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Drift-kinetic theory of neoclassical tearing modes close to threshold in tokamak plasmas

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A new drift-kinetic theory and computational approach to understand the plasma response to small magnetic islands associated with neoclassical tearing modes (NTMs) is presented. It demonstrates that drift effects associated with the passing particles support a pressure gradient across a sufficiently small magnetic island, leading to a suppression of the instability drive from the bootstrap current perturbation. This result is an important input to quantifying the control requirements of future reactor-grade tokamaks, such as ITER.

NTMs degrade the performance of tokamak plasmas. They may hamper progress towards high fusion power in planned JET deuterium-tritium (DT) plasmas 1, and they are a concern for ITER and future fusion power plants. The instability drive is understood: above a threshold in beta-poloidal, and if an initial "seed"magnetic island exceeds a critical width, the plasma pressure gradient is flattened within that island. This removes the bootstrap current there, resulting in a filamentation of the total current density that amplifies the initial seed island, removing more bootstrap current and driving the island to even larger widths. The resulting large saturated island degrades confinement.

A key question for theory is: What is the physics that determines the critical island width and threshold poloidal beta? This is important for understanding how to develop NTM avoidance strategies and for quantifying the requirements of control systems, such as the electron cyclotron current drive (ECCD) planned for ITER. Experimentally, the critical island width is found to be ~2-3 trapped ion banana orbit widths 2. Thus, a theoretical model must retain finite ion banana width effects, requiring a kinetic approach. This is the aim of the present paper –to develop a kinetic theory of the ion response to small scale magnetic islands, and explore the consequences for NTM threshold physics.

Drift-kinetic models in 5D space (3 spatial and 2 velocity coordinates) are challenging to solve, but simulations have shown that the ion contribution to the bootstrap drive is reduced for island widths below the ion banana width [3]. We extend that theory to also solve for the electron response and self-consistently determine the impact of the electrostatic potential required for quasi-neutrality. The problem is made tractable by exploiting the small ratio of poloidal ion Larmor radius to plasma minor radius, and developing an expansion to reduce the dimensions of the system. To leading order, one finds that the orbit trajectories for both trapped and passing particles are unperturbed by the presence of a magnetic island. Proceeding to next order, averaging over the orbits provides a solvability condition for the particle response in a reduced 4D space: the canonical toroidal angular momentum, the helical angle labelling magnetic field lines on a flux surface, and two velocity coordinates (speed and pitch angle).

We have previously solved this 4D system numerically, employing a simplified model for the electrons that exploits the small ratio of electron poloidal Larmor radius to island width [4,5]. The result for the passing ions is particularly interesting –their distribution function appears to be flattened across a "phase space"island structure (not the magnetic island) that is very similar to the magnetic island, but shifted radially relative to it (fig 1). When the flow of the passing particles along magnetic field lines is reversed, the radial shift of the phase space island relative to the magnetic island is also reversed. A consequence of this shifted island structure is that a pressure gradient is supported across the magnetic island (fig 2). When the island width is rather larger than the poloidal Larmor radius, the shift of the phase-space island relative to the magnetic island is negligible and the pressure is then flattened across the magnetic island as expected in the standard NTM model.

To understand the physics of the simulations, we further reduce the model by considering the limit of small collision frequency, much less than the island propagation frequency in the ExB rest frame [6]. Neglecting collisions to leading order, the orbit averaged equations reveal that particles follow streamlines that represent the combined effect of parallel streaming and cross-field drifts: grad-B, curvature and ExB. These streamlines, which we derive analytically, define "drift surfaces"(Fig 1). In the absence of the ExB drift we find that the drift surfaces for the passing particles are exactly the same as the magnetic island flux surfaces, but shifted radially by a few poloidal Larmor radii. When collisions are neglected, the particle distribution function is constant on these drift surfaces. Note in Fig 1 the agreement between the analytic drift surfaces and the "phase-space" island structures of the full, 4D numerical solution (colour contour plot). The origin of the pressure gradient that is supported inside the magnetic island is therefore a consequence of passing particle physics.

We have shown that the distribution function is constant on the drift surfaces, but we do not know how it varies across them. We re-introduce collisions into the model as a perturbative correction and average over the drift surfaces to derive a transport equation for the distribution function that balances collisional diffusion across the drift surfaces with pitch-angle scattering. This equation reveals two interesting boundary layers: one close to the separatrix of the island in the drift surfaces and one close to the trapped-passing boundary in pitch angle. The latter requires special attention as the collisions cannot be treated perturbatively there, so a new collisional boundary layer equation is derived. The solution of this layer equation connects trapped and passing particle solutions. An iteration procedure provides the self-consistent electrostatic potential and hence the full distribution function.

This semi-analytic calculation predicts a density profile that supports a gradient within magnetic islands that are sufficiently narrow (a few poloidal Larmor radii), confirming the conclusions of the 4D numerical solution. However, there remain some differences between predictions for the distribution function obtained using the two approaches, and these differences influence the current density distribution in the island vicinity. We show how the part of this current density that is in phase with the magnetic island influences whether it grows or decays (ie the conditions for a threshold). On the other hand, dissipation, which in our model is dominated by the effect of the trapped-passing boundary collisional layer, drives the part of the current density which is out of phase with the island; this determines the island propagation frequency.

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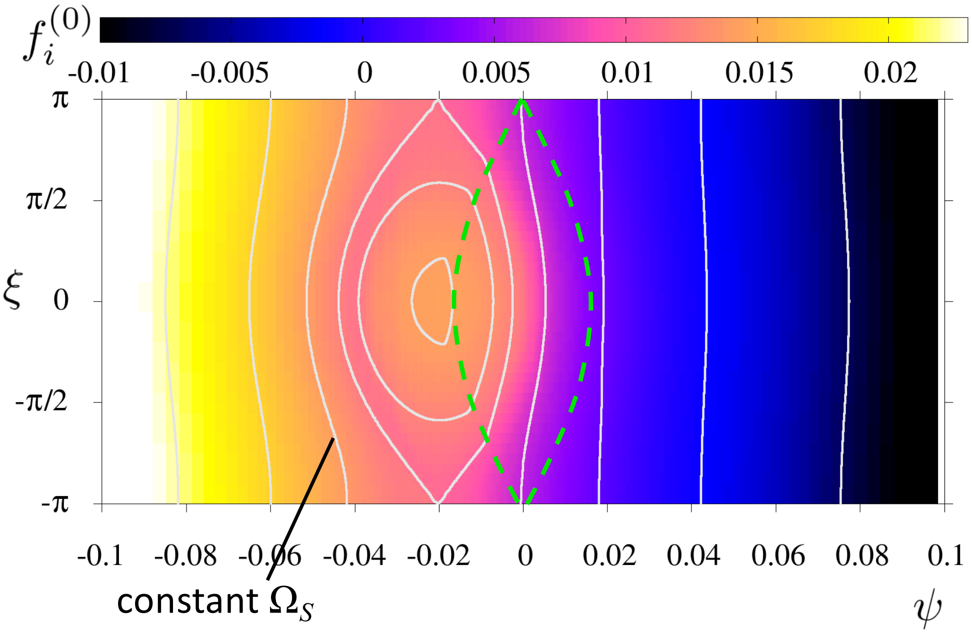

Figure 1: Contour plot of numerical solution for ion distribution function (colour contours) compared to magnetic island (dashed curve) in space of poloidal flux (psi) vs xi. Full curves show analytic drift surfaces, Omega_s.

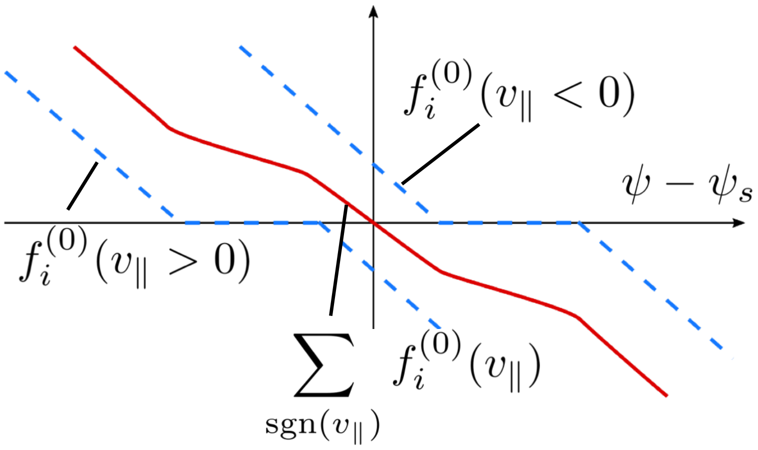

Figure 2: Distribution function (dashed curves) is flattened across drift islands, shifted relative to magnetic island by ~rho_theta, in opposite directions depending on sign of v||; summing over sign of v||, required for density moment, indicates a gradient in pressure across the magnetic island (full curve).

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