Phase-Locking of Multi-Helicity Neoclassical Tearing Modes in Tokamak Plasmas

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Conventional high-β tokamak plasmas are characterized by a single, relatively benign, neoclassical tearing mode (NTM)—typically, the $m = 3, n = 2$ mode. The so-called *hybrid scenario* combines comparatively high q_{95} operation with improved confinement compared with the conventional $H_{98,y2}$ scaling law. If this kind of scenario could be reproduced on ITER then it would enable high-Q operation at reduced plasma current. Somewhat unusually, hybrid discharges tend to exhibit simultaneous NTMs with different mode numbers. For example, $2, 1$ and $3, 2$ NTMs have been observed simultaneously in both DIII-D and JET hybrid discharges [1, 2]. In addition, $4, 3$ and $5, 4$ NTMs have been observed simultaneously in JET hybrid discharges [3]. In all cases, the different modes are eventually observed to phase-lock to one another, giving rise to a significant flattening, or even a reversal, of the core toroidal plasma rotation profile. This behavior is highly undesirable because the loss of core plasma rotation is known to have a deleterious effect on plasma stability (because it facilitates locked mode formation).

We present a simple cylindrical model of the phase-locking of two or more NTMs with different poloidal and toroidal mode numbers in a tokamak plasma. Such locking takes place via a combination of nonlinear three-wave coupling and conventional toroidal coupling: e.g., $2, 1 + 2, 1 = 4, 2$ and $3, 2 + 1, 0 = 4, 2$, where the $1, 0$ perturbation corresponds to the Shafranov shift of the equilibrium flux-surfaces.

In accordance with experimental observations, the model predicts that there is a bifurcation to a phase-locked state when the frequency mismatch is reduced to half of its original value. Furthermore, the phase-locked state is characterized by the permanent alignment of the X-points of the NTM island chains on the outboard mid-plane, and a modified toroidal angular velocity profile interior to the outermost coupled rational surface that is such that the core rotation is flattened, or even inverted.

References

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