R&D Needs for a U.S. Fusion Magnet Base Program

Yuhu Zhai, *Member, IEEE*, David Larbalestier, Robert Duckworth, Zachary Hartwig, Soren Prestemon, and Cary Forest

***Abstract*—Significant technology maturation efforts are underway by private fusion startups with the goal to demonstrate mature HTS magnet technology. To support the private sector development effort, the U.S. Fusion Magnet Community Workshop was held on March 14–15, 2023 in Princeton, NJ. This was the first U.S. community workshop focused on fusion magnet technologies aimed at determining the structure and technical direction for a public program designed to complement the private fusion industry landscape. Based on the wide range of different contributions, a set of general themes and R&D needs were identified and discussed. Feedback highlighted critical R&D gaps such as availability of existing large cable and coil test facilities, a magnet education program that can generate a trained and essential workforce by leveraging R&D capabilities of universities, national labs, and fusion industry. Other opportunities synergistic and complementary with high energy physics, high field magnets that are open for a broad range of science drivers. The defined R&D gaps underpin the need for a mid-term and long-term public program in fusion magnet, in developing the rationale and consent for such a base program. A self-consistent, fusion specific magnet program will complement and de-risk fusion pilot plants of promising magnetic configurations developed by private companies on a timeline consistent with the goal of bringing fusion to the U.S. grid. We describe magnet challenges presented and R&D needs discussed in the workshop. These challenges and R&D needs provide focus for the development of mid-term and long term roadmaps on enabling HTS for fusion.**

***Index Terms*—High field fusion magnets, high temperature superconductor, magnetic fusion, U.S. fusion magnet R&D program.**

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Yuhu Zhai is with Princeton Plasma Physics Laboratory, Princeton, NJ 08540 USA (e-mail: yzhai@pppl.gov).

David Larbalestier is with National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL 32310 USA (e-mail: larbalestier@asc.magnet.fsu.edu).

Robert Duckworth is with Oak Ridge National Laboratory, Oak Ridge, TN 37814 USA (e-mail: duckworthrc@ornl.gov).

Zachary Hartwig is with MIT Plasma Science and Fusion Center, MIT, Cambridge, MA 02319 USA (e-mail: hartwig@mit.edu).

Soren Prestemon is with Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA (e-mail: soprestemon@lbl.gov).

Cary Forest is with Madison and Realta Fusion, University of Wisconsin, Madison, WI 53715 USA (e-mail: cary.forest@wisc.edu).

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I. Introduction

DIFFERENT from the international fusion scientific community, the U.S. strategic reports on bringing fusion to the U.S. grid and the U.S. community plan for fusion energy and discovery plasma sciences [1], [2] described the goal of a fusion pilot plant (FPP) is to make 50–100 MW net electricity, steady state or extended to long pulse operations (over a few tens of seconds). The road map to achieve this goal is to begin the FPP design in 2020s, its construction in 2030s and the FPP operation in 2030s–2040s. The NASEM report [1] stated that 30 GW of additional generation resources are needed annually from 2040s to 2050s based on reference case analyses. Private sector is making significant progress on high temperature superconducting (HTS) fusion magnet technology and pushing on an aggressive high field approach [3], [4], [5]. Test results identified critical engineering issues being resolved. For example, quench in large-scale REBCO magnets remains the most significant technical challenge [4], [5], [6]. Unlike low temperature superconducting (LTS) magnets adopted by ITER, due to differences in thermal properties a hot spot in HTS coils tends to stay local in a small area with a much slower normal zone propagation velocity (on the order of mm/s, instead of m/s as typically seen in LTS coils during quench). As a result, coil quench detection and protection becomes extremely challenging in HTS, in particular coils wound with REBCO coated conductors. To this end, methods used to protect high current density LTS magnets may not be suitable and sufficient for the protection of high current HTS coils. A number of new diagnostics and protection methods have been proposed such as the use of optical fibers [7], acoustic methods for detection [8], [9], and no insulation (NI) [10], partial insulation [11] with insulation every few turns for coil protection. While the idea of a NI-like method is providing a bypass current path when a normal zone appears in the HTS coil, the partial insulation refers to a method to introduce small and finite resistance in the coil winding pack among turns to better control current paths and peak induced currents in the NI coils upon quench. This partial insulation method introduces an effective suppression mechanism for quench-induced current in NI coils. These new technologies have been successfully demonstrated in small scale, high field HTS coils. But the HTS magnet technology, while advancing impressively, has not demonstrated quench resilience yet. For example, a number of notably large HTS coils were damaged during quench, including the most recently built and tested toroidal field model coil (TFMC) for fusion by commonwealth fusion systems (CFS) and MIT-PSFC [4], [5].

To this end, more multiscale multiphysics modeling efforts to better understand quench dynamics and scalability are needed and verified by model coil testing.

Significant technology maturation efforts are underway to demonstrate the high field approach for commercial fusion but critical issues are being addressed to meet coil performance requirements, and demonstrate coil operation repeatability and reliability. The cost of a fusion magnet system scales with, at least, the square of the magnetic field and the volume of the plasma $(B^2V)^{0.6}$ [12], [13], [14]. The high cost and technical risks of high field HTS coils may hinder their design use in a FPP. To this end, exploring and enabling multiple viable conductor and cable options is vital. A base program to review a broad range of alternative fusion magnet options to de-risk aggressive high field approaches and to validate affordability, repeatability, and reliability is needed. The R&D activities will focus on strength and capability in fusion magnet options but not duplicate facilities and strength in high energy physics (HEP) and high field magnet labs. The program will align and support the FPP initiatives but will also look beyond FPP toward first of a kind (FOAK) and nth of a kind (NOAK) fusion power plant magnet needs.

II. Highlight of the Magnet Community Workshop

The first fusion magnet community workshop was held successfully at Princeton University on March 14–15, 2023 [15]. The goal is to develop rationale and discuss the content for a U.S. fusion magnet program to complement the US DOE milestone-based program and private fusion efforts for FPPs and beyond. Representatives from national labs, fusion startup companies, US universities, and conductor suppliers, and the DOE office of fusion energy science (FES) program manager attended the workshop. There are about 60 participants, who delivered 40 talks discussed in six technical sessions. The focus of this workshop is not on conductor or technology advantages but on identifying R&D gaps, critical needs and discussions of program objectives. Education and training programs were widely discussed in the workshop as it is a gap identified for building a pipeline of next generation workforce. Agenda of the workshop can be found on the workshop website [15]. Detailed discussions include advanced MOCVD coated conductor for fusion, the Bi-2212 coil technology, and high current cable configurations such as the conductor on round core (CORC), and its cable in conduit conductor form to be tested in SULTAN for compact fusion reactors. Although there are no detailed discussions on specific magnet designs, an integrated simulation was mentioned to identify advantages of each conductor, structural choice and point of diminishing return. Given the recent resurgence in superconducting magnet technology driven by the private fusion power magnet sector and the absence of a strong, federally sponsored fusion magnet program in the U.S. R&D needs for the U.S. fusion magnet program were presented, further discussion to reach consensus is planned toward next step directions. The example R&D needs presented include

- Test stands to integrate neutron irradiation effects of essential magnet materials (conductors, insulations etc.) into the magnetic field and cryogenic testing
- Quantifying capabilities of superconducting cables under both the static and transient operations. A magnet-design led conductor program is needed to address issues such as AC loss and quench dynamics.
- Utilization and accessibility of existing test facilities is required to test new cables and coil construction methods from both the public and private sectors. The near term impact is valuable while waiting for the new test facility under construction at Fermilab.
- Development of advanced multiscale modeling tools that de-risk FPPs and inform future fusion magnet design, fusion-specific conductor and high current cable, coil system test to support the development of HTS coil protection methodologies beyond FPPs.
- Development of QA/QC tools and standardization performance measurements of superconductors, high current cables and subscale model coils to provide reliable data in public databases [16], so as to inform new magnet design improvements.
- A workforce development program that engages integrated magnet design, construction, and operation from materials to applications.

III. Potential Base Program R&D Thrusts

A major issue for HTS is always protection against quench as is illustrated by quench tests [4], [5]. Furthermore, such magnets operate at high mechanical stresses and verification of mechanical robustness is vital, especially for fast ramping ohmic heating coils [17]. Due to the highly integrated nature of a FPP and compact fusion power plant, coordinated national teams such as those discussed in this program are needed to develop affordable, practical and reliable FPP and fusion power plant concepts. A public R&D program engaging the broad fusion magnet community complements and de-risks the aggressive high field HTS fusion magnets presently being targeted by the private sector. Such a program will also provide magnet technology feasibility for other promising configurations such as compact stellarators. The potential base program R&D thrusts include:

- Fundamental materials understanding of HTS conductor performance including neutron degradation, operational scaling properties, manufacturing qualities and variation from manufacturer to manufacturer, and cost parameters for FPP and beyond
- Understanding physics and engineering integration gaps of magnet systems beyond FPPs for a reliable power plant operation based on short term and long term development, and how are gaps different over the roadmap period or for different operational goals (fatigue and neutron degradation in a long pulse and/or steady state operating regime)
- Development of and detailed understanding of high current cables (alternatives) for relevant fusion magnet prototypes,

especially for cables that must be used for coils under pulsed operations. The desire to use partially insulated cables for occasionally ramped DC magnets requires a more detailed understanding of allowable turn to turn resistance and quench protection properties

- Development of testing methodologies to validate potential alternative cables and model coils for a broad range of fusion coil systems, and accelerated testing of all promising conductors (REBCO, Bi-2212, MgB_2, etc.) [16], [18], [19], [20], [21], [22] under high fidelity irradiation environments and under magnet operation conditions
- Manufacturability and risk mitigation of supply chain issues for the deployment of future magnets for first of a kind (FOAK) and Nth of a kind (NOAK) power plants beyond FPPs. Research into hydrogen and other non large-scale liquid helium systems for fusion magnets such as fundamental thermal hydraulic measurements to large-scale equipment to support moving beyond liquid helium based cryogenic systems. While liquid helium consumption is a huge issue for the consideration of Nb_3Sn to be used in commercial fusion reactors, it can be limited to the FPP development. For the midterm and long term development, conduction cooled design shall be considered for low cost LTS magnets in a compact configuration (central solenoid of spherical tokamaks)
- Integrated design optimization through modeling using the understanding developed in above items and coupling to other areas of technology innovation to fill gaps identified beyond FPPs are to be developed, and crossover integration into other fusion systems.

IV. Test Facilities and Supply Chain Issues

There are substantial cable and self-field magnet test facilities but due to limitations on the conductor and coil testing of advanced technology may not be possible on the existing facilities. New test capabilities for assessing HTS conductors under operation conditions need to be developed, for example, fusion-relevant irradiation under operating conditions shall be established. More specifically,

- Large bore (0.5 meter or greater), high field (15 T) superconducting magnet test capability to push stress in prototype coils and minimize the amount of conductor needed in a given coil geometry
- Pulsed current test facility to address issues of ac loss heating, cyclic stress during high ramp rates
- High DC current (25 kA or greater) to provide steady state evaluation of quench and the long-term operation stability
- Integrated advanced cooling for increased operating temperatures to address liquid supply issues

A complementary base program to review a broad range alternative fusion magnet options to de-risk aggressive high field approach and to validate affordability, repeatability and reliability was discussed. The base program will align and help support FPP initiatives but will also look beyond FPP toward first of a kind (FOAK) and nth of a kind (NOAK) power plant magnet needs. Table I presents the existing test facilities in the US universities and national labs. The CFS TFMC was tested to reach 20 T at 20 K at the MIT PSFC test facility [4], [5]. A CORC cable model coil solenoid was cyclic load fatigue tested at the FSU ASC test facility [17]. A new HTS cable testing and conductor qualification is under construction at FNAL [23]. ITER central solenoid modules were tested at the General Atomics test facility [24]. The BNL common coil dipole is suitable for high current HTS cable testing [25].

TABLE I
Present Test Facilities in the US Universities and Labs

	Operating currents	Testing space	Cryogenic cooling	Background fields
MIT PSFC	10-50 kA	20 m^3	SCHe at 20 K, 600 W	N/A
FSU ASC	10 kA	160 mm clear bore	4.2 K, LHe	12 T solenoid field
General Atomics	up to 50 kA	160 m^3	SCHe at 4.5 K, 1 kW	N/A
BNL	7.5 - 40 kA	500 mm to 610 mm 31 mm x 335 mm aperture	4.2 K, LHe	10.2 T dipole field
FNAL	2 - 28 kA 100 kA*	54 to 147 mm 94 x 144 mm aperture	1.8 - 100 K 4.5 to 50 K*	15 T 16 T*

*Joint FES and HEP facility under development at FNAL that is expected to come online in 2025 [23]

REBCO has the largest number of producers but it has a large range of properties and variable specifications. Bi-2212 has rather stable properties but it has limited commercial suppliers, and production of Bi-2212 could be scaled up as the powder in tube process is similar to the mature production process of Nb_3Sn. The cost reduction can be driven by funding subscale prototype fusion magnets. Bi-2212 can be a potential alternative material as a robust conductor resistant to damage from magnet quenching is needed [18], [19], [20], [21].

V. Conclusion and Next Steps

The first community workshop focused on fusion magnet R&D needs for a public program was held at Princeton on March 14–15, 2023. A number of site visits and in person meetings between the organizing committee (OC) and private companies were conducted to ensure full engagement of the private sector and transparency of the community-led process.

There is a pressing need to reestablish a strong U.S. public program in fusion magnet science to help deploy commercial fusion energy on the timelines proposed by private companies and the U.S. government: While rapid advances have been made in developing superconducting fusion magnets, including the maturation of REBCO as a large-volume conductor and its use in the first high-field fusion scale magnets, significant technical challenges remain such as conductor and coil qualification for diverse fusion concepts, quench detection and mitigation, radiation effects in magnet materials, high-strength cryogenic alloys, fabrication techniques, design/operation of test facilities. As technologies continue to be developed and deployed, new problems will be encountered, requiring collaboration between the public and private sector to solve. The successes of the U.S. fusion magnet program were possible as a direct result of the significant U.S. DOE investment in 1970–1990 s. This public program produced technicians, engineers, and scientists who led and built large magnets. A similar renewal of a public program is needed to provide the workforce to make it happen.

A more in-depth, community-led process should be conducted as a follow-up to this workshop to shape such a public program: The March 2023 workshop was the first in a series of meetings required to answer these questions. The first meeting gathered many of the relevant stakeholders together, assessed the need for a public program, and started to compile the list of science, engineering gaps and research needs that advance magnet technology and support commercialization of fusion. A consensus-based, actionable plan based on the needs and capabilities of stakeholders is now being developed. The following list conveys the impression of emerging needs that were shared by multiple stakeholders.

- *Radiation effects in superconducting magnet materials:* Understanding the performance evolution of superconductors at fusion-relevant conditions is essential for fusion power plant design, operation, and costing.
- *Test facilities for fusion-relevant radiation damage:* New capabilities, providing cryogenic irradiation with neutrons, under magnet operating conditions. are required to irradiate magnet materials under relevant conditions.
- *Performance of fusion conductor technologies:* A wide variety of cables suitable for fusion magnets based on REBCO have been proposed. Experiment and modeling help increase understanding and mitigation of issues such as thermomechanical degradation, insulation degradation, quench dynamics, current distributions, AC losses, and instrumentation and develop new approaches to cable fabrication and joint design. LTS materials, such as NbTi and Nb_3Sn, may be more optimal for certain fusion concepts - require further development and qualification. Supporting cable/coil test capabilities remains important.
- *Test facilities for large-scale cable and magnet tests:* Access to suitable test facilities is required to develop and qualify new cables and coil construction methods. An ideal role for the public program may be the design, construction, and operation of large-scale user test facilities, most of which presently exist outside the U.S. The new 15 T cable test facility at FNAL currently under construction is an example for establishing other critical facilities - a large-bore high-field test facility for 3D coils and a pulsed high-field test facility for AC coils, enabling cost-effective risk reduction at reduced scale.
- *Quench detection and mitigation strategies:* Quench remains the highest technical risk for HTS fusion devices, as the magnets are a major fraction of capital cost and considered lifetime components. The science of quench dynamics and evolution in various cables and coils should be further developed. Traditional voltage-tap approaches, particularly weak points in insulation penetration, could be improved. Novel approaches to detection (including fiber optic, acoustic, magnetic, etc) and quench robustness (including no-insulation and partial-insulation magnets) should be further demonstrated at fusion-relevant scale.
- *Magnet materials science and engineering:* Fundamental R&D is needed on non-REBCO materials, such as Bi-2212, MgB_2, and iron-based superconductors, to establish feasibility and then scale to fusion cables and coils. New test capabilities to provide high-throughput Ic(B,T,A) characterization, establish standardized test protocols and public databases of performance is desired.
- *Characterization and standards for commercial superconducting materials:* The public program can play an important independent role in characterizing the performance of commercial superconducting materials, in establishing standards and rigorous testing systems and protocols, and in making such data available in public databases. Such publicly available data has played key roles in accelerating new development and launching private companies and also serves to help manufacturers communicate the quality of their product to consumers.
- *Development of multiscale modeling capabilities:* Development of advanced multiscale modeling tools for fusion magnets is important for establishing cost-effective risk retirement tools for future fusion pilot plants, from the design and analysis of the basic conductor unit cell to the performance assessment of a complete magnet system integrated into the larger fusion devices. Such tools are particularly important to help address “the scale problem” in fusion magnets.
- *Science foundations for future magnet technologies:* A successful public program should be forward looking, identifying new materials, processes, and technologies that will be needed as fusion energy grows. This might include developing new materials, or establishing the basis for new technologies, such as large-scale hydrogen cryogenic systems necessary if fusion energy is to scale beyond a few fusion power plants.
- *Hands-on, at-scale opportunities for workforce development:* All thrusts above represent real, at-scale opportunities focused on superconducting magnet science and magnet building. The new R&Ds should incorporate workforce development programs at all levels, including technician, engineer, scientist, and faculty, desperately needed to provide the growing magnetic fusion energy industry with capable, well-trained magnet builders.

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