*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-4.189 (2004)*

High β electron micro-stability in Spherical Tokamaks

N J Joiner[1], D J Applegate[1], S C Cowley[2], W Dorland[3], C M Roach[4]

[1]*Imperial College, London, UK,* [2]*UCLA, Los Angeles, USA,* [3]*University of Maryland, College Park, USA,* [4]*EURATOM/UKAEA Fusion Association, Abingdon, UK*

Introduction

High β values achieved in spherical tokamaks, make experimental devices such as MAST [1] an attractive alternative route to fusion energy. Whether this can be realised depends on the underlying anomalous transport, and so understanding the behaviour of the micro-instabilities responsible for transport in these plasmas is very important. Electron scale micro-instabilities are investigated using the gyro-kinetic code, GS2 [2]. Variations of $\beta' = -\beta/L_p$ and global magnetic shear $\hat{s}$ are treated by a perturbative local equilibrium expansion [3] around MAST equilibrium flux surfaces [4]. In this way, linear stability is studied in regimes of steep pressure gradient and high local β.

Equilibrium Effects

A scan of the normalised pressure gradient $\alpha = -q^2 R\beta'$ is carried out for various values of the magnetic shear $\hat{s}$.The $\rho = \psi/\psi_{LCFS} = 0.4$ surface is used for analysis, and the parallel magnetic perturbation is taken to be zero. Ions are treated as adiabatic, and the plasma is taken to be collisionless.

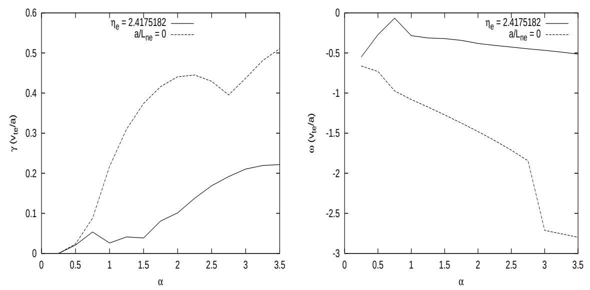

Figure 1: Growth rate γ vs. α, and real frequency ω vs α for $\eta_e = 2.42$ and $\nabla n = 0$ with $\hat{s} = 2.0$

Taking $k_y\rho_e = 0.6$ and decreasing the pressure gradient scale length (increasing the pressure gradient α) consistently between the equilibrium and gyro-kinetic equation, for the cases of finite $\eta_e = const.$ and $\nabla n = 0$, reveals the destabilisation and subsequent stabilisation of multiple electron scale micro-instabilities (Figure 1), with $\beta_e = const. = 0.05$ and $\hat{s} = 2.0$. Discontinuities in the plots of the real frequency indicate a change to a different mode or branch. Examination of the real frequency spectrum, for the $\nabla n = 0$ scenario, in Figure 2 shows that an increase in α brings about a more dominant mode at progressively longer perpendicular wavelengths.

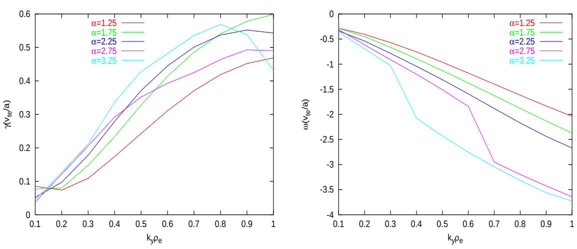

Figure 2: k_y spectrum for a series of α ($\hat{s} = 2.0, \nabla n = 0$) showing the transition between two branches as α is increased

The eigenfunctions of the two branches reveal a possible explanation for the branch change in Figure 1. Figure 3 shows the eigenfunctions for the electrostatic potential at $\alpha = 2.0$ and 3.0. The increased pressure gradient can destabilise higher parallel harmonics, giving the eigenfunction more parallel structure.

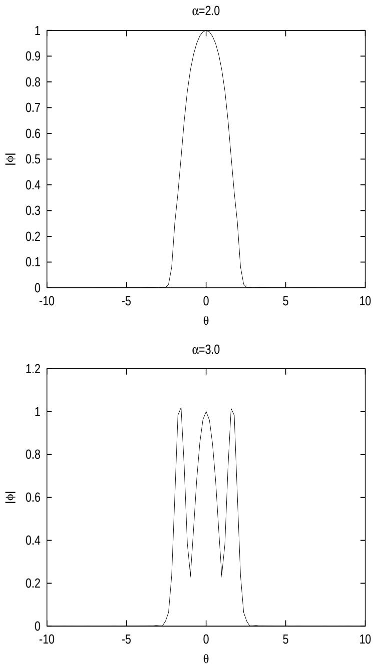

Figure 3: $|\phi|$ vs. θ for $\alpha = 2.0$ and 3.0 ($\hat{s} = 2.0, \nabla n = 0$)

Figure 4 shows that this effect occurs at different values of the global magnetic shear, for both the finite η_e case and the $\nabla n = 0$ case. The dispersion relation has been examined for a wide range of $\hat{s}$ and α, and shows a characteristic ETG curve. This work shows that there can be several different ETG branches characterised by the stability of their parallel components.The two competing effects of increasing α are: first to move the longer parallel wave lengths into a regime of second stability, and secondly to provide the energy to destabilise shorter parallel wavelengths. Similar research on a NSTX plasma [5] shows one well defined peak in the growth rate of the ETG mode in a β' scan for the fully electromagnetic case, and two peaks when $\delta B_{||} = 0$ (The form of which bears a strong resemblance to the $\hat{s} = 1.5$ curve in the left diagram of Figure 4). The parameters used by Bourdelle et. al [5] are $\beta = 0.3$, $\hat{s} = 1.3$, $\eta_e = 3$, $k_\theta \rho_e = 0.3$. Figure 2 suggests that their use of lower k_y than the current work, may reduce the sensitivity of the pressure gradient on the growth rate.

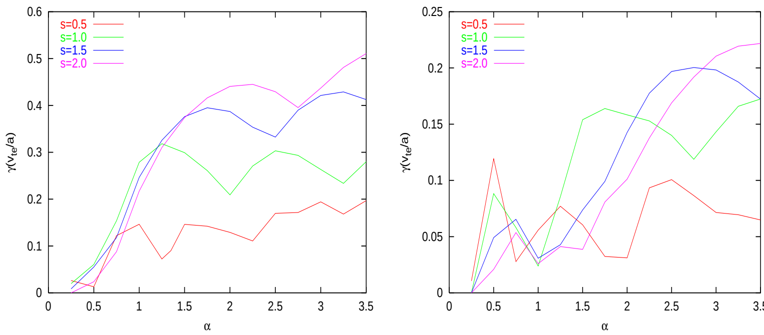

Figure 4: The effect of the pressure gradient on $k_y \rho_e = 0.6$ for $\hat{s} = 0.5, 1.0, 1.5, 2.0$, $\nabla n = 0$ (left) and $\eta_e = 2.4$ (right)

β effects

In this section the effect of β on the linear modes is investigated. We begin by varying β inconsistently with the equilibrium, in order to establish the electromagnetic effects on the ETG mode. Keeping to the $\rho = 0.4$ surface of the MAST equilibrium, using the fully electromagnetic terms of GS2, figure 5 shows that β has a stabilising influence on the ETG mode.

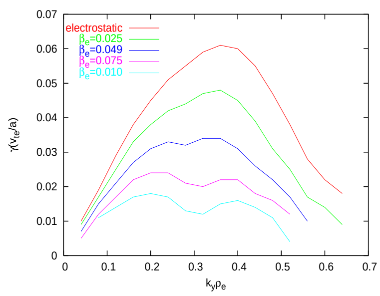

Figure 5: Growth rate vs. k_y for varying values of β_e, on the $\rho = 0.4$ flux-surface

Contrary to the conventional wisdom, that $\delta B_{||}$ can be neglected at low β, the β effect comes from $\delta B_{||}$ even at $\beta_e = 0.025$ (Figure 6)

The lack of β effect from the $A_{||}$ terms can be explained to some extent by considering the local dispersion relation. This can be derived [6] with $\delta B_{||} = 0$, using the gyro-kinetic equation, the quasi-neutrality condition and the parallel component of Ampére's law, giving,

$$1 + \tau - P_0 + \frac{P_1^2}{2k_\perp^2/\beta_e + P_2} = 0 \tag{1}$$

where,

$$P_m = \frac{1}{\sqrt{2\pi}} \int (v_{||})^m \frac{\omega - \omega_* \left[1 + \eta_e(v^2/2 - 3/2)\right]}{\omega - \omega_D - k_{||}v_{||}} J_0^2(k_\perp v_\perp) e^{-v^2/2} v_\perp dv_\perp dv_{||} \tag{2}$$

$\tau = T_e/T_i$, $\beta_e = 8\pi n_0 T_e/B^2$, $\omega_* = k_y$ and $\omega_D = \epsilon_n \omega_* (v_{||}^2 + v_\perp^2)$. The wave numbers $k_\perp$ and $k_{||}$ are normalised to the electron gyro-radius $\rho_e = v_{te}/\Omega_{ce}$ and density gradient scale length L_n respectively. Frequencies are normalised to v_{te}/L_n.

As noted by Kim and Horton [6], when $k_{||} = 0$, the integrand of P_1 is odd in $v_{||}$, and so $P_1 = 0$ and the electromagnetic contribution disappears. We have examined the $k_{||}$ power spectra for these eigenfunctions, and see that they are dominated by small parallel wavenumbers, which are uneffected by the electromagnetic term of equation 1. This illustrates how a local analysis at high $k_{||}$ [6] may overestimate the impact of β. We have used the analytic methods of Kim and Horton [6] to obtain a dispersion relation for the ETG mode with finite $\delta B_{||}$ and $A_{||} = 0$, and find that the electromagnetic term in this case is significant at low $k_{||}$. The above findings, have also been seen on the $\rho = 0.6$ and 0.8 surfaces, and in simulations on high aspect ratio, low β, analytic equilibria.

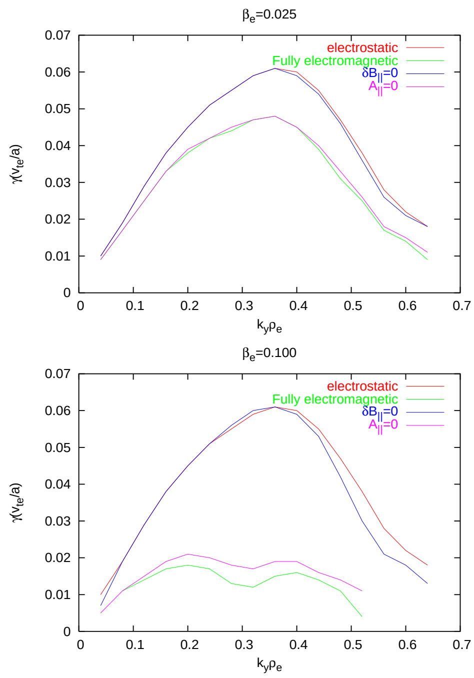

Figure 6: Comparison of the effects of $A_{||}$ and $\delta B_{||}$ for $\beta_e = 0.025$ and $\beta_e = 0.100$

Micro-tearing

Electromagnetic modes with tearing parity in the eigenfunctions have been observed to occur for $\hat{s} \gtrsim 1$ and $a/L_p \gtrsim 3$ at $k_y\rho_e \sim$ 0.01-0.15. The importance of these collisionless electron-tearing modes is illustrated in a conceptual Spherical Tokamak Power Plant (STPP) [7], where the ETG mode is found to be absolutely stabilised, leaving micro-tearing modes as the dominant instabilities. A Poincaré sectioning diagnostic (Figure 7) as been developed to show the evolution of the confining magnetic field to stochasticity from magnetic island growth.

Nonlinear Simulation

A nonlinear study has begun, to establish the effect of high β on turbulent ETG transport (Figure 8), and the significance of the micro-tearing mode, using EPSRC's HPCx and USDOE's Cheetah high performance computers.

The early results show experimentally significant transport, though convergence studies of the result in Figure 8 with respect to the x and y wavenumbers and flux-tube width have yet to be completed. Preliminary studies of the tearing mode show that magnetic transport is the dominant mechanism.

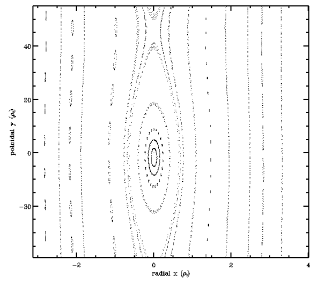

Figure 7: Islands produced by the micro-tearing modes visualised by Poincaré section

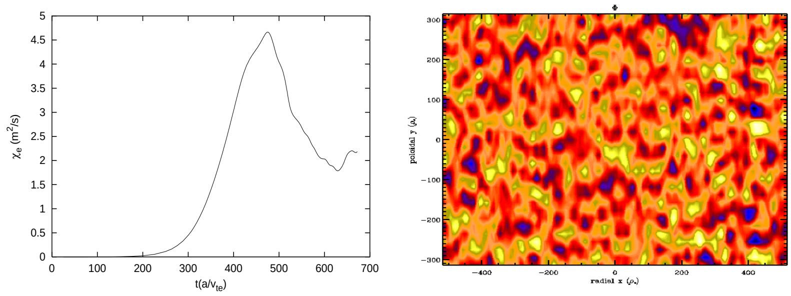

Figure 8: Nonlinear MAST simulation. Thermal diffusivity vs time (left) and contours of electrostatic potential ($\theta = 0$) (right)

References

[1] A.Sykes et al. Phys.Plasmas **8**, 2101 (2001).

[2] M.Kotschenreuther, G.Rewoldt and W.M.Tang, Comp.Phys.Comm. **88**, 128 (1995).

[3] J.M.Greene and M.S.Chance, Nucl.Fusion **4**, 453 (1981).

[4] D.Applegate et al.31st EPS conf. of Cont. Fusion and Plasma Phys, London (2004)

[5] C.Bourdelle et al. Phys.Plasmas **10**, 2881, (2003).

[6] J.Y. Kim and W.Horton Phys.Fluids **B3**, 3194, (1991).

[7] H.R.Wilson et al. submitted to Nucl.Fusion

This work is funded by the UK Engineering and Physical Sciences Research Council

The authors would like to thank Jack Connor for helpful discussion