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Anomalous and Neoclassical Transport of Hydrogen Isotope and Impurity Ions in LHD Plasmas

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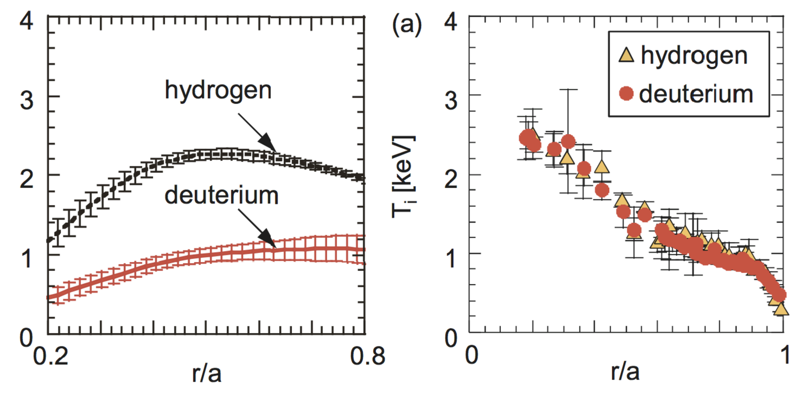
Abstract

Gyrokinetic and drift kinetic simulations are carried out to investigate anomalous and neoclassical transport of hydrogen isotope and impurity ions in Large Helical Device (LHD) plasmas. Turbulent transport in high electron temperature (T_e) regime, where the trapped electron mode (TEM) is dominant, is a critical issue for future burning plasmas. To clarify an impact of hydrogen isotope species on the turbulent transport in LHD system, TEM turbulence simulations in hydrogen and deuterium LHD plasmas with real-mass kinetic electrons have been carried out by gyrokinetic simulations. The strong isotope dependence on the growth rate of collisionless TEM branch appears through the stabilization effect due to a mass dependence in the normalized electron-ion collision frequencies. Nonlinear simulations clarify the significant dependence of the isotope species in the reduction of the electron and ion energy fluxes in deuterium plasma, where strong TEM stabilization in the deuterium plasma leads to the enhancement in the ratio of zonal flow energy to total energy. Transport in high ion temperature (T_i) plasmas with extremely hollow impurity density profiles is also a critical issue for high-performance in LHD plasmas. In high-Ti LHD plasma, the simulation indicates the neoclassical particle fluxes of electron and bulk ion species are outward directed, although the flux of the impurity carbon is extremely small and its value and direction are sensitive to the radial electric field. On the other hand, the microinstability analyses by gyrokinetic simulations show that the anomalous contributions of quasi-linear particle fluxes of all species are inward-directed which is consistent with the fact that the positive neoclassical particle fluxes and the negative turbulent fluxes should be balanced in a steady state. The ratio of each particle flux is almost consistent with the neoclassical contributions.

Introduction

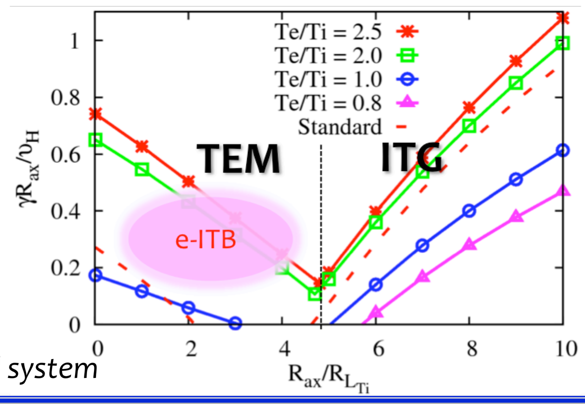
Isotope impact and ITG / TEM instabilities

- Several experiments clearly indicate better confinement in D-plasma than that in H-plasma.
  JT-60U: Urano NF2013;
  W7-AS: Stroth Phys. Sc.1995;
  TJ-II: Liu NF2105



JT60U H-mode: Urano NF2013

- Tokamak: Peaked density profile can cause ITG and TEM simultaneously.
- Helical: Flat density and/or optimized profiles cause ITG mode rather than TEM.
- TEM-dominated regime is also expected for high-Te LHD (e-ITB) plasmas.



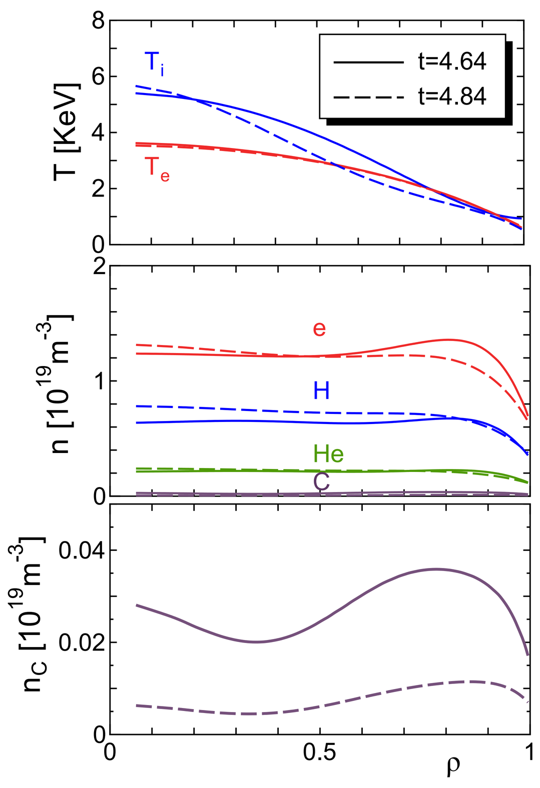
Microinstability map in helical system

Transport in high-Ti plasma with impurity

- In high-T_i LHD discharge #113208, T_i approaches higher than 5 keV on the axis, steep T_i gradients and extremely hollow carbon density profiles (impurity hole) are generated in low density plasmas heated by NBI.
- For steady state with negligible particle source, neoclassical particle fluxes should be balanced with anomalous ones;

$$\Gamma_s^{(\mathrm{ano})} + \Gamma_s^{(\mathrm{neo})} = 0$$

- We are trying to realize the precise consistent simulation analyses for NC and anomalous contributions in multi-species (e, H, He, and C) LHD plasma.



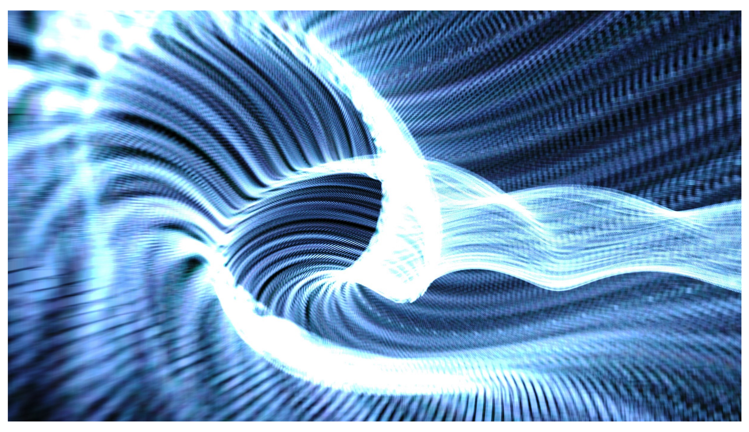
GKV code

GKV code solves gyrokinetic equation for perturbed distribution functions in local flux-tube domain.

Watanabe, NF (2006), Nunami, PFR (2010, 2015), Maeyama, CPC (2013), Nakata, CPC (2015)

- Treat 3D equilibrium obtained by VMEC code, reconstructing field corresponding to the experiment.
- Solve gyrokinetic ions and electrons with EM fluctuations.
- High scalability allows ITG/TEM/ETG simulations.
- Multi-Scale ITG/TEM/ETG turbulence simulations with real mass ratio and β value.
- Collision operator for multi-species with conservation laws for particles, momentum, energy, Boltzmann's H-theorem.

ES potential in LHD obtained by GKV simulation



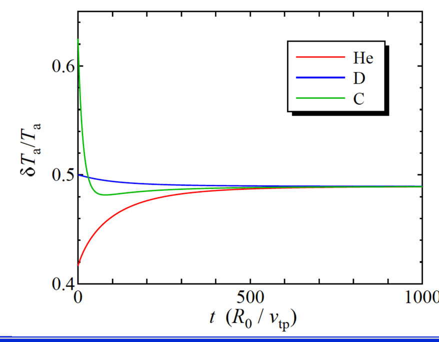
Tests of collision operator for multi-species plasma

Thermal equilibration among three-ion species (D, He and C) has been made for perturbed Maxwellian distribution with different T

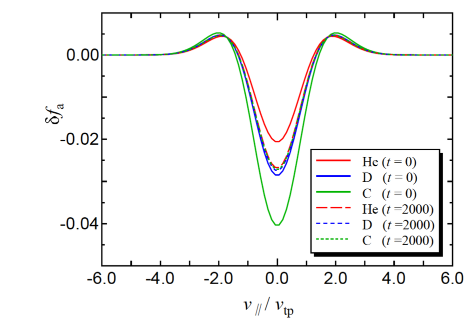
$$\delta f_a = F_{aM}\left(\frac{\delta n_a}{n_a} + \left(\frac{m_a}{T_a}\right)\vec{u}_a\cdot\vec{v} + \frac{\delta T_a}{T_a}\left(\frac{v^2}{v_{ta}^2}-\frac{3}{2}\right)\right)$$

We numerically solved the thermal equilibration, $\frac{\partial}{\partial t}\delta f_a = \sum_b \left(C^T_{ab}(\delta f_a) + C^F_{ba}(\delta f_b)\right)$

Time evolutions of temperature fluctuations



Distribution functions at t=0 & t=1000 [R0/vtD]



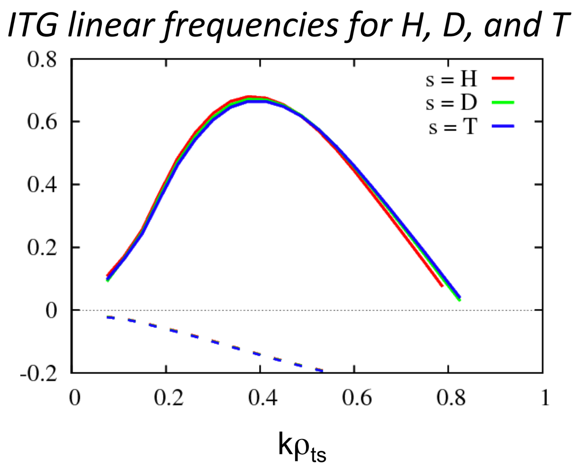
Isotope impact on helical-TEM turbulence

Isotope effect on microinstabilities in helical system

- There are little isotope effects on the normalized growth rate $\bar{\gamma}_s = \gamma R_{ax}/v_{ts}$ of ITG mode for small collisionality.
- In hydrogen gB unit, the transport becomes worse for heavier isotope ions due to

$$\chi_{\mathrm{turb}} \sim \frac{\sqrt{A_S}}{Z_s^2}\frac{\bar{\gamma}_s}{\bar{k}_{\perp s}^2}\chi_{\mathrm{H}}^{(\mathrm{GB})}$$

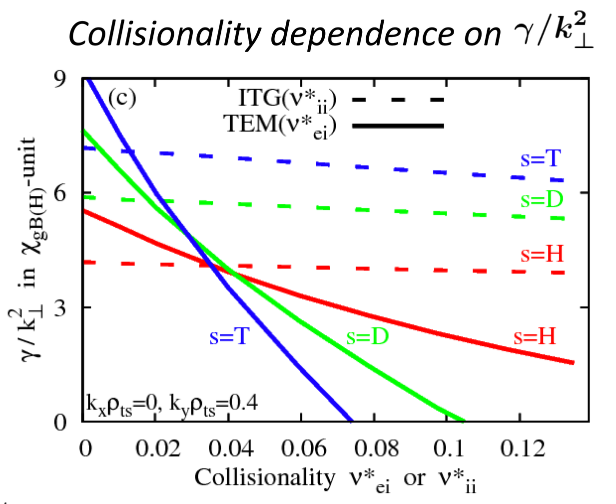
ITG linear frequencies for H, D, and T



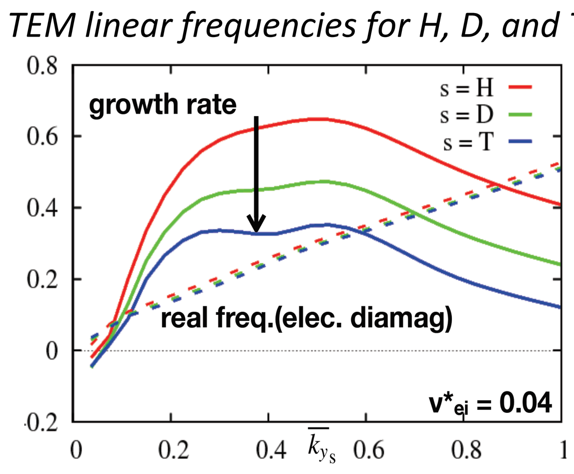
- On the other hand, the strong isotope dependence of the normalized growth rate of TEM (collisionless TEM branch) appears through the stabilization effect in the deuterium plasma.
- The stabilization effect is caused by the ion-mass dependence in the ratio of the electron-ion collision frequency to the ion transit frequency;

$$\nu_{ei}/\omega_{ti} \propto (m_i/m_e)^{1/2}$$

Collisionality dependence on $\gamma/k_\perp^2$



TEM linear frequencies for H, D, and T



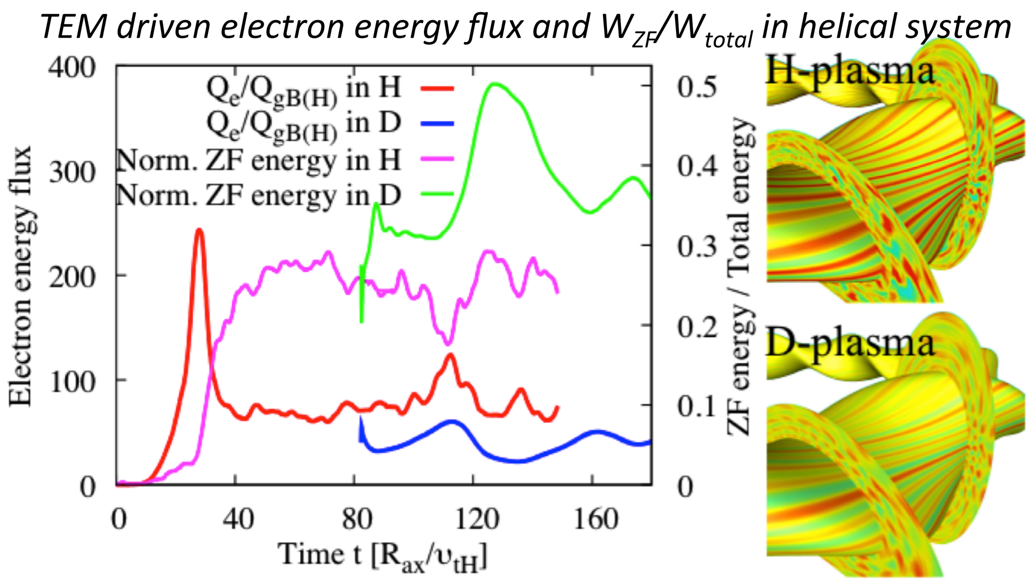
Isotope impact on helical TEM turbulent transport

- The first TEM turbulence simulations in LHD plasma with isotope species (D & H) are realized.
- Resultant transport reduction is clearly identified in D-plasma due to the stabilization effect;
  the electron energy flux in D-case is reduced to about 50% of that in the H-plasma.
- Stronger TEM stabilization in the deuterium plasma leads to the enhancement in the ratio of the zonal flow energy to the total energy W_{ZF}/W_{total}, where the ZF energy is given by

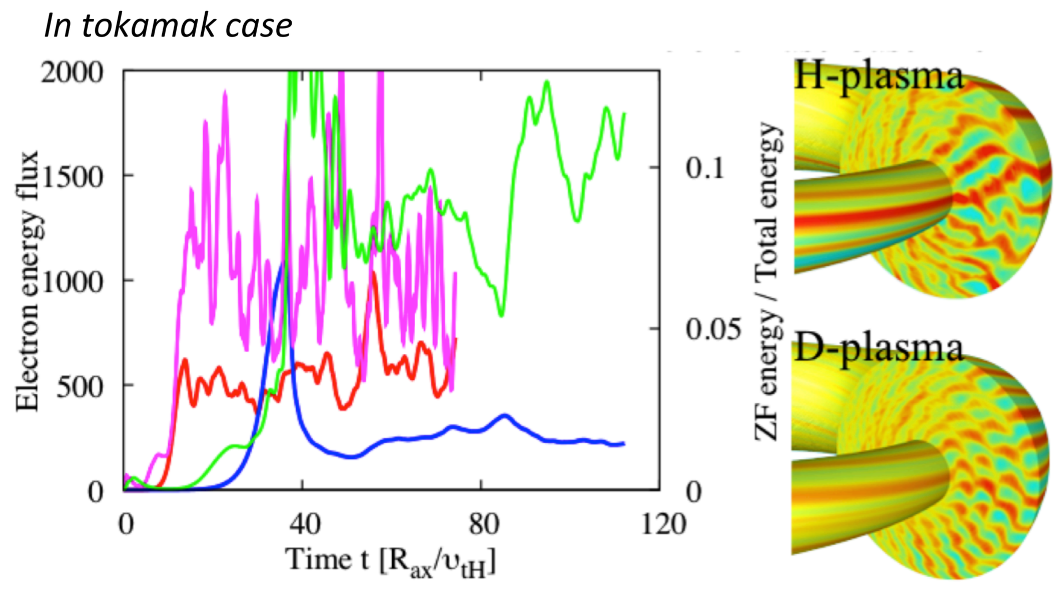
$$W_{ZF} = \left\langle \sum_{k_x, k_y=0} (e^2 n_s/2T_s)[1-\Gamma_0(k_\perp^2\rho_s^2)]|\delta\phi_{k_\perp}|^2 \right\rangle$$

- In tokamak case, the transport reduction due to similar stabilization effect and the zonal flow enhancement in D-plasma is also found.

TEM driven electron energy flux and W_{ZF}/W_{total} in helical system



In tokamak case

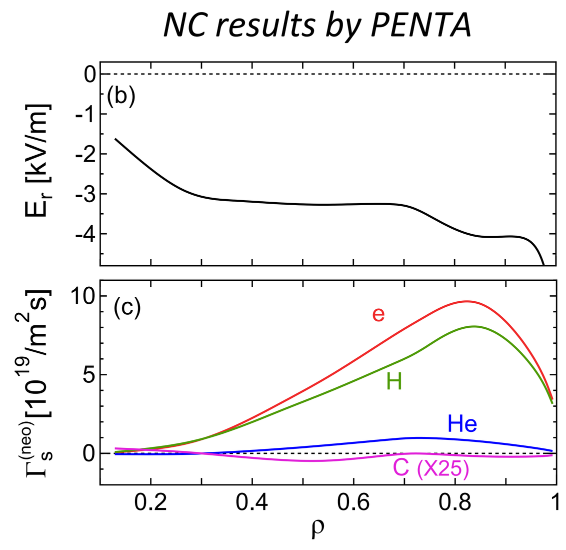


Transport in high-Ti plasma with impurity

Neoclassical contributions

- Using PENTA code, which correctly treats momentum conservation for calculation of neoclassical transport fluxes and radial electric field consistently from the ambipolarity condition, neoclassical simulations for LHD#113208 are performed.
- The simulations indicate negative radial electric field and outward particle fluxes of electron and bulk ions with and slightly small impurity carbon flux.

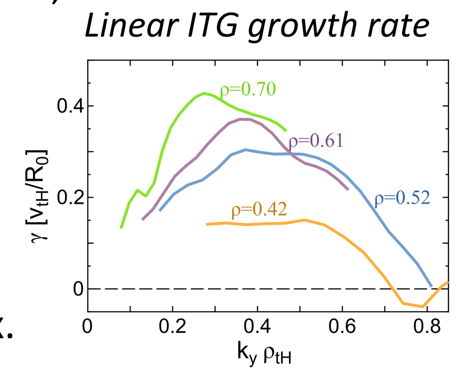
NC results by PENTA



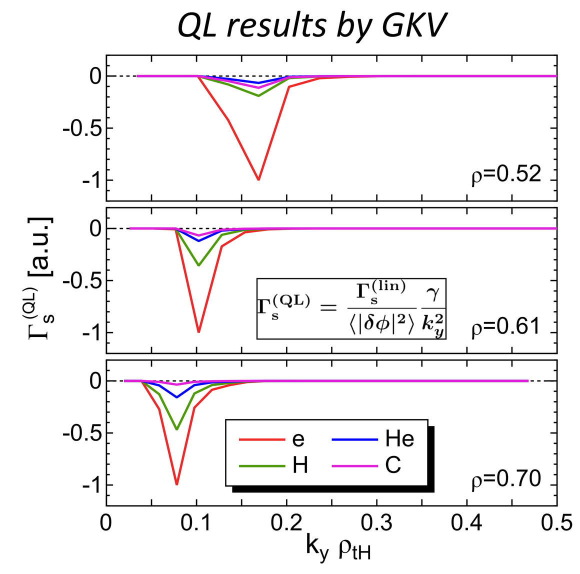
Anomalous contributions

- Using GKV code, the linear gyrokinetic simulations in multi-species plasmas (e, H, He, C) are performed.
- GKV show that ITG modes are unstable.
- In quasi-linear analyses by GKV, anomalous contribution of particle fluxes of all species are inward-directed with small carbon flux.
- Particle fluxes of bulk ions can be balanced with NC fluxes with small carbon flux.

Linear ITG growth rate



QL results by GKV



Summary

Anomalous and neoclassical transport of isotope ions with high-T_e and impurity ions with high-T_i in LHD are evaluated by kinetic simulations available for multi-species plasmas.

Isotope impact on helical-TEM instability & turbulence

- TEM is stabilized in D-plasma through the ion-mass dependence in the ratio of the electron-ion collision frequency to the ion transit frequency.
- Transport reduction is clearly identified in D-plasma compared with H-plasma.

⇒ Encourages improved confinement in LHD-DD Exp.

In high-Ti plasma with impurity hole

- We performed neoclassical and anomalous transport simulations for high-T_i plasma with impurity hole for the first time.
- Particle fluxes of bulk ions by QL analyses can be balanced with NC fluxes with small carbon flux.

Acknowledgement

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