Compressibility and nonlinear mode coupling in edge instabilities in a toroidal plasma*

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In magnetically confined fusion plasmas, predicting the mode numbers of plasma edge instabilities such as ELMs and inter-ELM modes is an important unsolved theoretical problem that is closely related to edge stability. MHD linear eigenmodes typically have a spectrum of toroidal harmonics with slowly varying growth rates, where the most unstable mode numbers are often much larger than those observed in experiment. In contrast, MHD nonlinear numerical simulations, started from the full range of toroidal harmonics, find moderate mode numbers and spatial structures similar to experiment. Several types of mode coupling exist: toroidal coupling due to $R - R_o = r\cos\theta$, nonlinear fg coupling of toroidal harmonics $n'' = n' + n$, radial overlap of modes with different m, n due to the rapidly varying safety factor q near the edge, and near-Hamiltonian stochasticity of the perturbed magnetic field in the presence of an X-point on the plasma separatrix. Study of an interior mode, the 1/1 internal kink, finds that compressibility is important. Particular $\mathbf{J} \times \mathbf{B}$ terms that are higher order in inverse aspect ratio change the linear growth rate scaling and allow a fast, non-resistive sawtooth crash driven by growing nonlinearity, even at small r_1/R. These terms are also important for edge instabilities, modified somewhat by the higher overall mode numbers and larger r/R. They most strongly affect the lowest harmonics $n = 1, 2$, etc., that are created by nonlinear mode beating of the dominant intermediate-n harmonics and often grow to comparably large amplitudes. The effects are demonstrated for large ELMs and a smaller KSTAR inter-ELM mode that saturates without a crash, using the M3D code. Reduced MHD lacks these terms and sees only partial effects, including a slow sawtooth crash.

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