Stabilization of Electron-Scale Turbulence by Electron Density Gradient in NSTX

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Theory and experiments have shown that electron temperature gradient (ETG) turbulence on the electron gyro-scale, $k_\perp \rho_e \lesssim 1$, can be responsible for anomalous electron thermal transport in NSTX [1, 2]. Electron scale (high-k) turbulence is diagnosed with a high-k microwave scattering system [3] in NSTX. Here we report on the stabilization effects of the electron density gradient on electron-scale density fluctuations in a set of NSTX NBI-heated H-mode plasmas, following previous work by Y. Ren *et al.* [4].

Electron density fluctuations on the electron gyro-scale ($k_\perp \rho_e \lesssim 1$) were measured with a 280 GHz microwave coherent scattering system implemented on NSTX [3]. Five collection channels simultaneously measure five different wave numbers in the range $5 \lesssim k_\perp \lesssim 30$ cm^{-1}. Measured wave vectors are primarily radial k_r, with a small binormal component k_b satisfying $k_b/k_r \approx 0.2 - 0.3$ (k_r is perpendicular to the flux surface and k_b is perpendicular to the local magnetic field and inside the flux surface). The near midplane trajectory of the probe beam and the k-response are computed using a ray tracing code. In the scattering experiment presented here the high-k diagnostic is sensitive to fluctuations taking place at $R \approx 135 - 136$ cm ($R_{maj} = 0.85$ m, r/a $\sim$ 0.7-0.8). Here we focus on a particular experiment of an NSTX NBI-heated H-mode discharge (shot 141767) on a time range after t = 0.3 s.

In figure 1 is plotted the frequency fluctuation spectrogram from channel 1 in a), the total scattered power (integrated in frequency) in b), the difference between the experimental and critical electron temperature gradient at the scattering location in c), and the critical electron temperature gradient formula $(cf.$ [5]) in $d)$. The critical gradient formula derived in [5] is given by $(R_0/L_{T_e})_{crit} = max\{0.8R_0/L_{n_e}, (1+\tau)(1.33+1.99\hat{s}/q)(1-1.5\varepsilon)(1+0.3\varepsilon d\kappa/d\varepsilon)\}$, where $\tau = Z_{eff}T_e/T_i$. The two-terms in the *max* function are plotted in $d)$. R_0/L_X are normalized gradients of the quantity X, such that $R_0/L_X = -R_0/(\mathrm{d}ln\mathrm{X}/dr)$, and R_0 is the corresponding flux surface center. The critical gradient was also explicitly computed using GS2 linear simulations (triangles in $1.d)$), and a good agreement is found with the Jenko critical gradient formula despite the high-β, tight aspect ratio condition of NSTX. High values of the electron density gradient will make the $0.8R_0/L_{n_e}$ term dominant, and it will determine the value of the critical gradient which should have a stabilizing effect on the ETG instability.

For early times ($t \lesssim 0.33$ s), the experimental temperature gradient is at marginal stability levels with respect to the critical gradient ($1.c)$), and no high-k fluctuations are observed in Fig. $1.a)-b)$. The intense spike at $t \approx 292$ ms corresponds to an ELM event and is independent of ETG fluctuations. At $t \sim 330$ ms, $R/L_{T_e}^{exp} - R/L_{Tec}^{Jenko}$ increases in Fig. $1.c)$, and ETG becomes unstable. At that time, electron density fluctuations start to develop in Fig. $1.a)-b)$. During the time span $t \sim 0.36-0.53$ s, a very similar value of $R/L_{T_e}^{exp} - R/L_{Tec}^{Jenko}$ gives rise to very different density fluctuation amplitudes in $1.a)-b)$. This suggests a nonlinear dependence of the fluctuation amplitude with different plasma parameters. We aim to show the nonlinear dependence of the density fluctuation amplitude on the equilibrium electron density gradient.

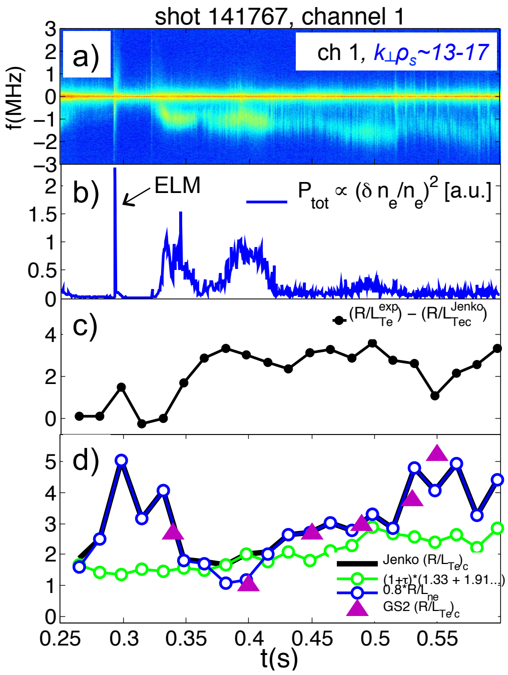

Figure 1: *a) Fluctuation spectrogram. b)Total scattered power from channel 1. c)* $R/L_{T_e}^{exp} - R/L_{Tec}^{Jenko}$. *d) Jenko critical gradient (black), both terms in the max-function, and GS2 computed critical gradient.*

The electron density gradient term (blue curve in Fig. $1.d)$) is dominant for most part of the time range of interest (t > 0.3 s). High values of R/L_{n_e} during $t \lesssim 330$ ms raise the critical gradient for ETG to the experimental temperature gradient value; ETG is marginally stable and no high-k fluctuations are detected (Fig. 1.$a) - b)$). As the electron density gradient drops at $t \approx 330$ ms, $R/L_{T_e}^{exp} - R/L_{T_ec}^{Jenko}$ increases and ETG is unstable; high-k fluctuations (Fig. 1.a)-b)) start to develop and the scattered power increases. ETG remains unstable and high-k fluctuations persist until the end of the discharge. Between $360 \lesssim t \lesssim 410$ ms, the electron density gradient term becomes subdominant and an enhancement of high-k fluctuations is observed in figure 1.a)-b). After a sudden increase in the electron density gradient at $t \approx 520$ ms, $R/L_{T_e}^{exp} - R/L_{T_ec}^{Jenko}$ is reduced and high-k fluctuations mitigate.

Linear gyrokinetic simulations carried out with the gyrokinetic code GS2 [6] show that the electron density gradient has a strong impact on the wavenumber corresponding to the maximum linear growth rate and the real frequency. The radial component k_r was set to 0 to find the most unstable mode. Electromagnetic effects and collisions were also included in these linear runs, and used local Miller equilibrium.

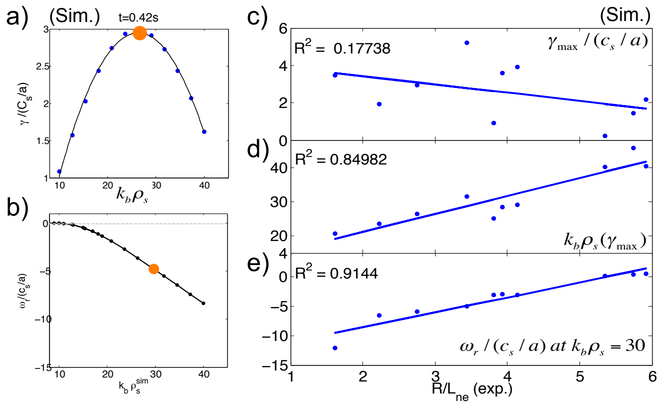

Figure 2: *Orange dots indicate values picked $\gamma_{max}/(c_s/a)$, $k_b\rho_s(\gamma_{max})$ and $\omega_r(k_b\rho_s = 30)$ to plot against R_0/L_{n_e}.*

At each time, the maximum linear growth rate ($\gamma_{max}/(c_s/a)$) and the wavenumber corresponding to the maximum linear growth rate $k_b\rho_s(\gamma_{max})$ are calculated. These two quantities are then computed for several times, and are plotted in Fig. 2.$c) - d)$ with respect to the local value of the density gradient R_0/L_{n_e}. No correlation is observed between $\gamma_{max}/(c_s/a)$ and R_0/L_{n_e}, however a clear correlation can be established between the density gradient and the wavenumber at the maximum linear growth rate $k_b\rho_s(\gamma_{max})$. To study the real frequency, we pick a fixed wavenumber ($k_b\rho_s = 30$), and calculate the frequency corresponding to that fixed wavenumber (Fig. 2.b)). A very clear correlation is observed between the real frequency $\omega_r(k_b\rho_s = 30)$ and the local value of R_0/L_{n_e}. A local scan on the electron density gradient (not shown here) was carried out using GS2 and completely confirms all correlations established here.

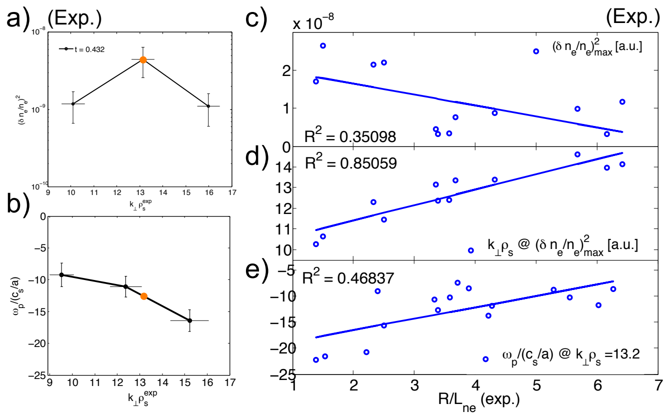

Figure 3: $(\delta n_e/n_e)^2_{max}$, $k_\perp\rho_s((\delta n_e/n_e)^2_{max})$ *and* $\omega_p(k_\perp\rho_s = 13.2)$ *from* $a),b)$ *plotted against* R_0/L_{n_e} *in* $c),d),e)$.

In figure 3 we make a very similar analysis, but this time using experimental measurements. A clear parallel between Fig. 2 and 3 can be made if linear growth rates in 2.a) are substituted with the wavenumber spectrum of fluctuations from experiment in 3.a) and the real frequency from GS2 in 2.b) is replaced with the Doppler subtracted, plasma frame frequency of fluctuations in 3.b). The maximum fluctuation level $(\delta n_e/n_e)^2_{max}$ in Fig. 3.c) is found to have a weak correlation with R_0/L_{n_e}, but the wavenumber corresponding to the maximum fluctuation level in Fig. 3.d) is found to have a very strong correlation with density gradient, similar to that shown in Fig. 2.d). The Doppler subtracted, plasma frame frequency corresponding to a fixed wavenumber ($\omega_p(k_\perp\rho_s = 13.2)$) is shown to have a notable dependence on density gradient. The same trends found from the linear GS2 simulation are reproduced from experimental data.

In summary, the electron density gradient is shown to affect high-k ETG turbulence (Fig. 1) through the linear threshold determined by the Jenko critical gradient expression, as well as a nonlinear stabilizing effect as shown in 1. Simulations (Fig. 2) and experiment (Fig. 3) suggest that the electron density gradient is shifting ETG turbulence to even higher wavenumbers and at the same time reducing the frequency of the instability. This work has been supported by US. D.O.E. contract DE-AC02-09CH11466.

References

[1] W. Horton. *et al*, Nucl. Fusion **45**, (2005) 976-985.
[2] E. Mazzucato *et al.*, Nucl. Fusion **49**, 055001 (2009).
[3] D. R. Smith *et al.*, Rev. Sci. Instrum., **79**, 123501 (2008).
[4] Y. Ren *et al*, Phys. Rev. Lett. **106** 165005 (2011).
[5] F. Jenko *et al*, Phys. Plasmas **8**, 4096 (2001).
[6] M. Kotschenreuther *et al*, Comput. Phys. Commun. **88** 128 (1995).