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Compressible Theory of Unmagnetized Islands in Inhomogeneous Plasma

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Plasma inhomogeneity can create magnetic islands through instabilities such as the classical, micro-tearing and neoclassical tearing modes (TM, MTM and NTM). Plasma inhomogeneity also affects how the plasma responds to applied resonant perturbations, such as those used for ELM control in tokamaks and for creating island divertors in stellarators. The IslET fluid model (Island Equilibrium and Transport) [1] describes islands in inhomogeneous plasma. It has recently been extended to account for ion compressibility, which allows island chains to couple to drift-acoustic waves. The compressible IslET model completes the equilibrium solution of Smolyakov et al. [2] by using transport equations to specify the *relaxed* form of the profiles (density, velocity and current) and in particular the degree to which they are flattened in the island.

Analytic solutions of the IslET model will be presented in the semi-collisional "unmagnetized" regime. This regime is such that island half-width W is wider than the width of the current channel found in linear theory but narrower than the ion-acoustic gyro-radius, $W<\rho_s$, with $\rho_s = c_s/\omega_{ci}$. It is also called the "supersonic" regime [3] because its islands have an azimuthal phase velocity that exceeds the speed of ion-acoustic waves, $\omega_* > k_\parallel c_s$. The new solutions extend a previous analysis [3] by removing the assumption that the phase velocity of the island is close to the electron drift velocity. This assumption can be violated in cases of interest, such as in the presence of temperature gradients or for islands interacting with external structures such as resistive walls, error fields, or other islands.

In the nonlinear regime, the evolution of a magnetic island resulting from a tearing mode is governed by the generalized Rutherford equations describing the rates of change of its half-width W and propagation velocity V. It is important for island models to describe both W and V for the following reasons:

- The polarization current, which depends on V, is often the *dominant contributor* to the island drive, especially for thin islands;
- The steady-state velocity can be a *multi-valued* function of the plasma island width, in which case both may exhibit hysteresis.

The Rutherford equations are:

$$dW/dt = 1.2\,\eta\,\Delta' + D(W,V);$$
$$dV/dt = F(W,V),$$

where η is the plasma resistivity in the tearing layer, Δ' and D(W,V) parametrize the drive for the tearing mode coming from respectively the external and internal current and pressure distributions, and F(W,V) represents the lateral force acting on the magnetic island. The IslET model calculates the two functions D(W,V) and F(W,V) for steady state islands, or for islands such that W and V are constant. Equivalently, it calculates the external drive parameter Δ' required for saturation of a tearing mode in the nonlinear regime. The model has contributed to the understanding of island evolution by clarifying the causes and effects of island magnetization and density flattening, accounting for the decrease of the island propagation velocity from the unmagnetized to the magnetized regime as well as the role of coupling to the drift wave and the effect of the electron temperature gradient on the island stability.
A limitation of previous versions of the IslET model [1], however, is its neglect of the ion parallel velocity. This results in an incompressible description of the ion fluid and suppression of the ion-acoustic or sound wave. In the linear regime, coupling to the sound wave is known to be responsible for the flattening of the density inside the island and the accompanying reduction in the island propagation velocity when its width is such that $k_\parallel c_s >> \omega_*$ (or $W >> \rho_s L_s/L_n$). By reducing the relative velocity between the island and the surrounding ions, it also has a stabilizing effect through the polarization current.

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