Superconducting Magnet Development for Next-Generation Accelerator Capabilities

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For the US MDP Team

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

• Motivation and background
• The US Magnet Development Program: main goals and roadmaps to achieve them
• Major technical areas being pursued
• Some key technical developments and progress
• Next steps
• Summary
Magnet technology is driving the cost and reach of a future collider

CERN cost estimates*:

- \$magnet$/\$tot

LHC: 57%

HE-LHC:
- 70% (26 TeV; Nb3Sn)
- 77% (33 TeV; HTS)

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* "TOE" talk

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From conductor to magnets

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Barletta
Nb₃Sn accelerator magnet technology is finally being installed in a collider - in the interaction region quadrupoles of the LH-LHC
The “magnet zoo” in colliders are all based on Cos(t) designs, whereas accelerator R&D magnets explore other options

- R&D magnet designs explore layouts that attempt to address issues associated with conductor strain (to avoid degradation) and reduction of conductor/coil motion (to minimize training)

- At high field “managing” stress through judicious force interception will be required
Magnets start with the superconductor: we are about to put Nb$_3$Sn into a collider for the first time, and are investigating the potential of HTS.
The US HEP Superconducting Magnet Programs are now integrated into the US Magnet Development Program

HEPAP Accelerator R&D Subpanel recommendations

**Recommendation 5b.** Form a focused U.S. high-field magnet R&D collaboration that is coordinated with global design studies for a very high-energy proton-proton collider. The over-arching goal is a large improvement in cost-performance.

**Recommendation 5c.** Aggressively pursue the development of Nb$_3$Sn magnets suitable for use in a very high-energy proton-proton collider.

**Recommendation 5d.** Establish and execute a high-temperature superconducting (HTS) material and magnet development plan with appropriate milestones to demonstrate the feasibility of cost-effective accelerator magnets using HTS.

**Recommendation 5e.** Engage industry and manufacturing engineering disciplines to explore techniques to both decrease the touch labor and increase the overall reliability of next-generation superconducting accelerator magnets.

**Recommendation 5f.** Significantly increase funding for superconducting accelerator magnet R&D in order to support aggressive development of new conductor and magnet technologies.
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$_3$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 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$_3$Sn and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.
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 Witherell/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 (“G7”)**
- K. Amm, BNL
- S. Prestemon, S. Gourlay, LBNL
- G. Velev, A. Zlobin, FNAL
- L. Cooley, D. Larbalestier, FSU
The program has well-defined goals, and is structured with technical leads who are responsible for delivery.

### Magnets

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<th>Magnets</th>
<th>Coordinator</th>
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<td>Cosine-theta 4-layer</td>
<td>Sasha Zlobin</td>
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<td>Canted Cosine theta</td>
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<td>Bi2212 dipoles</td>
<td>Tengming Shen</td>
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<td>REBCO dipoles</td>
<td>Xiaorong Wang</td>
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### Technology Area

<table>
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<tr>
<th>Technology Area</th>
<th>LBNL POC</th>
<th>FNAL POC</th>
<th>BNL POC</th>
<th>ASC POC</th>
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<tr>
<td>Modeling and Simulation</td>
<td>Lucas Brouwer</td>
<td>Vadim Kashikhin</td>
<td>Ramesh Gupta</td>
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<tr>
<td>Training and Diagnostics</td>
<td>Maxim Marchevsky</td>
<td>Stoyan Stoynev</td>
<td>Piyush Joshi</td>
<td>TBD</td>
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<tr>
<td>Instrumentation and quench protection</td>
<td>Maxim Marchevsky</td>
<td>Thomas Strauss</td>
<td>Piyush Joshi</td>
<td>Dan Davis</td>
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<tr>
<td>Materials studies — superconductors and structural materials properties</td>
<td>Tengming Shen</td>
<td>Steve Krave</td>
<td>TBD</td>
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**Cond Proc and R&D**  
Lance Cooley
The MDP Nb$_3$Sn magnet efforts continue to progress as outlined in the MDP Plan document, but the evolution will depend on results.

Area I: Nb$_3$Sn magnets

**Design studies**
A Cos(t) 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 that provide some prestress increase during cool down

- Status:
  - Magnet built
  - 1st test completed – world record!
  - Magnet disassembled, inspected
  - Coil support and end design improved
  - Reassembly readiness review completed
  - Magnet re-assembly underway
  - 15T test early next year

Thanks to CERN!
Results of 1\textsuperscript{st} test

- The goal of the 1\textsuperscript{st} test has been achieved
  - graded 4-layer coil design, innovative support structure and magnet fabricated procedure have been tested

**B_{\text{max}} = 14.10\pm0.04 \text{T} – record field at 4.5 K for accelerator magnets!**
Cos-theta has come to fruition – record field! - and subscale CCTs are under development to probe training

- A Cos(θ) design that minimizes midplane stress for highest field
- Leverages advances in Nb₃Sn - HEP-driven conductor development

⇒ Recent record Cos(θ) dipole field - 14T!
Maintaining US leadership - record fields for 20+ years

60-mm aperture, 4-layer graded coil

- Canted Cosine-theta:
  - New concept - high-risk high-reward
  - Introduce “stress management” to scale to higher field
Excellent progress on racetracks
CCT magnets fabricated, awaiting heat treatment
Steady progress on developing magnet technology
First 4-layer CCT underway, but significant conductor needed for next magnet
Connection/synergy with FES/fusion developing well

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

Area II:
HTS magnet technology
HTS accelerator magnets are making steady progress, and continue to exhibit stable performance – no training!

- Nano-spray combustion powder technology
- At 15 T, $J_e - 1365$ A/mm²
  - twice the target desired by the FCC Nb₃Sn strands!
- Bi2212 now exceeds RRP $J_e$ at 11T!
- At 27 T, $J_e - 1000$ A/mm², adequate for 1.3 GHz NMR.

- Bi2212 - multi filamentary round wire
  - At 15 T, $J_e - 1365$ A/mm²
  - Twice the target desired by the FCC Nb₃Sn strands!
  - Bi2212 now exceeds RRP $J_e$ at 11T!

- Bi2212 wire, blind @ 4.2 K, 20 T

- Conductor improvements translate to magnet improvements

- Note groundbreaking application at high field by NHMFL - 45.5T!
  - S. Hahn et al, Nature

- Today: 220 A/mm² at 21 T, 4.2 K, 30 mm bend radius
- Goal: Minimum $J_e$(21 T, 4.2 K) at 3.7 mm wire diam.: 540 A/mm² at 15 mm bend radius

- REBCO - “coated conductor”, tape
Bi-2212 RC7n8, the first 4.7 T dipole: demonstrated no quench training, stable performance => practical magnet engineering possible with HTS wires

Collaboration with NHMFL where OPHT was performed. Graphs by Daniel Davis, Laura Garcia Fajardo, Tengming Shen
We are looking closely at options for future high-field magnet designs that build on current efforts.

**Nb₃Sn design targets**

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 $J_c$ (16T, 4.2K)
- Calculated geometrical field harmonics, coil magnetization and iron saturation effects in magnet straight section at $R_{\text{ref}}=17$ mm for $B=1-16$ 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
We are looking closely at options for future high-field magnet designs that build on current efforts.

First look at Hybrid designs

“Stress-managed Cos(t)”

- Design studies of 16 T dipole with 60-mm aperture is complete
- 120-mm aperture SM coil design is complete
- Large-aperture SM coil technology development has started

Current focus for CCT

- 4-Layer CCT Design with option for insert
  - Target bore dipole field of 12 – 13 T operating at ~ 80 - 85% of short sample to allow for insert coils
  - Bore size of 90 – 120 mm (depends on HTS needs and results of magnet design study)
  - Very conceptual design studies have been to explore very high field scenarios

High-field concept

- LTS coils
- HTS coils in the high field region
SMD: Opportunities for DOE and Industry Return to the MDP program

- Brookhaven has unique capabilities and experience in HTS along with a high field test facility (>10T) for small test coils
- MDP is utilizing this capability to address the technology issues of interest today
  - CORC hybrid magnet quench propagation studies
  - Rapid testing of sample coils at high fields to address/understand coil components impacting quench at high fields in REBCO tape coils and field parallel magnetization measurements
- Studying conductor/coil configurations at high fields – what technology is needed above 20T?
- BNL is fully engaged with the MDP program to develop the roadmap and utilize its capabilities fully in the MDP program
  - Capability to produce magnet designs and prototypes – both conventional SC magnets and direct wind
  - Extensive testing and magnet characterization capability – utilized by NP and NSLS II
- Synergistic with industry interest in capabilities
BNL Nb$_3$Sn Common coil dipole - A Unique Test Facility for MDP

- A Nb$_3$Sn dipole providing a background field up to 10 T
- Large open space: 31 mm wide and 335 mm high
- Cable with large bend radius can be easily accommodated
- Cable can be looped inside the high field region for a long length in-field test
- To be used for HTS magnetization and CORC studies
Four Possible Configurations for Insert Coils and Cable Tests

1. Standard insert coil test configuration
2. One insert coil in one aperture
3. Cable test configuration
4. Two independent insert coils in two aperture
Rapid turn-around, Low-cost Hybrid Tests of R&D HTS Coils (total field: ~15 T)

Five Simple Steps/Components

1. Magnet (dipole) with a large open space
2. Coil for high field testing
3. Slide coil in the magnet
4. Coils become an integral part of the magnet
5. Magnet with new coil(s) ready for testing

Brookhaven is ready to test hybrid racetrack dipoles today at combined fields approaching 15T.
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.

**Area III:**

- 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
Diagnostics are critical for understanding of magnet performance and to provide feedback to magnet design

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

Acoustic signatures provide a wealth of data on energy perturbations in magnets
Novel magnetic measurement and quench antennae designs are providing new and complementary insight into magnet behavior

- **Flexible circuit quench antennae**
  - Inductive stationary pickup loops to detect magnetic transients
  - Diagnostic for determining quench start location and development ⇒ Have worked well for longitudinal localization of quench.

- Pads improved to withstand more heat during soldering

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

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

- Simultaneous sampling at 10-100kHz.
- Quench event detected as field disturbance in all coils
- Longitude quench location found by having multiple sets of MV antennas
- 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, etc.
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

```
Geometry Generation
Meshing
Boundary conditions
Loads
Replace code which builds element matrices: uel.f, uec.f -> compile custom ANSYS.exe

Element customized by defining
- element shape functions
- material properties if complex function desired (T,M,c,etc.)
- formulation
Element matrix generation is now determined by user program
- stiffness, damping, etc.

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

Electromagnetic Regions
- FEM
  - default (in ANSYS)
  - user defined (USER10)
  - conductor areas
  - current plane (IFCC, etc.)
  - quasi-static, current sharing
  - heat prop. (B, temp)
  - coupled with stranded formulation

Thermal Regions
- FEM
  - default (in ANSYS)
  - user defined (USER10)
  - conductor areas
  - quasi-propagation
  - heat prop. (B, temp, quench state)

Brouwer, LBNL; Auchmann, PSI/CERN

I/I_ma

Deviation due to IFCC only
Deviations from AC losses only
1st quench

1st quench

Deviations from AC losses only
Resistance growth, yoke saturation

Plenary presentation PL2-INV given at ISS, 3-5 December 2019, Kyoto, Japan.
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)

- Nb$_3$Sn advances continue to be pushed
  - Advances in understanding of the chemistry of Nb$_3$Sn heat treatment $\Rightarrow$ significant improvement in $J_c$ for small $d_{\text{eff}}$
  - Investigate potential for APC (and other advanced...) 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
There is a path forward for Nb$_3$Sn to higher fields!

• Hf additions to Nb-4Ta provide $<100$ nm Nb$_3$Sn grain size due to additional GB diffusion paths provided by enhanced recrystallization temperature.
  
  o Demonstrated in both ASC monofilaments and Hypertech-Fermilab multifilament conductors for Nb$_3$Sn reaction heat treatments at 625°C-675°C.

  o Enhanced $H_{\text{max}}$ (4.2 K) and unsuppressed $H_{\text{irr}}$ (4.2 K) is verified by Hyper Tech multi-filament conductor

  o Hyper Tech wires with Sn-oxide may provides additional interesting opportunities also.

• Nb-Ta-Hf conductors provide avenues in various architecture types.
  
  o Fine-grain (~50 nm) Nb$_3$Sn by optimization of Hf doping provides a direct avenue to implement the new alloy in RRP, bronze route, and PIT configurations.

  o Additions of oxygen as advanced by Ohio State-Hypertech-Fermilab seems to enhance $H_{\text{max}}$ and are being evaluated in PIT conductor form by them.

So what? Perhaps this opens up not just 16 T dipoles but also more economical 2-layer 14 T dipoles with 50% higher Jc?

- No 16 T dipole made from Nb$_3$Sn has been made
- Is 14 T much easier and capable of low-training quantity production?
- If much improved Nb$_3$Sn could be made would it allow 2-layer technology to be pushed to 15 or even 16 T?

Hf-4Ta filaments are at 100µm. Hf-4Ta total true strain of 10.6.

Multi-filament conductor made by HTRI (without SnO$_2$) in collaboration with Xingchen Xu Fermilab confirms the monofilament result of $H_{\text{max}}$ shift beyond 5 T, $H_{\text{irr}}$ (4.2 K) of 23.5 T.

Collaborative work within the NDF program to provide an SBIR-Fermilab independent validation

David Larbalestier – DOE-OHEP Seminar, August 27, 2019
**Bi-2212 Update: HTS conductors are test magnet ready**

- **Bi-2212** is now a magnet technology well into serious test magnets
  - 2212 conductor fabrication is by far the easiest of any HTS conductor and its present high price is artificial. Powder quality is now high and becoming well understood: large-scale pricing should be close to RRP Nb$_3$Sn, not present day boutique pricing

- The isotropic properties and truly multifilament architecture approximate Nb-Ti and Nb$_3$Sn low loss conductors suitable for magnets with high field quality. High RRR of Ag matrix does not require diffusion barriers that can break during cabling.

- The concerns about HTS magnet quench protection that especially exist with REBCO are very much reduced
  - Both in Rutherford cable dipoles and single-strand insulated solenoids, stable transition to the dissipative state can be used to trigger quench protection

- 50 bar overpressure heat treatment is not trivial but it is not “black magic” either. Compatibility with insulation and conductor strengthening has been demonstrated.
Next steps: focus on quantitative developments that provide lasting benefit to the community to enable high-field magnets

- Real progress in accelerator magnet performance will require improved understanding and control of the many (very many!) design choices, fabrication processes, and operational parameters that go into accelerator magnets
  - The priorities are somewhat different for HTS and for Nb$_3$Sn due to maturity of material as well as material characteristics
    - Nb$_3$Sn: understand and control magnet training and conductor strain,…
    - HTS: develop magnet fabrication processes, develop protection paradigms, understand and control conductor strain and degradation,…
  - Advance the “toolbox” of magnet materials and processes
    - Epoxies, structural materials, interfaces, surface prep. (e.g. eliminate Carbon residue),…
    - Simplified structures, process reproducibility, reduce parameter sensitivity,…
  - Advance the “toolbox” of diagnostics that provide feedback from conductor and magnet performance to magnet design
The US MDP Team at 2019 Collaboration Meeting
Summary

• High field magnet technology is actively progressing in the US
  o The US is playing a critical role in the interaction region quadrupoles for the LHC upgrade project
  o High field magnets are central technical elements, and the primary cost-driver, of a future collider

• DOE-OHEP initiated a national program - US MDP - to maintain leadership in high-field accelerator magnet research
  o Leverages strengths of longstanding programs at the National Laboratories and Universities

• We are balancing our efforts to maintain progress on multiple fronts
  o Significant progress on Nb$_3$Sn magnets
  o HTS magnet development - on both Bi$_2$212 and REBCO fronts
  o Critical technology developments that guide magnets... and are of value to the broader community
  o We have developed a coherent conductor R&D roadmap to continue advancing performance

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