Interaction between fast particles and turbulence

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Abstract. A systematic study of high energetic alpha particle interaction with microinstability driven turbulence (ITG) is presented. The alpha particles are considered to be passive, thus not modifying the fine structure of the turbulence, and modelled as Maxwellian distributed. Both the turbulent fields and the evolution of the alpha distribution are computed by means of an Eulerian, flux tube code. It is shown how significant transport of high pressure distributions can occur, and how the direction and the intensity of the particle flux is sensitive to the choice of the temperature scale length of the alpha distribution, due to thermodiffusive phenomena. The diffusivity of an ITER-like case is studied, starting from an analytical treatment of the density and temperature profiles, which we show to be significant. New interpretative tools, by means of a single particle following code, are also presented.

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INTRODUCTION AND MOTIVATIONS

In order to achieve ignition, alpha particles need to transfer their energy to the background plasma before being expelled. The two conditions of the confinement of fusion born alphas and the expulsion of Helium impurities (ash), are crucial. If the alpha particles are not confined during their slowing down (due to some transport mechanism), the heating power coming from fusion products will dramatically reduce. Meanwhile, if the classical slowing down process does not compete with anomalous transport mechanisms, there might still be the possibility to have inward pinch phenomena for low temperature populations, such as ash. The overall result would be an increase of Helium impurities in the core, and a consequent decrease of fusion reactions.

The GENE code offers a powerful tool for the investigation of transport phenomena. This code, based on Eulerian techniques, allows the choice of an arbitrary number of Maxwellian distributed passive species. Due to the relatively low density of alpha particles, their influence on the background field can be assumed negligible, and thus ignored. This technique gives great advantages in terms of computational effort.

In the following chapters, the study of the transport behavior of Helium populations, at different temperatures, is carried out. Of particular interest is the choice of the spatial macroscopic features of these distributions. As we will see, the particle flux is highly sensitive to temperature and density profiles of the passive species.

GENE SIMULATIONS

The GENE code solves the gyrokinetic Vlasov equation for the species j

$$\frac{\partial f_{1j}}{\partial t}+\left[1/L_{nj}+1/L_{Tj}\left(v_{\|}^{2}+\mu B-\frac{3}{2}\right)\right] f_{0j}\frac{\partial \phi}{\partial y}+\left[\frac{\partial \phi}{\partial x}\frac{\partial f_{1j}}{\partial y}+\frac{\partial \phi}{\partial y}\frac{\partial f_{1j}}{\partial x}\right]+$$

$$+\frac{\mu B+2v_{\|}^{2}}{2\sigma B}\left(C_x\frac{\partial}{\partial x}+C_y\frac{\partial}{\partial y}\right)G_j+\alpha v_{\|}\frac{\partial G_j}{\partial z}-\frac{\alpha}{2}\mu B^{2}\varepsilon_t\sin z\frac{\partial f_{1j}}{\partial v_{||}}=0$$

on a 5D grid, where f_0 is the unperturbed Maxwellian

$$f_0\left(\mu,v_{\|}\right)=\pi^{-3/2}e^{-(\hat{v_{\|}}^{2}+\hat{\mu}B)} \tag{1}$$

and the other parameter definitions, and normalisations, can be found in [1, 2]. The transport features of a passive species (i.e. not modifying the turbulent mode structure of the background fields) are then influenced by gyroaveraging, mass and charge scalings, and most importantly macroscopic characteristics, such as the normalised gradient lengths, namely $1/L_n$ and $1/L_T$. As shown in a quasilinear model in [3], the particle flux can be separated into several components, each one proportional to a certain macroscopic aspect of the distribution. In order to estimate the gyroaveraging effects, one can compute the particle fluxes for several alphas species, each one with a different temperature. The transport features of the alpha population can then be compared to those of the background ions, or to thermal Helium species. As pointed out in [3], the former normalisation is valid as long as background ion fluxes are not small.

Artificial Profiles

The parameters for our first analysis are chosen from the GA standard case [4], for the background plasma. The choice of the parameters for the alpha particle distribution may vary. For our first simulations, a flat temperature profile is considered. This choice has been made since fusion born alphas, assuming a maxwellian approximation, show a relatively flat temperature profile (an analytical calculation of this profile will be presented), for which $R_0/L_{ni,e,\alpha}=3$, $R_0/L_{Ti,e}=9$, $R_0/L_{T\alpha}=0$. The normalised alpha diffusivities can be seen in Fig. 1 (left plot). At high temperatures the diffusivity is non negligible. Indeed, we observe a residual 25% diffusivity at $T_\alpha=50\,T_e$, with respect to thermal helium diffusivity. It should be mentioned that this is approximately the temperature that balances the pressure of the maxwellian to a slowing down distribution function for a real case scenario (“equivalent” temperature). This result is surprising, since one might expect a faster decay of diffusivity with energy due to orbit and gyromotion averaging effects, which has an overall effect of decreasing the effective potential. A different normalisation can give similar results. Choosing a *particle per flux* normalisation [5], which permits a direct comparison to the transport features of background species, we observe the same general behavior as for the previous case (Fig. 1, right plot). The validity of this choice requires that the ion particle flux is non vanishing [3]. For these non linear

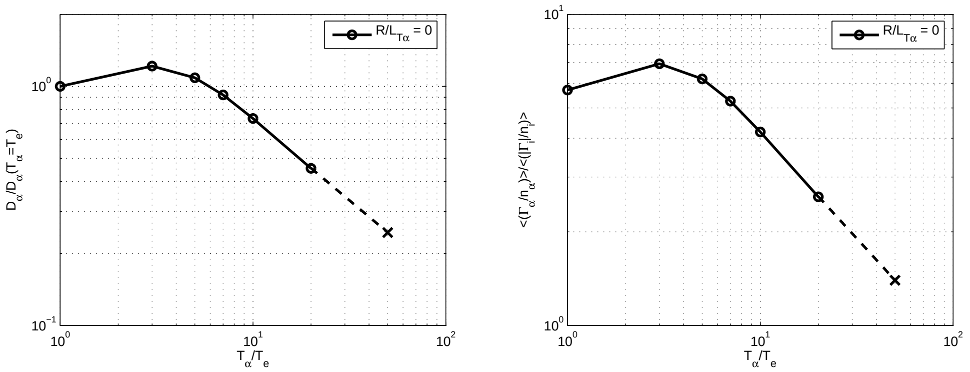

FIGURE 1. Alpha particle diffusivity (left) and flux per particle (right), as a function of temperature. The diffusivity is normalised with respect to ash ($T_\alpha = T_e$), while the flux is scaled to background ion transport features (as in Ref. [5]). In both cases, the cross indicates the position of the equivalent alpha temperature, obtained by a power law fit.

runs this is the case, since $\langle \Gamma_i \rangle_t \sim 10 \left[D_{gb} n_{0i}/R_0 \right]$. From this figure, it is evident how particle fluxes for alpha particles are higher than those of the background plasma, even at high temperatures.

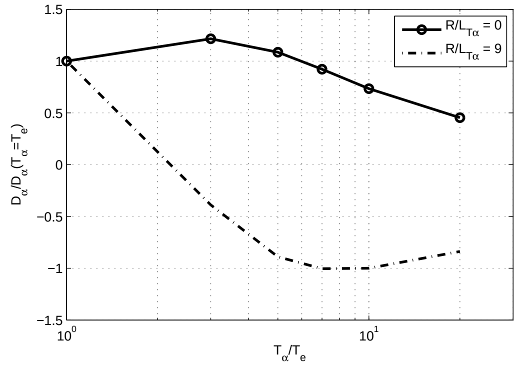

FIGURE 2. Alpha particle diffusivity as a function of temperature, for two different temperature gradient length. It is clear how a low temperature pinch appears for a steep alpha temperature profile, and $T_\alpha > 2T_e$.

We can now see what happens when a different temperature profile gradient for alpha particles is chosen. If we consider Helium impurities, it is reasonable to assume that the temperature profile will be in thermodynamic equilibrium with the background plasma profiles. Fig. 2 compares a temperature scan for $R_0/L_{T\alpha} = 9$ and $R_0/L_{T\alpha} = 0$. We notice both differences and similarities for the flat and steep temperature profiles. In both cases, the alpha diffusivity is non negligible, even at high temperatures. However, the presence of a low temperature pinch for the ash profiles, coming from thermodiffusive effects, is observed. From these arbitrarily chosen profiles, both of the following threatening conditions for future tokamaks can be observed. High pressure distributions show non vanishing diffusivity (up to 15% times those of a thermal case). Low temperature distributions, on the other hand, are characterised by inward fluxes, and impurity accumulations might take place.

In order to verify whether the results obtained so far can be a good approximation for a real reactor case, more accurate profiles for both the background plasma and the fast ion populations need to be calculated.

ITER Profiles

Let us define a generic background plasma profile as $f(r/a) = \left[1-(r/a)^2\right]^{\alpha_f}$ where α_f can be obtained by differentiation and choosing $1/L_n$ and $1/L_T$ at mid-radius, which is area of our interest. Now, a slowing down distribution function for fusion born alpha particles can be expressed as

$$f_s(r,v) = \frac{S_0\tau_s}{4\pi}\frac{\Theta(v_\alpha - v)}{v^3 - v_c^3} \tag{2}$$

where S_0 is the fusion production rate, $\tau_s \propto T_e^{3/2}/n_e$ and $v_c = \left[3/4\sqrt{\pi}m_e/m_\alpha Z_{\text{eff}}\right]^{1/3} v_{the}$. Once T_e and n_e, and thus f_s, have been defined, the moments of the slowing down distribution directly determine the profiles of our interest as $n_\alpha(r) = \int_{v_{min}}^{v_{max}} f_s(r,v)d^3v$ $T_\alpha(r) = m_\alpha/n_\alpha(r)\int_{v_{min}}^{v_{max}} v^2 f_s(r,v)d^3v$, where v_{min} and v_{max} can be set in order to focus on thermal or supra-thermal particles ($2v_{thi}$ has been chosen as the separation between the two cases). One finds that $n_\alpha(r) = \left[S_0\tau_S K(v_{max}/v_c, v_{min}/v_c)/3\right]$ and $T_\alpha(r) = \left[m_\alpha v_c^2\, g(v_{max}/v_c, v_{min}/v_c)/K(v_{max}/v_c, v_{min}/v_c)\right]$ where

$$K(a,b) = \log\left(a^3\right) - \log\left(b^3\right) \tag{3}$$

$$g(a,b) = \left[\frac{x^2}{2} - \frac{1}{\sqrt{3}}\text{atan}\left(\frac{2x-1}{\sqrt{3}}\right) + \frac{1}{3}\log(x+1) - \frac{1}{6}\log(x^2 - x + 1)\right]_{x=b}^{x=a} \tag{4}$$

Now, choosing a particular value for $R_0/L_{n,T}$ for the background will fully determine the temperature and density of the alphas. The choice of parameters has been made according to a typical steady state scenario in ITER at mid-radius [6], namely $R_0/L_{nei} = 0.5$ and $R_0/L_{Tei} = 7$

The resulting profiles and gradients can be seen in Fig. 3. As we can see, the flat temperature assumption for hot alphas is verified. More generally, the profiles of hot alphas are less steep than those of ash particles. From supra-thermal to thermal profiles, the density goes from $R_0/L_{n\alpha} = 15 \rightarrow R_0/L_{n\alpha} = 18$ while the temperature steepens as $R_0/L_{T\alpha} = 1.5 \rightarrow R_0/L_{T\alpha} = 7$. The biggest difference with respect to the artificial profiles case is the presence of very peaked density distributions. Steeper density profiles will compensate thermodiffusion, and the low energy pinch tends to disappear.

A temperature scan with these parameters has been performed in order to verify whether the low energy inward flux can be observed (Fig. 4). As expected, no pinch is found for low temperature distributions. The steepening of the density profiles really brings a beneficial effect overall. However, we observe that anomalous diffusivity of the alpha population is still non negligible ($D_\alpha \sim 15\% D_i$ at high temperatures).

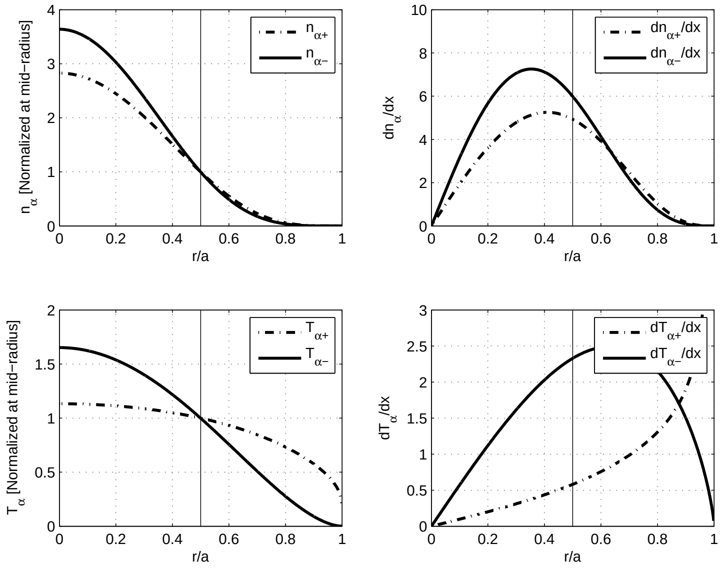

FIGURE 3. Alpha particle temperature and density profiles (left) for thermal and supra-thermal particles belonging to a slowing down distribution function (normalised at mid-radius). The gradient of the density and temperature profiles are shown (right).

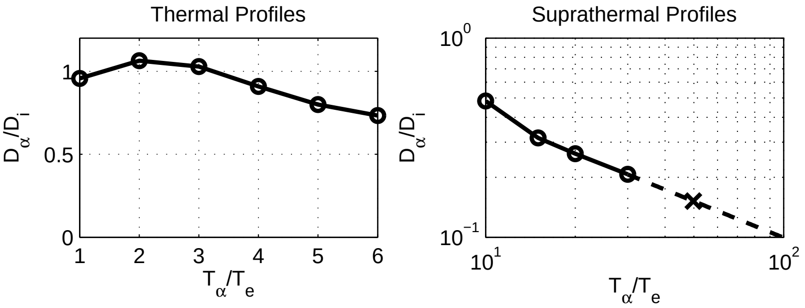

FIGURE 4. Alpha particle diffusivity, as a function of temperature, for low (left) and high (right) energy ranges of Eq. 2. The cross indicates the position of the equivalent alpha temperature, obtained by a power law.

The issue yet to be solved is whether classical and anomalous mechanisms might be in competition. We can calculate the characteristic slowing down time of a 3.5 MeV alpha particle in ITER, at mid-radius, and compare it with an estimate of the anomalous transport time for alphas, at $T_\alpha = 30\ T_e$. We find

$$\tau_{\alpha-sd} \sim 0.6s, \quad \tau_{anomalous} = a n_{\alpha 0} / \langle \Gamma_\alpha \rangle_t \sim 0.1s \tag{5}$$

Apparently, the anomalous transport can certainly compete with the classical one. The procedure used so far, however, assumed an already slowed-down population of alphas, modelled by Maxwellians. Consequently, we must point out that further work must be undertaken in order to verify Eq. 5, since the transport could be driven by the low energy part of the distribution. Such a situation could be beneficial to the plasma, with

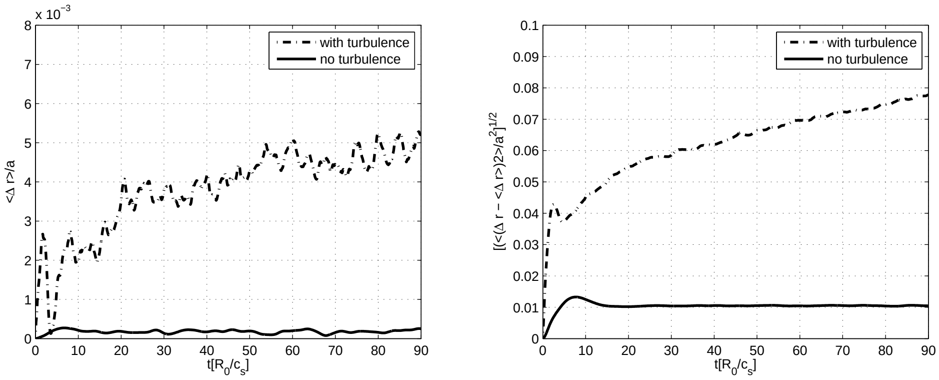

FIGURE 5. First and second moment of the spatial distribution of N=10^4 particles, Maxwellian distributed in phase space and delta distributed along radius, as a function of time. For this case, $T_\alpha = 10\ T_e$.

a reduction of $Z_{\rm eff}$ in the core. However, the classical confinement time will be different from the one calculated above. Other techniques need to be developed in order to give a more accurate estimate of the anomalous transport time.

GENE MAPPING AND HMGC

The drive mechanism responsible for the strong radial transport of high-energy populations is not clear from simulations. Recently [3, 7], it has been shown how possible resonant interactions can take place, thus increasing the perturbed distribution function and enhancing the transport. In order to investigate this further, and to give an estimate for $\tau_{anomalous}$, a single particle following code (the HMGC code [8]) has been updated and adapted. Interfaces have been written for mapping flux tube dependent fields to real space coordinates, exploiting GENE's boundary conditions and periodicities. The interface between three dimensional GENE electrostatic fields and the single particle code allows the use of arbitrary initial conditions for the ensemble of particle considered, both in velocity and real space. Particle diffusivity can then be calculated in terms of the statistical features of the spatial distribution of particles considered (Fig. 5). Future analysis will be focus on demonstrating the validity of the resonance assumption, and also on possible trapping/detrapping mechanisms, whose overall effects can lead to a net outward or inward flux.

CONCLUSIONS

In this work, it is found that high temperature distributions of alpha particles can be significantly transported by interactions with ITG turbulence. In all the cases studied, the alpha particle diffusivity at high temperatures is non negligible, with respect to Helium ash. Moreover, considering a flux per particle normalisation, it is observed how the alpha transport features are more significant than the background plasma. The validity of the former normalisation is appropriate providing that the background ion flux per particle is non zero. Employing a particular choice of the macroscopic features of the distribution, namely the temperature gradient length, the particle flux can be inward for Helium ash. For an ITER-like scenario, however, this pinch is not likely to occur due to steep density gradient of the Helium population. The collisional slowing down time for a fusion born alpha particle at mid-radius in ITER is calculated, and it is observed how anomalous transport can take place on shorter time scales. A single particle treatment, also shown in this work, is then necessary for discriminating different behaviors (low/high energy, trapped/passing particles). Future results can then indicate whether self sustained heating might be compromised by anomalous transport.

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