Helical core tokamak MHD equilibrium states

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Continuous long-lived modes that are observed in a variety of tokamak devices like TCV, MAST, NSTX as well as “snakes” in JET constitute manifestations that the plasma in these systems should be more appropriately described as novel magnetohydrodynamic (MHD) equilibrium states with a three-dimensional (3D) core embedded within an essentially axisymmetric external mantle. A version of the 3D VMEC code, ANIMEC [1], is applied to compute tokamak equilibrium states with nested magnetic surfaces and an imposed axisymmetric boundary. For conditions of weak to moderate reversed central magnetic shear and a minimum inverse rotational transform close to unity, bifurcated solutions of the MHD equilibrium exist. One of these is the standard axisymmetric solution that can be calculated with typical Grad-Shafranov solvers; the second displays a 3D helical core with characteristics similar to a saturated $m = 1, n = 1$ ideal internal kink mode. The equilibrium state that is obtained depends solely on the initial guess provided for the position of the magnetic axis. When a sufficiently distorted helix is chosen to describe the axis, the 3D equilibrium solution is obtained; otherwise the resulting equilibrium is axisymmetric. In most cases, the helical states persist even with vanishing pressure, although a few counter examples do require finite $\beta$ to trigger the bifurcation. Helical structures are easier to generate with high elongation, with large plasma current or with smaller aspect ratio. The ITER hybrid scenario is particularly susceptible to this bifurcated phenomenon, which we also observe in simulations of the TCV tokamak and the MAST spherical torus with flat central pressure profiles. We also reproduce the “snakes” in JET prescribing a peaked pressure profile without having to invoke the formation of a magnetic island on the $q = 1$ surface. The 3D helical core equilibrium states we calculate in nominally axisymmetric tokamaks constitute a paradigm shift for which the tools developed for stellarators in MHD stability, kinetic stability, drift orbits, wave propagation or heating, neoclassical transport, gyrokinetics, etc become applicable and necessary to more accurately evaluate magnetic confinement physics phenomena.

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References