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Mechanism of toroidal flow generation by electron cyclotron heating in HSX and LHD plasmas

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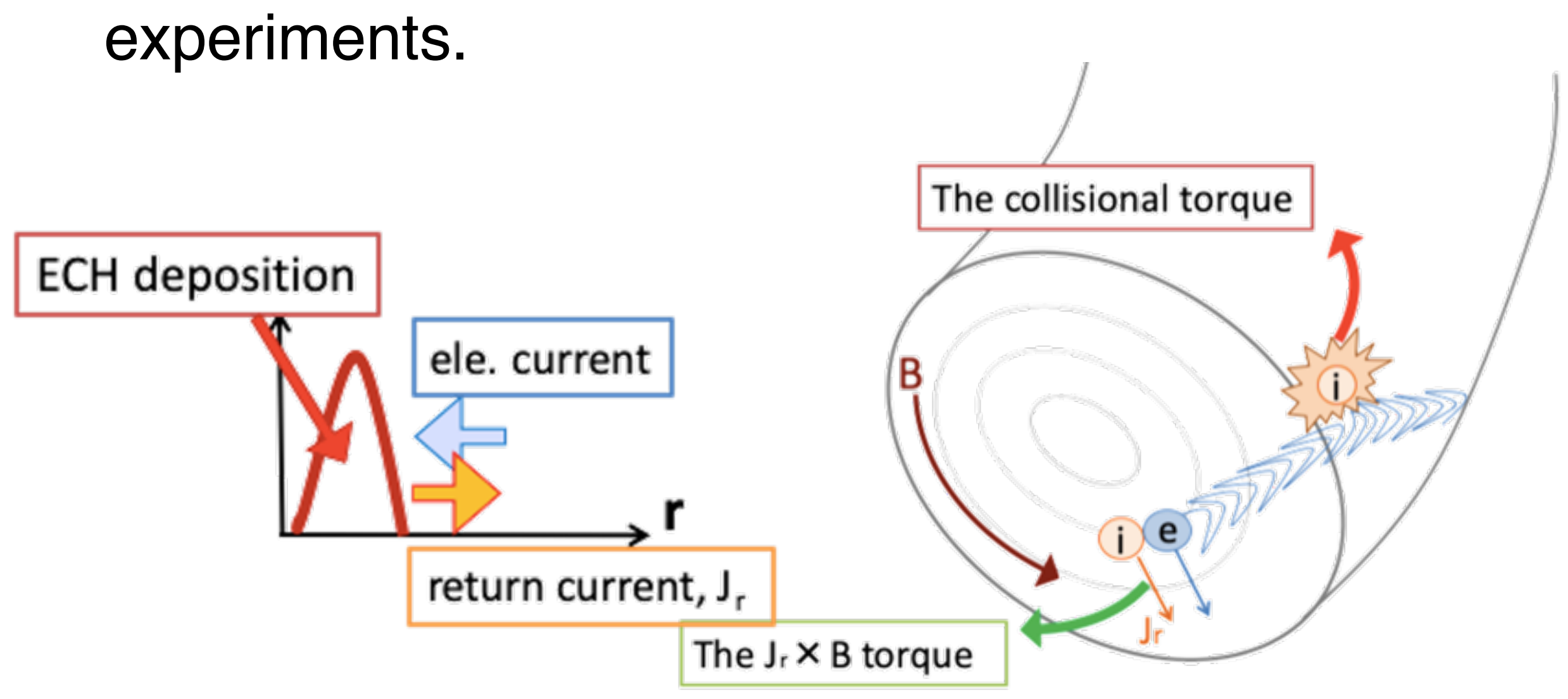
Abstract

- ✓ Spontaneous plasma flows have been observed in electron cyclotron heating (ECH) plasmas in HSX and LHD.
- ✓ We uncover that supra-thermal electrons generated by ECH can apply forces on the plasma through J×B and collisions, and the J×B force overcomes the collisional force in HSX and LHD.
- ✓ We evaluate the parallel flow, solving the momentum balance equations and the diffusion equation.
- ✓ As a result, the obtained flows have reasonable agreement with the experiments.

Introduction

- ✓ It has been observed that the toroidal flow and its shear are important for plasma confinement and MHD stability in many experiments.
- ✓ In a future reactor, NBI heating is not enough to drive a toroidal flow because of its high density and large size.
- ✓ Another method to drive the toroidal flow is required.
- ✓ Recently, the spontaneous toroidal flows driven by ECH has been observed in many tokamak and helical devices, e.g. JT-60U, LHD, HSX.
- ✓ In the previous studies, we have found that ECH can make the J×B & collisional forces, and the J×B force overcomes the collisional force in a non-symmetric configuration.
- ✓ In this study, we evaluate the toroidal flow driven by ECH force, and compare simulation results with experiments.



- ✓ Trapped supra-thermal electrons generate electron current due to the radial diffusion.
- ✓ Return current, J_r, cancels the electron current by ambipolar condition.
- ✓ The coupling with B makes the J_r×B force.

- ✓ The supra-thermal electrons drift toroidally due to the precession motion.
- ✓ During the slowing down, they transfer their momenta to the bulk plasma due to collisions.
- ✓ This is the collisional force.

Simulation model

GNET code [S.Murakami, NF (2000)]

- ✓ GNET code solves a linearized drift kinetic equation for energetic electrons in 5-D phase space based on the Monte Carlo technique .

$$\frac{\partial \delta f}{\partial t} + (\mathbf{v}_d + \mathbf{v}_{||}) \cdot \frac{\partial \delta f}{\partial \mathbf{r}} + \dot{\mathbf{v}} \cdot \frac{\partial \delta f}{\partial \mathbf{v}} - C^{coll} = S^{ql}$$

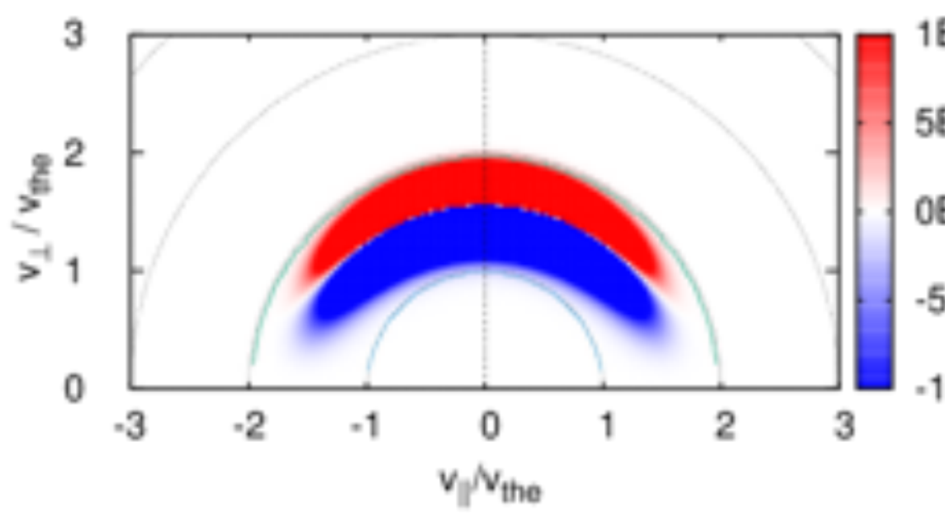
δf：oscillation part of velocity distribution
v_d：drift velocity,
C^{coll}：Collision operator,
$v_{||}$：parallel velocity,
S^{ql}：ECH quasi-linear diffusion operator

ECH quasi-linear source term

$$S^{\rm ql}(f_{\rm Max}) = \frac{\partial}{\partial v_i} D^{\rm ql}_{ij} \frac{\partial f_{\rm Max}}{\partial v_j}$$

r_0：heating point
D：Quasi-linear diffusion tensor
f_{Max}：Maxwell distribution

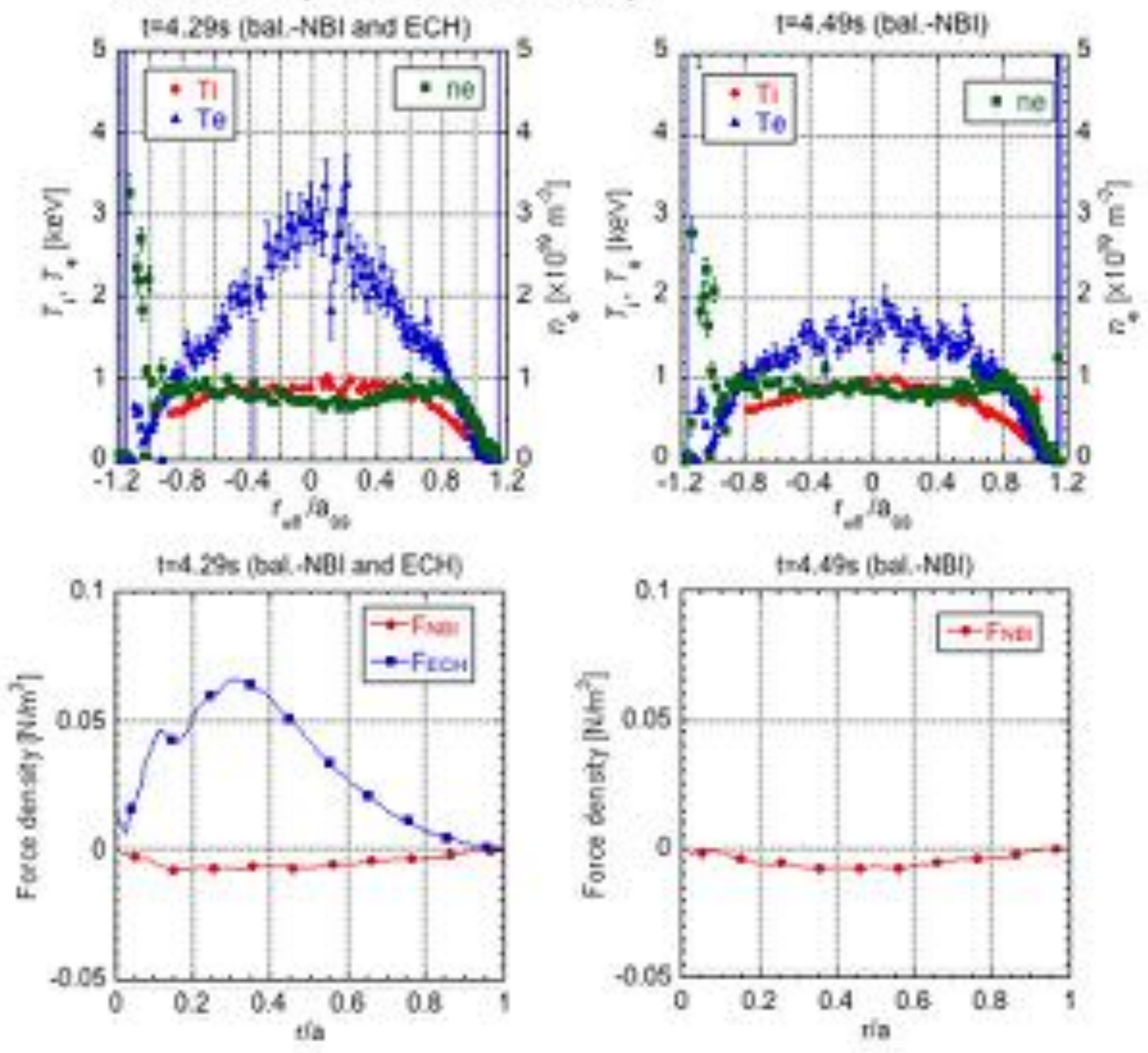
Example of the source term.
X-mode, $n\Omega_{ce}/\omega=1.02$, $N_{||}=0.0$



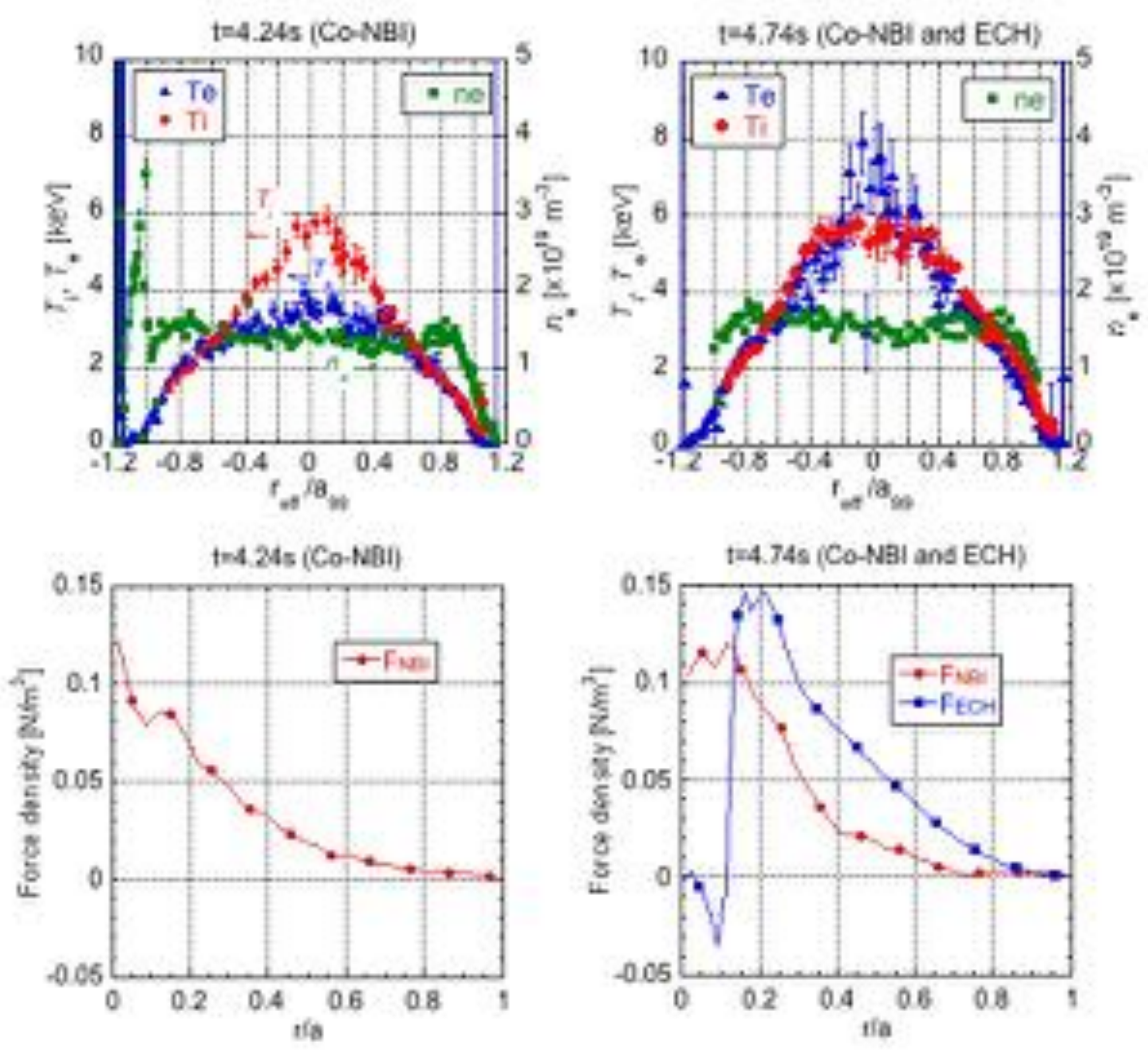
Simulation results

The Large Helical Device (LHD)

#129966 (bal.-NBI + ECH)



#129235 (Co-NBI + ECH)



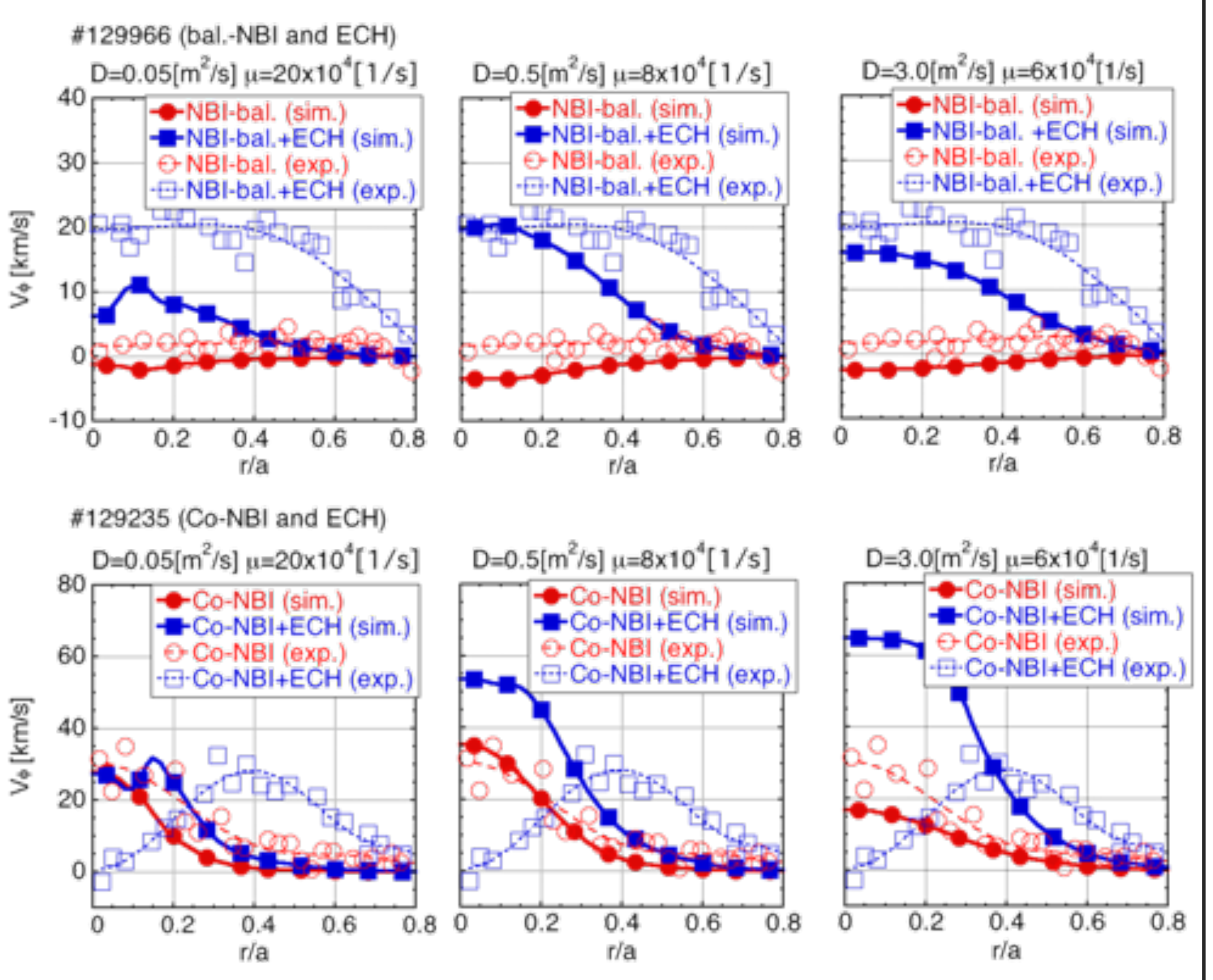
- ✓ The direction of the force is counter (co) direction in the inner (outer) region of the ECH heating location, and it qualitatively agrees with the experimental toroidal flow change.
- ✓ We can see the ECH force can be comparable with the NBI force.

Comparison with experiments

We evaluate the toroidal flow velocity in the steady state by solving momentum diffusion equation.

$$\frac{\partial V}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD\frac{\partial V}{\partial r}\right) + \frac{1}{m_i n_i}\left(F_{\rm ECH} + F_{\rm NBI} + F_{\rm NTV}\right)$$

$$F_{\rm NTV} = -m_i n_i \mu \left(\delta B/B\right)^2 V$$



- ✓ We reproduce the co-rotating toroidal flow quantitatively in the balanced-NBI+ECH heated case.
- ✓ With the relatively large coefficient (D = 0.5 & 3.0), the toroidal flow velocity increases over the entire minor radius.
- ✓ We see a difference in the toroidal flow profiles in the co-NBI+ECH heated case.

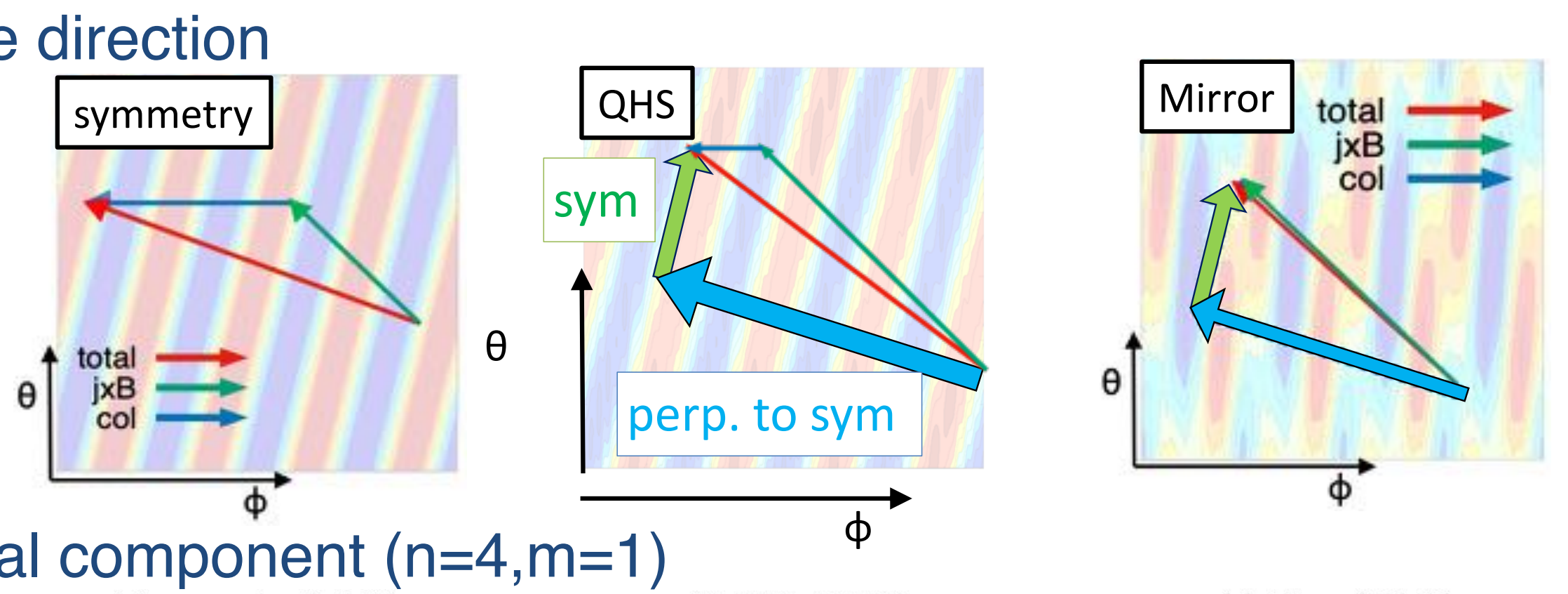
The helically symmetric experiment (HSX)

There are two typical configurations for HSX.

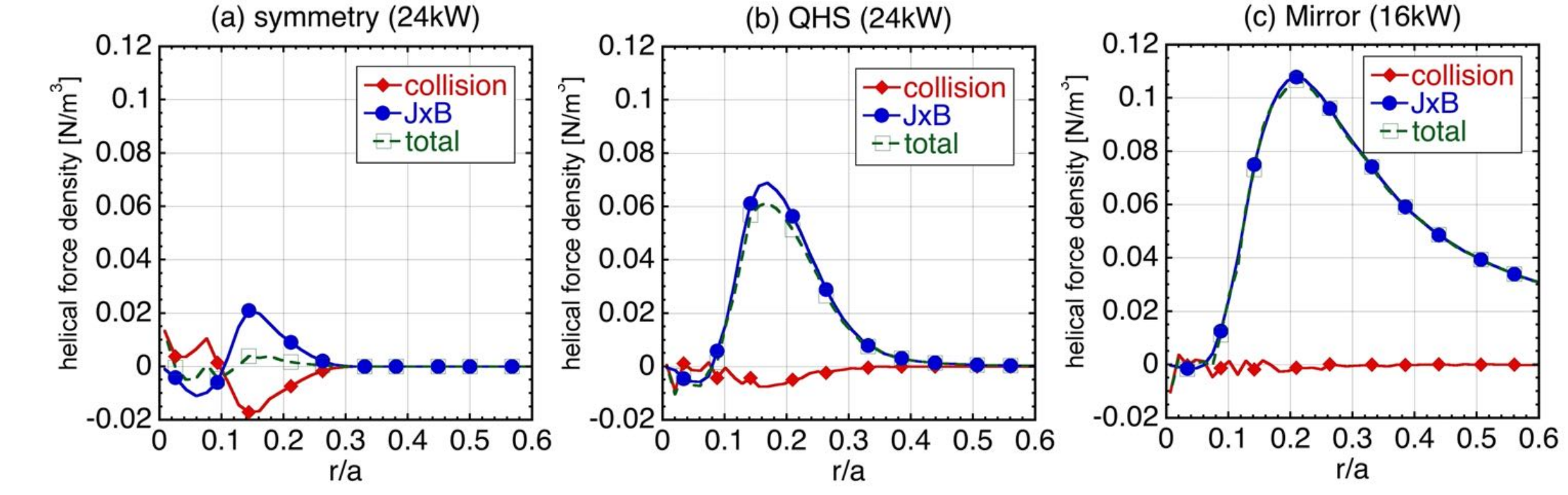
✓Quasi-Helical Symmetry (QHS) configuration
It has a single dominant helical component, $B_{(4,1)}$.

✓Mirror (FL14) configuration
Two toroidal mirror terms, $B_{(4,0)}$ & $B_{(8,0)}$, break the helical symmetry. Neoclassical viscosity of Mirror config. is larger than that of QHS config.

Force direction



Helical component (n=4,m=1)



Comparison with experiments

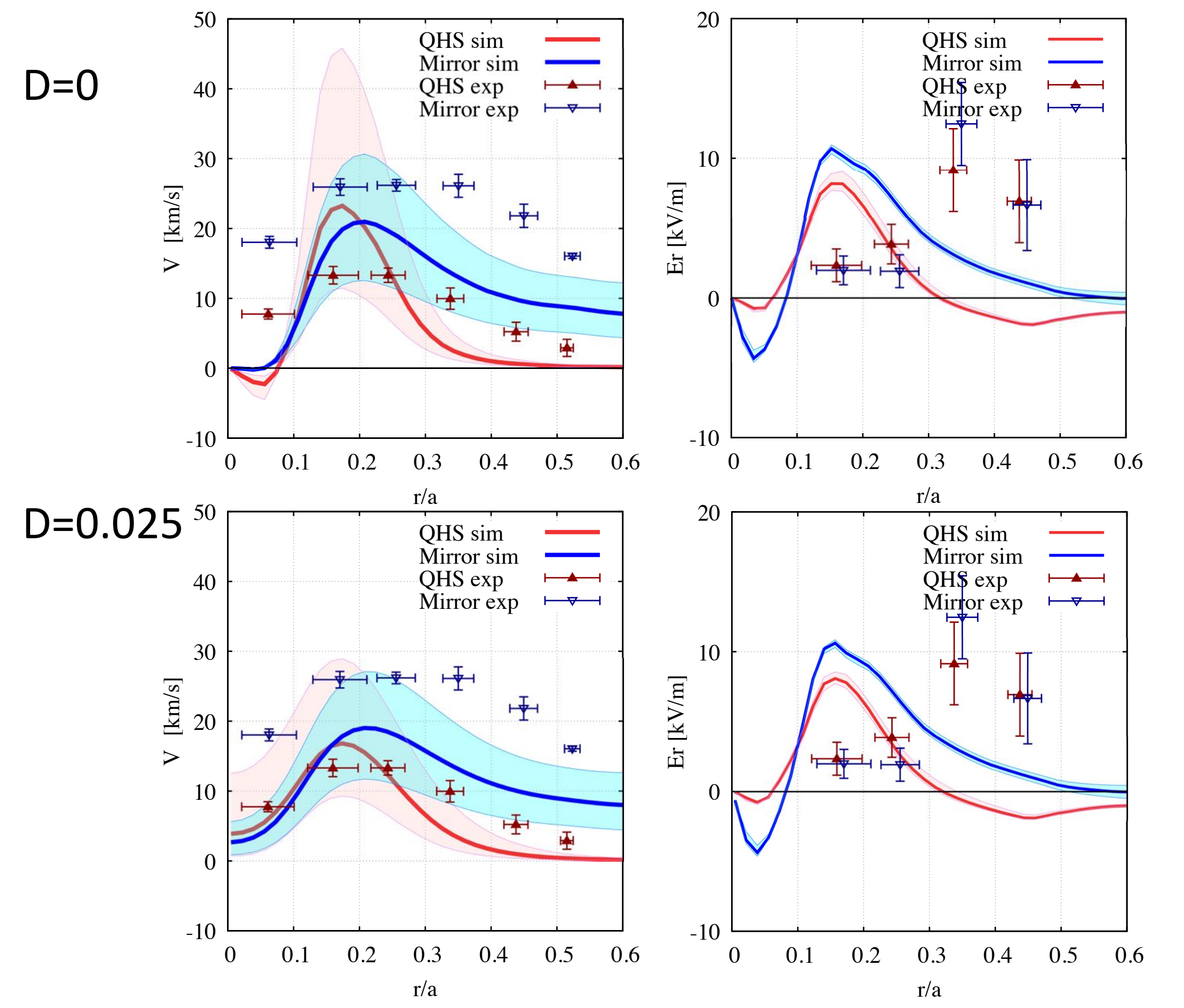
We solve the momentum balance equation and Ampere’s law to evaluate the toroidal flow and the radial electric field.

$$m_i N_i \frac{\partial}{\partial t}\langle \boldsymbol{B}\cdot\boldsymbol{U}\rangle = -\langle \boldsymbol{B}\cdot\boldsymbol{\nabla}\cdot\Pi_i\rangle - m_i N_i \nu_{in}\langle \boldsymbol{B}\cdot\boldsymbol{U}\rangle$$

$$m_i N_i \frac{\partial}{\partial t}\langle \boldsymbol{B_P}\cdot\boldsymbol{U}\rangle = -\frac{\sqrt{g}\boldsymbol{B}^{\zeta}\boldsymbol{B}^{\alpha}}{c}\langle \boldsymbol{J_{plasma}}\cdot\boldsymbol{\nabla}\rho\rangle - \langle \boldsymbol{B_P}\cdot\boldsymbol{\nabla}\cdot\Pi_i\rangle - m_i N_i \nu_{in}\langle \boldsymbol{B_P}\cdot\boldsymbol{U}\rangle$$

$$\frac{\partial}{\partial t}\frac{\partial \Phi}{\partial \rho}\langle \nabla\rho\cdot\nabla\rho\rangle = 4\pi\left(\langle \boldsymbol{J_{plasma}}\cdot\nabla\rho\rangle + \langle \boldsymbol{J_{ext}}\cdot\nabla\rho\rangle\right)$$

（+Diffusion term）



- ✓ In the case of the completely helically symmetric configuration, the helical components cancel each other.
- ✓ There is a net force in the symmetry direction even in QHS config. because other small magnetic modes enhance the radial diffusion.
- ✓ The force in Mirror config. is about twice as large as that in QHS config. despite the less absorbed power.
- ✓ The obtained velocity has reasonable agreement with experiment, especially with the diffusion effect.

Conclusion

- ✓ We have evaluated the J×B and collisional forces and toroidal flows using GNET code in order to clarify the mechanism of the toroidal flow change in HSX and LHD.
- ✓ The obtained force by ECH is the same order as NBI force, and its direction agree with experiment observation.
- ✓ The evaluated toroidal flows have reasonable agreement, except for the co-NBI+ECH case of the LHD experiment.
- ✓ It indicates that ECH force would drive the toroidal flow.

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