The High Field Stellarator Direct Path to Fusion Energy

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This presentation will review recent advances in the science and technology of stellarators, and discuss the scientific and technical advantages and remaining challenges for the high-magnetic-field, optimized stellarator as a rapid and robust path to commercial fusion energy. The Type One Energy Group (T1E) fusion technology development strategy, Fusion Direct, maximizes the utilization of these scientific and technical advances underpinning the highly encouraging results from stellarator experiments around the world (eg. HSX and W7-X), together with more recent breakthroughs in stellarator theory and modeling, while taking advantage of fusion-related technology advances in areas such as advanced manufacturing, and high-temperature superconductor (HTS) materials. Disciplined adherence to this Fusion Direct strategy is intended to credibly create the lowest possible risk, shortest possible schedule, path to an electricity-generating stellarator Fusion Pilot Plant (FPP) by the 2030’s, in response to the White House’s Bold Decadal Vision for Commercial Fusion Energy. T1E is now well capitalized to start realizing this mission. As has been reported at recent IAEA meetings, Wendelstein 7-X (W7-X) has demonstrated reduced neoclassical transport, plasma confinement on par with comparable tokamak devices, and stable, long-lived divertor detachment. Ongoing experiments at W7-X and other existing stellarator research programs are expected to continue informing and guiding the T1E stellarator FPP development (e.g., increasingly long plasma pulses with robust fusion performance). However, there are also open stellarator technical issues which may not be addressable by these research programs in time to properly inform T1E’s Fusion Direct plan. One example is the demonstration of plasma compatibility with reactor-relevant (carbon-free) first wall materials. Furthermore, technical issues that could credibly be addressed by W7-X experiments, but whose resolution are by no means guaranteed, include the demonstration of benign turbulence levels without the need for central particle fueling, and the demonstration of a highly efficient particle-exhaust concept utilizing the island-divertor design. Within the context of Fusion Direct, T1E is refining plans to address these in parallel with own facilities as well as synergistically with other efforts, for example W7-X. The ability to use HTS to generate high magnetic field, fusion-scale, superconducting magnets with fields in excess of 20 T, as demonstrated by the SPARC Toroidal Field Model
Coil test carried out in 2021 by MIT Plasma Science and Fusion Center and Commonwealth Fusion Systems, opens up a compelling path to compact stellarator fusion power plants. It is argued that stellarators, by virtue of achieving confinement of fusion-grade plasmas from magnetic fields produced entirely from external coils, benefit particularly from high magnetic field strengths, compared to concepts that rely on plasma currents for the creation of the key components of the confining magnetic field. The use of higher strength magnetic fields in the complex 3-dimensional (3D) architecture of a stellarator, however, imposes higher demands on the performance of reactor materials and mechanical design elements, in particular with regard to superconducting cables and the structural integrity of magnet assemblies. Stellarator engineering has historically also been challenging due to stringent requirements for the geometric accuracy of coils and in-vessel components. While the high electromagnetic loads and complex 3D geometry of stellarator magnets impose challenges on materials, design, and fabrication, initial experimental tests carried by T1E and MIT over the past year show that the VIPER HTS cable can be successfully bent into stellarator-relevant 3D shapes with bending radii as tight at 10 cm with no signs of degradation of the HTS conductor. Work is now underway to demonstrate scaleable fabrication of VIPER-based stellarator coils with the required reactor-relevant superconducting and electromechanical performance.

![Figure 1. Left: A modified VIPER cable was bent into a 3-D stellarator-relevant shape, filled with solder, and prepared for testing. Right: The test at T=77K demonstrated a critical current of 5.86 kA at T= 77 K, slightly above predictions, indicating no degradation of the superconductor properties.](image)

In addition to resolving open science issues, the Fusion Direct plan addresses the long-standing stellarator design engineering, manufacturing, and assembly challenges which have historically resulted in lengthy development and construction schedules. Techniques for significantly reducing the manufacturing and assembly schedule of the T1E high field optimized stellarator are being developed, not just to shorten the path to a first FPP, but also to make it a more economically competitive power generation technology. Accompanying and accelerating the FPP development, an intermediate-scale high-field optimized risk-retirement platform stellarator will be built and operated to validate key technologies, eg. HTS stellarator coils, superior core plasma performance through turbulence optimization, and the efficacy of novel divertor design concepts with improved particle exhaust.