Interaction between turbulence and neoclassical effects in global gyrokinetic simulations with GENE

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Introduction

The steep radial gradients of the temperature and the pressure cause a tokamak plasma to be in a state of turbulence and this phenomenon provides the dominant channel for the transport of particles, heat and momentum. Collisions and the toroidal geometry of the magnetic guide field, however, provide an additional channel, neoclassical transport, which can become relevant if the turbulence becomes weak or suppressed[1].

While both neoclassical and turbulent transport have been studied extensively and mainly separately in the last decades, their possible interactions leave a number of open questions. In particular, regions with steep gradients such as transport barriers may enable synergies between the two as the separation of the ion gyroradius scale and the gradient length scale does not hold there. By means of the gyrokinetic code GENE[2, 3] we investigate a potential interaction mechanism between ion-temperature-gradient (ITG) turbulence and neoclassical physics mainly via modifications of the zonal flow pattern by the long-range radial electric field connected to neoclassical effects.

Role of q in gradient-driven simulations

In prior work we found that in radially global fixed-gradient simulations of ITG turbulence the turbulent heat flux can be increased by 20-30% for $\rho_* > 1/300$ in the presence of neoclassical effects[4]. As expected the interaction vanishes when approaching the local limit. Here we demonstrate how the shape of the safety factor profile modifies the interaction for a system with $\rho_*(x/a = 0.5) = 1/150$. The temperature and density gradient profiles have the peaked shape shown in Fig. 1 and the magnetic flux surfaces are circular and concentric. Electrons are treated as adiabatic and ion-ion collisions are modelled with a linearised Landau-Boltzmann operator.

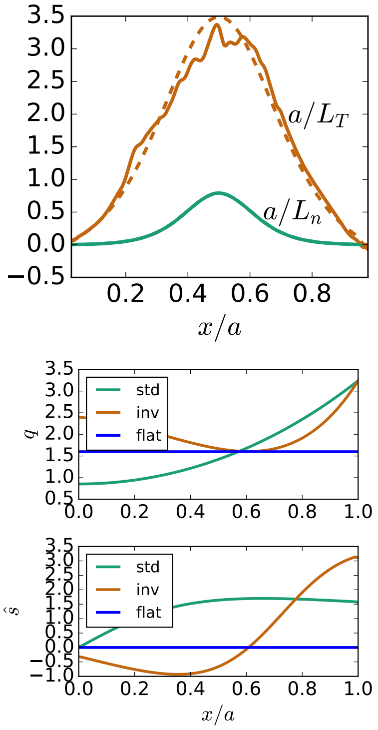
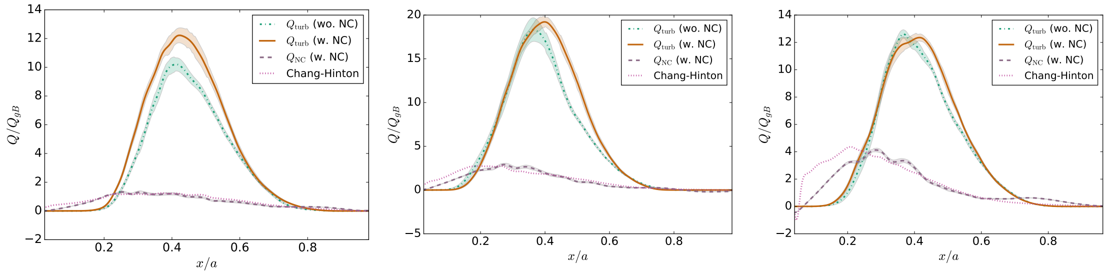
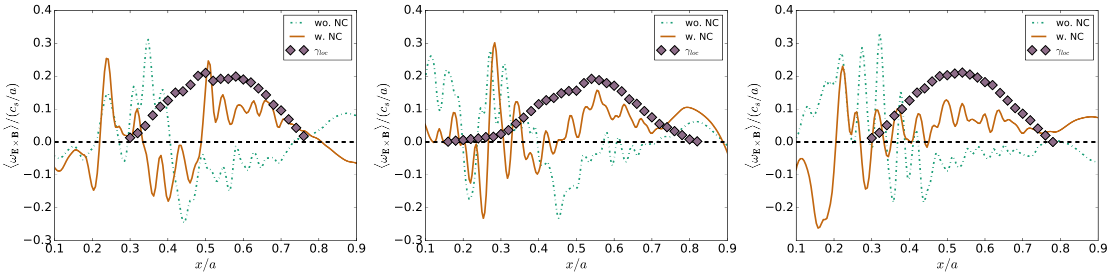


Figure 1: Gradient profiles, safety factor and magnetic shear profiles



(a) Monotonic q (b) Flat q (c) Inverse shear q

Figure 2: Time-averaged radial heat flux profiles in simulations with and without neoclassical effects for different q profiles



(a) Monotonic q (b) Flat q (c) Inverse shear q

Figure 3: Time- and flux-surface-averaged $E\times B$ shearing rate in simulations with and without neoclassical effects for different q profiles and local linear growth rates for comparison.

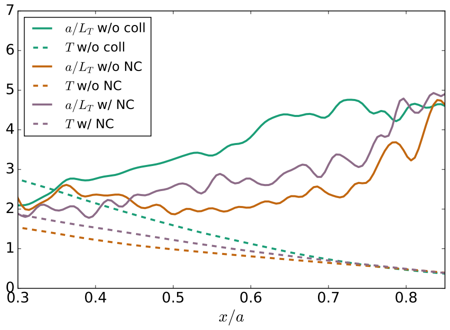
We study the described system with three different safety factor profiles $q(x)$: a monotonic one, one where constant $q = 1.6$ is set, so there is no magnetic shear, and one where a region of inverse (i.e. negative) magnetic shear occurs for $x/a < 0.6$ (Fig. 1). The time-averaged radial heat fluxes for all three scenarios are plotted in Fig. 2. If included in the simulation, the *neoclassical* flux is in good agreement with the well-established Chang-Hinton prediction[5] and due to its proportionality to q^2 increases to a significant fraction of the total transport at $x/a < 0.5$ in the inverse-shear case. The *turbulent* radial heat flux – both in cases with and without neoclassical effects – is larger by a factor of ~ 1.6 for the flat q profile than in the two other scenarios. This is consistent with local results on a maximum of the linear ITG growth rate at $\hat{s} \sim 0.5$[6].

If we compare the turbulent flux between the simulations with and without neoclassical effects for each of the three different q-profiles, an interesting trend can be observed: While the system including neoclassical effects exhibits a systematically higher (ca. 20%) heat flux compared to the purely turbulent one for the monotonic q, the flux is equal within the uncertainty for $x/a \lesssim 0.4$ with the flat and inverse shear q-profiles. In the latter case also the difference at $x \gtrsim 0.4$ is only around 10%.

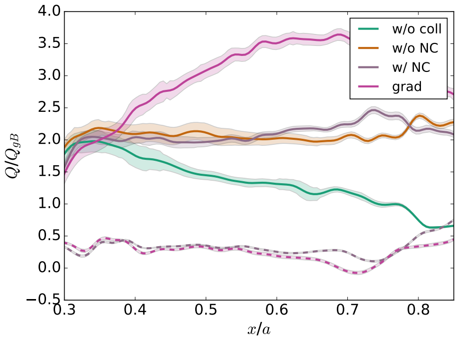
Since ITG turbulence typically saturates due to $\vec{E}\times\vec{B}$ shear generated by zonal flows, we study the radial profiles of the shear pattern $\omega_{\vec{E}\times\vec{B}}(x)$ for the three different q profiles. As can be seen in Fig. 3, the presence of the additional long-range radial electric field in the simulations with neoclassical effects modifies the time averaged shear. For monotonic q (Fig. 3a) the presence of neoclassical effects aligns a region of very low $\vec{E} \times \vec{B}$ shear with the maximum of the local linear growth rate at $x/a \sim 0.47$, which possibly explains the increase in transport. The scenario with inverse magnetic shear (Fig. 3c) on the other hand generates very similar average $\omega_{\vec{E}\times\vec{B}}$ - only with different sign - in the region with maximal growth rate. With the flat q profile (Fig. 3b) the picture is not as clear. The maximal linear growth rate, however, occurs farther out at $x/a \sim 0.58$.

Flux-driven simulations

For simulations with fixed power input a model system with $\rho_* = 1/150$ heated by a power source with a gaussian profile at $x = 0 - 0.4$ is studied. We compare a collisionless simulation, a collisional case without neoclassical effects and a simulation with comprehensive collisional physics (including neoclassical transport). In addition, the evolved temperature profiles from the last case are used for a gradient-driven simulation. As can be seen in Fig 4a, including collisions and neoclassical effects leads to lower average temperature and gradient. Since the system is quite close to marginality, this can be explained by the collisional Dimits shift softening[7]. The system with NC effects establishes a higher gradient than its collisional counterpart which means that the neoclassical channel has notable impact. The gradient-driven simulation on the other hand generates a higher heat flux, which implies that there is a considerable difference in the dynamics for the two heating schemes.



(a) Temperature and logarithmic gradient



(b) Radial heat flux, dashed: Q_{nc}, solid: Q_{turb}

Figure 4: Time averaged profiles for flux-driven simulations. The gradient-driven case uses the temperature profile of "w/ NC"

If we compare the probability density functions of the radial turbulent flux in Fig. 5, clear tendencies arise: First, transport in the collisional simulations is occurring on considerably higher levels compared to their collisionless counterpart. This is consistent with our previous argument on the softening of the Dimits shift. Secondly, while the difference between the simulations without and with neoclassical effects is not as drastic, the latter has a reduced level of high transport with $Q_{\mathrm{turb}} > 4Q_{gB}$ of the former. In presence of the neoclassical transport channel (which does not have a critical threshold) the build-up of energy is obstructed leading to less bursty behaviour of the system. Besides the higher average transport the gradient-driven simulation also exhibits a wider distribution. Hence, it is strongly fluctuating and we can confirm that the non-localized heating scheme has a notably large impact on the system.

Conclusions

In this work, previous studies of the interaction of neoclassical effects and ITG turbulence in gyrokinetic simulations[4] were expanded. In gradient-driven simulations it was found that the difference in turbulent transport between a system including or excluding neoclassical effects changes from on average 20% to below 10% depending on the shape of the safety factor profile. This has interesting implications for studies of internal transport barriers where the magnetic shear is often negative.

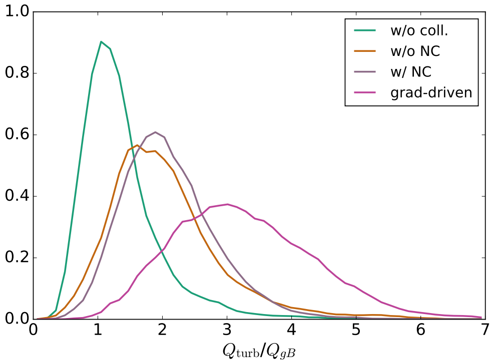


Figure 5: Probability density distributions for turbulent heat flux at $x/a = 0.4 - 0.75$

For a system with fixed power input it was demonstrated that the presence of collisions and with them neoclassical physics has a profound effect on the average gradients and heat fluxes as well as the temporal distribution of the heat flux which implies different intermittent behaviour. In addition, a gradient-driven simulation based on the evolved profiles reveals remarkably different heat fluxes, which suggest further investigation.

Acknowledgements

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