THE SPARC TOROIDAL FIELD MODEL COIL PROJECT
The foundation for an accelerated path to fusion energy via demonstrated large-scale >20 tesla superconducting magnet technology

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The SPARC Toroidal Field Model Coil (TFMC) Project was an approximately three-year effort between 2018 and 2021 that developed novel Rare Earth Yttrium Barium Copper Oxide (REBCO) superconductor technologies and then utilized those technologies to successfully design, build, and test a first-in-class high-field (~20 T) representative scale (~3 m in linear size) superconducting fusion magnet (See Fig. 1). The project achieved major advances in superconducting magnets and the ancillary technologies involved in testing them; however, the principal impact of the TFMC Project has been the opening of new compelling pathways to achieving commercial fusion energy through enabling compact, lower cost, and higher performance net-energy magnetic confinement devices on the accelerated timescales required to address global climate change [1].

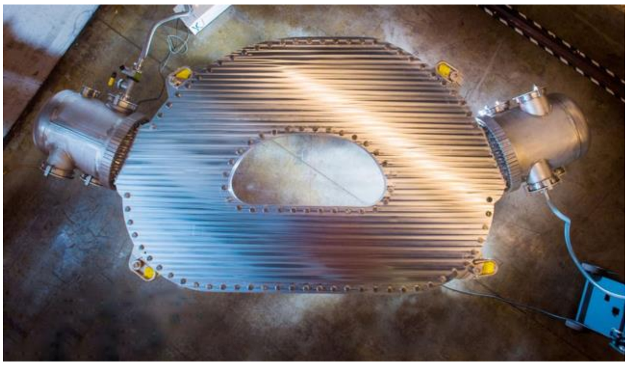

Figure 1: The SPARC Toroidal Field Model Coil

Weighing 9,270 kg and utilizing 270 km of REBCO superconductor, the TFMC achieved 20.3 T peak field-on-coil at a terminal current of 40.5 kA and a stored magnetic energy of 110 MJ during its first full performance test on September 5 2021 (See Fig. 2). Lorentz loads of over 800 kN/m were sustained on the innermost REBCO tape stacks without degradation, and target structural performance was met with the magnet case absorbing stresses approaching 1 GPa. Cryogenic performance of the system was excellent: the maximum temperature difference across the magnet was approximately 1 K during steady state operation with a total cryogenic heat load of only 112 W at 40.5 kA. Good thermal stability and control of the magnet was enabled by the pressure-vessel-style cooling scheme and the 32 internal pancake-to-pancake joints achieving ~1 nΩ per joint at 20 K at 40.5 kA despite having to operate in external magnetic fields up to 12 T. Two further test campaigns carried out in fall 2021 and focused on two objectives: (1) assessing the steady-state superconducting performance of the magnet under different operational conditions; and (2) initiating open-circuits at 31.3 kA to assess resiliency of the magnet against worst-case quenches. Both test campaigns successfully collected extensive experimental data that has been used to validate and advance 2D and 3D coupled electric, thermal, and mechanical FEA models that are now being used to design the next generation of large-scale no-insulation TF magnets for the SPARC tokamak.

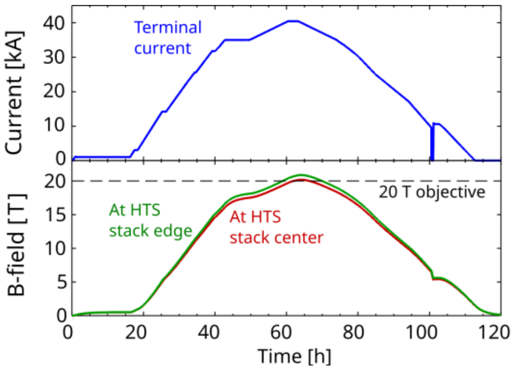

Figure 2: Experimental measurements of the terminal current (top) and peak field-on-coil (bottom) confirming the successful achievement of >20 T operation of the TFMC.

The TFMC design is based on no-insulation REBCO technology [2], in which turn-to-turn electrical insulation is eliminated towards achieving simpler manufacturing, low voltage (<1 V) operation, optimized single-pass cryogenic cooling, and resiliency to off-normal events including quench. The magnet winding pack is composed of 16 stacked pancakes with 16 turns each of REBCO for a total of 256 turns. The pancakes are made from high strength steel radial plates with machined channels on both sides, one side containing REBCO stacks and one side providing coolant access. A proprietary vacuum-pressure impregnation (VPI) solder process was developed and provides excellent mechanical, electrical, and thermal connectivity between the REBCO and surrounding components. Pancakes are mechanically bolted together and electrically connected by 32 internal demountable resistive joints. Top and bottom terminal plates with embedded superconducting leads complete the winding pack. The winding pack is enclosed by a machined high strength steel alloy case, which provides structural support for the large electromechanical forces generated by the magnet and serves as a pressure vessel for supercritical helium coolant flowing throughout the machined channels in the winding pack pancakes. High pressure plena on each end of the magnet provide access for the current, coolant, and instrumentation. The magnet includes an extensive array of embedded instrumentation within the winding pack, including approximately 200 voltage taps, 40 temperature sensors, 4 embedded hall probes, helium pressure and flow sensors, and strain gauges.

Figure 3: The TFMC being installed into the vacuum cryostat in the TFMC Test Facility at the MIT Plasma Science and Fusion Center.

To carry out the TFMC test campaigns, a new magnet test facility was built and commissioned at the MIT Plasma Science and Fusion Center between 2020 and 2021 (See Figure 1). A centerpiece of the test facility is a novel 50 kA high temperature superconductor feeder system that brings current from water-cooled copper bus at 297 K in atmosphere to the helium-cooled TFMC at 20 K in vacuum . The feeder system is composed of two main subsystems. The first is a novel set of 3 m tall, liquid nitrogen-cooled REBCO binary current leads, which were designed and built in-house and qualified for steady-state operation at 50 kA. The second is a chain of superconducting cold bus cables based on VIPER REBCO cable [3], which utilizes several sets of joints to maximize ease of assembly and absorbs the thermally induced strain between the current leads and TFMC during the cooldown. [2]. Another novel implementation is a liquid-free cryocooler-based cryogenic circulation system that provides supercritical helium at temperatures down to 20 K and pressures up to 25 bar-A at mass flow rates of up to 70 g/s for a cooling capacity of 600 W @ 20 K for the magnet and feeder system. The magnet is integrated with the feeder and helium cryogenic system inside a large 20 m^3 vacuum cryostat, which contains an internal liquid nitrogen radiation shield and access for all facility and magnet instrumentation. The test facility instrumentation suite includes two fiber optic current sensors to confirm amp-turns of current in the magnet as well as two high-precision 3D hall probes for redundant magnet field metrology.

Ultimately, the TFMC project advanced the state-of-the-art of high-field superconducting magnets for fusion applications from benchtop-scale experiments at universities to fusion-scale production magnets at private companies in under 5 years. Based on the REBCO technology developed under the TFMC Project, CFS has been enabled to undertake the design and fabrication of the TF, CS, and PF magnets for the SPARC tokamak in its pursuit of deploying a compact fusion power plant in the 2030s. Importantly, the TFMC Project’s impacts extend beyond CFS to the broader fusion energy community. From retiring many of the key technological risks for high-field REBCO magnets to dramatically increasing the supply and lowering the cost of REBCO to validating the high magnetic field pathway to fusion energy, the TFMC Project establishes a strong foundation for multiple high-field magnetic confinement fusion concepts, whether government- or company-based, to accelerate towards the deploying burning plasma experiments and prototype fusion power plants.

ACKNOWLEDGEMENTS

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