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Compact Stellarator Path to DEMO

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The US fusion program is considering what new facilities are needed in addition to ITER and existing facilities to prepare the way to a DEMO reactor. The broad issues are familiar: sustainment of an ignited/high-Q plasma in steady state, avoidance of disruptions and large variations in power flux to the wall, adequate confinement of thermal plasma and alpha-particles, control of a burning plasma, particle and power handling (divertors), etc. Stellarators have key reactor advantages: steady-state high-plasma-density operation without external current drive or disruptions, stability without a close conducting wall or active feedback systems, and low recirculating power. While stellarators are at present less developed than tokamaks because of the higher parameters obtained in large tokamaks, D-T operation in TFTR and JET, and the decision to proceed with ITER, stellarators do present an attractive alternate path to a DEMO reactor.

Compact stellarators, with moderate plasma aspect ratios, good confinement, and high-beta potential lead to the smaller-size reactors that are favored by the US utility industry. The ARIES group, which had previously analyzed different tokamaks, an ST, an RFP and a modular stellarator (SPPS) as reactors, has recently examined compact stellarators. The ARIES-CS study established that compact stellarators can be economically competitive with tokamaks as reactors, but face serious issues with divertors, as do other toroidal concepts.

The favorable physics properties of compact stellarators follow from their quasi-symmetric magnetic geometry, analogous to the axisymmetry of $|\mathbf{B}|$ in tokamaks and RFPs. Basic physics properties depend only on $|\mathbf{B}|$ in the Boozer coordinate system in which magnetic flux surfaces are concentric, axisymmetric tori. This fundamental property allows mapping of physics properties from tokamaks to analogous stellarators. The different types of quasi-symmetry (helical, toroidal and poloidal) manifest themselves in the magnitude, direction, and variation of flow and flow shear, and instability thresholds for trapped particle modes. Initial results from HSX, a helically symmetric stellarator, are in general agreement with expectations for quasi-symmetry, and demonstrate its effectiveness.

Many of the issues that need to be resolved before committing to a compact stellarator DEMO can be answered using the results of the large tokamaks and stellarator experiments already in operation (LHD, TJ-II, Heliotron J, HSX, CTH), under construction (W 7-X, NCSX) or in development (QPS). The compact stellarator route to a DEMO can also incorporate results from ITER D-T experiments and fusion materials, technology and component development programs. However, a large next-generation stellarator experiment will be needed to address some physics issues: size scaling and confinement scaling at DEMO-relevant density, temperature, and beta; the burning plasma issues of adequate fast-ion (alpha-particle) confinement, robustness to Alfven instabilities, and helium ash removal; and operation with a strongly radiative divertor. Technology issues include simplification of the 3-D coil, structure, and divertor fabrication, the use of rapid prototyping as in the aerospace industry, and reliable costing techniques.