Microturbulence-induced modifications to the alpha particle distribution and associated effects

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The transport of alpha particles is of critical importance to a burning DT fusion reactor. Among other important phenomena, turbulence driven by microinstabilities such as the ion temperature gradient (ITG) mode is one such source of transport. Previous work [1, 2] used linear theory to estimate the flux of alpha particles, and recently, this linear approach was generalized to account for energy-dependent fluxes [3]. Another key assumption is that alpha particles respond only passively to microturbulence. Apart from finite-beta effects that might occur in some cases, this is a reasonable assumption, and one that we retain to make the problem computationally feasible. However, we retain the fully nonlinear turbulent dynamics: what would otherwise be a monumental task requiring tens of millions of CPU hours can now be performed in seconds on a standard workstation using a newly developed tool.

The transport equation in the low-collisionality gyrokinetic hierarchy reads [4]:

$$\frac{\partial F_\alpha}{\partial t} + \frac{1}{V'}\frac{\partial}{\partial \psi}\left(V'\Gamma_\psi\right) + \frac{1}{v^2}\frac{\partial}{\partial v}\left(v^2\Gamma_v\right) = C\left[F_\alpha\right] + S_\alpha, \tag{1}$$

where $F_\alpha\left(\psi, v\right)$ is the alpha particle distribution, $V\left(\psi\right)$ is the volume of the flux surface labelled by a generalized radial coordinate ψ (here, the half-width of the flux surface at the height of the magnetic axis), and C is the test-particle collision operator for alphas colliding against deuterons, tritons, and electrons. The radial and energy fluxes can be decomposed respectively as:

$$\Gamma_\psi = -D_{\psi\psi}\frac{\partial F_\alpha}{\partial \psi} - D_{\psi v}\frac{\partial F_\alpha}{\partial v}, \qquad \Gamma_v = -D_{v\psi}\frac{\partial F_\alpha}{\partial \psi} - D_{vv}\frac{\partial F_\alpha}{\partial v}. \tag{2}$$

For details on how this decomposition follows from the structure of the gyrokinetic equation, the reader is directed to Refs. [4] and [5]. It is important to note that this decomposition only depends upon the trace approximation; one is not required to ignore the turbulent drift to take advantage of Eqs. (2). Including two Helium-like species in the turbulence simulation, each with different radial gradients, one can solve for the diffusion coefficients as a simple algebraic solve at each energy. This T3CORE does by post-processing existing GS2 simulations, then solving Eq. (1) with a 2D finite-volume method. The code has been tested with a nontrivial constructed analytic solution, the results of which are shown in Fig. 1.

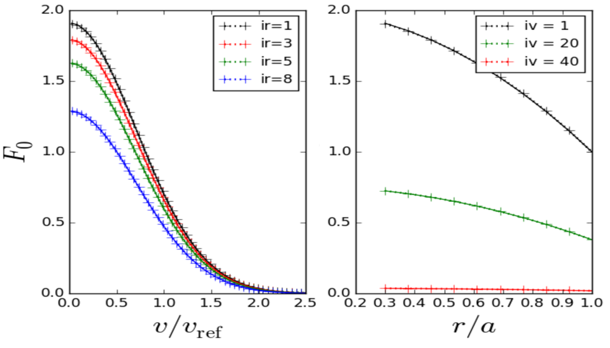

Figure 1: *Comparing a constructed analytic solution to Eq.* (1) *(solid lines) to the numerical solution from* T3CORE *(crosses) at representative cross-sections in radius (left) and energy (right). Resolution is* $N_r = 10 \times N_v = 100$. *Error converges toward zero by increasing the resolution further.*

As a representative example of a DT scenario, we use the radial profiles of ITER scenario 10010100 of the IPTA public database as the drive for the turbulence simulations. For this profile, ITG is only unstable for $\psi \gtrsim 0.5\psi_a \equiv \psi_{\min}$ (where ψ_a is the coordinate label of the separatrix), so that will mark the beginning of the computational domain. The gyrokinetics code GS2 is run at four equally spaced radii up to $\psi = 0.8\psi_a$, beyond which direct and ripple loss of alpha particles might become important. As is consistent with known results: at low energy, the diffusion coefficient is approximately equal to the bulk ion thermal conductivity χ_i [6]; at high energy it obeys a v^{-3} scaling [7]; and the radial diffusion term $D_{\psi\psi}$ is dominant [3]. There is little discernible difference in the transport simulations when the other three coefficients are removed. From this, we can conclude that ITG turbulence is incapable of providing a means of alpha "channeling".

Novel results (reported in Ref. [8]) that were found in steady-state transport simulations include the existence of a non-monotonic feature of the distribution at around 300keV, where the diffusivity is peaked, but the distribution is no longer Maxwellian. A similar feature of the alpha particle distribution was observed in the JET DT campaign [9]. The alpha particle pressure profile is, as a consequence, flattened by up to about 50%, and the heating rate is decreased by about 25% as compared to the local slowing-down distribution at select radial locations. The exact figure of course depends the amplitude and properties of the turbulence. Possibly important effects left out of these gyrokinetic simulations include electromagnetic fluctuations (which are expected to enhance the particle flux at high energy) and flow shear (which is expected to decrease it).

To see where in velocity space the loss of alpha heating comes from, Fig. 2 shows the integrand of the heating rate. Most of the alpha particle heating happens around the birth speed v_α, the bulk of which is absorbed by the electrons. As expected, turbulence has little effect on the heating near v_α, but the modified distribution results in a decrease in heating, or even a cooling effect, at lower energy. This impacts both the heating of ions and electrons.

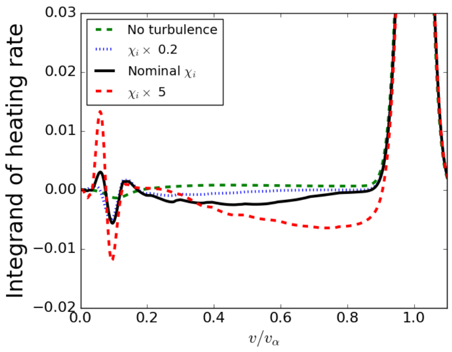

Figure 2: *The integrand of the heating rate (=* $- C[F_\alpha]\,\frac{1}{2}m_\alpha v^2 4\pi v^2$ *) in arbitrary units as a function of speed at* $\psi = 0.6\psi_a$*. The magnitude of the diffusion coefficients are artificially scaled up and down by a factor of five from the actual simulation results to demonstrate a feasible range of effect.*

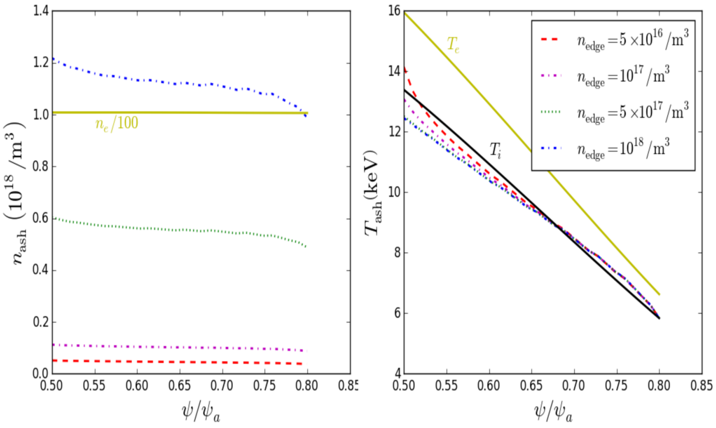

Figure 3: *The radial profiles of ash density (left) and temperature (right) as fitted from the distribution function at low energy. Shown are the results from a range of several chosen edge densities from* $n_{\mathrm{nedge}} = n_\alpha(0.8\psi_a) = 5\times10^{16}$ *to* $n_{\mathrm{edge}} = 10^{18}/\mathrm{m}^3$.

Much of the helium distribution is in approximate thermal equilibrium with the ions, rather than decelerating alpha particles. The transport of this low-energy Maxwellian part of the distribution is also captured with T3CORE, and is shown in Fig. 3. The flat density profile of ash is to be expected from previous results [10], and the internal helium density is therefore set by the density chosen at the edge. Furthermore, we see a modest departure from the bulk ion temperature. However, we believe even this relatively small difference in temperature is unphysical. The ash should transport similarly the ions, a known result that our turbulence simulations corroborate. The reason this happens is because the ion profile itself is fixed from previous transport simulations, while the helium responds consistently to the turbulence. This limitation is simply due the use of an approximate model for the anomalous transport in TRANSP. However, when more robust turbulence simulations are ran using these profiles, such as we do here, care must be taken. Therefore, going forward, it is important to use better equilibrium profiles provided by experiment, self-consistent turbulent transport simulations (using tools such as TRINITY or TGYRO), and/or more robust transport models. For now, we compensate for this by replacing the Maxwellian part of the distribution with one that is at the exact ion temperature.

The departure from the analytic slowing-down distribution is a consequence of the relatively weak dependence of the collision operator with energy (the characteristic time approaches an asymptote at high energy, the slowing-down time τ_s), while the characteristic transport time scales like v^{-3}. So even if newly-born alpha particles are well-confined, this can change at lower energies (see Ref. [5]). Exactly how the slowing-down distribution changes depends on the solution of the transport equation (1), but it is possible to identify a dimensionless parameter that characterizes this departure fairly well:

$$b \equiv \chi_i \tau_s \left| \frac{n''_\alpha}{n_\alpha} + \frac{n'_\alpha \chi'_i}{n_\alpha \chi_i} \right| |\nabla \psi|^2 / 100. \tag{3}$$

The primes denote differentiation with respect to ψ. The factor of 100 is ad-hoc and depends on the form of the alpha particle diffusion coefficient. However, we find that this is a good estimate for the departure from the slowing-down distribution (see Fig. 4), using the relative change in density as a proxy.

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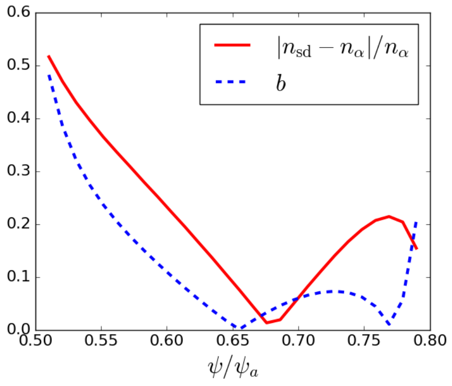

Figure 4: *The dimensionless parameter b from Eq.* (3)*, being compared to the relative change in alpha particle density from* T3CORE *simulations* (n_α) *and the analytic slowing-down distribution* ($n_{\rm sd}$)*. Both densities have the Maxwellian ash removed.*