JT-60Uにおける慣性力を通じた回転分布の熱輸送への影響

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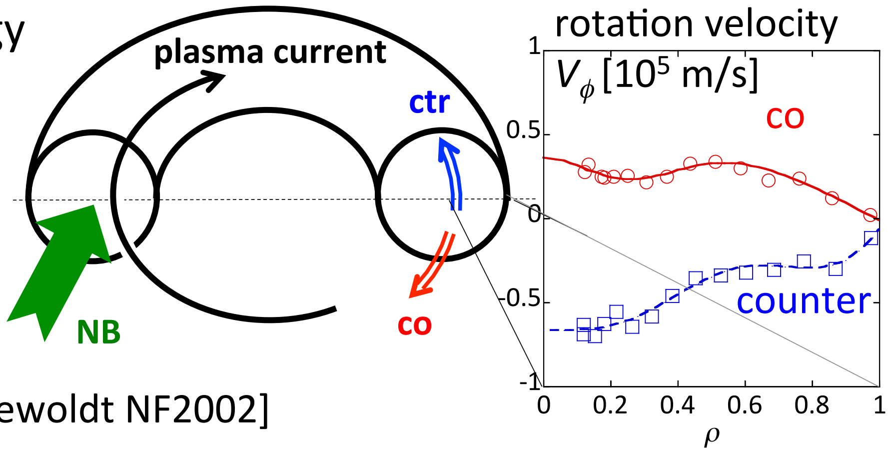
Effects of toroidal rotation direction on heat transport

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



Previous studies: strong E_r shear

- Core: the strong E_r shear stabilizes turbulent transport
  -> 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]

Recent progress: inertial effects

- Interplay between toroidal rotation and flow shear is investigated using gyrokinetic code GKW [Y. Camenen submitted to PoP]
- However, the effects on heat transport in experiments are not explained yet.

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

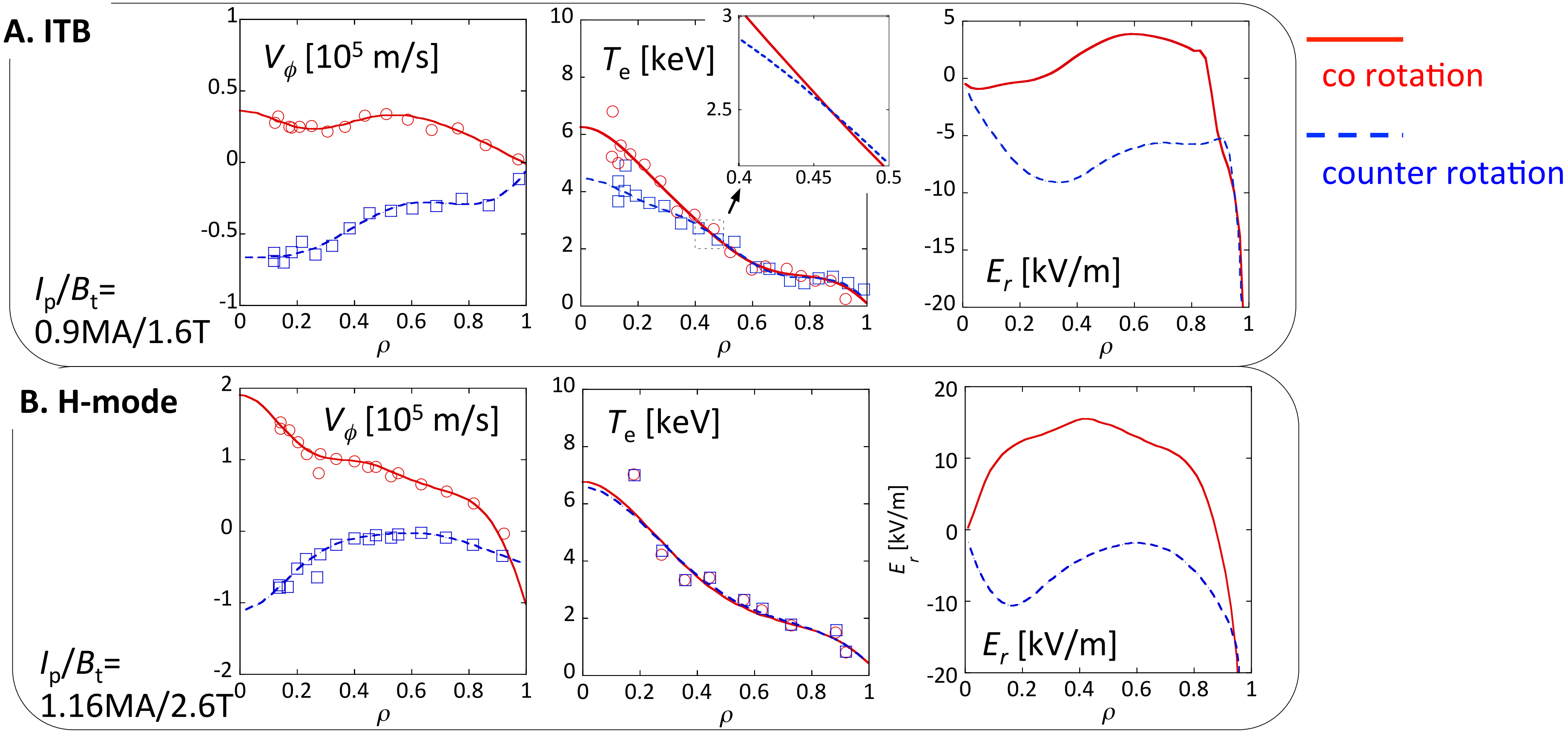
Effects of toroidal rotation observed in JT-60U

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]



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

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

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

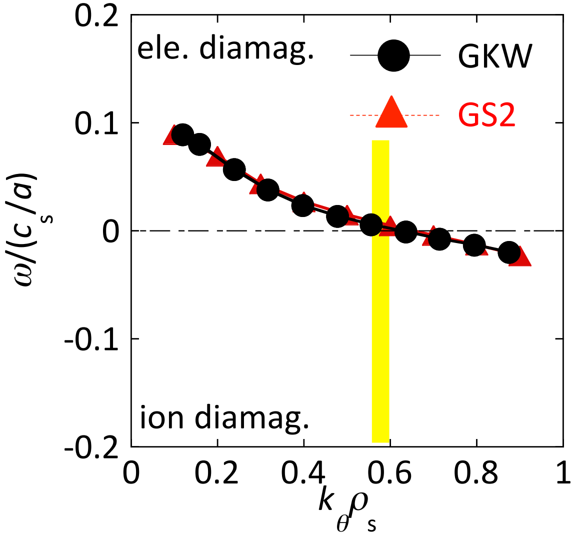
✓ Velocity of the co-moving frame: $\Omega = -\frac{\partial \Phi}{\partial \Psi}$ ⇨ $\boldsymbol{v}_{E\times B} = (\boldsymbol{b} \times \nabla \Phi)/B$ vanishes, but $\boldsymbol{v}'_{E\times B}$ is finite, as well as Ω'.

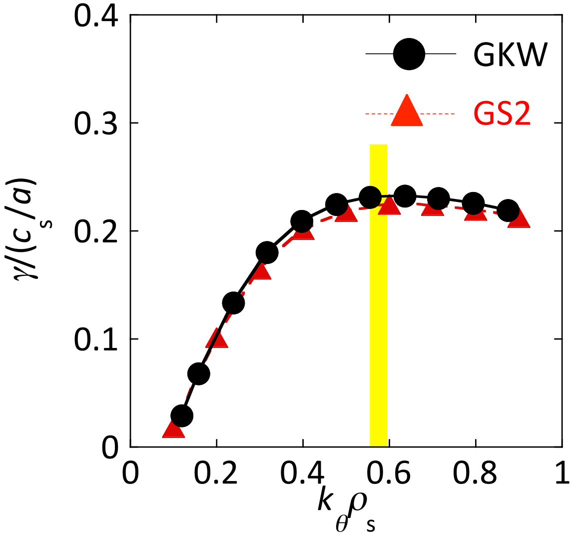
✓ In this paper, only the Coriolis drift is considered, and the centrifugal drift is neglected.

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

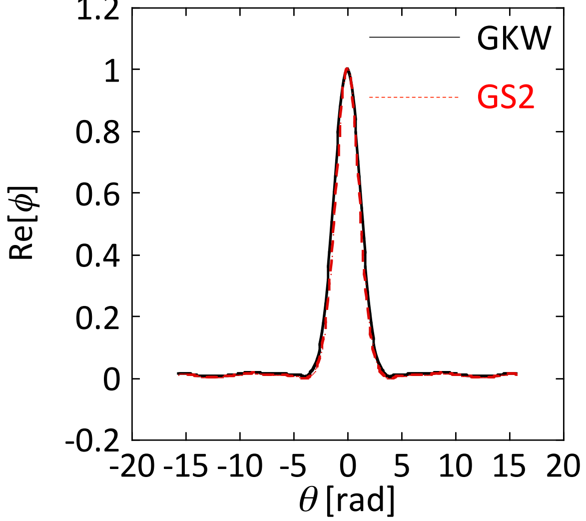
Conditions

- 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





$k_\theta\rho_s$ ~ 0.6



✓ Good agreement between GKW and GS2 is obtained.

Rotation effects on the linear growth rate in the ITB plasma

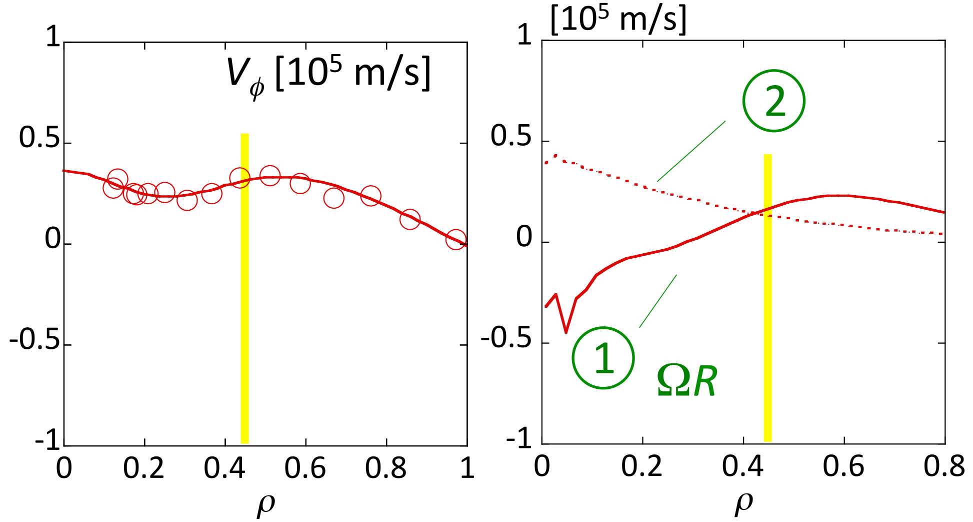
Velocity of the co-moving frame Ω

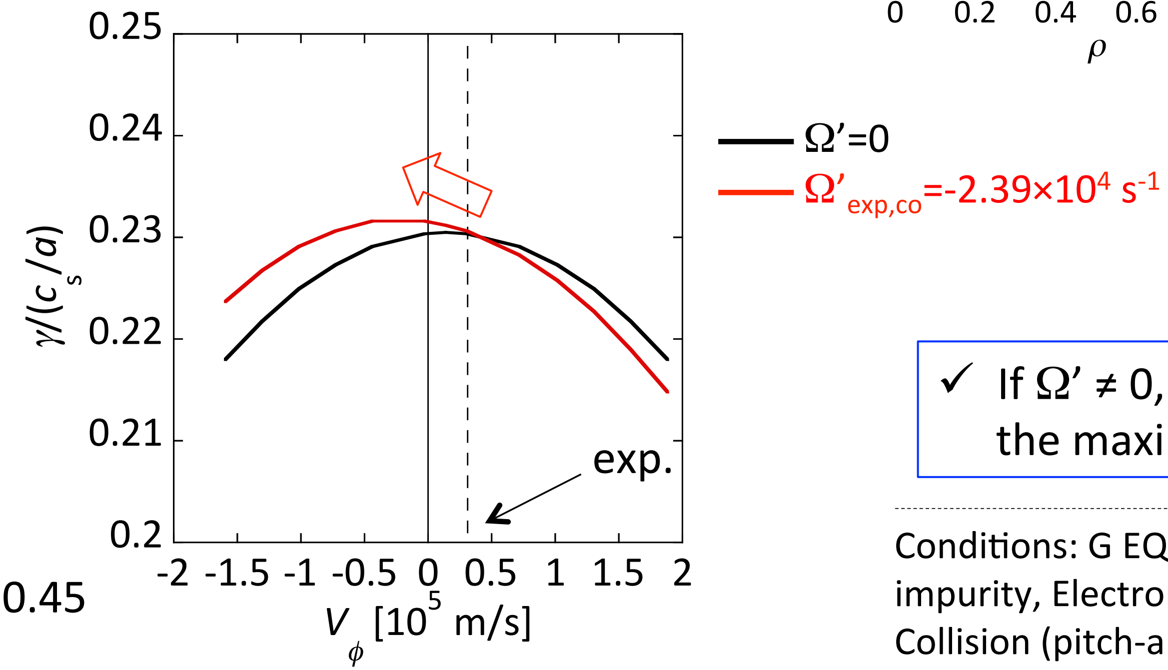
$$
\begin{aligned}
V_{\mathrm{C},\phi} &= \omega_{\mathrm{C}} R + \hat{u}_{\mathrm{C},\theta} B_\phi \\
&= \Big(\underbrace{-\frac{\partial \Phi}{\partial \Psi}}_{\text{①}} \underbrace{- \frac{1}{e_{\mathrm{C}} n_{\mathrm{C}}} \frac{\partial p_{\mathrm{C}}}{\partial \Psi}}_{\text{②}} \Big) R + \hat{u}_{\mathrm{C},\theta} B_\phi \\
&= \Omega
\end{aligned}
$$

Velocity gradient Ω'

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

co-rotation case





ρ=0.45

✓ If Ω' ≠ 0, V_ϕ at which γ becomes the maximum shifts.

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)

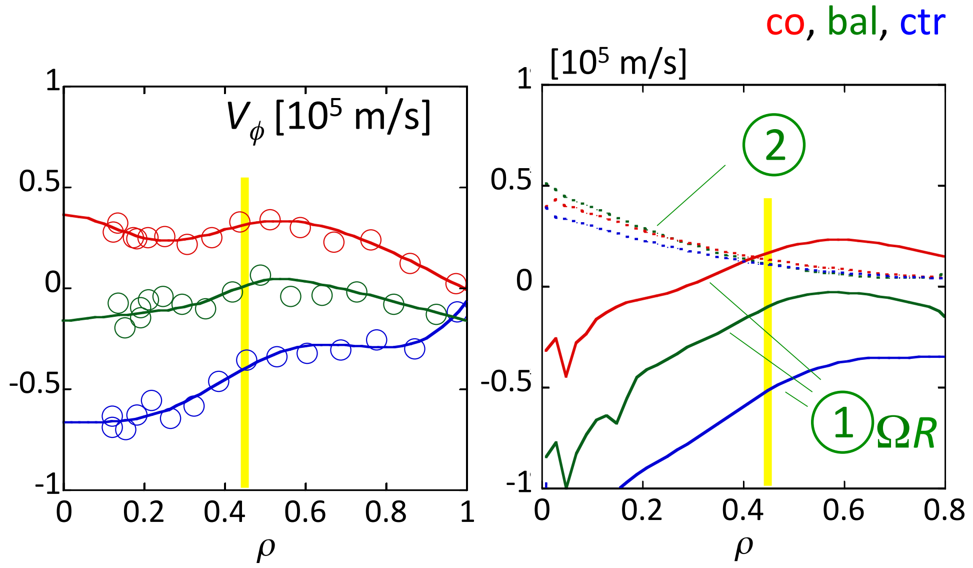
A change in the linear growth rate with the rotation direction in the ITB plasma

Velocity of the co-moving frame Ω

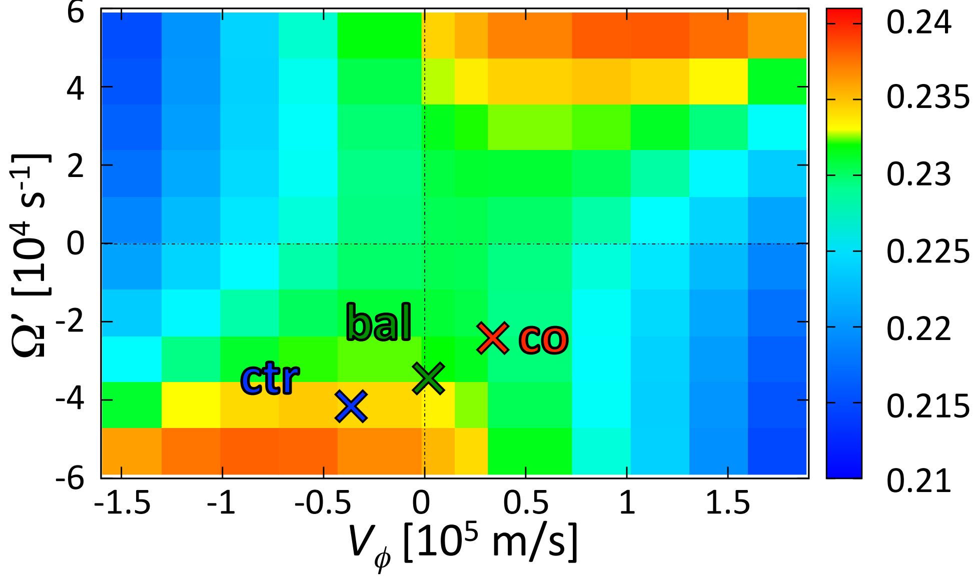
$$\begin{aligned} V_{\mathrm{C},\phi} &= \omega_{\mathrm{C}} R + \hat{u}_{\mathrm{C},\theta} B_\phi \\ &= \Bigg(\underbrace{-\frac{\partial \Phi}{\partial \Psi}}_{①} \underbrace{- \frac{1}{e_{\mathrm{C}} n_{\mathrm{C}}} \frac{\partial p_{\mathrm{C}}}{\partial \Psi}}_{②} \Bigg) R + \hat{u}_{\mathrm{C},\theta} B_\phi \\ &= \Omega \end{aligned}$$

Velocity gradient Ω’

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



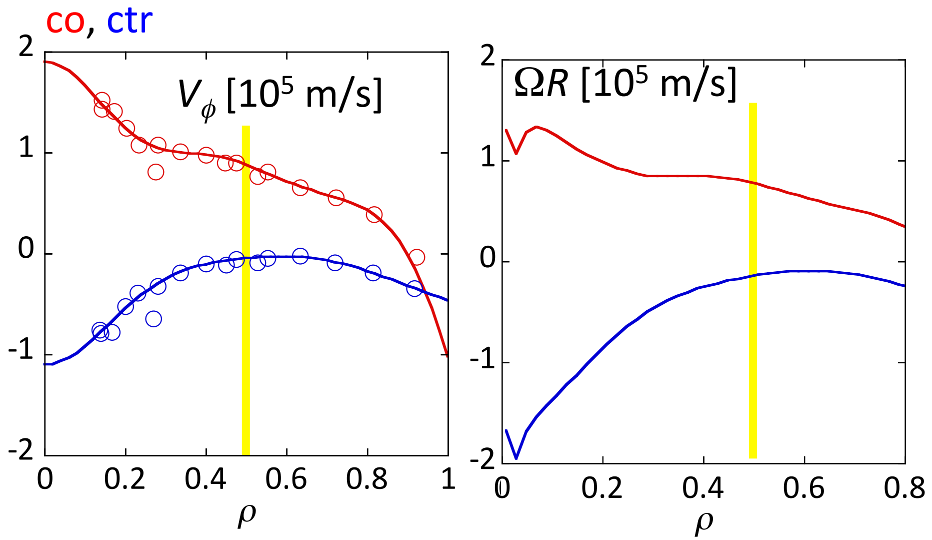
$\gamma/(c_s/a)$ at ρ=0.45 for $k_\theta\rho_s$=0.57



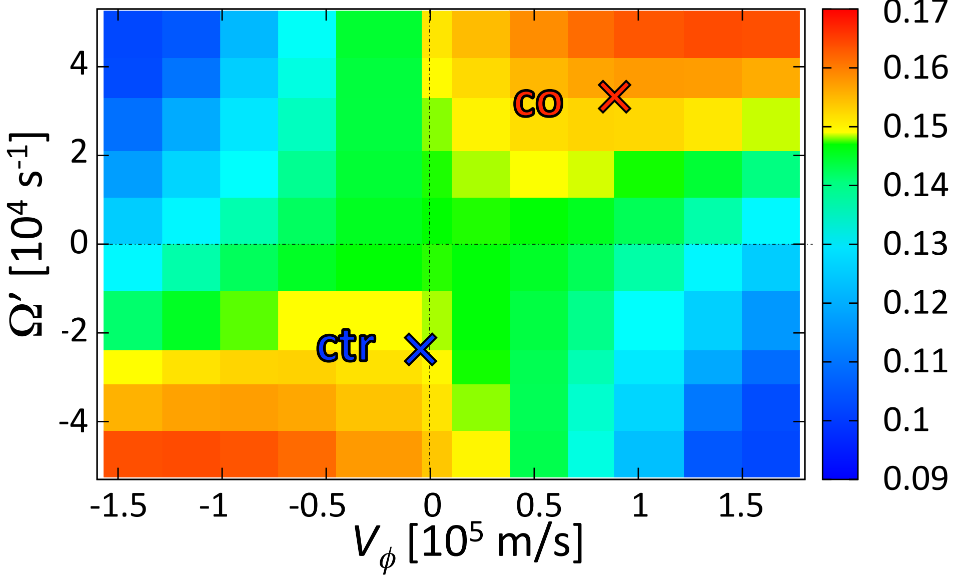
- ✓ all cases (co, bal and ctr) have Ω’ < 0.
- ✓ co -> bal -> ctr: Increase in γ
  - ➔ agreement with the experiment

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)

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



$\gamma/(c_s/a)$ at ρ=0.5 for $k_\theta\rho_s$=0.48

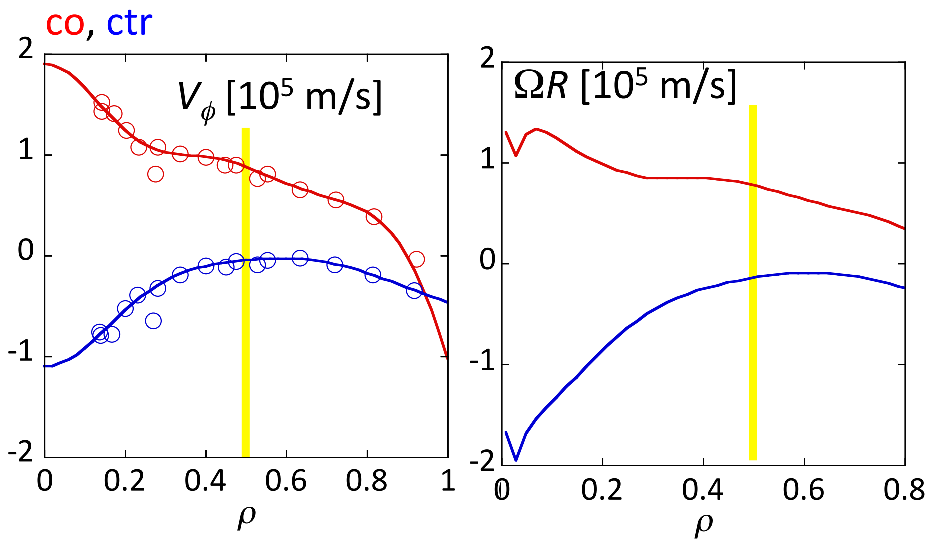


- ✓ co: $\Omega' > 0$, ctr: $\Omega' < 0$
- ✓ γ does not depend on the rotation direction.

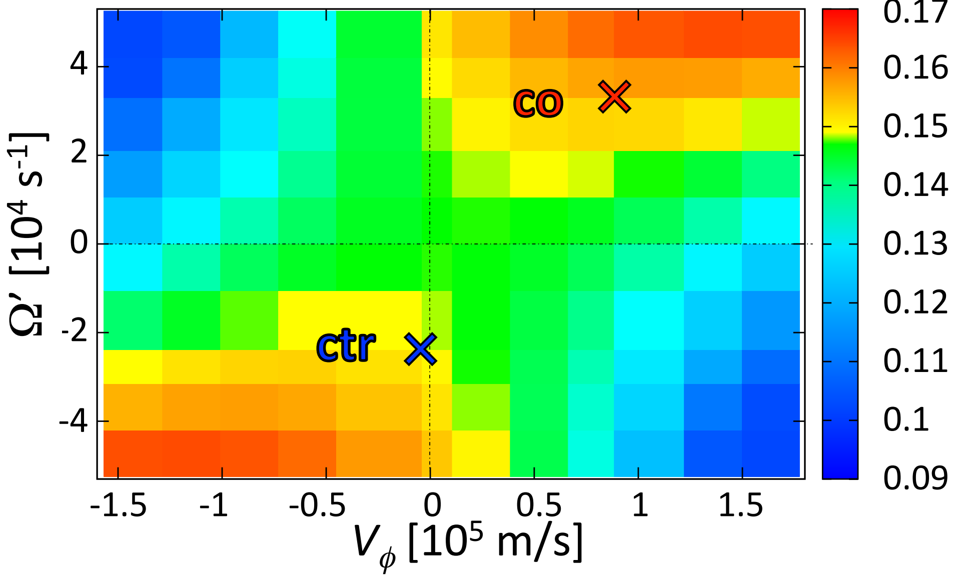
  ➔ agreement with the experiment

Conditions: Miller, Kinetic electrons, Main ions & an impurity, Electromagnetic ($B_\perp$ & $B_{//}$), $k_\theta\rho_s$=0.48, $k_x\rho_i$=0, Collision (pitch-angle scattering & energy diffusion)

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

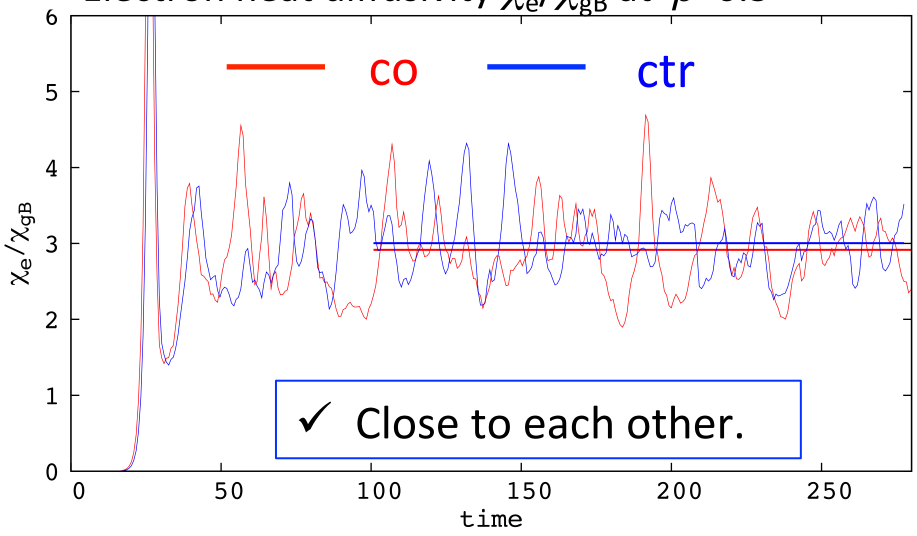


$\gamma/(c_s/a)$ at ρ=0.5 for $k_\theta\rho_s$=0.48

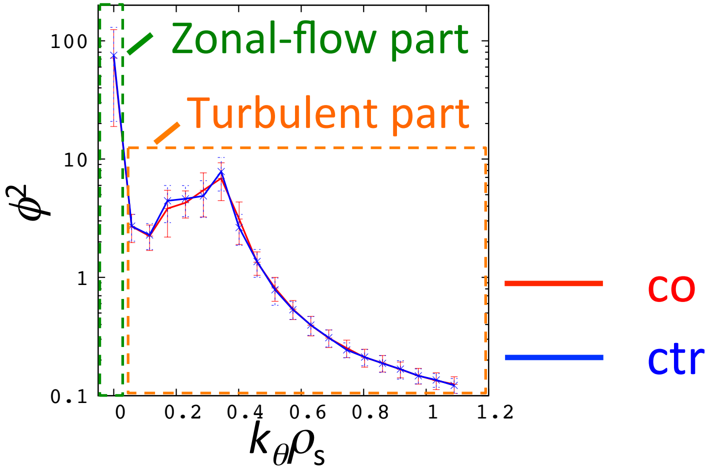


- Nonlinear simulations are performed for the H-mode plasma.

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



✓ Close to each other.



Conclusions and future work

☐ Inertial effects caused by toroidal rotation on heat transport 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 heat diffusivities for both rotation directions are close to each other.

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

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.