US MDP Vision, Goals, and Structure

2024 update

***Version 1 - Oct. 21, 2024 - Soren Prestemon***

## Vision:

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

## Goals:

* Explore and define the performance limits of superconducting accelerator magnets
* Develop, understand and demonstrate high field HTS magnet technology
* Investigate and understand the fundamental science of magnet design and performance
* Pursue conductor R&D with appropriate properties that enable our accelerator magnet goals
* Support the development of advanced workforce for superconducting magnet technology

Furthermore, MDP serves the mission to:

* Integrate the teams across the partner laboratories and Universities for maximum value and effectiveness to the program
* Identify and nurture HEP and cross-cutting / synergistic activities and opportunities with other programs to more rapidly advance progress towards our common goals.

## Program Structure - Synopsis of Areas and sub-Areas:



### Area I: Hybrid Accelerator Magnets

Using HTS-based dipoles in the bore of a Nb3Sn dipole magnet is the most cost-effective means of probing HTS accelerator magnet technology tot higher fields. To-date, MDP has focused on developing the core elements of a hybrid magnet: a) stress-managed Nb3Sn magnet technology, enabling large bore, high field dipoles, exemplified by the SMCT and CCT designs; and b) HTS accelerator magnet technology with REBCO and Bi2212 cables. Our goal now is to integrate these - up until now separate - thrusts in working hybrid accelerator magnets; Thus we have a twofold ambition - to bring the LTS SMCT and CCT magnets to fruition - they serve both as outstanding demonstrators of 12-14T large bore dipoles of relevance to applications such as a muon collider, as well as workhorse magnets to develop and demonstrate hybrid magnet technology - and to further advance HTS accelerator magnet technology in high magnetic field.

#### Near term challenges:

* Develop and test magnet protection of HTS magnets in a hybrid HTS/LTS configuration
* …

#### Sub-area I.a: Nb3Sn Stress-Managed Large Bore magnets

The development of stress managed large bore magnets is central to MDPs mission. The large bore challenges conventional cos-theta magnet designs at high field, and hence is an excellent proving ground for the concept of stress-management. Successful demonstration of reliable large-bore ≧120 mm) dipole operation in the 12-14T range, without exhibiting degradation due to strain and operational cycling, is a major milestone for the program. Furthermore, the demonstration will serve as a critical gate for a Muon collider, where high field, large bore dipoles are required to achieve high luminosity while supporting significant radiation shielding in the bore. Finally, the large bore dipoles will serve as workhorse magnets for the hybrid magnet program, enabling development and testing of HTS dipoles in high magnetic field.

#### Near term challenges:

* Demonstrate large bore dipoles in the 12-14T range with reliable performance under power and thermal cycling
* …

#### Sub-area I.b: Bi2212 insert dipoles

The DOE-OHEP has invested significantly in Bi2212, an isotropic, round-wire conductor with built-in current sharing, over the last decade. Bi2212 performance continues to evolve based on deeper understanding of the conductors, which has encouraged and enabled new powder suppliers and wire manufacturers to appear. The accelerator dipole technology has advanced, with multiple magnets demonstrating overcoming of key challenges, e.g. insulation, overall Jc, over-pressure reaction, etc. that encourage advance to the next stages. MDP is poised to perform the first hybrid test using a Bi2212 insert in a 90mm bore Nb3Sn magnet, and coils have been fabricated in preparation for testing in the flagship 12-14T, 120mm bore dipoles currently under development. The program will now focus on the development and testing of Bi2212 dipoles in high-field, where challenges of quench protection and strain management will need to be addressed.

#### Near term challenges:

* Resolve the leakage issue that plagues Bi2212 Rutherford cables
* Commissioning of the large furnace
* Arresting the recent degradation of Jc from BOST wire using EnGimat powder
* …

#### Sub-area I.c: REBCO insert dipoles

The superconductor REBCO has unique challenges but also the highest field and temperature capability which offer strong opportunities for HEP applications. The tape architecture, combined with the intrinsic superconducting and mechanical anisotropy of the material, introduces unique challenges for both magnet design and manufacture as well as for magnet protection. The opportunity, however, is tremendous due to the strong pull currently underway from the fusion community, where the promise of high-field, compact fusion devices is fueling extraordinary investments in REBCO conductor development. Our future program will leverage recent MDP developments to focus on cable and magnet design architectures that are compatible with insert magnet geometry constraints while probing REBCO dipole magnet operation in high-fields; of particular focus is addressing potential strain degradation induced during magnet fabrication and/or magnet operation, and developing and demonstrating reliable magnet protection / quench mitigation strategies.

#### Near term challenges:

* Develop a consistent model for predicting short-sample in REBCO cable configurations
* Map design limitations for REBCO conductors in accelerator magnet configurations
* …

### Area II: High Field Solenoids for HEP

The high energy physics community has identified a number of opportunities for new physics that exploit colliders and experiments that require advanced high field solenoids - prime examples include a muon collider and various Axion search experiments. Major advances in high field solenoids over the last decade have been led by the National High Magnetic Field Laboratory, motivated primarily by the provision of >30 T magnets for NHMFL users, culminating in the all-superconducting hybrid LTS/REBCO 32 T magnet. Bruker BioSpin have now sold about 10 28 T/1.2 GHz Nuclear Magnetic Resonance magnets based on similar LTS/REBCO hybrid design. The 2023 P5 report, coupled with the 2024 NAS report, motivate a strong partnering between MDP and the NHMFL to further advance high field solenoid technology tailored to the needs of HEP. This is a new Area within MDP, and the goal is to leverage synergies with the NHMFL and Fusion applications to rapidly develop solenoid technologies tailored to HEP needs.

#### Near term challenges:

* Identify experiments that can have the most impact on HEP Solenoid design and performance while leveraging existing capabilities at the NHMFL
* …

#### Sub-area II.a: Cable and Coil Development and Testing

A unique characteristic of HEP applications utilizing solenoids is the diversity of scale of their usage; for muon colliders, solenoid needs range from a few unique, very large bore, high field solenoids for the muon production area, to a kilometer-scale suite of high-field solenoids for the muon-cooling section of the collider. For Axion searches, a range of field strength and bore sizes are of interest, but generally the search sensitivity scales linearly with field volume and quadratically with field strength, motivating large bore, high field solenoids (we note that some Axion search concepts utilize dipoles, with similar field and bore scaling). Together, these applications motivate the use of scalable conductor architectures, allowing magnet designers to tailor the inductance to optimally address powering and protection considerations in light of the extraordinary amount of magnetic stored energy in the systems. Although scalable conductor architectures are routinely used in the large solenoids of collider detectors, they have not been incorporated in high field NMR, with the (perhaps unique) exception of cable-in-conduit conductor (CICC) usage in the Series-Connected Hybrid magnet currently in operation at the NHMFL. Such architectures are, however, under development by the nascent - but rapidly developing - compact fusion community. We intend to focus MDP’s first experimental efforts in the solenoid field in exploring and developing cable architectures - primarily using HTS materials - in a high-field solenoid background. Major goals are to determine performance boundaries and to develop protection methodologies that can be scaled.

#### Near term challenges:

* Explore cable behavior in solenoid configurations
* …

#### Sub-area II.b: Magnet Designs

 The unique characteristics of HEP solenoid needs, and in particular the likely use of scalable conductor architectures, motivate a review and adaptation of solenoid magnet design with respect to the high-field solenoid designs that are characteristic of high-field users, e.g. condensed matter science. Managing the large hoop, radial, and axial stresses in a reliable and cost-effective manner, and designing magnet protection methodologies that are compatible with the scale of field and volume envisioned, are significant challenges that require in depth design and analysis work. Due to the scale of the magnets envisioned, building demonstrations of such magnets is beyond the budget constraints of MDP; this is an area where synergies with other programs may be enabling. What is within MDP capabilities is to build high stress, high field demonstrators that take HTS conductors, still very primitive and evolving rapidly, into domains of field and stress of interest to future HEP uses, so as to identify and retire “unknown Unknown” risks and to set up project driven prototypes.

####  Near term challenges:

* Explore the design limitations unique to cable architectures in solenoid configurations
* …

### Area III: Supporting Technologies

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#### Lasting progress and advances in magnet technology rely on a solid foundation of experimental data coupled with analysis and modeling that together demonstrate an understanding of performance and that can guide the next stage of developments. To provide focus and alignment with MDP goals, four technology arenas have been identified that are critical to support the advance of magnet technology.

#### Sub-area III.a: Advanced Modeling

#### The ability to accurately predict magnet performance using modeling techniques is an essential ingredient to demonstrate understanding of the physics and engineering that drive the performance. Most importantly, the models can guide further magnet technology advances, and support the development of design and fabrication specifications and tolerances for applications. Due to the complex interplay between mechanical, electromagnetic, and thermal phenomena, and to the vast range of physical scales involved, a variety of advanced modeling techniques are needed that incorporate multi-physics and that can communicate between each other. To the degree possible, we strive for open-source models to allow broad community usage and to encourage further improvements from collaborators.

####  Near term challenges:

* Can we predict current sharing in REBCO cables?
* Can we model degradation mechanisms in magnets?
* …

#### Sub-area III.b: Magnet Diagnostics and Protection

#### Diagnostics and instrumentation serve as the basis for all magnet performance information obtained during magnet fabrication and testing, and are central to the MDP mission. Coupled with advanced models, the experimental data obtained from diagnostics inform our understanding of magnet performance and guide technology improvements. Furthermore, instrumentation is essential for magnet protection, identifying quench initiation and hence initiating critical magnet protection processes. As HTS accelerator magnet technology matures, we expect magnet diagnostics and instrumentation to be an essential part of the magnet design, fabrication, and testing. To-date there is no indication of positive training of HTS magnets via sequential quenching, but there are numerous ways in which HTS magnets can be damaged due to thermal excursions and/or mechanical strains. Magnet diagnostics can serve to identify safe operational regimes and/or quench precursors to avoid damage.

####  Near term challenges:

* Under what conditions can we safely protect HTS magnets?
* …

#### Sub-area III.c: Performance Analysis and Enhancement

#### Data from magnet testing is providing an ever-expand ing foundation for analyzing performance correlations as a function of a wide range of factors, including design parameters and coil and magnet training history. Systematically analyzing this data, along with identifying and conducting specific test campaigns to explore causal connections, can yield deeper insights into the factors driving magnet performance and guide future magnet development. Small-scale experiments and targeted developments have the potential to gradually enhance our understanding of key phenomena and aid in building and validating computer models of magnet behavior. These experiments, combined with new techniques and approaches, will lead to faster and more sustainable progress in magnet performance for both LTS and HTS. The cumulative impact of these efforts shapes a sub-area that is closely linked to many other sub-areas, with bidirectional information flow being crucial for advancements across all fields.

#### Near term challenges:

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#### Sub-area III.d: Materials and Conductors

#### All superconductors beyond Nb-Ti are strain sensitive and brittle in nature; in the case of Nb3Sn and Bi2212, the conductors are subjected to complex heat-treatments to form the superconducting compounds, and in most cases for accelerator magnets the heat treatments are performed after the coil is wound (i.e. “wind and react”) due to the strain sensitivity of the superconductor after heat treatment. To advance accelerator magnet technology, it is essential that we have a thorough understanding of the material properties at all stages of the fabrication process, and that associated magnet materials be selected and applied in a manner that optimizes magnet performance. Developing a robust database of materials properties and a process for materials selection and usage is a critical element of MDP.

#### Near term challenges:

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### Area IV: Exploratory Studies

#### The 2023 HEP P5 report identified a number of potential collider opportunities over the coming decades that will require advanced accelerator magnet technology to come to fruition. The facilities envisioned are of an extraordinary scale that will require international collaboration beyond the current level and the support from the broader public across many nations. Sustainability – both in the facility construction and in its long-term operation – will be an essential ingredient in getting humanity behind such an endeavor. To optimally prepare for such colliders, it is imperative that we collaborate closely with the accelerator design initiatives and identify the magnet advances that provide optimal value to the accelerator performance. Tradeoffs between field, field quality, aperture, operating temperature, magnet cost, and operational power requirements, for example, are an essential part of future facility design.

#### Near term challenges:

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#### Sub-Area IV.a: Higher Temperature / All HTS and Sustainability

Superconductors enable modern colliders by providing the beam’s guiding magnetic field without energy loss, i.e. the magnetic field is effectively stored potential energy. Nevertheless, there is energy consumed in the refrigeration power needed to keep the magnets at their operating temperature. The thermodynamic optimal, Carnot efficiency, scales with Qc~Twarm/Tcold, e.g. increasing the operating temperature from 1.9K to 4.2K results in more than a factor 2 reduction in wall-plug power. Operating at 20K would improve Carnot efficiency by a further factor of nearly 5. However, operating at higher temperature limits superconductor options, and comes at a cost of more superconductor due to the Jc(T) dependence. Furthermore, there are complex interrelations, for example related to superconductor magnetization and magnet protection, that can impact the viability of operation at higher temperature. Understanding the field and temperature limitations of each superconductor and associated accelerator magnet technology and the potential implications for collider sustainability is a critical role for MDP.

####  Near term challenges:

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#### Sub-Area IV.b: Interaction Region and Combined Function Magnets

#### While the focus of future collider magnet technology is typically on the ring dipoles due to their dominance in the overall facility cost and performance, there are additional accelerator magnets that drive collider performance, most noticeably the quadrupoles in the detector interaction region that maximize the luminosity of the collider. Advances in accelerator magnet technology can – and must - support the unique challenges of these magnets. Furthermore, innovative magnet designs, such as combined-function magnets that enable unique lattice opportunities, may allow for further collider design paradigms that yield overall improvements in physics capabilities.

#### Near term challenges:

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#### Sub-Area IV.c: Interfacing with Collider Studies

#### Based on the 2023 HEP P5 report, we anticipate the formation of collider design group(s) within the next 2-3 years, and it is essential that there be close collaboration and communication between those groups and MDP. Identifying the primary limitations on magnet performance, e.g. through guidance on achievable fields, field quality, operating parameters, etc. will be important contributions from MDP to enable credible collider designs. Furthermore, close communication can guide MDP developments on those elements of magnet advances that have most impact on collider performance, and/or that address the largest risks in collider operations.

Near term challenges:

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### Facilities Improvements

#### A suite of state-of-the-art test facilities are needed to enable the magnet tests associated with the Magnet Development Program described above. In particular, the ability to test hybrid magnets, i.e. separately-powered outsert and insert magnets, each with their own unique quench detection, power switching, and energy extraction capabilities are essential. Furthermore, the advanced magnet diagnostics and instrumentation require unique data acquisition capabilities, and the test facilities must evolve in concert with the MDP technology developments. Identifying new enabling technologies, best practices for implementation, and sharing magnet test experience and data is critical to the MDP mission.

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### Conductor Procurement and Research and Development (CPRD)

#### The Magnet Development Program requires access to state-of-the-art superconductors to enable rapid and successive development and testing of accelerator magnets. Furthermore, superconductor performance drives accelerator magnet performance, motivating continued feedback from MDP to the superconductor industry to enable conductor advances that benefit HEP. The mission of CPRD is therefore a) to identify future MDP magnet conductor needs and to procure the requisite conductor in a timely manner, and b) to work with industry to identify possible research opportunities that may lead to significant advances in superconductor performance. The research investments should complement existing funding opportunities such as SBIR, and should support the competitiveness of the US superconductor industry.

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## Appendix A

Draft 1, Oct. 21, 2024

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| **Table of Coordinators**  |
| Area | Sub-Area | Coordinator |
| I: Hybrid Accelerator Magnets | I.a: Nb3Sn Stress-Managed Large Bore magnets | S. Zlobin & D. Arbelaez |
| I.b: Bi2212 insert dipoles | T. Shen |
| I.c: REBCO insert dipoles | V. Kashikhin |
| I.d: Hybrid magnet integration | P. Ferracin |
| II: High Field Solenoids for HEP | II.a: Cable and Coil Development and Testing | D. Davis |
| II.b: Magnet Designs | J. L. Rudeiros, K. Badgley |
| III: Supporting Technologies | III.a: Advanced Modeling | G. Vallone |
| III.b: Magnet Diagnostics and Protection | M. Marchevsky |
| III.c: Performance Analysis and Enhancement | S. Stoynev |
| III.d: Materials and Conductors | S. Krave & X. Xu |
| IV: Exploratory Studies | IV.a: Higher Temperature / All HTS and Sustainability | L. Cooley, X. Wang |
|  | IV.b: Interaction Region and Combined Function Magnets | G. Ambrosio [TBD] |
|  | IV.c: Interfacing with Collider Studies | M. Palmer |
| **Critical support** |
| Facilities Improvements | R. Teyber, P. Joshi, S. Stoynev, D. Davis |
| Conductor Procurement and R&D | I. Pong |