For the US MDP Team:
The data shown in these slides are the result of work from Scientists and Engineers in the US MDP
Outline

• Introduction
• The US MDP Program
  o main goals and...
  o roadmaps to achieve them
• Technology development highlights
  o LTS magnets
  o HTS magnets
  o Technology development
  o Materials
• Summary
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 serve to guide the program

Technology roadmaps for each area: LTS and HTS magnets, Technology, and Conductor R&D
US MDP: vision

- **Maintain and strengthen US Leadership** in high-field accelerator magnet technology for future colliders

- Focus on the **four primary goals** identified in the original MDP Plan
  - Explore the performance limits of Nb\(_3\)Sn accelerator magnets, with a focus on minimizing the required operating margin and significantly reducing or eliminating training
  - Develop and demonstrate an HTS accelerator magnet with a self-field of 5T or greater, compatible with operation in a hybrid HTS/LTS magnet for fields beyond 16T
  - Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction
  - Pursue Nb\(_3\)Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets

- Further **develop and integrate the teams** across the partner laboratories and Universities for maximum value and effectiveness to the program

- Identify and **nurture cross-cutting / synergistic activities** with other programs to more rapidly advance progress towards our goals
The management structure of the MDP is well defined and the program is fully functioning.

Steering Council
Harry Weerts (ANL), DOE appointed Chairman
Mike Harrison (BNL), DOE appointed
Mike Witherrill/James Symons, LBNL
Nigel Lockyer/Sergey Belomestnykh, FNAL
Greg Boebinger/Eric Palm, NHMFL

Technical Advisory Committee
Andrew Lankford, UC Irvine – Chair
Davide Tommasini, CERN
Akira Yamamoto, KEK
Joe Minervini, MIT
Giorgio Apollinari, FNAL
Mark Palmer, BNL

MDP Management Group (“G6”)  
S. Prestemon, S. Gourlay, LBNL
G. Velev, A. Zlobin, FNAL
L. Cooley, D. Larbalestier, FSU

New!
BNL has joined the MDP and will integrate its expertise into the program.
The program is structured with technical elements directly aligned with program goals

### 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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</tbody>
</table>

### 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>Maxim Martchevsky</td>
<td>Thomas Strauss</td>
</tr>
<tr>
<td>Material studies – superconductor and structural</td>
<td>Ian Pong</td>
<td>Steve Krave</td>
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<tr>
<td>materials properties</td>
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<tr>
<td>Cond Proc and R&amp;D</td>
<td>Lance Cooley</td>
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### 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 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 Nb₃Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.
We have yearly collaboration meetings - excellent turnout, great opportunity for staff to present ideas and results and for technical discussions

- Collaboration meeting I, Feb. 17-19, 2017: Napa, California
- Collaboration meeting II: Jacksonville, Florida
- Collaboration meeting III, Jan. 11-13, 2019: FNAL, Illinois

So far meetings have been designed to precede the LTSW
- ~30% overlap of attendance; MDP serves as “magnet pull” for conductor development

TAC members are actively engaged
- Same members (and chair!) since the beginning of the MDP - provides continuity, good awareness of issues and progress

Issue identified in 2019:
- Significant number of presentations - very active group => may need 3 full days (have used 2.5 days to-date)

Example:
FY19 attendance

- 56 registrants
  - 14 attendees from LBNL; 13 talks
  - 17 attendees from FNAL; 12 talks
  - 6 attendees from ASC/NHMFL; 9 talks
  - 2 attendees from BNL; 2 talks
- Also OSU; CERN, KEK, PSI; (5 talks)
- Industry (SBIR)
The MDP Nb₃Sn magnet efforts continue to progress as outlined in the MDP Plan document, but the evolution will depend on results.

Area I:

**Nb₃Sn magnets**

Design studies
The MDP HTS magnet development is progressing well, and the long-term vision is starting to be fleshed out

Area II: HTS magnet technology

<table>
<thead>
<tr>
<th>2017</th>
<th>2019</th>
<th>2021</th>
<th>2023</th>
<th>2025</th>
<th>2027</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor &amp; tech development</td>
<td>Fundamental magnet technologies development</td>
<td>Coordination &amp; integration of conductor activities in U.S. with subscale magnet fab &amp; test</td>
<td>5-10 T common coil dipole</td>
<td>15-18 T Nb₃Sn/2212 hybrid</td>
<td>18-20 T Nb₃Sn/2212 hybrid</td>
</tr>
<tr>
<td>2212 Magnet</td>
<td>5 T CCT dipole</td>
<td>8-10 T CCT dipole</td>
<td>10 T dipole</td>
<td>7 T insert</td>
<td>20 T Nb₃Sn/REBCO hybrid dipole</td>
</tr>
<tr>
<td>REBCO Magnet</td>
<td>5 T dipole</td>
<td>2-3 T insert</td>
<td>1 T insert</td>
<td>20 T Nb₃Sn/REBCO hybrid dipole</td>
<td></td>
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Excellent progress on racetracks – CCT magnets fabricated, heat treated – testing later this summer
**Area III:**

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

- Plans getting fleshed out
- Leverage existing facilities (e.g. BNL) where appropriate
- Active area - need more magnet tests with variety of diagnostics!
- Good progress - great area for collaboration=> Universities, industry
- Expect to be a focal point over the next year
- Very good progress, but need to identify priorities and develop milestones
Conductor development is pursued through leveraged investments and coordination of industrial efforts

- 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 (e.g. SBIR program)

- \(\text{Nb}_3\text{Sn} \) advances continue to be pushed

- Advances in Bi2212 powder processing + overpressure processing...
  - ...and resulting progress in magnet performance

- REBCO development focused on leveraging SBIR and complementary programs;
  - MDP provides measurements and conductor performance feedback to developers and vendors

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See Larbalestier, “Recent progress on the development of high performance Bi-2212 wires and coils”
Some progress updates in the key program areas
A Cos(θ) 4-layer design, led by FNAL, is being pursued with the ultimate goal of achieving ~15T

- Design minimizes midplane stress for highest field
- A technical challenge is to provide adequate prestress on inner coils
- Intrinsic difficulty with 4 layers
- Collared-structure approach includes new features to provide some prestress increase during cool down

**Status:**
- Coils fabricated ✔
- Structure designed, fabricated ✔
- Mechanical model assembly completed ✔
- Assembly readiness review completed ✔
- Test completed ✔
- Reload at higher prestress
- Retest

Thanks to CERN!

See test results in next talk by Sasha Zlobin ⇒ Record Cos(θ) dipole field!

60-mm aperture, 4-layer graded coil
Very significant effort to develop the 4-layer \( \cos(\theta) \) magnet - coils, structure, instrumentation
The Canted-Cos(θ) concept, led by LBNL, is being explored as an alternative for high-field magnets

- **Canted Cosine-theta:**
  - CCT4 (the second Nb₃Sn CCT 2-layer magnet) was tested, and thermally cycled
  - CCT5 incorporated modifications based on CC4 experience
  - Magnet was tested and thermally cycled
  - Subscale CCT currently being pursued for fast turn-around technology development

<table>
<thead>
<tr>
<th></th>
<th>CCT3</th>
<th>CCT4</th>
<th>CCT5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore size [mm]</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Groove design</td>
<td>constant width</td>
<td>1.25 mm gap at pole</td>
<td>1.65 mm gap at pole</td>
</tr>
<tr>
<td>Conductor</td>
<td>RRP 54/61 Ta doped</td>
<td>RRP 54/61 Ta doped</td>
<td>RRP 108/127 Ti doped</td>
</tr>
<tr>
<td>HT Temp [°C]</td>
<td>650</td>
<td>660</td>
<td>665</td>
</tr>
<tr>
<td>Potting configuration</td>
<td>full magnet</td>
<td>full magnet</td>
<td>individual layers</td>
</tr>
<tr>
<td>Epoxy</td>
<td>CTD-101K</td>
<td>CTD-101K</td>
<td>FSU Mix 61</td>
</tr>
<tr>
<td>Layer-to-layer interface</td>
<td>bonded</td>
<td>mold released</td>
<td>bend &amp; shim</td>
</tr>
</tbody>
</table>
The use of novel diagnostics supported feedback that improved magnet performance - gaining insight in training mechanisms.

CCT5 Training Behavior

- Quench Current
- Quench Current Relative to SSL
- Thermal Cycle

9.1 T
On the HTS magnet front, Bi2212 has matured to become a magnet-ready conductor

- 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 dipoles have been wound and await reaction and testing soon
  - Roadmap integrates Bi2212 CCT in a high-field hybrid magnet design

- Nano-spray combustion powder technology

- At 15 T, $J_e$ - 1365 A/mm²
  - twice the target desired by the FCC Nb$_3$Sn strands!

- Bi2212 now exceeds RRP $J_e$ at 11T!

- At 27 T, $J_e$ - 1000 A/mm², adequate for 1.3 GHz NMR.

First test of CLIQ with Bi2212 ongoing now - test results anticipated at MT26! (Dan Davis, ASC/NHMFL/FSU)
Work on REBCO is focused on the development of CORC cable in a CCT configuration - steady progress towards MDP goals

- 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
  - 3-turn C2 has been fabricated and tested; full 40-turn C2 nearly completed - results by MT!
  - C3 magnet design well underway (5T); most of conductor procured

- Note groundbreaking application of REBCO at high field by NHMFL - 45.5T!
  - S. Hahn et al, Nature https://doi.org/10.1038/s41586-019-1293-1

- Today: 220 A/mm² at 21 T, 4.2 K, 30 mm bend radius
- Goal: Minimum $J_e$ at 3.7 mm wire diameter of 540 A/mm² at 21 T, 4.2 K, 15 mm bend radius
Diagnostics are critical for understanding of magnet performance and to provide feedback to magnet design.

Acoustic signatures provide a wealth of data on energy perturbations in magnets.

Wavelet analysis provides robust mathematics platform for transient signal analysis.

Active acoustics can utilize phase-shift of the complex signal response pattern to identify thermal changes in the system => independent mechanism to see transition.


Wavelet analysis provides robust mathematics platform for transient signal analysis.
Novel magnetic measurement and quench antennae designs are providing new and complementary insight into magnet behavior.

- Flexible circuit quench antennae
- Inductive stationary pickup loops
- Diagnostic for determining quench development => Have worked well for quench.

Each PCB has radial bucking of dipole and quadrupole at level of 100

Following idea of T. Ogitsu, et al., “Quench Antennas for Superconducting Particle Accelerator Magnets”

- Simultaneous sampling at 10^-100kHz.
- Quench event detected as field disturbance in all coils
- Longitude quench location found by having multiple sets of MV antennae
- Can locate quench in azimuth and radius (though outer layer quenches difficult) by solving for voltage response of set of probes*

Strong potential for applications:
- Can characterize persistent and eddy current behavior, magnetization effects, decay and snap-back at injection, magnetic field transients from mechanics or flux redistribution (spike) events,

• Flexible circuit quench antennae
• Inductive stationary pickup loops
• Diagnostic for determining quench development => Have worked well for quench.
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
Conductor R&D is a critical component of the US MDP, with very significant advances under development.

- Nb$_3$Sn R&D is proving the material has plenty more to offer
  - APC Nb$_3$Sn using Zr-doping - first demonstration of wire achieving FCC specification
    - X. Xu et al, rXiv:1903.08121
  - Hf-doping - S. Balachandran et al., SUST. 32 (2019) 044006
  - High-Cp doping with Gd$_2$O$_3$ - X. Xu et al, SUST. (2018) vol. 31, No 3

- Bi2212 continues to improve
  - better understanding of what drives higher $J_c$

- REBCO improvements with reduced substrate thickness, Zr pinning
  - Wang et al., SUST (2018) Vol 31, No 4

- Record $J_c$ of ~7,000 A/mm$^2$ at 15 T was achieved by using the new nGimat powder
MDP maintains a ‘living” list of international and industrial collaborations

- MDP provides the strategic framework for HEP high field magnet and conductor R&D in the US
- Leveraging well-organized collaborations is a key component for achieving the MDP goals

- International (9)
  - CERN, EuroCirCol, PSI, KEK

- Other OHEP-funded programs (4)
  - Ohio State, U. Houston, Penn State

- Industry (12) – Includes procurements

- Other (Pending or non-HEP funded) (4)

- SBIR/STTR are important contributors (mainly HEP, but also FES and NP)
Summary

• The US MDP is designed to advance high-field accelerator magnet research
  o Leverages strengths of longstanding programs at the National Laboratories and Universities

• The MDP is fully functioning and working hard to achieve the program goals
  o Management structure is aligned with the mission and goals
  o The teams are steadily integrating - particularly in areas of Technology

• We are balancing our efforts to maintain progress on multiple fronts
  o Nb₃Sn magnet development, currently focused on Cos(t) and CCT
  o HTS magnet development - on both Bi2212 and REBCO fronts
  o Critical technology developments that guide magnets... and are of value to the broader community
  o Conductor R&D - with a roadmap to continue advancing performance

• We have a strong, and growing, list of national and international collaborations