Qualification, Fabrication, and Commissioning of High-Temperature Superconducting Magnets for Compact Fusion

B.N. Sorbom[1] on behalf of the SPARC Team

Commonwealth Fusion Systems, Devens, MA, USA

Commonwealth Fusion Systems (CFS) is building the SPARC tokamak in Devens, MA, USA, with first plasma planned in 2026. The initial objective of SPARC will be scientific demonstration of Q>1 in a tokamak, with experiments then shifting to the goal of exploring operating regimes for ARC, the first fusion power plant. SPARC utilizes a high field, compact, pulsed tokamak design enabled by superconducting Toroidal Field (TF), Poloidal Field (PF), and Central Solenoid (CS) coils. These coils, along with their superconducting current bus and current lead systems are made possible by advances in the manufacturing techniques of Rare Earth Barium Copper Oxide (REBCO) superconducting tapes, also known colloquially as High Temperature Superconductors (HTS). The fusion power density in tokamaks scales as the strength of the toroidal magnetic field to the fourth power. One of the most important consequences of this scaling is that increasing the magnetic field in a tokamak enables a small device like SPARC to demonstrate net-energy production, leading to reductions in cost, timeline, and organizational complexity required to construct and operate the tokamak.

Although HTS material was discovered in 1986, difficulties in manufacturing the crystalline material into long lengths of usable superconducting wire precluded the possibility of using HTS to build full-scale fusion magnets until very recently. However, due to the combination of improved thin-film manufacturing techniques and a push to the HTS industry to scale by private fusion companies, the supply base now exists to provide the 1000's of km of superconducting wire (also known as "tape" due to its flat, rectangular form factor) required to build magnets large enough for fusion devices.

In 2018, CFS began to carry out early-stage R&D programs to qualify HTS for use in fusion magnets. A series of experiments were conducted to verify that soldered stacks of HTS tape would be able to withstand the high JxB forces on the magnets, as well as to provide enough current sharing between tapes in the stack to make the stack robust to potential defects in the HTS tape or magnet manufacturing processes. These tests culminated in a series of unit-scale experiments that proved the viability of two different magnet architectures based on HTS stacks.

The first architecture called HTS Non-Insulated, Non-Twisted (NINT) technology was designed for steady-state magnets that required cryostable operation at high fields. This architecture is created by inserting the HTS stack in a grooved plate or by winding stacks separated by a metallic co-wind, and is characterized by having no conventional insulator between the turns of each magnet unit, colloquially referred to as a "pancake," which is then stacked with other pancakes each connected to its neighbors by very low resistance joints to provide the full number of turns for the magnet. This technology and associated manufacturing techniques were de-risked in the Toroidal Field Model Coil (TFMC) program, which culminated in the successful build and operation of a large-scale NINT magnet at high field. The TFMC was approximately 2 m x 3 m in size, and operating at 20 K and a current of 40 kA in the superconducting stack achieved a field of 20 T and a stored magnetic energy of 110 MJ. The combination of high field and size represented a jump in ~100x over any previous HTS magnet that had been operated and de-risked NINT technology for use in SPARC.

Although this talk will focus on superconducting magnets for tokamaks, it is also important to point out that the NINT technology can be applied to other types of fusion magnets, and has been utilized in a pair of warm-bore, 17 T magnets that were delivered by CFS to the University of Wisconsin for the Wisconsin High-field Axisymmetric Mirror (WHAM) experiment. At the time of this talk, the WHAM 17 T end-cell magnets will have operated in a stable manner for almost a year (with only downtime associated with overall system maintenance).

The second type of magnet architecture called HTS Cable technology was designed for pulsed high field magnets and superconducting bus systems. This architecture is created by inserting the HTS stack in a helical copper former which is twisted around a central cooling tube, and covered by a structural jacket. Unlike the NINT technology, the turns of the Cable magnet technology are insulated from each other using a conventional insulator, and the entire magnet is potted in epoxy. HTS Cable-based magnets can be built by either wrapping the cable into horizontal pancakes which are stacked similarly to the NINT magnets, or by wrapping the cable into concentric vertical "layers." In both cases, the cable pancakes or layers are connected by low-resistance joints. The HTS Cable technology and associated manufacturing techniques were de-risked in the Central Solenoid Model Coil (CSMC) program, which culminated in the successful build and operation of a large-scale CS module that was operated at 20 K, 50 kA, and achieved a field ramp rate of 4 T/s. In addition to achieving SPARC operating conditions, the CSMC was also used to successfully demonstrate fiber-optic quench detection and protection. Since the SPARC CS operates at conditions much more stringent than the PF coils which utilize the same Cable-based HTS architecture, the CSMC also de-risked the technology for the PF coils.

After the underlying technology for all SPARC magnet systems was de-risked, CFS constructed a manufacturing facility to scale up this technology to build the SPARC TF, PF, and CS magnets. As a part of this operation, CFS constructed a set of test facilities to allow for the progressive testing of all magnet subcomponents through final tests of the full magnets themselves at SPARC operating conditions. At the component scale, facilities were built and qualified to allow for the testing of the input HTS material and low temperature and high field as well as testing the structural material of the magnets at low temperature. At the magnet sub-unit scale, facilities were built and qualified to test the superconducting performance of every pancake/layer at 77 K to uncover any potential manufacturing defects before the pancakes/layers were integrated into full coils. Finally, two large cryogenic, high current test stands were built and qualified to enable the full testing of every single TF, PF, and CS coil before being sent to SPARC for installation. In addition to achieving the required operating conditions for each step of testing, the test facilities were designed and built to match the high throughput achieved by the manufacturing line, and will ensure high confidence that every magnet delivered to SPARC will work as designed.