Impact of realistic fast ion distribution function in gyrokinetic GENE simulations

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Abstract

Understanding the stabilising mechanism of fast particles on plasma turbulence is an essential task for a fusion reactor, where the energetic particles can constitute a significant fraction of the main ions. While the consideration of equivalent Maxwellian distributed fast ions in the simulations has greatly improved the agreement with experiments, fast ion electromagnetic stabilization seems to be somewhat over-estimated. Power balance is usually reached only with increased plasma gradients. However, it is well known that to rigorously model highly non thermalised particles, a non-Maxwellian background distribution function is needed. To this aim, a previous study on a particular JET plasma has been revised and analysed with the gyrokinetic code GENE. Fast particles have been modelled with a number of different analytic and numerical distributions. The latter have been imported from the modelling tools NEMO/SPOT and SELFO.

Introduction

The study of fast particle stabilising effects on the plasma turbulence has recently become of particular interest due to the high concentration of energetic ions predicted for a realistic fusion reactor like ITER. Several numerical and experimental works have shown the beneficial fast ion impact on ion temperature gradient (ITG) modes [1, 2], mainly responsible for confinement degradation of nowadays tokamak reactors. In particular, fast ions can passively dilute the main ion species through a diminishing of the thermal ITG drive [3, 4], can increase geometric stabilisation, i.e. Shafranov shift stabilization [5] and finally can actively stabilise linear growth rates and nonlinear fluxes through an electromagnetic stabilization in the presence of fast ions suprathermal pressure gradients [1, 6]. Therefore, a better physics understanding and the optimisation of fast ions can significantly improve the further development of fusion reactors. However, in some of the most prominent examples where fast ion effects were found to be crucial to reproduce the correct order of magnitude in heat transport, the stabilisation appeared to be overestimated given that the main drive had to be increased to match the experimental fluxes. In the works just mentioned, the fast ion species were modelled as equivalent Maxwellian distributed particles. The aim of this work is to assess whether more realistic fast ion distribution functions might improve the agreement with experiments. We present numerical simulations with non-Maxwellian fast particles distribution functions with the code GENE [7], which has been modified so that the underlying equations now include any type of distribution function, given either analytically or numerically [8]. A particular JET L-mode plasma is revised and analysed with linear simulations [6]. The bulk plasma is composed of Deuterium, electron and Carbon impurities, while the fast particles are NBI fast Deuterium and ICR-heated ^{3}He. Low beta electromagnetic effects, collisions, impurities, fast ions, and experimental geometry are included. A detailed description of the input parameters can be found in Ref.[6].

Equilibrium distribution functions

The simulations presented in this work have been performed with the gyrokinetic code GENE. It solves the Vlasov-Maxwell system of equations employing the so called δf approach. The distribution function for each species is split in a time independent background, often considered a Maxwellian, and in a small perturbation which is let evolve in time. In this section the analytical and numerical non-Maxwellian background distribution functions employed throughout this work are introduced. The equilibrium distribution function F_0 for thermal electrons and ions has been modelled with a Maxwellian. For the fast ions different analytical backgrounds have been selected. For the case of NBI fast Deuterium a slowing down distribution function has been found to be a good approximation to the numerical distribution extracted by the NEMO/SPOT code [9]. Slowing-down distribtuion is defined as follows

$$F_{0,s}\left(\mathbf{x}, v_{\shortparallel}, \mu\right) = \frac{3 n_0}{4\pi \log\left(1 + \frac{v_\alpha^3}{v_c^3}\right)\left[v_c^3 + v^3\right]} \Theta\left(v_\alpha - v\right). \tag{1}$$

Here, the birth velocity is defined through the birth energy E_α in the following way $v_\alpha = \sqrt{2E_\alpha/m_\alpha}$, while $v_c = \left(\frac{3\sqrt{\pi} m_e}{4} \sum_{\text{main ions}} \frac{n_i z_i^2}{n_e m_i}\right)^{\frac{1}{3}} v_{th,e}$ represents the critical slowing down velocity. Furthermore, n_0 is the background density. The ICRH-^3He minority has been modelled with a bi-Maxwellian distribution function

$$F_{0,aM}\left(\mathbf{x}, v_{\shortparallel}, \mu\right) = \frac{n_0 \exp\left(-\frac{\mu B_0}{T_\perp}\right)}{\pi^{3/2} v_{th,\shortparallel} v_{th,\perp}^2} \exp(-v_{\shortparallel}^2 / v_{th,\shortparallel}^2). \tag{2}$$

Here, $T_{\shortparallel}$ and $T_\perp$ are respectively the parallel and perpendicular temperatures and B_0 the equilibrium magnetic field. The $T_\perp/T_{\shortparallel} = 2.2$ and $L_{T_{\shortparallel}}/L_{T_\perp} = 3$ anisotropies have been extracted from

SELFO (LION/FIDO) [10]. Regarding the numerical backgrounds, an interface routine from the SELFO/SPOT to the GENE coordinate system has been implemented. The fast Deuterium NB-heated distribution function has been extracted from a SPOT/NEMO simulation with 4191 test particles and has been interpolated on the GENE coordinate grid. From Fig. 1(a) a slowing down structure can be easily identified. Fast ions are injected with $T = 26\text{-}34keV$ and slowed down through interaction with thermal particles. Furthermore, in Fig. 1(b) the numerical SELFO distribution function is shown on the GENE coordinate grid. The non-Maxwellian fast particles temperature has been defined in the same way as in Ref. [11] in order to have the same equivalent Maxwellian kinetic pressure.

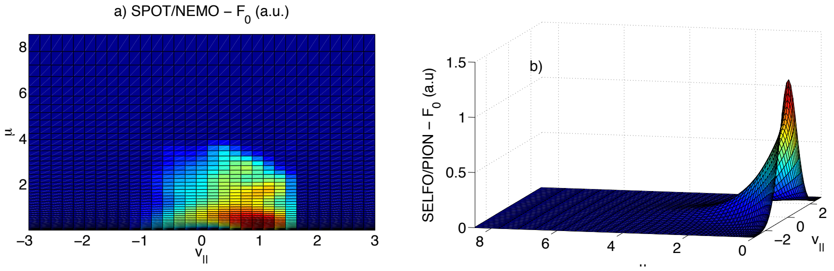

Figure 1: θ-integrated a) SPOT/NEMO and b) SELFO numerical distribution functions.

Linear growth rate analysis

In this section the impact of the more realistic distribution functions on the linear ITG growth rates is discussed. In Fig. 2(a) linear growth rates are shown for the 5 species setup for different $k_\theta \rho_i$, changing the distribution function only for the Fast Deuterium (NBI). The growth rates have been normalized to c_s/a with $c_s = (T_e/m_i)^{1/2}$. A low sensitivity to the change of the fast deuterium distribution function is observed. The relative difference in the linear results is of the order of $\sim< 10\%$. Furthermore, the slowing down distribution function can approximate better the numerical NEMO/SPOT results.

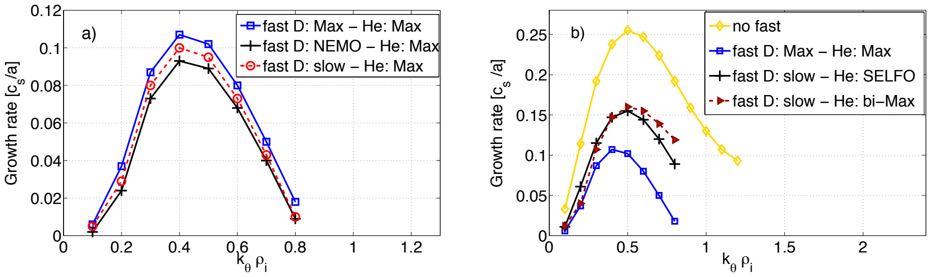

Figure 2: GENE calculation of the linear growth rates for different $k_\theta \rho_i$ changing the distribution function for the a) Fast Deuterium and b) fast ^3He.

A similar analysis can be performed for the fast ^{3}He, modelling the fast Deuterium with a slowing down or a Maxwellian distribution. In Fig. 2(b) linear growth rates are shown for different ^{3}He backgrounds. Compared to the case of equivalent Maxwellian fast ions a significant difference is observed, around $\sim 50\%$. The fast ion stabilization still holds even with the more realistic distributions but is weakened and higher growth rates are obtained. These results are in line with experimental results [6] which predict an overestimation of equivalent Maxwellian fast ion stabilisation. According to quasilinear models an increase in the linear growth rates might lead to a relative increase of the nonlinear fluxes, greatly improving the agreement with the experiments at the nominal plasma parameters. Furthermore, the bi-Maxwellian can well approximate the numerical SELFO results for small $k_\theta \rho_i$, except for the poloidal wave vector component of $k_\theta \rho_i = 0.2$. For this value an underestimation of $\sim 40\%$ is observed.

Conclusions

A previous equivalent Maxwellian study on a particular JET plasma with fast ion enhanced electromagnetic stabilisation has been revised and analysed with linear simulations employing more realistic distribution functions. Electromagnetic effects, collisions and experimental geometry have been included. In this context, linear growth rates are studied as a function of the wave number and compared with those obtained using an equivalent Maxwellian. It has been found that with the more realistic distribution function the increased fast ion stabilisation still holds, even if the strength of the effect of ICRH is weaker. Furthermore, a lack of sensitivity to the NBI fast ion distribution has been observed.

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