Effects of Electron Cyclotron Heating on the Toroidal Flow in Helical plasmas

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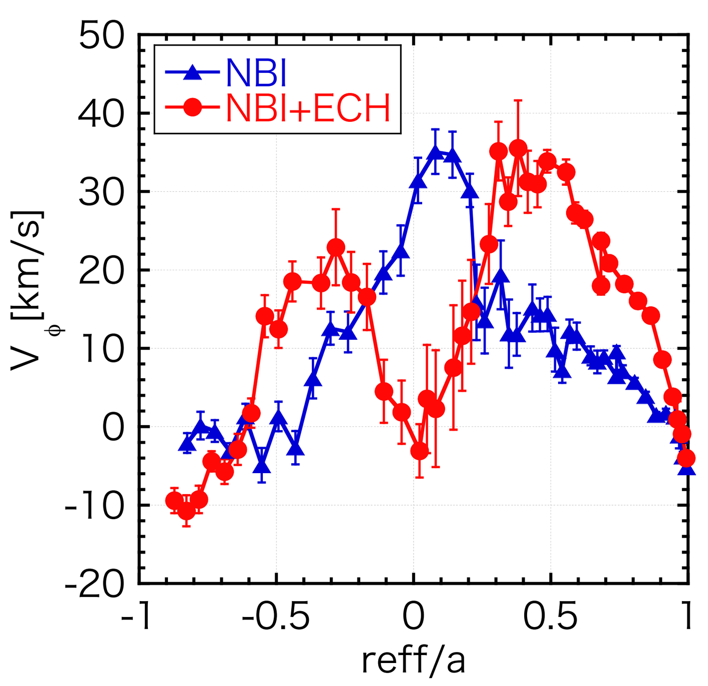
Introduction

- ✓ It has been observed that the toroidal flow and its shear are important for plasma confinement and MHD stability in many experiments.
- ✓ In the future reactor, NBI heating is not enough to make the 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 LHD, when ECH was applied into the NBI heated plasma, the profile of the toroidal flow was changed largely.

- ✓ In this study, we investigate the behavior of energetic electrons by ECH, whose return current may generate J×B force to drive the toroidal flow.
- ✓ The toroidal precession motions of trapped energetic electrons generate the averaged toroidal flow. The friction due to toroidal precession motion of electrons gives rise to the collisional force.
- ✓ We evaluate both torques and the toroidal flow velocity generated by these torques of the LHD experiment.

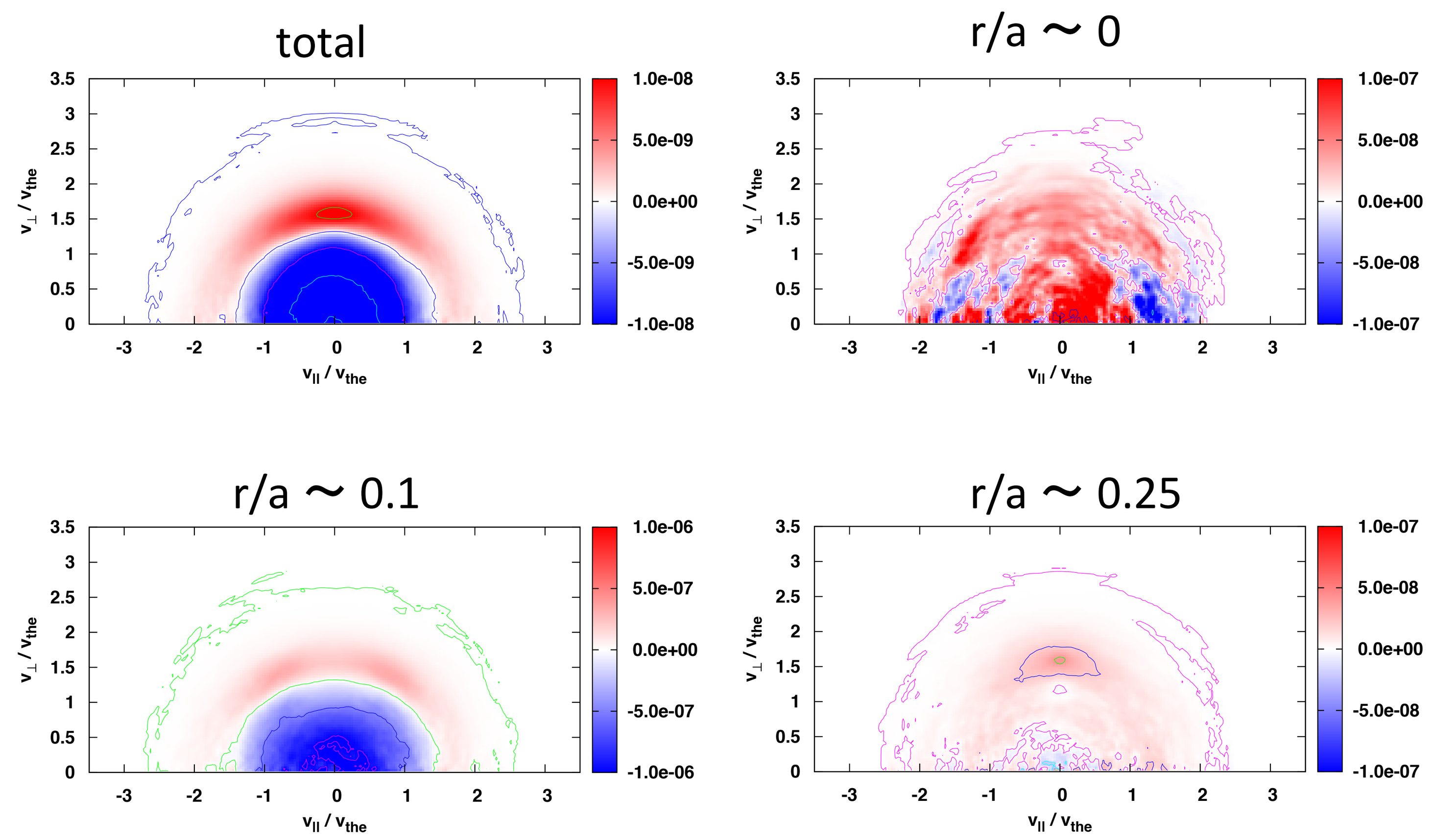


Typical plasma parameters

Temperature (T_i, T_e)	5.0 keV
Density(n_e)	$1.5\times10^{19}\,m^{-3}$
magnetic field	2.85 T
magnetic axis	3.60 m

Results

Velocity distribution



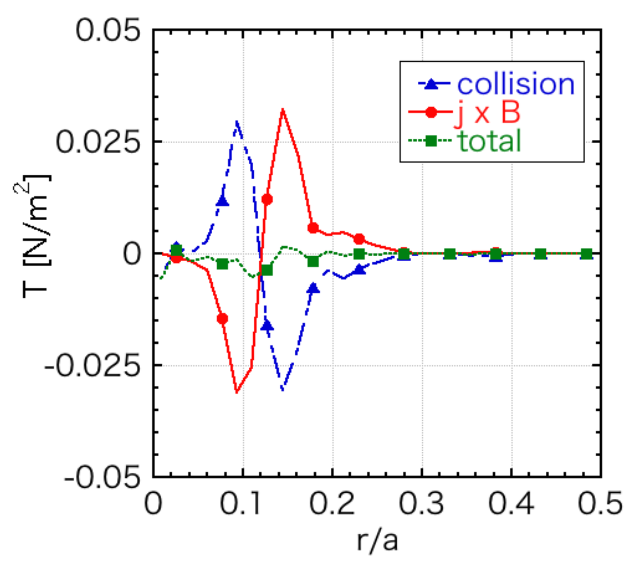
Energetic electrons can be found outer / inner regions apart from the heating point (r=0.1~0.2) .

⇨ The radial electron flux makes ion return current.

J×B・collisional torque

The JxB torque is a consequence of radial ion return current, in response to radial electron current. Therefore we evaluate toroidal torque $J_r x B_\theta$. Also the collisional torque is evaluated as the change of momentum due to collisions.

axisymmety configuration



- ✓ When the magnetic configuration is axisymmetry, the JxB and collisional torques of energetic particles cancel each other. [M.N. ROSENBLUTH, F.L.HINTON, NF,(1996)].
- ✓ We can see the cancellation of the two in ECH.

LHD configuration

Comparison of Toroidal flow

We consider a LHD size cylindrical plasma, and calculate the 1D-diffusion equation of the toroidal flow

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

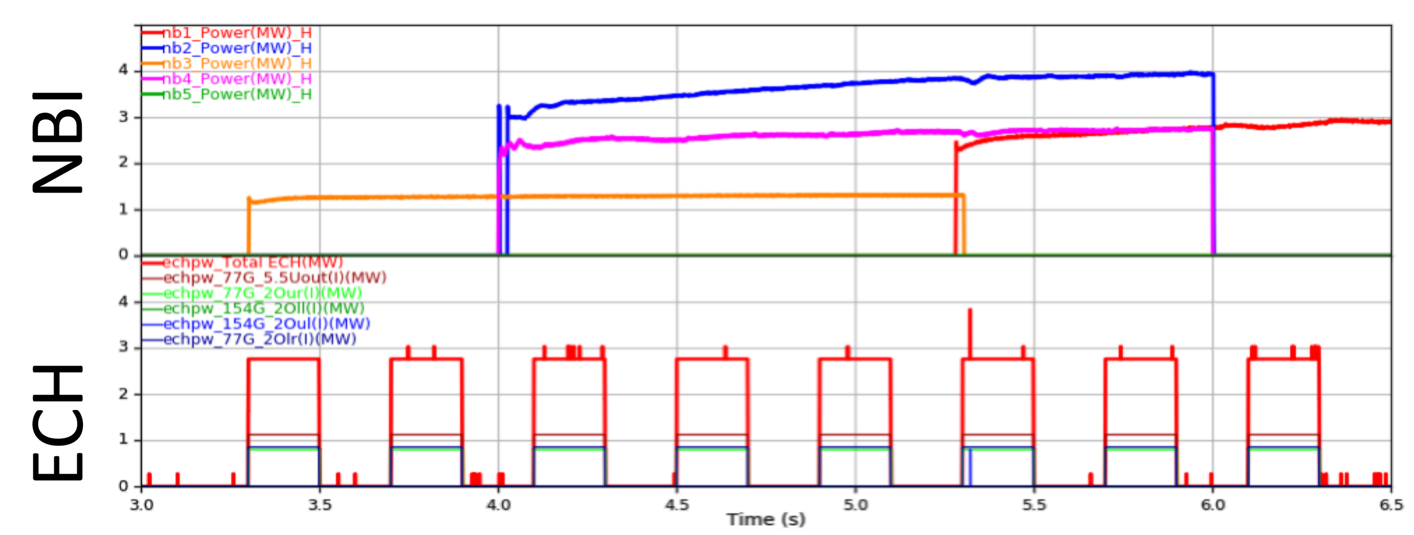
where D : radial diffusivity, T : (J×B, NBI, friction, NTV) torque. T_{NTV} is given as

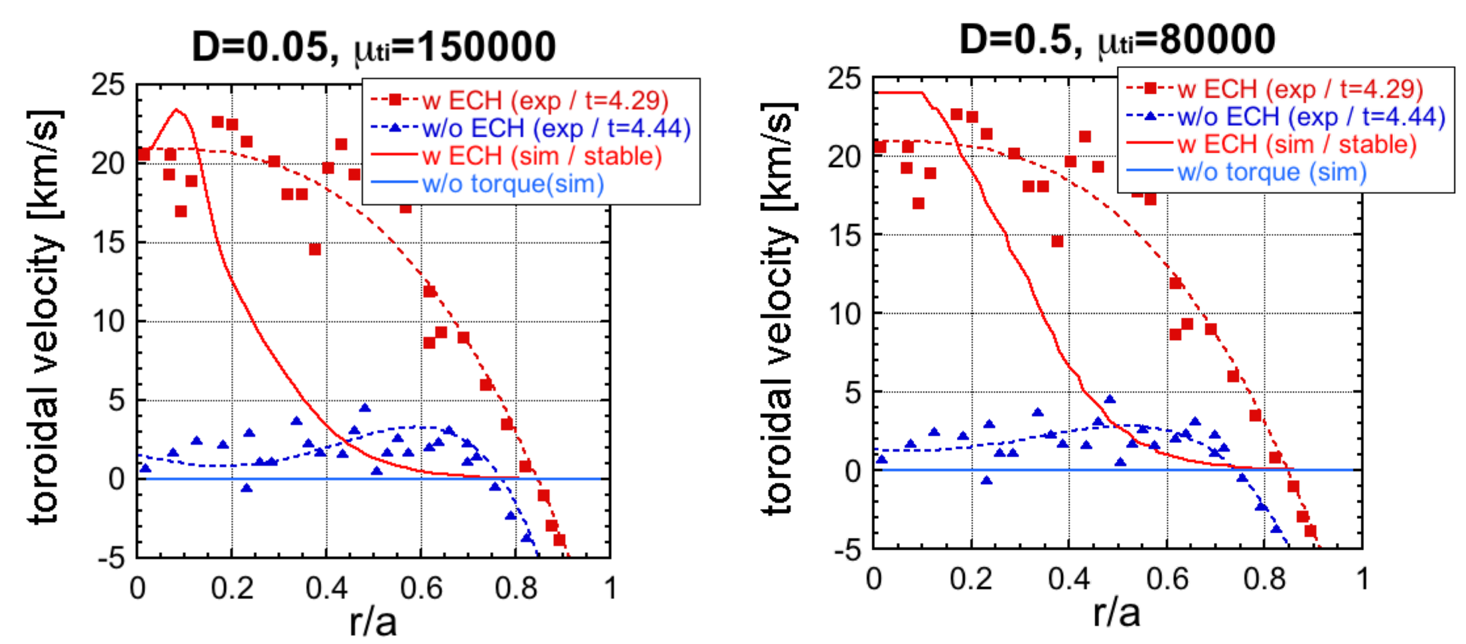
$$T_{\mathrm{NTV}} = -m_i n_i \mu_\parallel \langle RV \rangle \qquad \mu_\parallel = \mu_{ti}\frac{B_{\mathrm{eff}}^2}{B_0^2}$$

and we ignore the offset term this time.
The toroidal viscosity in CHS was approximately formulated and evaluated [K.Ida and N.Nakajima Phys. Plasmas (1997)] . According to the paper, we set the value of the viscosity, μ_{ti}, is 10^5 order.

Balanced NBI + ECH modulation

Bt=-1.375T , Rax=3.6m





Simulation model

GNET code

[S.Murakami et.al, Nucl.Fusion (2000)]

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

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

δf：oscillation part of velocity distribution

$v_\parallel$：parallel velocity,

v_d：drift velocity,

S^{ql}：ECH quasi-linear diffusion operator

C^{coll}：Collision operator,

ECH quasi-linear source term

$$S^{ql}(f_{\mathrm{Max}}) = \delta(\mathbf{r}-\mathbf{r}_0)\frac{\partial}{\partial v_i}D^{ql}_{ij}\frac{\partial f_{\mathrm{Max}}}{\partial v_j}$$

$$S^{ql} = -\delta(\mathbf{r}-\mathbf{r}_0)\frac{D}{v_{the}^2}\left(\frac{v_\perp}{v_{the}}\right)^2\left[2-\left(\frac{v_\perp}{v_{the}}\right)^2 - v_\perp^2\frac{\gamma^3}{\Delta c^2}\left(1-\frac{k_\parallel v_\parallel}{\omega}\right)X\right]\exp(-X^2)f_{Max}$$

$$(X = (\gamma(1-k_\parallel v_\parallel/\omega) - 2\Omega_{ce}/\omega)/\Delta)$$

v_{the}：thermal velocity

r_0：heating point

$v_\perp$：perpendicular velocity

$v_\parallel$：parallel velocity

γ：Lorentz factor

Ω_{ce}：electron cyclotron frequency

c：light speed

$k_\parallel$：parallel wave number

ω：wave frequency

f_{Max}：Maxwellian distribution

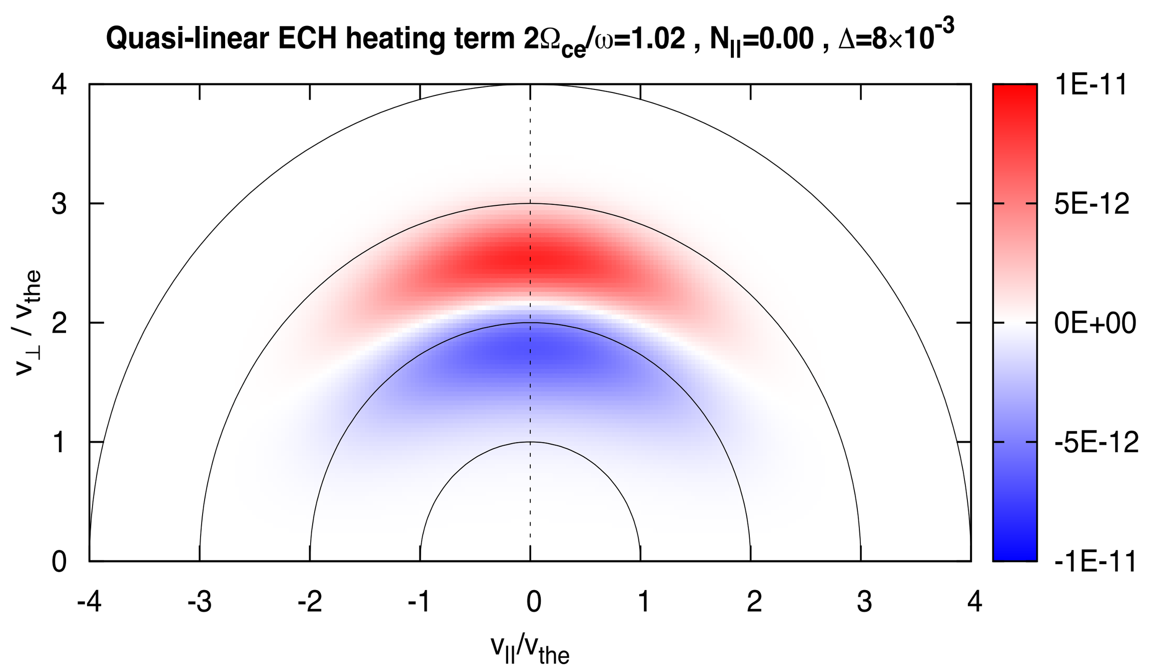
Δ：very small parametar (≪1)

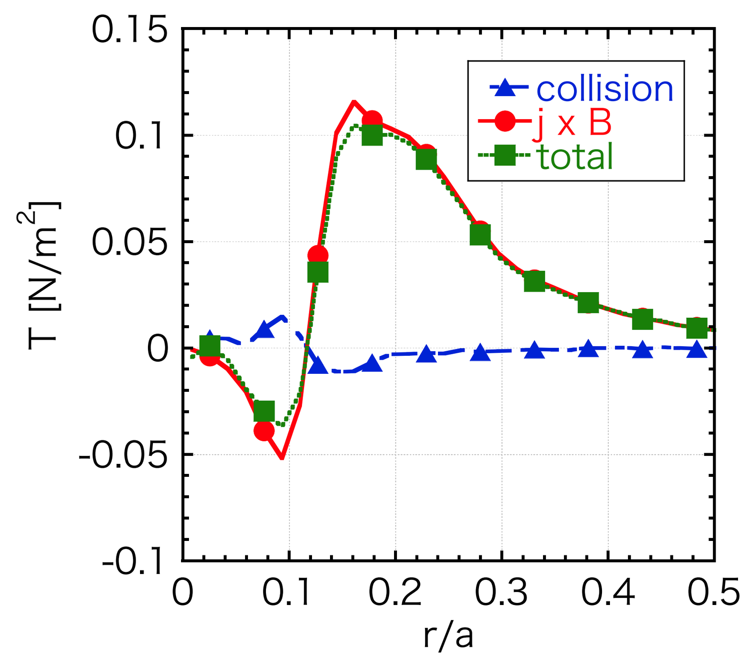
D：Constant value

An example of ECH quasi-linear source term.

- 154GHz, 2nd X-mode, $N_\parallel$=0

- The heating point (r_0) is decided by ray tracing.





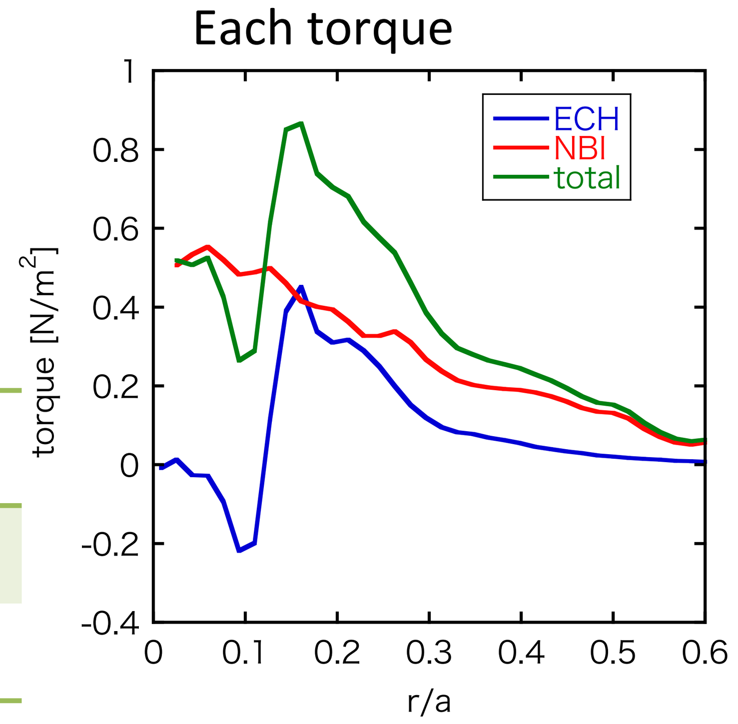
ECH:1MW

In LHD, the JxB torque is larger than the collisional torque sufficiently.

NBI torque

NBI heating parameters : injection energy and heating power.

Co #1	190keV	6.12MW
Ctr #2	176keV	4.75MW
Co #3	170keV	2.23MW



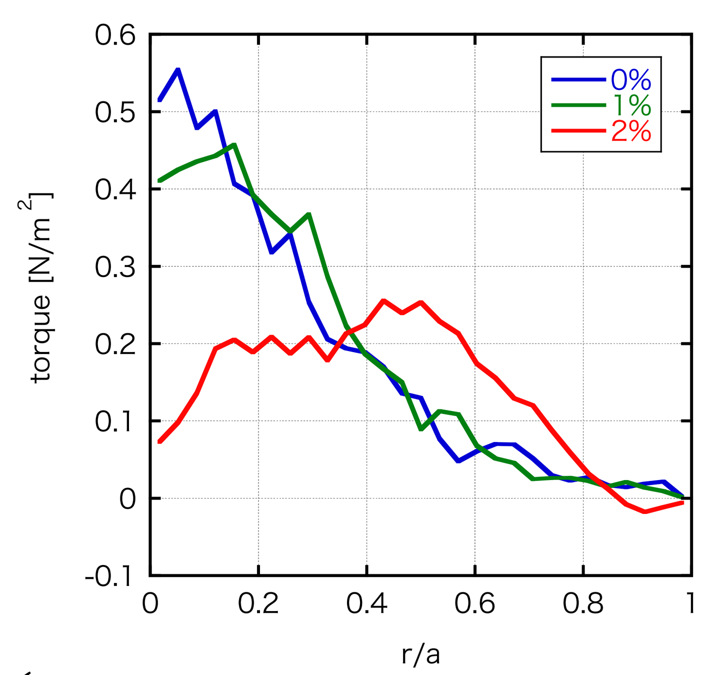
FIT3D code

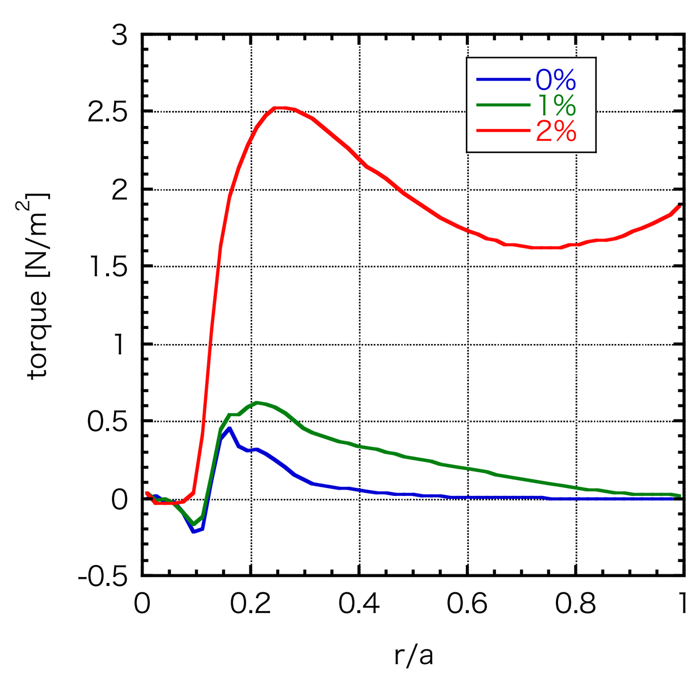
✓ FIT3D code can calculate the profile of heat deposion, beam pressure, and particle source by NBI heating in non-axisymmetry torus magnetic configuration.

✓ We calculate NBI torque, applying the FIT3D code.

J×B torque is the same order as NBI torque, and Ctr / Co direction at the inner / outer of heating point.

β value





✓ As plasma beta value increases, magnetic axis shifts and configuration is changed.

✓ As beta value increase, NBI torque becomes weaker and ECH torque become dominant.

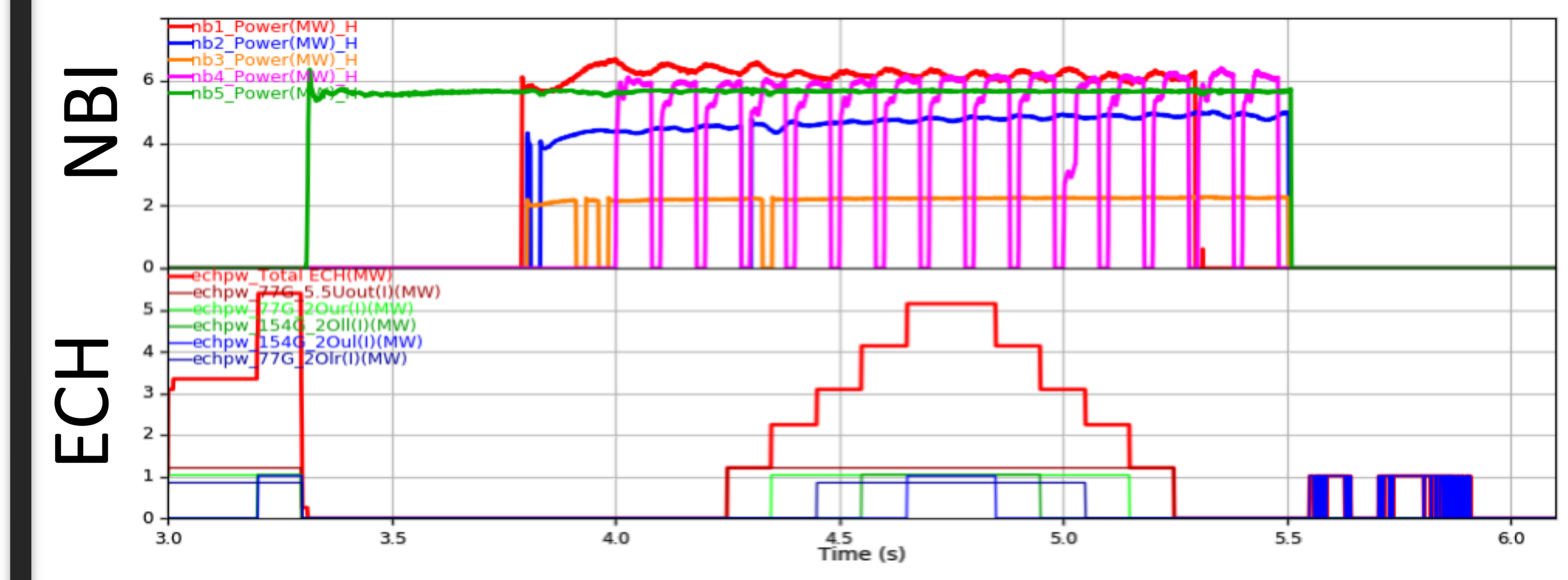
✓ In β 2% plasma, large number of energetic electrons get away from core region, so the JxB torque in the center region comes close to zero.

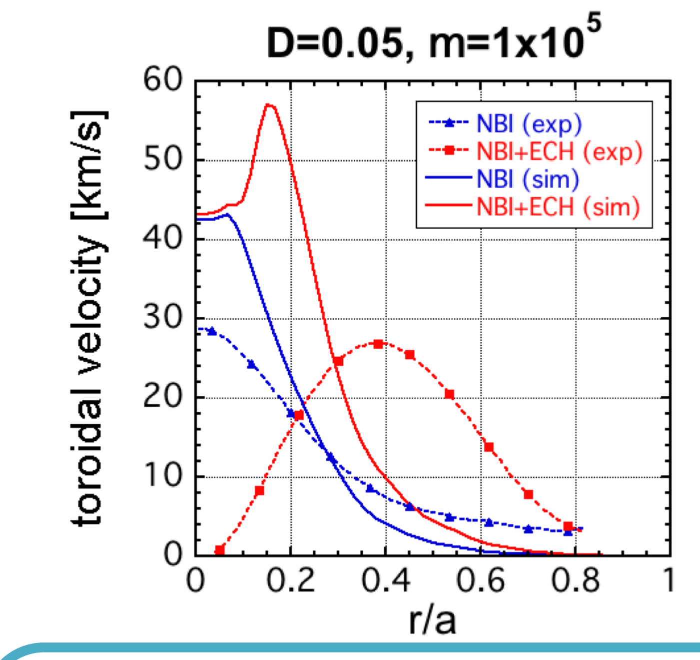
✓ It shows good agreement.

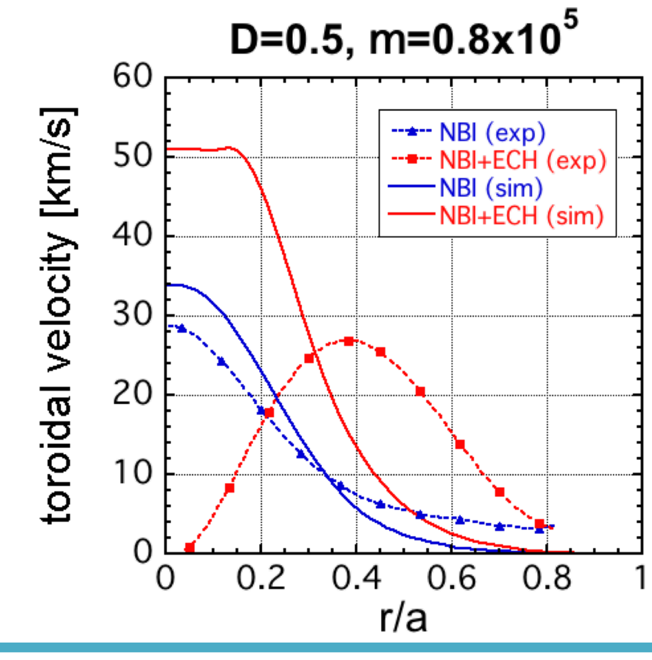
✓ The obtained flow velocity is much lower than experiment in the peripheral region. The damping effect is overestimated.

NBI(Co) + ECH5MW

Bt=-2.85T , Rax=3.6m







✓ The JxB torque of ECH suppresses / enhances the toroidal flow at the inner/outer of heating point.

✓ It agrees with experiment observation qualitatively.

✓ The velocity of the core region doesn’t reduces to zero.

✓ When D is large, it does not agree with experimental observation.

Summary

✓ We have evaluated the radial diffusion of energetic electrons by ECH using GNET code in order to make clear the mechanism of the toroidal flow change in LHD plasma heated by ECH and NBI.

✓ The obtained JxB torque is the same order as NBI torque and its direction agree with experiment observation.

✓ We have evaluated the toroidal flow velocity by NBI and ECH, and found that ECH would affect the toroidal velocity.