Turbulence Spectra, Transport, and ExB Flows in Helical Plasmas

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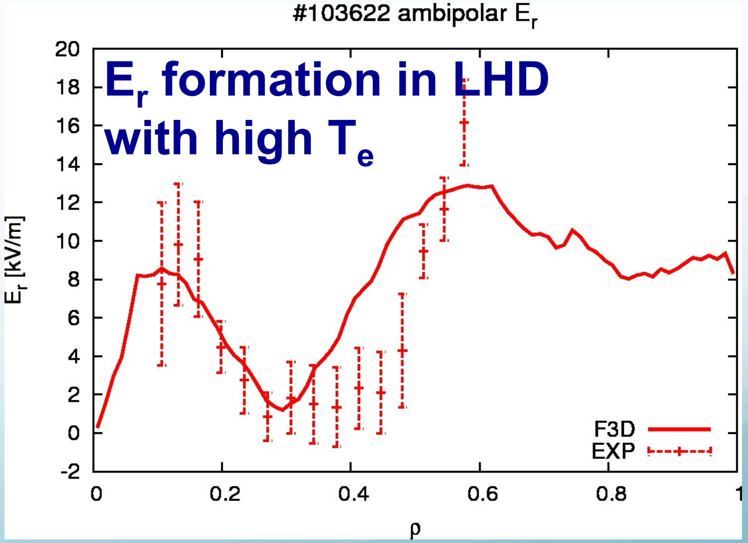
Non-axisymmetry: Big challenge in GK simulation of turbulence

- Non-axisymmetry introduces …
  - Complicated particle orbits (e.g. ripple trapped particles)
  - Non-uniform B both in θ and ζ directions
  - Fast parallel motions of passing particles through ripples
    - Major difficulty in EM GK simulation **Ishizawa et al. TH/P2-23**
  - Poloidal rotation due to the neoclassical transport
- Neoclassical transport => E_r
  - influences ZFs and turbulence which affect n & T profiles
- Zonal flow response depends on
  - Effective helical ripples
  - Equilibrium radial electric field



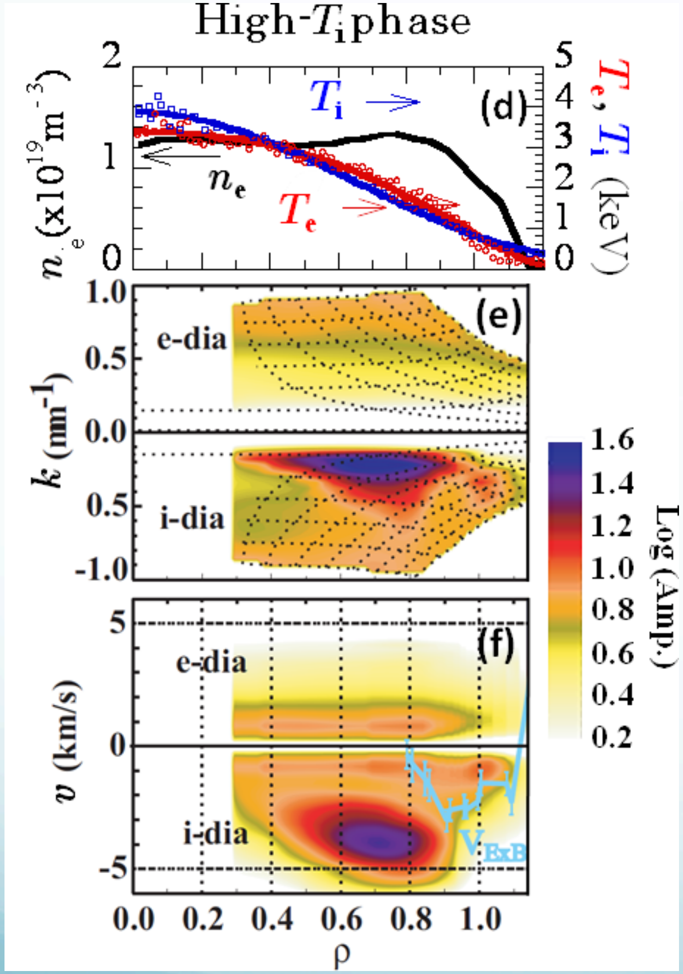
E_r formation in LHD with high T_e

FORTEC-3D results Matsuoka et al. 2012

Outline

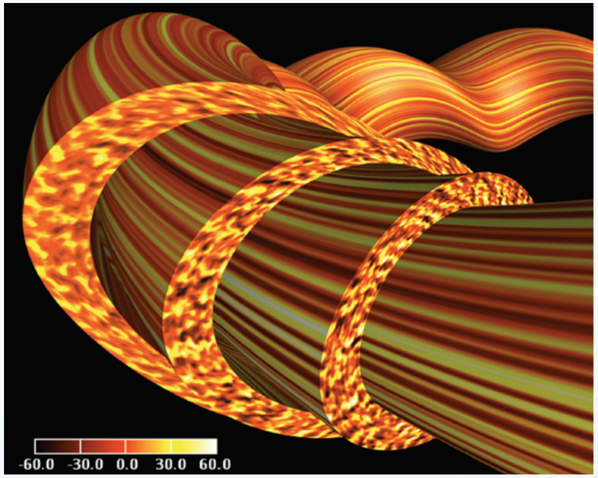
- Introduction
- Gyrokinetic simulations for high-T_i LHD plasmas
  - Validation against LHD experiments
- Turbulence spectra and entropy transfer through ZFs-turbulence interactions
- Multi-scale modeling of helical plasmas with poloidal ExB rotation
  - Collective growth of ZFs in the flux-tube bundle simulation
- Summary

Validation of GK simulations against LHD exp. has recently been advanced



Tanaka et al. PFR 2010

- GKV-X simulations for LHD high-T_i plasma with the 3D experimental configuration.

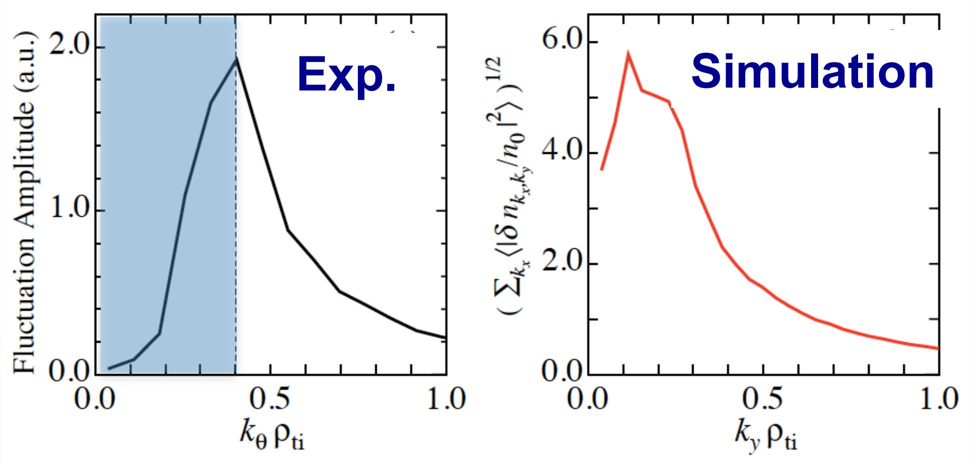


Nunami et al. PoP 2012

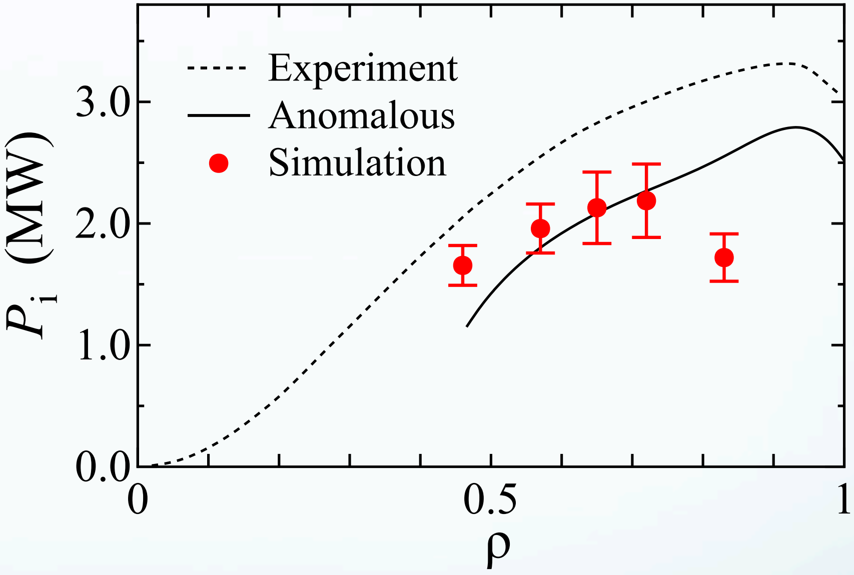
- Observed density fluctuations are consistent with results of the ITG turbulence simulations

Ion heat transport and turb. spectrum in the high-T_i LHD plasma (#88343)

Density fluctuation spectrum



Ion heat flux P_i



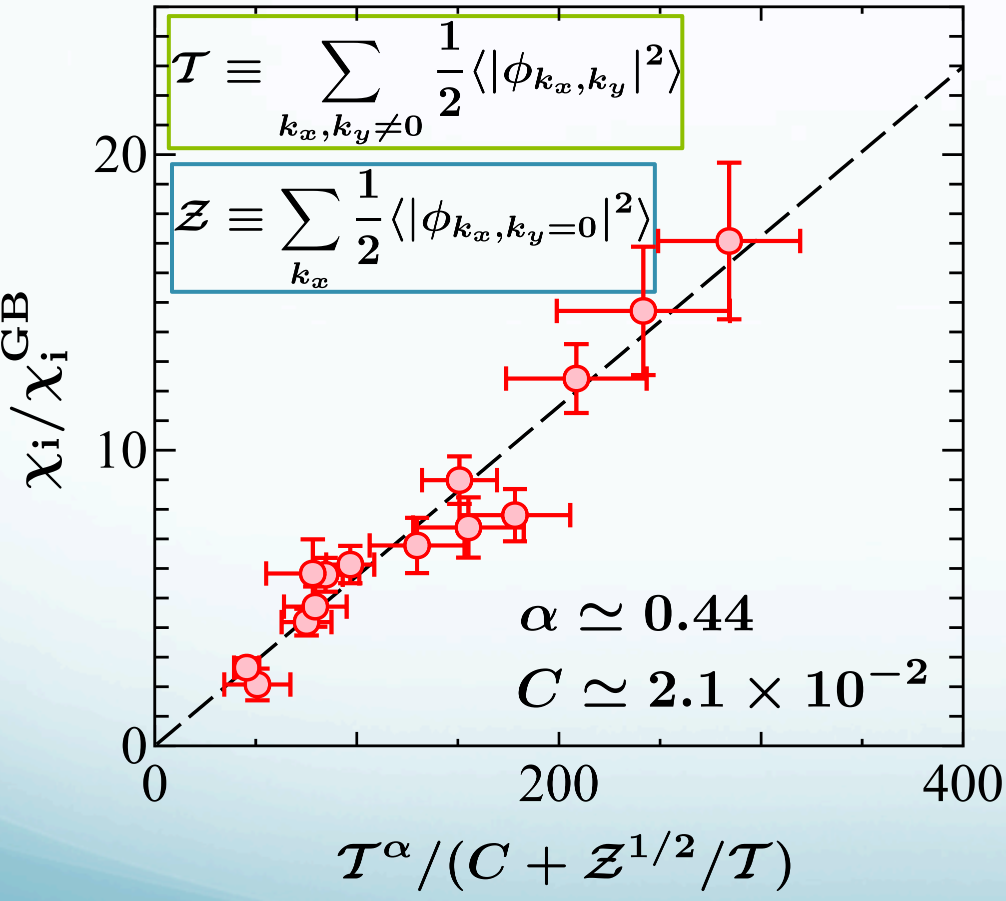
- The turbulence spectrum and the ion heat flux obtained from GK simulations are relevant to the experimental results.

Anomalous part
= Total heat flux – Neoclassical part

Neoclassical part
<= GSRAKE (Beidler et al. 1995)

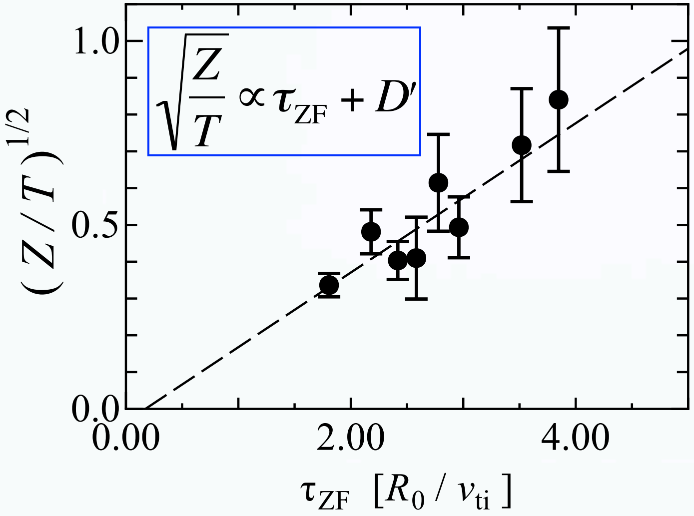
Summary of χ_i in terms of the turbulence and zonal flow energy

GKV-X runs for high-T_i and inward-shifted cases



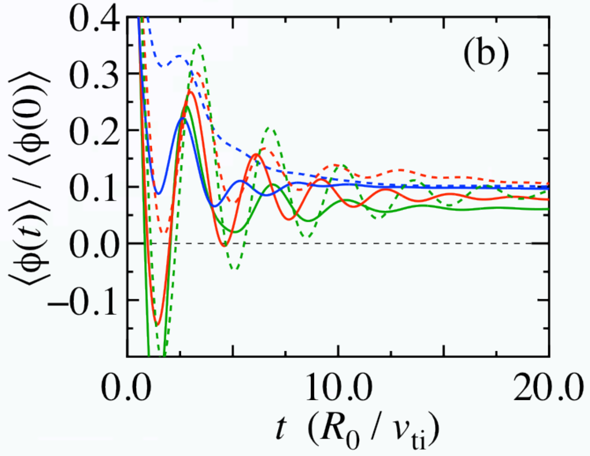
- Numerical modeling of the ion heat transport coefficient is tested.
- χ_i given by GK simulations are well fitted by means of turbulence and zonal flow energy (T and Z).
- Useful for construction of a reduced transport model.

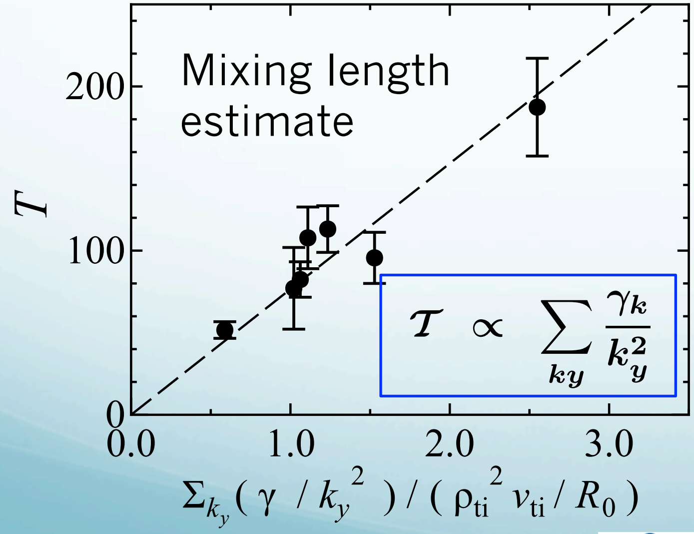
Turbulence and zonal flow energy modeled by linear quantities



ZF decay time

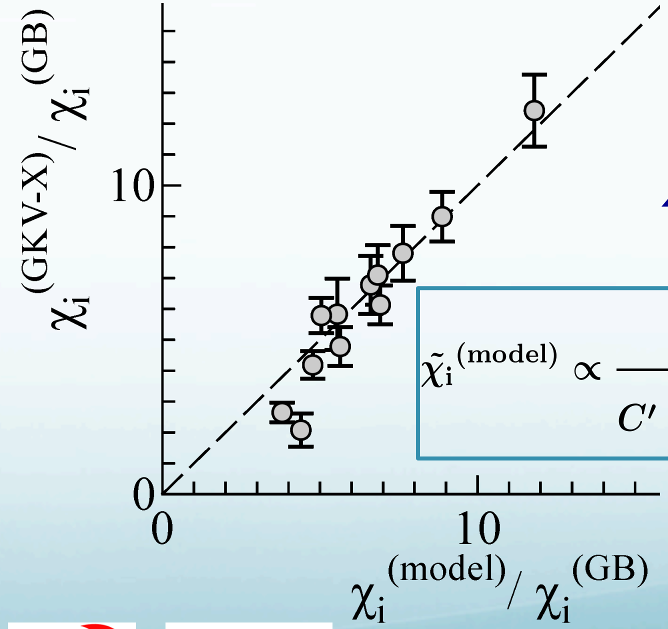
$$\tau_{\mathbf{ZF}} \equiv \int_0^{t_f} \frac{\langle \phi \rangle}{\langle \phi_0 \rangle} dt$$





Mixing length estimate

$$\mathcal{T} \propto \sum_{ky} \frac{\gamma_k}{k_y^2}$$

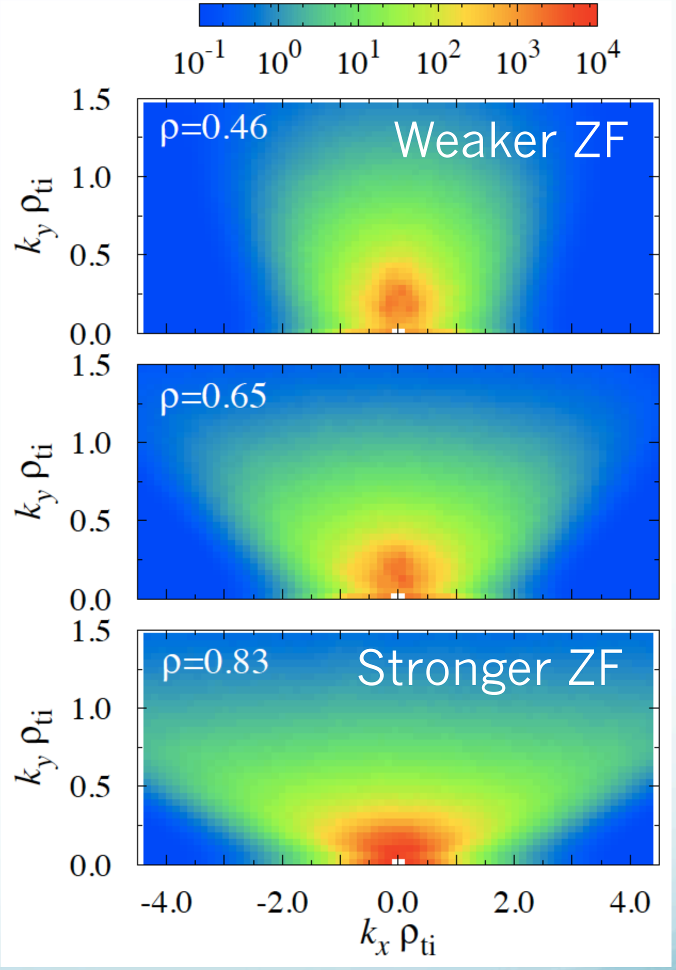


χ_i modeled with linear results

$$\tilde{\chi}_i^{(\mathrm{model})} \propto \frac{\left(\sum_k \tilde{\gamma}/\tilde{k}_y^2\right)^{\alpha}}{C' + (\tilde{\tau}_{\mathbf{ZF}} + D')/\left(\sum_k \tilde{\gamma}/\tilde{k}_y^2\right)^{1/2}}$$

Turbulence Spectrum and Entropy Transfer

The spectral spreading in k_r direction is attributed to the strong magnetic shear and zonal flows.



Nunami et al. PoP 2012

Turbulent entropy transfer function T_{ik} describes turbulence-ZF interactions

- From GK equations for each wavenumber **k**, one finds the entropy transfer among turbulence and ZF components

$$\frac{\partial}{\partial t}\left(\delta S_{\boldsymbol{ik}} + W_{\mathbf{k}}\right) = L_T^{-1} Q_{\boldsymbol{ik}} \enclose{circle}{+ T_{\boldsymbol{ik}}} + D_{\boldsymbol{ik}}$$

$$\boxed{\delta S_{\mathrm{i}\boldsymbol{k}_\perp} = \left\langle \int d\boldsymbol{v} \frac{|\delta f^{(\mathrm{g})}_{\mathrm{i}\boldsymbol{k}_\perp}|^2}{2F_{\mathrm{M}}} \right\rangle}$$

- δS_{ik}: Entropy variable, W_k: potential energy, Q_{ik}: turbulent ion heat flux, D_{ik} : collisional dissipation

- Entropy transfer function T_{ik} describes nonlinear ExB interactions among turbulence and ZFs **Nakata et al. PoP 2012**

$$\mathcal{T}_{\mathrm{i}\boldsymbol{k}_\perp} = \sum_{\boldsymbol{q}_\perp} \sum_{\boldsymbol{p}_\perp} \delta_{\boldsymbol{k}_\perp + \boldsymbol{p}_\perp + \boldsymbol{q}_\perp, 0} \mathcal{J}_{\mathrm{i}}[\boldsymbol{k}_\perp | \boldsymbol{p}_\perp, \boldsymbol{q}_\perp]$$

$$\mathcal{J}_i[\boldsymbol{k}_\perp | \boldsymbol{p}_\perp, \boldsymbol{q}_\perp] = \left\langle \frac{c}{B} \boldsymbol{b} \cdot (\boldsymbol{p}_\perp \times \boldsymbol{q}_\perp) \int d\boldsymbol{v} \frac{1}{2F_{\mathrm{M}}} \mathrm{Re}[\delta\psi_{\boldsymbol{p}_\perp} h_{\mathrm{i}\boldsymbol{q}_\perp} h_{\mathrm{i}\boldsymbol{k}_\perp} - \delta\psi_{\boldsymbol{q}_\perp} h_{\mathrm{i}\boldsymbol{p}_\perp} h_{\mathrm{i}\boldsymbol{k}_\perp}] \right\rangle$$

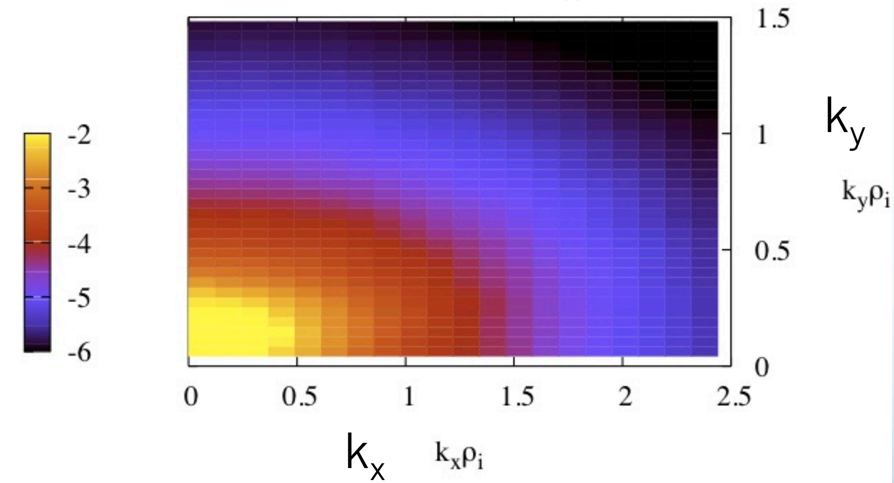
- Successive entropy transfer into high k_r region in ITG turb.

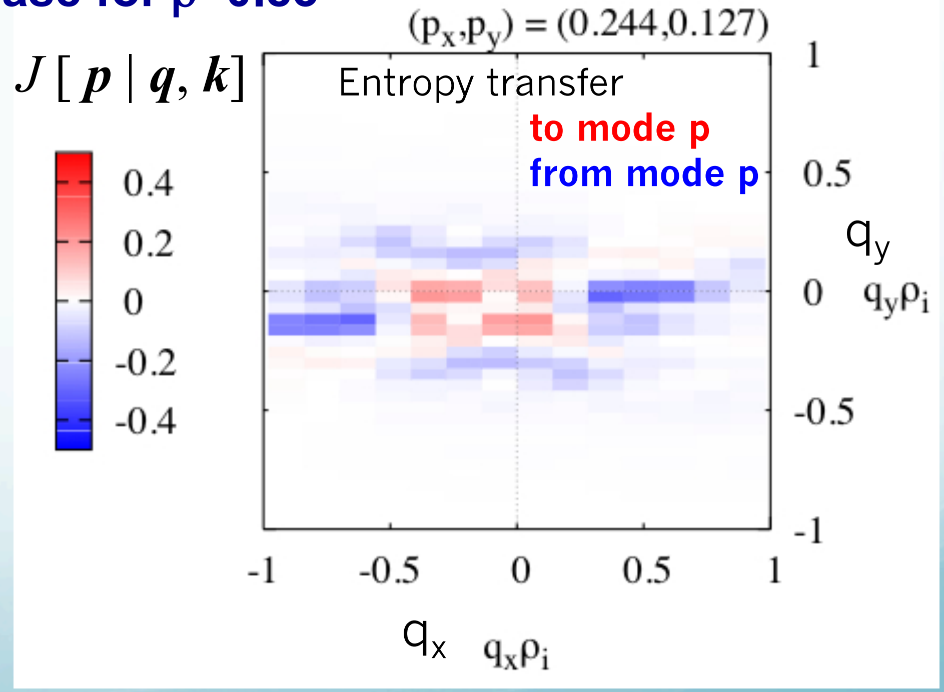
Successive entropy transfer function leads to spreading of turb. spectrum

- When ZFs are strongly generated in LHD plasma (e.g. inward-shifted or $\rho > 0.65$), the successive entropy transfer leads to spreading of the turbulence spectrum in k_r.

LHD high-T_i case for ρ=0.83

2-D Spectrum of $|\phi_k|^2$ at θ=0

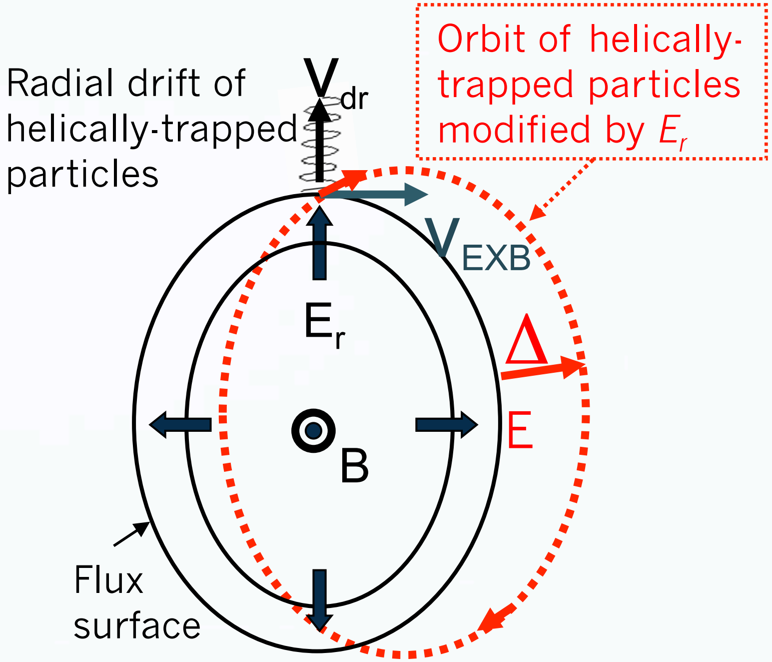


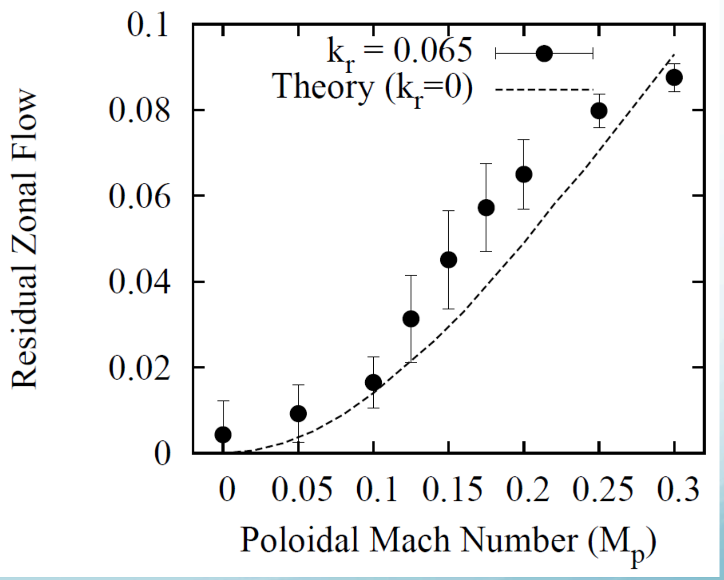


Enhancement of Zonal Flow Response by E_r

The equilibrium-scale radial electric field E_r generated by the neoclassical transport improves

- collisionless particle orbits, and
- simultaneously enhances the ZF response





Watanabe et al. NF (2011)

Flux-Tube Bundle Model for Multi-Scale Interactions of E_r, ZFs, and Turbulence

- Zonal flow components with α dependence (non-axisymmetry)

$$\left[\frac{\partial}{\partial t}+v_\parallel \boldsymbol{b}\cdot\nabla+v_{dx}\frac{\partial}{\partial x}-\frac{\mu}{m}(\boldsymbol{b}\cdot\nabla B)\frac{\partial}{\partial v_\parallel}+\omega_\theta q\frac{\partial}{\partial\alpha}\right]\widehat{f}=\left(-v_{dx}\frac{\partial\hat{\Phi}}{\partial x}-v_\parallel\boldsymbol{b}\cdot\nabla\hat{\Phi}\right)\frac{e}{T}F_M+C\left(\hat{h}\right)+S_i^{ZF}$$

- Turbulence components in the *i*th flux tube at α=α_i

$$\left[\frac{\partial}{\partial t}+v_\parallel \boldsymbol{b}\cdot\nabla+\boldsymbol{v}_d\cdot\nabla-\frac{\mu}{m}(\boldsymbol{b}\cdot\nabla B)\frac{\partial}{\partial v_\parallel}-\omega_\theta r_0\frac{\partial}{\partial y}\right]\tilde{f}+\frac{c}{B_0}\left\{\Phi,\delta f\right\}_i$$

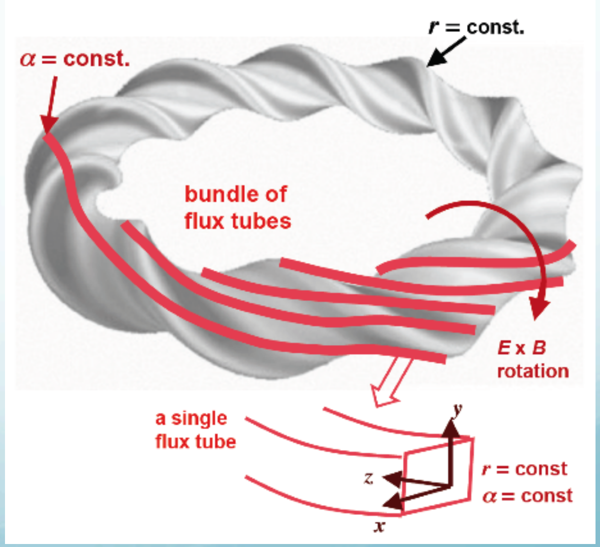
$$=\left(\boldsymbol{v}_*-\boldsymbol{v}_d-v_\parallel\boldsymbol{b}\right)\cdot\frac{e\nabla\Phi}{T}F_M+C\left(\tilde{h}\right)-S_i^{ZF}$$

where

$$\frac{c}{B_0}\left\{\Phi,\delta f\right\}_i\Rightarrow\sum_{\mathbf{k}=\mathbf{k}'+\mathbf{k}''}\mathbf{k}'\times\mathbf{k}''\Phi_{i,\mathbf{k}'}\delta f_{i,\mathbf{k}''}\qquad S_i^{ZF}=-\frac{c}{B_0}\overline{\left\{\Phi,\delta f\right\}}_i$$

$$\delta f_{i,k}=\begin{cases}\tilde{f}_i & \text{for } k_y\neq 0\\ \hat{f}\left(\alpha=\alpha_i\right) & \text{for } k_y=0\end{cases}$$

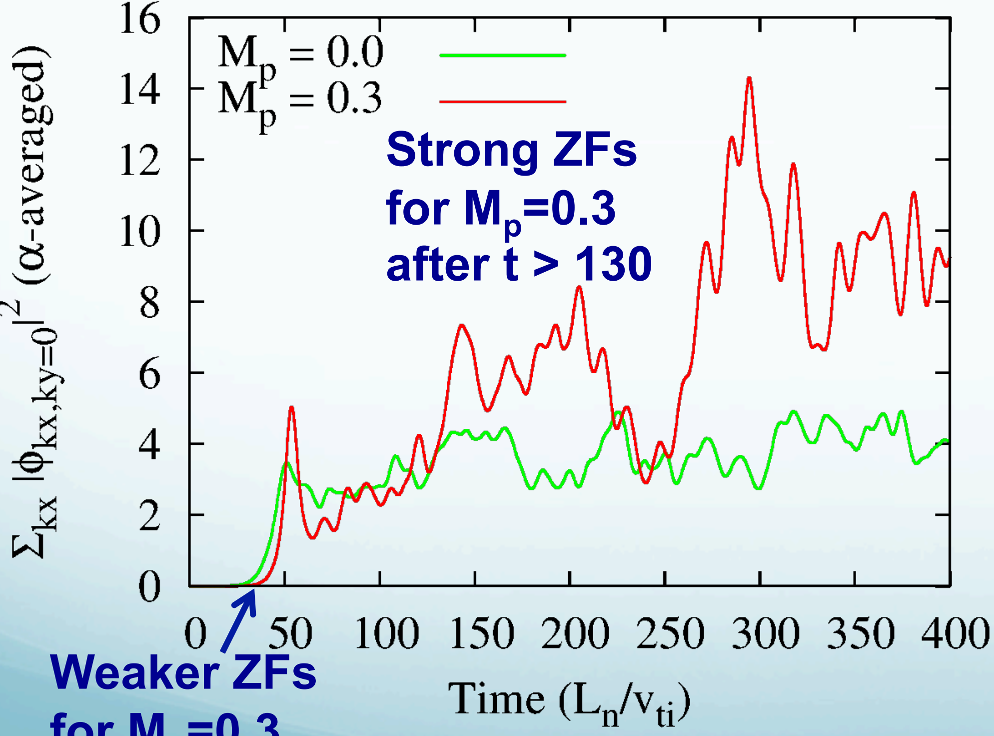
Flux tube at α=α_i
(i=0, 1, 2, ...)



Zonal flow generation by turbulence is enhanced by poloidal ExB rotation

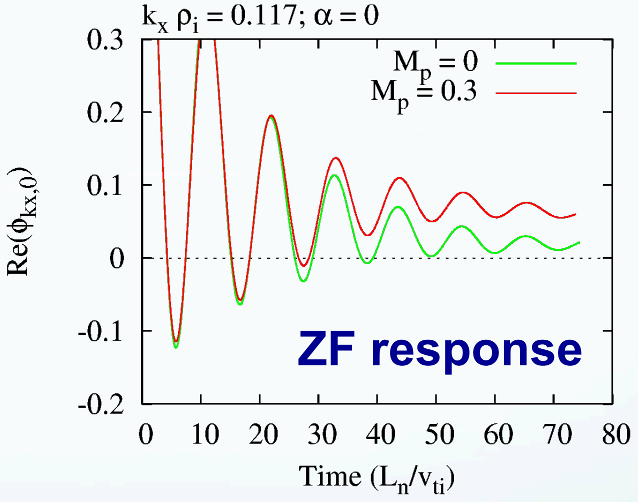
- Multi-scale simulation of the ITG turbulence with eight flux tubes for the inward-shifted LHD model

ZF energy averaged over flux tubes

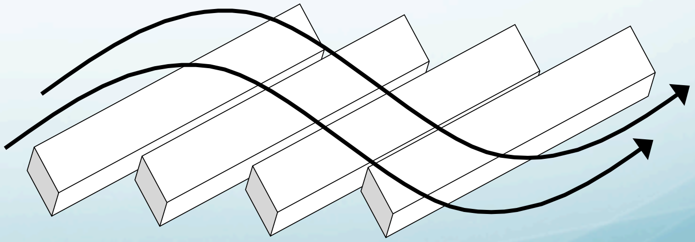


Strong ZFs for M_p=0.3 after t > 130

Weaker ZFs for M_p=0.3



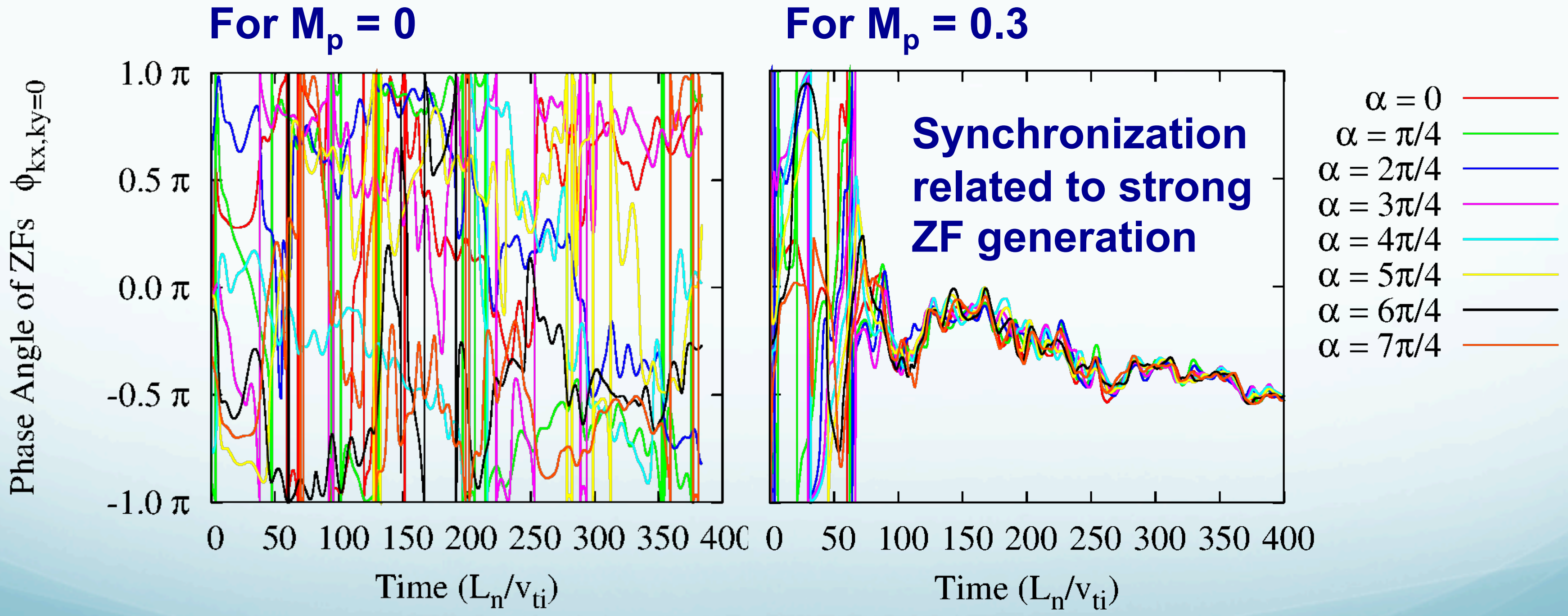
ZF response



Flux tube at $\alpha = \alpha_i$ (i=0, 1, 2, ...)

Poloidal ExB rotation synchronizes radial phase of ZFs in flux tubes

- Collective growth of ZFs in the flux-tube bundle model appears for $M_p = 0.3$ through matching of the radial phase angles, or synchronization.



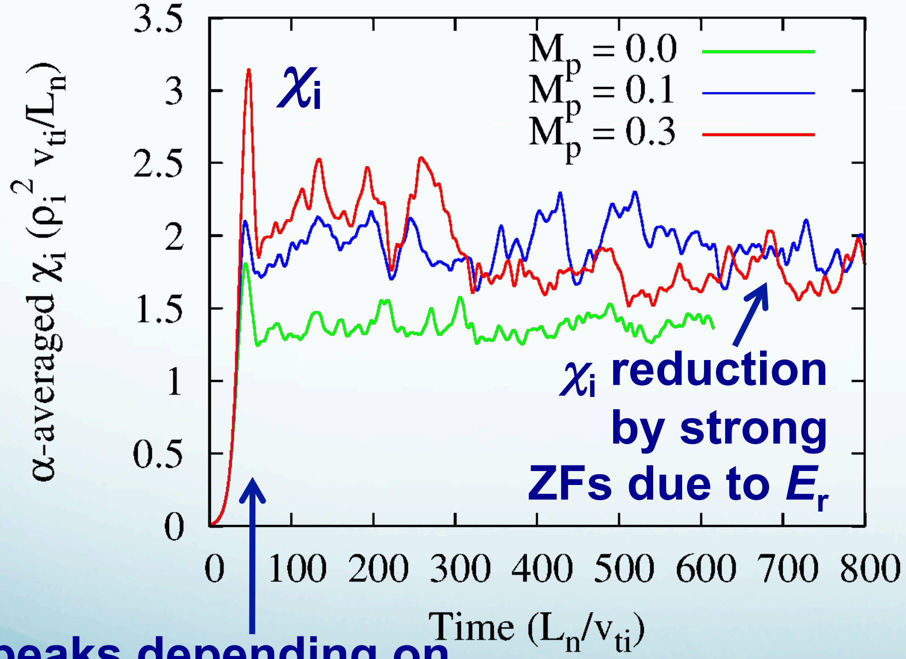
For M_p = 0

For M_p = 0.3

Synchronization related to strong ZF generation

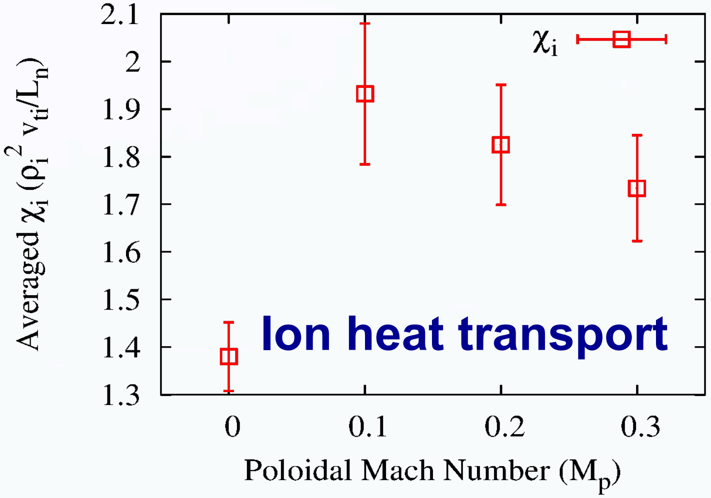
Transport reduction by ZFs enhanced in case with finite rotation ($M_p > 0.1$)

- For cases with $M_p > 0.1$, the turbulent transport is reduced by enhanced ZFs, while χ_i is still larger than that for $M_p = 0$.

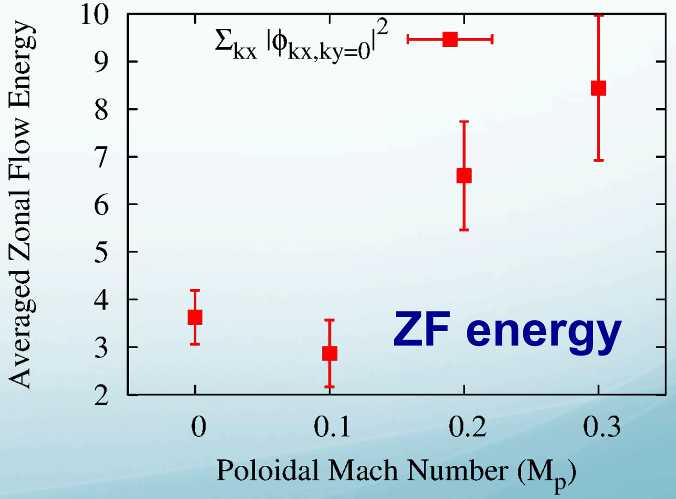


χ_i reduction by strong ZFs due to E_r

χ_i peaks depending on the initial ZF growth



Ion heat transport



ZF energy

Summary

- Recent developments of gyrokinetic simulations for LHD
  - Validation, modeling, multi-scale ZFs, electromagnetic etc.
- The gyrokinetic simulation of ITG turbulence for helical plasmas is validated against the LHD experiments.
  - Radial profile of ion heat transport flux relevant to LHD exp.
  - Transport modeling based on the turbulence and ZF energy.
- Entropy transfer analysis among turbulence and ZFs
  - Quantitative evaluation for ZF-turbulence interactions
  - Contribution to spreading of turbulence spectrum in k_r
- A multi-scale model developed for non-axisymmetric toroidal plasmas with mean E_r.
  - Collective growth of ZFs through the radial phase matching
  - Influence of the poloidal rotation on turbulent transport