High-Field Magnets for the Future of Particle Physics (DRAFT)

Accelerator Frontier: S. Gourlay, V. Shiltsev, D. Stratakis (Fermilab)
Cosmic Frontier: A. Chou (Fermilab)
Energy Frontier: S. Jindariani (Fermilab), P. Meade (Stony Brook University)
Precision Frontier: R. Bernstein, K. Lynch (Fermilab), B. Echenard (Caltech)

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1 Introduction

The Snowmass 2021 process identified key questions of particle physics and future facilities to address them [1]. The questions include detailed understanding of the mechanism for electroweak symmetry breaking, searches for the origin of Dark Matter, and probing new physics via both higher energy and better precision. Addressing these questions requires an aggressive and vigorous accelerator and detector technology R&D, stretching across multiple frontiers. In such an R&D program, synergies should be explored where possible in order to maximize the returns on investment. During Snowmass, development of large bore, high-field solenoidal magnets was identified as the key area of technological development that would enable future programs at the energy, precision, and cosmic frontiers. Specifically, future searches for Axion Dark Matter, Charged Lepton Flavor Violation, beam dump experiments, and the proposed Muon Collider facility all require large volume magnets, in some cases achieving fields in excess of 10 Tesla and operating in a high-radiation environment. The U.S. HEP community has long-standing interests in the above physics topics and during Snowmass expressed strong support for maintaining US leadership in neutrino and cosmic frontiers, while conducting R&D and building up the technology for the next generation of CLFV experiments and a high-energy Muon Collider at Fermilab in the post LBNF/DUNE era, a vision well aligned with the recently released P5 report [2]. This ambitious research plan provides motivation for evolution of the Fermilab's accelerator complex and will enable a multifaceted research program that would attract a large community of users from multiple frontiers. However, it requires, amongst other things, a mature technology for high field magnets on the timescale of approximately 10 years. The importance of superconducting high field magnet R&D was also emphasized in the P5 report, quotes from which are provided below:

- "Superconducting high field magnet R&D is essential to future proton (FCC-hh) and muon collider options; timely execution of magnet R&D would leverage expertise becoming available with the completion of the HL-LHC Accelerator Upgrade Project."
- "Development of technologies under accelerator R&D are essential to this effort, including superconducting magnets at higher field crucial to both future proton (FCC-hh) and muon colliders, and high temperature superconductors suitable for high field and temperature."

The combination of strong magnet expertise and facilities available at DOE national laboratories put the U.S. in a unique position to lead the development. In this letter we present the need for solenoids based on High Temperature Superconductor (HTS) and advocate for establishing a vigorous magnet R&D program with the goal to develop magnets with specific physics goals and targets in mind.

2 High Energy Physics Applications

2.1 Muon Collider

A multi-TeV muon collider provides a spectacular opportunity in the direct exploration of the energy frontier. Offering a combination of unprecedented energy collisions in a comparatively clean leptonic environment, a high energy muon collider has the unique potential to provide both precision measurements and the highest energy reach in one machine that cannot be paralleled by any currently available technology. However, technological and engineering challenges exist in many aspects of the design and significant R&D is necessary to make further design progress. In particular, high field magnets are prominently present in several muon collider sub-systems. In the baseline design, an intense beam of protons is smashed into a target and muons are produced in decays of pions and kaons originating at the target. A large-bore ($R = 120$ cm) HTS solenoid with 15 Tesla field is used to capture the mesons with high efficiency, which is necessary to achieve the collider luminosity goals. Additional complication of the production solenoid is that it will be exposed to high radiation doses and large beam energy depositions. Once muons are produced, the 6D emittance of the beam needs to be reduced by several orders of magnitude using the ionization cooling approach. In this approach, the beam is pushed through a sequence of cooling cells, each consisting of absorbers and RF cavities, both located either inside or near solenoidal magnets. It is estimated that more than 1000 solenoids are needed for the 6D cooling channel. These solenoids have varying aperture and strength. They start at 2 T ($R = 40$ cm) in the early cooling stages but are exceeding 15 T ($R = 5$ cm) in the later stages. Furthermore, the very last step of the cooling scheme (final cooling) relies on the emittance exchange process and requires nearly a dozen of 30-50 T solenoids, albeit with small bore ($R = 2.5$ cm) . Finally, high field dipoles and quadrupoles are needed in the final acceleration and the collider rings of the muon collider to achieve energy and luminosity goals of this machine. Plans to construct and operate various demonstration facilities call for significant advancements in the magnet technology over the next 5–10 years. For example, understanding the engineering feasibility of a cooling channel will require a multi-Tesla solenoidal magnet for a single cell prototype by the end of this decade. Moreover, a larger number of magnets for the full-scale demonstrator system is envisioned in the 2030s. It is evident that realization of a future muon collider relies critically upon availability of HTS magnets and the muon collider community calls for an effort to develop the technology in synergy and close coordination with other areas of HEP requiring similar magnet technology.

2.2 Axion Dark Matter Searches

The QCD axion is one of the most strongly-motivated candidates for dark matter, with the Peccei-Quinn axion model explaining the mysterious vanishing of the neutron electric dipole moment while simultaneously providing a cosmological origin story for the dark matter. Direct detection experiments searching for axion dark matter use a strong magnetic field as the scattering target, with large volume, high field magnets needed to intercept as much of the galactic dark matter flux as possible. By deploying state-of-the-art quantum sensors, the present generation of axion experiments has recently reached sensitivity to the tiny axion-photon coupling strengths predicted by the model – a tremendous accomplishment that was highlighted as motivation for the U.S. National Quantum Initiative. However the signal rates are still too low; using the small commercial Nb-Ti magnets available today, these slow radio scan searches are projected to take more than 10,000 years to cover the axion model parameter space. Larger and higher field magnets are desperately needed in order to be able to conduct a comprehensive search over the entire range of possible dark matter masses predicted by theory and to discover the axion!

For example, a 20 T, 2.4 m bore magnet similar to that envisioned for the production solenoid of the muon collider would provide a factor of greater than 400 - 20,000 speed-up in the signal frequency scan rate. While higher field strengths increase the scattering event rates for axions of any mass, larger magnet bores are especially important for lower mass axion searches as the bore size acts as a spatial high pass filter which suppresses longer wavelength signals. Combined with further advances in quantum sensing, high-field, large bore magnets would enable future axion search experiments to cover significant portions of axion parameter space and be completed on the time scale commensurate with a graduate student PhD program.

Given the long R&D time for the HTS cable and furthermore the 10-year construction time of magnets of this class, the community needs to begin the long range planning for large magnet user facilities that could host a collection of axion experiments to conduct simultaneous searches in complementary frequency bands. A coordinated experimental effort would make use of these magnet facilities to provide comprehensive coverage of the entire axion model parameter space in the initial search, and provide the needed event rate for high statistics follow-on studies once the axion is discovered. A necessary first step is to demonstrate the technological readiness of the HTS technology.

2.3 Charged Lepton Flavor Violation

Charged Lepton Flavor Violation (CLFV) provides an extremely sensitive window into the physics beyond the standard model, indirectly probing mass scales far greater than the direct reach of colliders. The observation of CLFV would provide unambiguous evidence for new physics and might shed light on the mechanism generating neutrino masses. Many well-motivated models predict CLFV rates accessible at muon experiments in preparation or underway at Fermilab, PSI, and J-PARC. To exploit the full potential of PIP-II, a staged program of next-generation experiments and facilities has been proposed at FNAL. Mu2e-II is a near-term evolution of the Mu2e experiment, proposing to improve Mu2e sensitivity by an order of magnitude. The Advanced Muon Facility is a more ambitious proposal for a new multi-MW muon science complex, delivering the world's most intense positive and negative muon beams. Both projects plan to use high-field solenoids to efficiently capture charged pions created in the interaction of a primary proton beam with a production target. Muons produced by pion decays are then directly transported towards a stopping target located near the detector (for Mu2e-II), or purified into a storage ring before being delivered to the experiments (for AMF). The production solenoid features a graded axial field that collects low momentum muons, significantly increasing the capture efficiency compared to conventional muon facilities, and creating the world's most intense muon beam. This scheme significantly increases the capture efficiency compared to conventional muon facilities. Besides the need for large inner bores and high fields, a major challenge arises from exposure to high radiation doses and large beam energy depositions. Solenoids are also employed to transport muons and to provide the axial magnetic field surrounding the detector. The radiation environment is less demanding than the production target area, but excellent field uniformity is required near the detector. Many challenges must be addressed to develop large, high-field magnets for multi-MW target stations. The realization of a future CLFV muon program depends critically on the availability of intense muon sources, and a vigorous R&D effort to develop these technologies is a key component of that program.

3 Synergies and Ancillary Benefits

HEP facilities based on superconductivity are powerful platforms for technology development. The boundary of superconducting technology is constantly pushed to satisfy scientific needs and at the same time creates and enlarges applications for society. The development of such technologies invariably happens in an international collaborative/competitive framework, with direct return (development and supply contracts) as well as indirect benefits.

Science assumes the risk of introducing novel superconducting technology and in the process, demonstrates reliable large-scale operation such as accelerators and high-magnetic field laboratories. The proven technology can then be transferred to applications of societal benefit (ultra-high-field NMR, HTS MRI, Hadron Radiotherapy, power transmission, high field motors and wind generators, etc). A robust HTS development program would indirectly benefit all of these applications.

3.1 Next generation magnetic confinement fusion

High field magnet systems are the ultimate enabling technology for magnetic confinement fusion devices. Modern design concepts for power producing commercial fusion reactors rely on superconducting magnets for efficient and reliable production of the required magnetic fields. High Temperature Superconductors could significantly change the economic and technical status of superconducting magnets. Operation at temperatures significantly above liquid helium, and the relative insensitivity of the critical current to temperature, results in magnets with much higher operating stability and significantly reduced heat load to the cryogenic system, perhaps even allowing the possibility of using LH2 cooling or the elimination of cryogens altogether.

3.2 High field MRI

MRI is a unique capability in medical imaging that has an extremely rich and robust advanced research community constantly developing new applications. MRI magnets based on HTS can lead to several improvements: more compact, lighter weight, cryogen-free operation for broader deployment in underdeveloped countries and higher fields for detailed studies of brain function. For commercialization of high field systems, significant development and process improvements will need to be done both for the conductor and the magnet designs.

3.3 Hadron Radiotherapy

Current facilities are based on Low Temperature Superconductors (LTS), but there could be innovative technical and economic improvements made by using HTS conductor technologies, most likely to reduce the weight and increase performance of gantry magnets. Increase in critical current density of HTS would enable new opportunities for compact systems leading to reduction in footprint of overall system size. Any further improvements in cryocooler technology or methods for conduction cooling will provide additional economic benefits for reduced operating power consumption and reduced reliance on liquid cryogens.

3.4 Workforce Development

Embarking on an aggressive technology program to support the realization of a Muon Collider will allow the HEP community to recruit, engage, train and maintain the required workforce necessary to maintain US technological leadership in HEP and broadly in the US. Quotes from the recent HEPAP International Benchmarking Panel [3]:

- “. . .it is imperative for the HEP community to provide compelling, inclusive, and equitable opportunities for all those who want to explore the secrets of the universe at their most fundamental level.”
- “Collaboration and competition lead to development of key capabilities and a strong workforce.”
- “A robust particle physics workforce will both leverage and be representative of the diversity of the nation. Attracting, inspiring, training, and retaining a diverse workforce is vital to the success of particle physics and more broadly to U.S. Science and Technology.”

4 Path Forward

The timing is excellent for taking advantage of the recent confluence of synergistic activities and develop a strategy for near-term development of REBCO magnet technology. Recent relevant activities include:

- New P5 priorities favorable to developing technology for a Muon Collider.
- Several non-collider high field magnet applications identified in HEP.
- Private investments in magnetic confinement fusion reactors driving down cost of REBCO.
- Rapid developments in hydrogen economy (Hubs) that may enable magnet cooling using liquid hydrogen.
- Focus on sustainability - development of magnets to operate at higher temperature would reduce power consumption.

It is very unlikely that a major accelerator facility will be able to afford any conductor for which this is no existing large-scale industrial capacity. Despite the considerable technical challenges, REBCO is the only conductor that is on the horizon thanks to the explosion in compact fusion reactor development.

HTS magnet technology has opened the door to substantial private and public investment in fusion. At the current Technical Readiness Level (TRL) for HTS magnets there is a large overlap with the magnet needs of a Muon Collider, thus creating an opportunity for HEP to benefit. Investment in fusion magnet technology has already resulted in a significant cost decrease and performance improvement in HTS based on Rare Earth Barium Copper Oxide (REBCO) superconductor. A collaborative directed US R&D effort is needed to realize the potential of HTS for a Muon Collider, as well as other HEP and societal applications.

The community should start to lay out scenarios for development of strategic partnerships between the DOE national laboratories, particularly FNAL, LBNL, BNL and the National High Magnetic Field Laboratory (NHMFL) to advance superconducting magnet technology as a critical national response. The next steps include:

- Explore complementary applications for future HEP collider facilities, e.g. dark matter experiments.
- Maximize the benefits from the substantial public investment in fusion-related technologies, e.g. ARPA-E, FES Milestone-based Program.
- Expand the portfolio to include a high-risk, high impact target.
- Define near-term, 3-year, R&D targets that would have the greatest impact on future applications.
- Identify the mid-term, 5-year, key challenges of REBCO conductor and magnet development and the path forward to address those challenges while exploring synergies with other programs among HEP, fusion, and other applications.
- Define the conductor and capability needs to address the R&D targets and provide the associated resources.

References

[1] J. N. Butler et al. “Report of the 2021 U.S. Community Study on the Future of Particle Physics (Snowmass 2021)”. In: (Jan. 2023). DOI: 10.2172/1922503.

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[3] *Report of the HEPAP International Benchmarking Panel,* https://science.osti.gov/-/media/hep/hepap/pdf/202308/HEPAPBenchmarking_HEPAP_202308.pdf.