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Energy exchanges in ITG and TEM turbulence

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In magnetically confined plasmas, turbulence induces particle and heat fluxes, and also causes energy exchange between electrons and ions [1]. In a previous study [2], the effect of turbulent energy exchange on the prediction of plasma density and temperature profiles is investigated under specific conditions and it is found to be negligible. However, the paper [2] does not compare the turbulent and collisional energy exchanges in the case of very high-temperature plasmas such as those in ITER, where the collision frequency is very low.

In this study, the effects of ITG and TEM turbulence on the energy exchange between electrons and ions in tokamak plasmas are investigated by the gyrokinetic simulation code GKV [3].

The pure ITG turbulence is found to be dominant in the energy exchange in equithermal or high-temperature plasmas in which collisional energy exchange is negligibly small. It is also shown that ITG turbulence fundamentally transfers energy from ions to electrons. Therefore, the direction of net energy transfer can be opposite to that of the collisional one from hotter to colder particle species, when ions are colder than electrons. This result does not contradict with the second law of thermodynamics because the entropy balance is still maintained by the entropy production, mainly due to the ion heat transport from hot to cold regions. Thus, in future reactors, the ITG turbulence is anticipated to prevent energy transfer from alpha-heated electrons to ions, which is considered a primary ion heating mechanism [4].

It is conjectured from the above-mentioned result that energy is generally transferred by turbulence from a particle species with larger entropy production due to particle and heat transport driven by the instability to other species regardless of which species is hotter. To verify this conjecture, the energy exchange and entropy balance of each particle species due to pure TEM and mixed ITG-TEM turbulence are investigated. It is found that the pure TEM turbulence transfers energy from electrons to ions, which is the opposite direction to that of ITG turbulence, with the large entropy production by the electron heat and particle transport.

Figure 1 shows the results of nonlinear calculations for mixed ITG-TEM turbulence with the ion temperature gradient as a scan parameter. It indicates that the sign of energy exchange (direction of energy exchange) basically agrees with the sign of the difference between the entropy productions for electrons and ions $\left(\frac{q_e^{\mathrm{turb}}}{T_e L_{Te}} + \frac{\Gamma_e^{\mathrm{turb}}}{L_{pe}}\right) - \left(\frac{q_i^{\mathrm{turb}}}{T_i L_{Ti}} + \frac{\Gamma_i^{\mathrm{turb}}}{L_{pi}}\right)$, where T_s, L_{Ts}, L_{ps}, q_s^{turb}, and Γ_s^{turb} are the temperature, temperature and pressure gradient scale lengths, and turbulent heat and particle fluxes for particle species $s = e$(electron), i(ion). However, both signs do not rigorously match each other when the difference is close to zero.

On the other hand, it is confirmed that the turbulent energy exchange tends to be represented by a linear function of the difference between electron and ion energy fluxes $\mathcal{E}_e^{\mathrm{turb}} - \mathcal{E}_i^{\mathrm{turb}}$, and that of the difference between the products of temperature and entropy production for electrons and ions $T_e\left(\frac{q_e^{\mathrm{turb}}}{T_e L_{Te}} + \frac{\Gamma_e^{\mathrm{turb}}}{L_{pe}}\right) - T_i\left(\frac{q_i^{\mathrm{turb}}}{T_i L_{Ti}} + \frac{\Gamma_i^{\mathrm{turb}}}{L_{pi}}\right)$.

References

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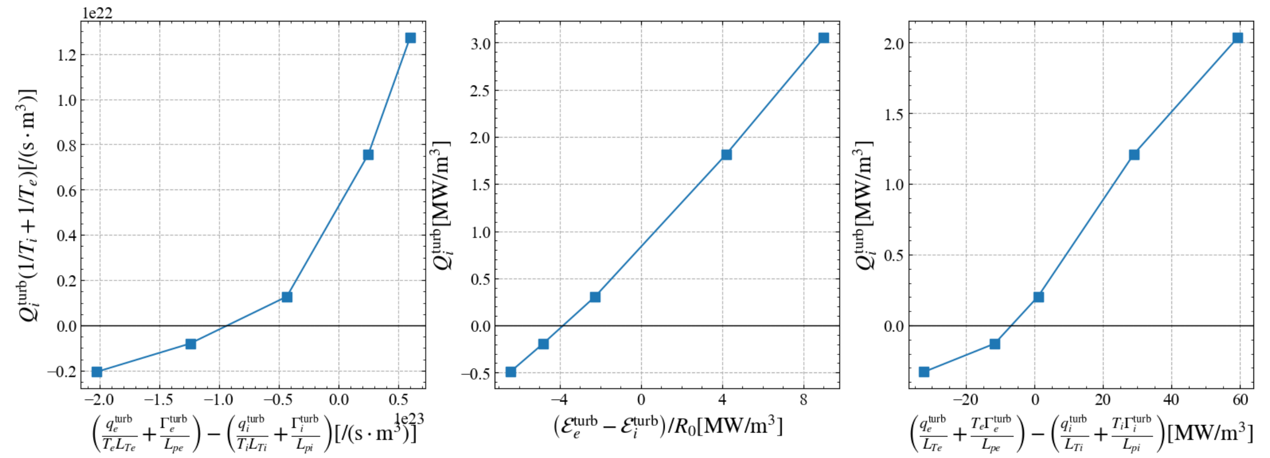

Figure 1. Energy exchange due to ITG and TEM turbulence as a function of the difference in entropy production between electrons and ions (left), difference in energy flux (center), and difference in the product of temperature and entropy production (right).