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A NEW GYROKINETIC QUASI-LINEAR TRANSPORT MODEL

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1. Introduction

In order to better understand turbulent transport mechanisms and therefore enhance the predictive capability, actual available transport models have to be improved. Ideally, nonlinear gyrokinetic electromagnetic simulations for all species should be systematically performed. Unfortunately, for the coming 10 years, this approach is still too costly in terms of computer time [1]. A pragmatic trade off is to develop a quasilinear transport model based on a rapid linear gyrokinetic code. Moreover, in a number of cases, the quasi-linear approach exhibits a rather good agreement with experiments [2,3] and with non-linear gyrokinetic simulations [4,5]. Nevertheless, major non-linear physics issues impacting turbulent transport (zonal flows, turbulence spreading, etc.) cannot be taken into account. Therefore, on a longer term basis, the quasi-linear model presented should be refined thanks to extensive comparisons with non-linear simulations and turbulence measurements. Here, we present and benchmark the first version of a quasi-linear calculation of heat and particle fluxes, QuaLiKiz, based on a fast linear electrostatic eigenvalue gyrokinetic code, Kinezero [6].

2. A new gyrokinetic quasi-linear model, QuaLiKiz

The quasi-linear equation is the time average of the nonlinear Vlasov equation over a time τ larger than the characteristic time of the fluctuations and smaller than the equilibrium evolution time. The fluctuations are assumed to be significantly smaller than the equilibrium quantities and the non-linear term is assumed to be constant over the time τ. Finally, we assume that the fluctuating distribution function $\tilde{f}$ linearly responds to the fluctuating electrostatic potential $\tilde{\phi}$ through the linearized Vlasov equation. Kinezero [6] is used to compute the linearized Vlasov equation. Kinezero accounts for two ion species and electrons in both their trapped and passing domains. It is an eigenvalue code that computes all unstable modes. For trapped electrons collisions are included [7]. Hence, the quasi-linear formulation of the particle flux for a species s, Γ_s, leads to:

$$\Gamma_s = \left\langle \tilde{n}_s \frac{ik_\theta \tilde{\phi}}{B} \right\rangle = -\frac{n_s}{R}\left(\frac{q}{r}\right)^2 \frac{1}{B^2} \sum_{n,\omega} n^2 \left\langle \sqrt{\xi} e^{-\xi} \left(\frac{R\nabla n_s}{n_s} + \left(\xi - \frac{3}{2}\right)\frac{R\nabla T_s}{T_s} + \frac{\omega}{n\omega_{Ds}} \right) \mathrm{Im}\left(\frac{1}{\omega - n\Omega_s(\xi,\lambda)} \right) \right\rangle_{\xi,\lambda} \left|\tilde{\phi}_{n\omega}\right|^2$$

n_s is the density, T_s, the temperature, n being the toroidal wave number, $k_\theta = \frac{nq}{r}$ the poloidal wave vector, ξ stands for the normalized energy, λ, for the normalized perpendicular velocity, ω is the frequency of the modes, $n\omega_{Ds}$, the curvature drift frequency and $n\Omega_s(\xi,\lambda)$, the transit frequency which differs for trapped or passing particles, more details in [6].

The most delicate part in estimating the quasi-linear fluxes is due to the fact that the linearized gyrokinetic equation does not allow having information on the amplitude of the fluctuating electrostatic potential $\left|\tilde{\phi}_{n\omega}\right|$ nor on its spectral shape versus the wave number n and the frequency ω.

For the wave vector spectrum, turbulence measurements performed by light scattering [8] have shown that the density fluctuations scale as $e^{-4k\rho_i}$ above $k\rho_i$=0.5. Measurements by Beam Emission Spectroscopy [9] showed the poloidal k spectrum is symmetric around k_{max}. The maximum value of $\left|\tilde{\phi}_{n\omega}\right|^2$ at k_{max} is chosen to scale like the mixing length flux, $\max\left(D_{eff} \approx \frac{R\Gamma_s}{n_s} \right)\Big|_{k_{\max}} = \frac{\gamma}{\left\langle k_\perp^2 \right\rangle}\Big|_{k_{\max}}$. Adding the impact of the MHD Shafranov parameter, α, on the curvature drift to the expression proposed by [4, 10, 11], one obtains for strongly ballooned modes: $\left\langle k_\perp^2 \right\rangle = k_\theta^2 \left(1 + (s-\alpha)^2 \left\langle \theta^2 \right\rangle\right)$. In the quasi-linear model presented in [4, 10, 11], the quasi-linear fluxes are computed at one k value, k=k_{max}. In our case, we sum over the k spectrum.

Concerning the frequency spectrum, measurements with light scattering diagnostics [12, 13] show the enlargement of the frequency spectrum of density fluctuations. A theoretical explanation of the turbulence broadening expression is given in [14]. In our model, we choose a lorentzian broadening: $\left|\phi_{n\omega}\right|^2 = \frac{1}{\pi} \frac{\gamma_0}{(\omega - \omega_{r0})^2 + \gamma_0^2} \left|\phi_n\right|^2$ Where ω_{r0} and γ_0 are respectively the real and imaginary part of the eigenvalues of the linear gyrokinetic equation.

QuaLiKiz has been benchmarked against the model proposed by [4, 10, 11] based on GS2 [15]. Since GS2 run linearly computes the most unstable mode only and is two order of magnitude slower than Kinezero, to benchmark the two models, we have restricted the flux estimation in QuaLiKiz to the most unstable mode and to one value of k, $k = k_{\max}$. The results obtained are very similar to the one published in [11] figure 3. In particular the particle fluxes reverse sign for the same values of $\frac{R}{L_n} = -R\frac{\nabla n}{n}$, see figure 1.

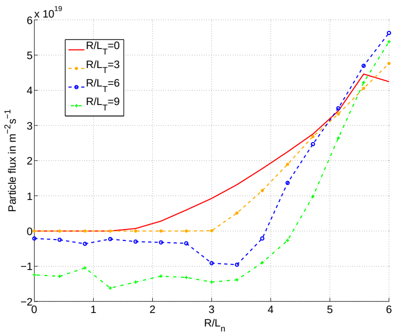


Figure 1: *Particle flux calculated using Kinezero, for the most unstable mode and at* $k = k_{\max}$, *versus* $\frac{R}{L_n} = -R\frac{\nabla n}{n}$ *for various values of* $\frac{R}{L_T} = -R\frac{\nabla T}{T}$

3. Impact on particle flux of summing over k_θ and over all unstable modes

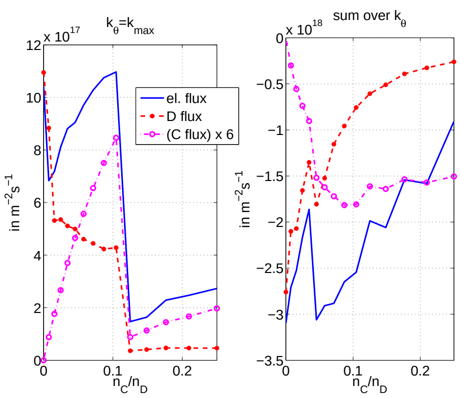
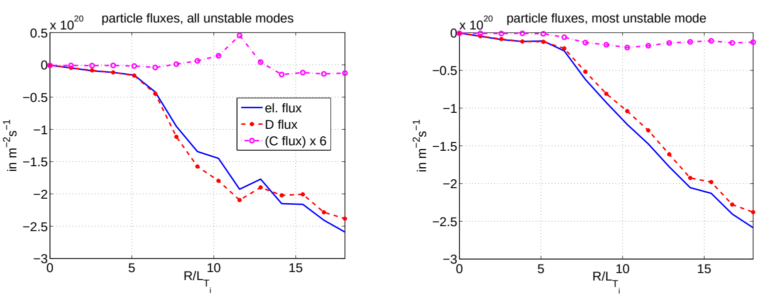


Figure 2: *electron, main ion, D, and impurity, C, particle fluxes versus the C concentration:* n_C / n_D. *a/ for the case where* $k_\theta = k_{max}$ *as proposed in [4,10,11], b/ when summing over* k_θ *as done in QuaLiKiz*

To illustrate the impact of summing over k_θ, we choose to run a case similar to the scan proposed in [16] dominated by electron heating, i.e. $\left(\frac{R}{L_{Ti}}, \frac{R}{L_n}, \frac{R}{L_{Te}}\right) = (0,0,9)$. In this example, all fluxes are directed outward when accounting for one $k_\theta = k_{max}$ and they are all directed inward when summing over k_θ as done in QuaLiKiz. Hence, the outward parallel compressibility of impurity identified in [16] to be a candidate to explain the JET electron heated experiments [17] is found to be directed inward when summing over k_θ.

Figure 3
Electron flux, full line; D flux, dashed line with asterisks; C flux, dashed dotted line with circles, versus $\frac{R}{L_{Ti}} = -R\frac{\nabla T_i}{T_i}$.

a/ b/



Concerning the impact of accounting for all unstable modes, $\frac{R}{L_{Ti}} = -R\frac{\nabla T_i}{T_i}$ is varied from 0 to 18, keeping fixed the electron density and temperature gradients. The particle fluxes are compared when all unstable modes contribute as done in QuaLiKiz, figure 3a, and when only the most unstable mode contribute to the fluxes as done in [4, 10, 11], figure 3b. The most striking differences are observed on the impurity fluxes between $\frac{R}{L_{Ti}} = 5$ and 13 which reverse direction where two unstable modes coexist.

4. Conclusions

With the longer term aim of improving first principle based transport models used in integrated transport codes, we propose a new quasi-linear gyrokinetic model, QuaLiKiz, based on a fast linear eigenvalue gyrokinetic code, Kinezero [6]. The k and frequency spectra chosen for the fluctuating electrostatic potential are based on turbulence measurements and non-linear simulations results. QuaLiKiz has been successfully benchmarked against the quasi-linear model based on GS2 proposed by [4, 10, 11]. We have shown that to give predictions, quasi-linear simulations accounting for all unstable modes, summing over k, are needed. To further test the validity of the quasi-linear approach, wider confrontations between non-linear simulations and turbulence measurements are needed: to improve the choices made for the k and frequency spectra and to understand in which range of parameters it is acceptable to neglect non-linear structures such as streamers or zonal flows.

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