Electromagnetic Gyrokinetic Analysis of Turbulent Transport in Finite-Beta LHD Experiments

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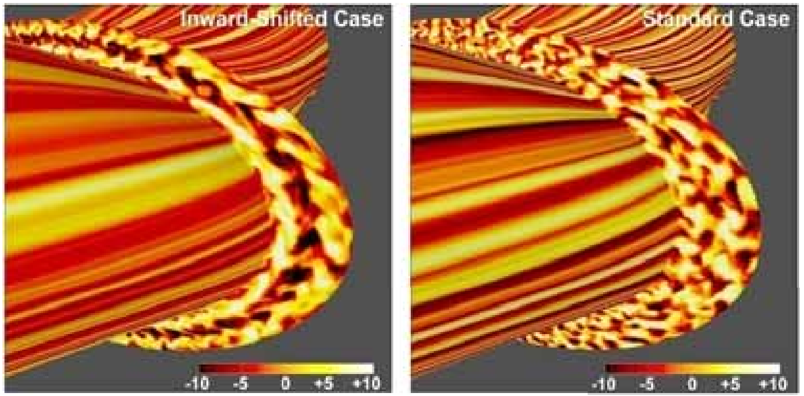
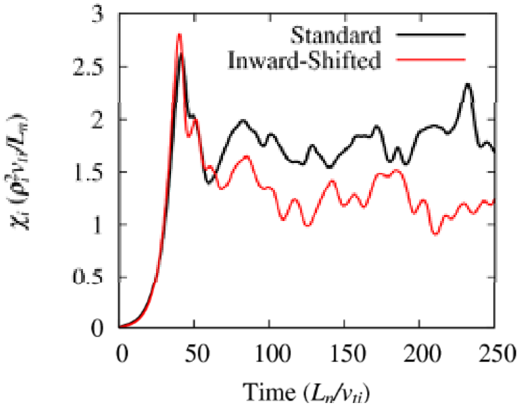
Introduction: GK simulations of LHD plasmas

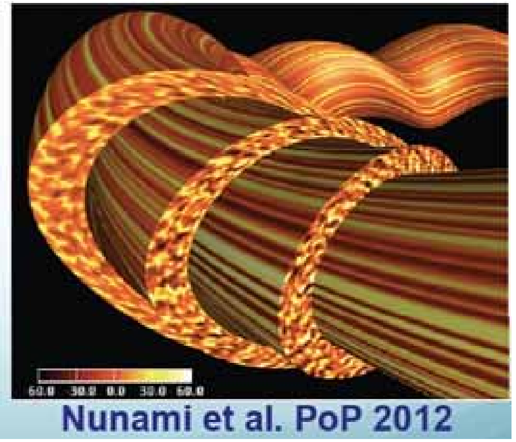
- Interplay between ITG turbulence and zonal flow in Large Helical Device (LHD)



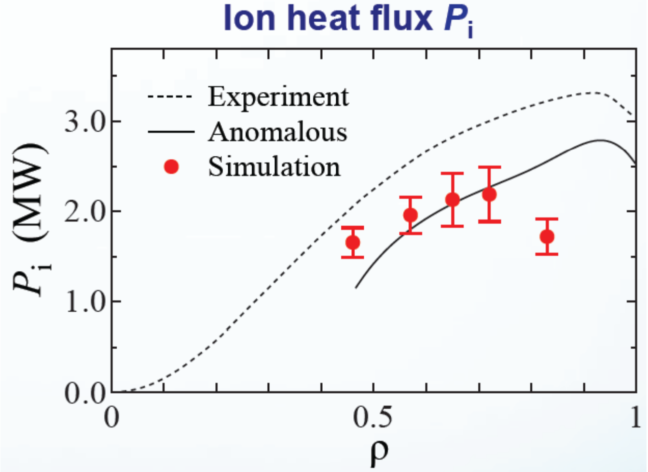


T.-H. Watanabe, PRL (2008)

- Validation of gyrokinetic simulations against ITG turbulence in LHD experiments

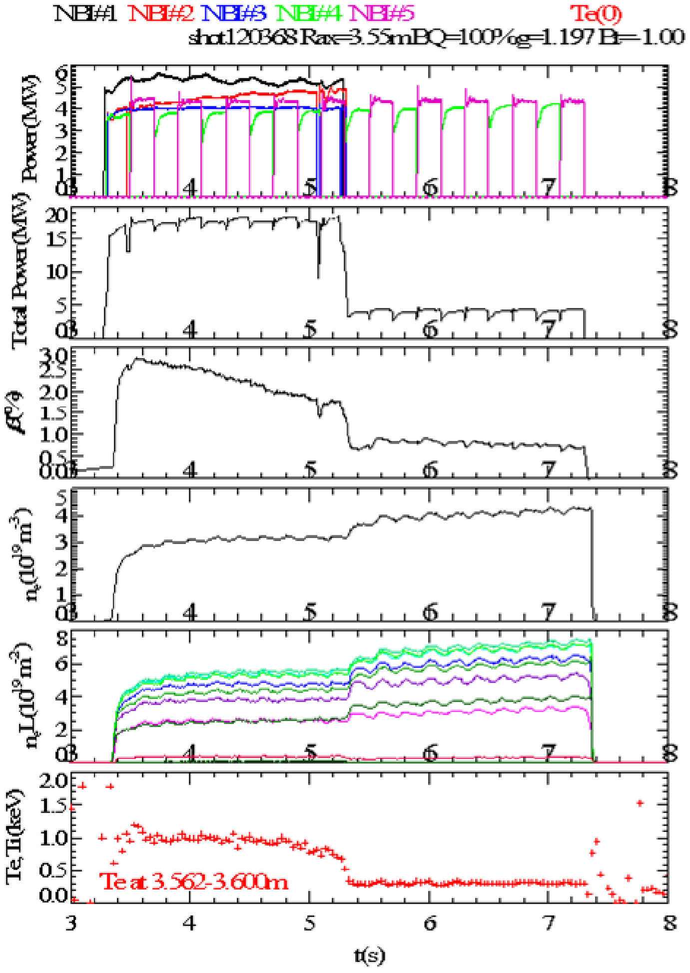


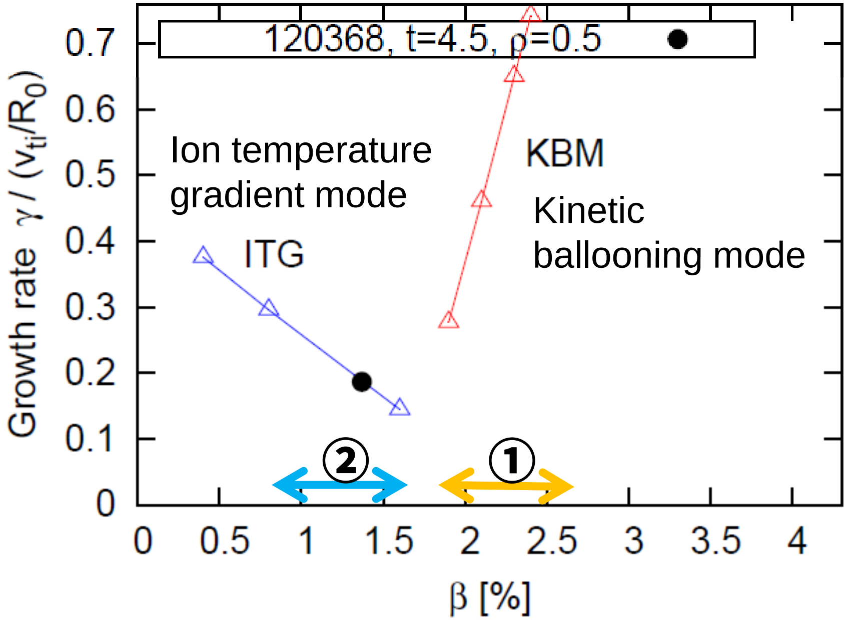
Nunami et al. PoP 2012



- Previous GK simulations of LHD plasmas assumed adiabatic electron response. We have extended the GK code to include kinetic electrons and magnetic perturbation. A. Ishizawa, Nuclear Fusion, 053007 (2013)

The first GK analysis of finite-beta LHD experiments



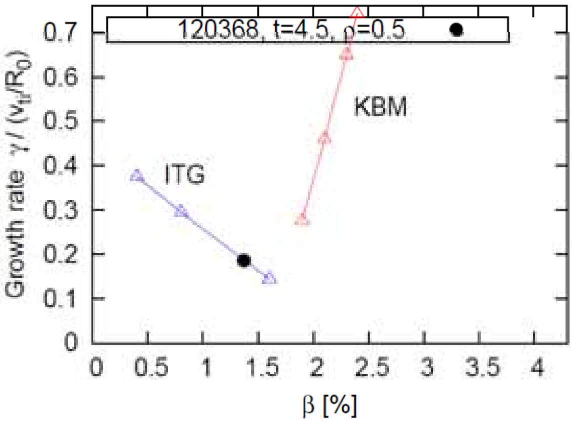


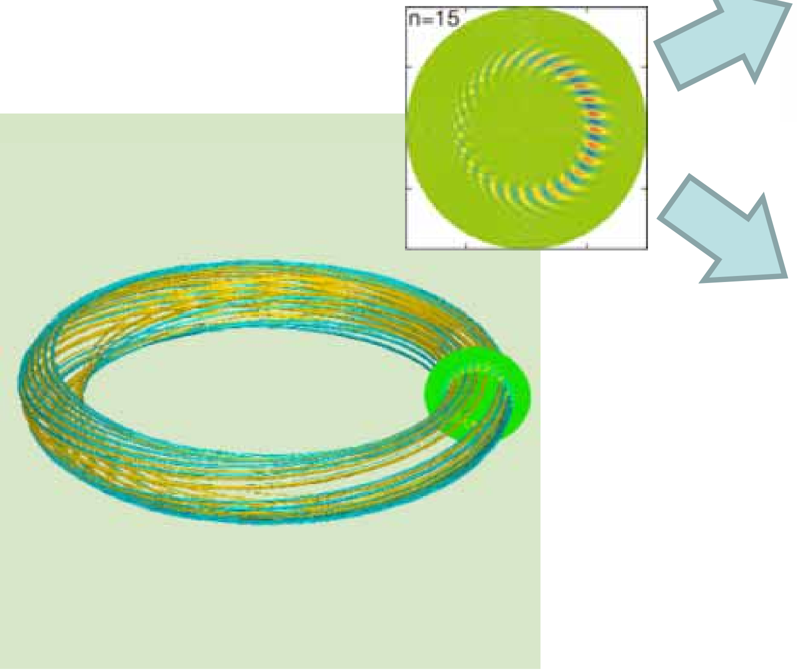
Beta of a helical fusion DEMO reactor (FFHR-d1) is about 8% (Miyazawa, NF2012)

① Prediction for higher beta LHD plasmas
Kinetic ballooning modes (KBM)

② Finite-beta LHD experiment #120368
Finite-beta ITG

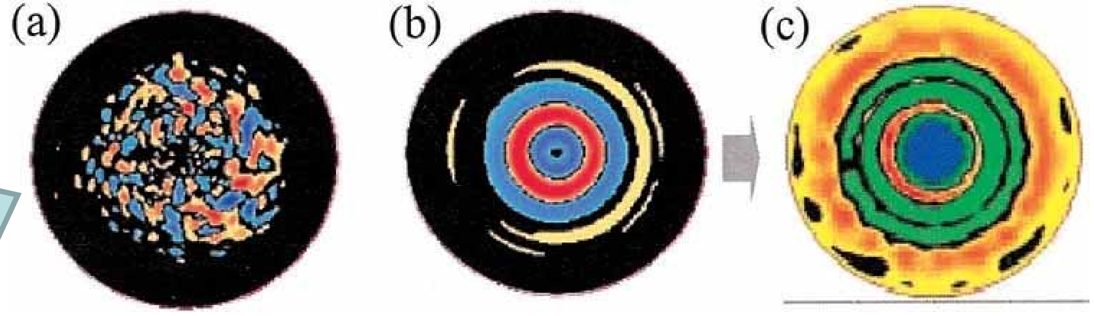
Structure formation that affects instability in magnetically confined plasmas



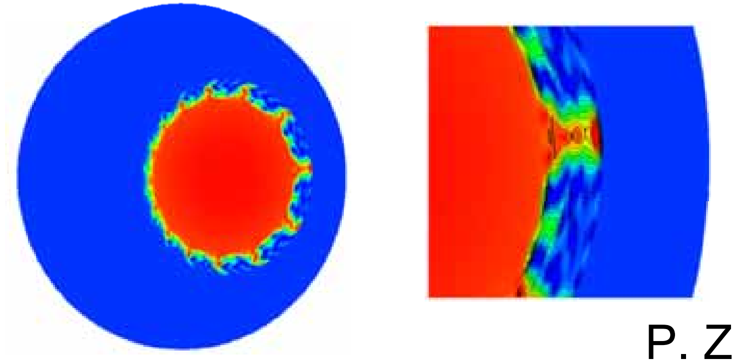


- Drift wave instability (ITG)
  - Stabilized by zonal flow structure.

Y. Kishimoto



- Ballooning (MHD) instability
  - Acceleration by finger-like structure

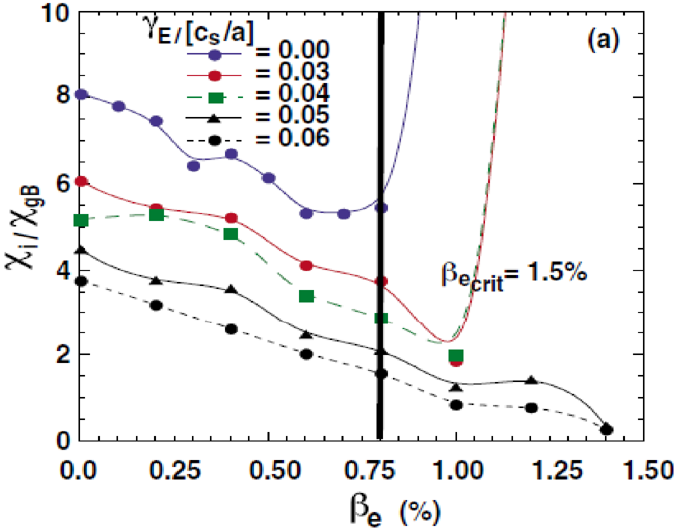


P. Zhu

Saturation problem in finite beta plasmas

Failure of the transport levels to saturate at finite beta in gyrokinetic simulations in flux tube geometry

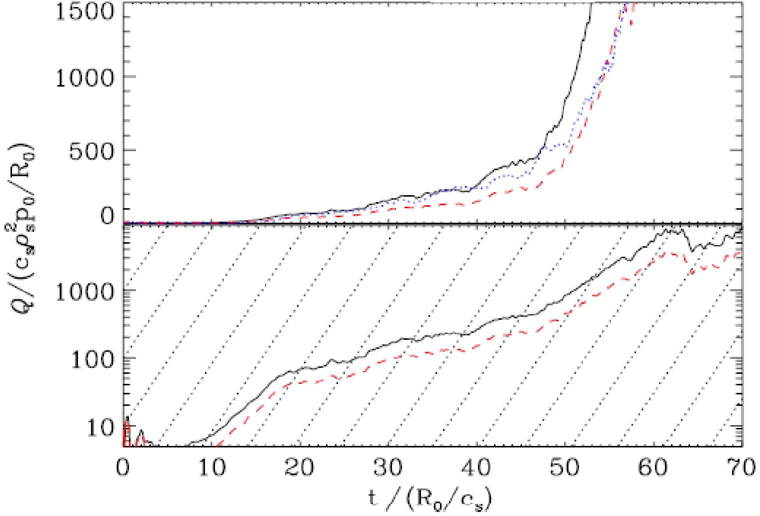
Finite beta (ITG) Runaway above $\beta_e = 0.75\%$



R. E. Waltz, Phys. Plasmas, (2010)

Cyclone base case (tokamak)

Finite beta (ITG) $\beta = 0.9\%$



M. J. Pueschel, Phys. Rev. Lett., (2013)

Zonal flows are weak.

EM delta-f gyrokinetic equations

$$\frac{D\delta f_{sk}}{Dt} + v_{Ts} v_{//} \mathbf{b}^* \cdot \nabla \delta f_{sk} - v_{Ts} \mu \mathbf{b} \cdot \nabla B \frac{\partial \delta f_{sk}}{\partial v_{//}} = -i\mathbf{v}_{ds} \cdot \mathbf{k}_{\perp} \left(\delta f_{sk} + \frac{q_s F_{sM}}{T_s} \phi_k J_{0s}\right)$$

$$+ i\mathbf{v}_{*s} \cdot \mathbf{k}_{\perp} \frac{q_s F_{sM}}{T_s} (\phi_k - v_{Ts} v_{//} A_{//k}) J_{0s} + v_{Ts} v_{//} \frac{q_s F_{sM}}{T_s} E_{//k} + C(\delta f_{sk})$$

$$\lambda_{Di}^2 k_{\perp}^2 \phi_k = \sum_s \left(q_s \delta n_{sk} - \frac{q_s^2}{T_s} [1 - \Gamma_{0s}] \phi_k \right) \qquad k_{\perp}^2 A_{//k} = \beta_i \sum_s q_s \delta u_{sk}$$

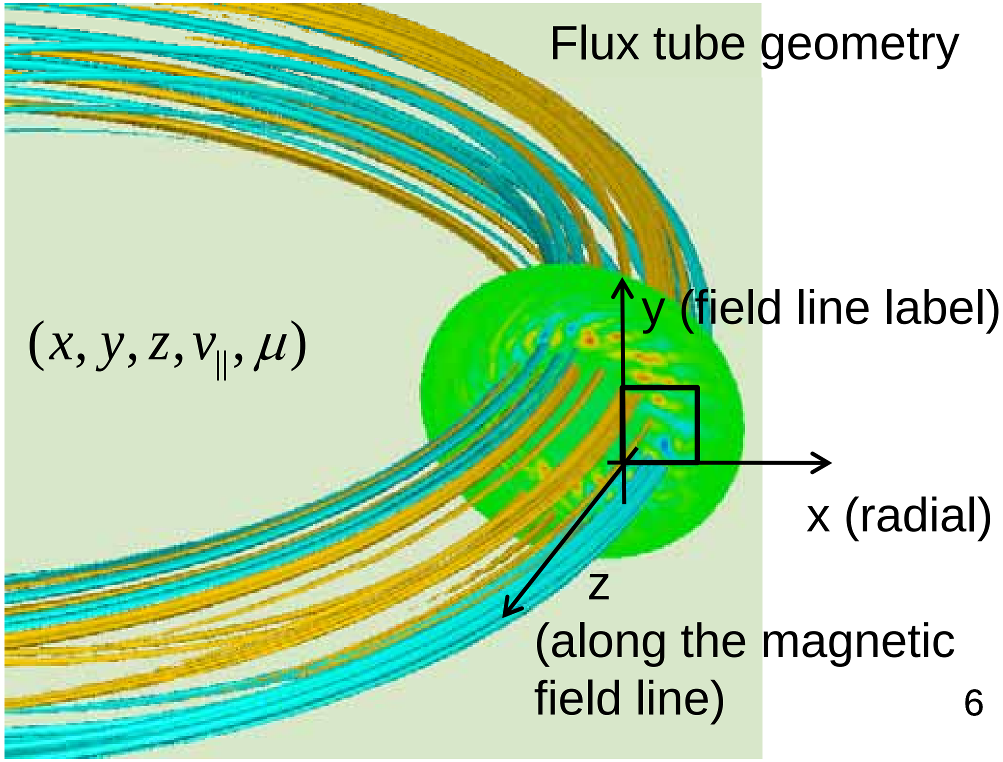
$$E_{//k} = -\mathbf{b}^* \cdot \nabla \phi_k J_{0s} - \frac{\partial A_{//k}}{\partial t} J_{0s}$$

$$\delta n_{sk} = \int dv^3 \delta f_{sk} J_{0s}$$

$$\delta u_{sk} = \int dv^3 v_{//} \delta f_{sk} J_{0s}$$

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \frac{1}{B} [\phi J_{0s}, \quad]_k$$

$$\mathbf{b}^* \cdot \nabla = \mathbf{b} \cdot \nabla - \frac{1}{B} [A_{//} J_{0s}, \quad]_k$$


Flux tube geometry

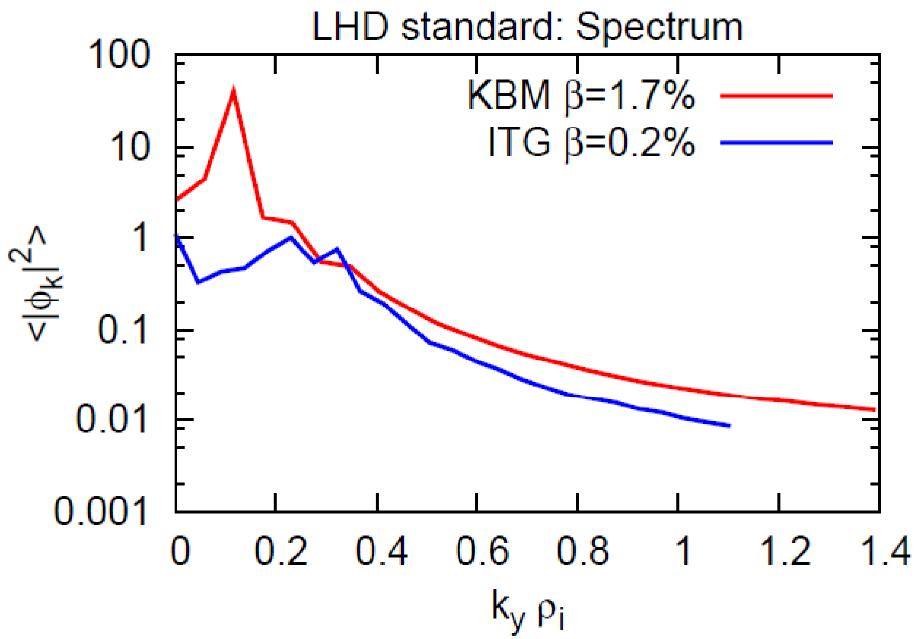
$$(x, y, z, v_{||}, \mu)$$

① Prediction for higher beta LHD plasmas

Kinetic ballooning modes

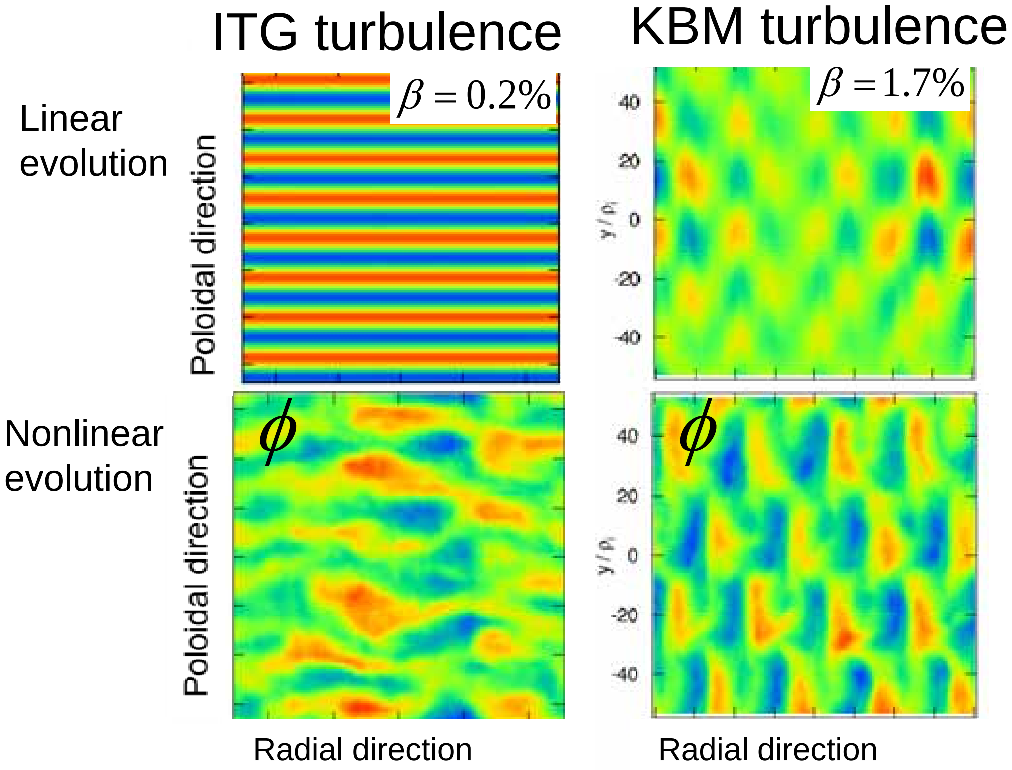
in a model configuration

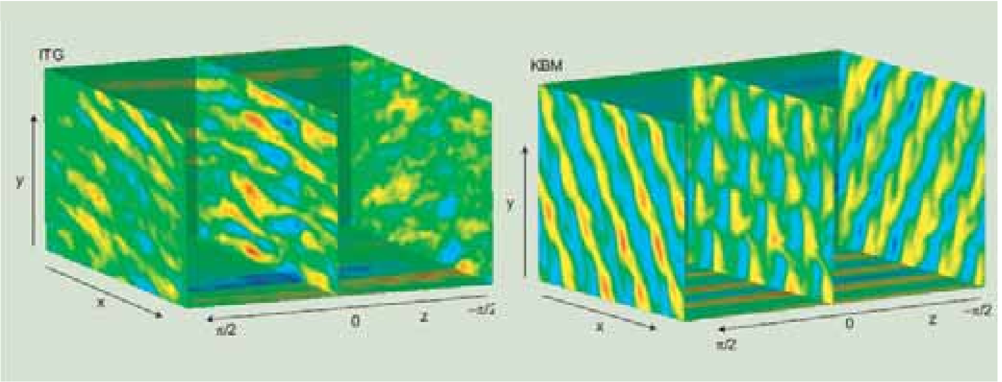
Weak zonal flow



- Zonal flow of KBM turbulence is much weaker than that of ITG turbulence.

New saturation mechanism of turbulence with weak zonal flow

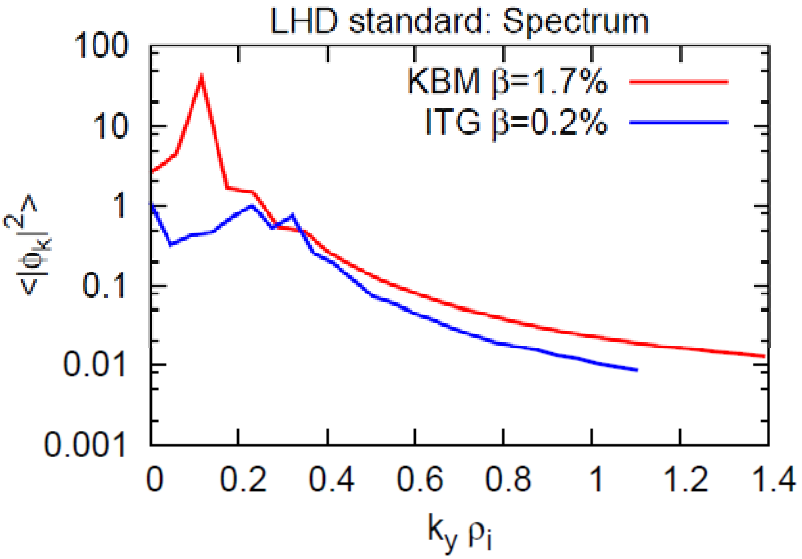




$\eta_e = 0$

- Most unstable KBM has an inclined mode structure (finite theta_k)
- Saturation of the KBM turbulence is caused by nonlinear interactions between inclined modes.

Low efficiency of KBM turbulence in transport



Energy flux

ITG $Q_i = 5 n_0 T_i v_{Ti} \rho_i^2 / L_n^2$

KBM $Q_i = 3 n_0 T_i v_{Ti} \rho_i^2 / L_n^2$

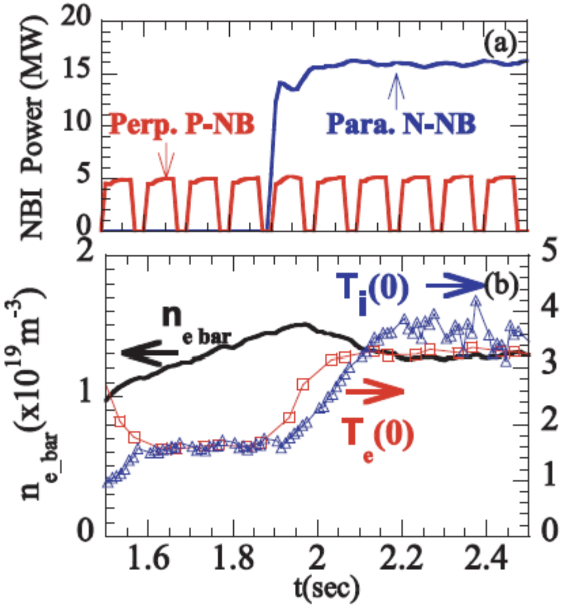
- KBM turbulence is not efficient in the transport compared with ITG turbulence

② Finite-beta LHD: #120368

Finite-beta ITG

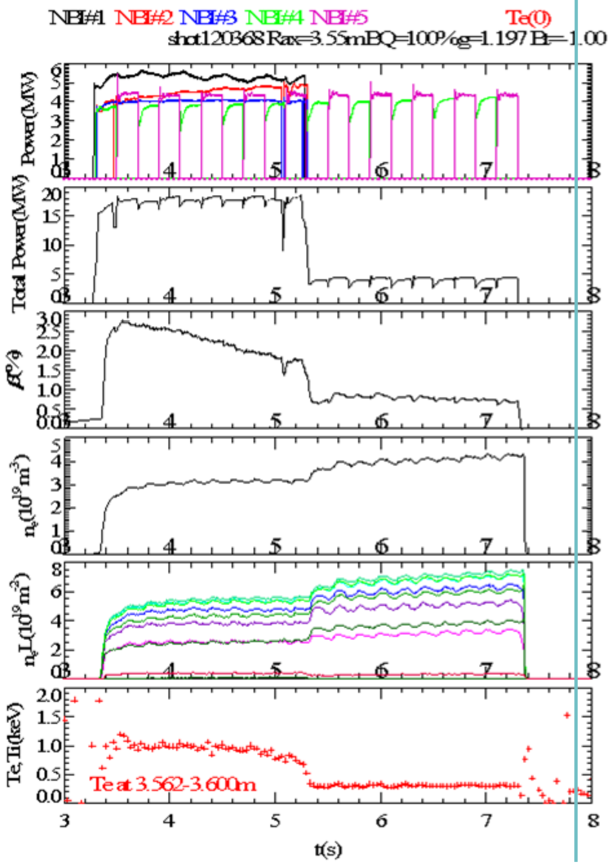
Analysis of #120368

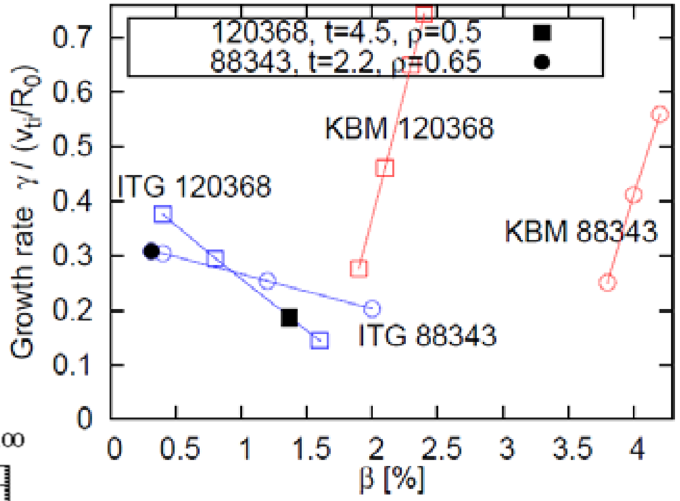
- 88343: High Ti discharge
  - B_0=2.75T, Rax=3.6m (shifted to 3.75m)
  - Beta(r/a=0.65)= 0.3%
  - banana regime



Tanaka, PFR 2010

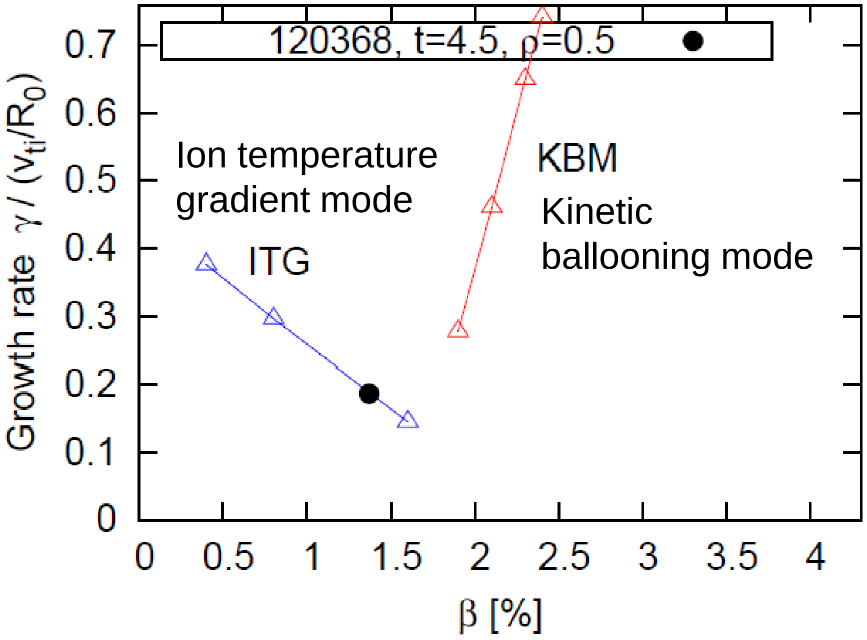
- 120368
  - B_0=1T , Rax=3.55m (shifted to 3.66m)
  - Beta(r/a=0.5)=1.4 %
  - plateau regime



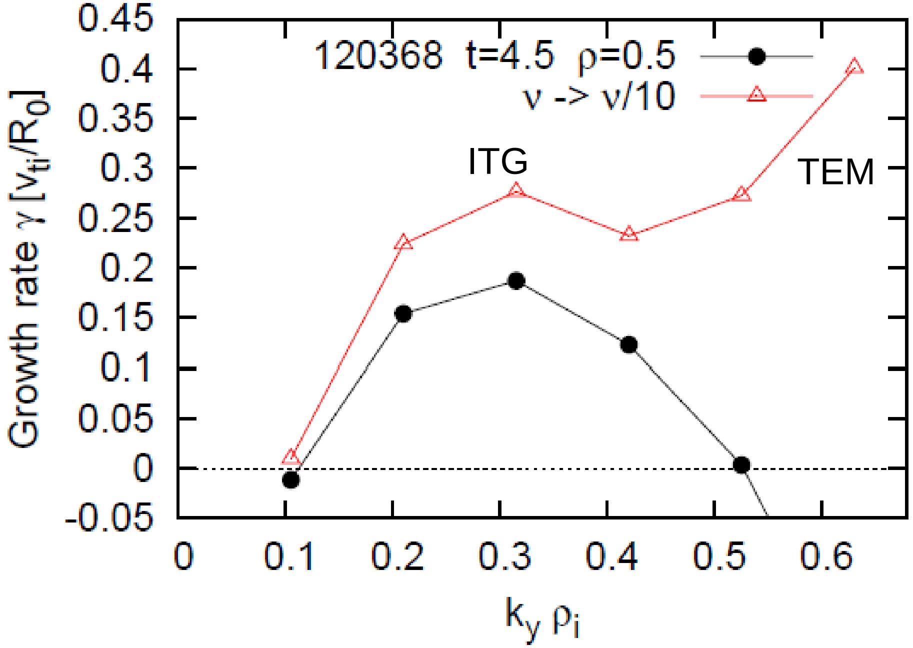


Reduction of ITG and appearance of KBM with increasing beta

Beta dependence

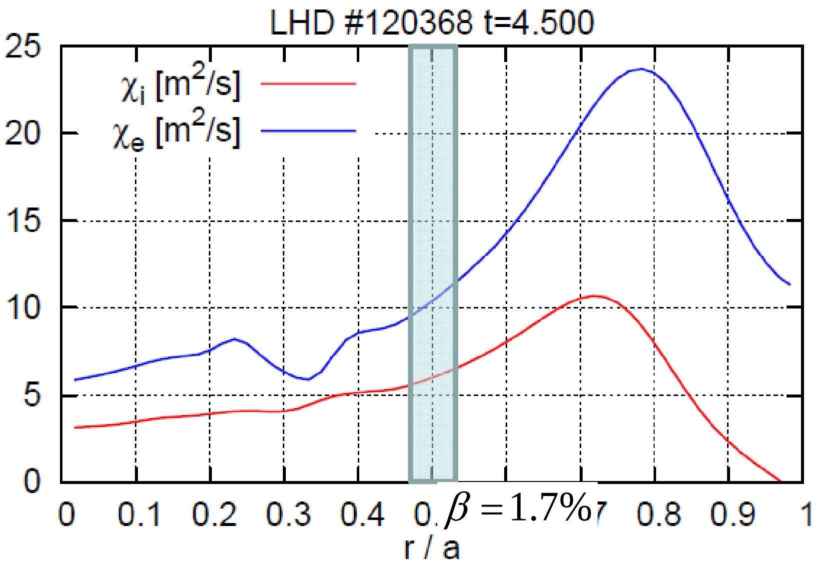


Collisionality dependence



- The ITG mode growth rate decreases with increasing beta, and the KBM becomes a dominant instability for local beta values larger than 1.9%.
- If the collisionality is decreased, then TEM appears at high-poloidal wavenumber.

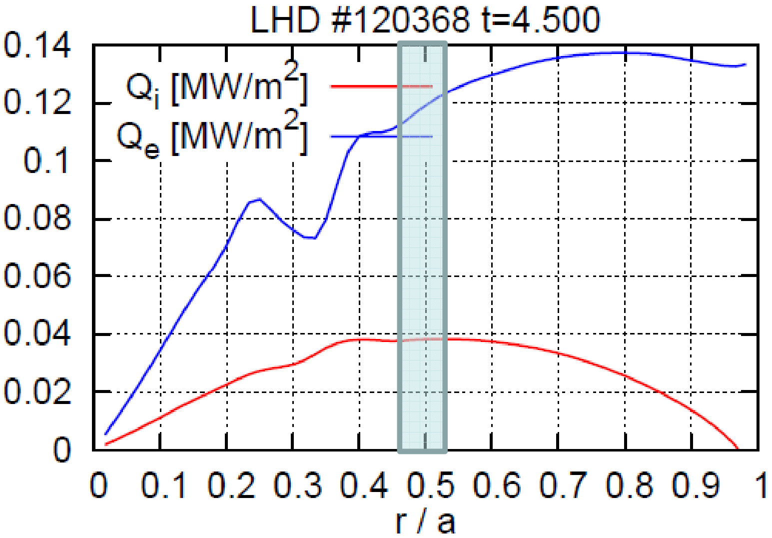
Transport coefficients



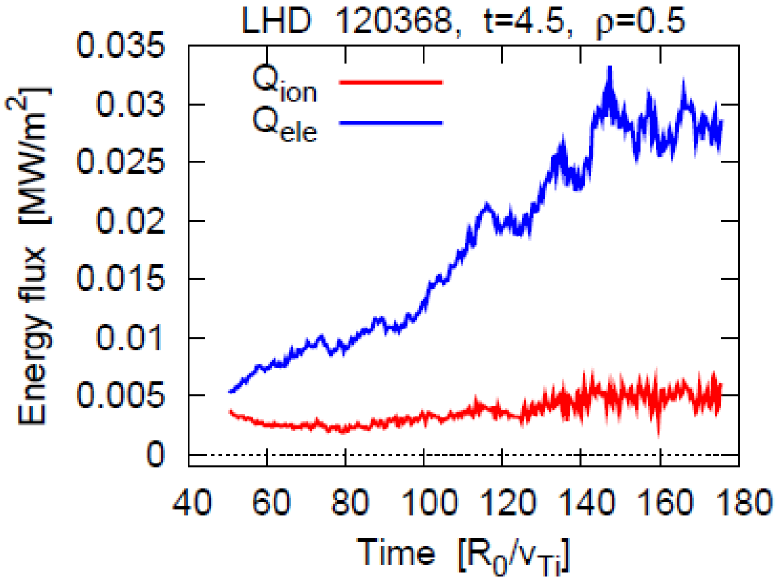
m^2/s	χ_i	χ_e	D
Experiment	6	10	0.9
Simulation	0.8	2.8	0.3

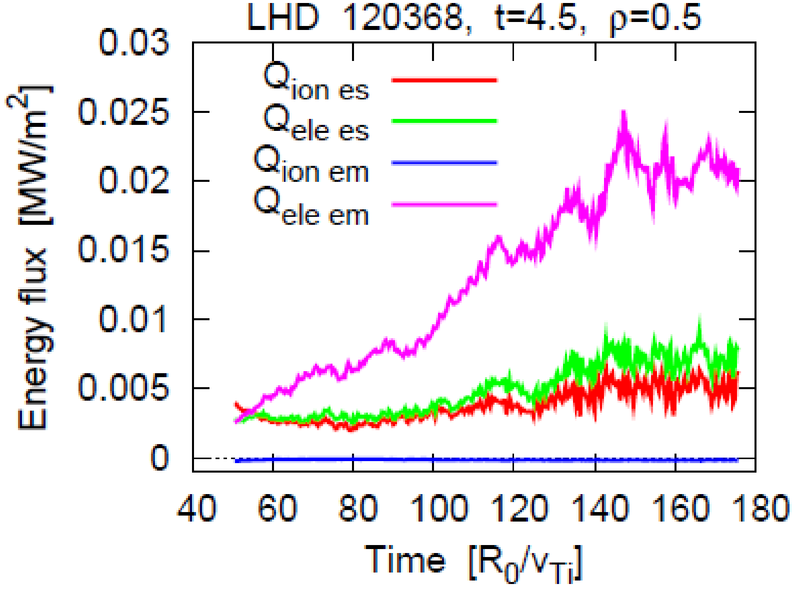
- Electron heat transport coefficient is larger than the ions because of magnetic perturbations.
- The coefficients evaluated from the simulation is smaller than those by the experiments.

Energy flux



- Energy fluxes are smaller than those of the experiments
- Electron energy flux is larger than ions because of the magnetic flatter.





Summary

- The first GK analysis of finite-beta LHD experiments
  - Suppression of ITG and destabilization of KBM with increasing beta (similar to the tokamak case)
- ① Kinetic ballooning turbulence (model)
  - Weak zonal flow and small efficiency in transport (similar to the tokamak case)
  - A new saturation mechanism: shearing between oppositely inclined modes. The mechanism
  - The new mechanism may also cause saturation of turbulence in finite-beta tokamaks in the presence of three-dimensionality such as toroidal ripples and resonant magnetic perturbation (RMP).
- ② Finite-beta ITG turbulence (120368)
  - Energy and particle fluxes are smaller than the experimental observations.
  - The ratio of electron to ion energy flux is in agreement with the experimental observations.