Executive Summary of 2nd Fusion Magnet Community Workshop (1/21-23, 2025)

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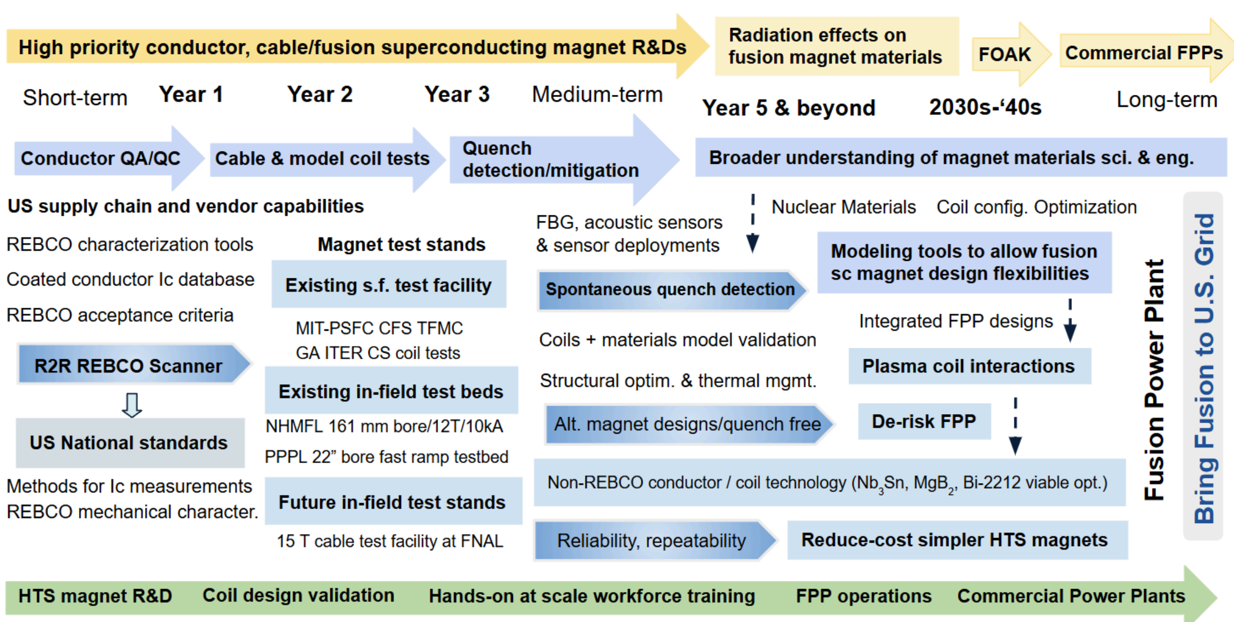
This draft report summarizes initial outcomes and the principal recommendations emerging from the 2nd fusion magnet community workshop hosted by the National High Magnetic Field Laboratory (NHMFL) at the Florida State University on January 21-23, 2025 (website). The summary is based on presentations from ~60 participants, some of which incorporated materials from ~40 white papers received last year. **The principal goal of this workshop was to develop an R&D roadmap to support the fusion industry in meeting their aggressive goal of developing a first-of-a-kind fusion pilot plant (FPP) in the 2030s. To this end, a new program for fusion magnets is described centered around the needs to 1) understand radiation effects in magnet materials, 2) address the need for appropriate cable and prototype magnet test stands, 3) develop comprehensive and easily deployable REBCO coated conductor characterization tools 4) better understand magnet quench detection and mitigation strategies, 5) develop a broader understanding of the magnet materials science and engineering and modelling tools needed to allow fusion magnet design flexibility, and 6) develop a plan for hands-on, at-scale workforce training at all levels (technician to PhD).**

A timeline to close critical R&D gaps and enable industry-led FPP and beyond



Prioritized R&D thrusts	Years	Budget ($M/yr)	Comments
REBCO conductor characterization & QA/QC tools; acceptance of commercial tapes; National standards on Ic measurement	3	3	R2R, angular dependence, methods for measurements, Ic acceptance & US standards for commercial tapes, establish a public Ic database etc.
Magnet test stands (cables, model coils)	3	5	Existing steady state, fast ramp test bed + new high field, large bore in-field cable/coil test stands
Quench detection & mitigation strategies	3	3	AI/ML (integrated modeling & quench testing)
Radiation effects (neutron & gamma)	5	5	near operating conditions (conductor, insulation, stabilizer etc.) to quantify magnet radiation limits
Fundamental magnet materials science	5-10	5	REBCO and non-REBCO conductors (Nb_3Sn, MgB_2, Bi-2212)
Hands-on at-scale workforce training	5-10	5	at all levels (technicians, MS, PhD)
Modeling tool for coil design flexibilities	5	3	Coil-plasma interaction, all device models etc.

I. The PPPL Workshop - March 2023

A key focus of this initial fusion magnet community workshop was to leverage the strengths of the public sector to reinforce private sector progress to accelerate fusion commercialization. These goals align well with recent initiatives in the U.S. fusion program (FES Bold Decadal Vision), the DOE National Fusion S&T Roadmap development efforts in support of the NASEM report to bring fusion to the US Grid, Fusion Energy Science Milestone program, and the FESAC Long Range Plan (LRP). The workshop sessions were organized to enable a wide range of stakeholders (private fusion companies, public research entities, universities, and HTS conductor manufacturers) to present their perspectives in response to direct prompt questions; open discussions followed each presentation. The organizing committee made several visits to multiple companies about their views on what thrusts a public program should emphasize. White papers were also solicited from the PPPL workshop participants. The PPPL workshop concluded that a future public fusion magnet program should concentrate on understanding radiation effects on superconducting magnet materials, understanding the performance-relevant HTS conductor technologies, develop and provide test facilities for significant scale cable and magnet tests, better understand quench detection and quench mitigation strategies, and provide at-scale opportunities for workforce development.

II. The NHMFL Workshop - January 2025

The focus of the second fusion magnet community workshop was to a) define a new base program for fusion magnets, b) prioritize research addressing R&D gaps and outstanding technical challenges c) develop a R&D roadmap and timeline to close gaps d) identify critical opportunities and synergies with other research fields e) development a fusion magnet education/training program. There were six (6) key issues addressed in the workshop. We detail issues discussed in the following sections.

IIa. Conductors

A core area of review during this workshop was examination of the particularities of REBCO coated conductors as opposed to all other available superconductors were presented from an NHMFL perspective and a viewpoint on making REBCO coated conductor magnets in the multi-sector Korean national HTS program followed. An important lesson from the 18 years of

REBCO and Bi-2212 conductor development program at NHMFL is that while REBCO occupies the largest performance space of any magnet-available superconductor, it is quite different from all other superconductors which are isotropic and multifilament with filaments embedded in a good normal conductor that assures good current sharing and resilience to local damage, and significant quench tolerance. An important point of reference may be provided by the Chinese program which has recently published important demonstrations of conventionally insulated MgB_2 and CIC Bi-2212 magnets to cover cases where 20 T at 20 K (which can only be achieved by REBCO) is not the only requirement. Quench also remains one of the highest technical risks for superconducting fusion devices. Our community is still struggling with fundamental issues like an accurate estimation of the critical current of a given HTS cable or magnet and an understanding of the spatial and temporal behaviors of currents, both under nominal operation and on quench, especially in the fully soldered partial (or no) insulation schemes favored by the leading fusion companies. As a result, modern REBCO magnets have been designed and operated without full confidence in a precise estimation of their electrical and mechanical limits, meaning that a precise science of quench dynamics and quench evolution in HTS cables and coils is not available in the public domain, even if, privately, much progress has been made. Reliable quench detection methods are still far from guaranteed despite much R&D on various new detection methods. Meanwhile, we have observed an increasing number of failures of high field HTS magnets, both mechanical and electrical, over the last few years. Some novel approaches to quench detection and development of quench robustness (including no-insulation and partial-insulation magnets) still need substantial improvement. Public sector benchtop development can help ultimate integration into production fusion-scale coils by providing a general open-source confidence with small, inexpensive test articles. It was recognized among workshop participants that high field HTS magnets currently in routine service are extremely rare. Thus, to advance more effective quench protection strategies, alternative philosophies to re-define robustness of HTS cable and magnet such as long-term operation reliability and quench prediction need formulation, discussion and community acceptance.

IIb. Magnet test stands

It was recognized by all in the workshop that there are insufficient cable and in-field coil test facilities in the U.S, even though high current, self-field test facilities such as those at GA, MIT-PSFC and CFS do exist. What is lacking are facilities with significant external background magnetic fields that could enable sub-scale cable and model coil validation to de-risk FPPs developed by private companies. There was strong support for new test capabilities to assess HTS conductors at or near the magnet operation conditions. This includes a pulsed field test facility to address cable ac loss issues. Several companies representing non-Tokamak configuration FPPs expressed their interest in ac loss measurements. An important concern is that ac losses can also affect operations during startups and plasma transient events. There are only two presently available more-than-standard bore magnet test facilities: The first is the 161 mm bore, 12 T/4.2 K/10 kA superconducting magnet at ASC-NHMFL, presently the largest existing available US magnet test bed while the second is the 22" warm bore, 24kA/10 T/s fast ramp dummy load test facility at PPPL which can support HTS/LTS cable ac loss testing.

Name/Location	Magnetic Field	Bore/type	Available current for insert	Status and Comments
Existing facilities				
ASC-NHMFL	12 T, SS	161 mm at 4.2 K /solenoid	10 kA	Used for many 2212 and some CORC magnets with some fatigue testing done
PPPL	3T, 10T/s	550 mm warm bore	20 kA	Available today
BNL	10T, 1T/s	29mmx330mm cold	10 kA	Available today
Future facilities				
ORNL-SNS	13 T CIC Nb_3Sn	500 mm warm bore	Not presently set up	Magnet is at ORNL but not presently installed
Fermilab	15 T dipole field	~ 1m length	16 kA DC and 100 kA flux transformer	FY27 completion
NHMFL	23 T at 195 mm warm bore or 350 mm bore at 11.5 T	Resistive magnet		Funding being sought now – potential service in 2028
Challenge coil in NASEM report	14 T	900 mm all HTS magnet		Requires an integrated plan with sub-scale R&D coils

There are several possible future test beds of interest to fusion magnet users of which the OFES-supported. Fermilab 15 T large aperture dipole test magnet is fully funded and the closest to completion (FY28). Another very interesting medium-term magnet is the CIC 50 cm warm bore, 13 T Nb_3Sn made for the Hahn Meitner Neutron Scattering facility in Berlin (HZB). Another possibility is to follow up on the all-HTS Grand Challenge magnet described in the recent NASEM report on “The Current Status and Future Direction of High Magnetic Field Science in the United States”. This would be for a 14 T 900 mm bore all HTS-magnet that could serve as both a technology demonstrator for large bore REBCO magnet technology and serve many users in high field MRI, Axion search/Muon Collider, magnet test facility. Such a magnet could hugely leverage US magnet R&D capabilities.

IIc. Radiation test stands

The ideal radiation test facility for fusion magnets and their components can expose samples to high-energy neutrons at 20 K, apply high magnetic fields and measure in situ the evolution of the samples' properties - while keeping the sample at 20 K throughout the entire campaign to prevent annealing. Such a cryogenic neutron irradiation facility is currently being constructed at the 6 MW research reactor at MIT-PSFC and should become operational in 2025. First experimental results are highly anticipated by the fusion community. High-fidelity data will enable developing optimized fusion and accelerator magnets and determining shielding requirements to achieve the desired operational lifetime. In addition, the MIT facility can also be used for study of insulations, structural stabilization, and instrumentation which were also expressed as a key community need. While this facility will likely provide highly anticipated results for the fusion community, additional facilities would be beneficial to benchmark results and accelerate reduction of uncertainty in radiation degradation. However, discussion with some private stakeholders at the workshop indicated that they are basing current designs on information currently available so the need is not urgent. However, updated guidance in the next five years would be welcome as their approaches move toward full-scale manufacture. Data and facilities could also address needs in other potential partner programs such as high energy physics and NASA where cryogenic irradiation is an important operating consideration.

IId. Characterization capabilities for REBCO coated conductors

The fact that those making high field REBCO magnets must invest in substantial critical current testing was noted, unfavorably, by many. Especially small companies without the financial and personnel capacity of CFS and the NHMFL remarked upon the desirability of companies doing more of the testing required by the end user. But the tape-producing companies pointed out that this is in conflict with the desire to upscale production and downscale cost. A third possibility of having one or more private entities capable of providing all-angle, variable temperature (4-30K), high field (up to 20 T or more) Ic measurements was floated. Faraday Factory has embraced this approach by having the same 12 T SuperCurrent device used by CFS. To go to higher fields users must go to the one of the national high field magnet labs like Tohoku 25 T or the NHMFL 31 T magnets. Such testing is however only on discrete very short samples 20-30 mm long. Due to the well-known dropouts found in present tapes from all manufacturers, a strong desire for continuous, in-field measurement in high-fields at low temperatures was expressed. Instruments of this type are presently being prototyped at both PPPL and the ASC-NHMFL.

IIe. Quench detection and mitigation strategies

Magnet protection is a fundamental aspect of superconducting magnet design and operation. Quench remains one of the highest technical risks for superconducting fusion devices. The science of quench dynamics and its evolution in HTS cables and coils needs is so far little developed and most data lies behind private paywalls. Magnet protection is accomplished by preventing, mitigating, and/or safely handling abnormal events that may cause the sudden loss of superconductivity and the concomitant conversion of magnetic stored energy into heat. Voltage tap approaches compromise Paschen-tight insulation, one of the biggest weaknesses of insulated magnets; improved techniques and good alternatives are needed. Novel approaches to quench detection (including fiber optic, acoustic, magnetic, superconducting methods, and others) and development of quench robustness (including no-insulation and partial-insulation magnets) need benchtop development and verification at small scale and ultimately integrated demonstration in fusion-scale coils. In the limiting case of non-insulated coils, current redistribution occurs without active engagement of external systems, i.e. the magnet is passively protected; determining the limits for design and safe operation of non-insulated magnets at fusion-scale is one critical area for public sector research. Advanced analysis techniques need to be used to design and make tailored small-scale model coils to verify the models. In support of this, model magnet design, construction and test facilities are needed. For insulated or partially insulated coils, detection of the onset of quench, or precursors to quench-onset, are a critical element of protection. Traditional voltage tap techniques have significant drawbacks for HTS-based fusion magnets due in particular to noise and sensitivity. Multiple alternatives are under active development. Fiberoptics are being pursued in industry as well as at National Laboratories (FNAL and LBNL) due to their ability to provide high sensitivity to temperature in a distributed manner. Ultrasonic and RF-based distributed sensors are also under development, as they may prove more robust. R&D is proposed to rapidly advance these technologies, and to improve their sensitivity via multiple routes, including engineering improved sensor materials, new data acquisition & processing techniques, and in-situ calibration methods.

IIf. Magnet materials science and engineering

There are opportunities to improve materials for superior superconducting fusion magnets. Science is needed to continue to drive higher performance, reduced cost REBCO. One of the most basic challenges of REBCO coated conductors is providing characterizations in field (B), temperature (T), angle (θ) space relevant to the magnet receiving the conductor. 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 experimental capabilities such as torque magnetometry to provide high-throughput $I_c(B, T, \theta)$ characterization and establishing more standardized test protocols and public databases of commercial materials performance are desired. Development of high-strength cryogenic alloys suitable for the demanding Lorentz loads and cycling of high-field fusion magnets is needed. Superior epoxies and other high-voltage insulators robust to fabrication, operation, and radiation damage could be pursued.

IIg. Workforce Development

Both PPPL and ORNL described active programs for educating non-tradiationally by partnering with smaller universities and technical colleges by providing on-site training, often with substantial hands-on experience. PPPL has a MS of Engineering pilot program that is on site and on campus at Princeton University. There is also a PPPL Apprenticeship program that takes high school diploma students in good standing for a paid 4-year program. MIT and FSU have concentrated on more typical academic instruction for graduates that is partly based on classroom instruction supported by MS or PhD research efforts. The notable success of the TFMC depended greatly on a large cohort of PSFC students but this was paid for largely by CFS and has now fallen to a low level. The FSU efforts are largely in the Applied Superconductivity Center where 4 teaching faculty supervise about a dozen PhD and MS students and about the same number of undergrads. This is generating 1-2 graduates per year, most of whom get strong offers from the magnet and superconductor industry. Plans to expand this are well in hand but expansion of the funding for students, presently all supported by competitively awarded research grants, would require new funding vehicles that recognize the training aspects of the education rather than the research.

The following list conveys our impression of immediate and emerging needs for fusion magnet research and development that were shared by multiple stakeholders and that should be addressed by a public program.

- Radiation effects in superconducting magnet materials (Medium)
- Test facilities for large-scale cable and magnet tests (High)
- Characterization capabilities for commercial superconducting materials (High)
- Quench detection and mitigation strategies (High)
- Broader understanding of magnet materials science and engineering (Low)
- Hands-on, at-scale opportunities for workforce development (technician to PhD)

Further ongoing discussions between stakeholders with a stronger public engagement will define the best approaches to address these needs within a base program that leverages and complements current private fusion magnet development. A stronger public program can help define requirements for both conductors and high field magnets across a range of promising configurations.