Energy exchange between electrons and ions induced by ITG-TEM turbulence

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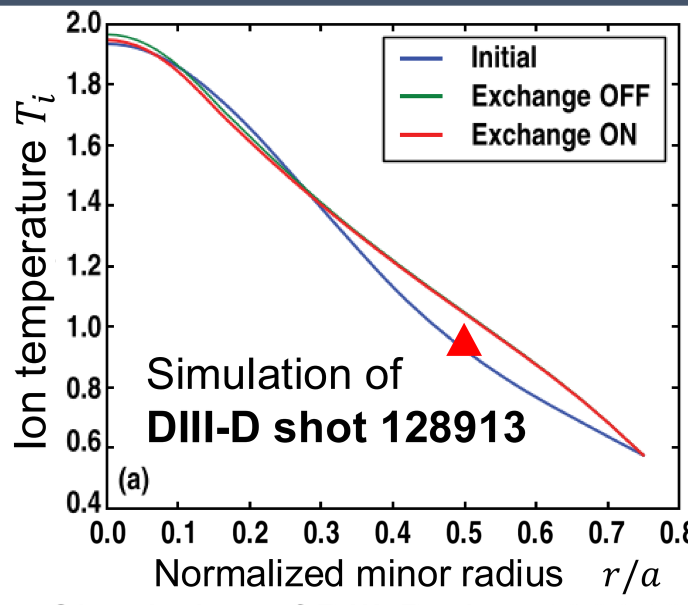
Background

- In magnetically confined plasmas, turbulence induces energy exchange between electrons and ions as well as particle and heat fluxes.
- In a previous study, the effect of turbulent energy exchange on prediction of plasma density and temperature profiles was investigated under specific conditions and it was found to be negligible.
- However, a detailed comparison between the turbulent and collisional energy exchanges has not been shown in the case of very high- temperature plasmas such as those in ITER, where the collision frequency is very low.



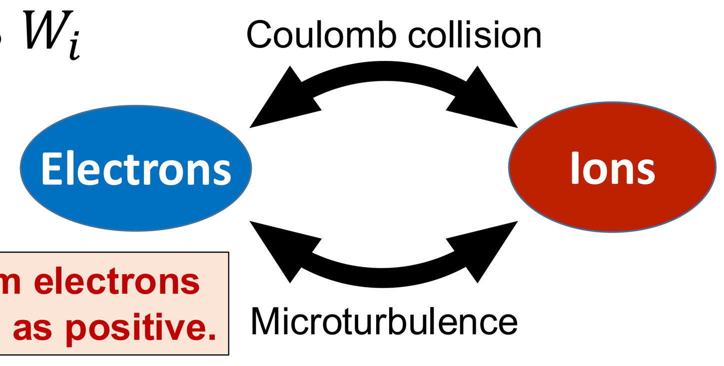
Simulation of DIII-D shot 128913.
[J. Candy, Phys. Plasma 20, 082503(2013)]

- **Compare energy exchanges induced by microturbulence with by Coulomb collision.**
- **Investigate energy exchange and entropy balance in pure Trapped Electron Mode turbulence and mixed ITG-TEM turbulence.**

Turbulent energy exchange in ITG-TEM turbulence

Energy exchange from electrons to ions W_i

$$W_i = Q_i^{\text{coll}} + Q_i^{\text{turb}}$$



Collisional energy exchange

$$Q_i^{\text{coll}} = \frac{3m_e}{m_i} n_e \nu_e (T_e - T_i)$$

The direction from electrons to ions is defined as positive.

Turbulent energy exchange [H. Sugama *et al*, Phys. Plasmas, 1996]

$$Q_i^{\text{turb}} = e_i \int d^3v \sum_{\boldsymbol{k}_\perp} \left\langle h_i^*(\boldsymbol{k}_\perp) \frac{\partial \psi_i(\boldsymbol{k}_\perp)}{\partial t} \right\rangle$$

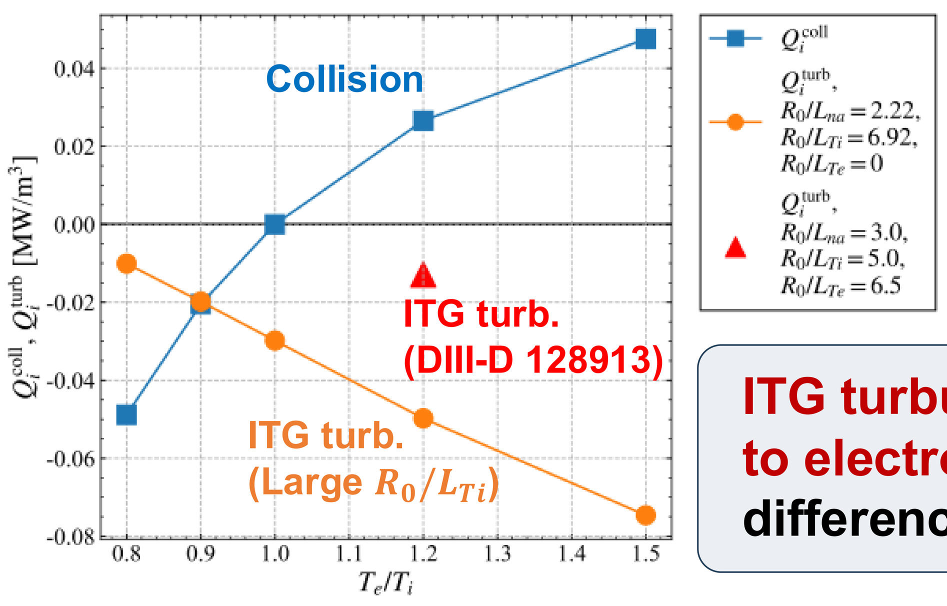
$$h_s = f_{sk}(\boldsymbol{k}_\perp) + \frac{e\phi(\boldsymbol{k}_\perp)}{T_a} J_0\left(\frac{k_\perp \rho}{\Omega}\right) F_M$$

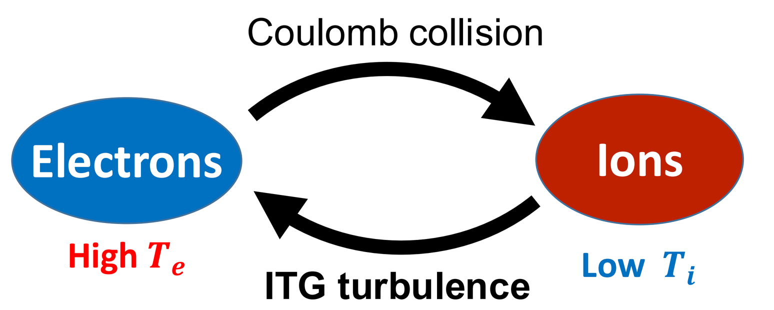
$$\psi_s(\boldsymbol{k}_\perp) = J_0\left(\frac{k_\perp \rho}{\Omega}\right)\left(\phi(\boldsymbol{k}_\perp) - \frac{v_\parallel}{c} A_\parallel(\boldsymbol{k}_\perp)\right) - J_1\left(\frac{k_\perp \rho}{\Omega}\right) \frac{v_\perp}{c} \frac{B_\parallel(\boldsymbol{k}_\perp)}{k_\perp}$$

Energy exchange induced by ITG turbulence

Tokamak configuration(CBC)

Simulation results obtained by the local gyrokinetic simulation code, GKV
[T.-H. Watanabe *et al*, *Nucl. Fusion* 46, 24(2006)]





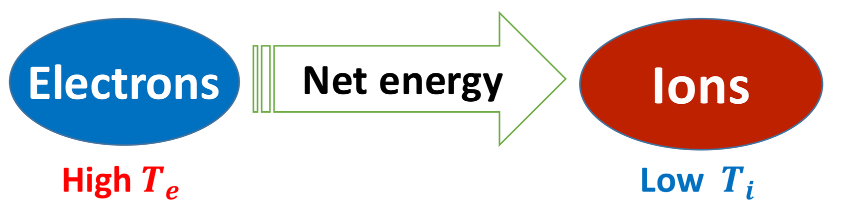
ITG turbulence transfers energy from ions to electrons regardless of the temperature difference between electrons and ions.

Estimation of effects of energy exchanges and turbulent energy flux $\mathcal{E}_s^{\text{turb}}$

Case of $n = 2.0 \times 10^{19}[\text{m}^{-3}]$, $T_i = 0.9[\text{keV}]$

Q_i^{turb}	Q_i^{coll}	$\mathcal{E}_i^{\text{turb}}/r$	$\mathcal{E}_e^{\text{turb}}/r$
-0.013	0.027	0.27	0.15

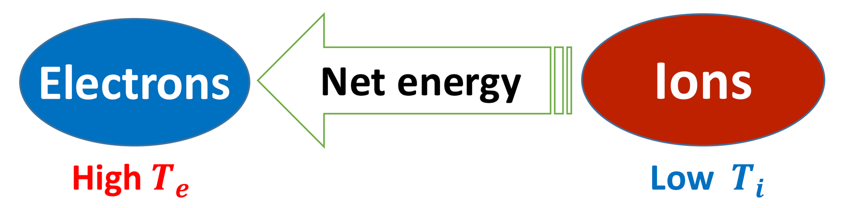
Total input power for ions $4\pi R_0 r \times \mathcal{E}_i^{\text{turb}} = 1.7$ [MW]
Total input power for elec. $4\pi R_0 r \times \mathcal{E}_e^{\text{turb}} = 1.0$ [MW]



Case of $n = 2.0 \times 10^{19}[\text{m}^{-3}]$, $T_i = 1.5[\text{keV}]$

Q_i^{turb}	Q_i^{coll}	$\mathcal{E}_i^{\text{turb}}/r$	$\mathcal{E}_e^{\text{turb}}/r$
-0.047	0.020	0.97	0.54

Total input power for ions $4\pi R_0 r \times \mathcal{E}_i^{\text{turb}} = 6.2$ [MW]
Total input power for elec. $4\pi R_0 r \times \mathcal{E}_e^{\text{turb}} = 3.5$ [MW]

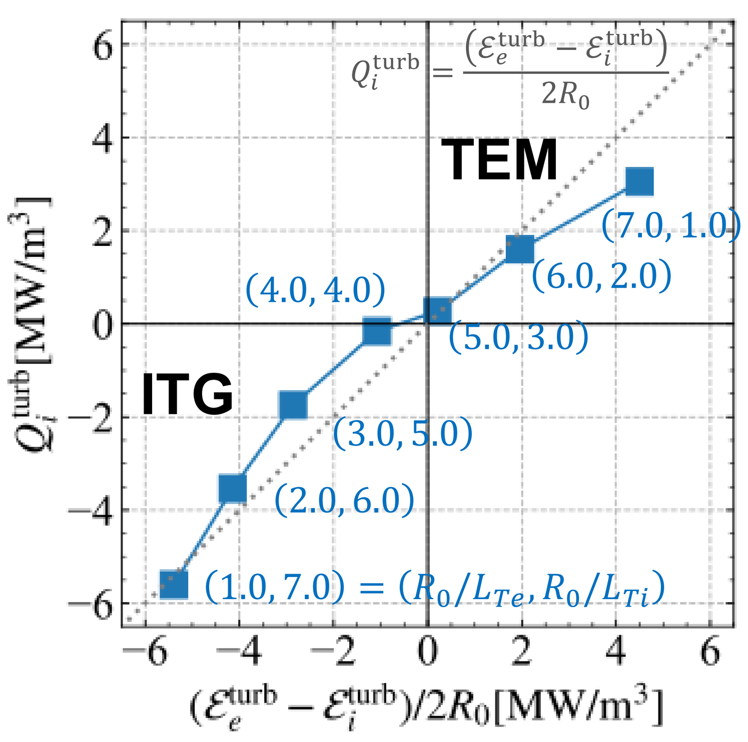


As the plasma temperature increases, the amount of turbulent energy exchange exceeds that of collisional one, which can change the direction of total energy exchange between electrons and ions.

Transport simulations predicting global temperature profiles should include the effect of the turbulent energy exchange for future fusion reactors.

Energy fluxes and energy exchange in ITG-TEM turbulence

$R_0/L_{ns} = 2.22$, $(R_0/L_{Te}, R_0/L_{Ti}) = (1.0, 7.0) \sim (7.0, 1.0)$, $T_e/T_i = 3.0$



Approximation using energy fluxes

$$Q_i^{\text{turb}} \approx \Delta EF \equiv \frac{(\mathcal{E}_e^{\text{turb}} - \mathcal{E}_i^{\text{turb}})}{2R_0},$$

Turbulent energy flux: $\mathcal{E}_s^{\text{turb}} = q_s^{\text{turb}} + (5/2) T_s \Gamma_s^{\text{turb}}$
Turbulent particle/heat flux: $\Gamma_s^{\text{turb}}, q_s^{\text{turb}}$

- **Energy is transferred from electrons to ions in TEM turbulence.**
- **Turbulent energy exchange can be approximated, within a factor of two, by ΔEF.**

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Prediction of energy exchange by the quasilinear model

Quasilinear heat fluxes and energy exchange (Direct approach)

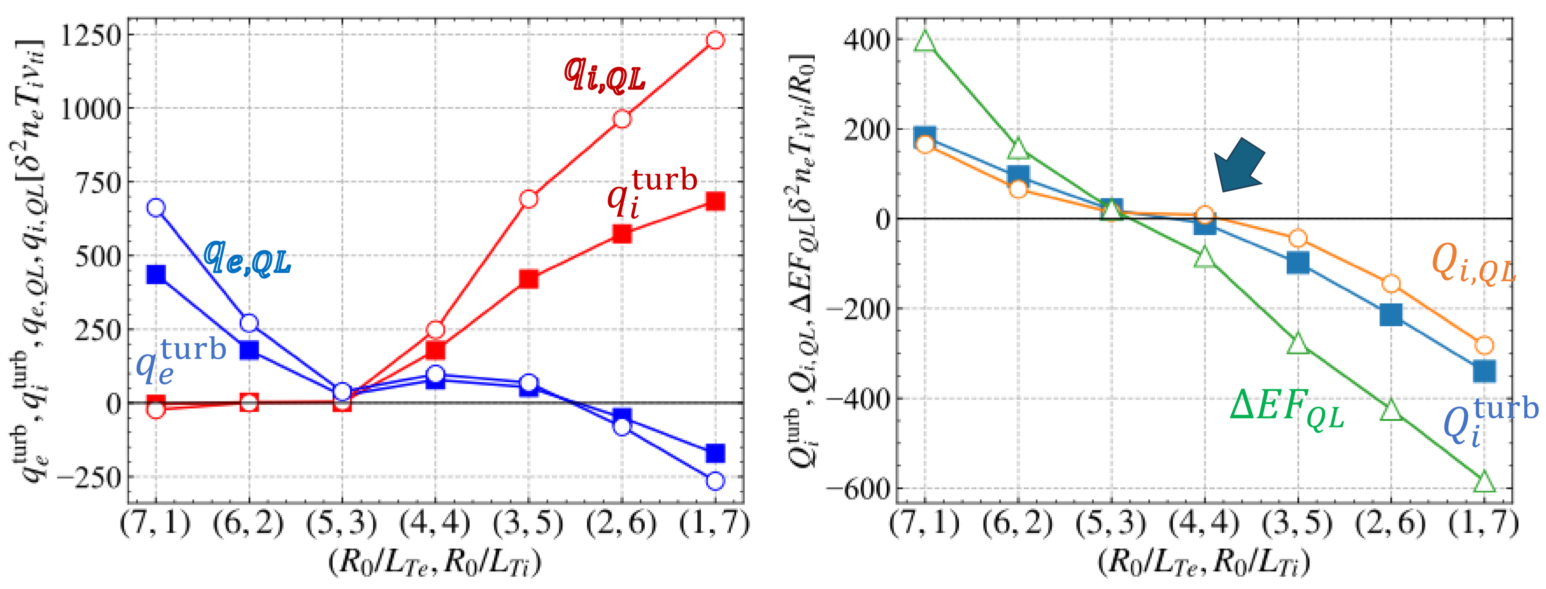
$$(q_{s,QL}, Q_{s,QL}) = \sum_{\boldsymbol{k}_\perp} \left[\frac{\left(q_{s,L}^{\text{turb}}(k_\perp), Q_{s,L}^{\text{turb}}(k_\perp)\right)}{\left\langle|\tilde{\phi}|^2\right\rangle_L (k_\perp)} \times \left\langle|\tilde{\phi}|^2\right\rangle_N (k_\perp) \right]$$

Weights — Linear simulations
Saturation rule — Nonlinear simulations

Assume to obtain accurate spectra.

Alternative method using energy fluxes

$$\Delta EF_{QL} \equiv \frac{(\mathcal{E}_{e,QL} - \mathcal{E}_{i,QL})}{2R_0} \qquad \mathcal{E}_{s,QL} = q_{s,QL} + \frac{5}{2} T_a \Gamma_{s,QL}$$



Case of DIII-D shot 128913 ($r = 0.5a$)

$R_0/L_{ns} = 2.22$, $R_0/L_{Ti} = 5.0$, $R_0/L_{Te} = 6.5$, $T_e/T_i = 1.2$

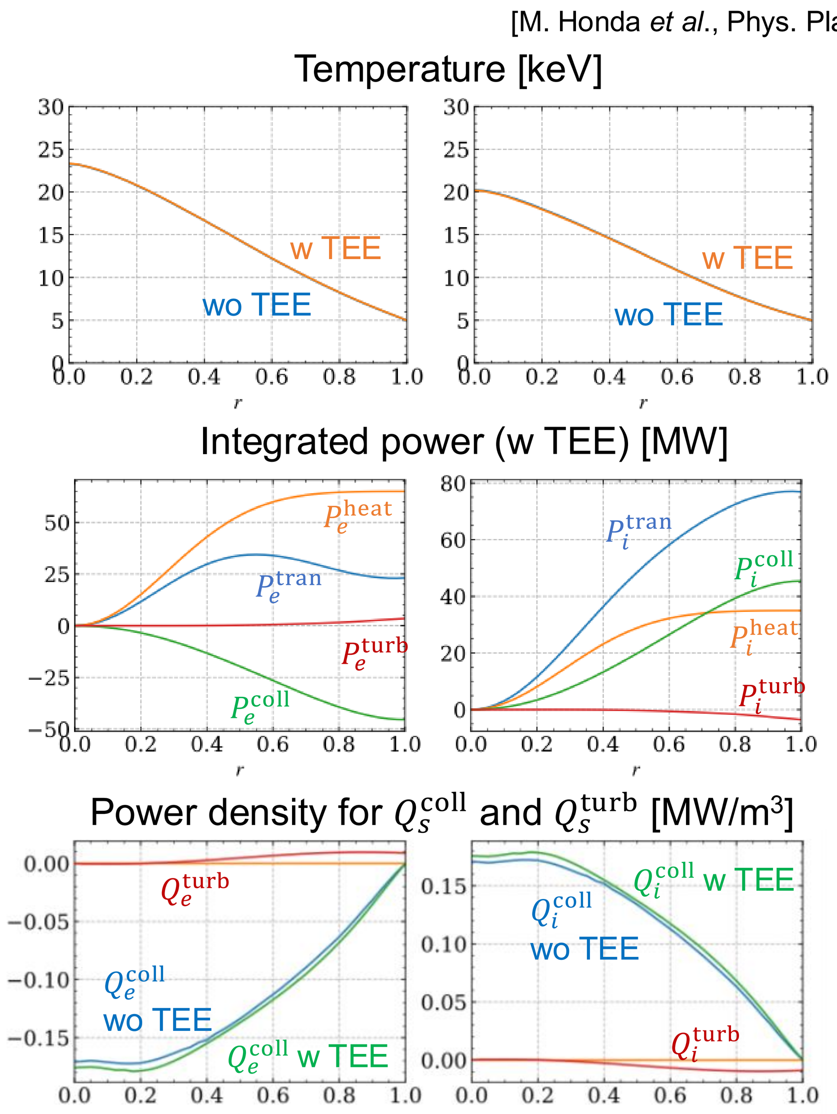
Ratio of quasilinear results to nonlinear results

$q_{e,QL}$: 137%, $q_{i,QL}$: 136%,
$Q_{i,QL}$: 27%, ΔEF_{QL}: 87%.

The quasilinear model and alternative method can provide a reasonable estimate of energy transfer even in parameter regimes relevant to experimental conditions.

Global temperature profiles including the effect of TEE

Prediction of temperature profiles with GOTRESS + BgB model under the ITER-like condition
[M. Honda *et al.*, Physics Plasmas 26, 102307 (2019)] [N. T. Howard *et al.*, Nucl. Fusion 65 016002 (2025)]



Incorporate turbulent energy exchange as ΔEF into GOTRESS.

$$W_s = Q_s^{\text{coll}} + Q_s^{\text{turb}}$$

$$Q_i^{\text{turb}} = -Q_e^{\text{turb}} = \frac{(\mathcal{E}_e^{\text{turb}} - \mathcal{E}_i^{\text{turb}})}{2R_0}$$

Difference between results of "w TEE" and "wo TEE"

ΔT_e[keV]	ΔT_i[keV]	ΔP_i^{turb}[MW]	ΔP_i^{coll}[MW]
0.05	-0.05	-3.5	2.1

Since the effect of collisional energy exchange increases so as to counteract the energy transfer caused by ITG turbulence, the resulting temperature change is not significant for the ITER Baseline scenario.

Conclusion

- Regardless of the temperature difference between electrons and ions,
  ITG turbulence: energy is transferred **from ions to electrons**,
  TEM turbulence: energy is transferred **from electrons to ions**.
- Since the amount of turbulent energy exchange can exceed that of the collisional one, **transport simulations predicting temperature profiles should include the effect of turbulent energy exchange** in high-temperature plasmas dealt with in future fusion reactors.
- We **propose a method to predict turbulent energy transfer based on the difference in energy flux** between electrons and ions. This approach **successfully reproduces the energy transfer**, even in a case where the quasilinear model fails.