U.S. MAGNET
DEVELOPMENT
PROGRAM

Overview of the US magnet development programme

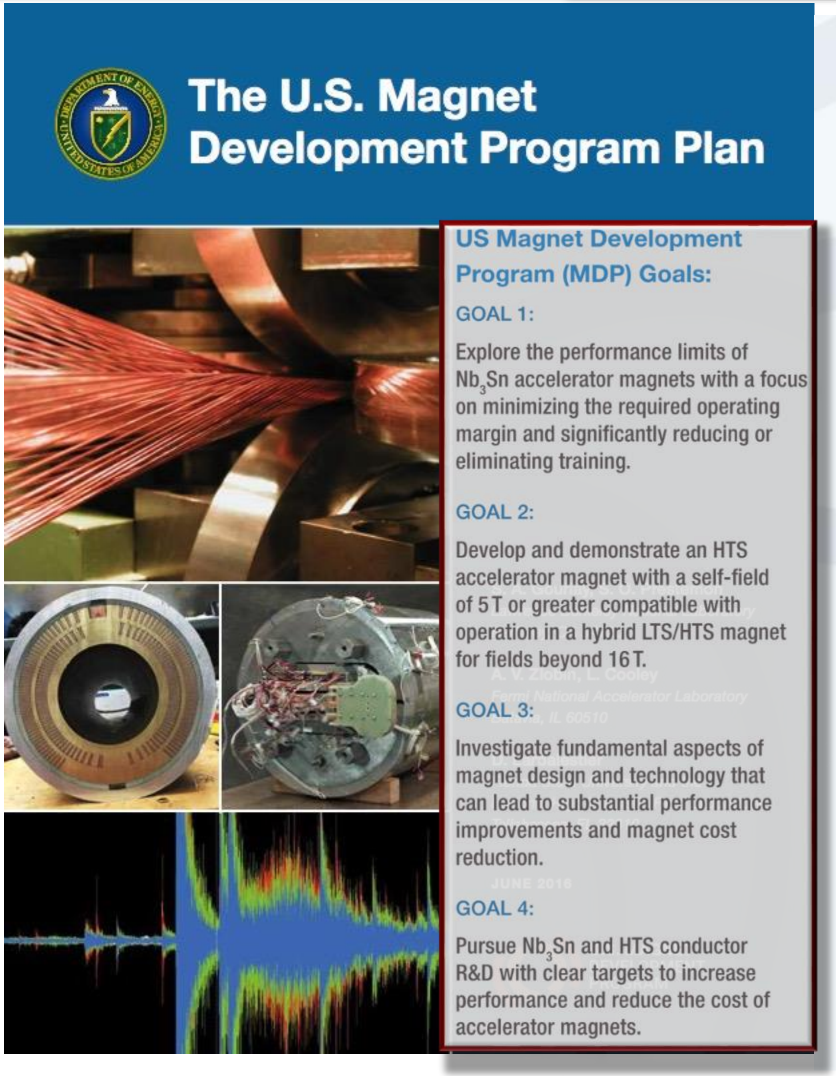
Soren Prestemon
Director
US Magnet Development Program
Lawrence Berkeley National Laboratory

Outline

- Context for high field accelerator magnet R&D
  - 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

U.S. MAGNET DEVELOPMENT PROGRAM

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



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.

Table of Contents

ptual design studies and critical path
ergy proton-proton colliders.
ip role in superconducting magnet
dual goals of increasing performance

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

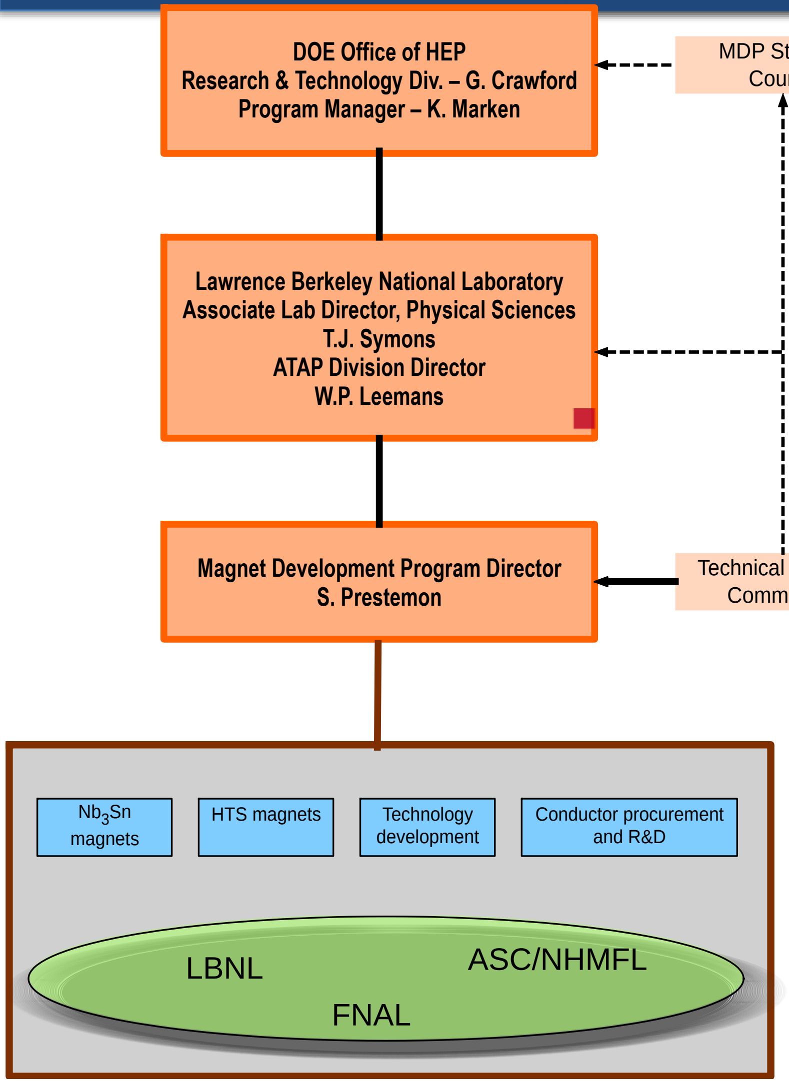
rsue the development of Nb_3Sn magnets
oton-proton collider.

xecute a high-temperature super-
development plan with appropriate
y of cost-effective accelerator magnets

and manufacturing engineering
h decrease the touch labor and increase
superconducting accelerator magnets.

ease funding for superconducting
port aggressive development of new

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



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
T.J. Symons
ATAP Division Director
W.P. Leemans

Magnet Development Program Director
S. Prestemon

Technical Advisory Committeee

Nb_3Sn magnets

HTS magnets

Technology development

Conductor procurement and R&D

LBNL

ASC/NHMFL

FNAL

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 matches 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

See Tuesday presentations from P. Lee and D. Larbalestier

These efforts are coordinated with additional research efforts by the US community, e.g.

- ***Nb_3Sn strand and cable R&D****: Xingchen Xu and Emanuela Barzi*
- ***Development of APC (ZrO2) Nb3Sn multifilamentary and ternary conductor****: Mike Sumption*

See Tuesday presentations from A. Zlobin and Mike Sumption

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**

Design teams	Lead
16T dipole designs	Sasha Zlobin & GianLuca Sabbi
High-field Utility Structure	Mariusz Juchno

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

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

US-MDP First General Meeting

6-8 February 2017

Marriott Napa Valley
US/Pacific timezone

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

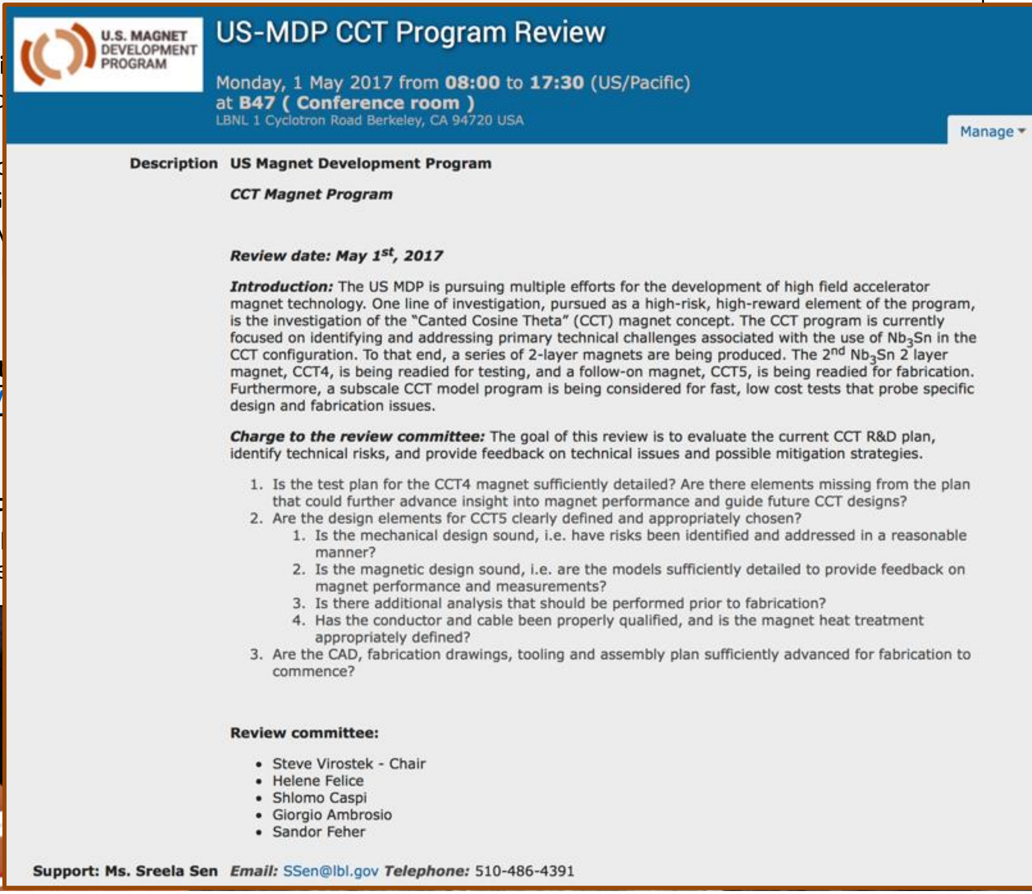
There will be no registration fee, but all attendees m

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

Commi
Giorgi
Jeffrey
Shlom
Arup G
Peter
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

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

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?

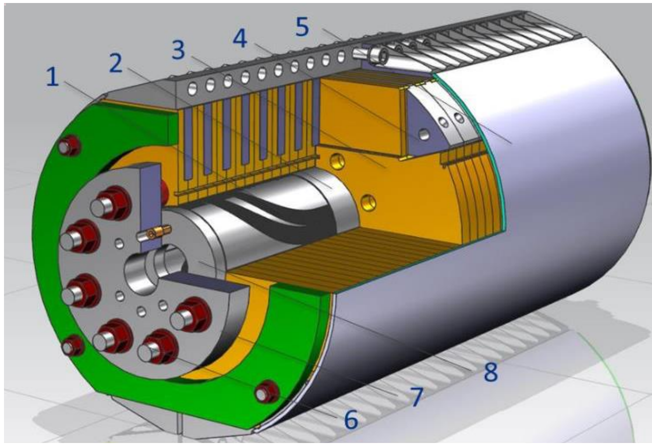
The Program is guided by **Driving Questions…** **related to conductor development**

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?**

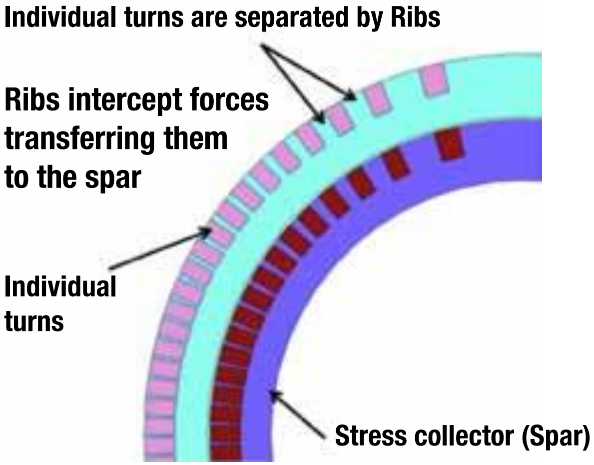
High Field Dipoles are exploring the Limits of Nb_3Sn

Two-pronged approach

- A reference design based on cosine-theta
- ***See presentation by Sasha Zlobin***



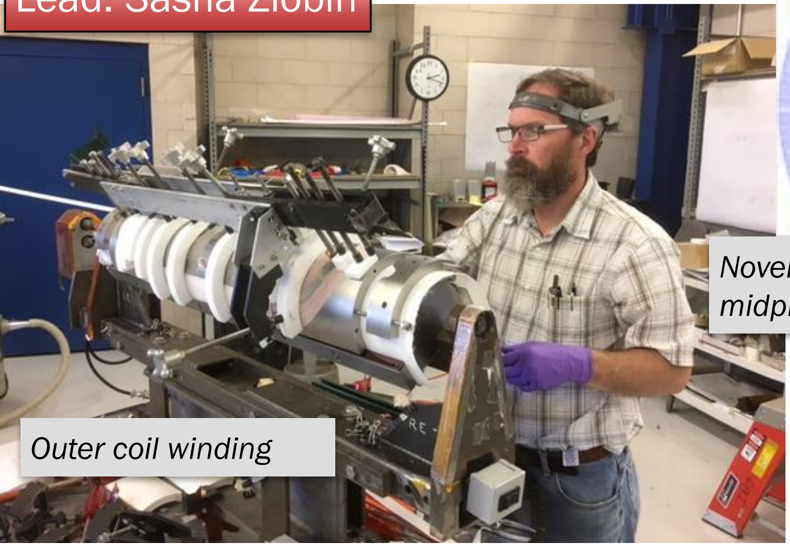
- A path to explore innovative designs – starting with the CCT



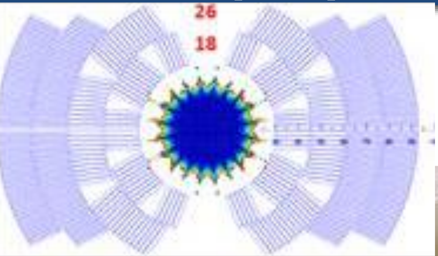
The Cosine-theta 4-layer magnet is proceeding well at FNAL, with first coil prepared for VPI

Lead: Sasha Zlobin

See presentation by A. Zlobin, this session



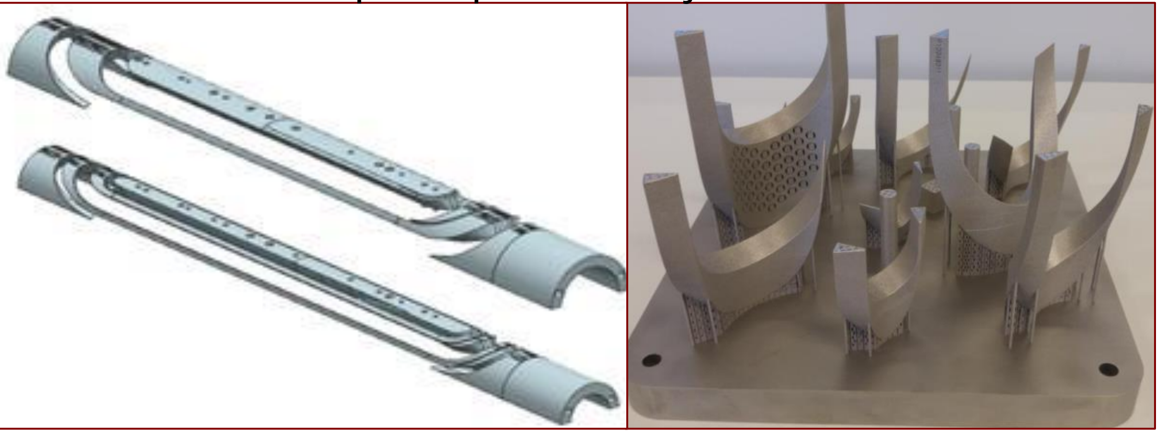
Outer coil winding



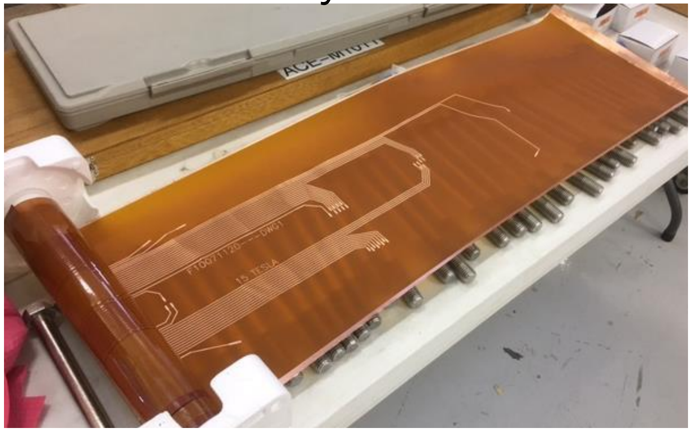
Novel coil layout addressing midplane stresses and field quality

Preparations for VPI

Coil parts provided by CERN



Traces by LBNL



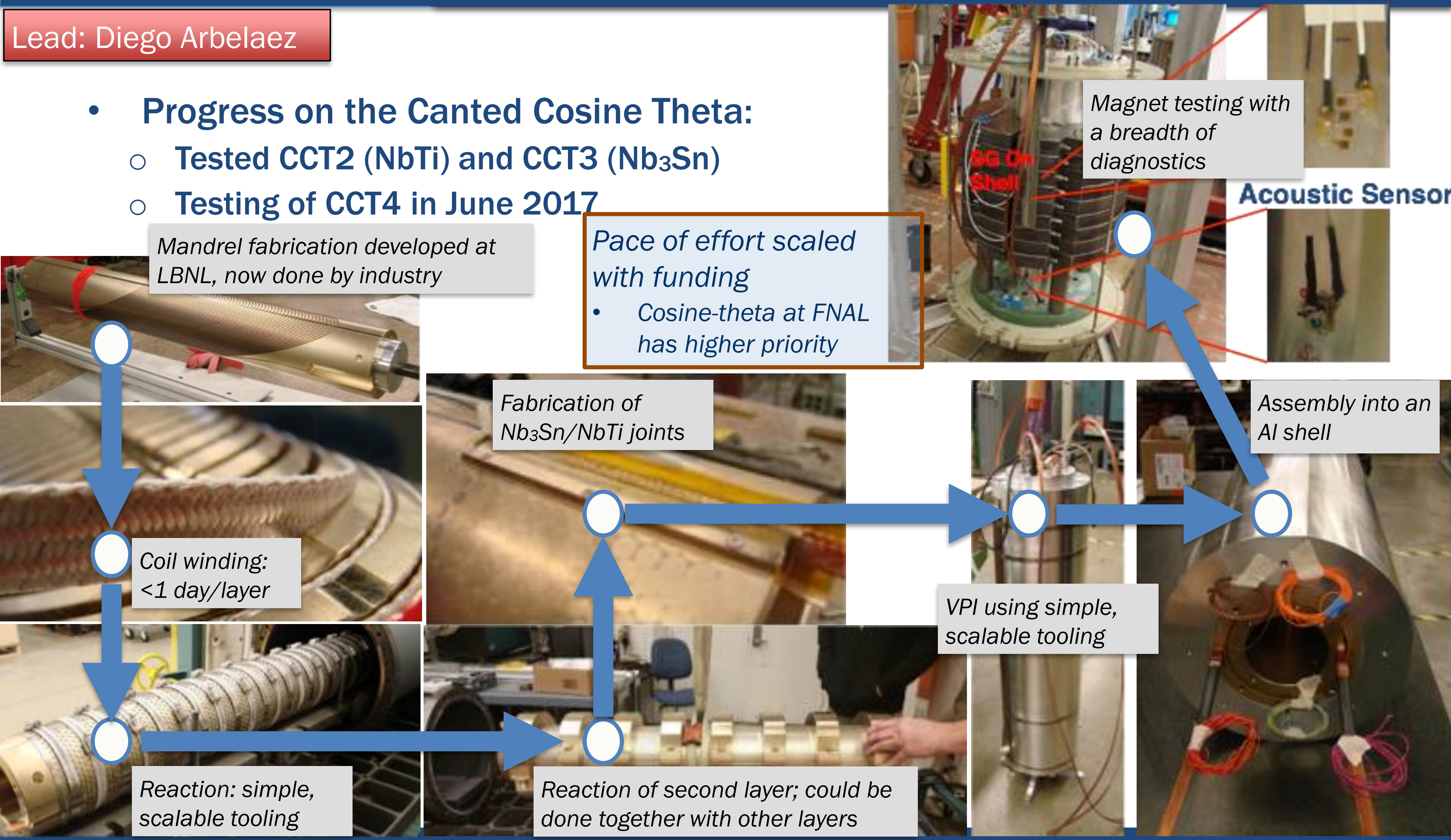
The CCT program is proceeding to systematically address technical issues

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*



Mandrel fabrication developed at LBNL, now done by industry

Coil winding: <1 day/layer

Reaction: simple, scalable tooling

Reaction of second layer; could be done together with other layers

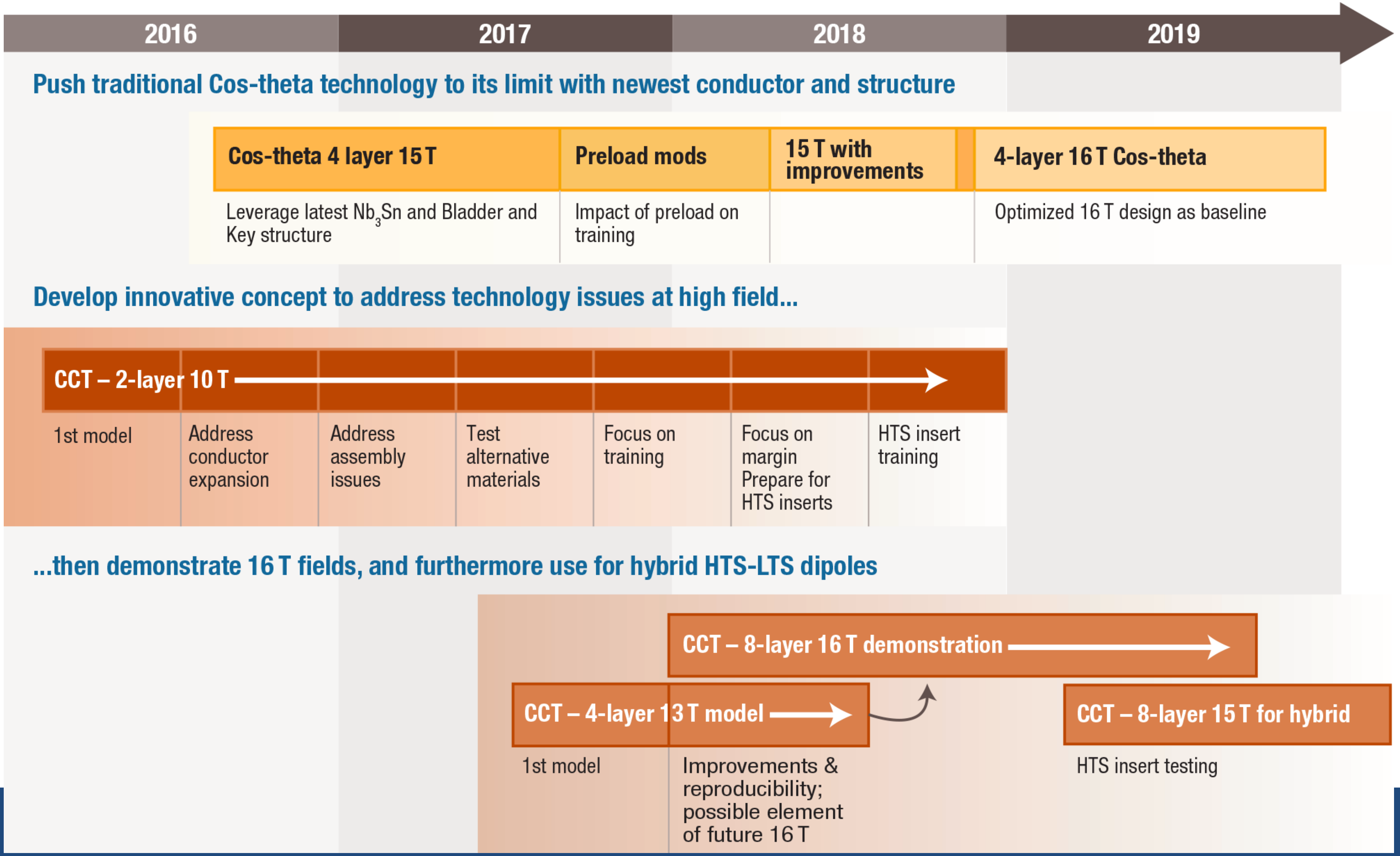
Fabrication of Nb_3Sn/NbTi joints

VPI using simple, scalable tooling

Assembly into an Al shell

Magnet testing with a breadth of diagnostics

Overview of the Nb_3Sn Milestone Plan, Highlighting the Cos(θ) Reference Magnet Development (top) and the Innovation Route with CCT: ~10 T Subscale Magnet Development (middle), Followed by 16 T Model Magnets



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 – 8-layer 16 T demonstration

CCT – 4-layer 13 T model

1st model

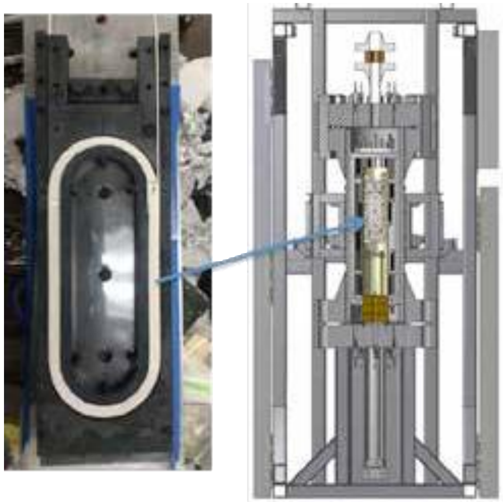
Improvements & reproducibility; possible element of future 16 T

CCT – 8-layer 15 T for hybrid

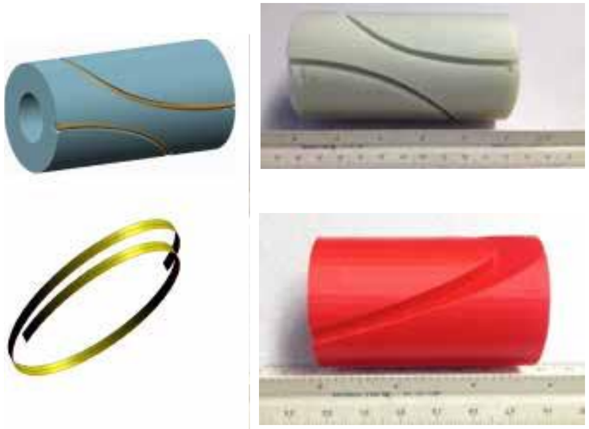
HTS insert testing

Exploring and pushing the limits of HTS for high-field dipole applications

Two candidate HTS conductors



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



- REBCO
  - Cable characterization and dipole magnet development

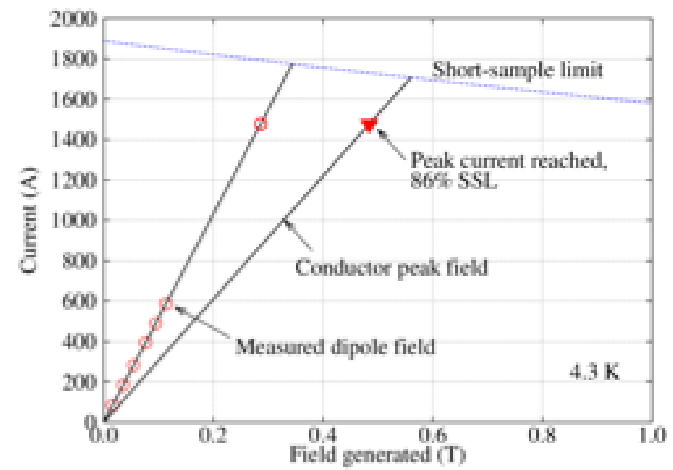
U.S. MAGNET DEVELOPMENT PROGRAM

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

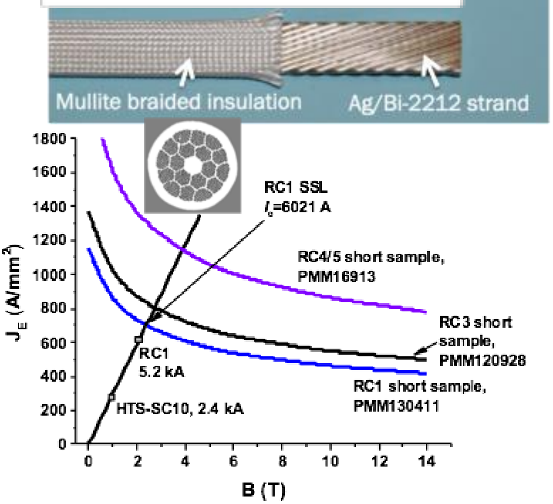
Lead: Tengming Shen

LBNL Bi2212 magnets:

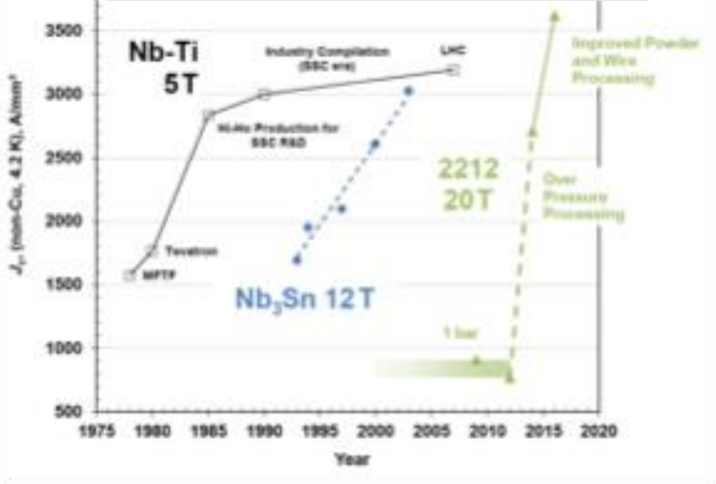
- Racetrack coils fabricated and pushed to their electrical, mechanical, and quench limits
- CCT magnet prototyping in progress.

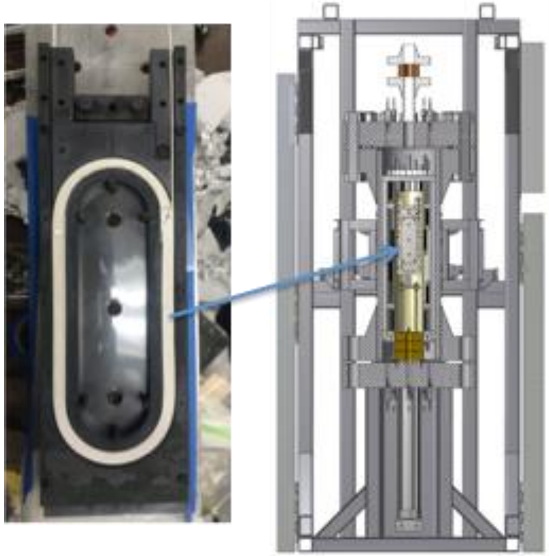


Significant improvement: double J_E from RC1 to RC4/5



Continued recent progress: 30% increase in J_c, and long lengths!



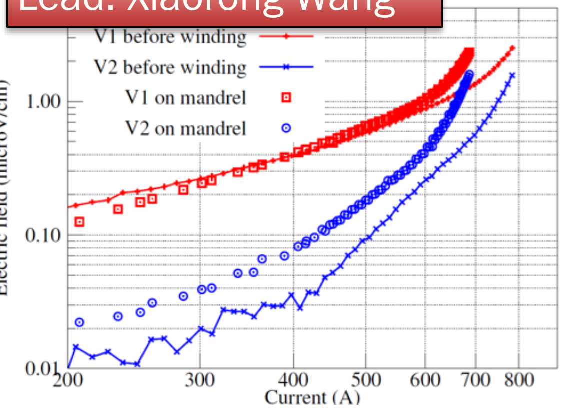


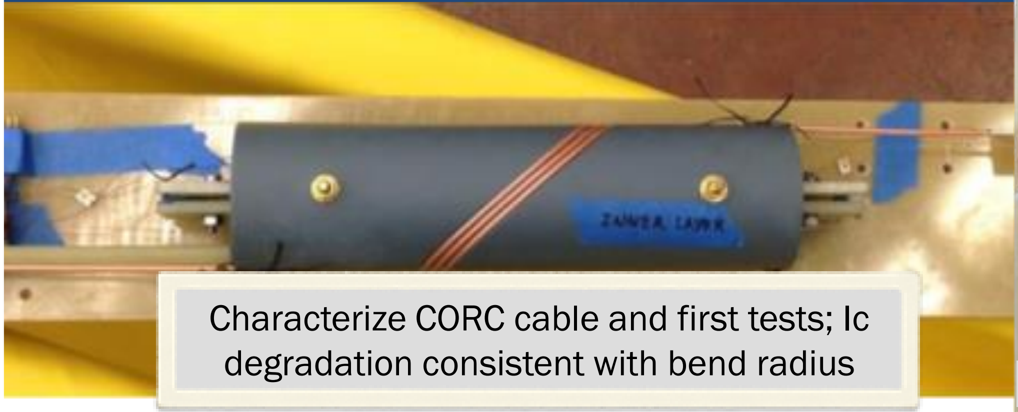
U.S. DEPARTMENT OF ENERGY | Office of Science

U.S. MAGNET DEVELOPMENT PROGRAM

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

Lead: Xiaorong Wang

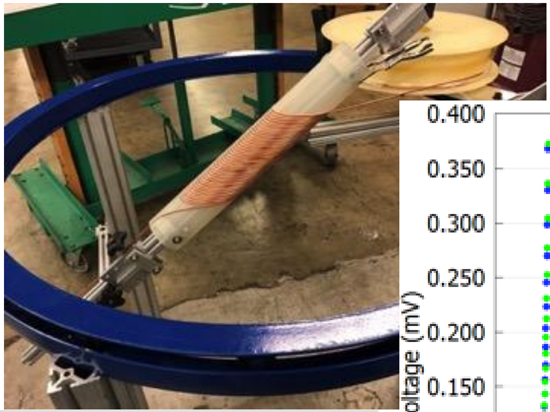




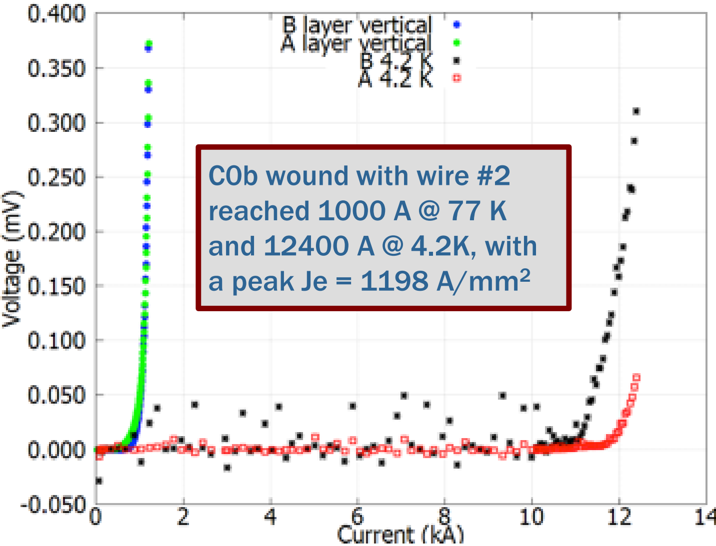
Characterize CORC cable and first tests; Ic degradation consistent with bend radius

Image courtesy by J. Weiss and D. van der Laan, Advanced Conductor Technologies

Assembly of 1st 2-layer REBCO CCT



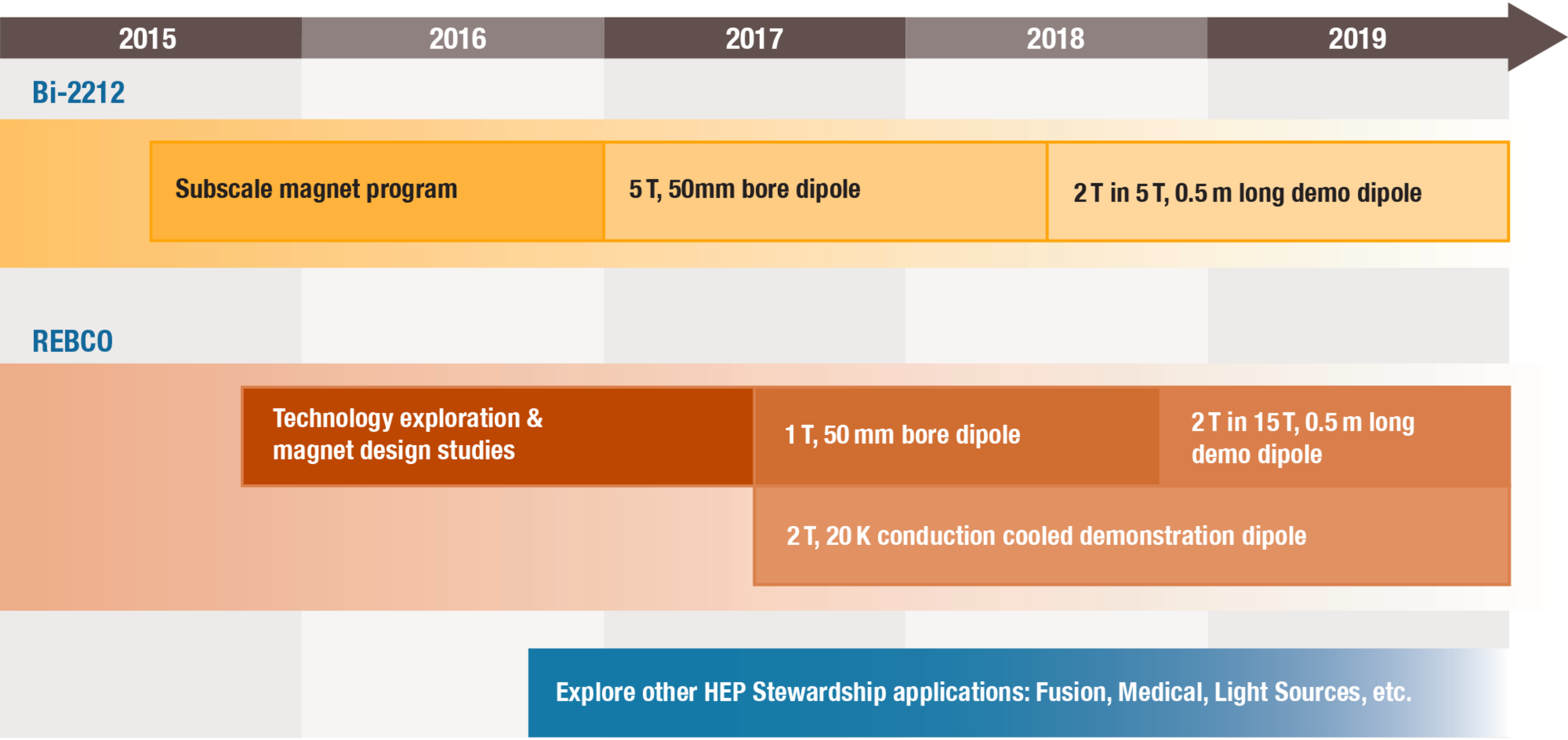
Tooling developed for winding of 40-turn prtototype



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

U.S. DEPARTMENT OF ENERGY | Office of Science

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



Backbone of the Program: Magnet Science and Developing Underpinning Technologies

Some examples:

- 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

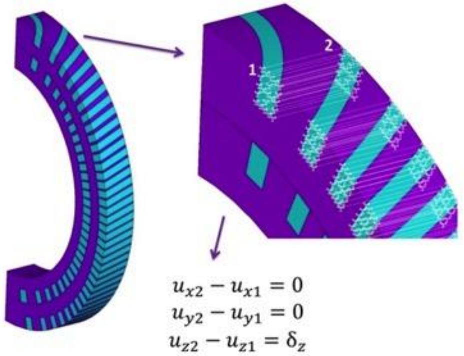
Improvements from the technology development program are integrated into Nb_3Sn and HTS magnets

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

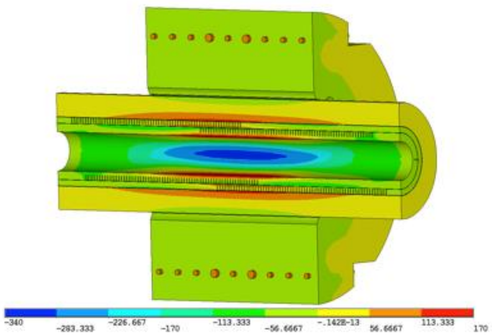
Lucas Brouwer

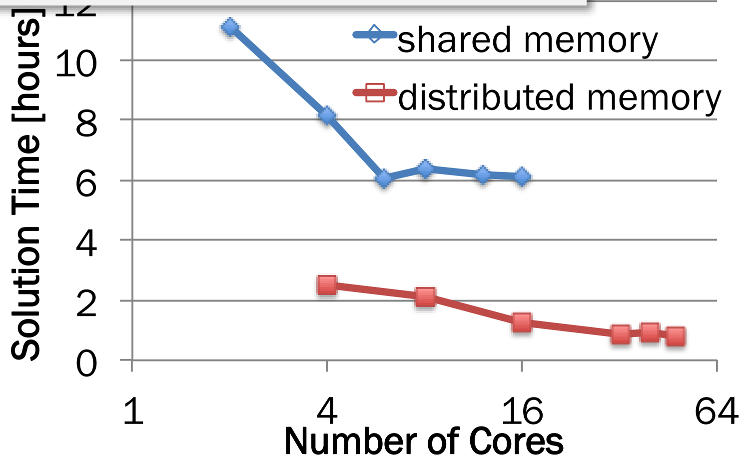
Full 3D simulations – utilizing the computing cluster Lawrencium at LBNL

Periodic Model



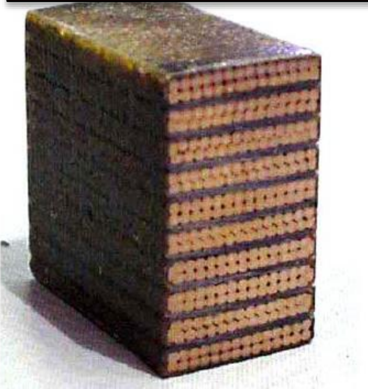
Full Model

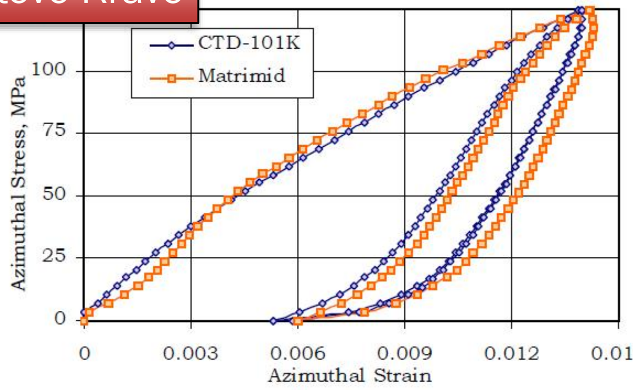


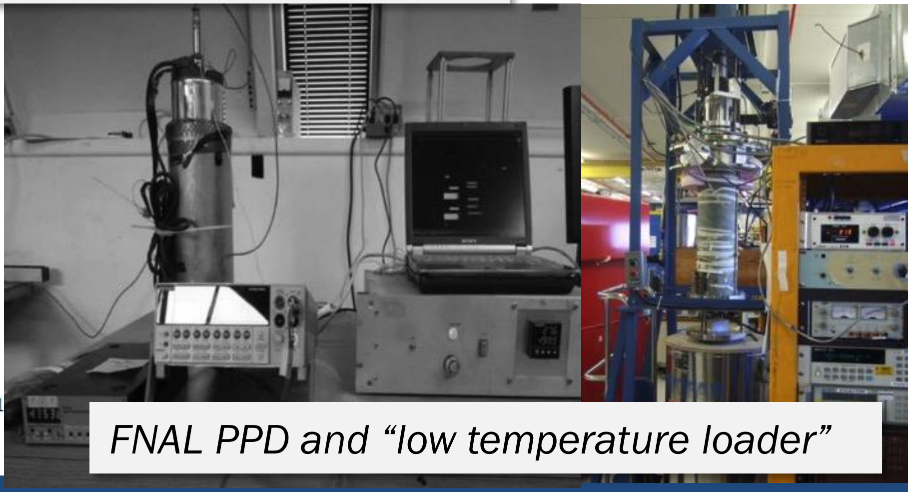


Ten-stack measurements provide critical materials properties

Leads: Ian Pong & Steve Krave







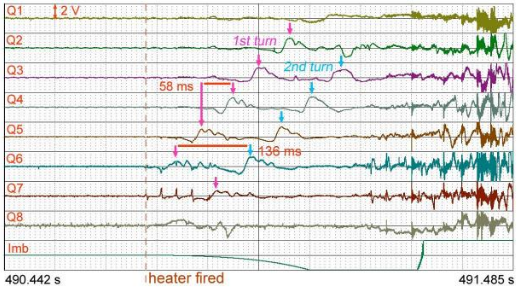
FNAL PPD and “low temperature loader”

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

Leads: Maxim Marchevsky & Stoyan Stoynev

Warm-bore quench antennas

Senses axial gradient of the axial field

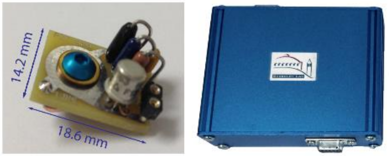


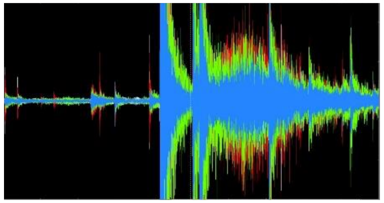
Propagation of a heater-initiated quench in HQ02b at 6 kA

"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

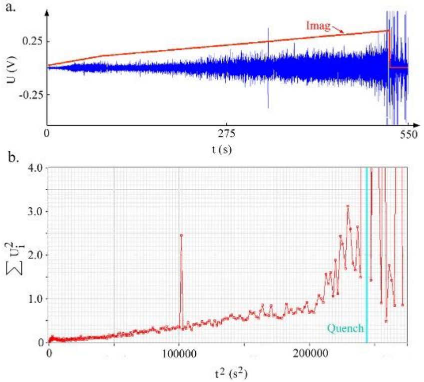
Acoustic emissions as detectors

(c)





Acoustic emission detection and quench localization system



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.

Acoustic emissions for localization

2D

$(x_0-x_1)^2+(y_0-y_1)^2=R_1^2$

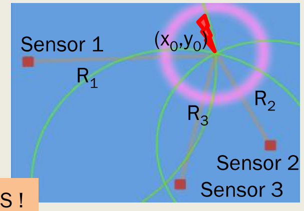
$(x_0-x_2)^2+(y_0-y_2)^2=R_2^2$

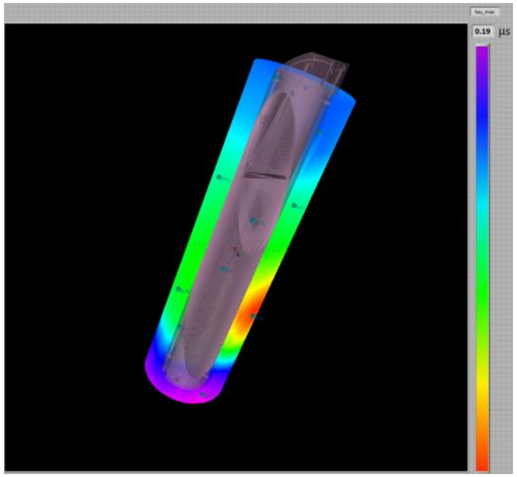
$(x_0-x_3)^2+(y_0-y_3)^2=R_3^2$

$|R_1-R_2|=V{\downarrow}s\ Dt_{12}$

$|R_1-R_3|=V{\downarrow}s\ Dt$

Think GPS !

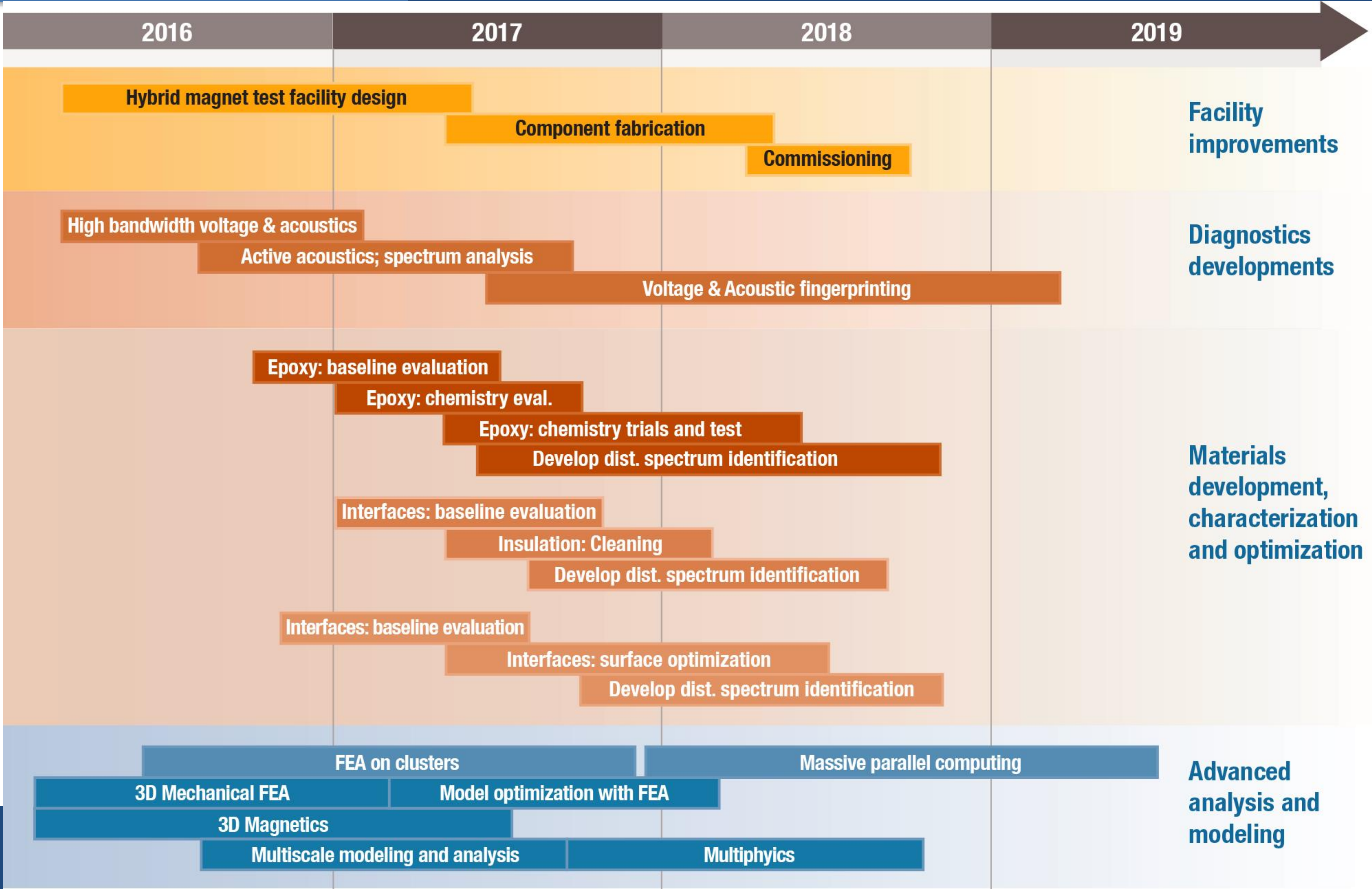




Pre-quench mechanical event location in CCT3 triangulated using acoustic emission sensors (color map of arrival times)

U.S. MAGNET DEVELOPMENT PROGRAM

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



2016 | 2017 | 2018 | 2019

Facility improvements
- Hybrid magnet test facility design
- Component fabrication
- Commissioning

Diagnostics developments
- High bandwidth voltage & acoustics
- Active acoustics; spectrum analysis
- Voltage & Acoustic fingerprinting

Materials development, characterization and optimization
- Epoxy: baseline evaluation
- Epoxy: chemistry eval.
- Epoxy: chemistry trials and test
- Develop dist. spectrum identification
- Interfaces: baseline evaluation
- Insulation: Cleaning
- Develop dist. spectrum identification
- Interfaces: baseline evaluation
- Interfaces: surface optimization
- Develop dist. spectrum identification

Advanced analysis and modeling
- FEA on clusters
- Massive parallel computing
- 3D Mechanical FEA
- Model optimization with FEA
- 3D Magnetics
- Multiscale modeling and analysis
- Multiphyics

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;

See Tuesday presentation by Lance Cooley

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

Summary

- We have…
  - an MDP Plan that lays out our goals and a roadmap for achieving them
  - 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 acheived,
  - making real dipoles from HTS and integrating them with LTS
  - procuring sufficient conductors for the program, and identifying opportunities for conductor R&D