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3D toroidal physics: testing the boundaries of symmetry breaking[1]

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Toroidal symmetry is an important concept for plasma confinement; it allows the existence of nested flux surface MHD equilibria and conserved invariants for particle motion. However, perfect symmetry is unachievable in realistic toroidal plasma devices. For example, tokamaks have toroidal ripple due to discrete field coils, optimized stellarators do not achieve exact quasi-symmetry, the plasma itself continually seeks lower energy states through helical 3D deformations, and reactors will likely have non-uniform distributions of ferritic steel near the plasma. Also, some level of designed-in 3D magnetic field structure is now anticipated for most concepts in order to lead to a stable, steady-state fusion reactor. Such planned 3D field structures can take many forms, ranging from tokamaks with weak 3D ELM-suppression fields to stellarators with more dominant 3D field structures. There is considerable interest in the development of unified physics models for the full range of 3D effects. Ultimately, the questions of how much symmetry breaking can be tolerated and how to optimize its design must be addressed for all fusion concepts. Fortunately, significant progress is underway in theory, computation and plasma diagnostics on many issues such as magnetic surface quality, plasma screening vs. amplification of 3D perturbations, 3D transport, influence on edge pedestal structures, MHD stability effects, modification of fast ion-driven instabilities, prediction of energetic particle heat loads on plasma-facing materials, effects of 3D fields on turbulence, and magnetic coil design. A closely coupled program of simulation, experimental validation, and design optimization is required to determine what forms and amplitudes of 3D shaping and symmetry breaking will be compatible with future fusion reactors. The development of models to address 3D physics and progress in these areas will be described.

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