The US Magnet Development Program after one year

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Lawrence Berkeley National Laboratory

For the US MDP Team
Outline

• High level program overview
  o Review of the program foundation
  o Management and technical oversight structure

• Progress on the MDP roadmap

• Flavor of some technology developments underway

• Overview of MDP-aligned collaborations

• Conclusions
The US Magnet Development Program was founded by DOE-OHEP to advance superconducting magnet technology for future colliders.

Strong support from the Physics Prioritization Panel (P5) and its sub-panel on Accelerator R&D

A clear set of goals have been developed and serve to guide the program

Technology roadmaps have been developed for each area: LTS and HTS magnets, Technology, and Conductor R&D

US Magnet Development Program (MDP) Goals:

GOAL 1:
Explore the performance limits of Nb,Sn 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 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,Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.
The program has well-defined goals, and is structured with leads who are responsible for delivery.

### Magnets

<table>
<thead>
<tr>
<th>Magnets</th>
<th>Lead</th>
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</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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### Technology area

<table>
<thead>
<tr>
<th>Technology area</th>
<th>LBNL lead</th>
<th>FNAL lead</th>
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</thead>
<tbody>
<tr>
<td>Modeling &amp; Simulation</td>
<td>Diego Arbelaez</td>
<td>Vadim Kashikhin</td>
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<tr>
<td>Training and diagnostics</td>
<td>Maxim Martchevsky</td>
<td>Stoyan Stoynev</td>
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<tr>
<td>Instrumentation and quench protection</td>
<td>Emmanuele Ravaioli</td>
<td>Thomas Strauss</td>
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<tr>
<td>Material studies – superconductor and structural</td>
<td>Ian Pong</td>
<td>Steve Krave</td>
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<td>materials properties</td>
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<td></td>
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<tr>
<td>Cond Proc and R&amp;D</td>
<td>Lance Cooley</td>
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</table>

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**GOAL 4:**
Pursue Nb$_3$Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.
We are building strong programmatic interconnections between the participating labs

- Clear leadership roles in:
  - Cosine-theta: FNAL
  - CCT: LBNL
  - CPRD: ASC/NHMFL

- Joint advances on HTS and Technology

- Significant interaction on all fronts

Overview

- Committee: Giorgio Apollinari, Joe Minervini, Mark Palmer, Davide Tommasini, Akira Yamamoto (excused), Andy Lankford (designated outsider)

- Very impressive progress and accomplishments during the past year.
  - As reported in an excellent set of presentations on a wide range of important, essential, challenging topics
The MDP team is progressing on the path for magnets outlined in the MDP Plan document

Area I: Nb$_3$Sn magnets
The MDP team is progressing on the path for magnets outlined in the MDP Plan document

**Area II:**

**HTS magnet technology**

**BI-2212**
- **2015**: Technology exploration & magnet design studies
- **2016**: Subscale magnet program
- **2017**: 2T, 50mm bore dipole
- **2018**: 2T in 15T, 0.5m long demo dipole

**REBCO**
- **2015**: Technology exploration & magnet design studies
- **2016**: 1T, 50mm bore dipole
- **2017**: 2T, 20K conduction cooled demonstration dipole
- **2018**: 2T in 15T, 0.5m long demo dipole

**Explore other HEP Stewardship applications: Fusion, Medical, Light Sources, etc.**
Area III:

The science of magnets: identifying and addressing the sources of training and magnet performance limitations via advanced diagnostics, materials development, and modeling

Key science components of the MDP Plan are Technology Development and Conductor R&D

- Hybrid magnet test facility design
- Component fabrication
- Commissioning
- High bandwidth voltage & acoustics
- Active acoustics; spectrum analysis
- Voltage & Acoustic fingerprinting
- Epoxy: baseline evaluation
- Epoxy: chemistry evaluation
- Epoxy: chemistry trials and test
- Develop disturbance spectrum identification
- Interfaces: baseline evaluation
- Insulation: Cleaning
- Develop disturbance spectrum identification
- FEA on clusters
- Model optimization with FEA
- Massive parallel computing
- 3D Mechanical FEA
- 3D Magnetics
- Multiscale modeling and analysis
- Multiphysics
Progress on high-field magnet concepts

- **Block Cosine-theta magnet** fabrication is progressing well, with testing anticipated this year.

- **Canted Cosine-theta:**
  - Subscale CCT currently being pursued for fast turn-around technology development.
  - CCT4 (the second Nb$_3$Sn CCT 2-layer magnet) was tested, and thermally cycled.
  - CCT5 is in design, incorporating feedback from CCT4.
Progress on HTS magnet front

- Bi2212 has made dramatic strides in $J_c$ over last 3 years – ready for magnets
  - Wire has been cabled and tested in racetrack configuration (RC5)
  - First Bi2212 CCT dipole has been wound; reaction and testing soon
  - Roadmap integrates Bi2212 CCT in a high-field hybrid magnet design

- REBCO development focused on CORC® cables and magnet technology development
  - 3-turn C0 “dipole” was used to develop winding tooling, fabrication processes
  - 40-turn C1 dipole was then fabricated and tested
  - Anticipate >x3 improvement in tape $J_E$ and transfer function
We are looking closely at options for future high-field magnet designs that build on current efforts.

** Nb$_3$Sn design targets **

1. Each magnet concept should provide
   - Description of magnet design including
     - Strand, cable and insulation (before and after reaction)
     - Coil cross-section (number of layers, number of turns, conductor weight/m/aperture)
     - Coil end design concept
     - Magnet support structure including transverse and axial support
     - Quench protection system in the case of no energy extraction
   - Maximum magnet bore field $B_{\text{max}}$ at conductor SSL for 1.9 K and 4.5 K
   - Dependence of $B_{\text{max}}$ on conductor $J_c(16\,\text{T},4.2\,\text{K})$
   - Calculated geometrical field harmonics, coil magnetization and iron saturation effects in magnet straight section at $R_{\text{ref}}=17\,\text{mm}$ for $B=1-16\,\text{T}$
   - Stress distribution in coil and structure at room and operation temperatures and at the nominal (16 T) and design (17 T) fields
   - Coil-pole interface (gap) at the nominal (16 T) and design (17 T) fields
   - Coil maximum temperature and coil-to-ground voltage during quench w/o energy extraction
   - Cost reduction opportunities

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** Design Team **

** 16 T Dipole design: **
Lead: Zlobin and Sabbi

** Utility Structure design: **
Lead: Mariusz Juchno

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** First look at Hybrid designs **
Caspi, Brouwer, et al

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<table>
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<tr>
<th>ID (kA)</th>
<th>By-bore</th>
<th>Bmod (HTS)</th>
<th>Bmod (CCT)</th>
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<td>ANSYS</td>
<td>11</td>
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<td>Opera2D</td>
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<td>%diff</td>
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<td>1.06</td>
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- Poisson (Neumann boundary) 11
  - 20.600
  - 20.77
  - 17.96
  - 16.90
- Poisson (parallel boundary) 11
  - 19.370
  - 19.58
  - 16.80
  - 15.82
- Poisson (Average) 19.085
  - 20.18
  - 17.38
  - 16.36
- %diff 1.35
  - 1.51
  - 1.73
  - 2.87
Quench memory and two distinct training regimes

Marchevsky, LBNL

"kink" in the training curve

cracking

slip-stick
Progress on Technology front - Application of high-bandwidth acoustic sensors on magnets opens avenue for new insights into magnet behavior

- Large number of acoustic events occur during magnet ramping - potentially contain valuable insight into magnet behavior and the disturbance spectrum that initiates quenches

Wavelet analysis provides robust mathematics platform for transient signal analysis
New acoustic quench detection technique was developed and benchmarked against temperature and voltage measurements.


Technique was successfully tested in ReBCO CORC and Bi-2212 HTS subscales.
Progress on Technology front - Modeling capabilities continue to be developed that have broad applicability to superconducting magnet technology

- Advanced multi-physics coupling using custom elements, and leveraging of computing clusters with FEA

Replace code which builds element matrices: uel.f, uec.f -> compile custom ANSYS.exe

Available
- node location
- loads
- node temperature
- material prop.
- ANSYS functions

Element customized by defining
- element shape functions
- material properties: if complex function desired (T,B,K,etc.)
- formulation

Element matrix generation is now determined by user program - stiffness, damping, etc.

coupled with standard formulation

Soren Prestemon      FCC Week, Amsterdam, Holland          April 11th, 2018

Brouwer, LBNL; Auchmann, PSI/CERN
CPRD: Balanced effort of supplying sufficient conductor for magnet R&D and serving as catalyst for the next generation conductor

Area IV: Continue the extremely successful paradigm of OHEP’s Conductor Development Program

- A Roadmap has been developed to clarify CPRD’s vision of furthering conductor development, supporting ongoing magnet development needs, and coordinating critical R&D from other funding sources in support of MDP goals
- Nb$_3$Sn advances continue to be pushed
  - Advances in understanding of the chemistry of Nb$_3$Sn heat treatment ⇒ significant improvement in $J_c$ for small $d_{eff}$
  - Equal-channel angular extrusion evaluation by Bruker/OST
- Investigate potential for APC Nb$_3$Sn
  - Ohio State, FNAL LDRD, FSU
- Advances in Bi2212 powder processing + overpressure processing
- REBCO development focused on leveraging SBIR and complementary programs;
  - MDP provides measurements and conductor performance feedback to developers and vendors
International and industrial collaborations are underway in support of the MDP mission

<table>
<thead>
<tr>
<th>Activity</th>
<th>MDP Relevance</th>
<th>Collaborating Institution</th>
<th>Contact(s)</th>
<th>Contact(s)</th>
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<tbody>
<tr>
<td>International</td>
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<td>Provide coil parts</td>
<td>15T Dipole</td>
<td>EuroCirCol/CERN</td>
<td>Tommasini, D., Shoerling, D.</td>
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<td>History and Documentation of Nb3Sn</td>
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<td>Development of High Performance Bi-2212 Precursor powder</td>
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<td>Magnetization studies</td>
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<td>Fiber Optic Quench Detection</td>
<td>HTS</td>
<td>PSU/Lupine Materials and Technology</td>
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<td>Shen, T.</td>
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</table>
Conclusions

• We are following the MDP roadmap to develop high field accelerator magnets for DOE-OHEP

• We have a fully functioning management structure

• We are balancing our efforts to maintain progress on multiple fronts
  • Significant progress on Nb$_3$Sn magnets
  • HTS magnet development - on both Bi2212 and REBCO fronts
  • Critical technology developments that guide magnets… and of value to the broader community

• We have developed a coherent conductor R&D roadmap

• We have a strong, and growing, list of national and international collaborations
One full year is now behind us...
The management structure of the MDP is well 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
Mark Palmer, BNL

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S. Gourlay, LBNL
D. Larbalestier, FSU
A. Zlobin, FNAL