Influence of fine scale turbulence on the transport of high energy populations in burning plasmas

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Abstract

We investigate the transport of fast ions in the presence of electromagnetic turbulence in an ITER steady state scenario. Linear and nonlinear analyses are carried out focusing on the transport features of passive deuterium. It is shown that the anomalous diffusion of NBI ions in ITER can become important. In particular the neutral beam driven current is radially redistributed by the turbulence, thereby affecting the key properties of this important scenario.

Introduction

Recent experimental and theoretical results have unveiled previously unexpected enhancement in the transport of energetic particles by microturbulence [1, 2, 3, 4, 5]. Turbulent fields have been shown to have the largest impact on particles at intermediate energy range ($E \leq 10T_e$) and small gyroradius (passing particles). Such particles include those generated by injection of neutral beams (NBI) in the plasma, contributing to plasma heating and influencing stability. In contrast, fusion born alpha particles are only negligibly transported due to their large gyro-radii, and no corresponding redistribution of heat deposition is expected [6]. At the same time, numerical simulations demonstrated that the heat load of the alpha population on plasma facing materials is not influenced by microturbulence [7].

In this work, we model the turbulent transport of NBI populations in the ITER steady state scenario. We first carry out a detailed linear simulation using the GENE code [8], thereby generating the background turbulence, comprising a mixture of ITG and TEM modes. In more advanced nonlinear simulations we then identify a broad region of velocity space where the radial transport of energetic ions is important. Finally, we evaluate the consequences of this transport by developing a neutral beam model for the single particle pushing code VENUS [9] and show that anomalous current profile redistribution is to be expected in thermonuclear plasmas.

GENE simulations

Our analysis is focused on the turbulent properties of an ITER steady state scenario without internal transport barrier [10] using the GENE [8] gyrokinetic code. This configuration is highly dependent on neutral beam current drive, and is therefore particularly sensitive to anomalous diffusion of NBI ions. In particular, a flat safety factor profile in the center is envisaged in this plasma regime, thus any core current redistribution has a serious impact on the q profile and its

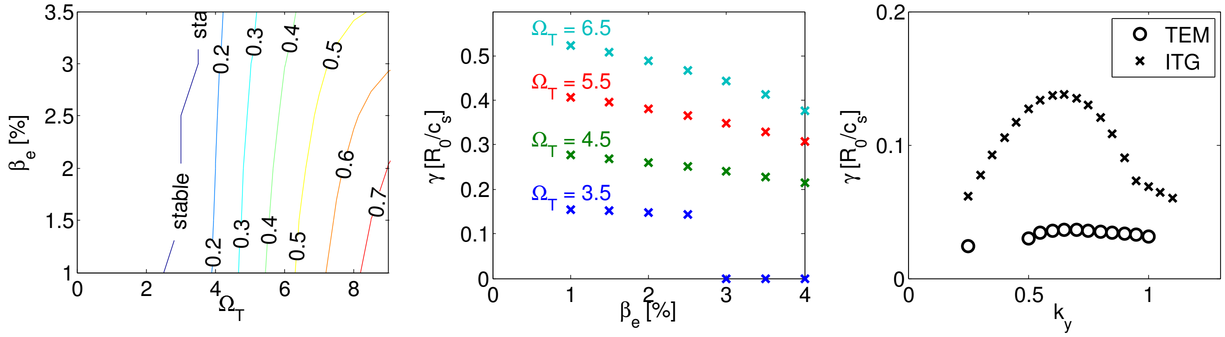

Figure 1: Left panel: linear growth rate in units of R_0/c_s as a function of Ω_T and β_e, showing how large temperature gradients lead to stronger instability. Central panel: finite β_e stabilization of ITG modes, at different values of Ω_T. Right panel: growth rate of the two most unstable modes (ITG and TEM) as a function of k_y for $\Omega_T = 3.5$ and $\beta_e = 1.5\%$.

shear. *Linear Simulations* - Before trace fast ions are added to the model, we assess the linear stability of the background plasma which comprises deuterium ions and electrons. The aim is to avoid unreasonably strong plasma turbulence and to simulate a scenario close to marginal stability. The impact over small scale instabilities of two important parameters is investigated. The first is the normalized logaritmic temperature gradient of the background species, defined in the GENE code as $\Omega_T = -(R_0/a)(1/T)dT/d\rho_t$. Here R_0 and a are the major and minor radius of the tokamak. The radial coordinate is defined as $\rho_t = \sqrt{\psi_t/\psi_{t,edge}}$, where ψ_t is the toroidal flux. The value of Ω_T determines the proximity to marginal stability. The other parameter we examine is the electron plasma pressure $\beta_e = n_e T_e/(B_0^2/2\mu_0)$. This variable regulates the influence of magnetic effects and can either stabilize ITG modes or, at values largely exceeding $\beta_c \simeq 2\%$, lead to the destabilization of kinetic ballooning modes (KBMs) [11]. We perform a linear scan over these two variables to determine the most reasonable set of parameters for nonlinear simulations (Fig. 1). We observe that ITG modes, the most unstable microinstabilities in the system, are damped for values of $\Omega_T < 3$. Furthermore, the stabilizing effect of β_e can be inferred. From these results and those reported in Ref. [11] we conclude that in this scenario KBMs are stable. A scan over k_y, where y is the binormal coordinate, is also shown in Fig. 1. The presence of subdominant TEM modes can be observed when $\Omega_T = 3.5$ and $\beta = 1.5\%$. Consequently it is seen that the background turbulence is generated by a mixture of ITG and TEM modes.

Nonlinear Simulations - Following the introductory linear analysis, nonlinear GENE simulations are performed. We now introduce an additional passive species of energetic deuterium, representative of NBI ions. The transport features of this population are evaluated via the energy dependent particle diffusivity defined in Ref. [4]. The background turbulence over which the NBI ions are traced is again generated by a mixture of deuterium and electrons. Both these species are characterized by $\Omega_T = 3.5$, while the temperatures are similar ($T_D = 0.8T_e$). The electron beta has been set to 1.5%. The real space resolution is $(n_x, n_y, n_z) = (192, 64, 48)$, where x is the radial coordinate, y the binormal coordinate and z the field aligned coordinate. The dimension of the real space domain is $(L_x, L_y) = (123, 80)\rho_s$ and one poloidal turn in the z

direction. The simulated nonlinear ion heat flux is reasonably small, $\chi_i(\rho_t = 0.5) \simeq 2\ \mathrm{m}^2 \cdot \mathrm{s}^{-1}$.

The particle transport of NBI ions is shown in Fig. 2. We observe diffusivities of the order of 1 $\mathrm{m}^2 \cdot \mathrm{s}^{-1}$ up to 80 keV, and smaller than 0.1 $\mathrm{m}^2 \cdot \mathrm{s}^{-1}$ only above 250 keV. This is particularly true for passing particles, in agreement with previous findings [3, 5, 4]. The diffusive transport driven by magnetic fluctuations is well below 0.1 $\mathrm{m}^2 \cdot \mathrm{s}^{-1}$and therefore negligible in this scenario. To assess the potential j_{nbi} redistribution, we develop a single particle NBI model.

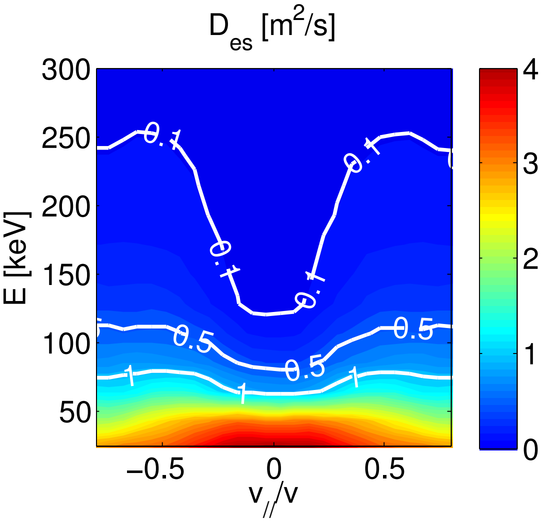

Figure 2: Electrostatic particle diffusivity, as a function of energy and pitch, of passive deuterium over a mixture of ITG and TEM turbulence. Energetic particle are transported above previous estimates up to 300 keV for passing particles.

The VENUS NBI Model

The single particle following code VENUS[9] is employed for calculating the impact of anomalous diffusion on the neutral beam driven current. To model the NBI population, we follow particle trajectories whose initial conditions are determined by the beam geometry. The weight of the particle i is proportional to the beam ionization at the point $\mathbf{x}_i$ along the NBI line. The pitch is calculated by intersecting the beam trajectory with the magnetic field $\mathbf{B}$ at the position $\mathbf{x}_i$. The particle motion is then influenced by the unperturbed drifts, Coulomb collisions and anomalous diffusion. Particle slowing down and pitch angle scattering are introduced in order to simulate Coulomb collisions and the consequent neoclassical transport. A Monte Carlo operator in real space, on the other hand, regulates the impact of turbulent transport. At each time step, the particle is subject to stochastic radial kicks determined by the amplitude of the anomalous diffusion coefficient. Three numerical simulations are illustrated in Fig. 3. For all of them, the ion guiding center orbits are subject to classical Coulomb collisions. For the simulations corresponding to the red and green curves of Fig. 3, the ion orbits are subject to anomalous transport generated by an ad hoc diffusion coefficient. The red curve is obtained by employing a constant $D_{anom} = 0.1\ \mathrm{m}^2 \cdot \mathrm{s}^{-1}$. The green curve is produced using an energy dependent diffusivity

$$D_{anom}/D_0 = \begin{cases} 1 & \text{if } E \leq 3T_e \\ [3T_e/E]^2 & \text{elsewhere} \end{cases} \tag{1}$$

where $D_0 = 1.5\ \mathrm{m}^2 \cdot \mathrm{s}^{-1}$. Equation (1) is chosen in order to obtain a lower boundary for the impact of microturbulence upon j_{nbi}. In both cases where anomalous transport is present we

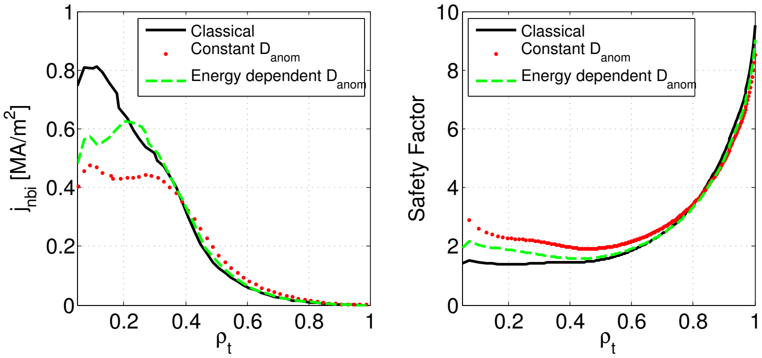

Figure 3: Left panel: neutral beam driven current density profile in a purely collisional case (solid black), with the addition of a constant anomalous diffusivity $D = 0.1\ \mathrm{m}^2 \cdot \mathrm{s}^{-1}$ (dotted red) and an energy dependent particle diffusivity (dashed green). On the right panel we can observe the impact on the safety factor, computed by the CHEASE code [12] with the addition of the bootstrap current and ECCD at mid-radius [10].

observe a large current redistribution. Turbulent transport flattens the current profile, with a significant fraction of j_{nbi} transported from the core to mid-radius. The safety factor value therefore increases in the core creating an unexpected shear reversal. This would dramatically change the transport features and the stability properties of the plasma discharge.

Conclusions

In this work we have performed linear and nonlinear gyrokinetic simulations demonstrating that the transport of suprathermal ions can be important in burning plasmas. The largest transport occurs for passing particles and in the energy range where most of the slowing down particles are found, thus leading to important changes to the driven current and to the expected sustainment of steady state scenarios. In order to directly quantify these effects, we have developed a single particle NBI model. For realistic ITER steady state scenario parameters, the safety factor profile can be significantly modified.

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