Overview of Experimental results from Stellarator

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531. WE-Heraeus-Seminar on
3D versus 2D in Hot Plasmas

Physikzentrum Bad Honnef
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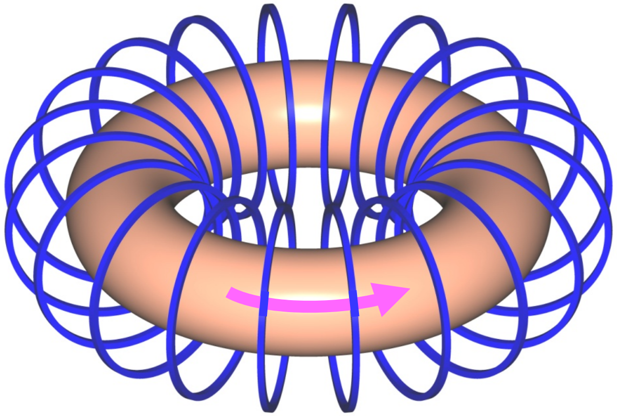
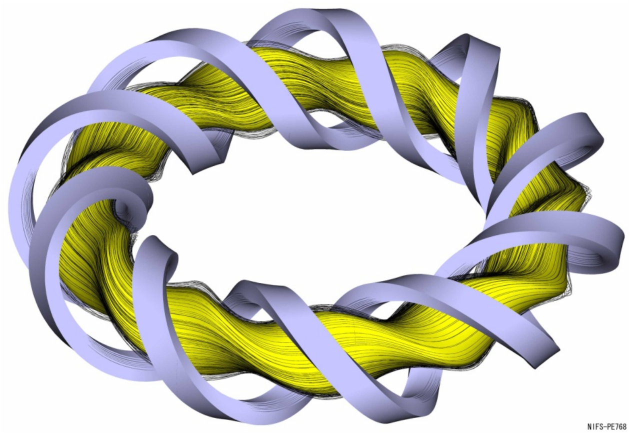
April 30, 2013

OUTLINE

There are two 3 D effects (symmetry and topology)

Symmetry? with/without Toroidal symmetry



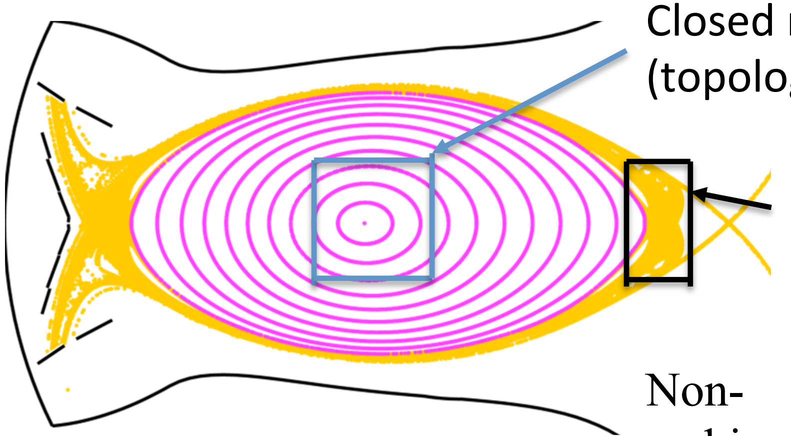


Lack of symmetry

Magnetic field ripple

Toroidal (parallel) viscosity

Topology ? 2D Magnetic flux surface or 3D magnetic field such as magnetic island or stochastization

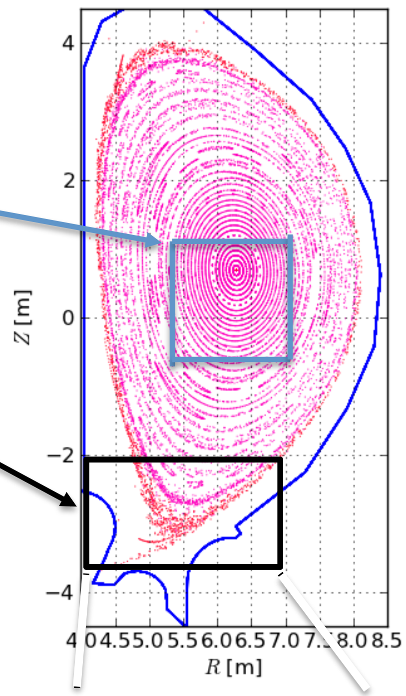


Closed magnetic flux surface (topologically 2 dimensional

open magnetic flux surface

Non-ambipolar loss

Parallel transport



3D effect in toroidal plasma

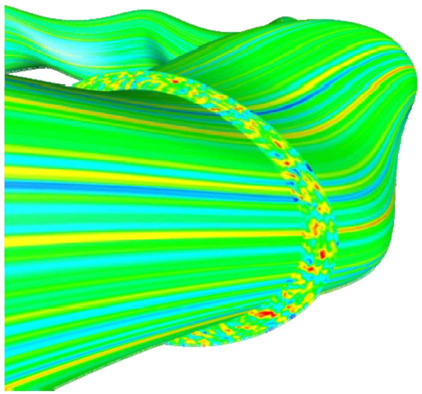
3-D effects in helical system and tokamak (with RMP)

Transport

Viscosity

Mean flow — Neoclassical transport

Zonal flow — Turbulent transport



Interaction

3-D equilibrium and transport are determined self-consistently

Topology

Magnetic island — Mode locking

Stochastic mag. field — ELM control

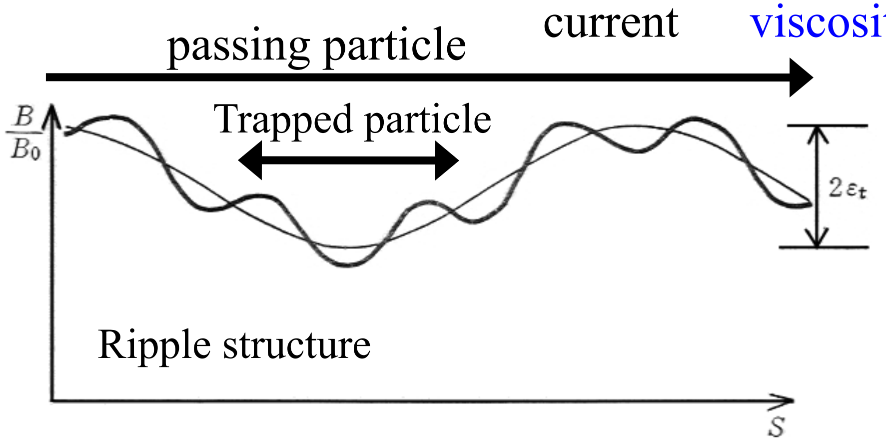
MHD stability

Resonance

3D effect on parallel and perpendicular viscosity

$$P_\phi(r) = \frac{1}{r}\int_0^r r'\left(T_{col}(r') + T_{jxB}(r') + T_{vis}(r') - T_{no}(r')\right)dr' = n_i(r)m_i\left\langle \tilde{V}_r(r)\tilde{V}_\phi(r)\right\rangle$$

collision | radial current | Parallel viscosity | neutral | Reynolds stress



Friction between the passing particles and trapped particles

Poloidal flow in tokamak plasma
both poloidal and toroidal flow in helical plasma

Diffusive term | Non- Diffusive term

$$\left\langle \tilde{V}_r\tilde{V}_\phi \right\rangle = -\mu_\perp \nabla V_\phi + V_{pinch}V_\phi + \Gamma_\phi^{RS}$$

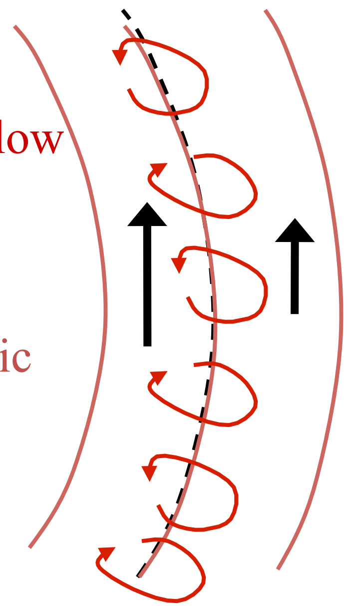
Perpendicular viscosity | Pinch term | Residual stress term

Residual stress : part of Reynolds stress
not proportional to ∇V_ϕ, V_ϕ

$\mu_\perp$

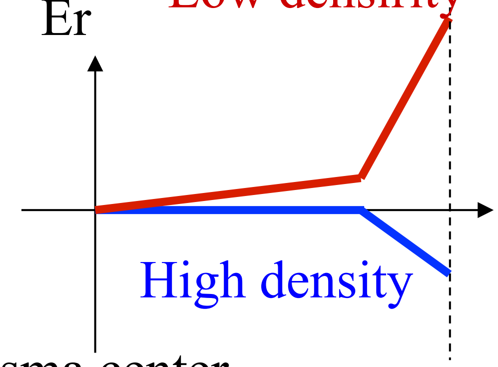
Plasma vortex flow (Turbulence)

Plasma magnetic flux surface

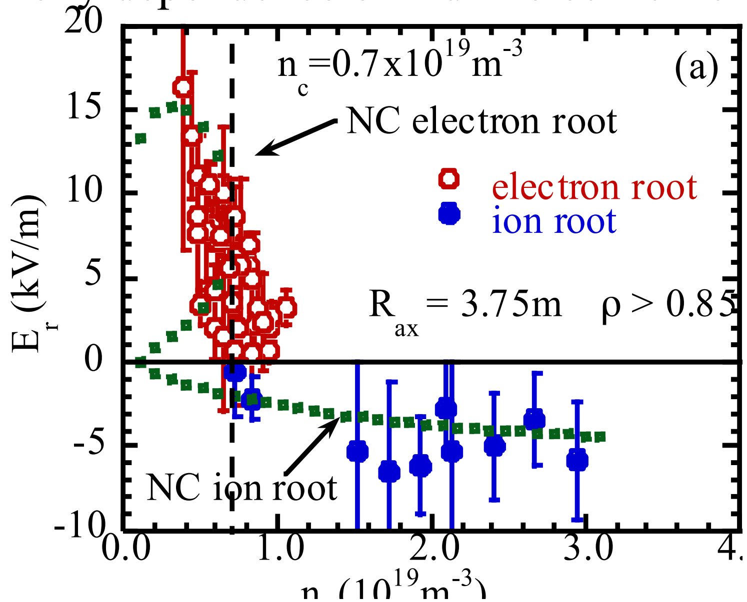


Ripple loss produce non-ambipolar flux and Er

Bifurcation of radial electric field (Er)



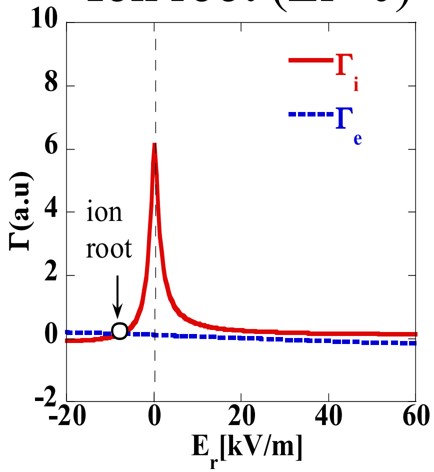
Density dependence of radial electric field



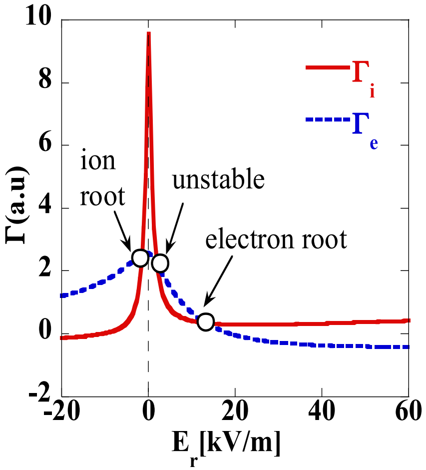
Er is determined by the ambipolar condition Γi = Γe

K.Ida et al., Phys. Rev. Lett. 86 5297(2001).

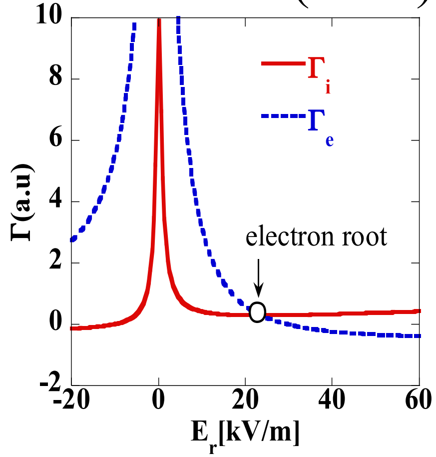
Ion root (Er<0)



Er transition



electron root (Er>0)

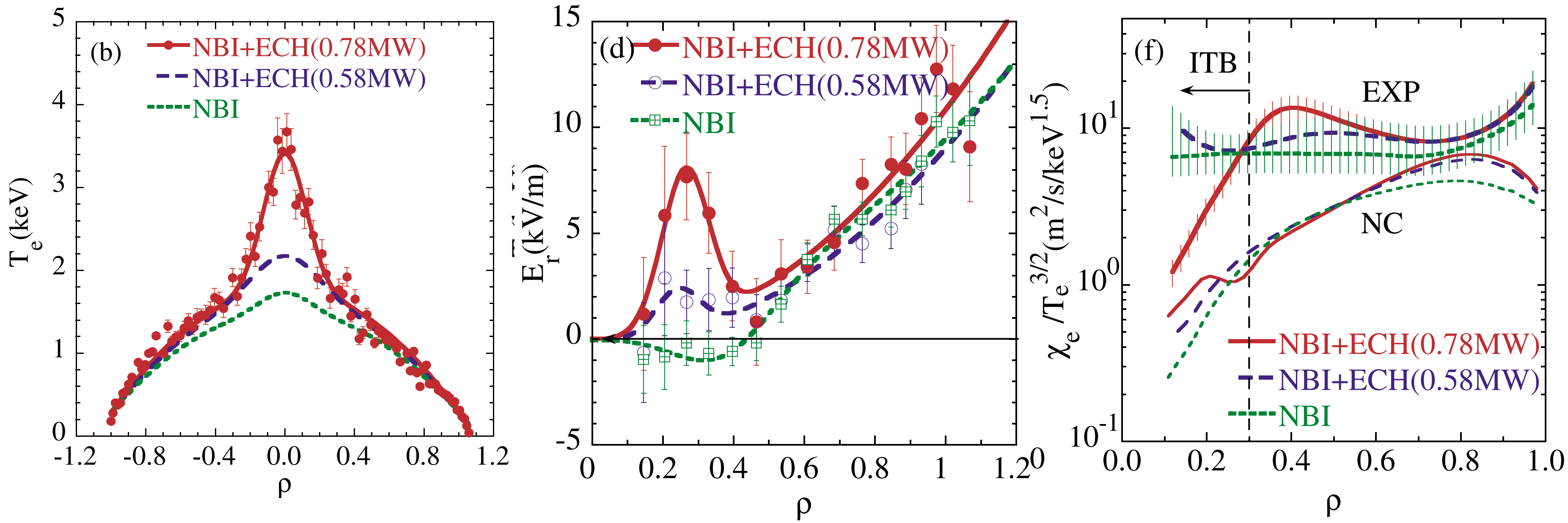


suppression of ripple loss by Er in the plasma with e-ITB

Peaked Te profile in the plasma e-ITB

Large radial electric field (Er) is produced

NC transport is suppressed much below the turbulence transport



K.Ida et al., Phys. Rev. Lett. 91 (2003) 085003.

3D effect of ripple loss on heat transport (enhancement of thermal diffusivity) was not observed because of the self-organized radial electric field in the 3D configuration.

3D effect on heat transport → negligible

3D effect on particle transport → Er and screening → important on impurity transport

3D effect on momentum transport → enhance parallel viscosity → mean and zonal flow

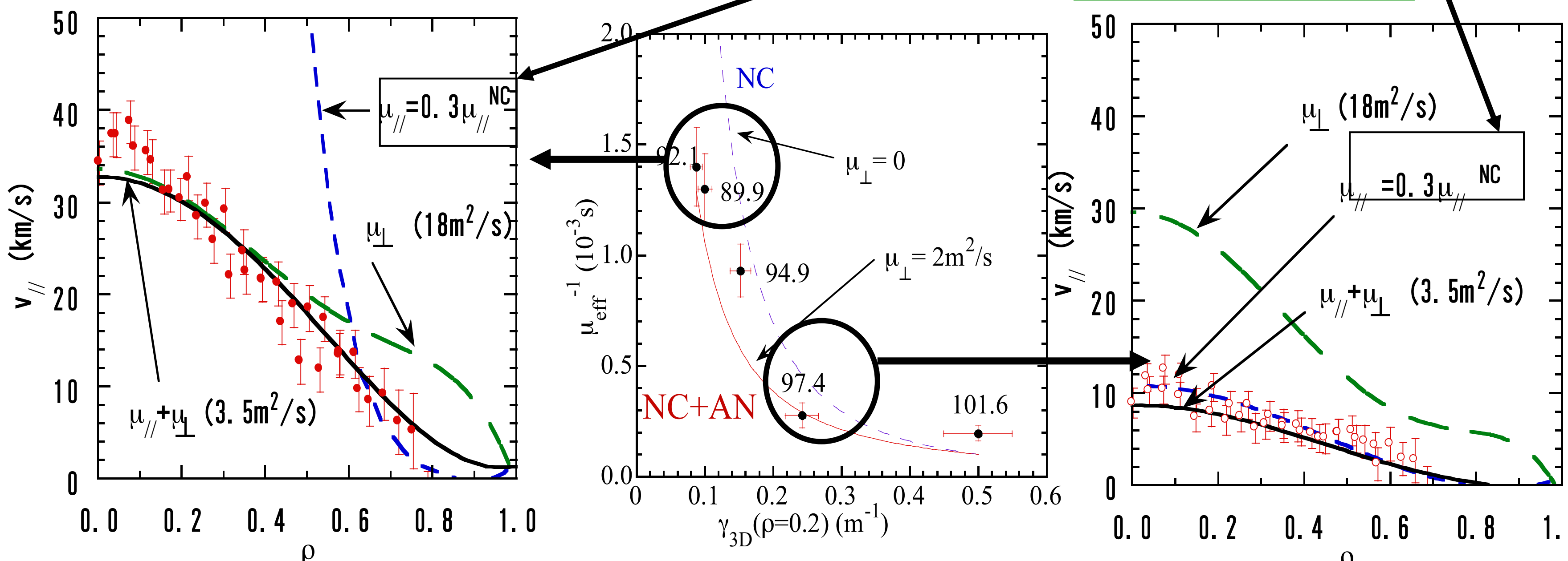
Toroidal flow damping due to parallel visocisty

$$\Gamma_M = m_i n_i[- \mu_\perp^D \, dv_\phi/dr + \mu^N (v_{th}/T_i)(eE_r) - \mu_{||} v_\phi]$$

Anomalous perpendicular viscosity

Non-diffusive term

Neoclassical parallel viscosity



Small ripple configuration

→ $V_{mes} << V_{cal(NC)}$

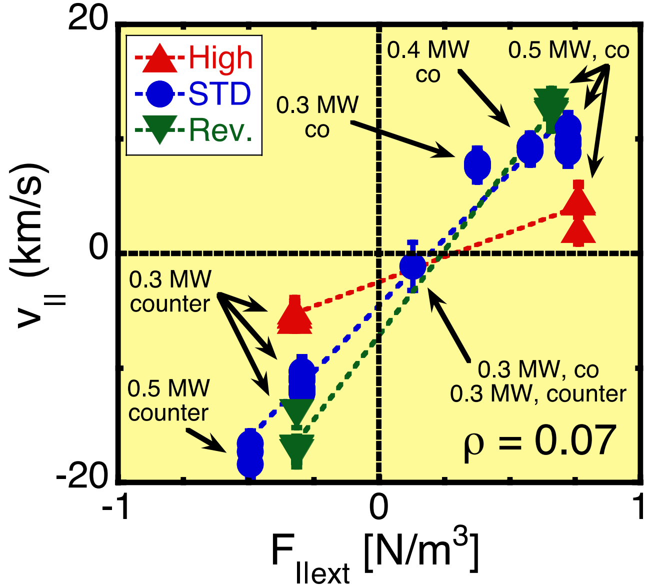
Large ripple configuration

→ $V_{mes} \sim V_{cal(NC)}$

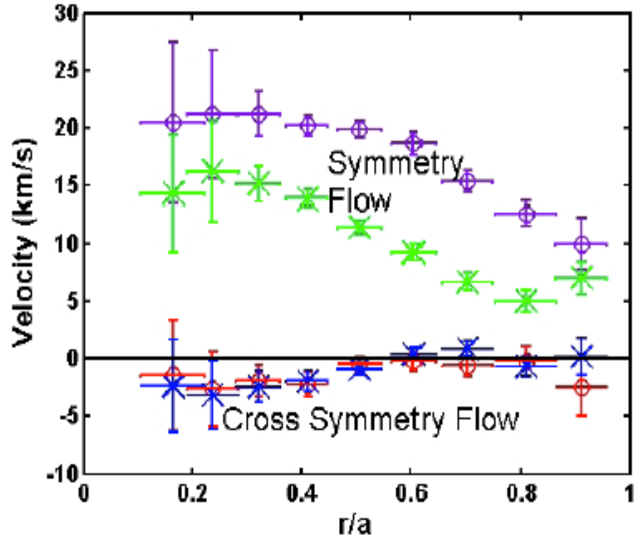
In the configuration of small ripple the anomalous perpendicular viscosity is dominant in the plasma core ($\rho < 0.6$) even in helical plasmas

K.Ida et al., Phys. Rev. Lett. 67 (1991) 58

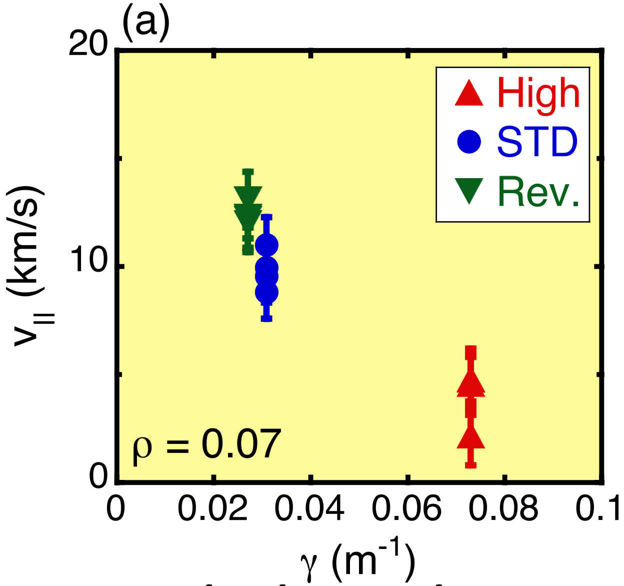
Coupling between toroidal and poloidal flow



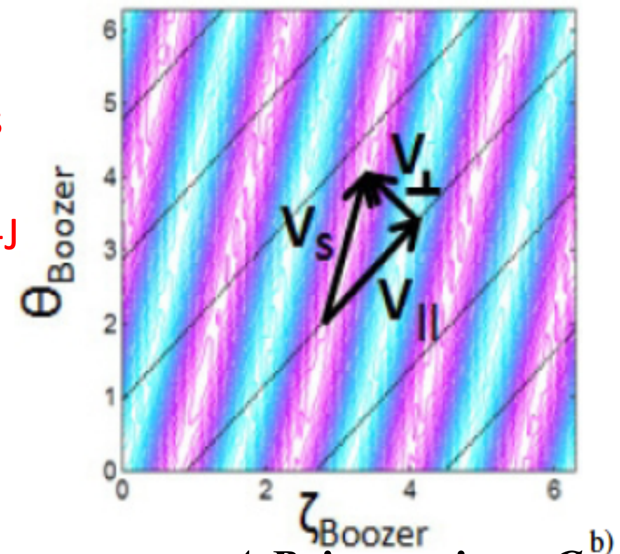
H-J



HSX



Similar results have been reported in H-J

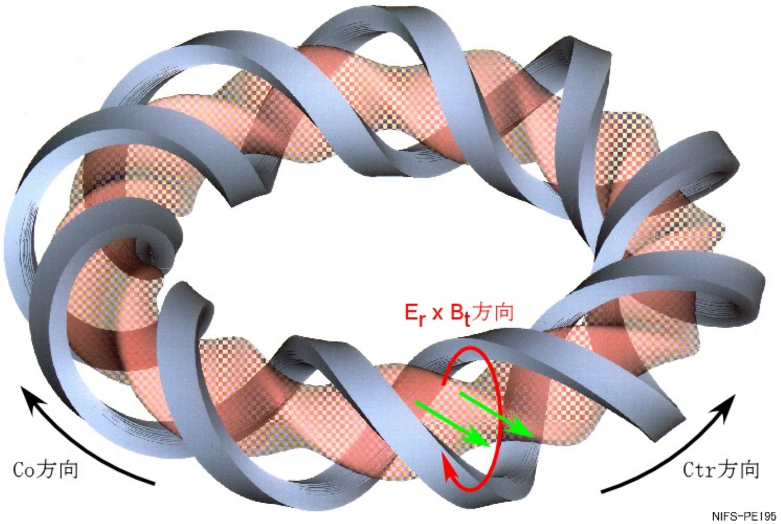


Plasma flow tends to be parallel to the minimum viscosity (symmetry) direction

H.Lee, et. al., Plasma Phys Control Fusion 55 (2013) 035012

A.Briesemeister Contrib. Plasma Phys. 50 (2010) 741

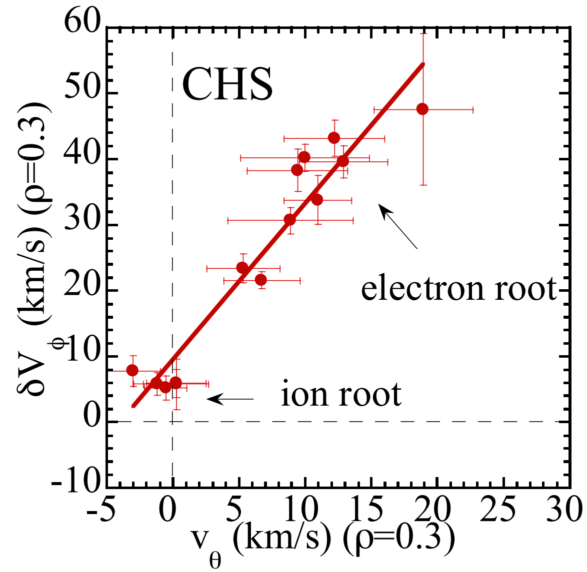
Relation between poloidal and toroidal flow

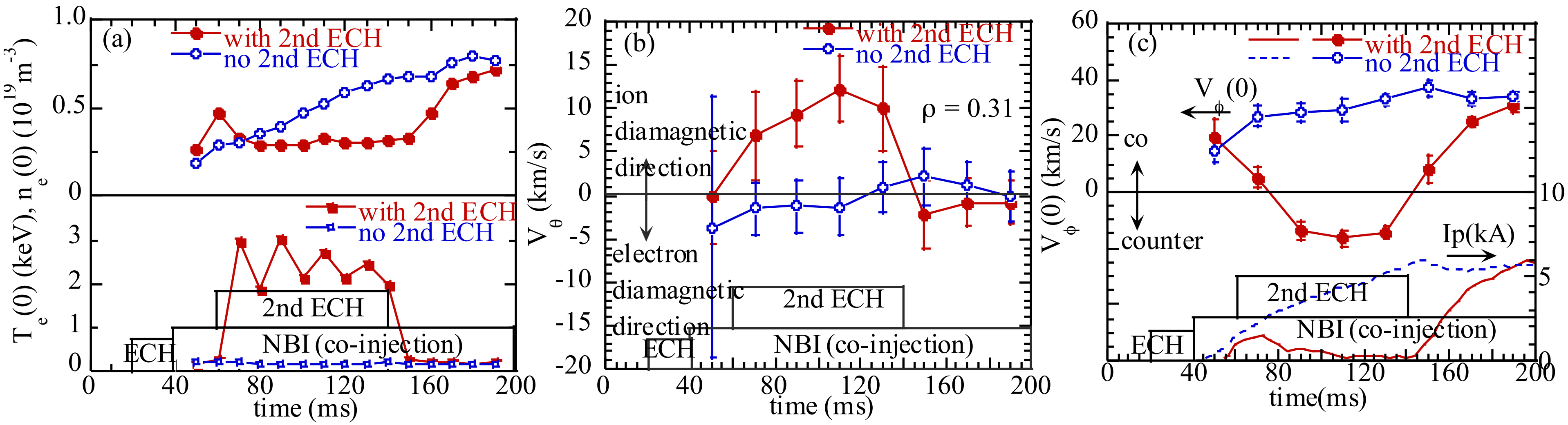


Both of poloilda and toroidal rotation are driven by ECRH

↓

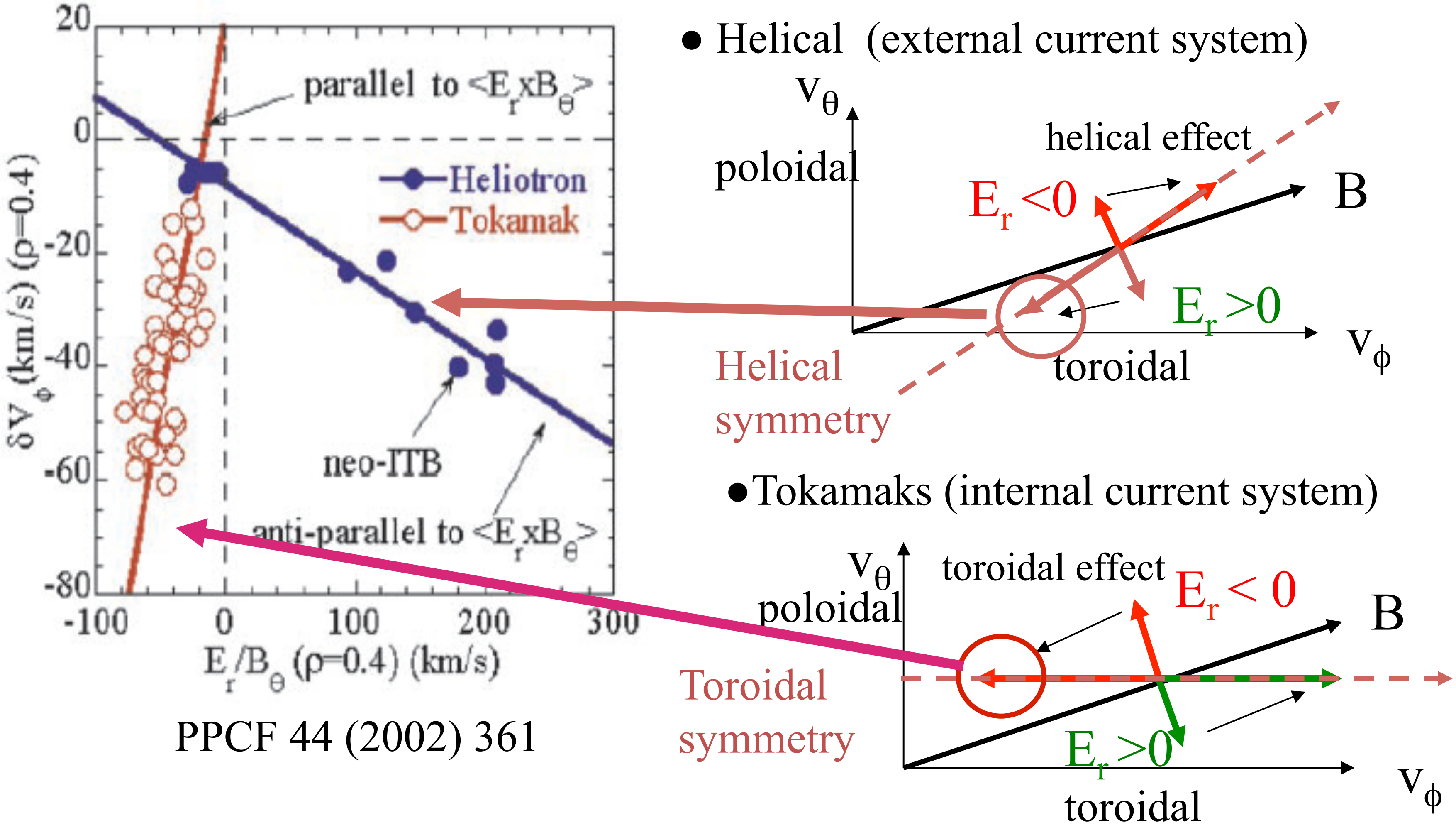
The relation between poloidal and toroidal flow are clarified





K.Ida et al., Phys. Rev. Lett. 86 (2001) 3040

Difference between tokamak and helical system



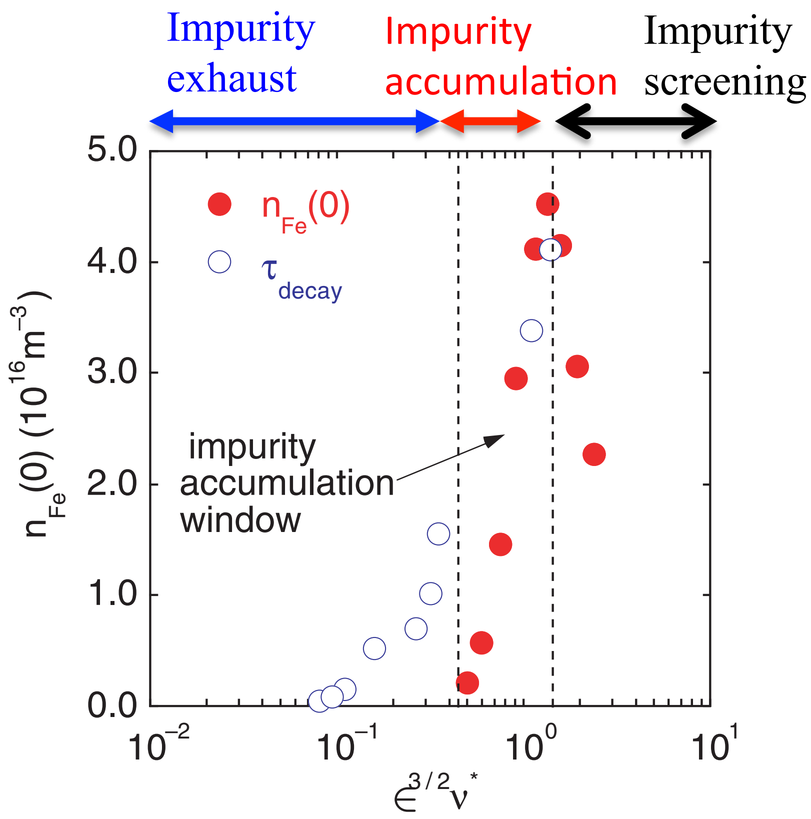
PPCF 44 (2002) 361

Tokamak : negative E_r → counter spontaneous flow $V=1.3E_r/B_\theta$

Helical : positive Er → counter spontaneous flow $V=0.16E_r/B_\theta$

K.Ida, et. al., Plasma Phys Control Fusion 44 (2002) 361

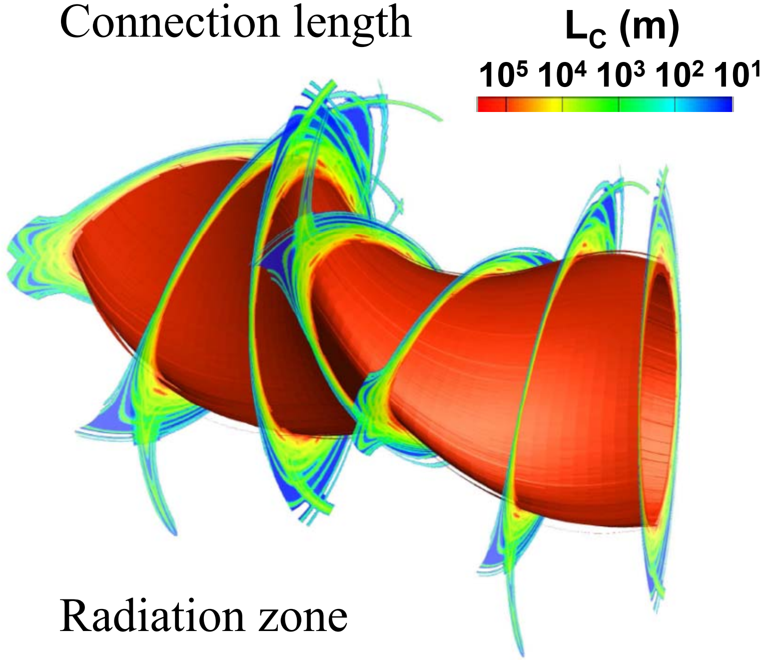
3D effect on impurity



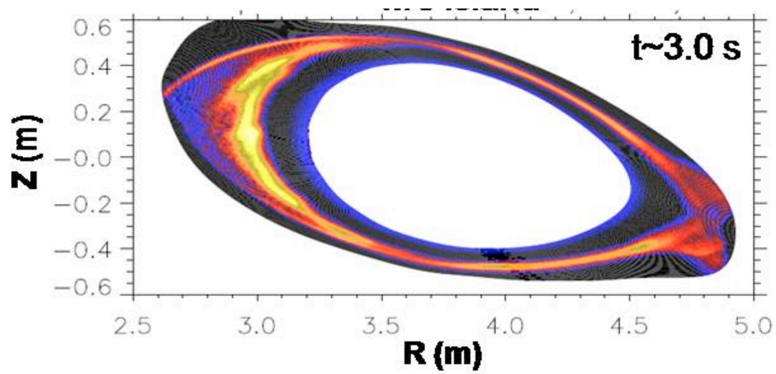
Low collisionality → positive Er
High collisionality → impurity screening

Y.Nakamura et. Al., Nucl. Fusion 43 (2003) 219

Connection length



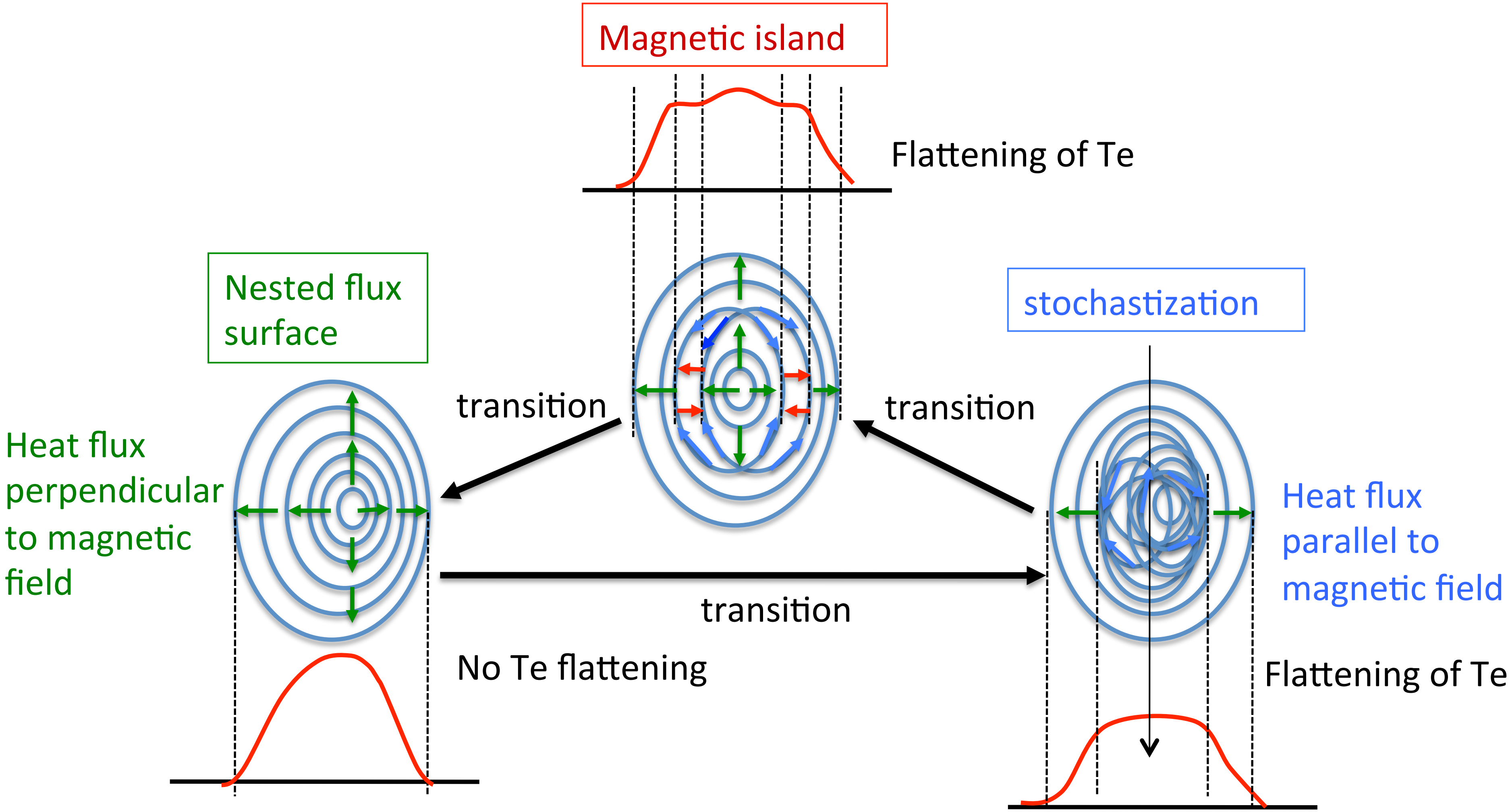
Radiation zone



Radiation zone is localized in the open field region because of impurity screening

M.Kobayashi, et. Al., Phys. Plasmas ***17****, (2010) 056111*

Topology bifurcation



1 Heat pulse propagation

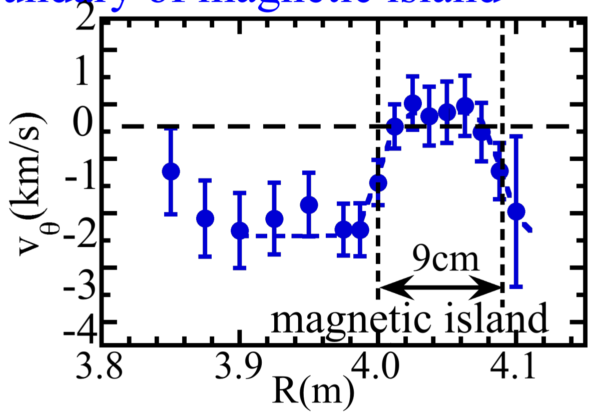
Because the heat flux parallel to magnetic field is much larger than Heat flux perpendicular to magnetic field.

2. Plasma flow and radial electric field

Because plasma flow and radial electric field is sensitive to magnetic topology.

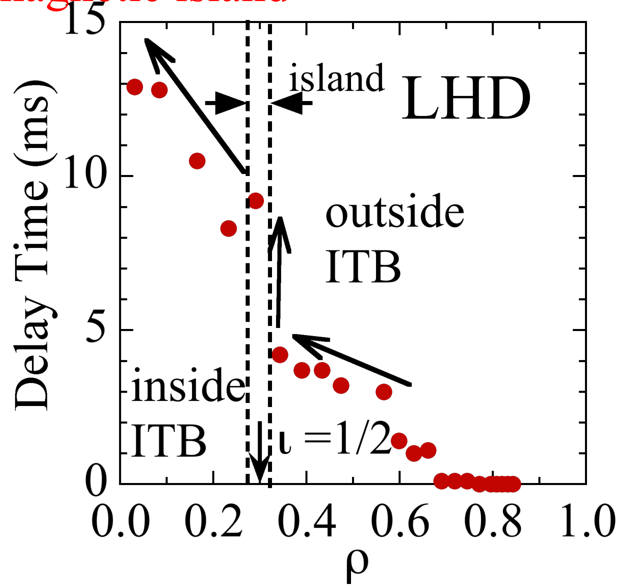
Transport near the magnetic island

Large Er shear is observed at the boundary of magnetic island



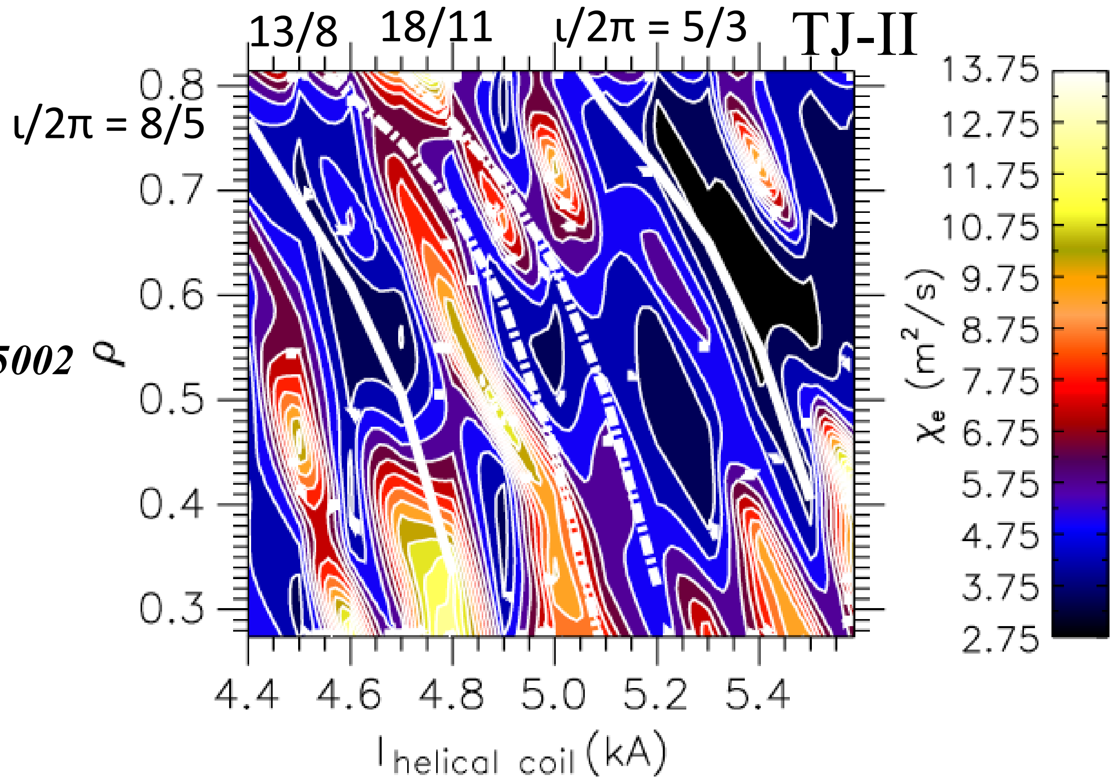
K.Ida et. al., Phys Rev Lett 88 (2001) 015002

Delay time shows the jump at the magnetic island



K.Ida et. al., Phys plasmas 11 (2004) 2551

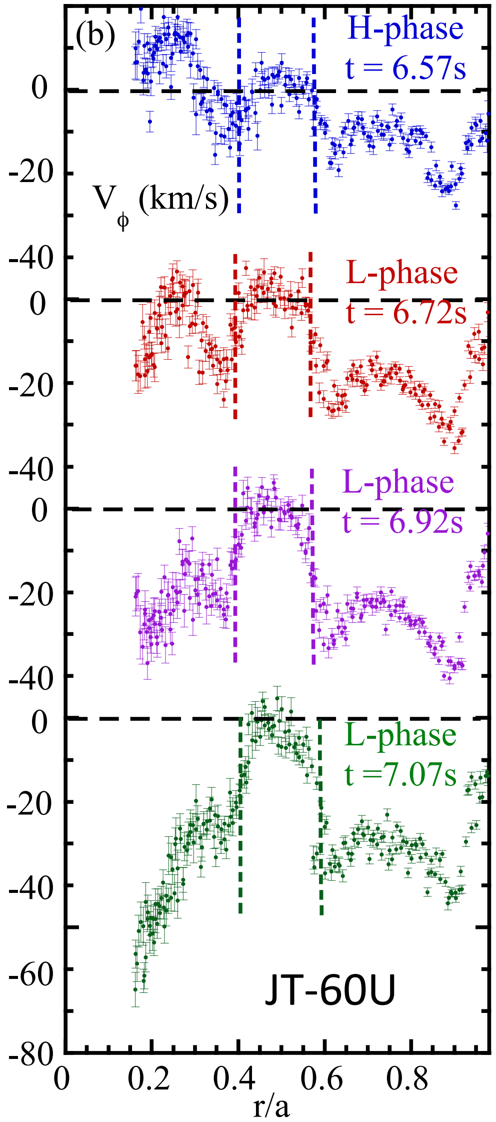
What is the transport near the magnetic island?

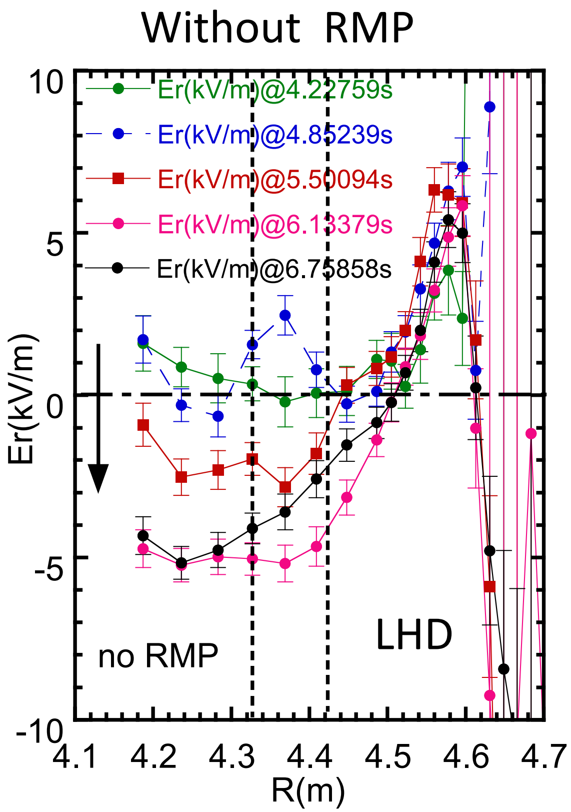


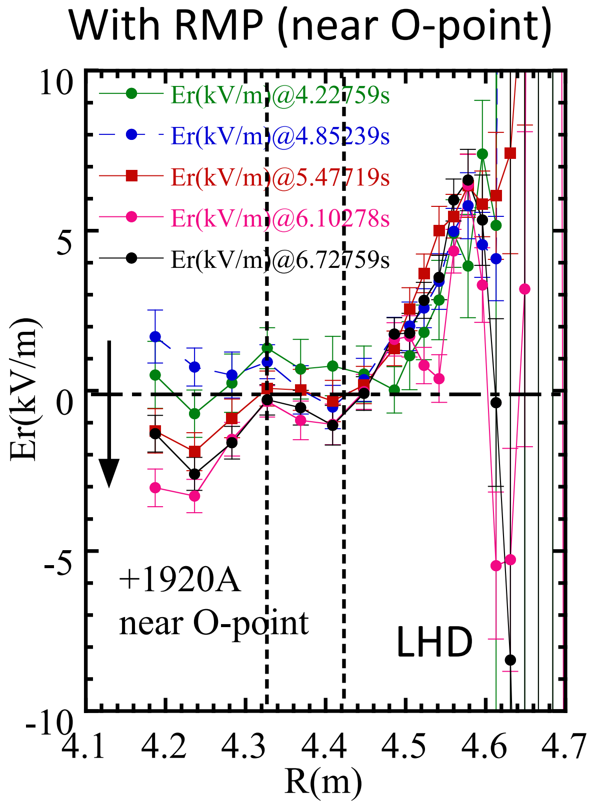
Profiles of electron thermal diffusivity as a function of helical coil current.
Reduction of thermal diffusivity near the low order rational surface

Vargas V.I. et al 2007 Nucl. Fusion 47 1367.

Damping of toroidal flow







Damping of toroidal flow and large velocity shear at the boundary of magnetic island are observed both in tokamak and stellarator → This is good example of topology 3D effect.

K.Ida et. al., Phys Rev Lett 109 (2012) 065001

Magnetic island and stochastization

The direction NBI is exchanged from co- to counter-direction

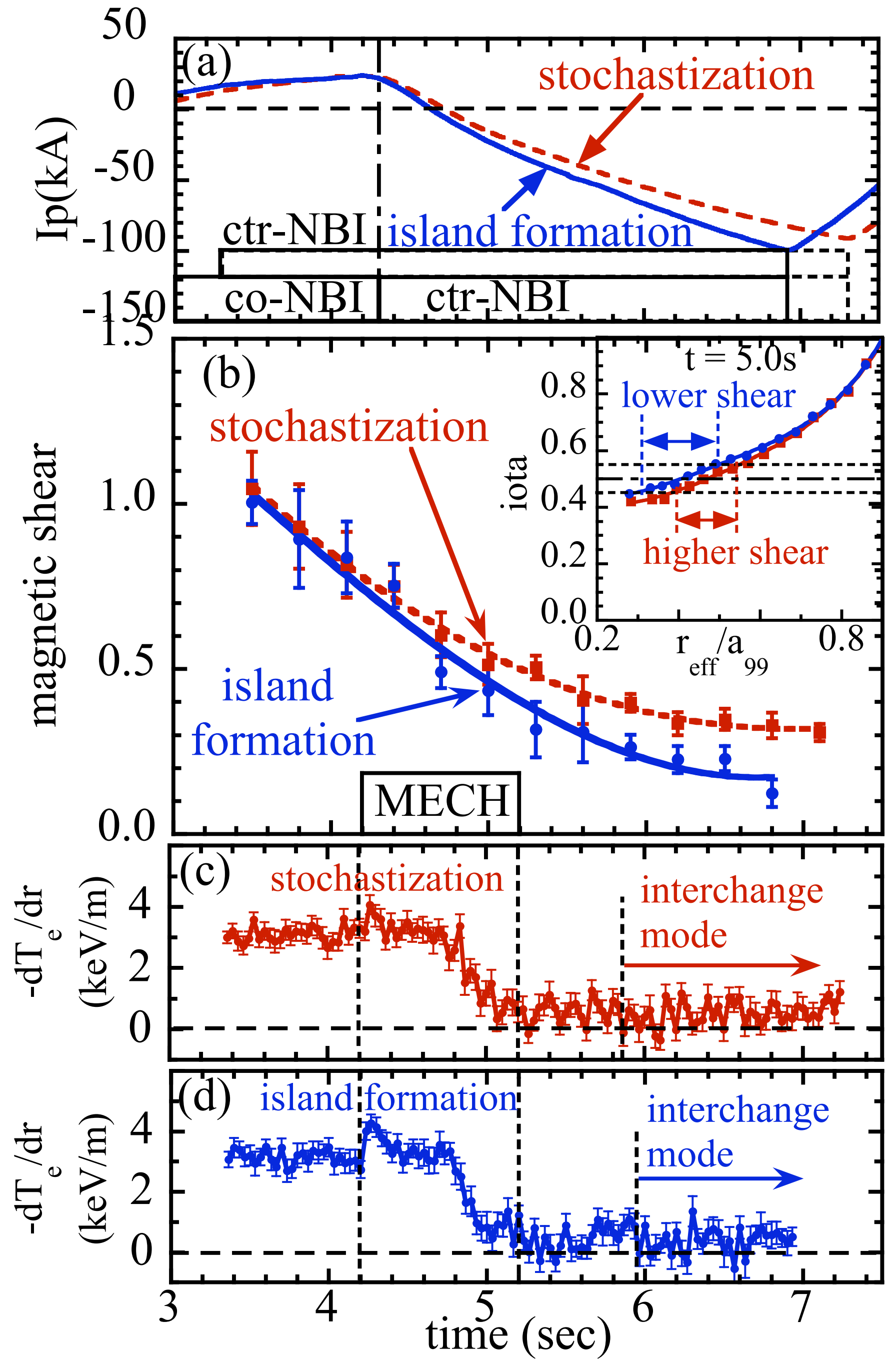
Decrease of magnetic shear causes "nesting magnetic island" or " stochastic region" near the rational surface of iota = 0.5

Depending of the rate of decay of magnetic shear, two states are observed

1) magnetic island formation

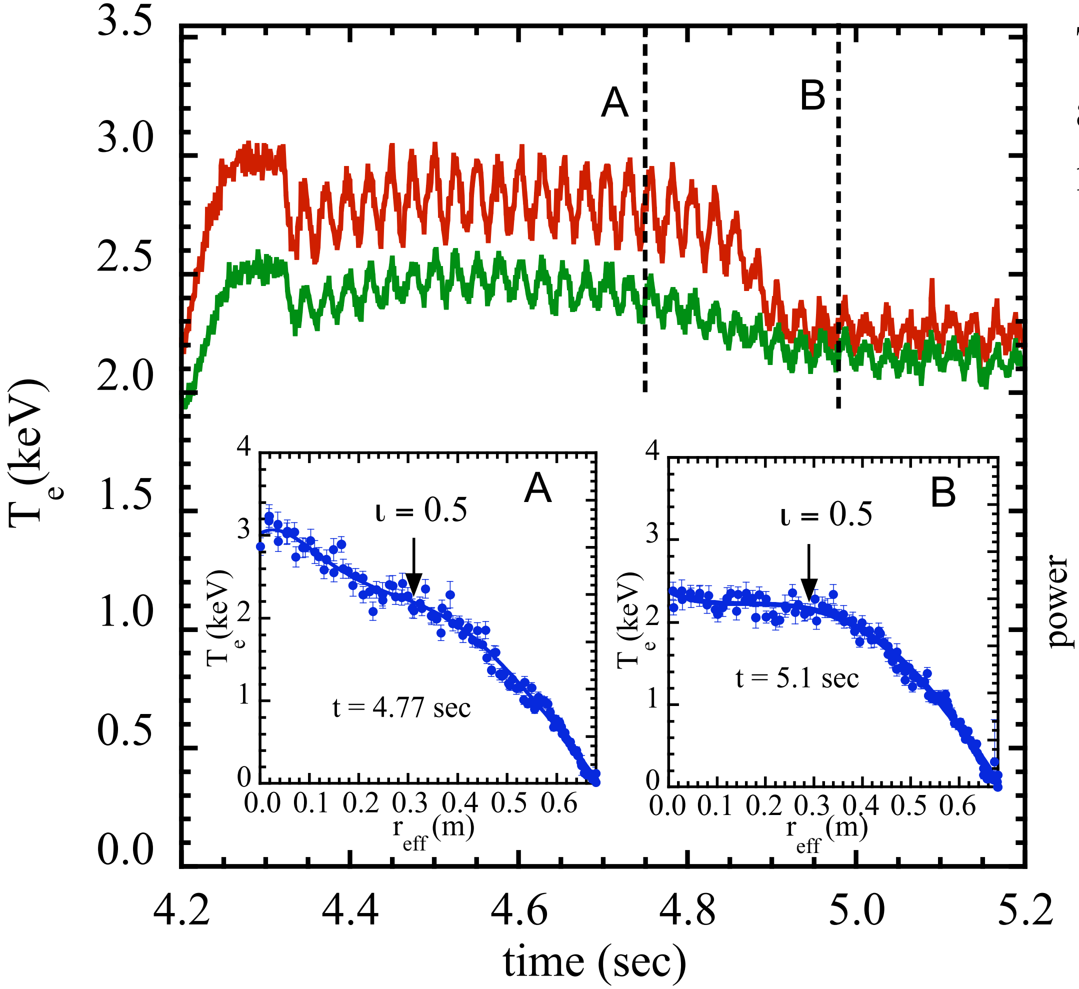
2) stochastization

Temperature gradient at i=0.5 is close to zero

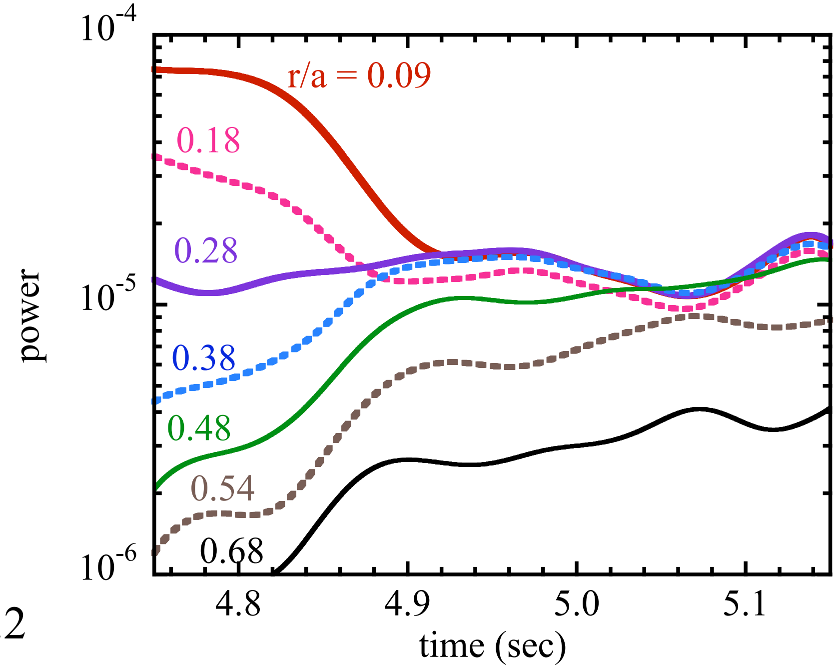


Heat pulse propagation by Modulation ECH

modulation ECH is applied to study the heat pulse propagation in the Te flat region



The modulation power (square of amplitude) drops at r/a ~ 0 and increases at r/a ~ 0.5



Flattening of modulation power suggests that heat pulse propagates radially faster than the transport time scale determined by thermal diffusivity χe.

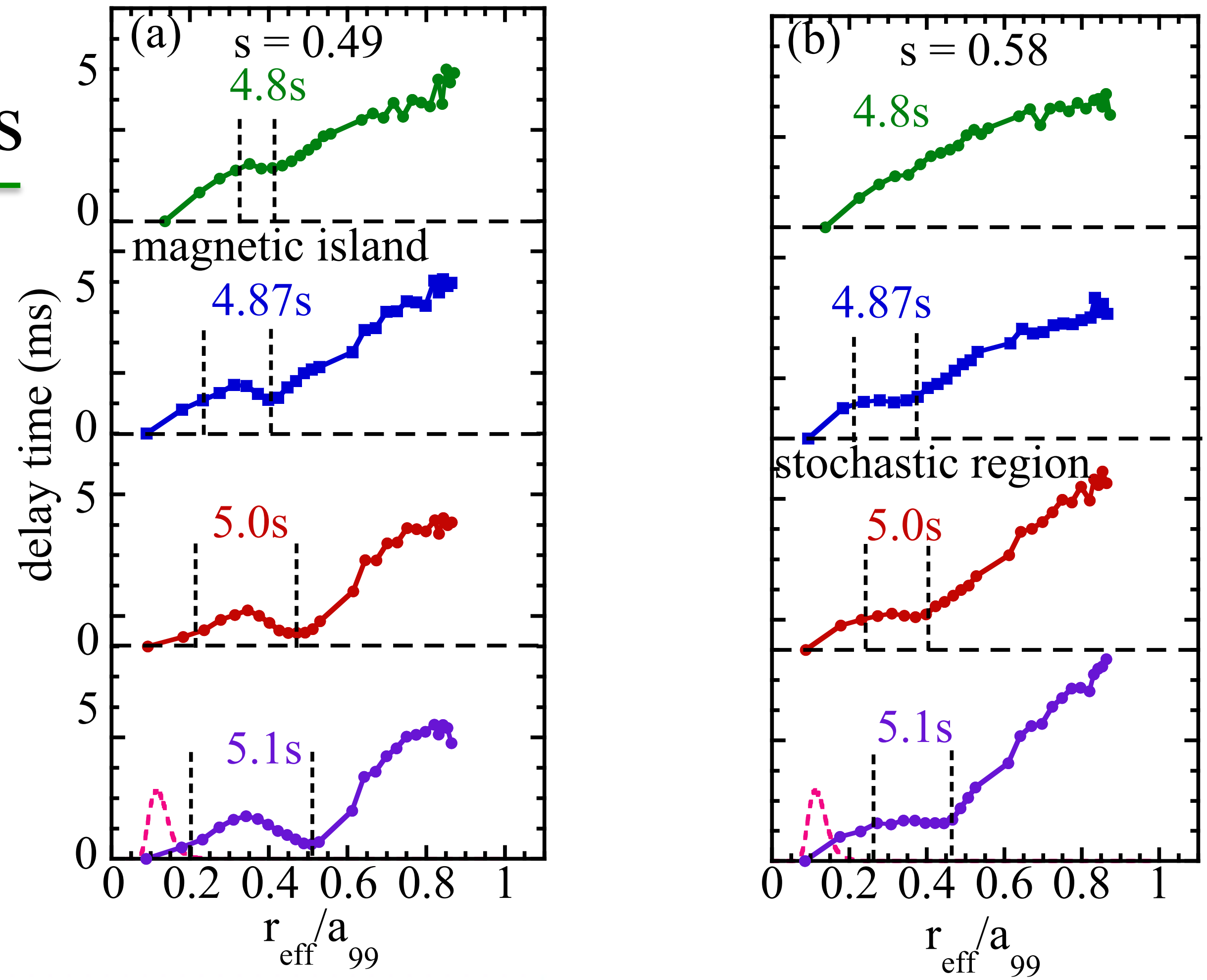
Two pattern of delay time profiles

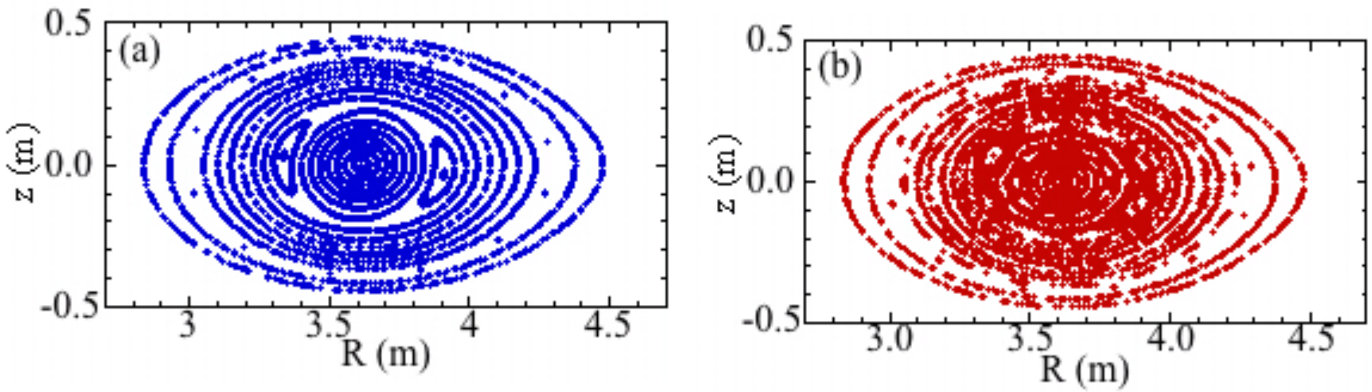
There are two pattern of radial profiles of delay time of heat pulse

Slow delay time with peaked profile
→ Magnetic island

Fast delay time
→ Stochastic magnetic filed

K.Ida et. al., New J. Phys. 15 (2013) 013061.



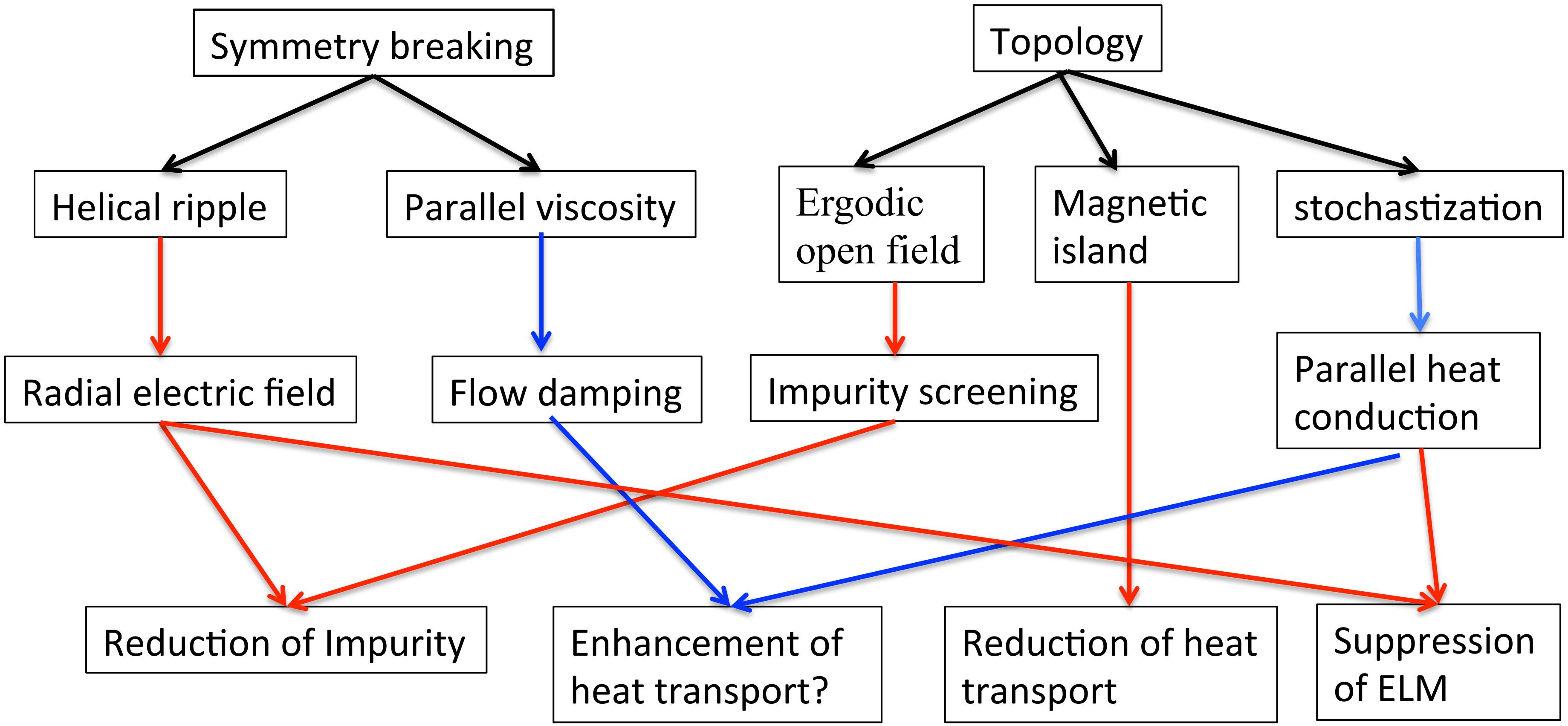


Summary

There are two 3D effects

1 Symmetry : tokamak⇔ helical → ripple and viscosity

2 Topology: 2D closed flux surface ⇔3D magnetic field strucutre



3D effects contribute reduction of impurity but not reduction of heat transport because of flow damping and also suppression of ELM trough change in transport and Er (flow)