The US Magnet Development Program
Status and Plans

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The HEP community needs advances in superconducting magnet technology to explore new physics realms via colliders

- A strategic whitepaper detailing progress in magnet R&D was submitted
  - 14 “Statements” are highlighted in the document that summarize key points and future goals for our field
  - Complementary strategic whitepapers were submitted describing the European efforts in the field, as well as complementary US initiatives for directed-R&D – see following presentations!

https://arxiv.org/abs/2203.13985
Magnet technology drives the cost and reach of a future collider

Cost/field-strength is the critical metric

Dominant cost drivers for a pp collider: Magnets and tunnel
The “magnet zoo” of design alternatives

• 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)

• Colliders (to-date) all based on Cos(t) designs – efficient

• At high field “managing” stress through judicious force interception will be required
R&D efforts for accelerator magnet technology are becoming more structured

• DOE created the US Magnet Development Program (MDP) in ~2016
• Europe recently formed the High Field Magnet program (HFM)

The programs strive to coordinate efforts to more rapidly advance technology development

The US DOE approach balances long-range R&D and project preparation

http://arxiv.org/abs/2201.07895
Initiated by DOE-OHEP in response to 2013 Snowmass/P5

**Vision**
- Maintain and strengthen US Leadership in high-field accelerator magnet technology for future colliders;
- Further develop and integrate magnet research teams across the partner laboratories and US Universities for maximum value and effectiveness to MDP;
- Identify and nurture cross-cutting / synergistic activities with other programs (e.g. Fusion), to more rapidly advance progress towards our goals.
- Motivate and grow a new generation of magnet experts for future facilities

**Overarching goals:**
- **Explore the performance limits of Nb3Sn accelerator magnets**, with a sharpened 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 Nb3Sn and HTS conductor R&D** with clear targets to increase performance, understand present performance limits, and reduce the cost of accelerator magnets
Major results from MDP on multiple fronts

- Progress on multiple fronts
  - Cos-theta magnet MDPCT1 (FNAL) achieved 14.5T (60mm aperture)!
  - First two 2-layer Nb$_3$Sn Canted-Cos-theta (CCT) magnets (90mm bore) tested
    - Reached 86-88% short-sample; different epoxy => improved training;
  - Steady progress on REBCO CORC™-based magnet technology
  - Significant progress on Bi2212 magnet technology
    - 4.7T common coil => no training!
  - Variety of developments and improvements in diagnostics
  - Important developments in conductor R&D (with industry)
    - Record Nb$_3$Sn via Zr doping; strong promise from Hf alloying
    - “High-Cp” as a means to improve Nb$_3$Sn quench performance
    - Record Bi2212 wire performance
      - Significantly exceeds “FCC spec” at 16T
      - New Bi2212 powder producers – seeded by SBIR
  - And many others...
MDP results and developments prepare for high-field prototypes – stress-managed and hybrid magnets

- MDP Magnet R&D results pave path to stress-managed high-field hybrid HTS/LTS magnets
- Conductor/cable samples
- Diagnostics & materials dev.
  ➞ Fast turn-around, specific experiments

- Subscale / HTS insert magnets
  ➞ Critical to develop magnet technology

- Full size R&D magnets
  ➞ Final demonstration of MDP deliverables

Cryo-Field-programmable gate array
Plastic optical fiber
Development of advanced epoxies with US industry
CTD 701X After 10 Thermal Cycles
CTD 101X After 10 Thermal Cycles
Subscale CCT with new flexible quench antenna

Open Scientific Reports
Stable, predictable and training-free operation of superconducting Bi-2212 Rutherford cable racetrack coils at the wire current density of 1000 A/mm²

Aluminum bronze mandrel
Iron pad
Bladder
Nb,Sn conductor
Horizontal key
Vertical key
Iron yoke
Aluminum cylinder
Program roadmap for the 2020-2024 period

• Strategic directions for the (2020) updated plan:
  o Probing stress management structures
  o Hybrid HTS/LTS designs
  o Understanding and impacting the disturbance-spectrum
  o Advancing both LTS and HTS conductors, optimized for HEP applications

We also introduced a new technology element

20T Hybrid Magnet Design & Comparative Analysis,

=> designed to prepare for future milestones and directions
Ten-year roadmap

- A 10-year high-level roadmap recognizes this Snowmass process and possible program adjustments

- Significant synergies with other programs
  - NHMFL development of high field solenoid technologies
  - Fusion development of high-field HTS-based Tokamaks
  - The DOE HEP and FES offices are investing now in a High Field Cable Test Facility
  - We are working with DOE’s ARDAP to identify means to strengthen US industrial/laboratory ecosystem in superconductors and magnets

- MDP can provide critical developments for many of the HEP science applications advocated at Snowmass – but will require enhanced funding
Progress in magnet technology is critical to enable future colliders, and is currently resource-limited

• MDP is a mature, effective multi-lab program – Limited by funding resources!
  o Strong oversight by independent experts
    • Technical Advisory Committee (2-3 times / year):
      – A.J. Lankford (Chair); G. Apollinari, A. Ballarino, J. Minervini, M. Palmer, A. Yamamoto/T. Ogitsu
    • Steering Council (~1 / year):
      – H. Wheerts (Chair); T. Raubenheimer, + Lab Directors (or delegates)

• Reviewed by DOE-OHEP in December 2019
  o A.J. Lankford (UCI), Chair; Ruben Fair (Jefferson Lab); Pierre Vedrine (CEA-Saclay)

Comments: Effectiveness in implementing a prioritized and optimized program: MDP management has been effective in establishing a successful R&D program. It has also been effective in implementing its strategic plan, as demonstrated by the important accomplishments in each of its thrust areas.
Summary: A strong magnet R&D program is essential to deliver on HEP science facility needs

MDP focuses on "generic" magnet R&D that builds the foundations for Particle Physics applications
- Strong modeling and analysis developments – leverage HPC, AI/ML
- Strong diagnostics developments – insight into magnet performance, protection, control
- Development of core magnet technologies – materials, processes, testing
- Development of superconductors – performance, scalability and cost
- And most critically => development of the next generation of magnet experts for the community!

MDP can be effectively complemented by directed R&D when the time is right - i.e. a potential project is on the horizon

A long-range magnet R&D program, designed to advance magnet technology while fully leveraging the broader community’s strengths, is vital to HEP and the future of particle physics.