Global gyrokinetic simulations of electrostatic microturbulent transport using kinetic electrons in LHD stellarator

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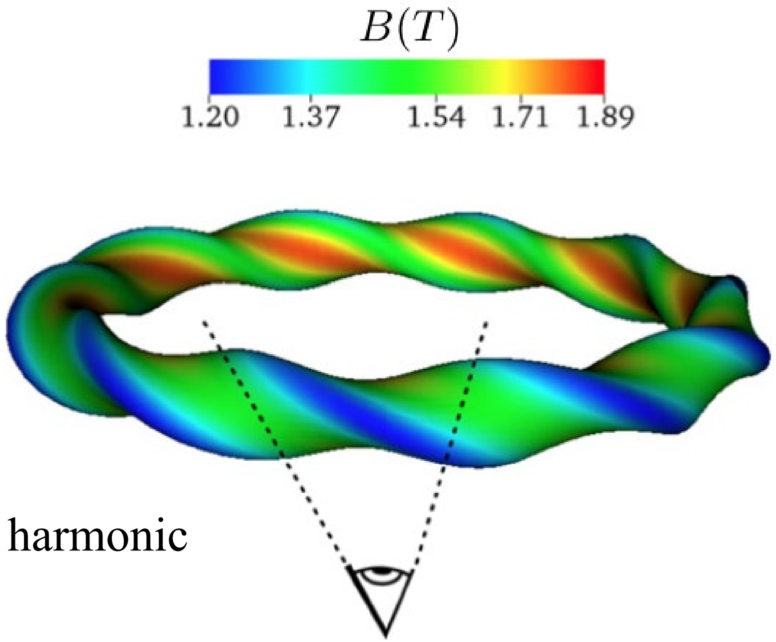
LHD Equilibrium

- GTC uses non-axisymmetric equilibrium generated by ideal MHD code VMEC
- The equilibrium geometry and magnetic field are provided by VMEC as the Fourier series in both the poloidal and toroidal directions on a discrete radial mesh with equidistant in the toroidal flux.
- These 3D data in the left-handed straight fieldline coordinates are then transformed to the Boozer coordinates

$$B(\psi,\theta,\zeta)=\sum_n\left[B_c(\psi,\theta,n)\cos(n\zeta)+B_s(\psi,\theta,n)\sin(n\zeta)\right]$$

n is the toroidal harmonic



- Field period in LHD is 10; therefore, all equilibrium quantities have periodicity $2\pi/10$ in the toroidal direction
- Therefore, there are ten drift wave eigenmode families corresponding to the ten field periods for turbulent transport.

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Simulation and Physics Model using GTC

❑ Dynamics in 5D phase space

$$\left(\partial_t + \dot{\vec{X}} \cdot \nabla + \dot{v}_{\|}\partial_{v_{\|}}\right) f_i(\vec{X}, \mu, v_{\|}, t) = C_i f_i,$$

$$\dot{\vec{X}} = v_{\|}\hat{b} + \vec{v}_E + \vec{v}_c + \vec{v}_g,$$

$$\dot{v}_{\|} = -\frac{\vec{B}^*}{m_i B} \cdot (\mu \nabla B + Z_i \nabla \phi),$$

$$f_i = f_{0i} + \delta f_i$$

Gyrokinetic Poisson equation

$$\frac{e\tau}{T_e}(\phi - \tilde{\phi}) = \frac{\delta \bar{n}_i - \delta n_e}{n_0}$$

Lowest order

$$\frac{(\tau+1)e\delta\phi^{(0)}}{T_e} - \frac{\tau e \delta\tilde{\phi}^{(0)}}{T_e} = \frac{\delta\bar{n}_i - \langle\delta\bar{n}_i\rangle}{n_0}$$

Kinetic hybrid model for electrons

Lowest order (adiabatic)

$$f_e = f_{0e} + \delta f_e^{(0)} + \delta h_e$$

equilibrium

Higher order (kinetic)

First order drift kinetic equation

$$\frac{dw_e}{dt} = \left(1 - \frac{\delta f_e^{(0)}}{f_{0e}} - w_e\right)\left[-\vec{v}_E \cdot \nabla \ln f_{0e}|_{v_\perp} - \frac{\partial}{\partial t}\left(\frac{e\delta\phi^{(0)}}{T_e}\right) - (\vec{v}_d + \delta\vec{v}_E) \cdot \nabla\left(\frac{e\phi}{T_e}\right)\right]$$

electrostatic potential to the first order is obtained from

$$e^{e\delta\phi/T_e} = e^{e\delta\phi^{(0)}/T_e} - \frac{\delta n_e - \langle\delta n_e\rangle}{n_0},$$

Higher order — Lowest order

$$\delta n_e = \int \delta h_e \, d^3\vec{v}.$$

higher order electron density (kinetic)

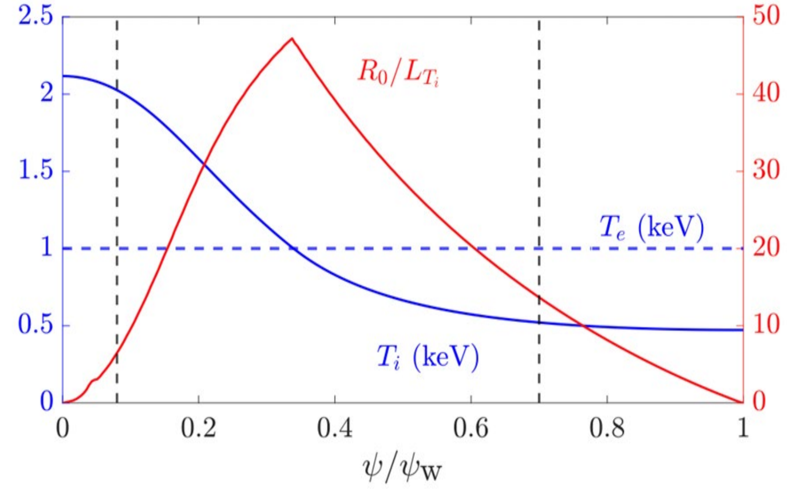
Lowest order (adiabatic)

$$\delta\phi = \delta\phi^{(0)} + \delta\phi^{(1)}$$

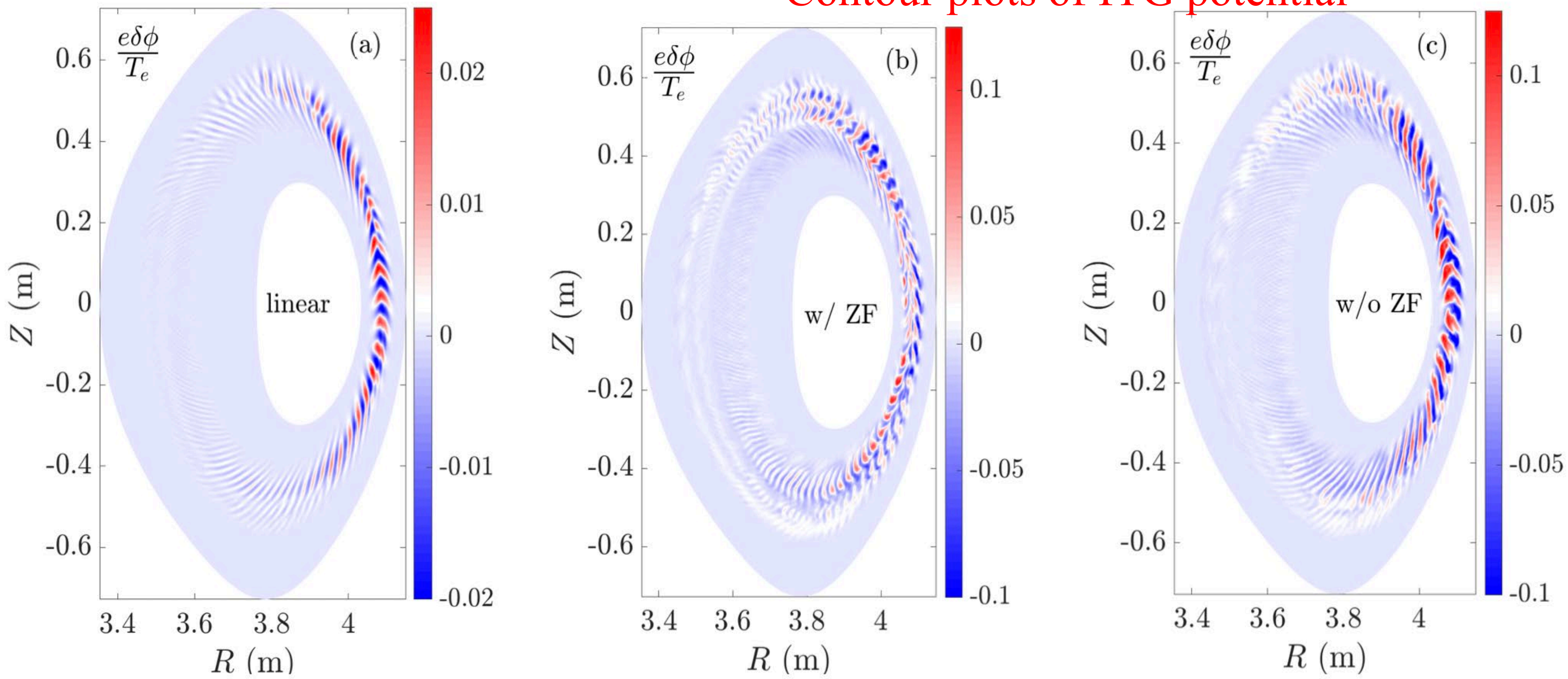
First-order (kinetic)

Microinstabilities (ITG for $\eta = \infty$) in LHD

Plasma profiles

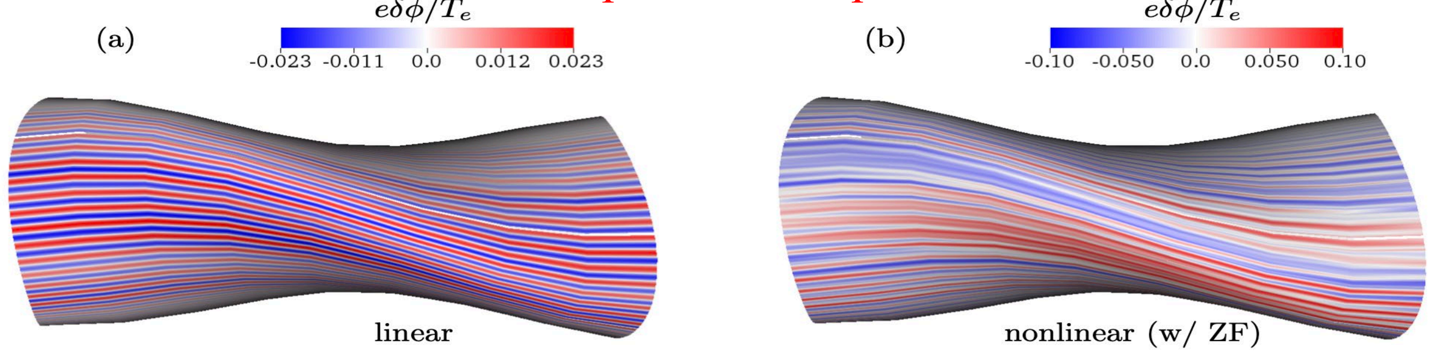


Contour plots of ITG potential



ITG mode structure is localized on the outer midplane, similar to tokamak

3D plots of ITG potential



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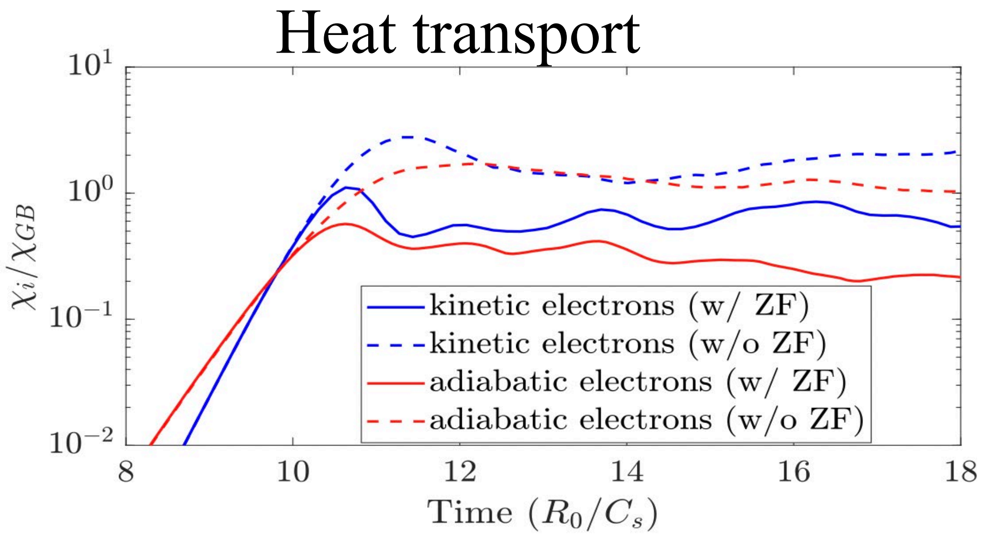
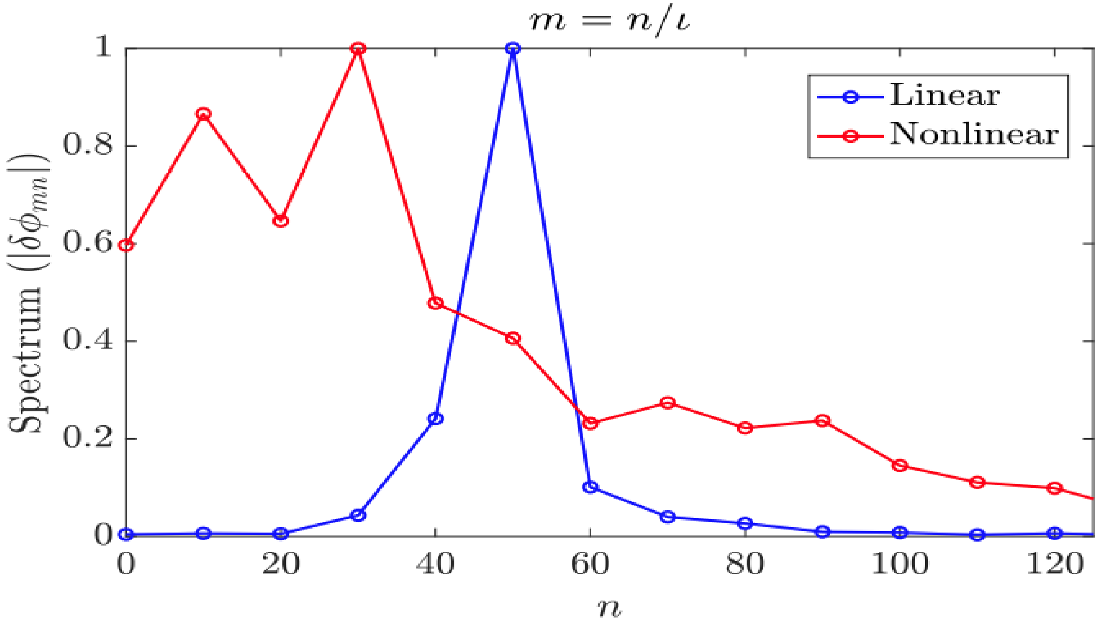
Microturbulence (ITG for $\eta = \infty$) in LHD

- ❑ Kinetic electrons increase the ITG growth rate.
- ❑ Kinetic electrons reduce zonal flow and hence increase ITG turbulent transport.
- ❑ Zonal flow plays an important role in regulating the ITG plasma transport



- ❑ The spectrum in the linear phase is narrow, width of $\Delta n \sim 20$
- ❑ During the nonlinear phase, the toroidal spectrum after the inverse cascade becomes broader due to nonlinear mode coupling.



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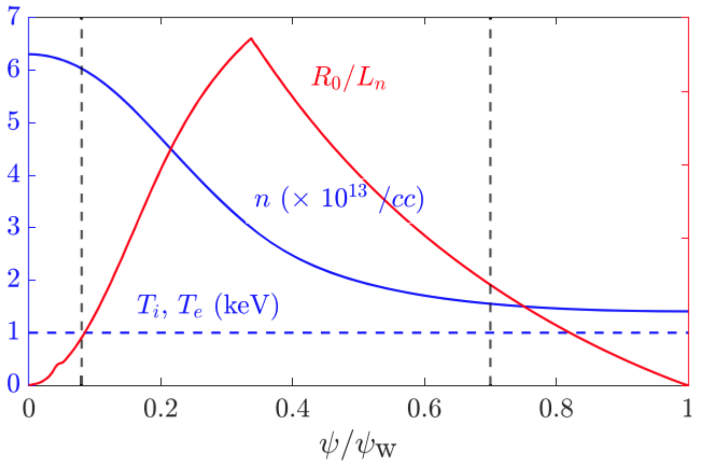
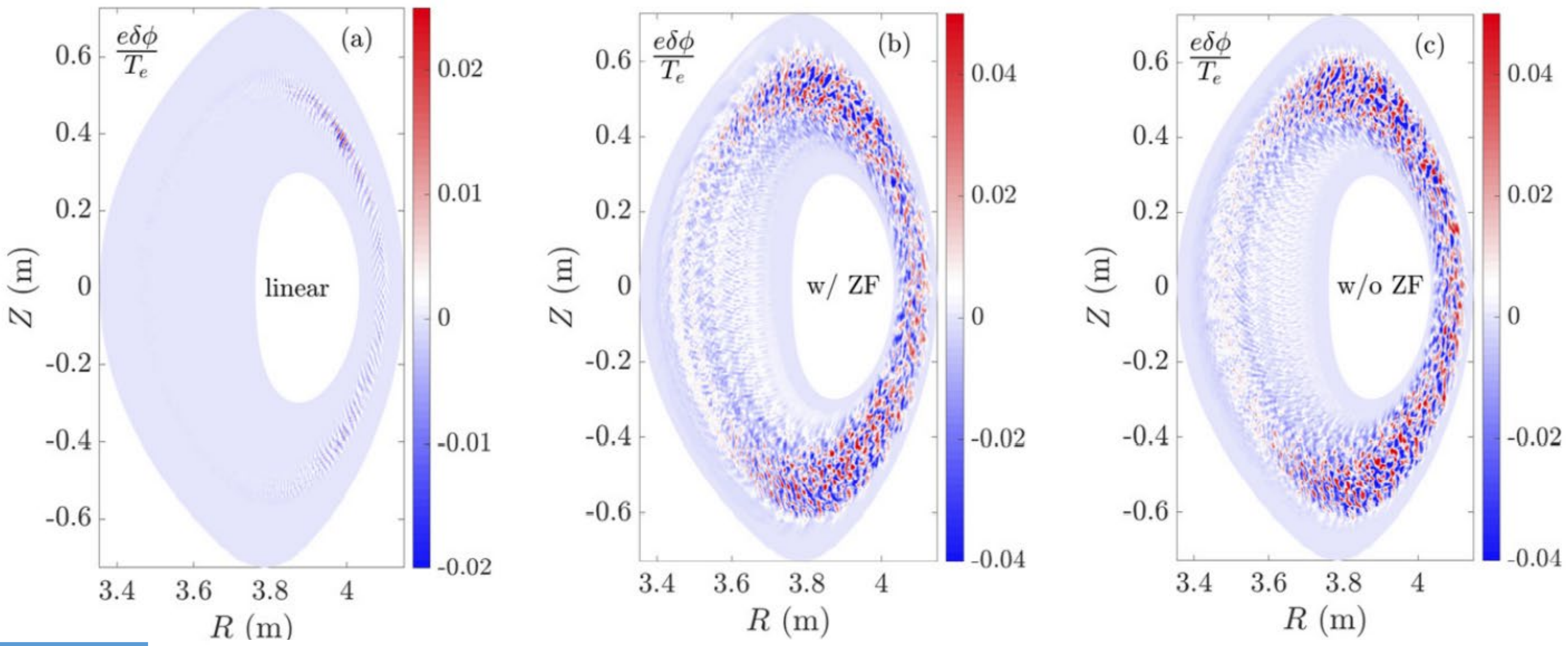
Microinstabilities (TEM for $\eta = 0$) in LHD

Plasma profiles

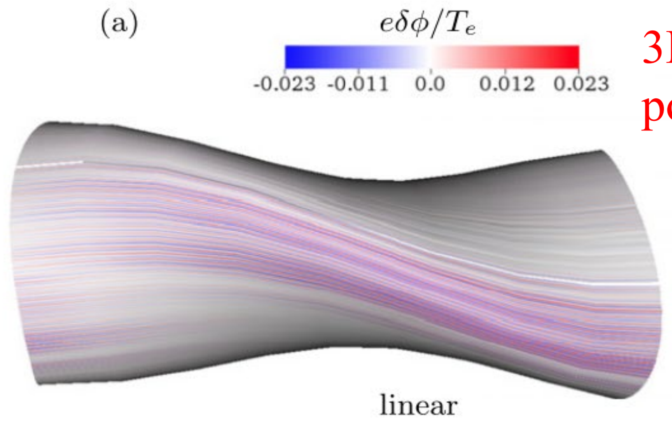


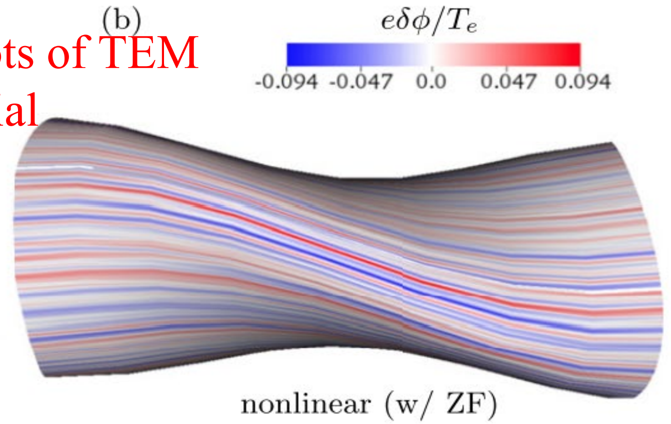
Contour plots of TEM potential



TEM mode structure is localized on the outer midplane, similar to tokamak

3D plots of TEM potential





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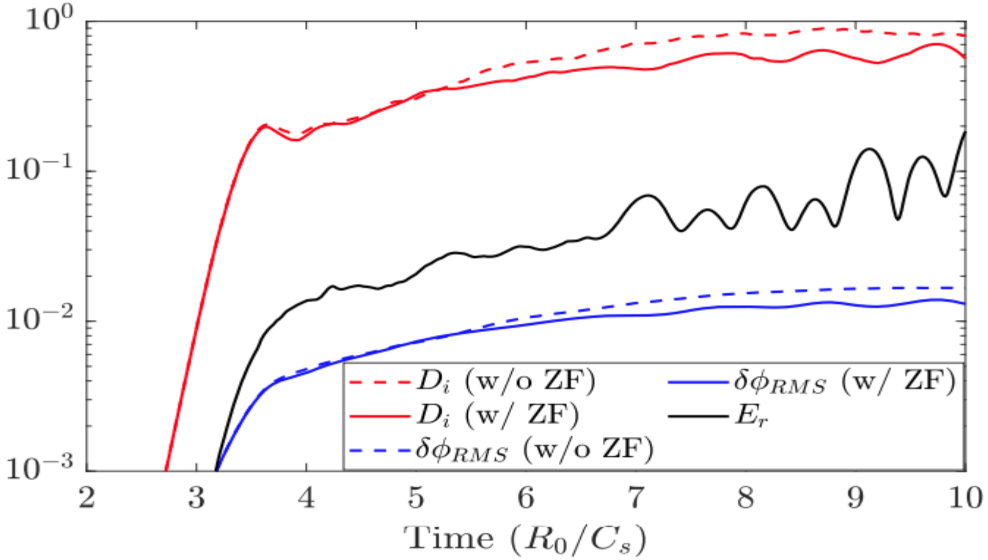
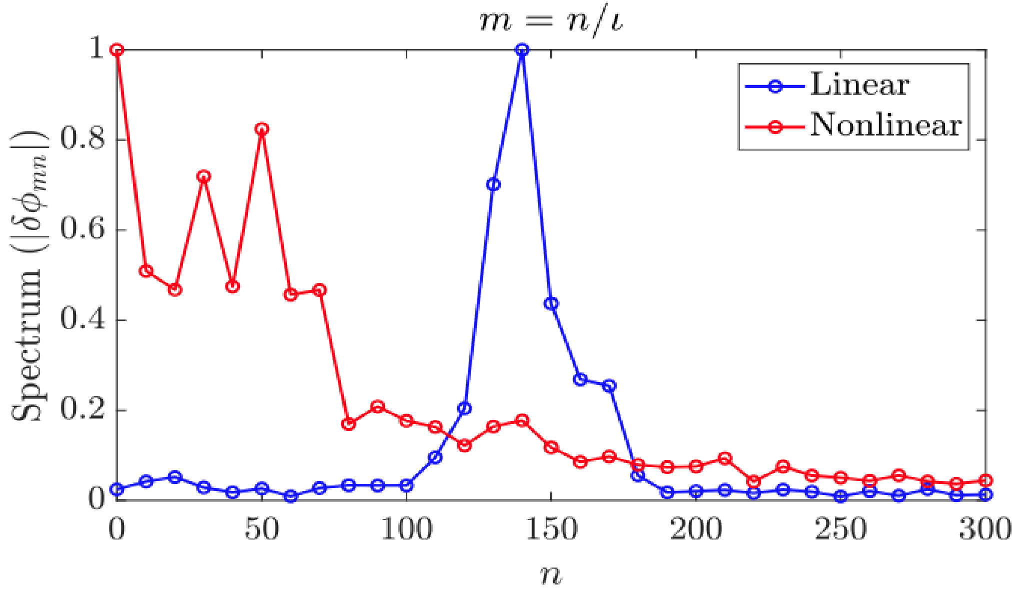
Microturbulence (TEM for $\eta = 0$) in LHD

Ion particle transport





- Turbulence spreading is observed during the nonlinear phase, but the turbulent eddies are barely affected by zonal flows. Unlike ITG turbulence, the zonal flow is not playing an important role in the case of TEM turbulence.

- During the nonlinear saturation, the nonlinear poloidal and toroidal mode coupling leads to an inverse cascade from high to low mode numbers, the main reason for the saturation of the mechanism.

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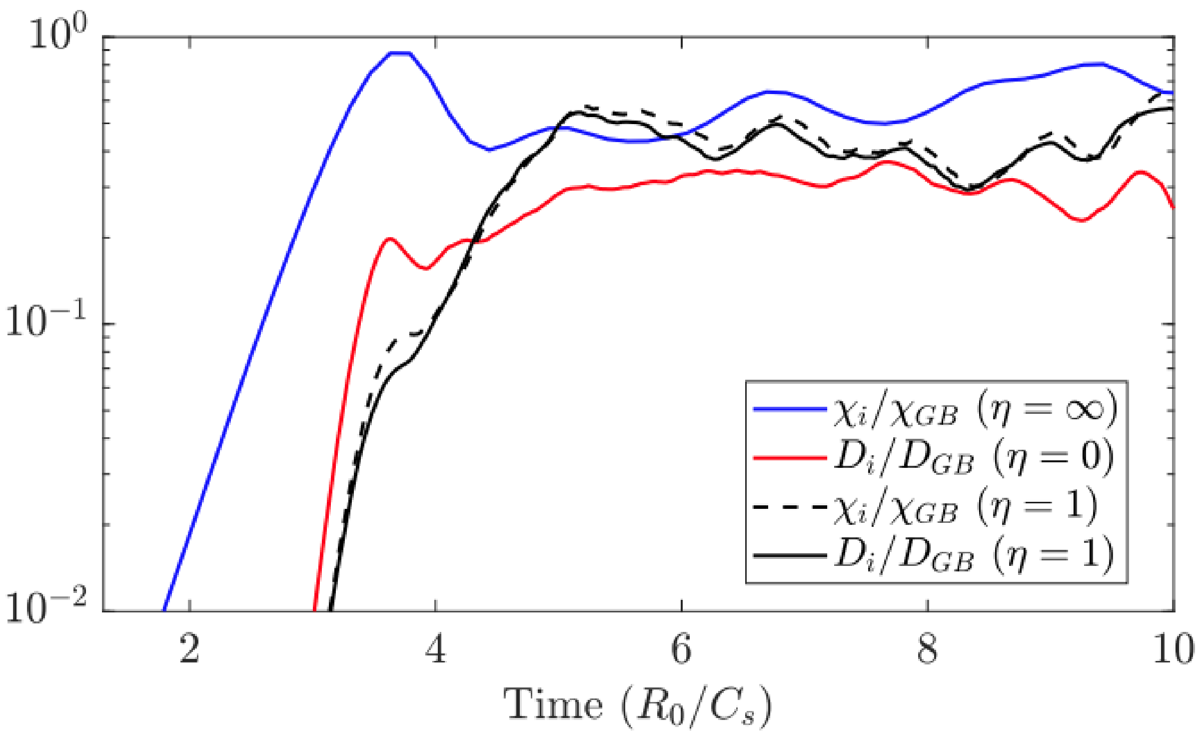
Microturbulence (for $\eta = 1$) in LHD

- The dominant mode is propagating in the ion diamagnetic direction: ITG
- The volume average ion diffusivity and conductivity are almost identical for $\eta = 1$ case
- Transport with $\eta = \infty$ case is the highest, while $\eta = 0$ has the lowest transport level.



Conclusion: In the present scenario similar plasma profile gradients, the ITG turbulence acts as the primary drive for the heat conductivity transport, whereas the TEM turbulence is effective for the particle diffusivity

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