Fixed-gradient and fixed-flux full-f simulations of global ion temperature gradient driven turbulent transport

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Introduction

First principle based gyrokinetic simulations are promising approaches for analyzing turbulent transport processes in magnetically confined plasmas. Historically, most of gyrokinetic simulations were based on a local fluxtube(FT) model or a global delta-f fixed-gradient(FG) model with an adaptive heat source, and then, ion temperature gradient(ITG) driven turbulent transport, the most fundamental transport process, has been extensively investigated so far. On the other hand, recent progress of High-Performance-Computing numerical approaches encourages numerical experiments by using a global full-f model with an external fixed-flux(FF) source as in actual plasma experiments. Although the credibility of such codes has been improved through validation studies, the difference of transport characteristics among FF, FG, and FT models has rarely been discussed.

In this study, we perform systematic comparisons of the ITG driven turbulent transport among the FT, FF, and FG models by using a FT code GKV[1], a FF code GT5D[2, 3], and the FG version of GT5D, where an adaptive heat source providing the delta-f FG like model is newly implemented. Through the verification study, it is found that the plasma size (ρ^*) and the collisionality (ν^*) scalings of turbulent transport can be significantly different depending on the calculation model.

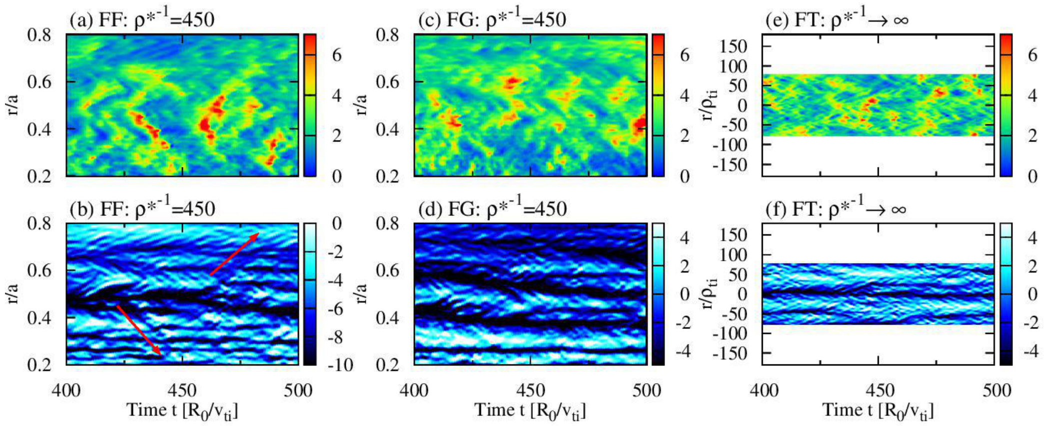

Figure 1: *Spatio-temporal evolutions of ion heat diffusivity χ_i [(a),(c),(e)], and radial electric field E_r [(b),(d),(f)] for FF, FG, and FT models.*

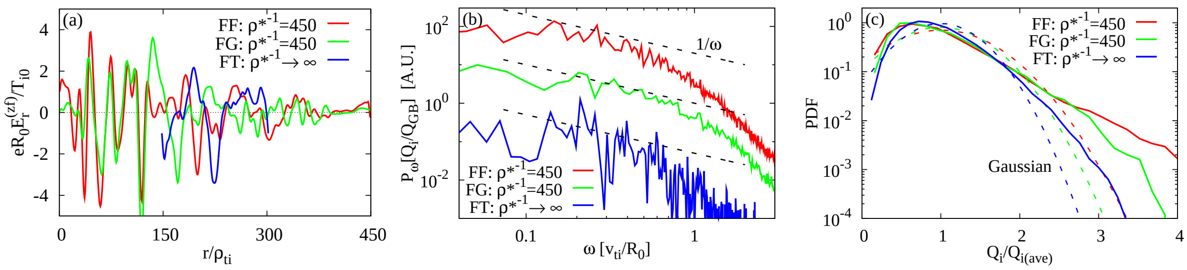

Figure 2: *Comparisons of (a)zonal-E_r, (b)frequency spectra, and (c)PDF in FF/FG/FT models.*

Comparisons of turbulence characteristics in local limit

In the ρ^*-scaling studies for the ion heat diffusivity χ_i, global delta-f FG simulations showed a transition from Bohm to gyro-Bohm scaling, where asymptotic transport levels in the local limit regime of $\rho^{*-1} \geq 300$ well converge to the FT results[4, 5]. Although the recent ρ^*-scan with the full-f FF model was limited to $\rho^{*-1} \leqslant 225$, the Bohm (or worse-than-Bohm) like scaling and the relevant non-local transport dynamics were revealed[3]. In this study we extend the ρ^*-scan with the FF model towards the local limit regime of $\rho^{*-1} = 450$, where the heating power is simultaneously scaled with the plasma size. Then, the similarity and difference on turbulence characteristics among FF, FG, and FT models are discussed. From the ρ^*-scan over $\rho^{*-1} \geq 300$, we found that the steady ion temperature profiles T_i show strong stiffness, where the mean levels in the source free region are constrained near critical gradient value ($R_0/L_{T_i} \sim 6$). As a result of such T_i-stiffness and the the external heating scaled with the plasma size, the Bohm-like scaling of $\chi_i \propto \rho^{*-1}$ appears over $150 \leqslant \rho^* \leqslant 450$. It is also found that the transport dynamics in the FF model is qualitatively different from that in the FG and FT models, i.e., the bursty behavior and its avalanche like radial propagations are still remarkable even for $\rho^{*-1} = 450$.

Spatio-temporal evolutions of χ_i and the radial electric field E_r are compared in Figs. 1, where the heating power in the FF case and the time-range are chosen such that the mean χ_i is similar to the FG and FT cases. Large burst events and its ballistic propagations with significant radii are identified only in the FF case. On the other hand, small-scale avalanches bounded by the zonal-E_r scale are commonly observed for all the cases. They also show similar propagation speed, width, and directions depending on the sign of zonal-E_r shear. Note that the large burst events across the zonal-E_r are no longer identified in the FG and FT cases.

The statistical properties are compared in Figs. 2. The similar steady radial structures of zonal-E_r are observed [Fig. 2(a)], where the zonal-E_r is defined as deviations from a mean profile obtained from Gaussian filtering. In the frequency spectra, the SOC like ω^{-1}-spectrum appears in the FF and FG cases while the FT case shows stronger decay in the low- and high-frequency regions[Fig. 2(b)]. A strongly non-Gaussian feature with significant long-tail compo-

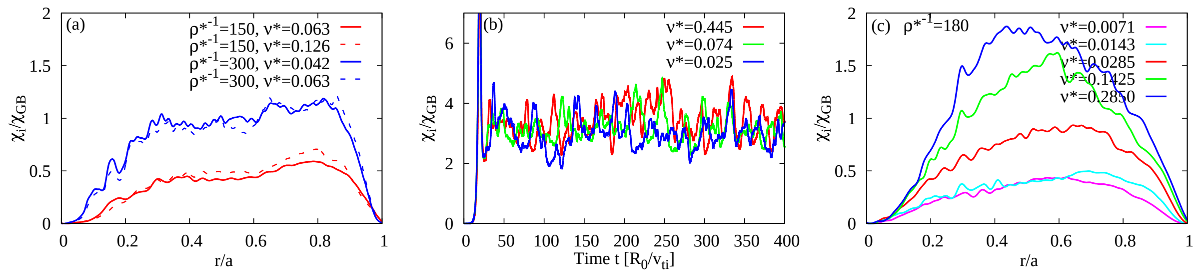

Figure 3: *(a)*$\chi_{\rm i}/\chi_{\rm GB}$ *in the FF model (*$R_0/L_{T_{\rm i}} \simeq 6$*), (b)*$\chi_{\rm i}/\chi_{\rm GB}$ *in the FT model (*$R_0/L_{T_{\rm i}} = 6.92$*), and (c)*$\chi_{\rm i}/\chi_{\rm GB}$ *in the FG model (*$R_0/L_{T_{\rm i}} = 6.92$*).*

nents is found in PDF of the FF case, while it becomes less significant in the FG and FT cases [Fig. 2(c)]. The decrease of the tail-components is associated with the fact that the large burst events propagating across the zonal-E_r become less significant in the FG and FT models.

While there are some similarities in transport properties among the FF, FG, and FT models, it is stressed that consistent interactions between profile evolutions and turbulent transport are unique for the FF case, and can lead to bursty transport and the avalanche like propagations. This mechanism is absent in the FG and FT models, i.e., turbulent flux is uniquely determined by a given gradients, and explains the different PDF structures from the FF model.

Different collisionality dependences among FF/FG/FT models

Another important scaling factor for the prediction of turbulent transport levels is collisionality (ν^*). A recent work on the global FG simulations of collisional ITG turbulent transport reported strong ν^*-dependence even at far-above-critical gradients[7]. However, this seems to contradict with former ν^*-scan in L-mode experiments, which reported weak ν^*-dependence of $\chi_{\rm i}$[8]. In this study, we verify such different ν^*-dependence by the comparisons among the FF, FG, and FT models in the Cyclone base case parameters.

In the ν^*-scans with GT5D and GKV, no significant ν^*-dependence is observed for both the FF and FT cases [Fig. 3(a) and 3(b)]. For such cases, it has been confirmed that the collisional zonal flow (or mean-E_r) damping is less effective as long as $R_0/L_{T_{\rm i}}$ is sufficiently higher than the critical gradient value. In contrast, the FG case shows strong ν^*-dependence of $\chi_{\rm i}$, which was reported in the earlier FG simulations[7] [Fig. 3(c)]. Since $R_0/L_{T_{\rm i}}$ is much higher than the critical value in the present FG cases, the observed transport enhancement is attributed to the other mechanism rather than the collisional zonal-flow damping. An alternative mechanism leading to the strong ν^*-dependence has been identified that the ν^*-dependent heating/sink from the adaptive heat source, which compensates the equilibrium profile relaxation due to neoclassical heat transport, affects the ITG-mode stability through the deformation of the velocity distribution. This is verified by single toroidal mode ITG simulations for the neoclassical equilibria with and without the adaptive heat source. The former is given by the steady distribution function in the neoclassical simulations($n=0$, m = finite) with the adaptive heat source, while the latter is given by the distribution function at $t \sim \tau_i$(the ion collision time) in the case without the source. As shown in Figs. 4, the strong ν^*-dependence is qualitatively reproduced in the linear growth rate and the peak saturation level for the former case [Fig. 4(a)], while no significant ν^*-dependence is confirmed in the latter case [Fig. 4(b)]. In the conventional delta-f simulations solving only perturbations from a neoclassical equilibrium, the adaptive heat source should ideally compensate a temperature variation induced by turbulent transport, not by collisional profile relaxation. Thus, a special care must be taken for the FG simulations including neoclassical transport processes when the collisionality dependence is investigated towards the high-ν^* regime.

Summary

In the ρ^*-scan with the FF model, it is found that when the heating power is scaled with ρ^{*-1}, the formation of stiff T_i-profile and associated Bohm like ρ^*-dependence of χ_i appear even in the local limit regime($\rho^{*-1} \geq 300$). Although some similarities among the FF/FG/FT models are found in zonal-E_r structures and frequency spectra, a strongly non-Gaussian PDF associated with bursty transport and the avalanche like propagations appears in the FF model even for the local limit regime ρ^*. The ν^*-dependence at far above the marginal ITG stability is also verified through the inter-model comparisons. The FF and FT models give a weak ν^*-dependence, while the FG model shows a strong ν^*-dependence. It has been revealed that the FG model provides such strong ν^*-dependence through the change of ITG mode stability due to ν^*-dependent deformation of the velocity distribution function by the adaptive heat source.

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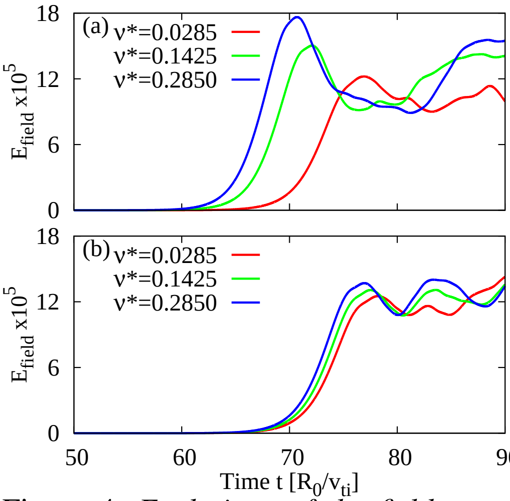

Figure 4: *Evolutions of the field energy* $E_{\rm field}$ *in the single toroidal mode simulations by using neoclassical equilibria (a)with and (b)without the FG source.*