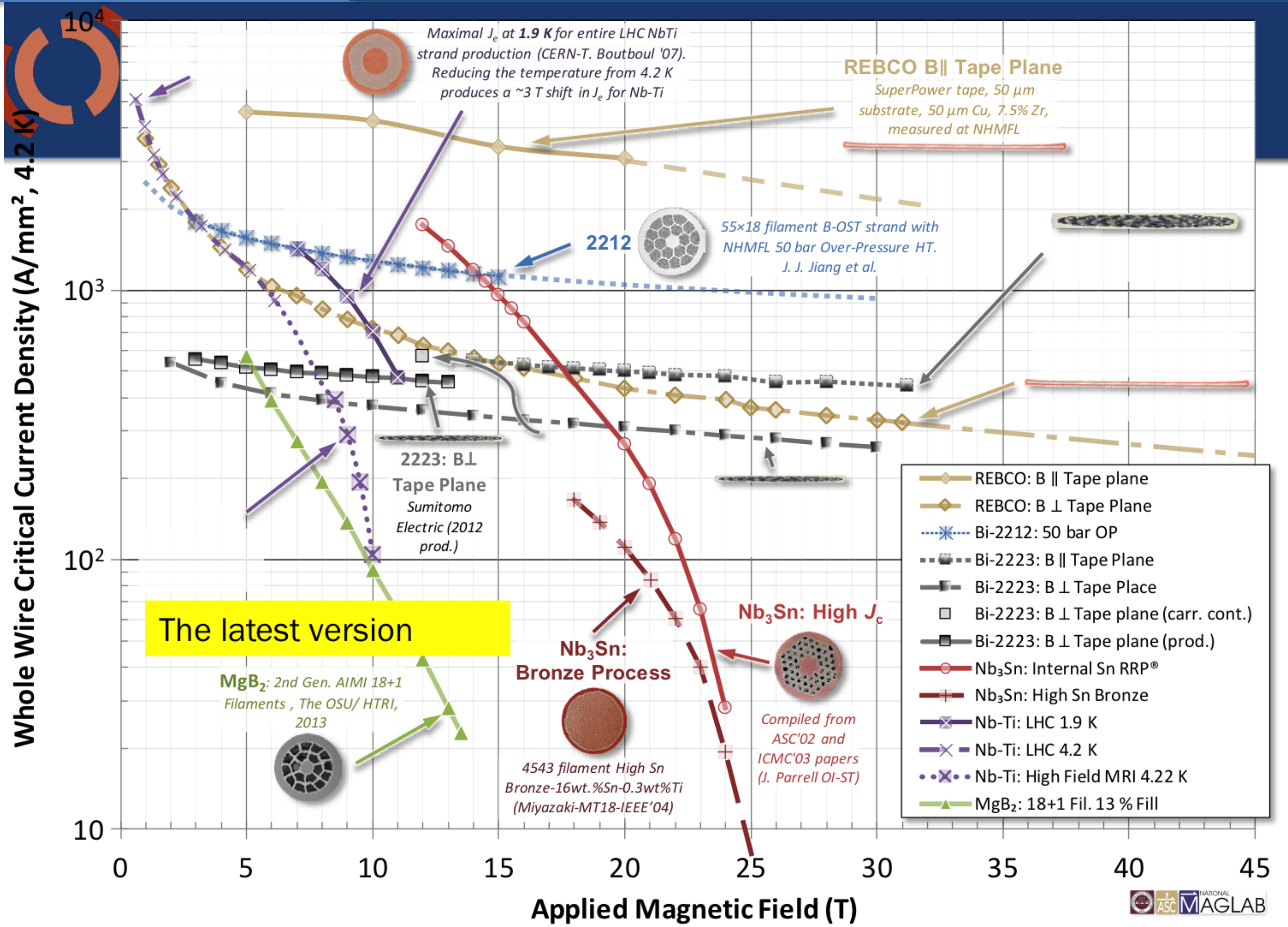
Trociewitz et al. MT25
Larbalestier et al. MT25
Jiang et al EUCAS
David et al. EUCAS

Conclusions

- The US has invested heavily in high-field Nb_3Sn superconducting accelerator magnets…
- …Has invested in transitioning basic magnet R&D to the HL-LHC project via the LARP technology readiness program,…
- …And continues investments in basic magnet R&D with a focus towards the next generation collider
- Throughout, significant research and expertise has been focused on **Nb_3Sn superconductor development**, with tremendous dividends in conductor performance

Backup slides

Exciting advances in HTS properties, but cost remains a major hurdle



The Program is guided by **Driving Questions… related to performance**

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

The Program is guided by **Driving Questions…related to cost**

5. Can we provide accelerator quality Nb_3Sn magnets in the range of 16 T?
6. Is operation at 16 T economically justified? What is the optimal operational field for Nb_3Sn dipoles?
7. What is the optimal operating temperature for Nb_3Sn and HTS magnets?
8. Can we build practical and affordable accelerator magnets with HTS conductor(s)?
9. Are there innovative approaches to magnet design that address the key cost drivers for Nb_3Sn and HTS magnets that will shift the cost optimum to higher fields?

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The Program is guided by **Driving Questions…** **related to conductor development**

⑩ **What are the near and long-term goals for Nb_3Sn and HTS conductor development? What performance parameters in Nb_3Sn and HTS conductors are most critical for high field accelerator magnets?**