Fundamental physics of the fast ion stabilization of electromagnetic ITG turbulence

G. J. Wilkie, A. Iantchenko, E. G. Highcock, I. Pusztai, I. G. Abel, T. Fülöp

Chalmers University of Technology, Gothenburg, Sweden

One of the most important roadblocks to achieving controlled nuclear fusion via magnetic confinement is the stiff energy transport from microturbulence. In particular, the ion temperature gradient mode (ITG) prevents the core from reaching sufficiently high temperatures without excess auxiliary heating. This heating is achieved by either injecting energetic particle beams (NBI) into the plasma, or by injecting radio waves which selectively heat a minority species (ICRH). It has recently been discovered [1] that the fast ions from this auxiliary heating can have a significant stabilization effect on ITG, and it remains an open question whether alpha particles, produced from the fusion reaction itself, are capable of similarly stabilizing ITG. Alpha particles have been previously studied in the context of electrostatic microturbulence [2, 3], but the recently observed effect is suspected to be electromagnetic. Follow up work [4, 5, 6] provided more details on the phenomenon, more accurate modelling, and more comparisons to experiments and between codes. However, a firm understanding of the fundamental physics responsible for the phenomenon remains elusive. In this work, we take a more basic theoretical approach in order to gain insight into this stabilization. We derive a model accounting for the active kinetic response of fast ions under a large temperature approximation. We will find that the bare electromagnetic response of fast ions is not very strong and that dilution, especially of neighboring flux surfaces leading to change in the bulk ion density gradient, adequately explains the nonlinear stabilization of JET shot 73224.

Theory

Simplified dispersion relations were derived for electrostatic ITG with fast ions and electromagnetic ITG respectively in Refs. [7] and [8]. Here, we derive the ITG dispersion relation in a similar way, this time including both electromagnetic effects and energetic impurities:

$$\left[R_{0i}+R_{0f}-\left(\frac{n_i}{n_e}+\frac{T_i}{T_e}\right)\right]\left[R_{2i}+R_{2e}+R_{2f}+\frac{T_e}{T_i}\frac{k_\perp^2\rho_i^2}{2\beta_e}\right]-(R_{1i}+R_{1e})^2=0, \tag{1}$$

where R_{ns} are the response functions of species s. For electrons and ions, these can be found in Ref. [8]. To derive this dispersion relation we assumed a strongly ballooning mode structure such that it is localized at the outboard midplane; that electrons respond adiabatically to the electrostatic potential (i.e. $R_{0e}=-T_i/T_e$); and that compressional magnetic fluctuations are negligible. For fast ions, we note that, in the high-temperature limit, the magnetic drift and radial gradient terms dominate the gyrokinetic equation. This means that the fast ions respond linearly even to the turbulent electromagnetic fields, and we can write the fast ion response functions as:

$$R_{nf} = Z_f^2 \frac{n_f}{n_e} \frac{T_i}{T_f} \frac{R}{2L_{nf}} \left(\frac{v_{tf}}{v_{ti}}\right)^n \int \hat{v}_\parallel^n \frac{1+\eta_f\left(\hat{v}^2-3/2\right)}{\hat{v}_\parallel^2+\hat{v}_\perp^2/2} J_0^2\left(k_\perp \rho_f \hat{v}_\perp\right) \frac{e^{-\hat{v}^2}}{\pi^{3/2}} d^3\hat{\mathbf{v}}. \tag{2}$$

Here, $\hat{\mathbf{v}} = \mathbf{v}/v_{tf}$ (where $v_{ts} = \sqrt{2T_s/m_s}$) is decomposed into parallel and perpendicular components: $\hat{v}^2 = \hat{v}_\parallel^2 + \hat{v}_\perp^2$; ρ_s is the thermal Larmor radius of species s; J_0 is the Bessel function of the first kind; $k_\perp$ is mode wavenumber perpendicular to the equilibrium magnetic field $\mathbf{B}$; n_s and T_s are the species density and temperature, $\beta_e = 8\pi n_e T_e/B^2$, R is the radius of the magnetic axis, r is the half-width of the flux surface; and $r = a$ at the last closed flux surface. The gradient length scales are defined from $n_s'(r) = -n_s(r)/L_{ns}$ and $T_s'(r) = -T_s(r)/L_{Ts}$, while $\eta_s = L_{ns}/L_{Ts}$. In writing Eq. (2), we assumed high-aspect ratio circular flux surfaces and a Maxwellian fast ion distribution for simplicity. Note that R_{1f} vanishes by oddness of the integrand in Eq. (2).

Analogously to Ref. [9], which considered only electrostatic turbulence and did not include the fast ion response, we can derive the following "effective" parameters that in some ways mimic the presence of fast ions in simulations that otherwise do not include them:

$$\tau_{\text{eff}} = \frac{n_e}{n_i}\left(\frac{T_i}{T_e} + \frac{Z_f^2 n_f}{n_e}\frac{T_i}{T_f} - R_{0f}\right) \tag{3}$$

$$\beta_{\text{eff}} = \beta_e\left(1 + 2\beta_e \frac{T_i}{T_e}\frac{R_{2f}}{k_\perp^2 \rho_i^2}\right)^{-1}. \tag{4}$$

Note that these relations can be derived directly from the field equations, so they apply to the nonlinear case as well, only requiring that the fast ion kinetic equation is linear (which it is in the limit that magnetic drifts dominate). Some sample response functions are shown in Fig. 1. It is interesting that, even though R_{0f} has a smaller prefactor than R_{2f}, upon integrating one ends up with an electrostatic response on par with the electromagnetic response.

These effective parameters help in interpreting the response functions: higher T_i/T_e and higher β_e are both stabilizing for ITG. Their values are plotted in Fig. 2 for the example case of $n_f = 0.1n_e$, $T_f = 10T_i$, and $\beta_e = 0.01$. We see that the electromagnetic effect is quite small, changing β_{eff} only by about one percent, except at low $k_\perp$, where it goes down to zero. The electrostatic effect τ_{eff} is more substantial: according to known scalings of ITG turbulence with temperature ratio [10], one expects about a factor of three difference in the ITG heat flux for these kinds of parameters. The effect of local dilution is encapsulated in τ_{eff} by the fact that $n_i < n_e$. However, this does *not* include the effect of dilution on the bulk plasma density gradients, which is a strong effect [11] and is included in the simulations that follow.

Simulation

First, we demonstrate confidence in our results by comparing GS2 to other gyrokinetic codes. Figure 3 shows the comparison between GS2, GYRO, and GENE. The simulations parameters

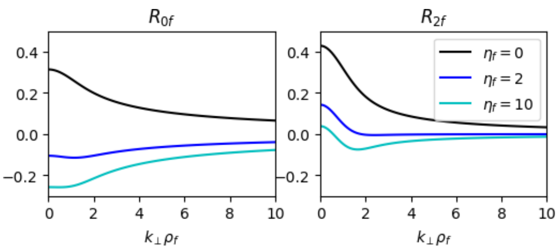

Figure 1: Fast ion electrostatic (left) and electromagnetic (right) response functions from Eq. (2) for select values of η_f. When changing η_f, we also adjust L_{nf} to keep the pressure gradient constant: $R/L_{nf} + R/L_{Tf} = 20$. Other parameters are: $n_f/n_e = 0.1$, $T_i = T_e = 0.1T_f$, and $\beta_e = 0.01$.

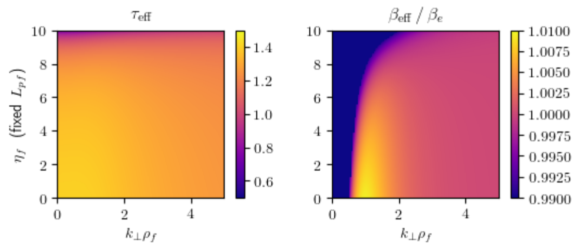

Figure 2: The effective parameters of Eqs. (3) (left) and (4) (right) for the same parameters as Fig. 1. Pressure gradient is kept constant as η_f is adjusted. At low $k_\perp \rho_f$, $\beta_{\rm eff}$ goes off scale and rapidly decays to zero.

are for JET shot 73224 at a radial position $r = 0.375a$, where ITG is the dominant unstable mode. The physical parameters were from Ref. [12] and further details on these simulations are given in Ref. [6]. Even though flow shear is not included in our GS2 simulations (though it was included in the others), the agreement is remarkable. In figure 4, we show the dramatic effect that fast ions have on the saturated ion heat flux q_i. Here, nonlinear GS2 simulations were ran with a resolution of $N_x \times N_y \times N_\theta \times N_E \times N_\mu = 64 \times 64 \times 31 \times 16 \times 32$. Convergence was established with respect to a perpendicular box size of $63\rho_i$ squared. The bulk ion heat flux is reduced by nearly a factor of 10 when fast ions (both NBI and ICRH, which together contribute 20% of the total ion charge) are present. In these nonlinear simulations, in order to maintain quasineutrality of the bulk plasma, when fast ions are present, density and density gradient are taken from the bulk thermal deuterium in order to be consistent with existing literature. However, the opposite choice where additional electron density accompanies fast ions is more physically meaningful for ICRH minority heating and ionization of neutral beams.

The dominant effect of dilution seen in Fig. 4 might seem to contradict previously reported results, which claimed that dilution is an important, but not dominant, effect. Ultimately, this disagreement is only one of semantics of what one calls “dilution”. In Ref. [4], dilution was modelled by considering fast ions with zero radial gradients of any kind: $\partial F_{0f}/\partial r = 0$. In addition to there being another (albeit small) source term in the gyrokinetic equation, this method prevents fast ions from having an effect on the bulk density gradients when quasineutrality is strictly enforced.

In order to understand this effect, a comprehensive study of linear physics was undertaken in Ref. [6]. There it was found, in agreement with [5], that fast ions do indeed have an effect on

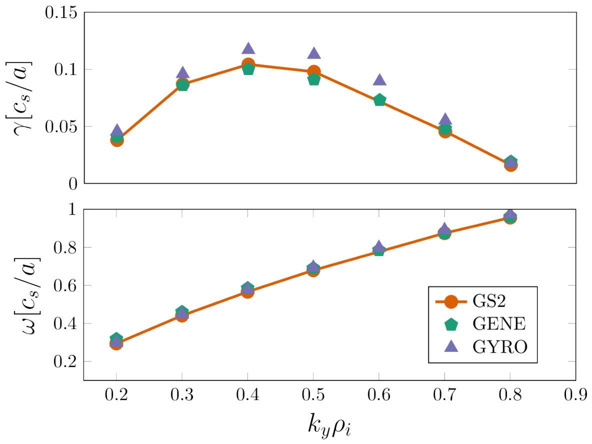

Figure 3: Comparing growth rate (top) and frequency (bottom) spectrum for the benchmarking case of Ref. [12].

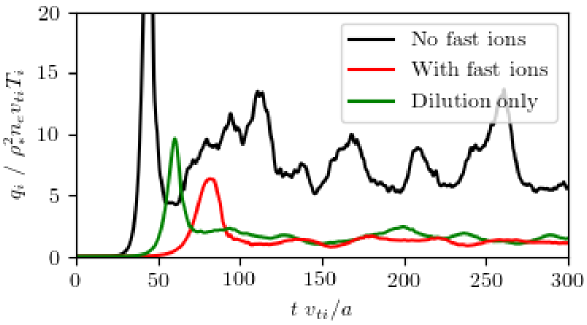

Figure 4: Time history of the bulk deuterium radial heat flux in nonlinear GS2 simulations, both with and without fast ions. In the case of "dilution", fast ions are not included as a kinetic species, but their effect on the bulk ion density and density gradients are kept. The normalized time-averaged heat fluxes are 9.5, 0.9, and 1.0, respectively in the order listed in the legend.

the magnetic geometry due to their significant contribution to the total pressure. While they do not affect the shape of the flux surfaces, they do significantly influence the safety factor, shear, and Shafranov shift profiles, which have an impact on the turbulence. However, the magnetic geometry was not changed in the simulations shown in Fig. 4. It was further found that different classes of fast ions affect ITG differently. In fact, at low β, stronger fast ion density gradients actually have a *destabilizing* influence, though this is not enough to overcome the beneficial effect of dilution.

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