TH/6-2

Multi-machine analysis of turbulent transport in helical systems via gyrokinetic simulation

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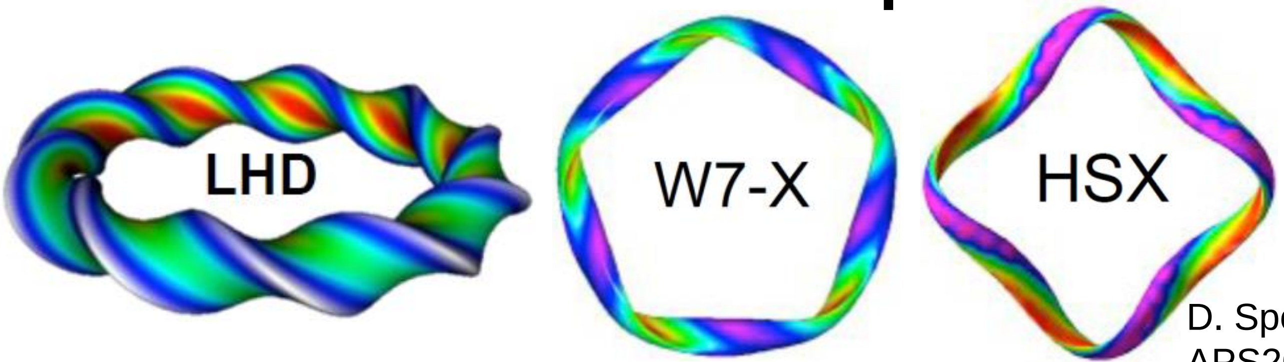
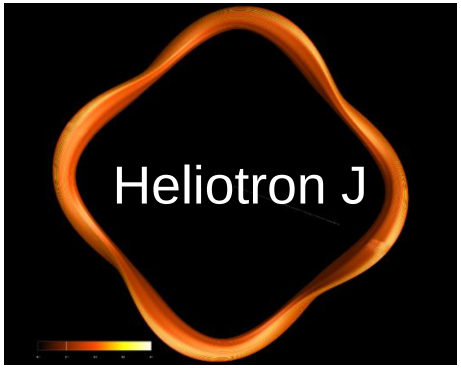
Outline

- Introduction
- Turbulent transport in Large Helical Device (LHD)
- Turbulent transport in Heliotron J (HJ)
- Comparison of helical systems
- Summary

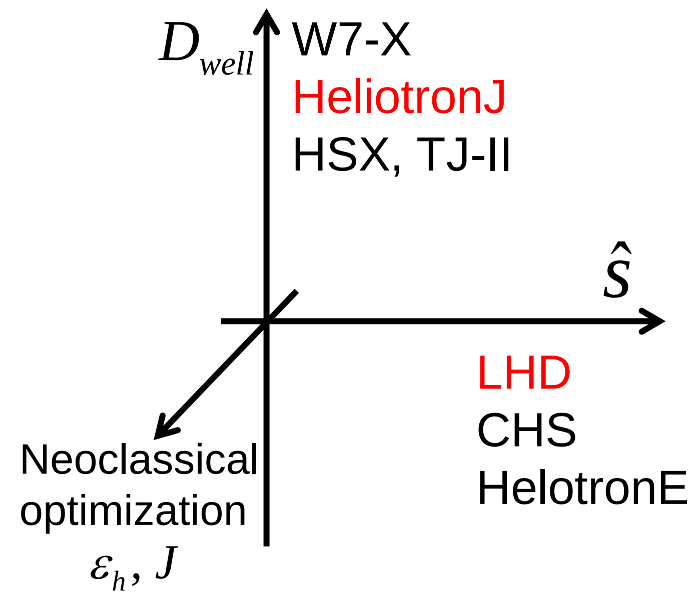
Helical plasmas



D. Spong, APS2014



- Helical plasmas are studied for optimization by improving MHD stability and neoclassical transport.
  - W7-X: optimized against neoclassical transport as well as MHD stability.
  - Heliotron J : optimized against MHD stability by producing the magnetic well.
  - LHD: better neoclassical transport for the inward-shifted configuration, while it has better MHD stability for the outward-shifted one.
- Two strategies for stability
  - Utilizing magnetic shear: LHD, CHS, Heliotron-E
  - Utilizing magnetic well (Mercier well index): W7-X, Heliotron-J, HSX, TJ-II
- Recently, optimization against turbulent transport becomes a hot topic.

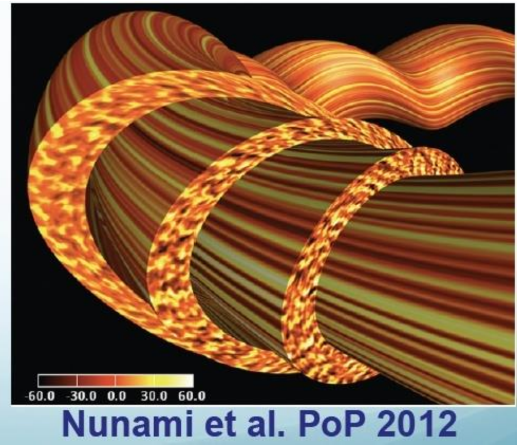


Parameters of LHD and Heliotron J plasmas

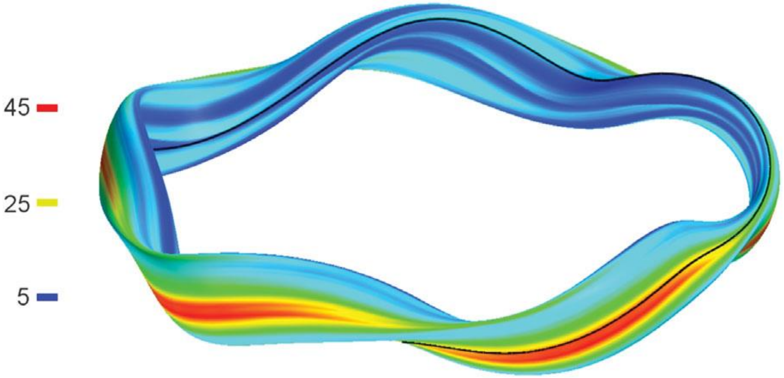
- The aspect ratio R/a, safety factor q, normalized Larmor radius, and temperature ratio Te/Ti, are similar. On the other hand, the normalized collision frequency and the density gradient length Ln are significantly different.
- The LHD is the inward-shifted configuration, and it is the magnetic hill with a moderate shear.
- The Heliotron J is the magnetic well with a very weak shear.

	LHD-L	HJ-ST
R_0/a	6.2	7.3
$\rho = r/a$	0.68	0.5
q	1.5	1.7
$\rho_* [10^{-3}]$	2.	4.5
ν_i^*	0.083	3.2
$\beta\,[\%]$	0.2	0.05
T_e/T_i	0.96	1.3
R_0/L_n	2.7	9.3
R_0/L_{Ti}	8.7	13.
R_0/L_{Te}	9.1	17.
$\hat{s}$	1.2	0.023
D_{well}	-0.01	0.74

Progress of gyro-kinetic analysis of turbulent transport in helical systems

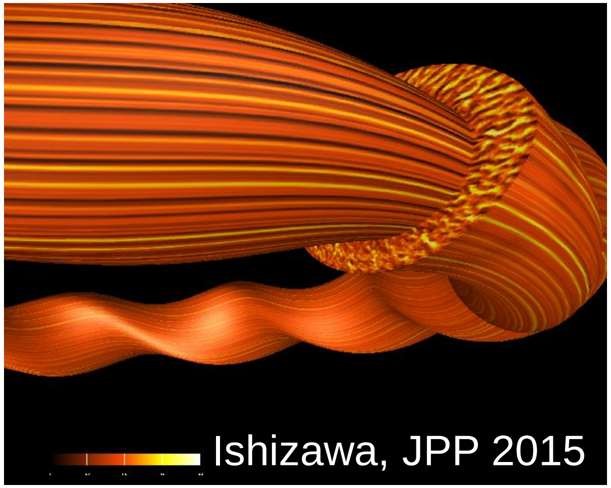


- Adiabatic electron simulations
  - LHD: T.-H. Watanabe Phys. Rev. Lett. (2008)
    M. Nunami, Phys. Plasmas (2012, 2013)
  - W7-X: P. Xanthopoulos, Phys. Rev. Lett. (2007)
    P. Xanthopoulos, Phys. Rev. Lett. (2014)
  - NCSX: H. Mynick, Phys. Rev. Lett. (2010)
    H. Mynick, Plasma Phys. Cont. Fusion (2014)



Xanthopoulos, PRL 2014

- Kinetic electron simulations
  - Enable us to evaluate particle and electron heat fluxes.
  - Trapped electron effects enhance the growth rate of ITG mode.
  - HSX: B. J. Faber, Phys. Plasmas (2015)
  - LHD: A. Ishizawa, Nuclear Fusion (2013, 2015)
    A. Ishizawa, Phys. Plasmas (2014)
    A. Ishizawa, J. Plasma Phys. (2015)

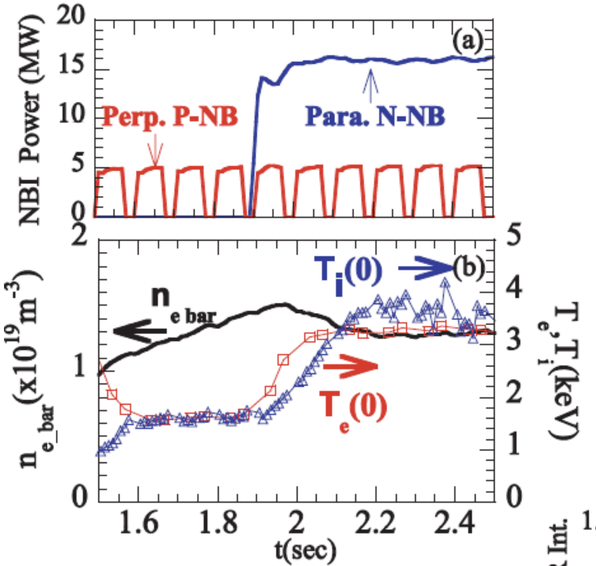


Ishizawa, JPP 2015

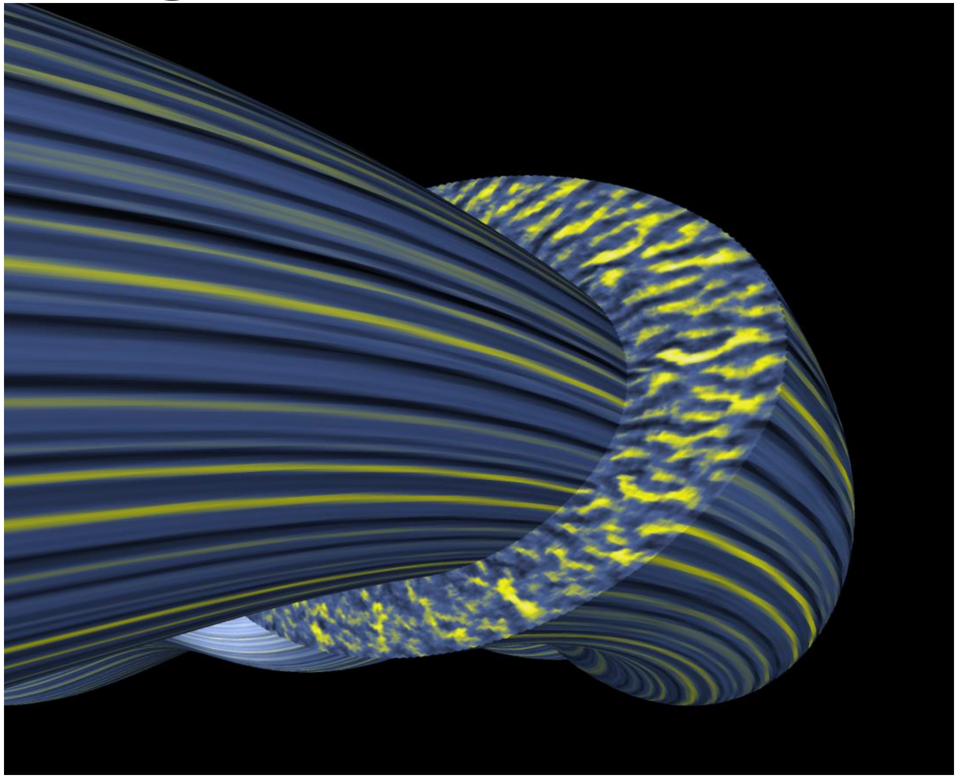
- This conference
  - TH/P2-3, M. Nunami
  - TH/P4-10 D. Spong
- We use GKV code (Local flux tube code).

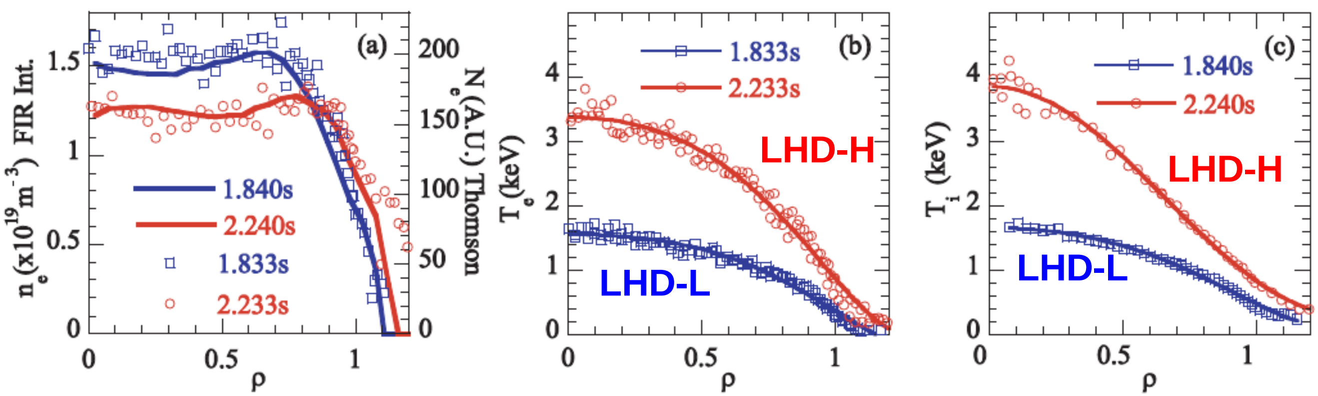
LHD discharge #88343

- B=2.75T, R=3.6m
- Low-Ti phase: Ti=1.6keV t=1.8s
- High-Ti phase: Ti=3.9keV t=2.2s
  - Beta(r/a=0.65)=0.3%
  - Collision: 1/v regime

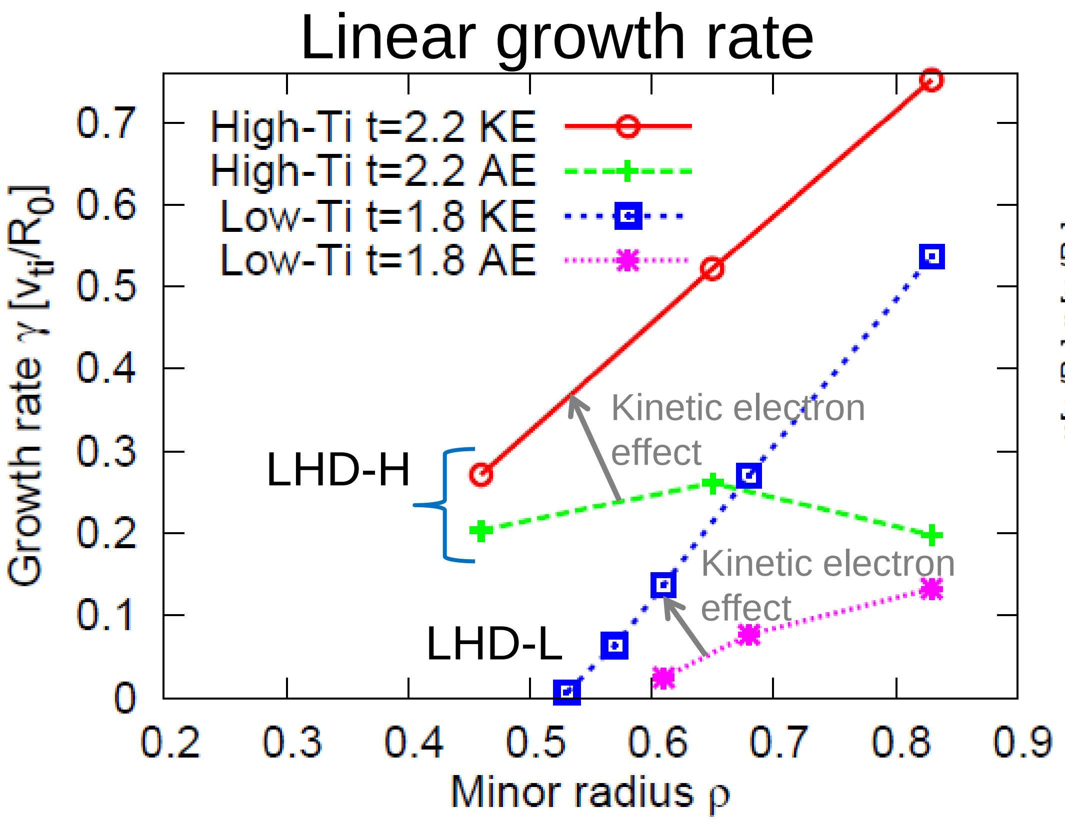


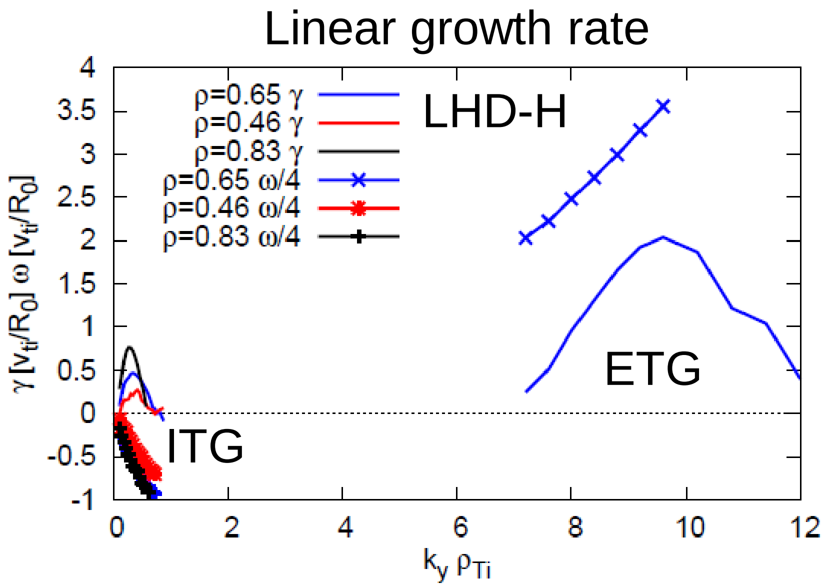
Tanaka, PFR 2010





Kinetic electron effects enhance ITG mode



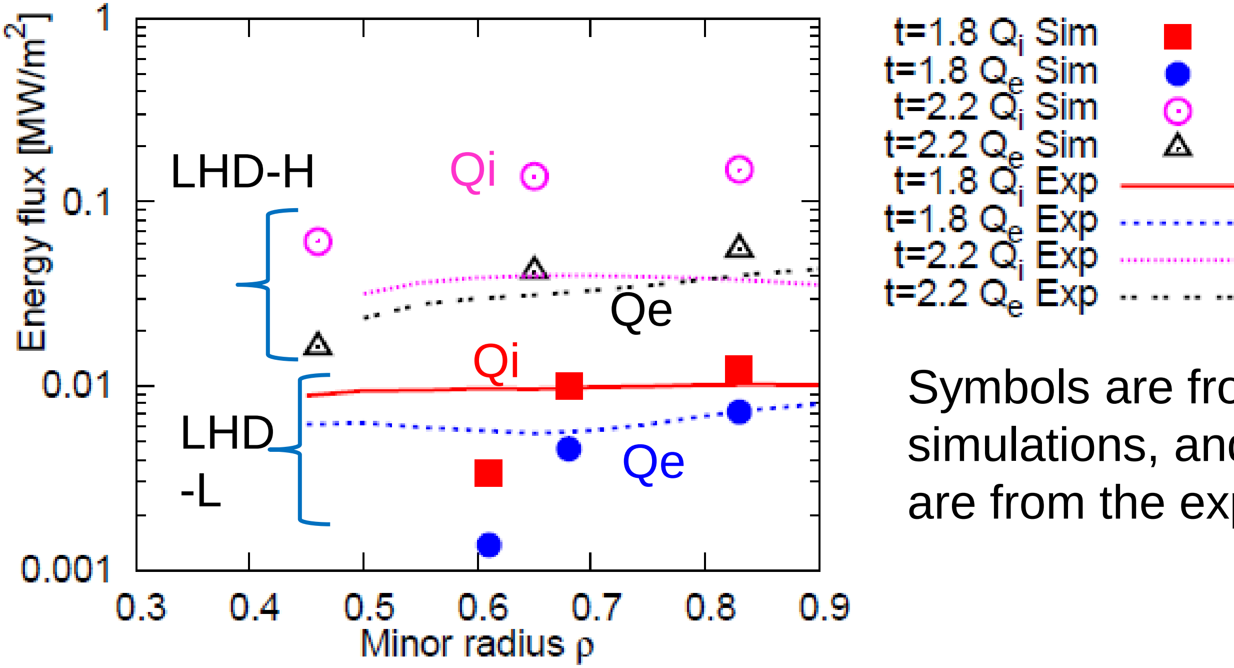


KE: Kinetic electron,
AE: Adiabatic electron

- Ion temperature gradient (ITG) modes are unstable.
- Kinetic electron (KE) effects enhance the ITG mode.
  - ETG modes are unstable at high wavenumber.

Importance of kinetic electrons in validation

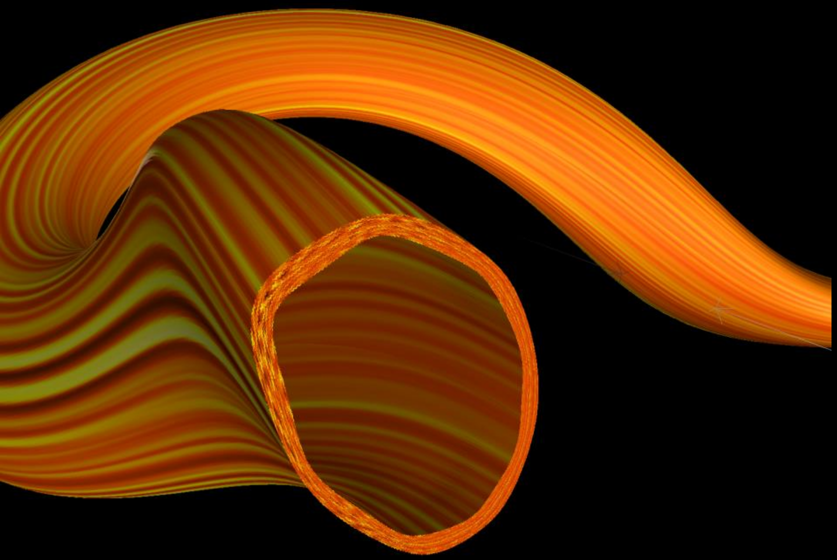
Ion and electron energy fluxes due to turbulence, Qi and Qe.

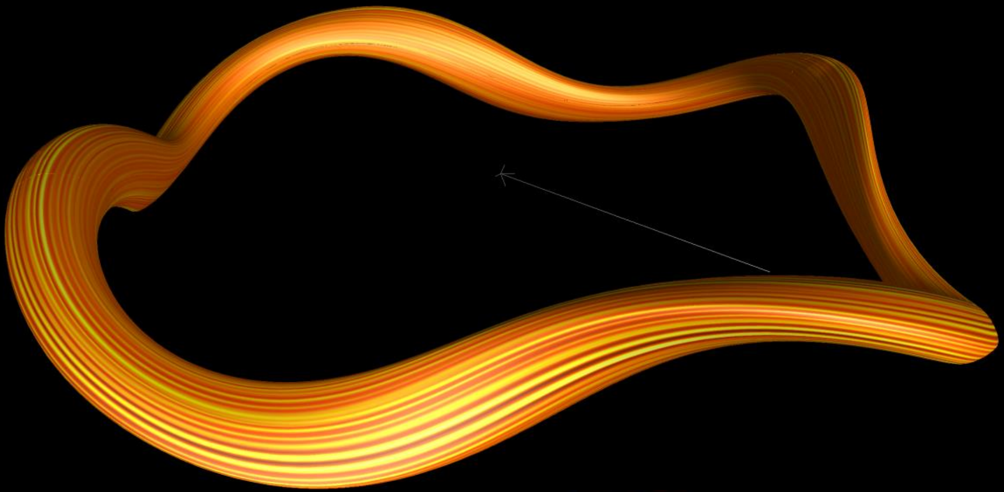


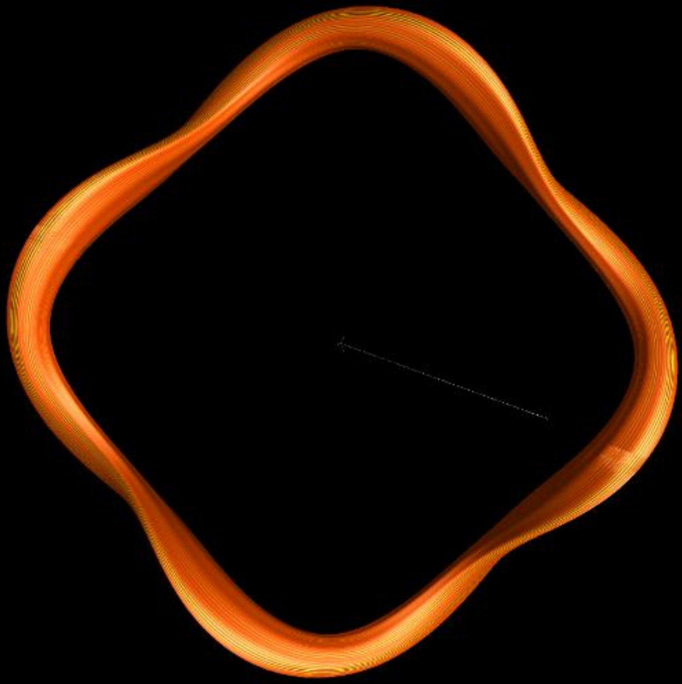
Symbols are from the simulations, and curves are from the experiments.

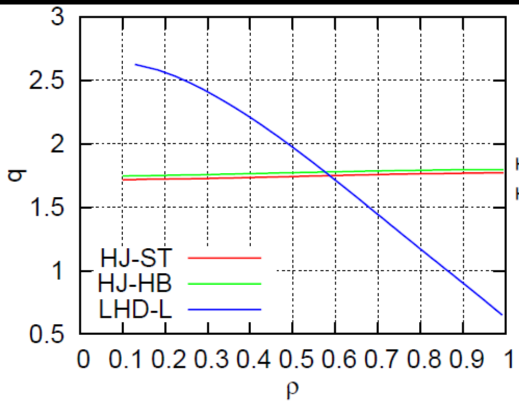
- The energy fluxes are in good agreement with experimental results at rho>0.7 in the low-Ti phase (LHD-L, Ti=1.6keV).
- The electron energy flux is in good agreement with experimental results in the high-Ti phase (LHD-H, Ti=3.9keV).
- Prediction of temperature gradient length by flux matching has 20% error.
- There is no short-fall problem, which suffers GK analysis of some tokamaks.

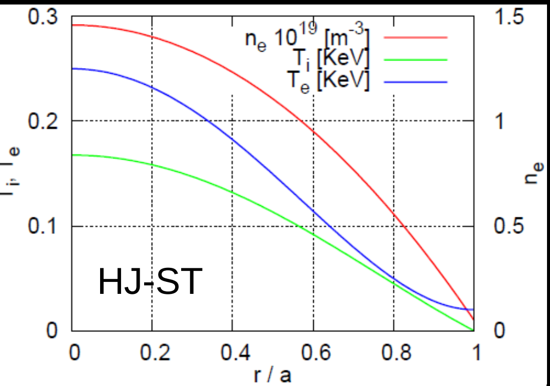
Turbulence in Heliotron J







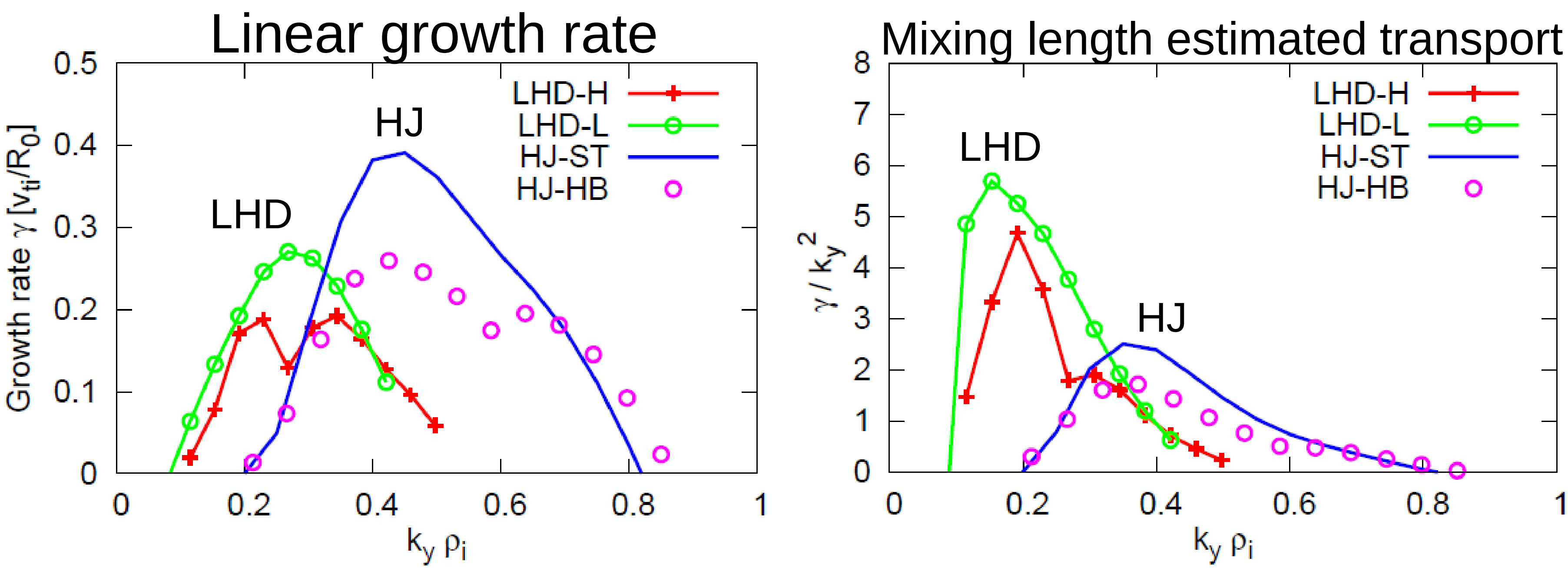




HJ-ST: standard configuration

HJ-HB: High-bumpiness (high-mirror ratio)

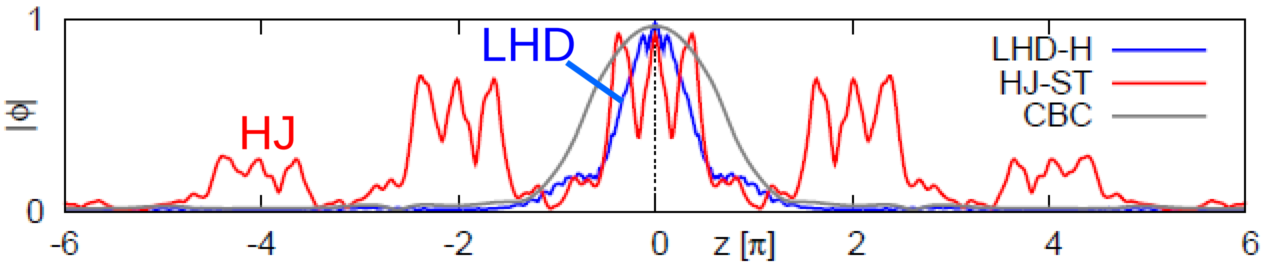
HJ plasmas are unstable against ITG mode

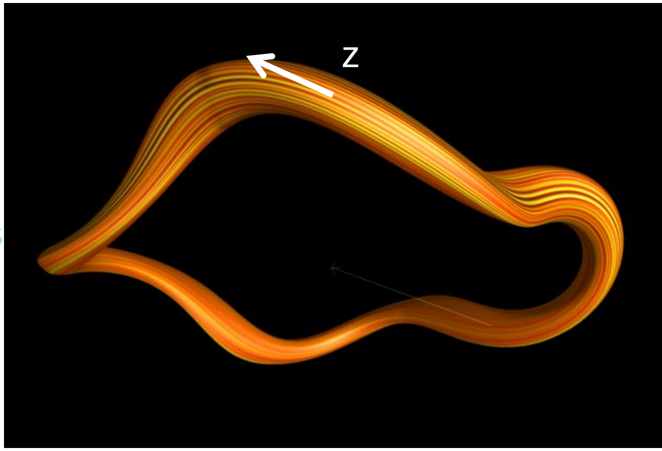


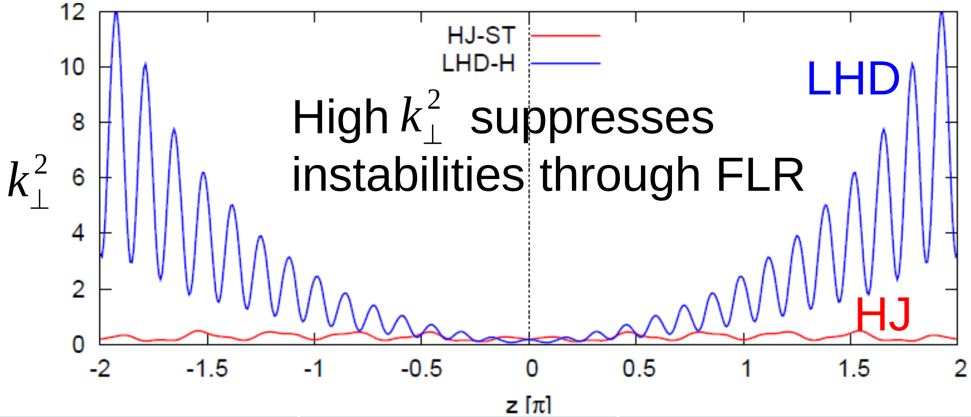
- HJ plasma is unstable at higher wavenumber regime than LHD.
- Mixing length estimation predicts lower transport in HJ than LHD.

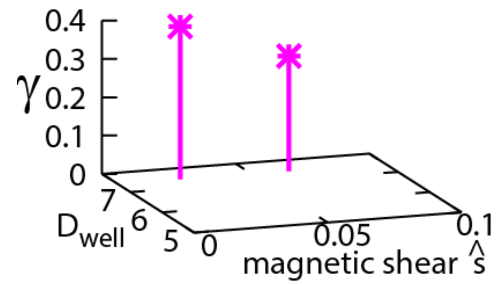
Elongated mode structure in HJ

- The mode structure is elongated along the field line in HJ.
- That is due to the weak shear and clearly seen in the profile of $k_\perp^2$
- The stabilizing effect of shear is confirmed by the reduction of growth rate by increasing the shear.









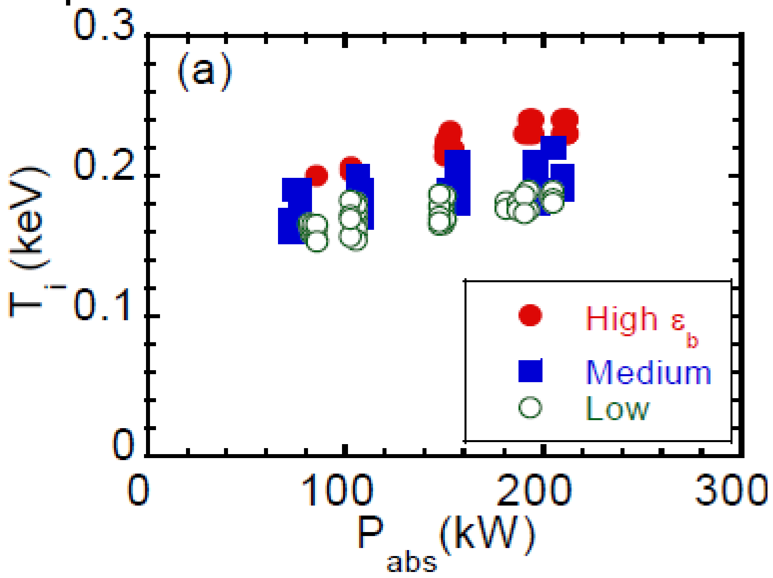
	HJ standard	HJ with shear	LHD
Magnetic shear $\hat{s}$	0.023	0.064	1.2
Growth rate γ	0.4	0.3	0.26
$\gamma / k_\perp^2$	2.5 [GB]		5.7 [GB]

High mirror-ratio reduces turbulent transport

Heliotron J	Standard (HJ-ST)	High mirror-ratio (HJ-HB)
Growth rate γ	0.40	0.26
Heat transport χi, χe	5.9, 2.4 [GB]	4.2, 1.7 [GB]
$\gamma / k_\perp^2$	2.5 [GB]	1.7 [GB]

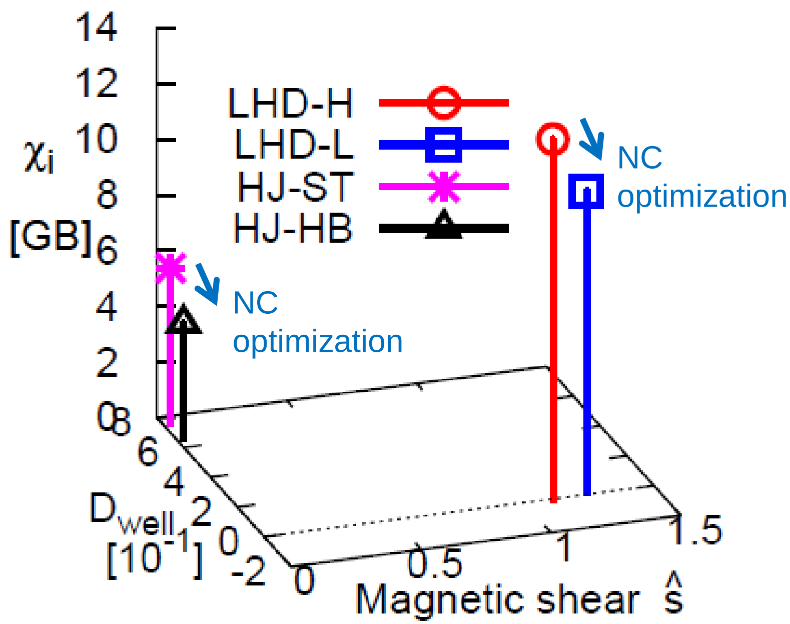
- High mirror-ratio (HJ-HB) reduces ITG mode, and thus suppresses turbulent transport.
- Qualitatively consistent with the experimental observation.

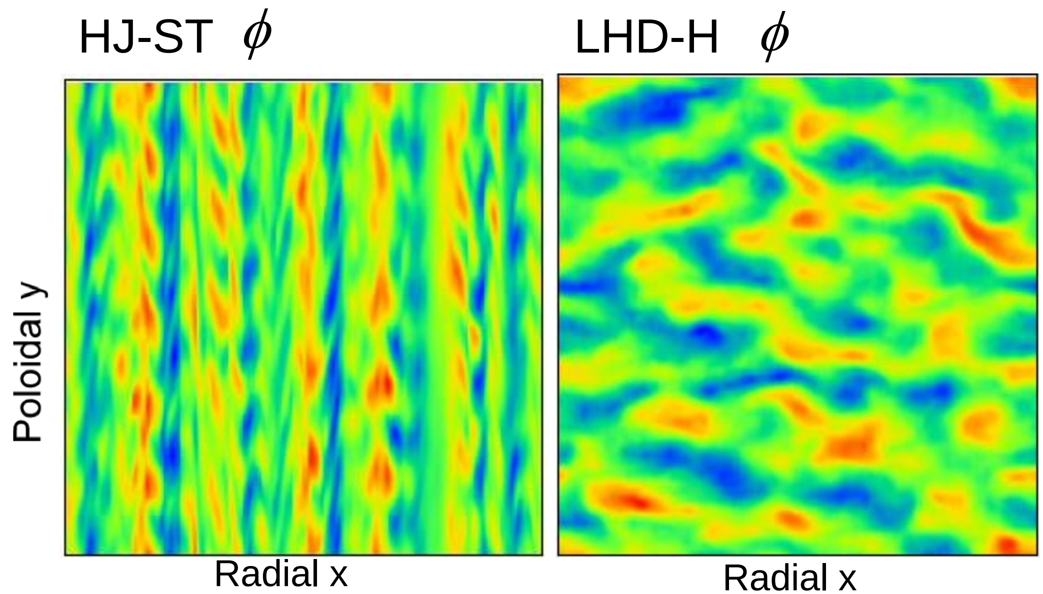
Experimental observation in Heliotron J



S. Kobayashi, IAEA-FEC 2008

Turbulent transport and zonal flows

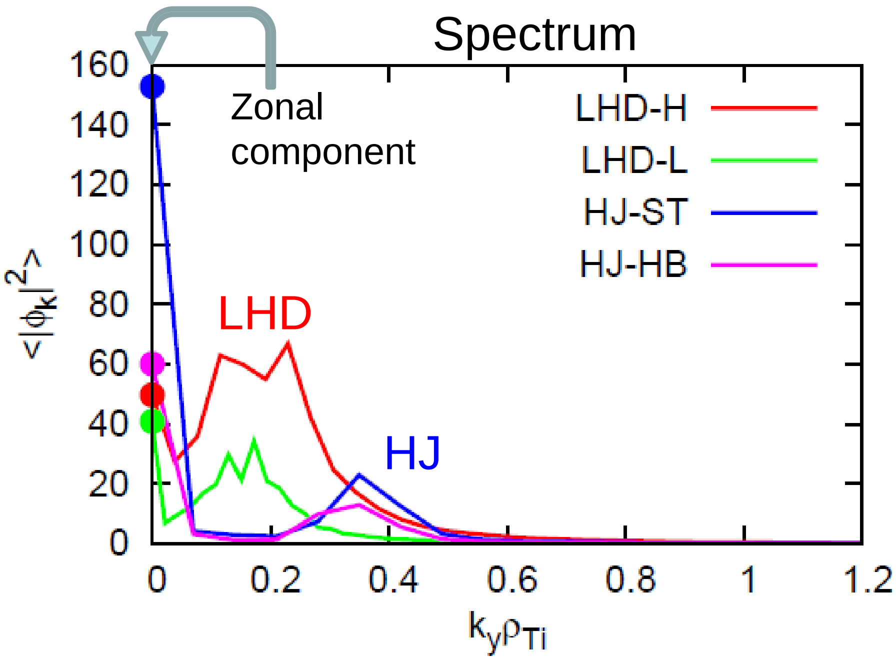


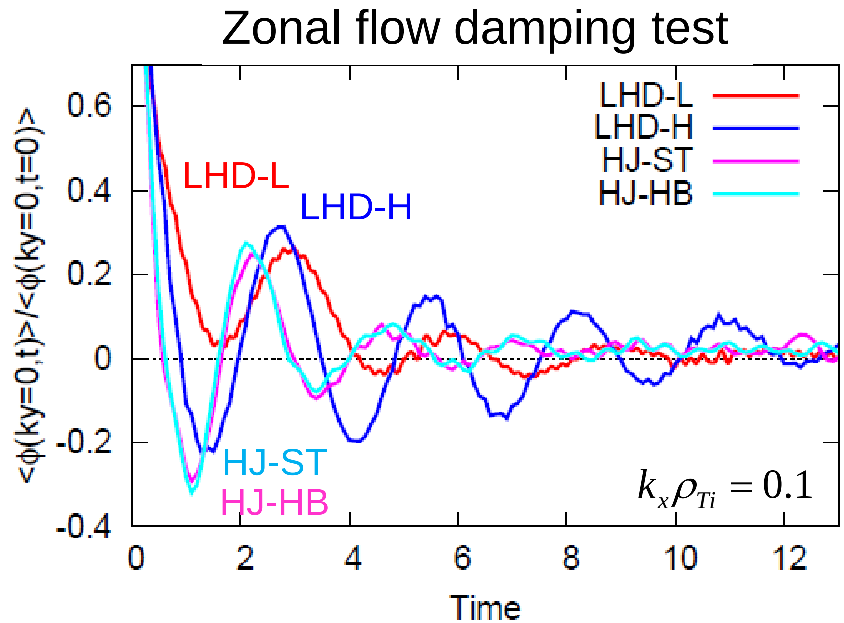


- The neoclassical optimization (high-bumpiness) improves turbulent transport in Heliotron J.
- Weak magnetic shear of Heliotron J does not lead to high turbulent transport.
- Zonal flow in HJ is stronger than LHD.

	LHD-L	HJ-ST
Instability	ITG	ITG
$\gamma\ [v_{Ti}/R_0]$	0.27	0.4
$R_0/L_T - R_0/L_{T\mathrm{crit}}$	2.6	5.2
$\chi_i\ [v_{Ti}\rho_{Ti}^2/R_0]$	11.	5.9
$\chi_e\ [v_{Ti}\rho_{Ti}^2/R_0]$	4.8	2.4

Strong zonal flow in Heliotron J





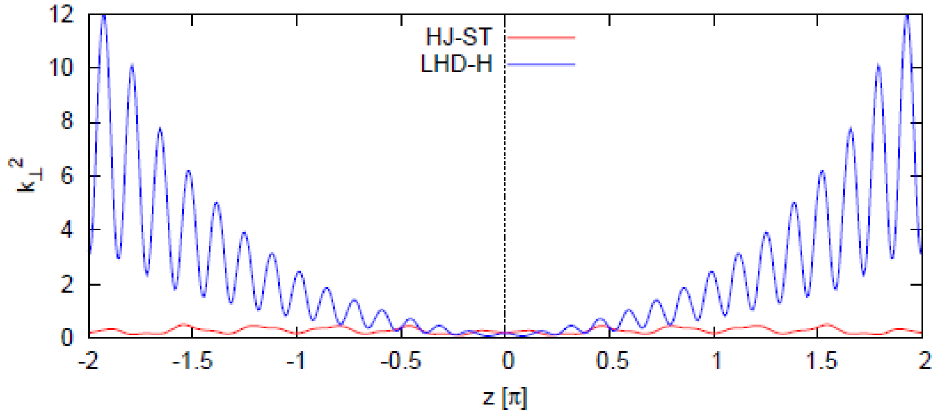
- LHD
  - $\chi_{i,e}$ in LHD-L is smaller than LHD-H, while $\gamma / k_\perp^2$ in LHD-L is larger than LHD-H. This is explained by more inward shifted axis and larger τ_{ZF} in LHD-L.
- Heliotron J
  - $\chi_{i,e}$ in HJ-HB is smaller than HJ-ST, which is explained by smaller $\gamma / k_\perp^2$ in HJ-HB.
- Zonal flow relaxation time and the residual level do not explain the strong zonal flow in HJ.
- The strong zonal flow is expected to be produced by nonlinear interaction.

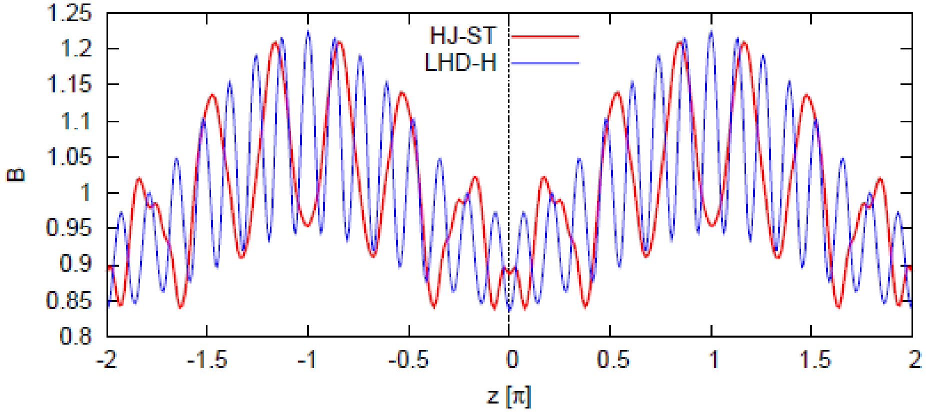
Summary

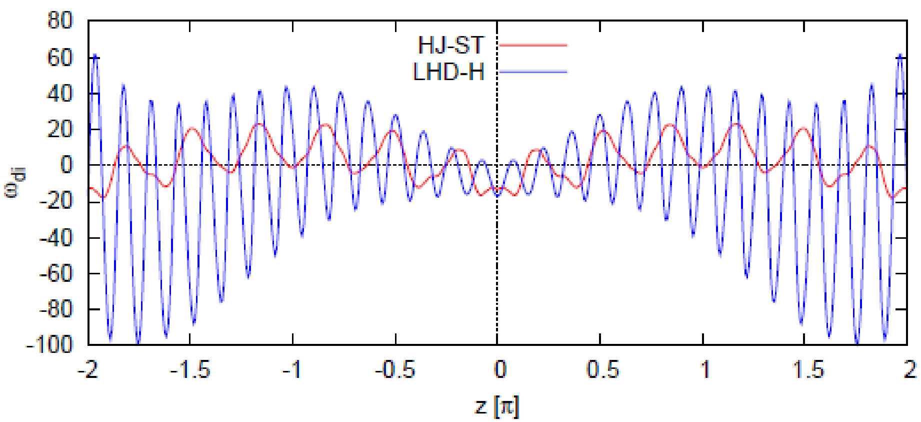
- We have investigated turbulent transport in helical systems, LHD and Heliotron J, by gyrokinetic simulations.
- LHD (Validation)
  - Including kinetic electrons is crucial for the validation.
  - There is no short-fall problem near the edge.
  - The inward-shifted magnetic axis of LHD-L leads to smaller turbulent transport than LHD-H in GB unit because of longer zonal flow relaxation time.
- Heliotron J
  - High mirror ratio (neoclassical optimization) reduces turbulent heat transport.
- In this comparison of those typical cases, turbulent transport in HJ is lower than that of LHD in GB unit. Lower mixing-length estimated transport and higher amplitude of zonal flows can be the mechanism.
- Strong zonal flow in HJ can be produced by elongated mode structure of ITG due to weak shear.

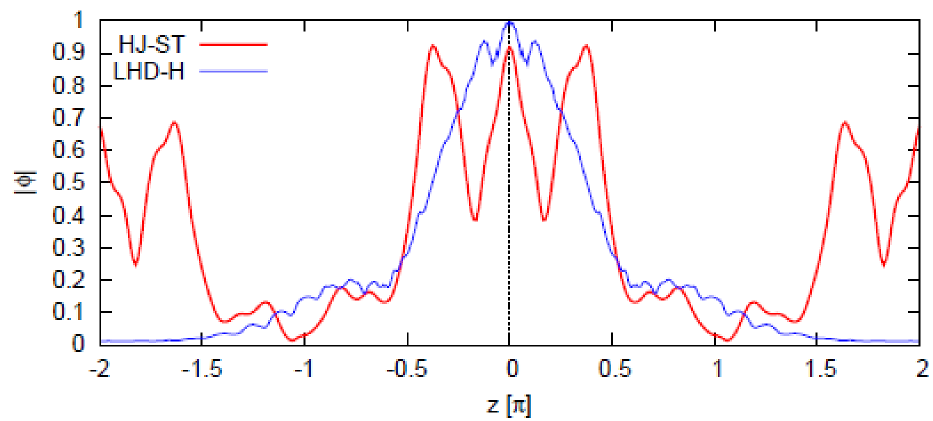
Additional slides

Profiles along the field line

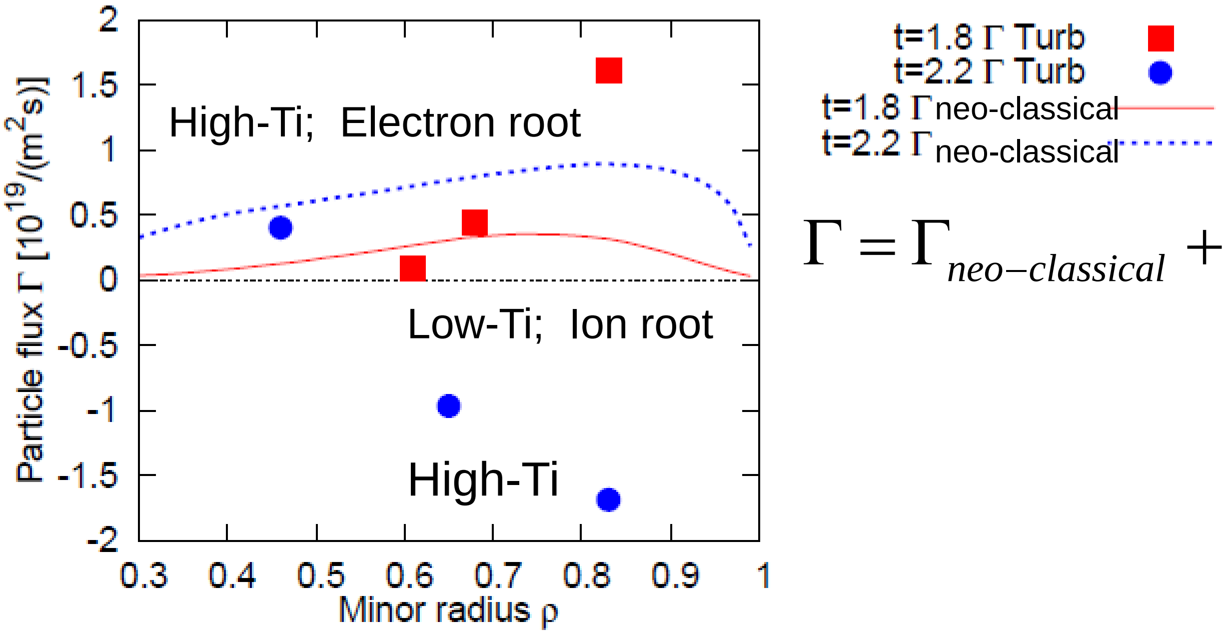








Turbulent particle flux



$$\Gamma = \Gamma_{neo-classical} + \Gamma_{turbulence}$$