

Microstability Analysis of NSTX Plasmas

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High beta operation in the National Spherical Torus Experiment (NSTX) and the profile diagnostics enable, for the first time, examination of the microstability properties of high beta spherical tokamaks.

Spherical Tokamaks present several unique features affecting the microstability. The low aspect ratio implies a strong variation of the toroidal magnetic field between the outer and the inner mid-planes. In Figure 1, the variation of the total magnetic field versus poloidal angle is large, as illustrated for $r/a=0.875$. Towards the center the variation is less accentuated, as found in a standard tokamak. These differences in the magnetic configuration affect the curvature and ∇B drifts. Due to good curvature, passing particles are less sensitive to the interchange instability. The magnetic wells being deeper, there are more trapped particles. A high value of beta implies also more magnetic perturbations and a stronger Shafranov shift (related to the MHD α parameter):

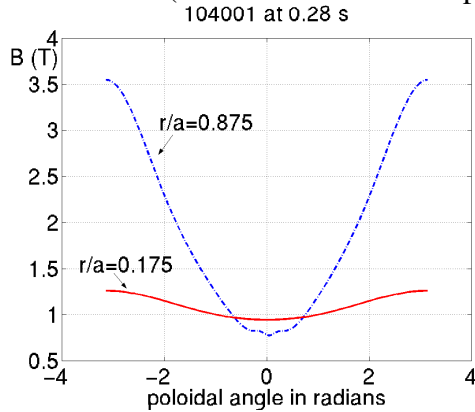


Figure 1

Variation of the total magnetic field as a function of the poloidal angle in radians, #104001 at 0.28s.

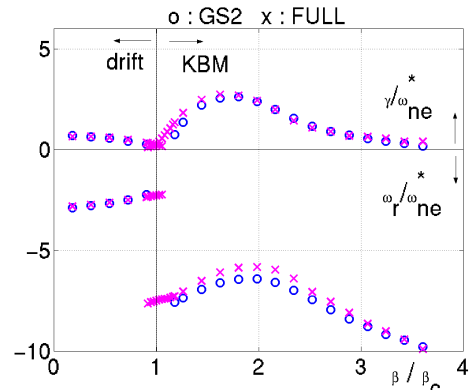


Figure 2

Benchmark between GS2 and FULL for a TFTR plasma, parameters of fig. 5 of ref. [1], including δB_{\perp} and going over β_c .

The microstability analysis is done using gyrokinetic codes including electrostatic perturbations as well as magnetic perturbations (δB_{\parallel} and δB_{\perp}). The Vlasov equation, coupled to Maxwell equations, is solved. A benchmark between two codes using two different computational methods has been done to insure the correct treatment of magnetic perturbations. One is GS2 [1], an initial value code that finds the most unstable mode. The other is the eigenvalue code FULL [2]. The benchmark is shown in Figure 2 for an analytic TFTR equilibrium case published in ref. [1], but where δB_{\parallel} is now included and beta is pushed to values over the beta critical (β_c). The value of β_c over which the Kinetic Ballooning Modes are destabilized is of order of 2% in this TFTR case. In NSTX this value is higher, around 20-30%, since the KBM are an “interchange-like” instability and are therefore sensitive to the good curvature configuration of a spherical tokamak.

Two experimental plasmas are analyzed using GS2, one with Neutral Beam Injection (2 MW) and the other with Radio Frequency heating (1.5 MW). They have similar central electron densities ($4 \times 10^{19} \text{ m}^{-3}$) and similar toroidal magnetic field on axis (0.4T and 0.3T

respectively). But the temperature profiles are very different, in particular the temperature ratios (Fig. 3). Also the toroidal velocity is much lower in the RF plasma compared to the NBI one (22 km/s versus 200 km/s).

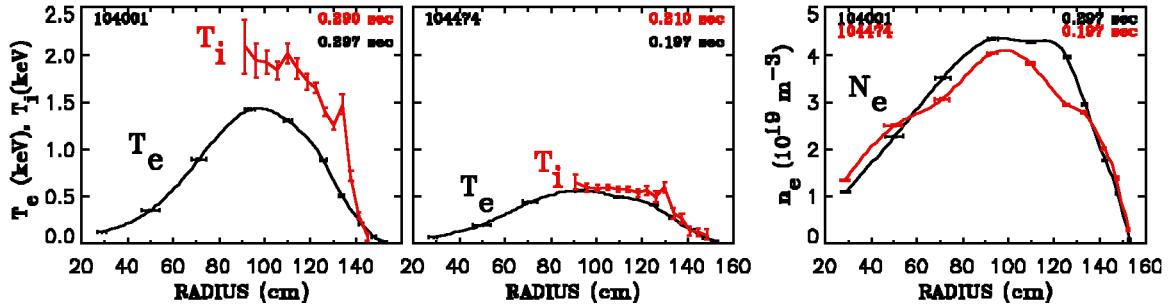
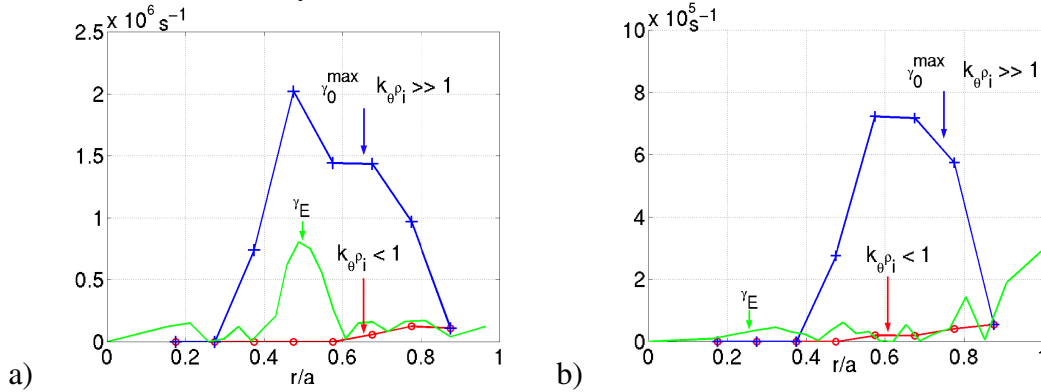


Figure 3

Ion and electron temperatures profiles for the NBI (#104001) and the RF (#104474) heated plasmas analyzed here, as well as their electron density profiles.

The microstability analyses of both plasmas show nevertheless some striking similarities (Fig. 4a and 4b). In both cases the high k_θ modes due to passing electrons, called Electron Temperature Gradient modes, are unstable at most radial positions. By contrast, the lower k_θ modes, called Trapped Electron Modes and Ion Temperature Gradients modes, are stable until around mid-radius. They are destabilized towards the edge due to steeper temperature profiles. Their growth rates are of the same order as the $\mathbf{E} \times \mathbf{B}$ shearing rate (γ_E) evaluated by NCLASS [3]. Given the large error bars on γ_E , it is not possible to assess the impact of the $\mathbf{E} \times \mathbf{B}$ shear on microstability.

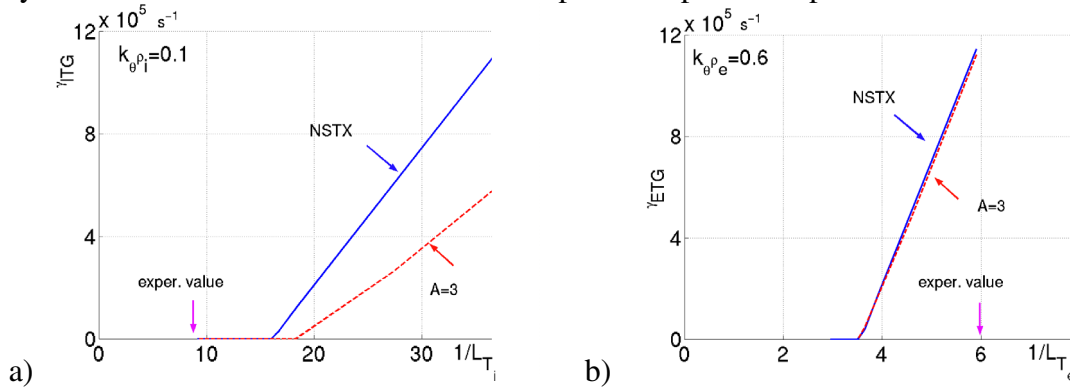


Figures 4 a) and b)

Results of GS2 microstability analysis for #104001 at 0.28s (a), and #104474 at 0.21s (b).

It is important to understand the parametric dependences of the modes encountered here in order to propose some experimental directions to improved confinements. First, the geometric aspects are tested. In particular, we attempt to understand the impact of the aspect ratio (A). Previous studies have done scans in A in different ways. One, by G. Rewoldt et al [4], where the aspect ratio was varied keeping q_{95} and β constant but changing B_T and I_p , concluded on a stabilizing effect of low aspect ratio. Another by Kotschenreuther et al [5], where A was lowered together with an increase of β in order to keep β near the β_c , found no effect due to a change in aspect ratio alone. Here, we keep the NSTX toroidal cross-section shape while increasing the aspect ratio. B_{T0} and β are kept to their NSTX case values. To obtain a consistent equilibrium, the q profile is modified, $s/q=1.7$ instead of 0.9 in NSTX, α is lower by a factor of about 3. A higher value of s/q is expected to be stabilizing whereas a lower value of α is expected to be destabilizing. We find a lower critical temperature gradient for low k_θ modes for higher A , implying that the stabilizing effect of s/q seems to

dominate (Fig. 5a). We also find no effect on the ETG threshold (Fig. 5b). This preliminary study shows that it is difficult to isolate the impact of aspect ratio per se.



Figures 5 a) and b)

Critical ion (a) and electron (b) temperature gradient for #104001 at 0.28s $r/a=0.575$, full line and for an EFIT equilibrium with a larger R such that $A=3$, dashed line.

$B_{T0}=0.4T$, $\beta_T=8.6\%$ in both cases.

The effect of lower β is studied. Two cases where β is changed consistently with α are compared. In both cases, the density and temperature gradients are identical, the q and s values are similar. We observe that a decrease of both β and α has a stabilizing effect on the ETG part of the spectrum where the maximum growth rate is reduced by about 30% (Fig. 6). Nevertheless, this stabilizing effect is not systematic. For the same plasma at a different radius ($r/a=0.575$ instead of 0.375), very little effect of lowering β is found.

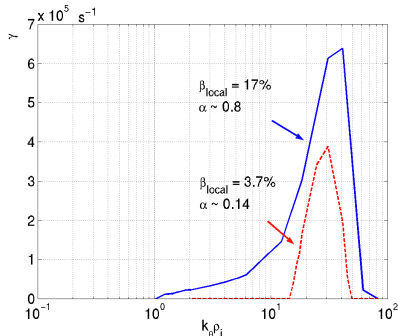


Figure 6

#104001 at 0.28s, $r/a=0.375$. Two different EFIT equilibria for the real β , full line, and for a lower β , dashed line. Both cases have similar q and s , within 10%.

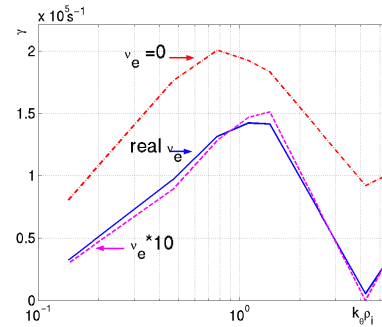


Figure 7

#104001 at 0.28s, $r/a=0.575$. Effect of electron collision frequency (ν_e) on the lowest part of the growth rates spectrum.

It is found that collisions play an important stabilizing role for low k_{θ} modes. While the ETG appears to be destabilized by collisions, the physics of this is presently not understood. Changing the collisions on electrons alone allows us to assess the role of TEM, since trapped particles become adiabatic at high collisionality. In Figure 7, we can see that switching off collisions on electrons is in fact destabilizing, but increasing the collision frequency (ν_e) by a factor of 10 does not change the growth rates. This suggests that the actual value of the frequency is high enough to detrap the electrons. Therefore, the TEM is not expected to play a significant role here.

The last parameter that is tested is the temperature ratio T_i/T_e . In Figure 8, the effect of lowering T_i/T_e on the two parts of the spectrum is found to be opposite. The low k_{θ} modes are destabilized whereas the ETG are stabilized. It is interesting to note that due to high values of the $\mathbf{E} \times \mathbf{B}$ shearing rate around mid-radius in the NBI plasma, the growth rates of

destabilized ITG modes remain well below γ_E . Finally, the critical electron temperature gradient scales as in standard tokamaks [6]: $\left| R \frac{\nabla T_e}{T_e} \right|_c \propto 1 + \frac{Z_{eff}}{T_i/T_e}$.

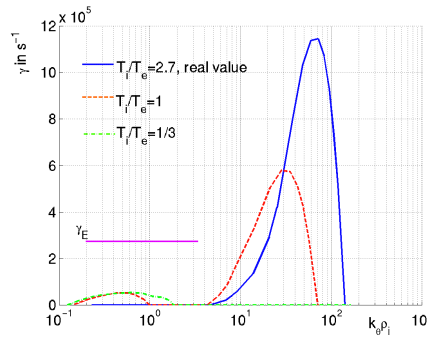


Figure 8

#104001 at 0.28s, $r/a=0.575$. Effect of T_i/T_e on the growth rates spectrum.

Non-linear simulations are needed for a more complete understanding of turbulence. The first non-linear simulation using GS2 has been performed on ETG modes. No elongated radial structures called streamers were found [7]. The level of electron transport is similar to its quasi-linear estimation. Still this quasi-linear level is higher in NSTX than in a standard tokamak due to larger Larmor radius, and it is easy to obtain electron thermal diffusivities on the order of $1 \text{ m}^2/\text{s}$.

In the present analysis, it is found that the ETG are stabilized by low values of T_i/T_e . On the contrary, the ITG are stabilized by high values of T_i/T_e and of course by $\mathbf{E} \times \mathbf{B}$ shearing rates higher than the ITG growth rates [8]. The TEM are stabilized in high collisionality regimes. The ETG unstable modes found in the analyzed plasmas are consistent with the evidence that the electron heat transport dominates in these plasmas.

Recently, the ratio of T_i/T_e has reached values lower than 1/3 using high harmonic fast wave heating. These plasmas may provide useful tests of the trends indicated here. In addition, non-linear simulations will be extended. Finally, these analyses suggest the importance of high k turbulence studies to establish the existence or not of ETG modes.

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