Overview of the US magnet development programme

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Director
US Magnet Development Program
Lawrence Berkeley National Laboratory
Outline

• Context for high field accelerator magnet R&D
  o P5 and the Accelerator R&D Subpanel recommendations

• The US Magnet Development Program
  o How we are structured

• Technical status of each area
  o Progress and current status
  o Corresponding roadmap within the MDP plan

• Summary
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 Nb₃Sn 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 5T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16T.

GOAL 3:
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

JUNE 2016

GOAL 4:
Pursue Nb₃Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

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Participate in global conceptual design studies and critical path 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.

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

Pursue the development of Nb₃Sn magnets for proton-proton collider.

Execute a high-temperature superconductor development plan with appropriate cost-effective accelerator magnets.

Pursue aggressive development of new and manufacturing engineering decrease the touch labor and increase superconducting accelerator magnets.

Increase funding for superconducting
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 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

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

- **Nb$_3$Sn 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 P. Lee and D. Larbalestier

See Tuesday presentations from A. Zlobin and Mike Sumption
Technical areas have leads who are responsible for coordination and planning.

### Magnets

<table>
<thead>
<tr>
<th>Technical area</th>
<th>Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosine-theta 4-layer</td>
<td>Sasha Zlobin</td>
</tr>
<tr>
<td>Canted Cosine theta</td>
<td>Diego Arbelaez</td>
</tr>
<tr>
<td>Bi2212 dipoles</td>
<td>Tengming Shen</td>
</tr>
<tr>
<td>REBCO dipoles</td>
<td>Xiaorong Wang</td>
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</tbody>
</table>

### Design teams

<table>
<thead>
<tr>
<th>Lead</th>
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<tbody>
<tr>
<td>16T dipole designs</td>
</tr>
<tr>
<td>High-field Utility Structure</td>
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</tbody>
</table>

### Cond Proc and R&D

<table>
<thead>
<tr>
<th>Lead</th>
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<tr>
<td>Lance Cooley</td>
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### Technology area

<table>
<thead>
<tr>
<th>Technology area</th>
<th>LBNL lead</th>
<th>FNAL lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modeling &amp; Simulation</td>
<td>Diego Arbelaez</td>
<td>Vadim Kashikhin</td>
</tr>
<tr>
<td>Training and diagnostics</td>
<td>Maxim Martchevsky</td>
<td>Stoyan Stoynev</td>
</tr>
<tr>
<td>Instrumentation and quench protection</td>
<td>Emmanuele Ravaioli</td>
<td>Thomas Strauss</td>
</tr>
<tr>
<td>Material studies – superconductor and structural properties</td>
<td>Ian Pong</td>
<td>Steve Krave</td>
</tr>
</tbody>
</table>
The MDP is being managed and reviewed for program coherence and technical strength.

The first annual collaboration meeting of the US MDP, from Monday, Feb. 6 until approximately noon on Wednesday, Feb. 7, was held at the Marriott Hotel and Spa.

As this is the first meeting of the MDP, the primary purpose is to review the management structure, current status of active projects, and expansion of the program. There will be a working lunch, and a social hour will be held to maximize interaction and discussion among the members.

There will be no registration fee, but all attendees must register online in advance. The deadline for registration is January 25, 2017.

Committee:
Giorgio Ambrosio
Jeffrey Grabow
Shlomo Faber
Arup Ghosh
Peter Minkiewicz
Alfred Richter

Website:
https://www.fnal.gov/MDP/

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

Committee:
Giorgio Ambrosio - Chair
Helene Felice
Shlomo Faber
Giorgio Ambrosio
Sandor Fehér

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 Cylindrical Theta" (CCT) magnet concept. The CCT program is currently focused on identifying and addressing primary technical challenges associated with the use of Nb3Sn in the CCT configuration. To that end, a series of 2-layer magnets are being produced. The 2nd Nb3Sn 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 CCT3 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 heat treatment appropriately defined?
3. Are the CAD, fabrication drawings, tooling and assembly plan sufficiently advanced for fabrication to commence?

Review committee:
- Steve Virosi - Chair
- Helene Felice
- Shlomo Faber
- Giorgio Ambrosio
- Sandor Fehér

Support:
SSen@fnal.gov Telephone: 510-486-4391
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$_3$Sn and HTS accelerator magnets?

3. What are the mechanical limits and possible stress management approaches for Nb$_3$Sn and 20 T LTS/HTS magnets?

4. What are the limitations on means to safely protect Nb$_3$Sn and HTS magnets?
<table>
<thead>
<tr>
<th>Driving Questions...related to cost</th>
</tr>
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<tbody>
<tr>
<td><strong>5.</strong> Can we provide accelerator quality Nb$_3$Sn magnets in the range of 16 T?</td>
</tr>
<tr>
<td><strong>6.</strong> Is operation at 16 T economically justified? What is the optimal operational field for Nb$_3$Sn dipoles?</td>
</tr>
<tr>
<td><strong>7.</strong> What is the optimal operating temperature for Nb$_3$Sn and HTS magnets?</td>
</tr>
<tr>
<td><strong>8.</strong> Can we build practical and affordable accelerator magnets with HTS conductor(s)?</td>
</tr>
<tr>
<td><strong>9.</strong> Are there innovative approaches to magnet design that address the key cost drivers for Nb$_3$Sn and HTS magnets that will shift the cost optimum to higher fields?</td>
</tr>
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</table>
What are the near and long-term goals for $\text{Nb}_3\text{Sn}$ and HTS conductor development? What performance parameters in $\text{Nb}_3\text{Sn}$ and HTS conductors are most critical for high field accelerator magnets?
High Field Dipoles are exploring the Limits of Nb$_3$Sn

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

- Outer coil winding
- Preparations for VPI
- Novel coil layout addressing midplane stresses and field quality

Coil parts provided by CERN

Procurement at CERN

- L1-2 parts procurement at CERN

Procurement at FNAL

- Skin contact tooling
- L1/2 curing tooling
- Reaction retort (new tooling)
- Dummy coils for MM
- L4 Cu trace received

Procurement at LBNL

- L4 SS traces
- Traces for 1st L3-4 coil received
The CCT program is proceeding to systematically address technical issues.

- Progress on the Canted Cosine Theta:
  - Tested CCT2 (NbTi) and CCT3 (Nb$_3$Sn)
  - Testing of CCT4 in June 2017

  Mandrel fabrication developed at LBNL, now done by industry

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

  Coil winding: <1 day/layer

  Fabrication of Nb$_3$Sn/NbTi joints

  Reaction: simple, scalable tooling

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

  VPI using simple, scalable tooling

  Assembly into an Al shell

  Magnet testing with a breadth of diagnostics

Lead: Diego Arbelaez
Overview of the Nb$_3$Sn Milestone Plan, Highlighting the Cos(\theta) Reference Magnet Development (top) and the Innovation Route with CCT: ~10 T Subscale Magnet Development (middle), Followed by 16 T Model Magnets

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

<table>
<thead>
<tr>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cos-theta 4 layer 15 T</strong></td>
<td>Preload mods</td>
<td>15 T with improvements</td>
<td>4-layer 16 T Cos-theta</td>
</tr>
<tr>
<td>Leverage latest Nb$_3$Sn and Bladder and Key structure</td>
<td>Impact of preload on training</td>
<td>Optimized 16 T design as baseline</td>
<td></td>
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**Develop innovative concept to address technology issues at high field...**

<table>
<thead>
<tr>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CCT – 2-layer 10 T</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st model</td>
<td>Address conductor expansion</td>
<td>Address assembly issues</td>
<td>Test alternative materials</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Focus on margin Prepare for HTS inserts</td>
</tr>
</tbody>
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...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
Two candidate HTS conductors

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

• REBCO
  • Cable characterization and dipole magnet development
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 $J_c$ from RC1 to RC4/5

Continued recent progress: 30% increase in $J_c$, and long lengths!
REBCO program developing quickly: conductor and cable characterization, magnet design and prototyping underway

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

Assembly of 1st 2-layer REBCO CCT

Lead: Xiaorong Wang

C0b wound with wire #2 reached 1000 A @ 77 K and 12400 A @ 4.2K, with a peak Je = 1198 A/mm²
Overview of the HTS Milestone Plan, Highlighting the Bi-2212 Magnet Development (top) and the REBCO Magnet Development

<table>
<thead>
<tr>
<th>Year</th>
<th>Bi-2212</th>
<th>REBCO</th>
</tr>
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<tbody>
<tr>
<td>2015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>Subscale magnet program</td>
<td>Technology exploration &amp; magnet design studies</td>
</tr>
<tr>
<td>2017</td>
<td>5 T, 50mm bore dipole</td>
<td>1 T, 50 mm bore dipole</td>
</tr>
<tr>
<td>2018</td>
<td>2 T in 5 T, 0.5 m long demo dipole</td>
<td>2 T in 15 T, 0.5 m long demo dipole</td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td>2 T, 20 K conduction cooled demonstration dipole</td>
</tr>
</tbody>
</table>

Explore other HEP Stewardship applications: Fusion, Medical, Light Sources, etc.
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$_3$Sn and HTS magnets
Numerous technology advances are essential to address the high field magnet challenge.

**Periodic Model**

$u_{x2} - u_{x1} = 0$
$u_{y2} - u_{y1} = 0$
$u_{z2} - u_{z1} = \delta_z$

**Full Model**

Solution Time [hours]

- **Shared memory**
- **Distributed memory**

**Number of Cores**

1 - 64

**Ten-stack measurements provide critical materials properties**

**leads: Ian Pong & Steve Krave**

**Periodic Model**

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

**FNAL PPD and “low temperature loader”**
Advanced diagnostics are providing new and critical insight into the mechanisms of training and magnet performance

Warm-bore quench antennas

Senses axial gradient of the axial field

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


Acoustic emissions as detectors

Acoustic emissions for localization

Acoustic precursors to quenching (HD3 dipole) during current ramp


Pre-quench mechanical event location in CCT3 triangulated using acoustic emission sensors (color map of arrival times)
Superconducting Materials Procurement and R&D is Critical for Program Success

- Push performance limits of Nb$_3$Sn and HTS conductors based on magnet needs
- Understand –
  - Uniformity and reliability
  - Scalability and future cost

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Target</th>
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<tbody>
<tr>
<td>Diameter</td>
<td>0.7 to 1.2 mm; (hold @ 1.3)</td>
</tr>
<tr>
<td>Unit length</td>
<td>95% yield at 150 m</td>
</tr>
<tr>
<td>Jc (16 T, 4.2K)</td>
<td>1300 A/mm$^2$ (best effort) 1240 in cable</td>
</tr>
<tr>
<td>Jc std. dev.</td>
<td>&lt; 100 A/mm$^2$</td>
</tr>
<tr>
<td>RRR</td>
<td>&gt;100; &gt;50 at cable edge or in strand rolled to 15% reduction</td>
</tr>
<tr>
<td>Cu:NC</td>
<td>0.9 to 1.1 (e.g. 150/169)</td>
</tr>
<tr>
<td>D$_{SE}$</td>
<td>&lt;60 μm</td>
</tr>
<tr>
<td>HT duration</td>
<td>&lt;240 hours</td>
</tr>
</tbody>
</table>

Initial specifications for Nb$_3$Sn conductor;

See Tuesday presentation by Lance Cooley.
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 achieved,
- making real dipoles from HTS and integrating them with LTS
- procuring sufficient conductors for the program, and identifying opportunities for conductor R&D