U.S. MAGNET DEVELOPMENT PROGRAM

The U.S. Magnet Development Program

Soren Prestemon
Director
US Magnet Development Program
Lawrence Berkeley National Laboratory

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Context for high field accelerator magnet R&D
  - Motivation
  - P5 and the Accelerator R&D Subpanel recommendations
- The US Magnet Development Program
  - How we are structured
- Technical status of each area
  - Progress and current status
  - Corresponding roadmap within the MDP plan
- Summary

Advanced superconducting accelerator magnet technology is critical for a future collider

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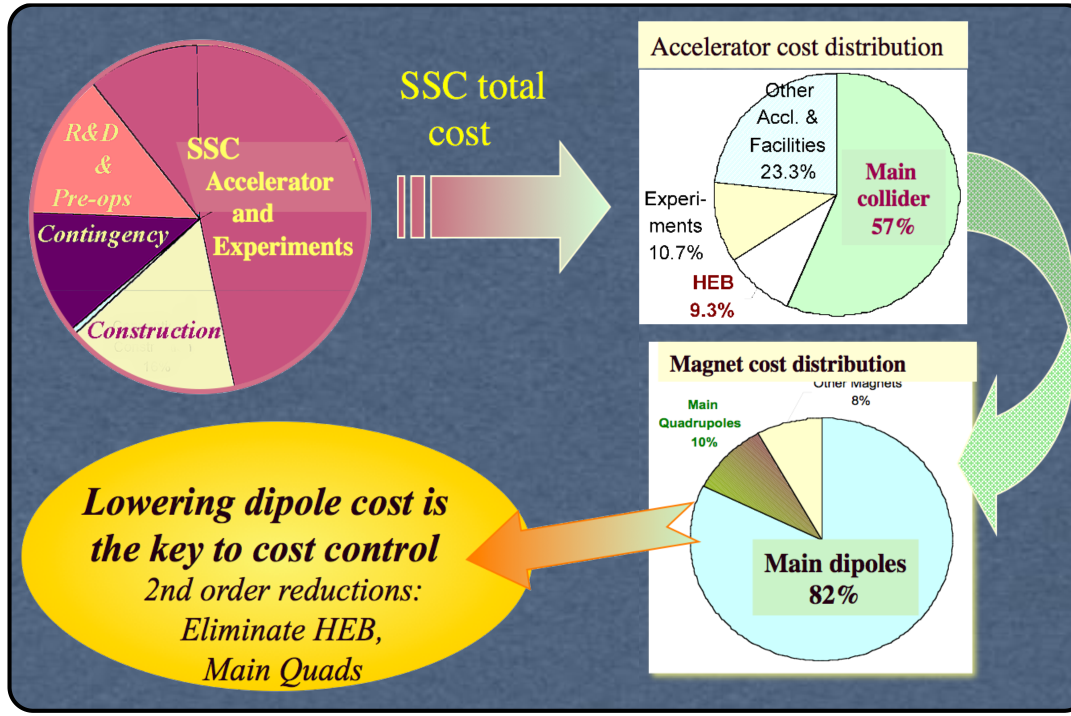
A large Hadron collider entails...

- A high intensity proton source,
- Fast-cycling magnets for the injection chain,
- New magnets - probably high-field
- A new tunnel
    - Exception: HE-LHC could reach E_{cm}=33TeV with 20T dipoles…



Barletta

Dominant cost drivers for an pp collider: <u>Magnets</u> and tunnel

Cost/performance is the critical metric

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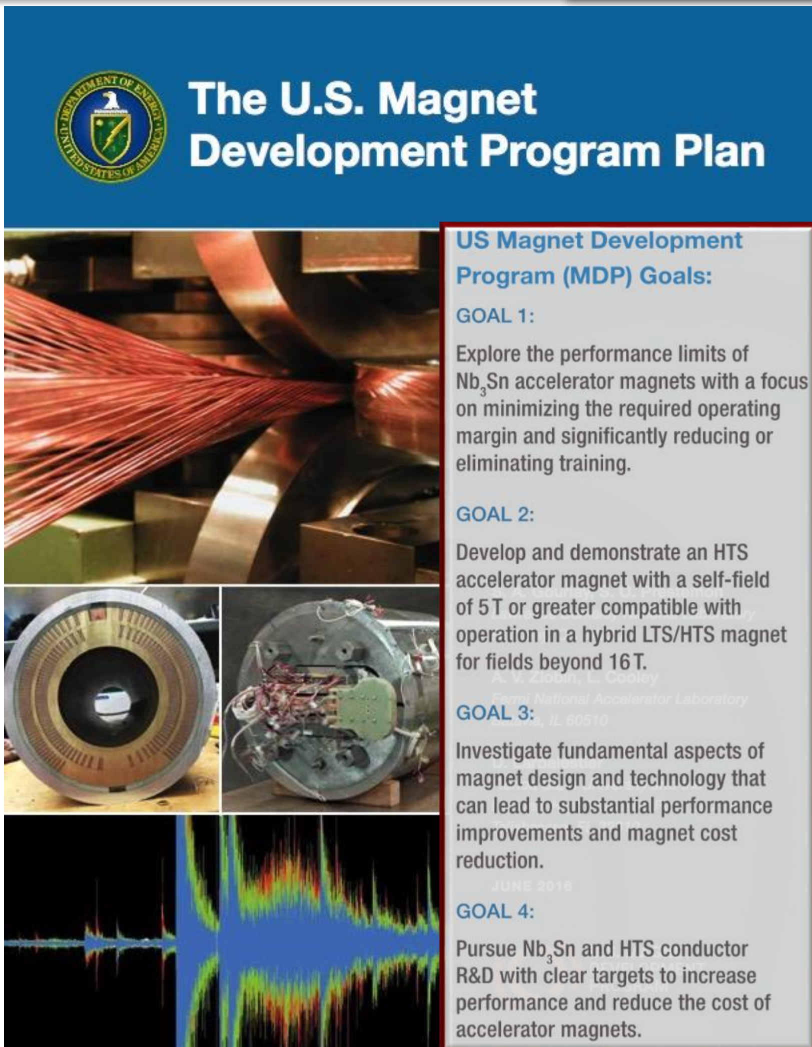
The US HEP Superconducting Magnet Programs are now integrated into the US Magnet Development Program



ns

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

oursue the development of Nb_3Sn magnets proton-proton collider.

execute a high-temperature super- et development plan with appropriate ility of cost-effective accelerator magnets

th

ce

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

crease funding for superconducting upport aggressive development of new

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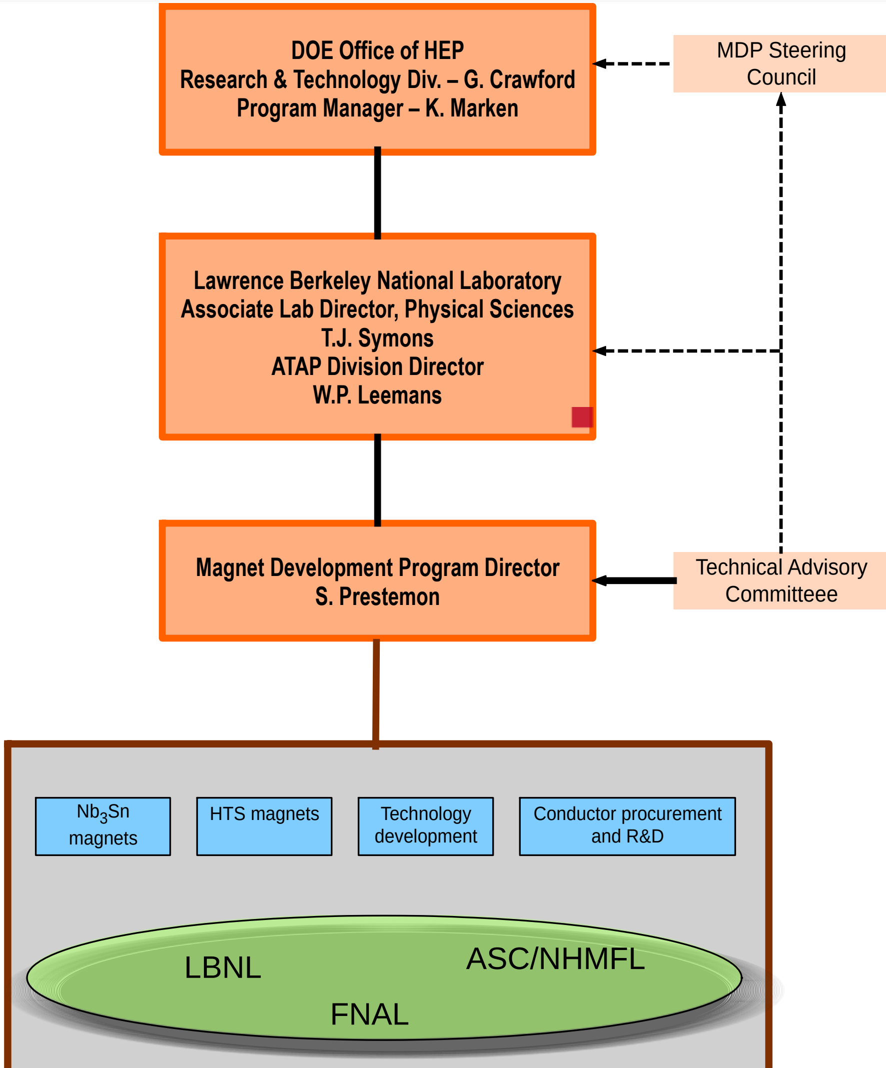
The management structure of the MDP is clearly defined and the program is fully functioning



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 (***Deputy***)

L. Cooley, FNAL

S. Gourlay, LBNL

D. Larbalestier, FSU

A. Zlobin, FNAL

Initial technical roles of participants matched with strengths and interests

- **FSU**
  - Conductor R&D
  - Leverage Bi-2212 and REBCO R&D Program
  - Shared infrastructure – overpressure furnace for sub-scale coils
- **FNAL**
  - Primary focus and responsibility for Cos-Theta
- **LBNL**
  - Primary responsibility for CCT
  - Lead mechanical support structure effort between labs
  - Primary responsibility for HTS component

- Significant leverage with other programs, e.g.
  - *FES (on high temperature superconductors)*
  - *SBIR program*
  - *Early Career Research Program*
  - *University programs (e.g. Ohio State, Tufts, U. of Houston, MIT, Florida State/NHMFL)*
- Close connection with LARP/HL-LHC AUP

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
[illegible]	[illegible]
Cond Proc and R&D	**Lance Cooley**

Nb_3Sn

HTS

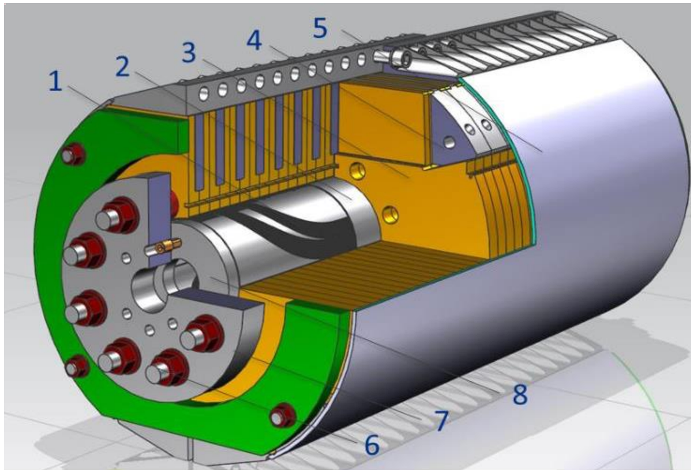
Conductor R&D

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

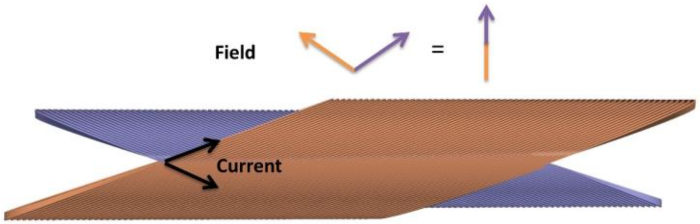
Technology development

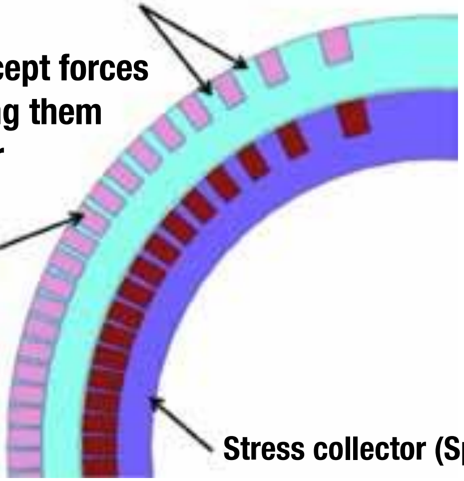
We have initiated a two-prong approach to high field dipoles to explore the limits of Nb_3Sn

- 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

The Cosine-theta 4-layer magnet is proceeding well at FNAL, with first coil prepared for VPI

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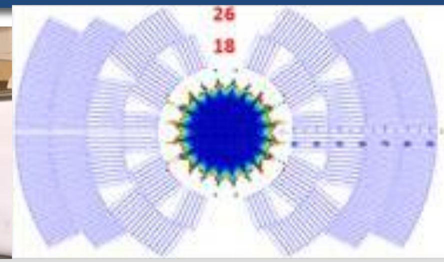
Lead: Sasha Zlobin

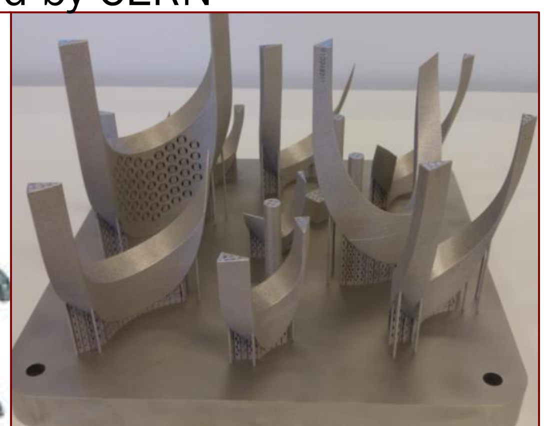
Outer coil winding



Novel coil layout addressing midplane stresses and field quality

Preparations for VPI

Coil parts provided by CERN



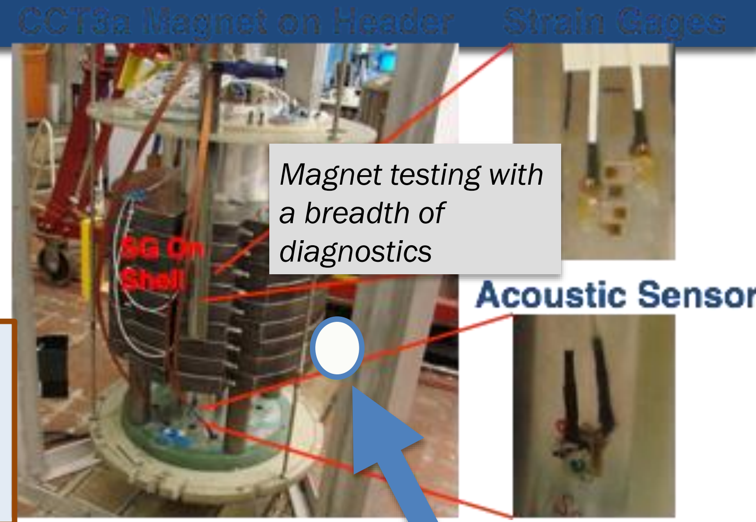
Traces by LBNL

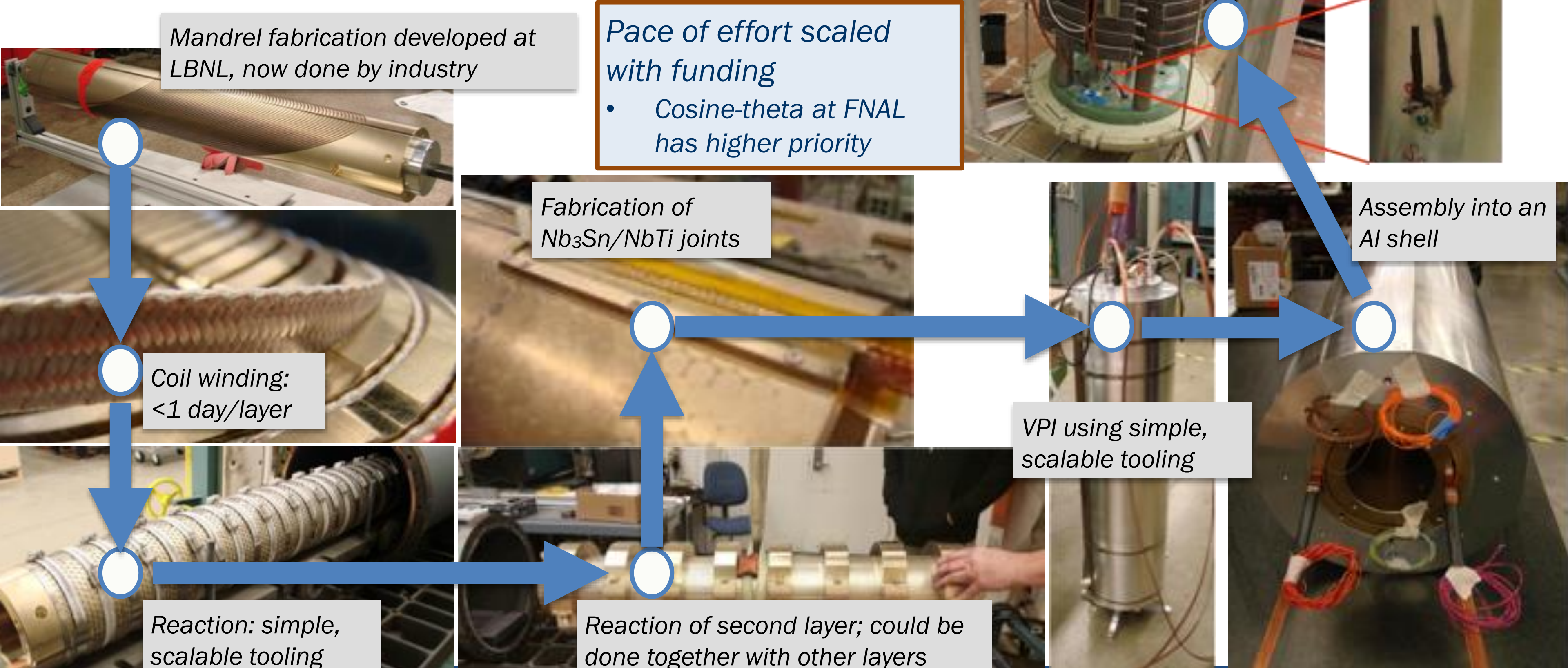
The CCT program is proceeding to systematically address technical issues

Lead: Diego Arbelaez

- **Progress on the Canted Cosine Theta:**
  - **Tested CCT2 (NbTi) and CCT3 (Nb_3Sn)**
  - **Testing of CCT4 in June 2017**

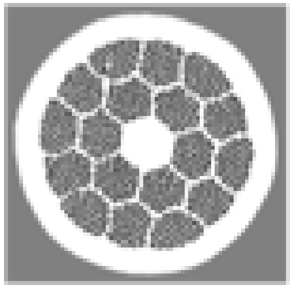
Pace of effort scaled with funding
- *Cosine-theta at FNAL has higher priority*

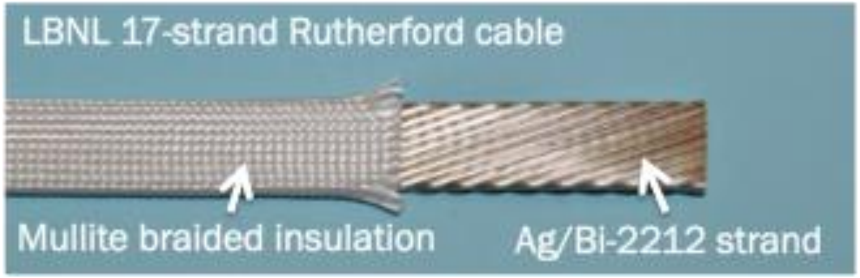


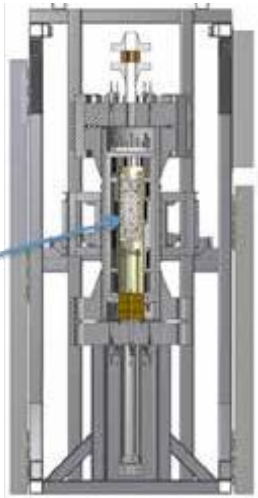


Two candidate HTS conductors are pursued to explore and push the limits of HTS for high-field dipole applications

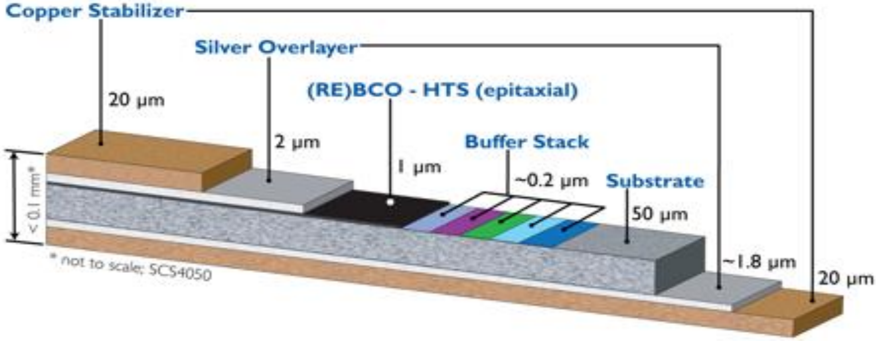
- Bi-2212
  - Rutherford cables and sub-scale magnets in racetrack and CCT configuration







- REBCO
  - Cable characterization and dipole magnet development



CORC®, from Advanced Conductor Technologies, Inc.

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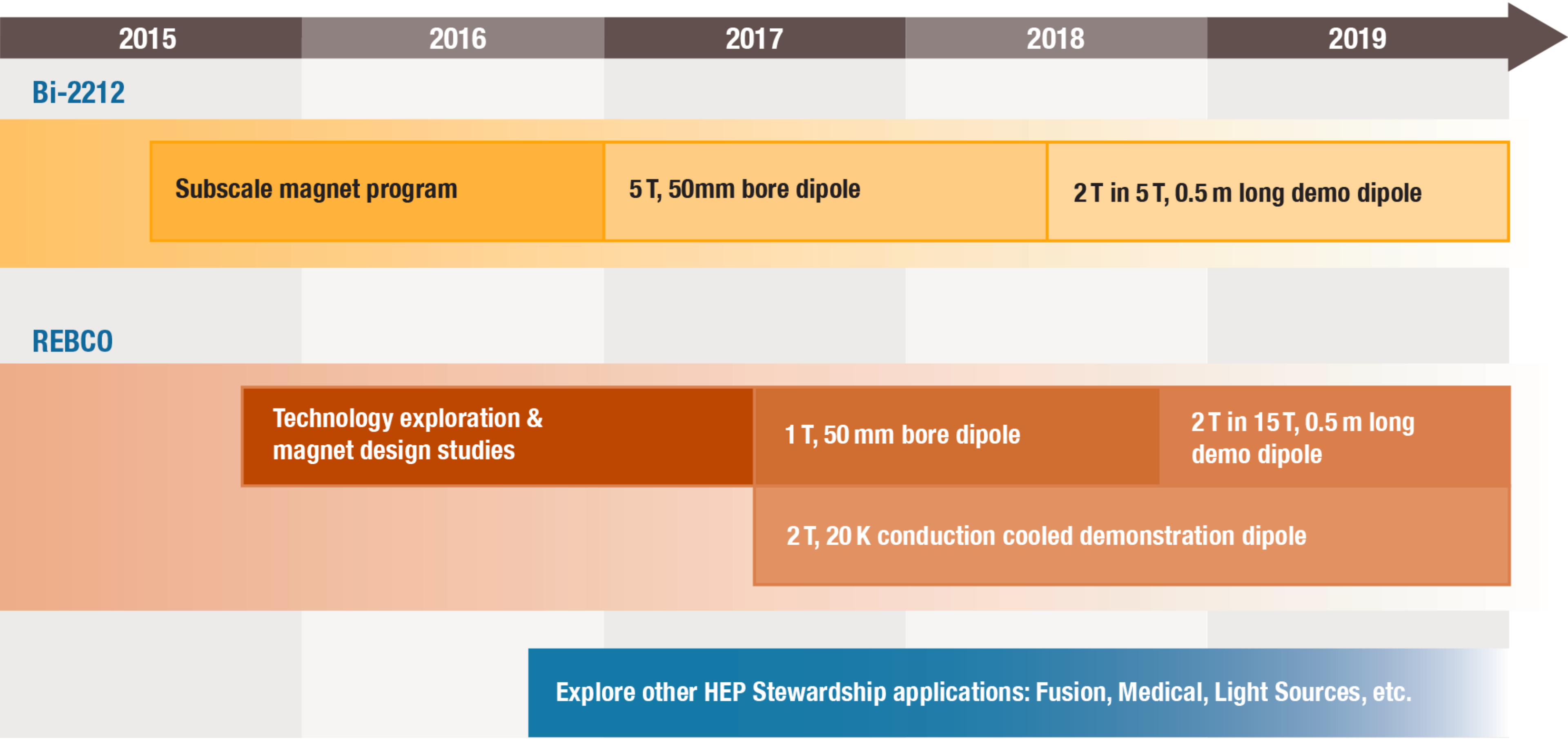
Overview of the HTS Milestone Plan, Highlighting the Bi-2212 Magnet Development and the REBCO Magnet Development

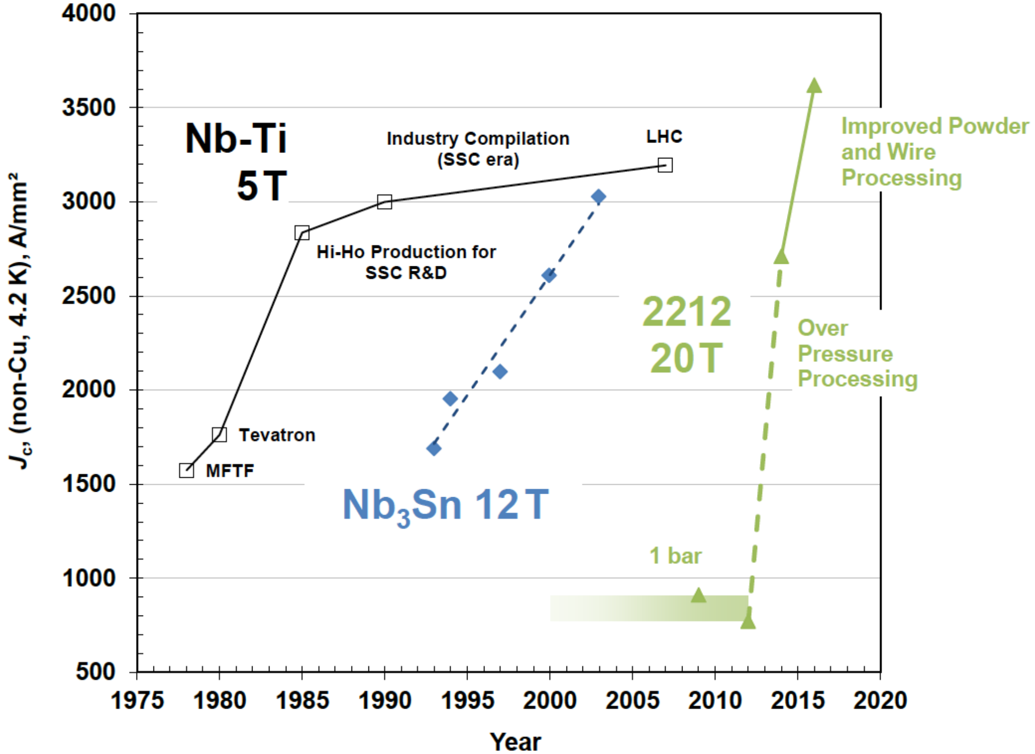


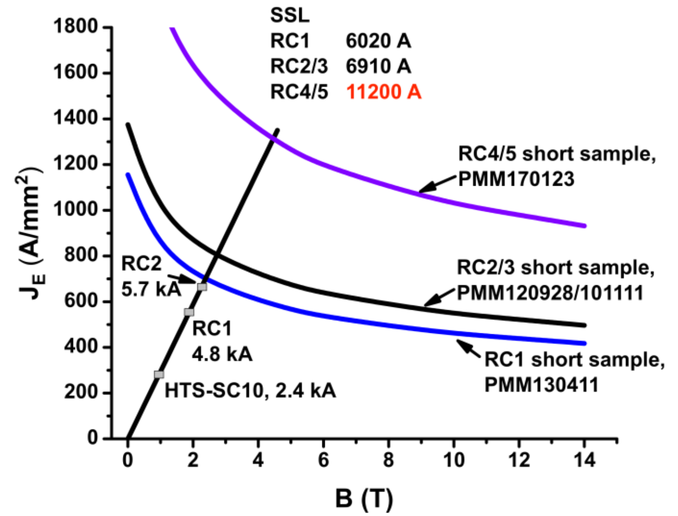
Significant progress on the Bi2212 HTS magnet front: Leveraging overpressure boost in magnet configurations

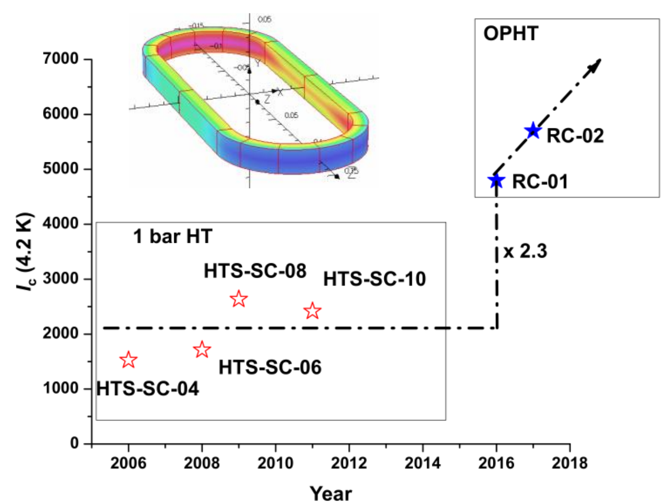
Lead: Tengming Shen

LBNL Bi2212 magnets:

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







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

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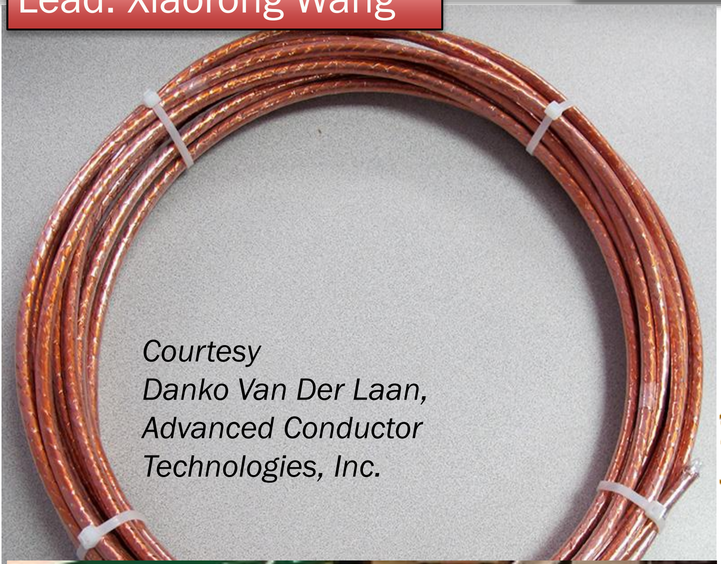
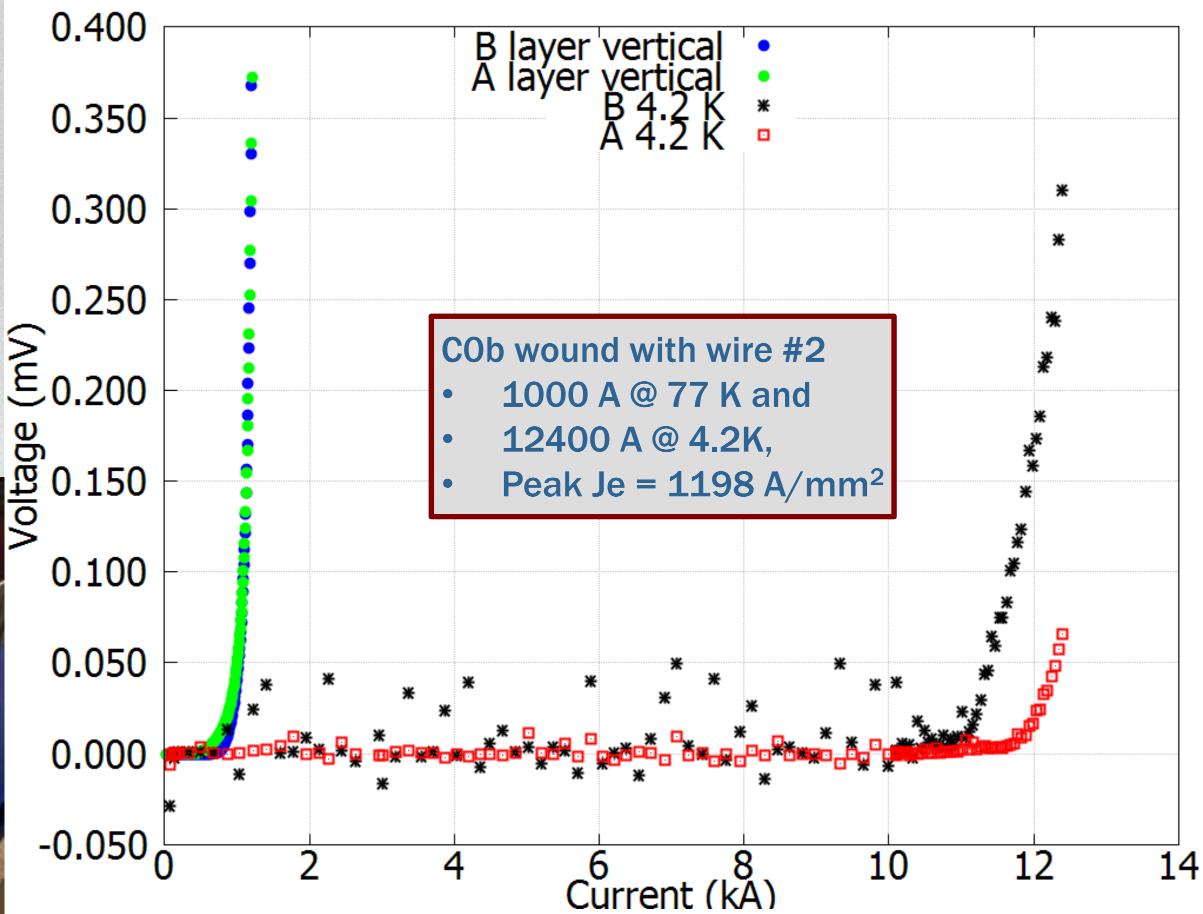
Lead: Xiaorong Wang



Courtesy Danko Van Der Laan, Advanced Conductor Technologies, Inc.

Tooling developed for winding of 40-turn prtotype



C0b wound with wire #2
- 1000 A @ 77 K and
- 12400 A @ 4.2K,
- Peak Je = 1198 A/mm^2

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

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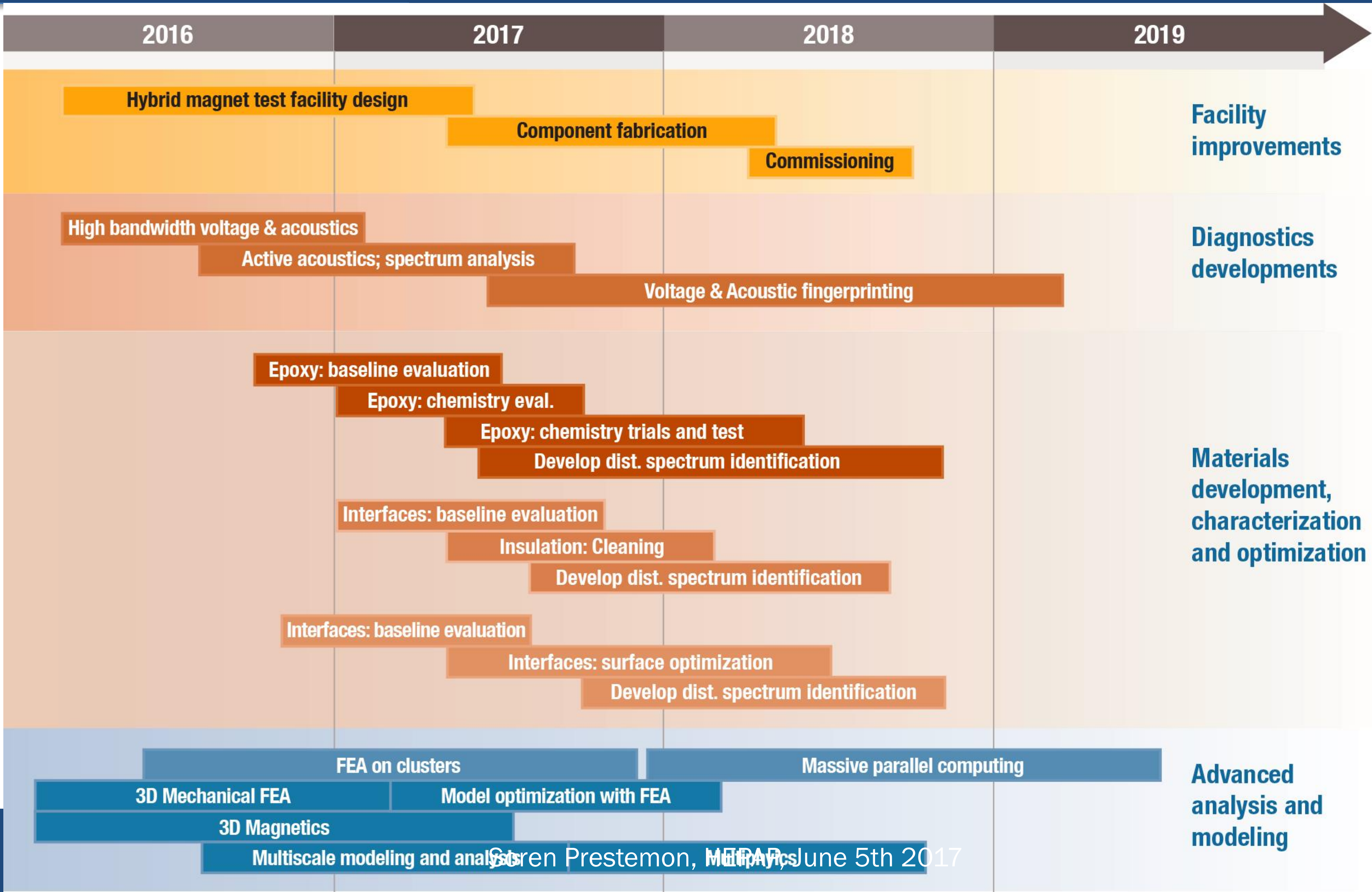
Overview of the Technology Development Milestone Plan, which Feeds the Nb_3Sn and HTS Magnet Program Elements



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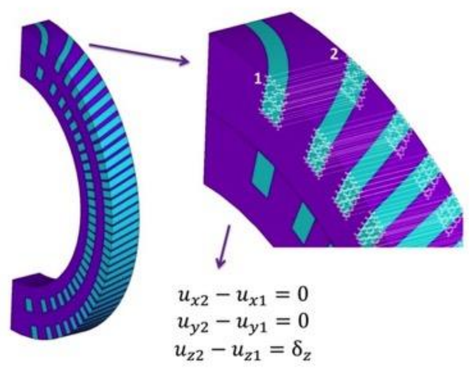
Numerous technology advances are essential to address the high field magnet challenge

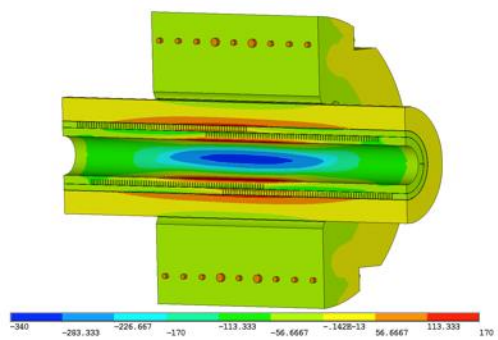
Lucas Brouwer

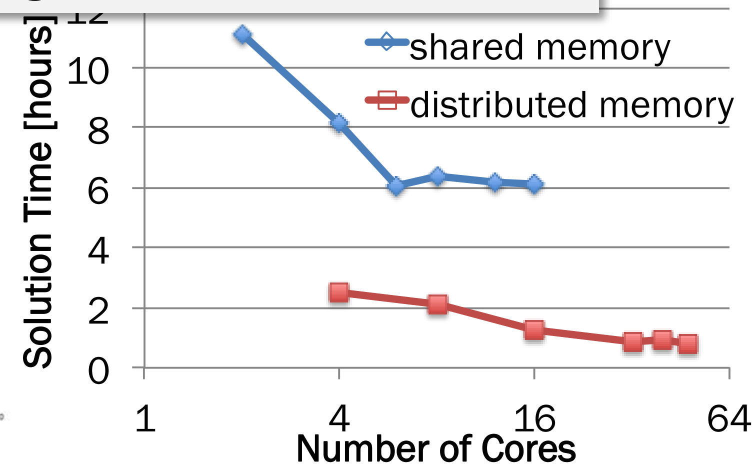
Full 3D simulations – utilizing the computing cluster Lawrencium at LBNL

Periodic Model



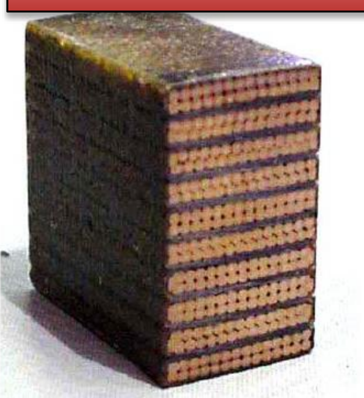
Full Model

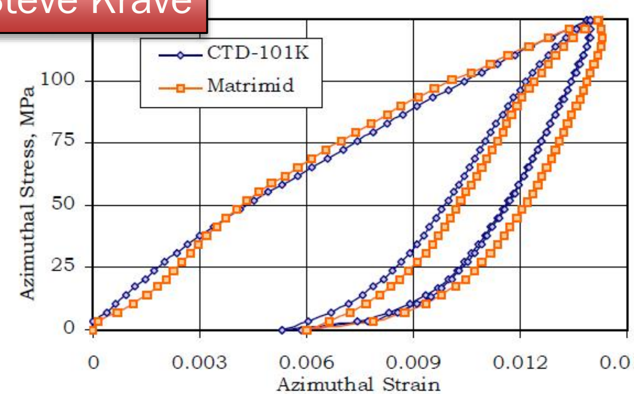


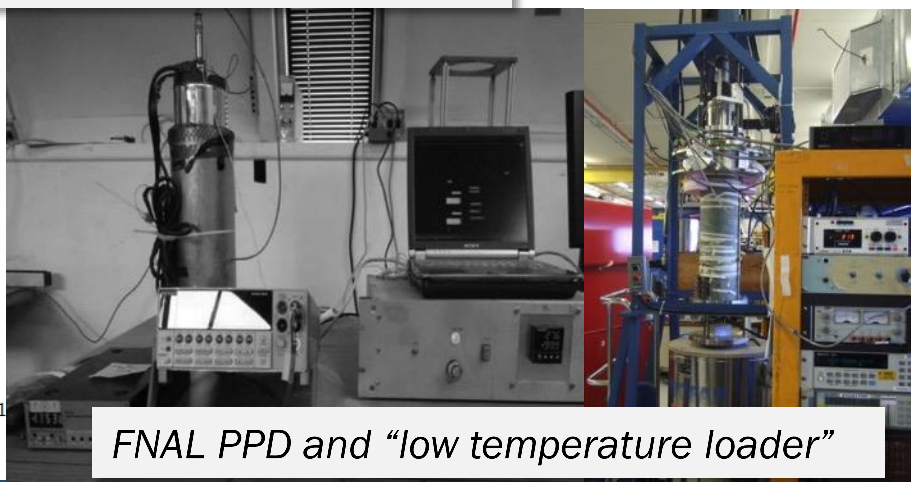


Ten-stack measurements provide critical materials properties

Leads: Ian Pong & Steve Krave







FNAL PPD and "low temperature loader"

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

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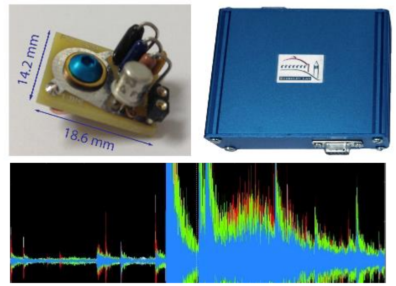
Leads: Maxim Marchevsky & Stoyan Stoynev

Warm-bore quench antennas

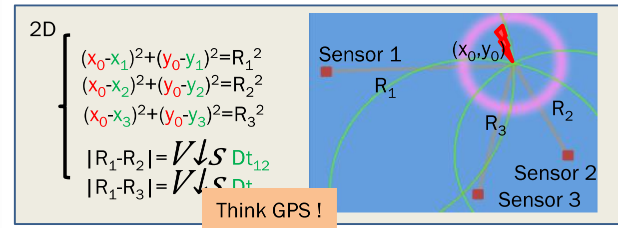
Senses axial gradient of the axial field

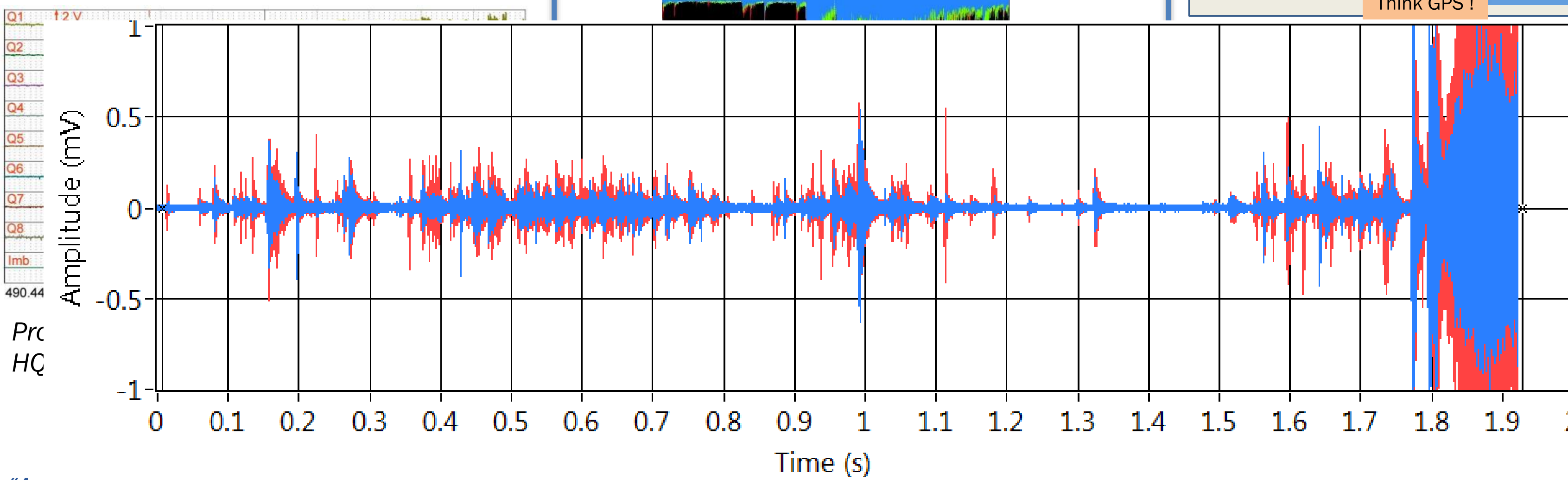
Acoustic emissions as detectors

(c)

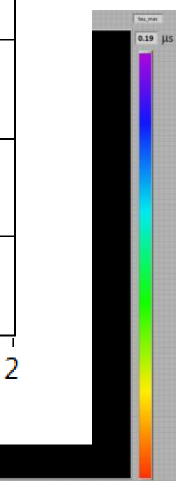


Acoustic emissions for localization





Pro
HQ



“Axial 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

Lead: Lance Cooley

- Push performance limits of Nb_3Sn and HTS conductors based on magnet needs
- Understand –
  - Uniformity and reliability
  - Scalability and future cost

Initial specifications for Nb_3Sn conductor

Intend to procure Bi2212 wire soon utilizing existing Bi powder from SBIR programs

Quantity	Target
Diameter	0.7 to 1.2 mm; (hold @ 1.3)
Unit length	95% yield at 150 m
Jc(**16** T, 4.2K)	1300 A/mm2 (best effort) 1240 in cable
Jc std. dev.	< 100 A/mm2
RRR	>100; >50 at cable edge or in strand rolled to 15% reduction
Cu:NC	0.9 to 1.1 (e.g. 150/169)
D_{SE}	<60 μm
HT duration	<240 hours

The MDP is being managed and reviewed for program coherence and technical strength

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US-MDP First General Meeting

6-8 February 2017

Marriott Napa Valley
US/Pacific timezone

- Overview
- Scientific Programme
- Lodging
- Timetable
- Transportation
- Contribution List
- Author List

The first annual collaboration meeting of the US Ma
from Monday, Feb. 6 until approximately noon on W
Marriott Hotel and Spa.

As this is the first meeting of the MDP, the primary
management structure, current status of active proj
expansion of the program. There will be a working l
maximize interaction and discussion among the me

There will be no registration fee, but all attendees m

Report of
Fermilab High Field Magnet Program Design Review
April 28 – 29, 2016

Commi
Giorgio
Jeffrey
Shlomo
Arup G
Peter N
Alfred

Websit
https:/

Report
This re
followe

US-MDP CCT Program Review

Monday, 1 May 2017 from **08:00** to **17:30** (US/Pacific)
at **B47 (Conference room)**
LBNL 1 Cyclotron Road Berkeley, CA 94720 USA

Manage

Description **US Magnet Development Program**

CCT Magnet Program

Review date: May 1st, 2017

Introduction: The US MDP is pursuing multiple efforts for the development of high field accelerator magnet technology. One line of investigation, pursued as a high-risk, high-reward element of the program, is the investigation of the "Canted Cosine Theta" (CCT) magnet concept. The CCT program is currently focused on identifying and addressing primary technical challenges associated with the use of Nb_3Sn in the CCT configuration. To that end, a series of 2-layer magnets are being produced. The 2nd Nb_3Sn 2 layer magnet, CCT4, is being readied for testing, and a follow-on magnet, CCT5, is being readied for fabrication. Furthermore, a subscale CCT model program is being considered for fast, low cost tests that probe specific design and fabrication issues.

Charge to the review committee: The goal of this review is to evaluate the current CCT R&D plan, identify technical risks, and provide feedback on technical issues and possible mitigation strategies.

1. Is the test plan for the CCT4 magnet sufficiently detailed? Are there elements missing from the plan that could further advance insight into magnet performance and guide future CCT designs?
2. Are the design elements for CCT5 clearly defined and appropriately chosen?
    1. Is the mechanical design sound, i.e. have risks been identified and addressed in a reasonable manner?
    2. Is the magnetic design sound, i.e. are the models sufficiently detailed to provide feedback on magnet performance and measurements?
    3. Is there additional analysis that should be performed prior to fabrication?
    4. Has the conductor and cable been properly qualified, and is the magnet heat treatment appropriately defined?
3. Are the CAD, fabrication drawings, tooling and assembly plan sufficiently advanced for fabrication to commence?

Review committee:

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

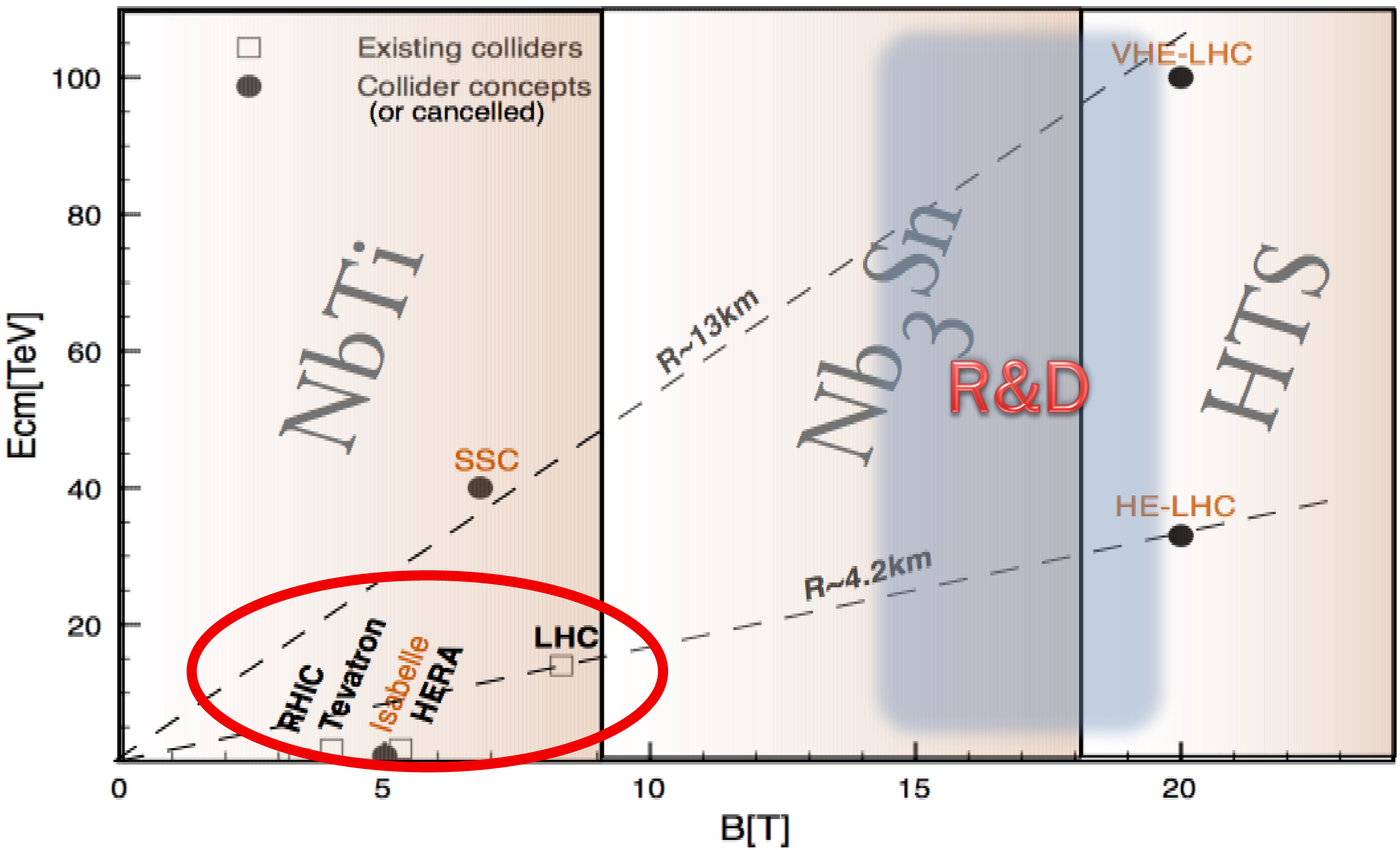
Support: Ms. Sreela Sen ***Email:*** SSen@lbl.gov ***Telephone:*** 510-486-4391

We have an active program focused on advancing high-field LTS and HTS accelerator magnet technology for future pp colliders

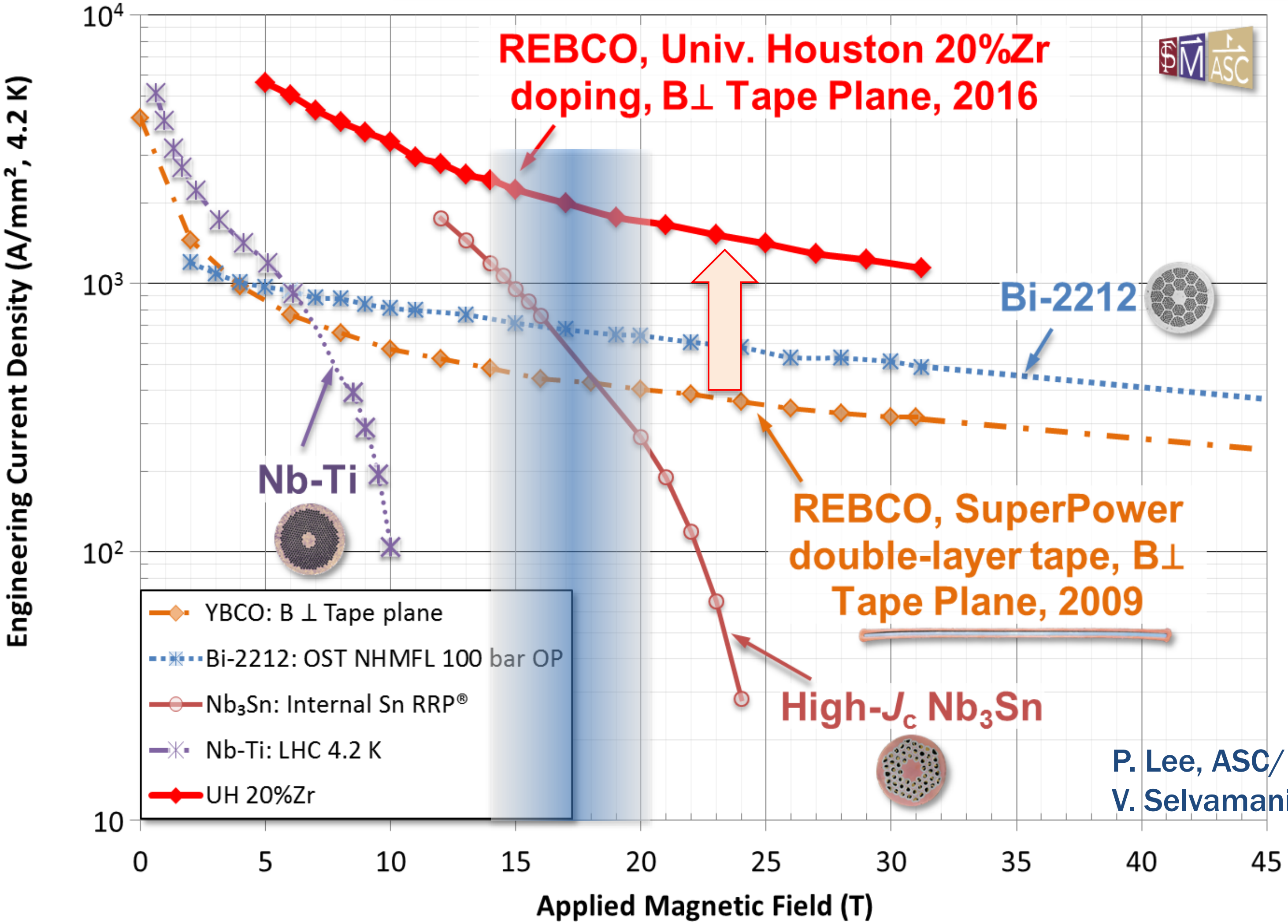
- We have…
  - an MDP Plan that lays out our goals and a roadmap for achieving them, fully aligned with the P5 report and the HEPAP Accelerator R&D Subpanel report
  - established an excellent Technical Advisory Committee to provide guidance on our program
  - identified individuals who will lead and coordinate efforts within the program
  - organized our first yearly workshop to work through the program, identify technical issues, and provide input for budgets moving forward
- Our focus now is delivering on our near term goals –
  - making the Cosine-theta 4-layer magnet a success – potential new record field
  - progressing through technical issues with the CCT to see if potential can be achieved
  - making real dipoles from HTS and integrating them with LTS
  - procuring sufficient conductors for the program, and identifying opportunities for conductor R&D

Backup slides

Cost-effective high-field superconducting magnets are essential for a future collider



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



P. Lee, ASC/FSU
V. Selvamanickam, U. Houston

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?

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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?

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?