The US Magnet Development Program - Preparing for the Next Generation Colliders

Kathleen Amm, Lance Cooley, Steve Gourlay, David Larbalestier,
Soren Prestemon, Gueorgui Velev, Alexander Zlobin

I. Introduction

Today's colliders are built on a foundation of superconducting magnet technology that provides strong dipole magnets to maintain the beam orbit and strong focusing magnets to enable the extraordinary luminosities required to probe physics at the energy frontier. The dipole magnet strength plays a critical role in dictating the energy reach of a collider [1], and the superconducting magnets are arguably the dominant cost driver for today's collider facilities. As the community considers opportunities to explore new energy frontiers, the importance of advanced magnet technology – both in terms of magnet performance and in the magnet technology's scalability for cost reduction – is evident, as the technology status is essential for informed decisions on targets for physics reach and facility feasibility.

II. The US Magnet Development Program Vision and Goals

The US Magnet Development Program (MDP) is a national research program sponsored by the Department of Energy's Office of High Energy Physics, focused on developing the next generation of superconducting accelerator magnet technologies for future colliders. The MDP's vision is summarized in the following elements:

- 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.

By pulling together long-standing research groups from Lawrence Berkeley National Laboratory, Fermi National Laboratory, the Applied Superconductivity Center of the National High Magnetic Field Laboratory, and most recently from Brookhaven National Laboratory, the MDP harnesses long-standing experience, expertise, and facilities for the DOE-OHEP. These groups have significant experience with both low- and high-temperature superconductors (LTS and HTS) (see for examples [2]–[12]). To advance superconducting accelerator magnet technology as effectively as possible, the MDP focuses on the following overarching goals:

- Explore the performance limits of Nb_3Sn 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 Nb_3Sn and HTS conductor R&D with clear targets to increase performance, understand present performance limits, and reduce the cost of accelerator magnets

These goals provide a balanced approach, simultaneously advancing the current state-of-the-art Nb_3Sn magnet technology while developing and exploring the still nascent HTS accelerator magnet arena. Central to MDP's mission is a focus on understanding magnet performance through the development of improved modeling, diagnostics, and data analysis that provide critical feedback to magnet design. At the core of superconducting magnet technology is the conductor itself - the MDP builds on a legacy of HEP-driven conductor development performed in close coordination with industry; following the successful paradigm of HEP's original Conductor Development Program [13], the program continues to nurture conductor development by supporting, and closely coordinating the yearly MDP Collaboration meetings with, the yearly Low Temperature Superconductor Workshop (LTSW).

III. Importance of a general R&D program

Innovative research programs such as the MDP, focused on developing technology aligned with HEP's mission but operating with sufficient freedom to explore technology routes without direct application motivation, are critical to enable research focused on fundamental understanding that can lead to long-range breakthroughs in the field. We strongly advocate for the strategic and highly successful technology development paradigm used by HEP, wherein long-rage general R&D programs are supported and maintained and, when a future project appears on the horizon, a directed-R&D program is initiated that leverages the current state-of-the-art from the generic program and brings the technology to a state of readiness for the initiation of a DOE project. An excellent example is the LHC Accelerator Research Program (LARP), initiated in 2003 to ready accelerator technologies for a possible luminosity upgrade of the LHC; the US's contribution to the latter, predominantly focused on Nb_3Sn magnet technology developed by the US research programs, formally became a project in 2016. Balancing generic R&D, directed R&D, and project portfolios is critical for HEP's continued, and long-term, success.

IV. - Value to the broader HEP community and International context

The fundamental nature of the MDP R&D, together with its culture of collaboration and outreach to the broader superconducting magnet community, make the MDP program's research of significant value to other areas of the HEP community. Examples include synergies with developments for detector magnets, magnets for Axion searches, and advanced magnets for potential future muon colliders. In addition, advances in diagnostics, modeling, and analysis have cross-connects with other areas of HEP. One highly relevant example is ongoing research into "cold cryogenics"; early work in MDP focused on analog to digital conversion at cryogenic temperature has found commonality in Physics programs interested in cold electronics for detectors and integrated circuits such as CMOS.

The importance of superconducting magnet technology to the future of High Energy Physics, and the scale and cost of the R&D required to prepare for a future collider - which will undoubtedly be of international-scale - makes the MDP intrinsically part of an international endeavor to advance the field. With the recent completion of the European Strategy Update for Particle Physics [14] and its strong advocacy for enhanced research to advance magnet technology, there is an excellent opportunity for MDP to further engage with international collaborators to more rapidly advance on its goals for the benefit of the HEP community.

In addition to specific technical contributions and value to the broader community, the MDP also serves as an incubator for the next generation of magnet scientists for HEP. Staff from MDP routinely serve as Instructors for courses on superconducting materials and superconducting magnets at the US Particle Accelerator School, and the MDP is highly sought after by postdoc and early career scientists due to the dynamic and highly innovative culture and research it fosters. The coexistence of a longe range R&D program such as the MDP alongside a directed R&D or large-scale project such as the current HL-LHC AUP furthermore provides the latter access to unique and invaluable expertise and resources to mitigate issues should they arise.

Our Whitepaper will expand on the MDP near and long term vision for superconducting accelerator magnet R&D in the US, highlight our strategy to align with the outcome of the current Snowmass community planning exercise and the DOE-HEP Physics Prioritization ("P5") process that is anticipated to follow, and discuss opportunities for enhanced collaborations with the international community.

References

[1] *William Barletta, Marco Battaglia, Markus Klute, Michelangelo Mangano, Soren Prestemon, Lucio Rossi, and Peter Skands. Future hadron colliders: From physics perspectives to technology R&D.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 764:352 – 368, 2014.*

[2] *Daniel Schoerling and Alexander V. Zlobin, editors.* Nb_3Sn Accelerator Magnets : Designs, Technologies and Performance. *Springer Nature, 2019.*

[3] *S.A. Gourlay. Superconducting accelerator magnet technology in the 21st century: A new paradigm on the horizon?* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 893:124 – 137, 2018.*

[4] *A. V. Zlobin, I. Novitski, E. Barzi, V. V. Kashikhin, J. Carmichael, S. Caspi, G. Chlachidze, S. Krave, C. Orozco, D. Schoerling, S. Stoynev, D. Tommasini, and D. Turrioni. Development and first test of the* $15T$ *Nb_3Sn Dipole Demonstrator MDPCT1.* IEEE Transactions on Applied Superconductivity*, 30(4):1–5, 2020.*

[5] *Xiaorong Wang, Stephen Gourlay, and Soren Prestemon. Dipole Magnets above 20 Tesla: Research Needs for a Path via High-Temperature Superconducting REBCO Conductors.* Instruments*, 3:62, 11 2019.*

[6] *Tengming Shen and Laura Garcia Fajardo. Superconducting Accelerator Magnets Based on High-Temperature Superconducting Bi-2212 Round Wires.* Instruments*, 4(2):17, 2020.*

[7] *R. Gupta, K. Amm, M. Anerella, J. Cozzolino, P. Joshi, S. Joshi, S. Plate, W. Sampson, and P. Wanderer. New approach and test facility for high-field accelerator magnets R&D.* IEEE Transactions on Applied Superconductivity*, 30(4):1–6, 2020.*

[8] *Seungyong Hahn, Kwanglok Kim, Kwangmin Kim, Xinbo Hu, Thomas Painter, Iain Dixon, Seokho Kim, Kabindra R. Bhattarai, So Noguchi, Jan Jaroszynski, and David C. Larbalestier.* 45.5*-tesla direct-current magnetic field generated with a high-temperature superconducting magnet.* Nature*, 570(7762):496–499, 2019.*

[9] *Shreyas Balachandran, Chiara Tarantini, Peter J Lee, Fumitake Kametani, Yi-Feng Su, Benjamin Walker, William L Starch, and David C Larbalestier. Beneficial influence of Hf and Zr additions to Nb4at%Ta on the vortex pinning of Nb_3Sn with and without an o source.* Superconductor Science and Technology*, 32(4):044006, feb 2019.*

[10] *J. Jiang, Griffin Bradford, S. Hossain, M. Brown, J. Cooper, E. Miller, Y. Huang, H. Miao, J. Parrell, M. White, A. Hunt, S. Sengupta, Rao Revur, Tengming Shen, F. Kametani, U. Trociewitz, E. Hellstrom, and D. Larbalestier. High-performance Bi-2212 round wires made with recent powders.* IEEE Transactions on Applied Superconductivity*, 29:1–5, 2019.*

[11] *Tengming Shen, Ernesto Bosque, Daniel Davis, Jianyi Jiang, Marvis White, Kai Zhang, Hugh Higley, Marcos Turqueti, Yibing Huang, Hanping Miao, Ulf Trociewitz, Eric Hellstrom, Jeffrey Parrell, Andrew Hunt, Stephen Gourlay, Soren Prestemon, and David Larbalestier. Stable, predictable and training-free operation of superconducting Bi-2212 Rutherford cable racetrack coils at the wire current density of 1000 A/mm2.* Scientific Reports*, 9(1):10170, 2019.*

[12] *Xingchen Xu. A review and prospects for Nb_3Sn superconductor development.* Superconductor Science and Technology*, 30(9):093001, aug 2017.*

[13] *R. M. Scanlan and D. R. Dietderich. Progress and plans for the U.S. HEP conductor development program.* IEEE Transactions on Applied Superconductivity*, 13(2):1536–1541, 2003.*

[14] *European strategy update for particle physics. 2020. https://home.cern/sites/home.web.cern.ch/files/2020-06/2020\%20Update\%20European\%20Strategy.pdfm.*