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Micro-Tearing Modes in MAST

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Recent linear gyrokinetic calculations carried out using spherical tokamak equilibria suggest that these devices are susceptible to instabilities producing magnetic reconnection at ion gyro-radius scale lengths. These so called micro-tearing modes have been identified in H-mode equilibria from MAST at Culham and NSTX at Princeton. In the past it was suggested these instabilities may provide an explanation for the anomalous heat transport in tokamak plasmas, but more recent work points towards the ion temperature gradient (ITG) driven instability as the main source of heat flux in conventional tokamaks. However, experimental data suggests that in NSTX H-mode plasmas [1], the heat transport occurs mainly through the electron channel, which is uncharacteristic of ITG transport. This transport may instead be due to electrons free streaming along stochastic magnetic fields, caused by the growth of micro-tearing instabilities.

Gyrokinetic simulations of an ELMy H-mode MAST discharge (#6252) were carried out previously in [2]. There the initial value gyrokinetic code GS2 [3] was used to perform a fully electromagnetic linear stability survey of the discharge. The results showed that micro-tearing modes were competing with ITG modes for dominance at ion gyro-radius length scales.

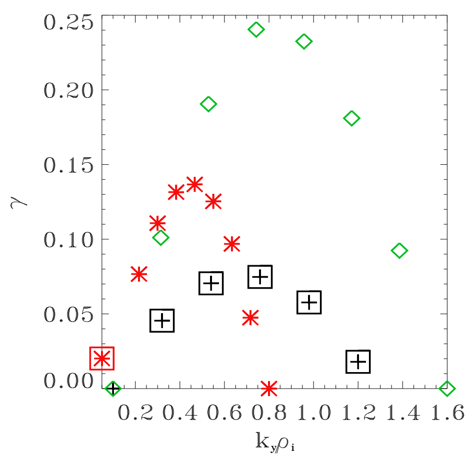

Figure 1: Growth rates γ against poloidal wavenumber k_y for poloidal flux ψ/ψ_{MAX} = 0.4 (crosses), 0.6 (stars), and 0.8 (triangles). The micro-tearing modes are boxed.

In Figure 1 the growth rates (normalised to the ion thermal velocity/minor radius) of these ion scale instabilities are given as a function of poloidal wavenumber (normalized to $1/\rho_i$) for three different poloidal flux surfaces ($\psi/\psi_{MAX} = 0.4, 0.6, 0.8$). ITG modes are mainly present on the outer surfaces whilst on the inner (0.4) surface the micro-tearing instabilities are dominant. These tearing instabilities are readily characterised by the even parity of the parallel vector potential (Figure 2) often referred to as tearing parity since it is required for magnetic reconnection. Similar results have been found on another MAST discharge (#8500) [4] and also on NSTX [1]. Mixing length estimates of the heat transport from these instabilities suggest that they could be experimentally relevant.

Poincaré plots are presented here to illustrate the effect these micro-tearing instabilities have on the magnetic field structure. In order to do this the perturbed magnetic field data from GS2 is used to calculate the path magnetic field lines take as they wrap around the torus. A cross-section is then taken through the field lines to produce the Poincaré plot.

GS2 utilises a flux tube simulation domain [5] which is essentially a long thin tube parallel to the magnetic field lines. The parallel length of the tube is labelled using the *poloidal* angle θ, which makes contact with traditional ballooning theory, and the two perpendicular coordinates are x and y, where x is in the radial direction. Poincaré plots can be made by taking cross-sections through the magnetic field lines in the flux tube at constant θ.

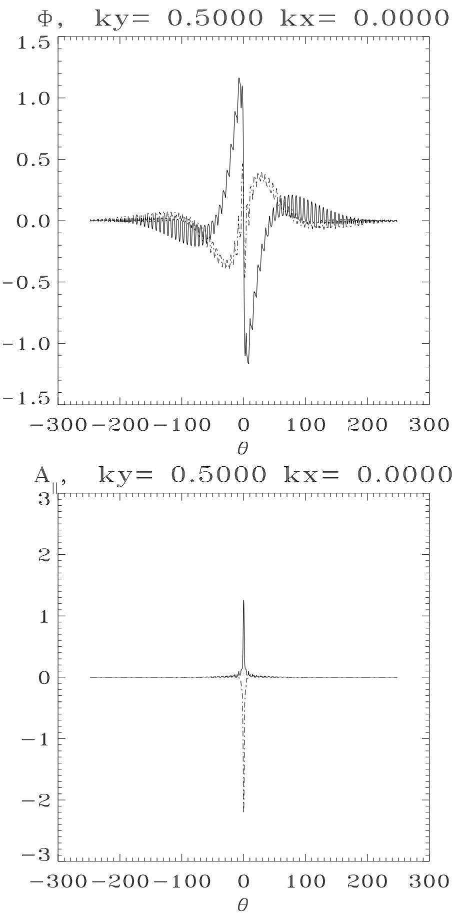

Figure 2: (Top) Electrostatic potential ϕ and (Bottom) parallel vector potential $A_{\|}$ as functions of the ballooning angle θ.

The Poincaré sections in Figure 3 were calculated at $\theta = 0$, using $A_{\|}$ data for a single harmonic mode with $k_y\rho_i = 0.66$. Each plot is identical except for the amplitude of the field perturbation which increases in each plot from left to right. Every plot has a magnetic island structure at the rational surface $q = \frac{34}{25}$ which increases in size and complexity as the amplitude of the perturbation is increased. Amplifying the perturbation even further eventually causes the magnetic surface structure to break down so that the field lines follow stochastic paths. (One should note these are only linear calculations so the plots produced at large amplitude are somewhat unphysical because they neglect nonlinear effects).

Further study of these instabilities has shown they are much more dependent on electron physics than ion physics and that they occur for both flat and finite density gradients. Altering the ion temperature gradient or ion collisionality has little effect on the instability while finite electron temperature gradient and electron collisionality are both crucial to the instability. Cal-

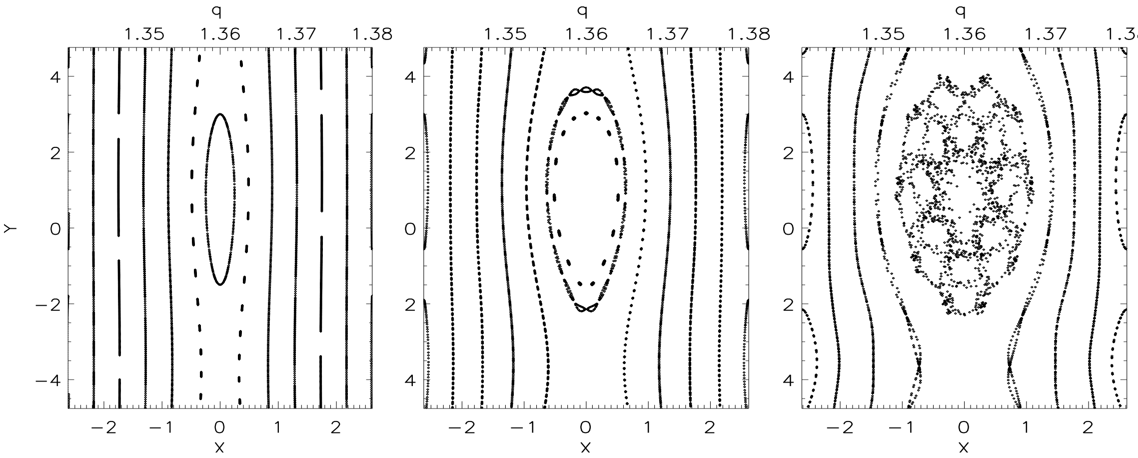

Figure 3: Poincaré plots for the tearing instability found at $k_y \rho_i$=0.66. The x and y axis are given in units of ρ_i.

culations have been performed in which ions have been given a Boltzmann response and these confirm that ion physics plays a minor role in the instability (see Figure 4).

The dominance of electron physics follows from the length of the eigenfunctions along the field line. Since the radial wavelength of the instability is roughly proportional to the inverse of the ballooning angle θ, it becomes much smaller than the ion Larmor radius far along the field lines, and the ions become unmagnetised and adiabatic. Conversely the electron Larmor radius is 60 times smaller and comparable to the mode wavelength at these large values of θ.

This MAST instability is neither collisionless, which would require it to be independent of collisions, nor collisional, where the electron collisionality is assumed much larger than the mode frequency $(\nu_e \gg \omega)$ [6]. Rather it seems to lie between these regimes with $\omega \sim \nu_e$. Slab calculations in [6] [7] show that the electron temperature gradient can destabilise a micro-tearing mode when an energy dependent collision operator is used. This is contrary to our calculations for the MAST instability which show the mode is still unstable with an energy independent collision operator (see Figure 5). Later papers using toroidal geometry [8] [9] also emphasize the need for trapped particle physics for micro-tearing instabilities and work is underway to see how important trapped particle physics is to the MAST instability.

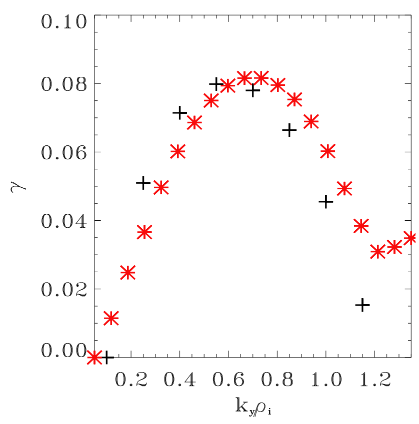

Figure 4: Plot of growth rate versus $k_y \rho_i$ for single species model (crosses) with Boltzmann ion reponse, and two species model with full ion physics (stars).

Another interesting property of the tearing mode is its dependence on the magnetic field topology. Increasing the magnetic shear is destabilising to the instability up to a certain point and then it starts to have a stabilising influence. This phenomenon is also mentioned in [7] where it is explained in terms of field line bending. We also found the spherical tokamak geometry was not critical in destabilising the mode; calculations at much higher aspect ratios, using a circular $s-\alpha$ geometry, still found the mode unstable.

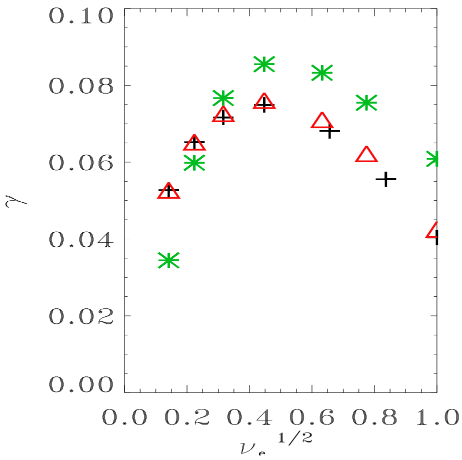

Figure 5: Plot of growth rate γ vs. $\nu_e^{1/2}$ using GS2 Lorentz collision operator (crosses), full Lorentz collision operator (triangles), and using energy independent collision operator (stars). Calculations had $k_y\rho_i$=0.5.

Finally, while working with GS2 we decided to add some additional terms to the collision operator. These terms are often neglected in gyrokinetic calculations which has been pointed out by Alexander Shekochihin[10]. Consider the gyro-averaged Lorentz collision operator for a mode with perpendicular wavenumber k,

$$\langle \mathscr{C}[h] \rangle = \frac{\nu(\mathrm{v})}{2}\left[\frac{\partial}{\partial\xi}\bigg|_{\mathbf{R}}(1-\xi^2)\frac{\partial h}{\partial\xi}\bigg|_{\mathbf{R}} - \frac{\mathrm{v}^2(1+\xi^2)}{2\Omega^2}k_\perp^2 h\right] \quad (1)$$

where h is the non-adiabatic part of the perturbed distribution function, ϕ is the gyro-phase angle, the derivatives in $\xi = \mathrm{v}_\parallel/\mathrm{v}$ (parallel particle velocity divided by total velocity) are at constant guiding centre position $\mathbf{R}$, and Ω is the gyrophase frequency. In GS2 the second term is neglected since it is usually small, but this may not be true for the micro-tearing mode which exhibits particularly large $k_\perp^2\rho_i^2$. However, from Figure 5 it is clear the extra term has little effect on the growth rate of the mode, and this is thought to be due to the effectively Boltzmann response of the ions at large $k_\perp^2\rho_i^2$. Intriguingly, initial results seem to suggest the new collision operator does become important for nonlinear micro-tearing calculations.

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