Inertial effects caused by toroidal rotation on heat transport in JT- 60U plasmas

E. Narita, M. Honda, M. Yoshida, N. Hayashi, H. Urano, and S. Ide
JAEA

Acknowledgement: M. Nakata (NIFS) and Y. Camenen (CNRS)

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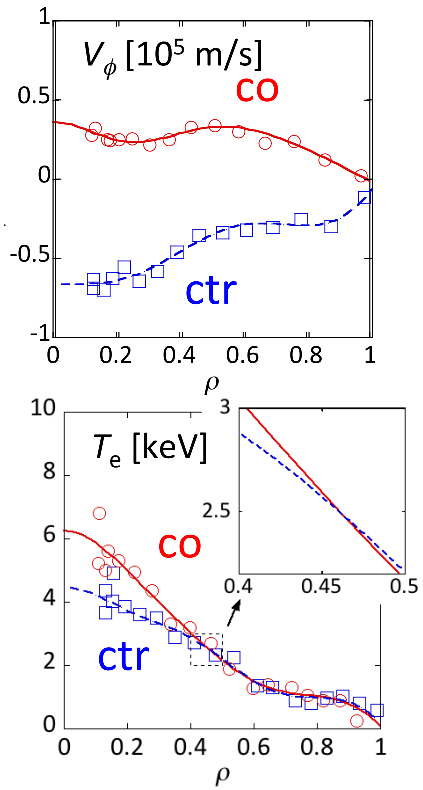
Effects of toroidal rotation direction on heat transport

☐ *Toroidal rotation*: key to improve the energy confinement in tokamak plasmas

<u>Previous studies</u>

- With strong E_r shear
  - core: the strong E_r shear stabilizes turbulence
    -> formation of ITBs [H. Shirai NF1999, Rewoldt NF2002]
  - pedestal: the steeper E_r shear with co-toroidal rotation
    -> improved confinement due to rotation
    [H. Urano NF2008, M.Honda NF2013]
- Without strong E_r shear
  - the better T_e-ITB with co-toroidal rotation [Oyama NF2007]
  - decrease in Z_{eff} with co-toroidal rotation
    -> change in the real frequency of the fastest growing mode is observed with GS2 [E. Narita PFR2015]



However, the rotation direction was not considered.

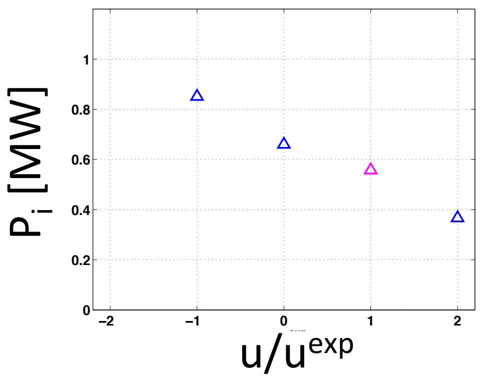
Impacts of toroidal rotation are reported using simple parameters

- Simple fluid model [A.G. Peeters PoP2009]
  - The linear growth rate of the ITG mode with the adiabatic electron

$$\gamma/(c_s/a) = k_\theta \rho_s \frac{a}{R}\sqrt{2\frac{R}{L_T} - \frac{1}{4}\left(\frac{R}{L_n}\right)^2 - \frac{1}{3}\frac{R}{L_n} - \frac{49}{9} + \frac{R/L_n - 2}{R/L_n - 2/3}\left[4(u+k_\parallel)u' - 2(u+k_\parallel)^2\left(\frac{R}{L_n}+\frac{26}{3}\right)\right]}$$

u: rotation velocity, $k_{//}$: parallel wave number related to the parallel mode structure ,
u': rotation velocity gradient

- Interplay between toroidal rotation and flow is investigated using gyrokinetic code GKW, which can take into account inertial effects. [Y. Camenen submitted to PoP]
  - turbulence stabilization due to rotation is observed with the DIII-D shortfall case



⇨ Can similar dependence of transport on rotation be seen with JT-60U parameters?

> - Focus on JT-60U experiments with moderate E_r shear in the core region
> - Assess the inertial effects caused by toroidal rotation using GKW

Rotation effects in GKW

- The following Vlasov equation is solved with the Poisson eq. and Ampère's law in a rigidly rotating frame.

$$\frac{\partial g}{\partial t} + \boldsymbol{v}_\chi \cdot \nabla g + (v_\parallel \boldsymbol{b} + \underline{\underline{\boldsymbol{v}_\mathrm{D}}}) \cdot \nabla f - \frac{\boldsymbol{b}}{m} \cdot (\mu \nabla B + \nabla \mathcal{E}_\Omega) \frac{\partial f}{\partial v_\parallel}$$

$$= -(\boldsymbol{v}_\chi + \underline{\underline{\boldsymbol{v}_\mathrm{D}}}) \cdot \nabla F_\mathrm{M} + \frac{F_\mathrm{M}}{T}(v_\parallel \boldsymbol{b} + \underline{\underline{\boldsymbol{v}_\mathrm{D}}}) \cdot (-Ze\nabla\langle\phi\rangle - \mu\nabla\langle B_\parallel\rangle)$$

where $g = f + \frac{Zev_\parallel}{T}\langle A_\parallel \rangle F_\mathrm{M}$

$$\boldsymbol{v}_\mathrm{D} = \underbrace{\frac{1}{Ze}\left[\frac{mv_\parallel^2}{B} + \mu\right]\frac{\boldsymbol{B} \times \nabla B}{B^2} + \frac{mv_\parallel^2}{2ZeB}\beta' \boldsymbol{b} \times \nabla\psi}_{\text{grad-B drift and curvature drift}} + \underbrace{\frac{2mv_\parallel}{ZeB}\boldsymbol{\Omega}_\perp}_{\text{Coriolis drift}} + \underbrace{\frac{1}{ZeB}\boldsymbol{b} \times \nabla\mathcal{E}_\Omega}_{\text{background potential and centrifugal drift}}$$

$$\mathcal{E}_\Omega = Ze\Phi - \frac{1}{2}m\Omega^2(R^2 - R_0^2)$$

✓ Velocity of the co-moving frame: $\Omega = -\frac{\partial \Phi}{\partial \Psi}$ ⇨ $\boldsymbol{v}_{E\times B} = (\boldsymbol{b} \times \nabla\Phi)/B$ vanishes, but $\boldsymbol{v}'_{E\times B}$ is finite, as well as Ω'.

✓ In this paper, only the Coriolis drift is considered, and the centrifugal drift is neglected.

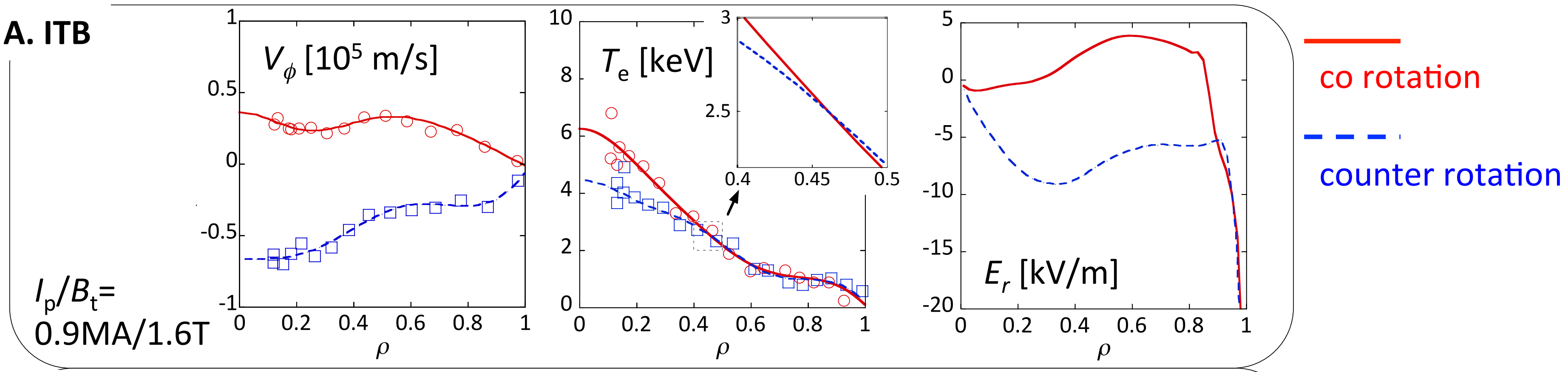
Effects of toroidal rotation observed in JT-60U

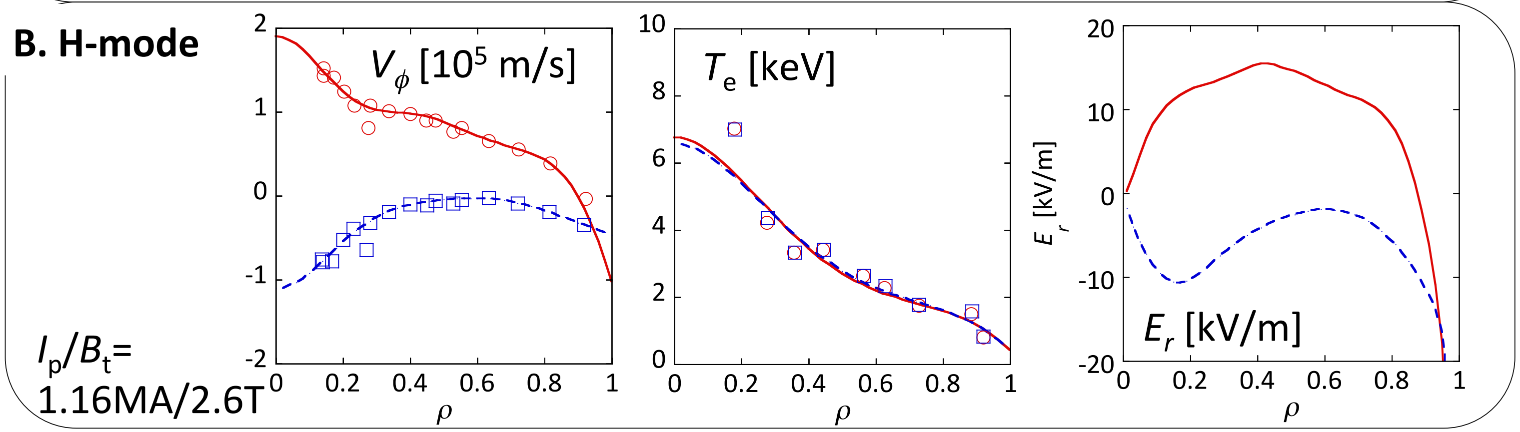
A. ITB plasma:

Steep gradient of T_e-ITB with co rotation [N. Oyama NF2007]

B. Conventional H-mode plasma:

Independence of core heat transport from toroidal rotation [H. Urano NF2008]

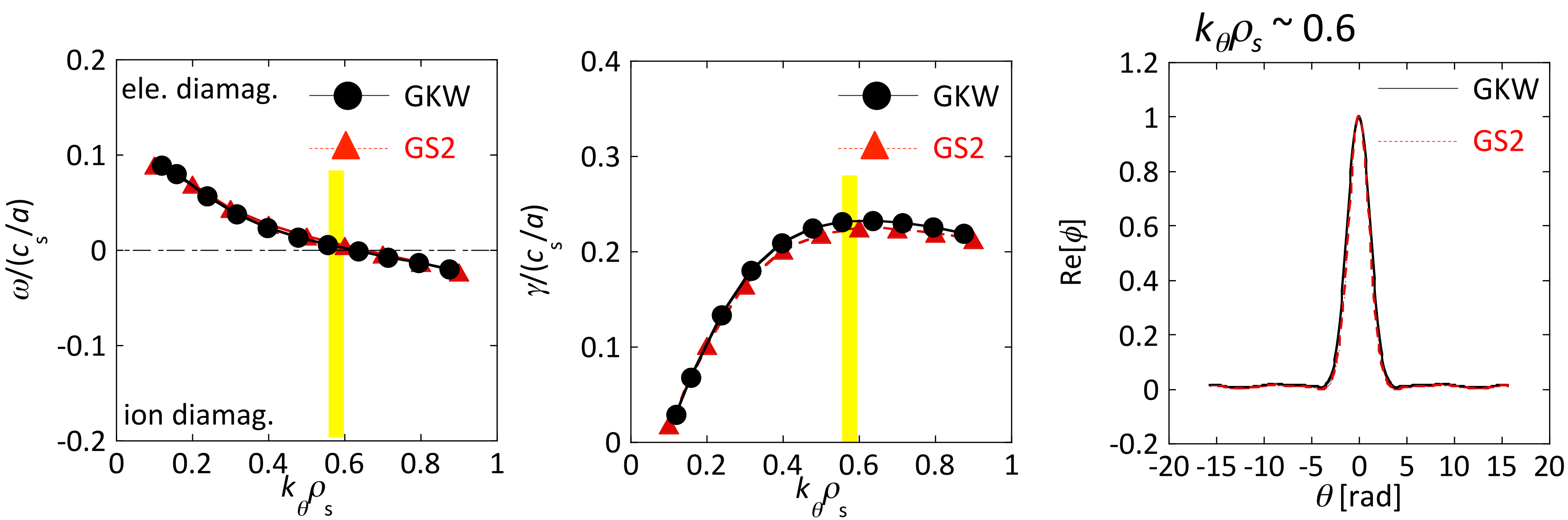




Both GKW and GS2 show that the ITG/TEM mode is the fastest growing mode

Conditions

- Miller geometry
- Kinetic electrons
- Main ions & an impurity
- Electromagnetic ($B_\perp$ & $B_{//}$)
- $0<k_\theta\rho_s<1$
- $k_x\rho_s=0$
- Collision (pitch-angle scattering & energy diffusion)
- w/o toroidal rotation



✓ Good agreement between GKW and GS2 is obtained.

Rotation effects on the linear growth rate in the ITB plasma

Velocity of the co-moving frame Ω

$$V_{\mathrm{C},\phi} = \omega_{\mathrm{C}} R + \hat{u}_{\mathrm{C},\theta} B_\phi$$

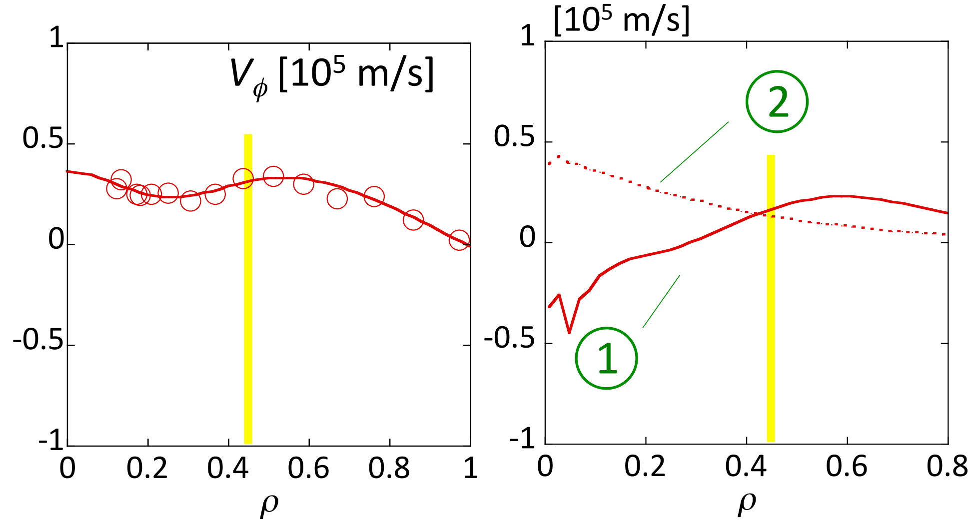
$$= \left(\underbrace{-\frac{\partial \Phi}{\partial \Psi}}_{①} \underbrace{- \frac{1}{e_{\mathrm{C}} n_{\mathrm{C}}} \frac{\partial p_{\mathrm{C}}}{\partial \Psi}}_{②} \right) R + \hat{u}_{\mathrm{C},\theta} B_\phi$$

$$= \Omega$$

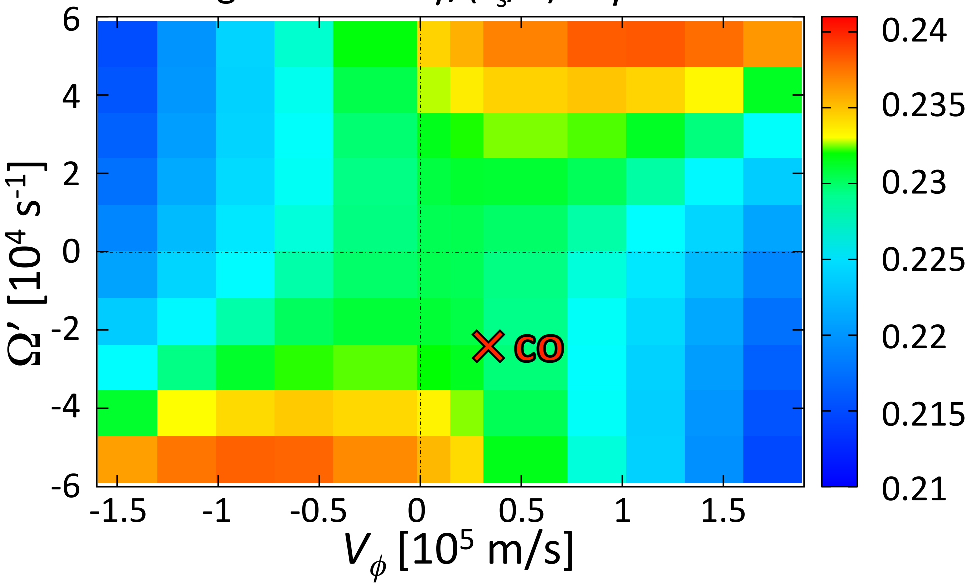
Velocity gradient Ω’

$$\Omega' = -\frac{\partial \Omega}{\partial \rho}$$

co-rotation case



linear growth rate $\gamma/(c_s/a)$ at ρ=0.45



Conditions: G EQDSK, Kinetic electrons, Main ions & an impurity, Electromagnetic ($B_\perp$ & $B_{//}$), $k_\theta \rho_s$=0.57, $k_x \rho_i$=0, Collision (pitch-angle scattering & energy diffusion)

Rotation effects on the linear growth rate in the ITB plasma

Velocity of the co-moving frame Ω

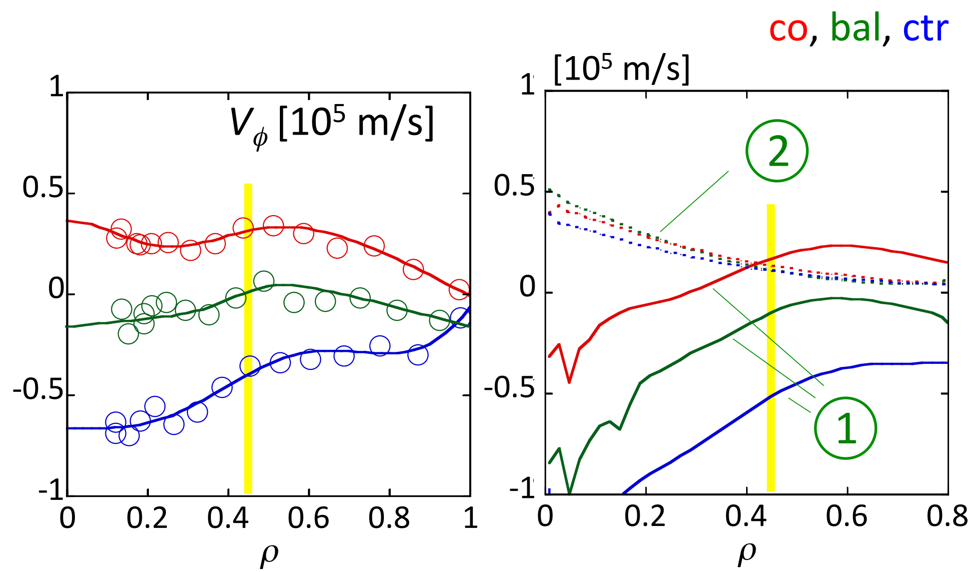
$$V_{\mathrm{C},\phi} = \omega_{\mathrm{C}} R + \hat{u}_{\mathrm{C},\theta} B_\phi$$

$$= \left(-\frac{\partial \Phi}{\partial \Psi} - \frac{1}{e_{\mathrm{C}} n_{\mathrm{C}}} \frac{\partial p_{\mathrm{C}}}{\partial \Psi} \right) R + \hat{u}_{\mathrm{C},\theta} B_\phi$$

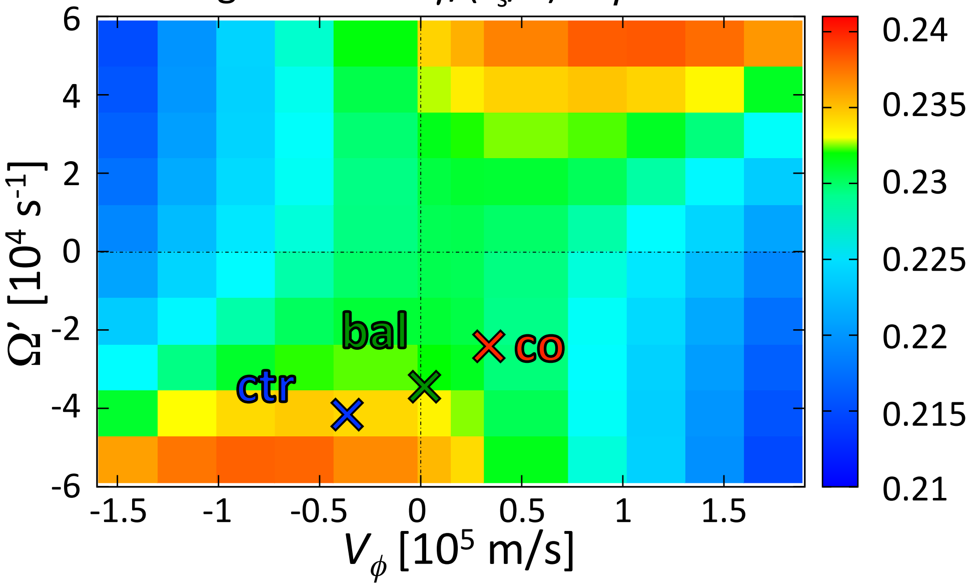
$= \Omega$ ① ②

Velocity gradient Ω'

$$\Omega' = -\frac{\partial \Omega}{\partial \rho}$$



linear growth rate $\gamma/(c_s/a)$ at ρ=0.45



- ✓ all cases (co, bal and ctr) have $\Omega' < 0$.
- ✓ co -> bal -> ctr: Increase in γ

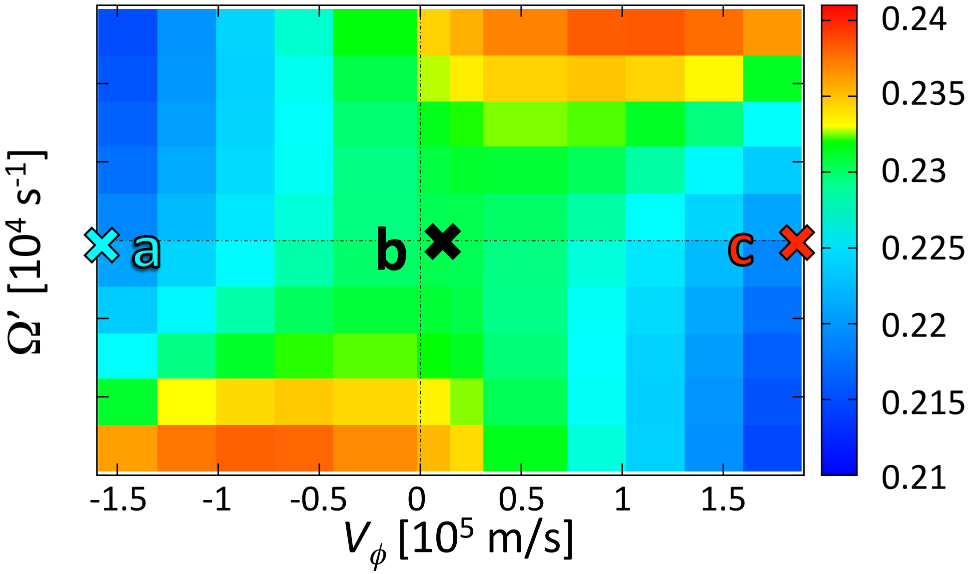
  ➔ agreement with the experiment

Conditions: G EQDSK, Kinetic electrons, Main ions & an impurity, Electromagnetic ($B_\perp$ & $B_{//}$), $k_\theta \rho_s$=0.57, $k_x \rho_i$=0, Collision (pitch-angle scattering & energy diffusion)

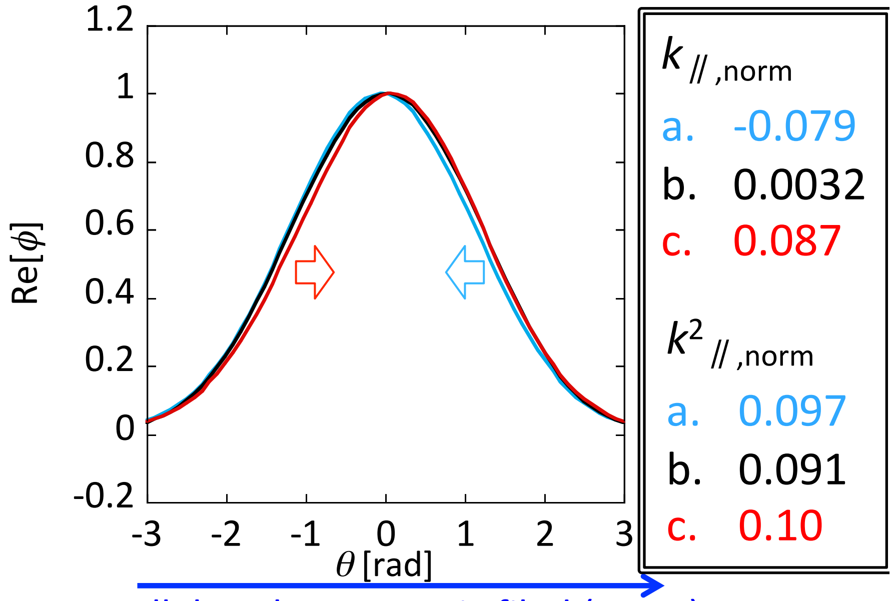
Effects of rotation velocity on parallel mode structure w/o a finite velocity gradient

- Effects of rotation velocity on the parallel mode structure are suggested by the fluid model. [A.G. Peeters PoP2009, Y.Camenen PoP2009]
- The parallel mode structure is represented by $k_{//}$ in the fluid model.

linear growth rate $\gamma/(c_s/a)$ at ρ=0.45



✓ Structures change symmetrically.



Parallel to the magnetic filed ($\propto z$)

$$\phi(k_\parallel) = \int_{z_{\min}}^{z_{\max}} \phi(z) e^{-ik_\parallel z} \mathrm{d}z, \;\; k_{\parallel,\mathrm{norm}} = \frac{k_\parallel R}{2\sqrt{2} k_\theta \rho_s}$$

$k_{//}$: symmetry about θ=0, $k^2_{//}$: narrowness

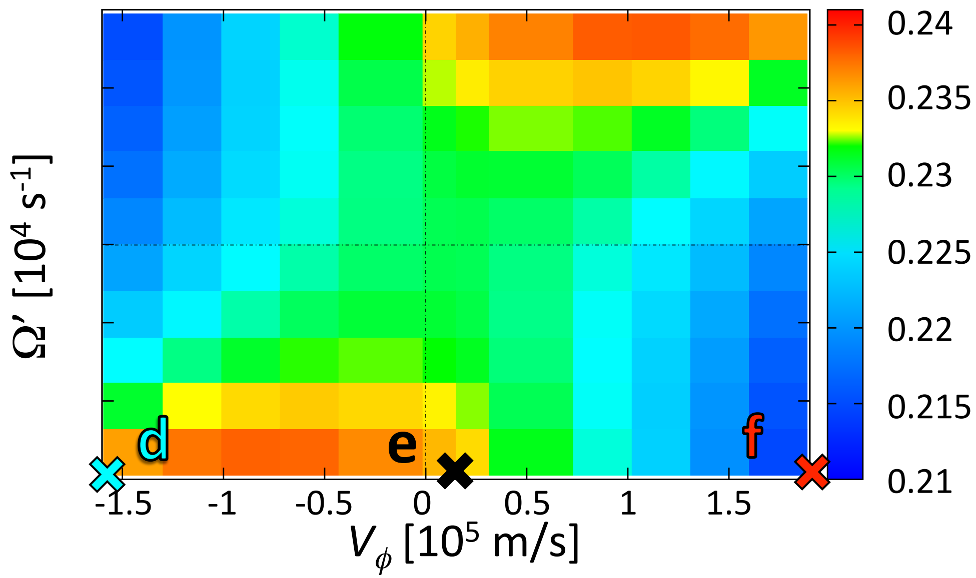
Conditions: G EQDSK, Kinetic electrons, Main ions & an impurity, Electromagnetic ($B_\perp$&$B_{//}$), $k_\theta \rho_s$=0.57, $k_x \rho_s$=0, Collision (pitch-angle scattering & energy diffusion)

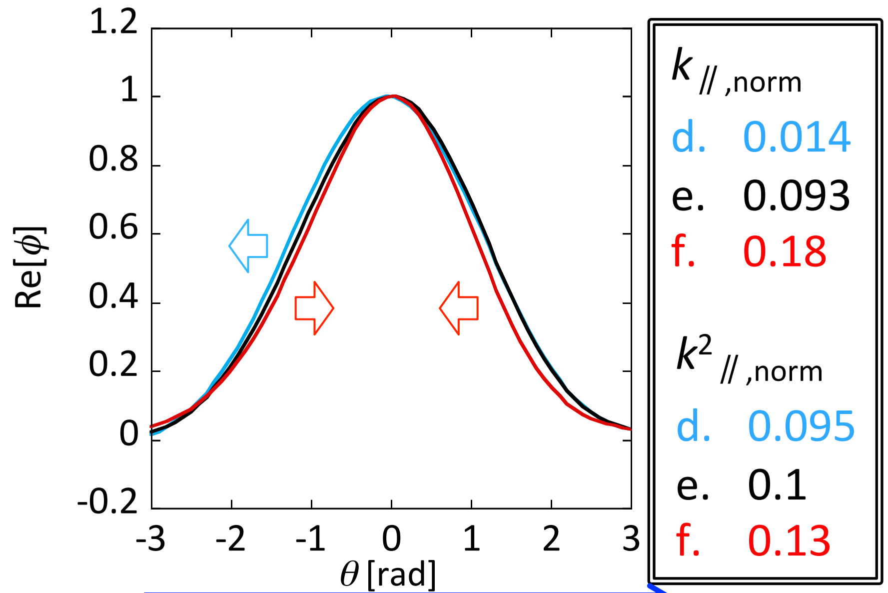
Effects of rotation velocity on parallel mode structure w/ a finite velocity gradient

- Effects of rotation velocity on the parallel mode structure are also checked with a finite Ω'.

✓ Structures change asymmetrically: co case (f) has fluctuations in the narrower region than ctr case (d).

linear growth rate $\gamma/(c_s/a)$ at ρ=0.45





Parallel to the magnetic filed ($\propto z$)

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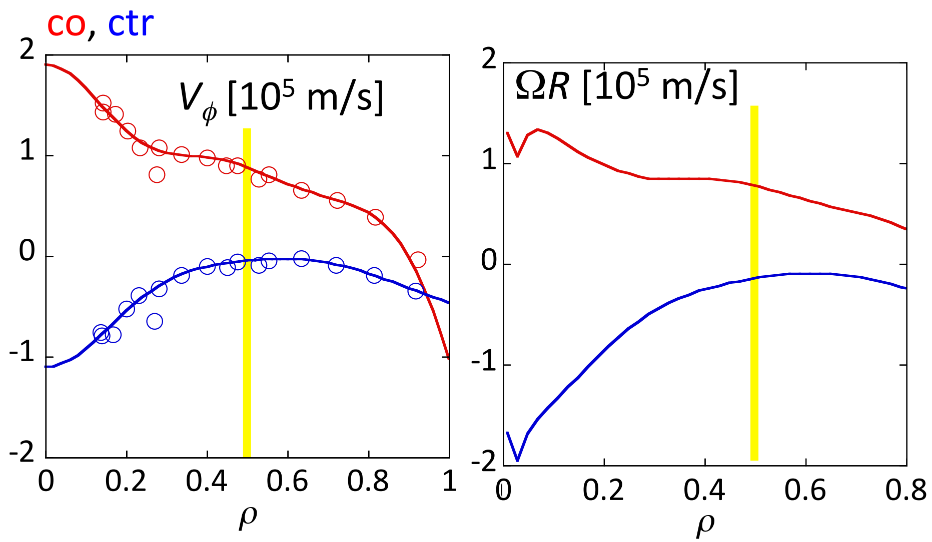
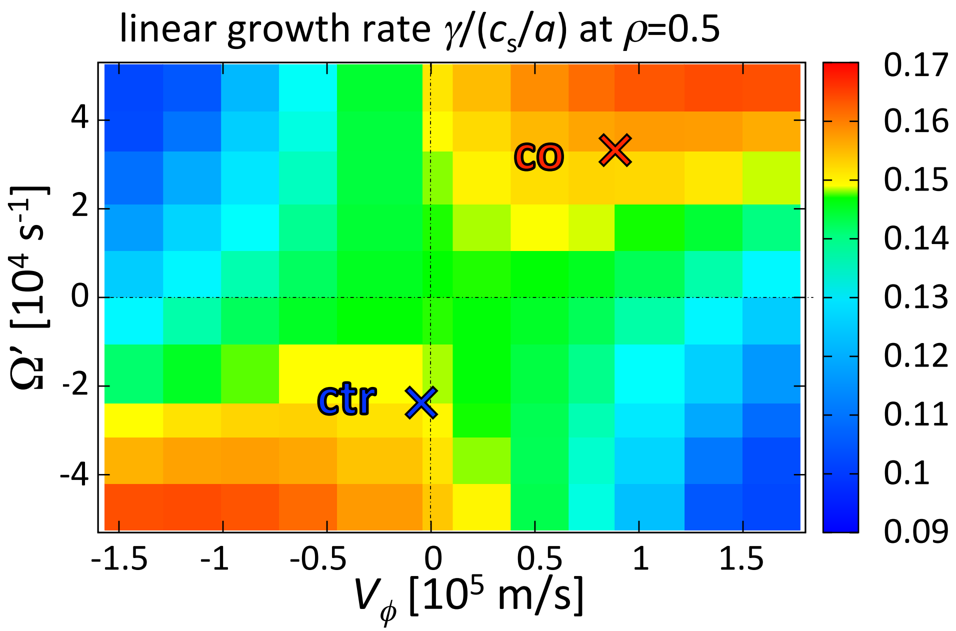
Conditions: G EQDSK, Kinetic electrons, Main ions & an impurity, Electromagnetic ($B_\perp$&$B_{//}$), $k_\theta \rho_s$=0.57, $k_x \rho_s$=0, Collision (pitch-angle scattering & energy diffusion)

Rotation effects on the linear growth rate in the conventional H-mode plasma

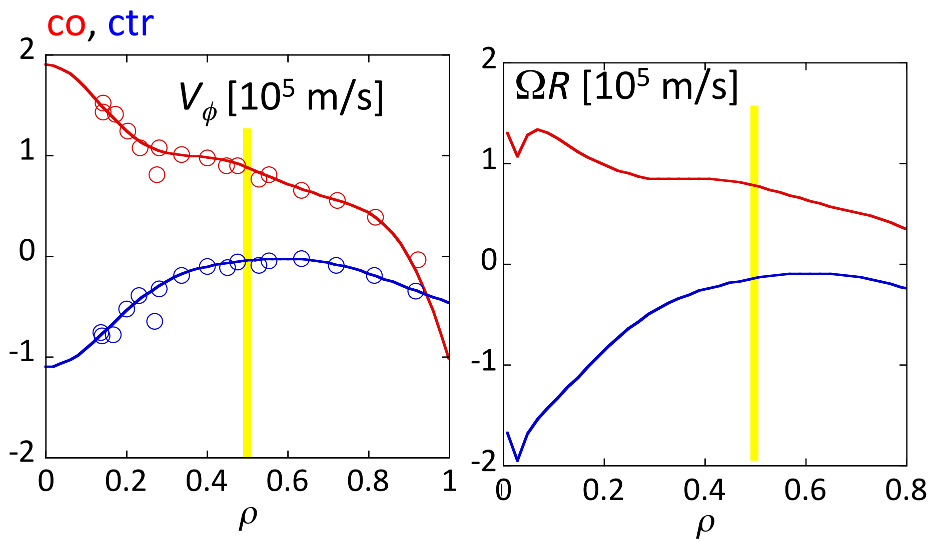




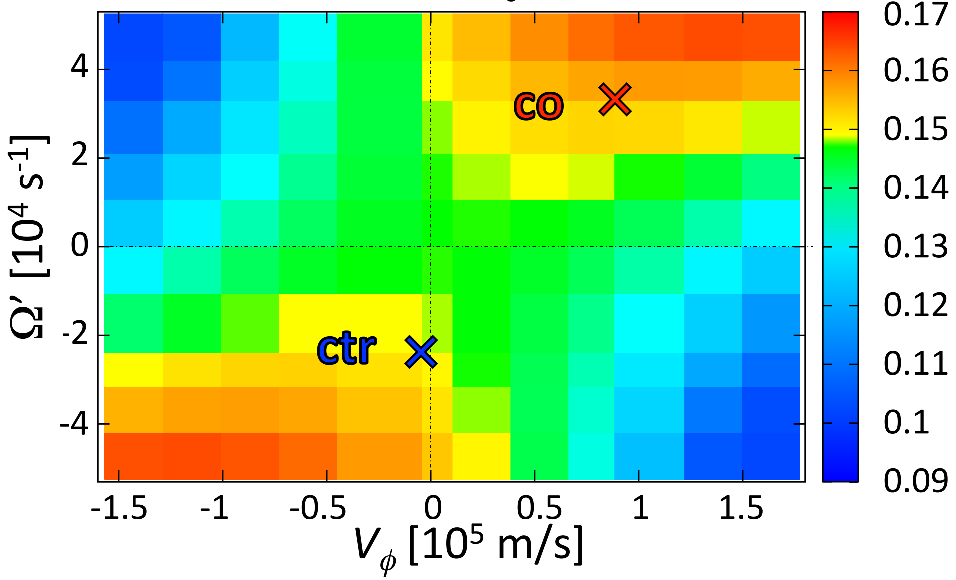
- ✓ co: $\Omega' > 0$, ctr: $\Omega' < 0$
- ✓ γ does not depend on the rotation direction.

  ➔ agreement with the experiment

Rotation effects on the heat diffusivity in the conventional H-mode plasma

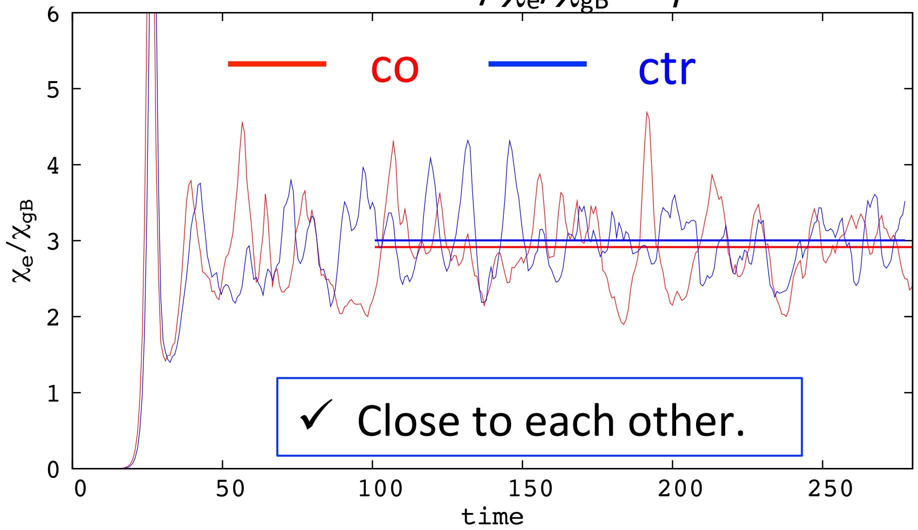


linear growth rate $\gamma/(c_s/a)$ at ρ=0.5

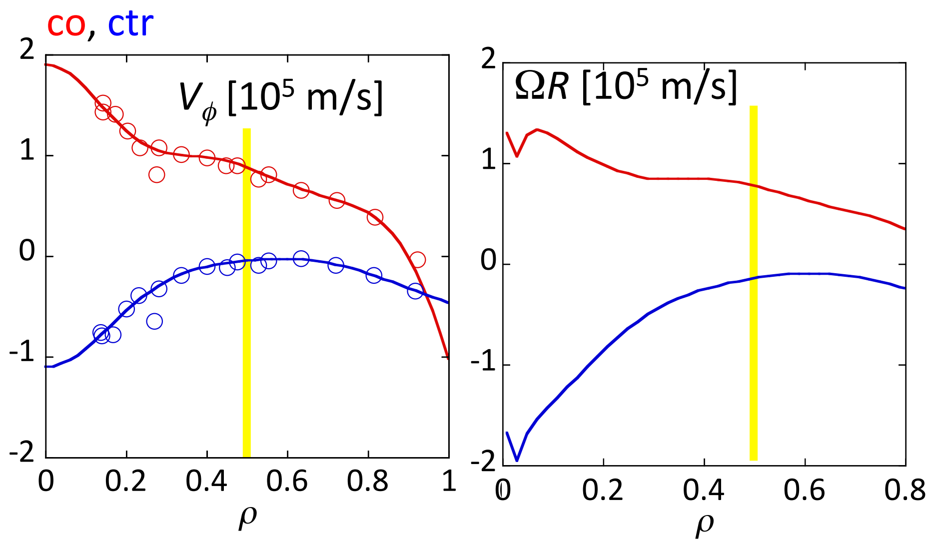


- Nonlinear simulations are performed for the H-mode plasma.

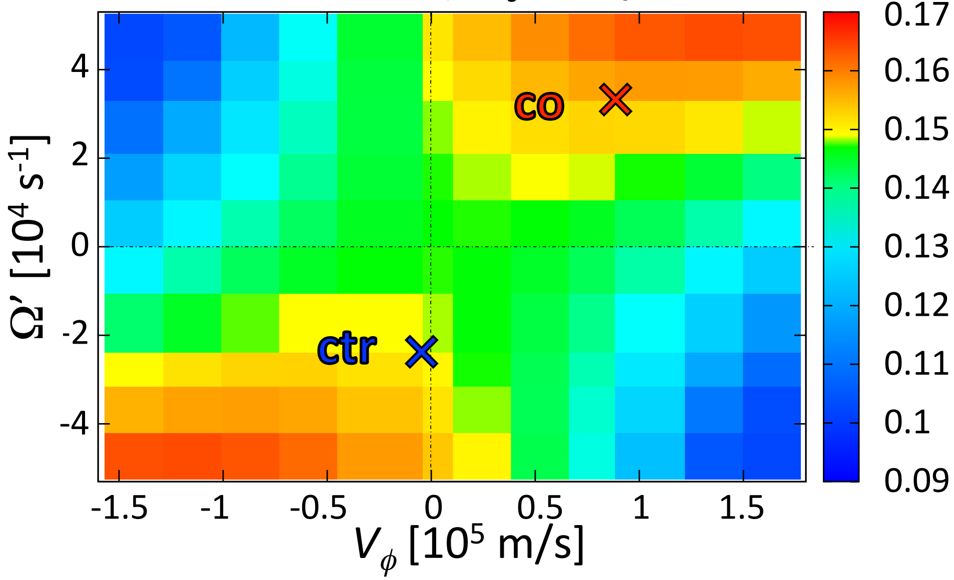
Electron heat diffusivity χ_e/χ_{gB} at ρ=0.5



Rotation effects on the heat diffusivity in the conventional H-mode plasma

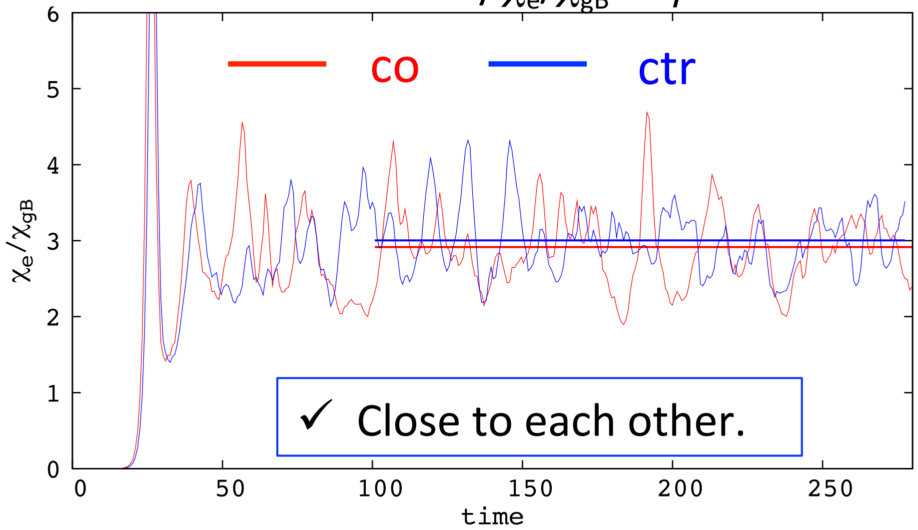


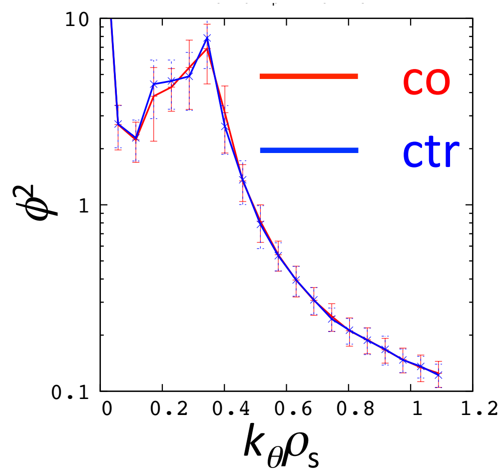
linear growth rate $\gamma/(c_s/a)$ at ρ=0.5



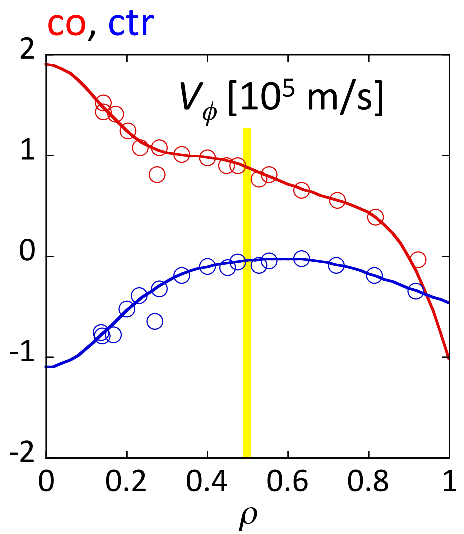
- Nonlinear simulations are performed for the H-mode plasma.

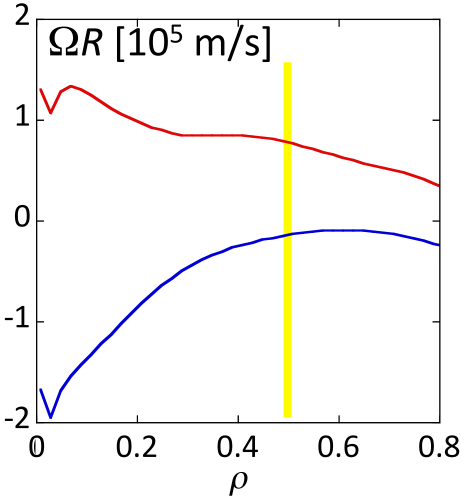
Electron heat diffusivity χ_e/χ_{gB} at ρ=0.5

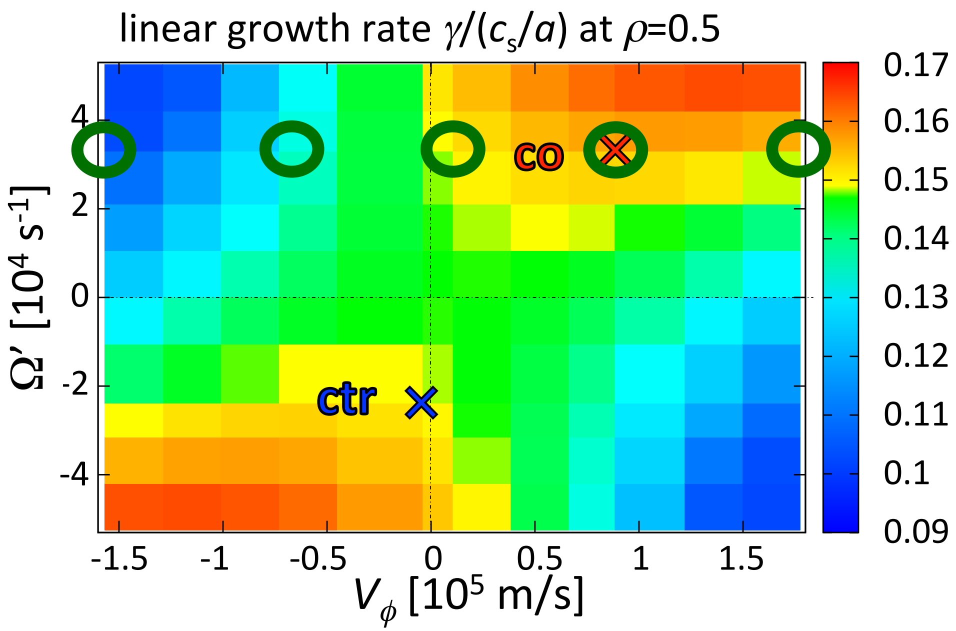




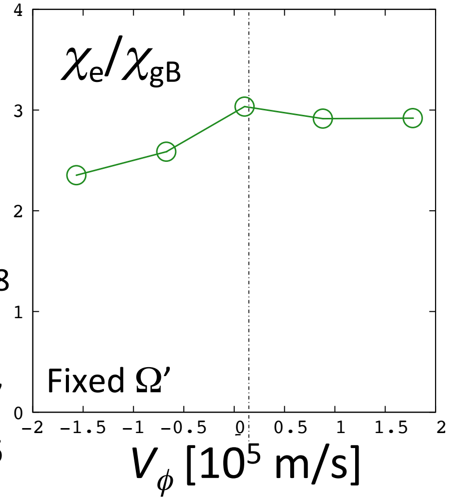
Rotation effects on the heat diffusivity at constant Ω'

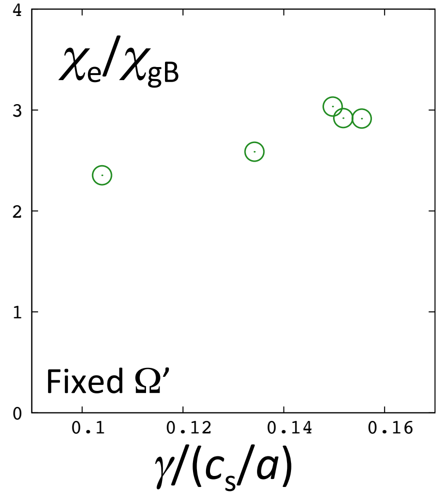






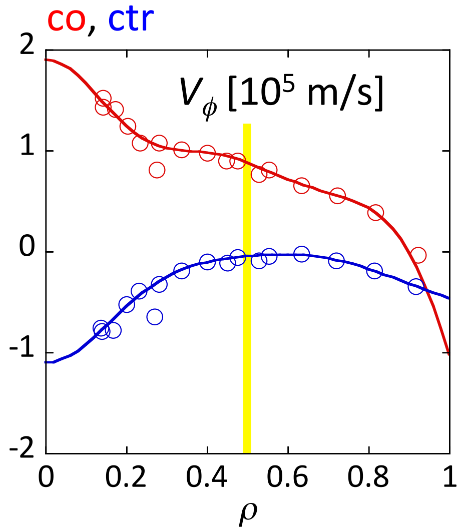
- Nonlinear simulations are performed for the H-mode plasma.

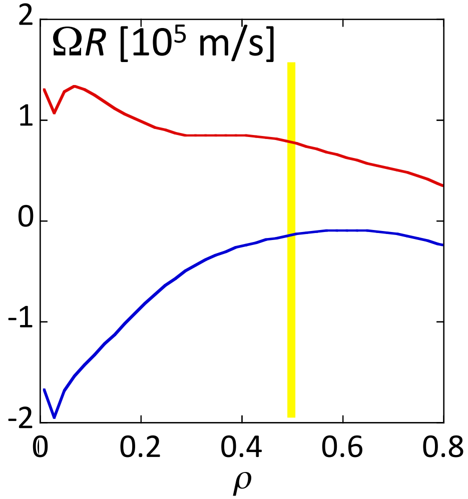




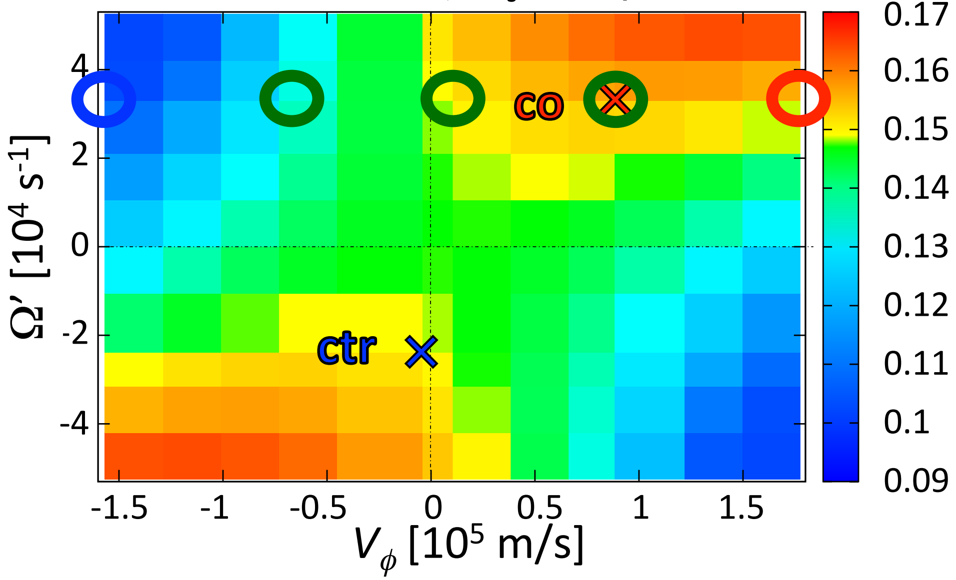
✓ The correlation between γ and χ_e is confirmed.

Rotation effects on the heat diffusivity at constant Ω'

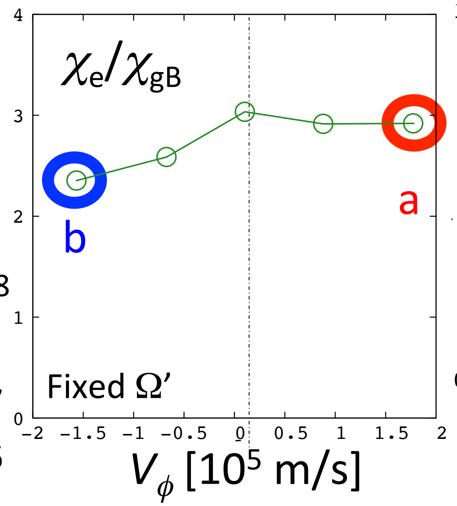


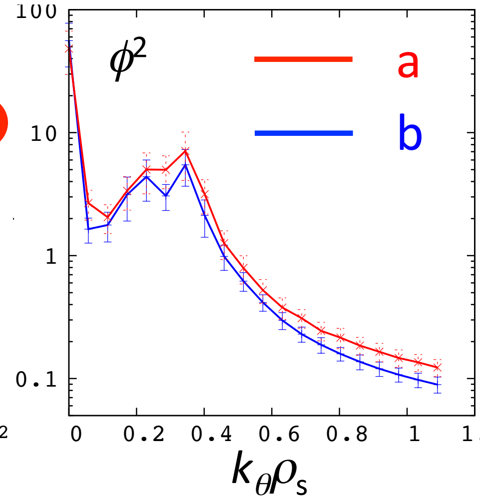


linear growth rate $\gamma/(c_s/a)$ at ρ=0.5



- Nonlinear simulations are performed for the H-mode plasma.





- ✓ The correlation between γ and χ_e is confirmed.
- ✓ Difference in ϕ^2 is checked.

Conclusions and future work

- Effects of toroidal rotation direction on instabilities were examined using GKW.

The qualitative agreement with JT-60U experiments is obtained.

- ✓ **ITB plasma**:
  γ changes with the rotation direction.
- ✓ **Conventional H-mode plasma**:
  γ does not depend on the rotation direction.

The difference is caused by the magnitude of the rotation velocity and its gradient.

- ✓ Nonlinear simulations show that the heat diffusivity changes in similar manner to γ.

Future work

- ➢ The change in heat diffusivity is compared between the experiments and the nonlinear simulations for the ITB plasma parameters.
- ➢ The effects of toroidal rotation are verified with other discharges.