32nd EPS Conference on Plasma Phys. Tarragona, 27 June - 1 July 2005 ECA Vol.**29C**, P-4.034 (2005)

Microstability analysis of e-ITBs in high density FTU plasmas

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Electron internal transport barriers (e-ITBs) are routinely produced on FTU (Frascati Tokamak Upgrade) using radio frequency electron heating (Lower Hybrid and ECRH heating). In the presence of an e-ITB central temperatures $T_e > 11$ keV at densities $n_e(0) \approx 0.8 \cdot 10^{20}$ m^{-3}, have been sustained longer than 35 confinement times, [1]. The common understanding about ITB formation is that the phenomena is associated to local turbulence stabilization and improvement of the thermal conductivity. Several mechanisms are candidate for explaining the stabilization of turbulence among which magnetic shear stabilization, ExB shear, Zonal flows and collisionality effects [2]. FTU high density plasmas are particularly suited to explore high collisionality regimes and the effects on turbulence and transport. In this work we have considered two discharges with similar plasma parameters and auxiliary heating power: one of them developed an e-ITB whereas the other did not. We have analyzed turbulence in the two discharges both experimentally by analysing reflectometer density fluctuations and numerically by using the electrostatic gyrokinetic stability code Kinezero. The version of Kinezero used in this work includes collisionality. The KineZero code calculates the stability of electrostatic drift modes in a toroidal plasma. These modes are characterized by wave numbers $k_\theta \rho_i$ ranging between 0.1 and 10^3 (ρ_i is the ion Larmor radius). In particular two subranges can be identified: modes linked to the ion drift dynamics and trapped electrons ($0.1 < k_\theta \rho_i < 2$), commonly referred as ion temperature gradient driven modes (ITG) and trapped electron modes (TEM) and modes linked to the electron drift dynamics ($2 < k_\theta \rho_i < 10^3$), commonly known as electron temperature gradient driven modes (ETG). In order to include collisionality effects in Kinezero we have considered the linearized Vlasov equation for the perturbed electrons distribution function $f_{1,e}$ with a Krook collision operator [4]:

$$\frac{\partial f_{1,e}}{\partial t} + [f_{1,e}, H_{0,e}] + [f_{0,e}, H_{1,e}] = -\nu_{fe} f_{1,e} - \nu_{fe} \frac{H_{1,e}}{T_e} f_{o,e} \quad (1)$$

where $\nu_{fe}(\varepsilon,\lambda) = \nu_{ei}(\mathrm{v_{the}}/\mathrm{v})^3 Z_{eff} \left(\frac{1}{|(1-r/R_0)-\lambda|^2} \frac{0.111\delta+1.31}{11.79\delta+1} \right)$, with $\delta = [|\omega|/(\nu_{ei} Z_{eff} \times 37.2 R_0/r)]^{1/3}$ and $f_{o,s}$ is the equilibrium maxwellian distribution [4, 5].

The corrections for finite collisionality at zero order approximation are negligible for passing particles as long as $k_{\|} \mathrm{v}_{\|} \gg \nu_{\mathrm{fe}}$. Electron-electron collisions effects have been neglected since they give a correction to Z_{eff} in the expression ν_{fe} which is negligible for $(\mathrm{v}/\mathrm{v}_{\mathrm{the}}) \ll 1$ as it is in our ordering [5]. We consider the ordering $\nu_{fe} < \omega_{be}$ (ω_{be} being the electron bounce frequency). It is worth to note that although Eq. (1) does not conserve momentum and energy, the fraction of trapped electrons remains unchanged in the banana regime. By following the same procedure used in [3] we arrive to the modified non adiabatic response of trapped electrons in the dispersion relation for electrostatic drift modes:

$$L_{te} = \langle \int \frac{dk_r}{2\pi} J_0^2(k_\perp \rho_{ce}) J_0^2(k_r \delta_e) \frac{\omega - n\omega_e^*}{\omega - n\omega_{de} + i\nu_{fe}} |\tilde{\phi}(k_r)|^2 \rangle_t \qquad (2)$$

$J_0^2(k_\perp \rho_{ce})$ and $J_0^2(k_r \delta_s)$ are the Bessel functions standing for the gyro-average over the cyclotron and the bounce motion respectively. The term $n\omega_{de}$ is the vertical drift frequency. The average $\langle \ldots \rangle_t$ implies an integral on energy $\varepsilon = E/T_e$ and on $\lambda = \mu B/E$ which is solved numerically in the code.

The new version of the code has been benchmarked with the results obtained with the gyrokinetic code GS2 [5] and presented in [6] where runs at different collisionalities and two different values of the normalized logarithmic density gradient A_n, have been performed. It has been shown that at high collisionality the density gradient has a stabilizing effect for low $k_\theta \rho_i$ instabilities whereas at low collisionality the effect is opposite. We performed Kinezero runs for the same discharge (12747) considered in [6] and using the same scan parameters. The results obtained are schematically shown in Fig. 1. The maximus linear growth rate γ as function of $k_\theta \rho_i$ at the radial position $r/a = 0.7$, for two values of A_n and at two different collisionality is plotted. The results are in good agreement with GS2 and confirm the above dependence of turbulence on the density gradient at different collisionality. Furthermore values of the growth rate obtained with Kinezero are of the same order as those obtained with GS2 runs as can be seen by comparing Fig. 1 with Fig. 8 of the paper [6]. FTU has a major radius $R_0 = 0.935$ m and minor radius $a = 0.3$ m. The considered discharges 26669 and 26672 have low plasma cur-

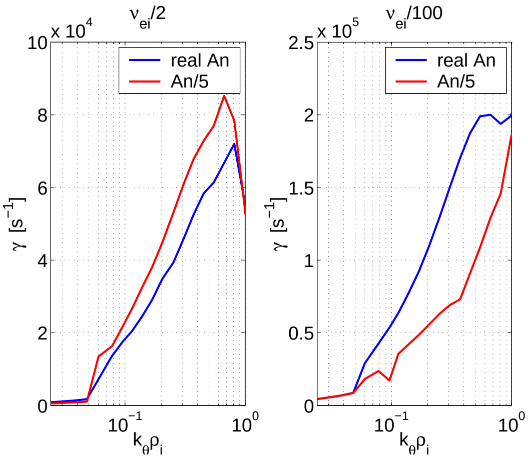

Figure 1: *Growth rate dependence on collisionality and density gradient A_n*

rent, $I_p \approx 360$ kA, magnetic field $B = 5.3$ T and central line averaged density $n_o \approx 8 \cdot 10^{19}$ m^{-3}. The heating power used in the two shots is 0.7 MW of lower hybrid plus 1.0 MW of electron cyclotron for pulse 26669 and 1.3 MW of lower hybrid for pulse 26672. During the heating phase, the central electron temperature was respectively $T_e \approx 5.5$ keV and $T_e \approx 3.5$ keV.

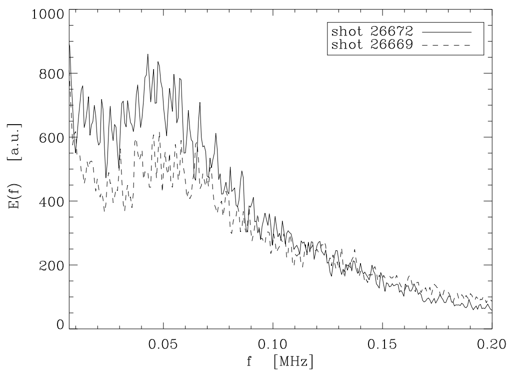

Figure 2: *Fourier spectra of reflectometer signals taken during the heating phase*

Discharge 26669 developed an e-ITB with foot at $r/a \approx 0.33$ whereas the discharge 26672 did not develop a barrier. For further details on the formation of the barrier in the above pulses and the establishment of high T_e gradients we refer the reader to the invited talk and related paper of V. Pericoli at this conference. It is known that the application of auxiliary heating power increases the turbulence level. Turbulence level in the discharges considered here can be compared since they have similar input power. High frequency reflectometer measurements have been analyzed during the heating phase ($0.6\text{ s} \leq t \leq 0.8$ s). In both cases the reflection radius was localized at $r/a \approx 0.4$ (that is sligthly outside the foot of the barrier for pulse 26669).

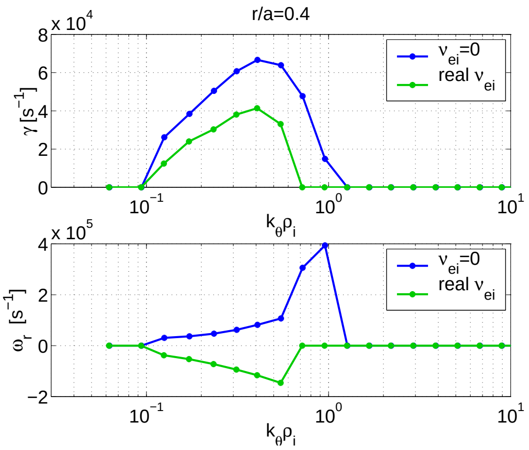

Figure 3: *Change of turbulence with collisionality from TEM-ITG to ITG*

We found that high frequency turbulence for the e-ITB discharge is lower than in shot 26672 in which the barrier did not develop. This is clearly shown in Fig. 2. The result supports the idea that the formation of ITBs is associated to turbulence suppression. The suppression of turbulence is clearer if we consider that the e-ITB pulse was characterized by an slightly higher heating power level. Results presented here refer to the preliminary study with KineZero of the stability of discharges 26669 and 26672 at $t = 0.8$ s during the heating phase and at the reflection radius position $r/a = 0.4$. The main stability parameters of the two discharges are: $q = 1.7$, $s = 1$, $\alpha = 0.1$, $A_n = R/L_{ne} = 3.2$, $R/L_{Te} = 11.5$, $Z_{eff} = 2.45$, $\nu_{ei}/\varepsilon n\omega_{de} = 2.2$ ($k_\theta \rho_i = 1$), for pulse 26669 and $q = 1.9$, $s = 1$, $\alpha = 0.1$, $A_n = R/L_{ne} = 4.5$, $R/L_{Te} = 10$, $Z_{eff} = 2.1$, $\nu_{ei}/\varepsilon n\omega_{de} = 3.6$ ($k_\theta \rho_i = 1$), for pulse 26672. As expected for an high collisional plasma, we find that FTU collisionality can change the nature of turbulence from a TEM-ITG dominated turbulence to pure ITG turbulence.

This can be seen in Fig. 3 where the linear growth rate γ and the real part of the frequency ω_r of the modes are plotted versus $k_\theta \rho_i$ for pulse 26669. Positive ω_r correspond to modes propagating in the electron diamagnetic drift direction whereas negative ω_r correspond to modes propagating in the ions direction. It is evident that high collisionality changes the mode rotation while the growth rates for $k_\theta \rho_i \approx 1$ are suppressed. All these indications suggest that at FTU collisionality TEM are stabilized and only ITG modes can be destabilized. Since ITG modes are destabilized by high values of $\eta = \frac{\nabla T_i}{T_i} \frac{n_e}{\nabla n_e}$ and T_e/T_i, the measurement of $T_i(r)$ plays and important role at for the stability of these modes. At present ion temperature is measured in FTU by the multicollimator. Since the considered discharges have low plasma current they are characterized by a low neutron rate production and the $T_i(r)$ far from the plasma center is affected by strong errors. For this reason we decided to perform a scan in η in order to find the threshold for unstable ITG. In Fig. 4 the growth rate of $k_\theta \rho_i \leq 1$ modes has been plotted as a function of η either at FTU collisionality or without including the collisionality corrections. It is evident the presence of a threshold at high collisionality whereas at low collisionality there is not such a strong dependence on η since turbulence is dominated by TEM. According to the measurements the two considered discharges must have η close the threshold, which suggests the possibility that the discharge that develops an ITB is characterized by stable ITG modes having η below the threshold.

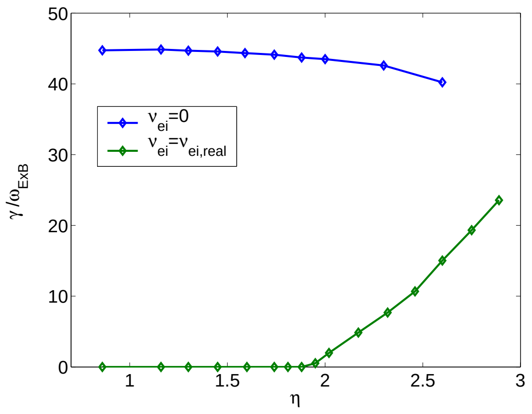

Figure 4: *Normalized growth rate γ/ω_{ExB} versus η at two different collisionality values*

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