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Simulation studies of core heat transport in JT-60U plasmas with different toroidal rotation profiles

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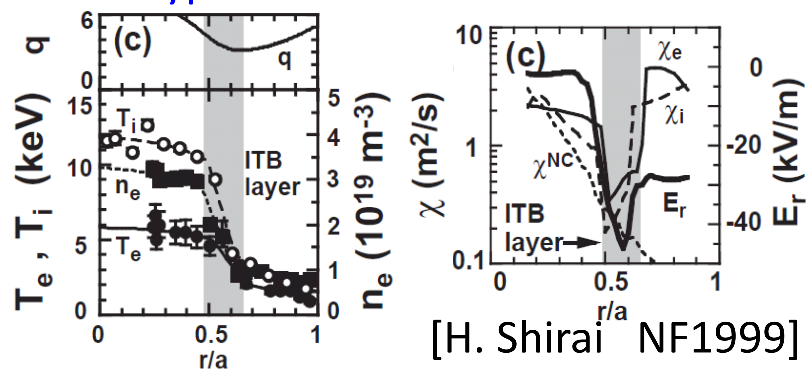
This work was carried out using the HELIOS supercomputer system at International Fusion Energy Research Centre, Aomori, Japan, under the Broader Approach collaboration between Euratom and Japan, implemented by Fusion for Energy and JAEA.

Improved confinement related to toroidal rotation

- The improved confinement mode with internal transport barriers (ITBs) has been observed in plasmas with the strong E_r shear.

Box type ITB

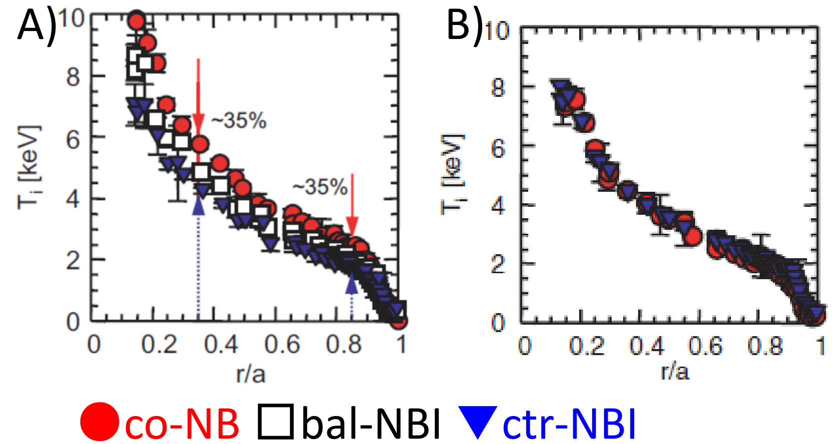


[H. Shirai NF1999]

A) The pedestal temperature increases with co-toroidal rotation and profile stiffness.

B) Identical core temperature profiles have been observed for co- and counter- rotating plasmas with identical pedestal temperature.

Conventional H-mode



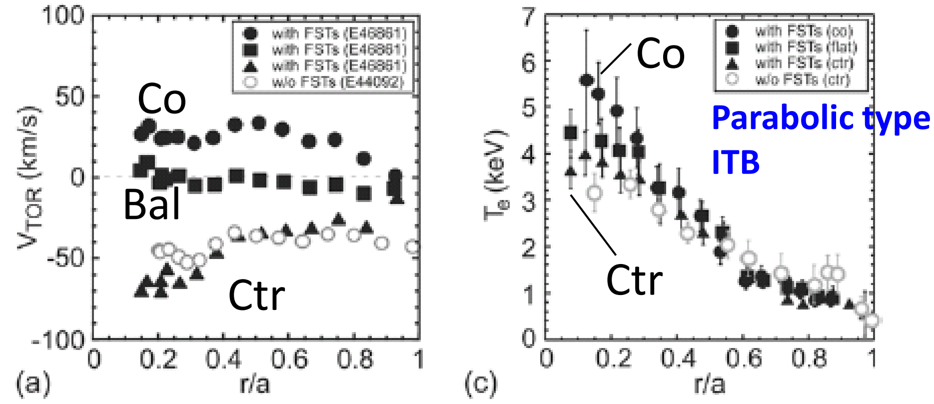
[H. Urano NF2008]

➡ Does toroidal rotation have little influence on core hear transport without the strong change in E_r shear?

Influence of co-toroidal rotation on T_e-ITB

- The better T_e-ITB with co-toroidal rotation has been observed.
- The difference in E_r shear is small.

[N. Oyama NF2007]



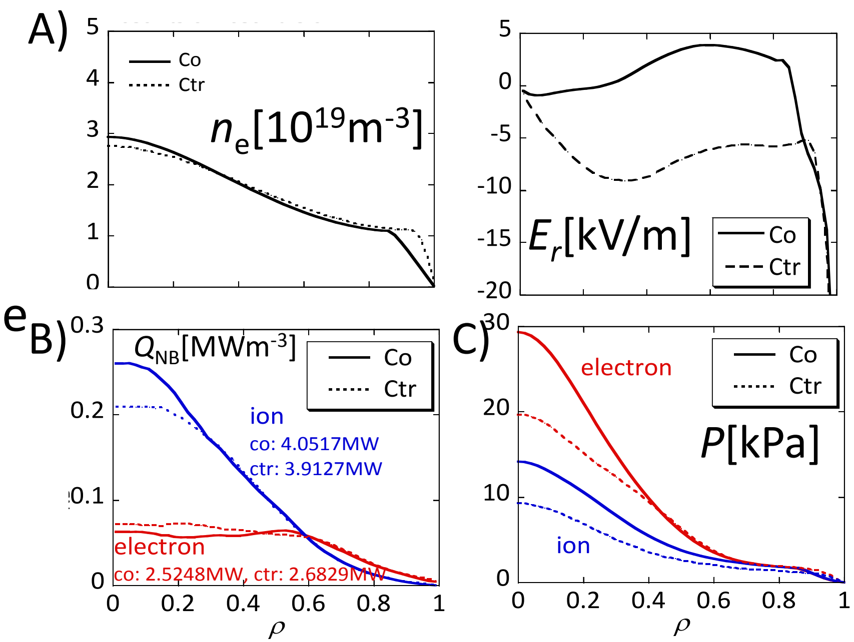
<u>Points of these plasmas</u>

A) The slight difference in the core n_e profile

B) Similar power deposition profiles

C) With a change in the toroidal rotation profile

- P_e increases larger in the core region
- P_i increases larger in the pedestal region and is maintained with similar profile



Investigation of toroidal rotation effects on core heat transport

Investigate effects of toroidal rotation on core heat transport in conventional H-mode and parabolic type ITB plasmas using

- Transport models implemented in the transport code TOPICS
- The flux-tube gyrokinetic code GS2

First order equilibrium flows in Tokamaks

$$\mathbf{V_a} = \underline{\omega_\mathrm{a}(\psi) R\hat{\boldsymbol{\phi}}} + \underline{\hat{u}_{\mathrm{a}\theta}\mathbf{B}}$$

Toroidal flow

Parallel flow

↓

$$\omega_\mathrm{a}(\psi) \equiv \underline{\underline{-\frac{d\Phi}{d\psi}}} - \frac{1}{n_\mathrm{a} e_\mathrm{a}}\frac{dp_\mathrm{a}}{d\psi}$$

Including radial electric field effects

<u>Focus on *ExB* shear representing toroidal rotation in this study</u>

Integrated suite of codes TOPICS

TOkamak Prediction and Interpretation Code System [N. Hayashi PoP2010]

- 1D transport & 2D MHD equilibrium
- Time-dependent / Steady-state analysis of JT-60U experiment
- Simulation with transport model

  Neoclassical : MI method or NCLASS, Anomalous : CDBM, GLF23, BgB, MMM95
- Development of toroidal momentum eq. solver consistent with E_r (M. Honda)
- Tuning of CDBM model to LH transition (M. Yagi, PET2011)

Components

- NB & High energy particle : 1D or 2D FP, 3D MC (F3D-OFMC)
- EC : Ray tracing & Relativistic FP (EC-Hamamatsu)
- IC : Full wave analysis (TASK/WM), LH : Bonoli module in ACCOME
- MHD stability : Kink / Ballooning / Peeling (MARG2D)
- Impurity : 1D transport (IMPACT)
- Neutral : 2D MC
- Radiation : Impurity line radiation model (Coronal eq.), Synchrotron (CYTRAN)
- SOL / Div. : Five-point model (D5PM), 2D Fluid & MC (SONIC)
- Pellet : Ablated Pellet with ExB drift (APLEX)

* ——— ･･･used in this study

Transport models implemented in TOPICS

- *Given*: The MHD equilibrium, the q profile, the density profile
- *Calculate*: ion and electron temperatures in $\rho < 0.85$
- The anomalous heat diffusivity is given by following transport models.

- Current Diffusive Ballooning Mode (CDBM) [e.g. A. Fukuyama PPCF1995]

$$\chi_{\mathrm{CDBM}} = C\frac{c^2}{\omega_{\mathrm{pe}}^2}\frac{v_{\mathrm{A}}}{qR}|\alpha_{th}|^{3/2}F(s,\alpha)G(\kappa)H(\omega_{E\times B})$$

Thermal pressure

$$H(\omega_{E\times B}) = \frac{A}{1+(B\omega_{E\times B}/\gamma_{\mathrm{CDBM}})^K}$$

$$\begin{cases} \omega_{E\times B} = \frac{RB_\theta}{B_{\mathrm{t}}}\left|\frac{d}{dr}\frac{E_r}{RB_\theta}\right| \\ \gamma_{\mathrm{CDBM}} = |\alpha|^{1/2}\frac{v_{\mathrm{A}}}{qR}F(s') \end{cases}$$

- GLF23 [R. E. Waltz PoP1997, J. E. Kinsey PoP2005]
  - Mixing length formula is used to obtain the heat diffusivity with 10 wavenumbers for ion temperature gradient(ITG) and trapped electron mode(TEM) and 10 wavenumbers for electron temperature gradient(ETG) mode.
  - ITG/TEM is stabilized by the effect of *ExB* shear.

$$\gamma_{\mathrm{net}} = \gamma - \alpha_{\mathrm{E}}|\gamma_{E\times B}| \qquad \gamma_{E\times B} = \frac{RB_\theta}{B_{\mathrm{t}}}\left|\frac{d}{dr}\frac{E_r}{RB_\theta}\right|$$

- Bohm/gyro-Bohm (BgB) [modified from M. Erba PPCF1997]

$$\begin{cases} \chi_{\mathrm{e}} = 8\times 10^{-5}\chi_{\mathrm{B}}F_{\mathrm{shear}} + 7\times 10^{-2}\chi_{\mathrm{gB}} \\ \chi_{\mathrm{i}} = 1.6\times 10^{-4}\chi_{\mathrm{B}}F_{\mathrm{shear}} + 1.75\times 10^{-2}\chi_{\mathrm{gB}} \end{cases}$$

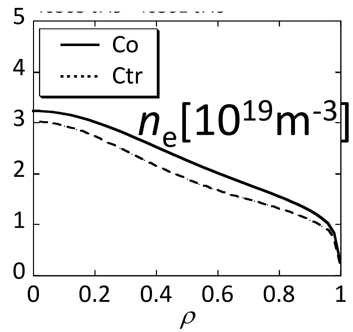
$$\begin{cases} \chi_{\mathrm{B}} = \frac{\nabla(n_{\mathrm{e}}T_{\mathrm{e}})}{n_{\mathrm{e}}B_{\mathrm{t}}}q^2\left(\frac{T_{\mathrm{e}}(0.8\rho_{\max})-T_{\mathrm{e}}(\rho_{\max})}{T_{\mathrm{e}}(0.8\rho_{\max})}\right) \\ \chi_{\mathrm{gB}} = \rho^*\frac{|\nabla|T_{\mathrm{e}}}{B_{\mathrm{t}}} \end{cases}$$

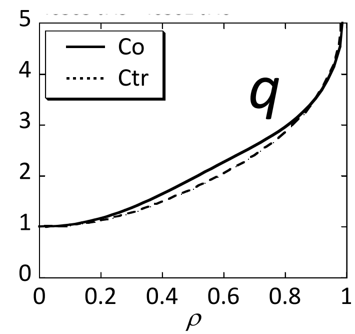
$$F_{\mathrm{shear}} = \frac{1}{1+\exp\{20(0.05+\omega_{E\times B}/\gamma_{\mathrm{ITG}})-s\}}$$

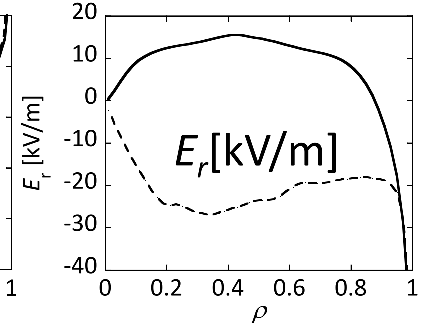
$$\gamma_{\mathrm{ITG}} = 0.1\frac{c_{\mathrm{s}}}{a}\left(\frac{a}{L_{n_{\mathrm{i}}}}+\frac{a}{L_{T_{\mathrm{i}}}}\right)^{0.5}\left(\frac{T_{\mathrm{i}}}{T_{\mathrm{e}}}\right)^{0.5}$$

Calculations with CDBM for H-mode shots

Co	Ctr
I_p =1.16MA	I_p=1.16MA
B_t=2.56T	B_t=2.56T
H=1.074	H=1.049
W_e=0.7705MJ	W_e=0.6741MJ
W_i=0.5778MJ	W_i=0.4551MJ







CDBM model

Ion

T_i similar to exp. for $\rho > 0.3$

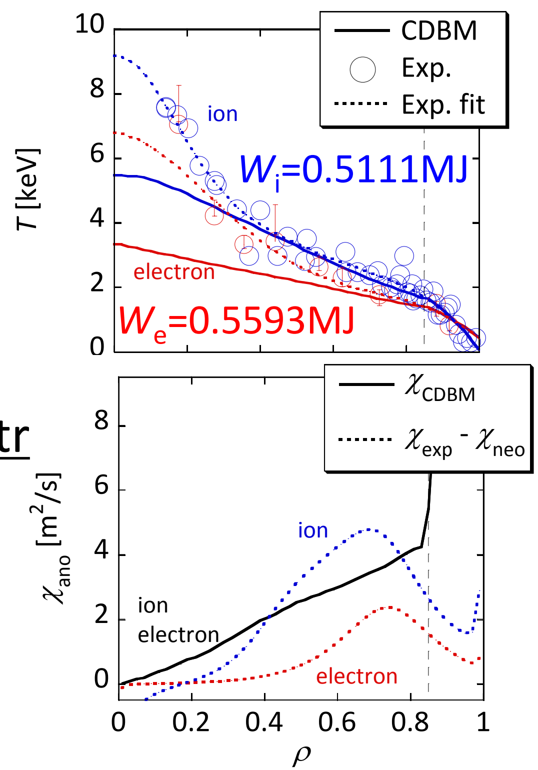
Electron

T_e lower than exp. with high χ_e

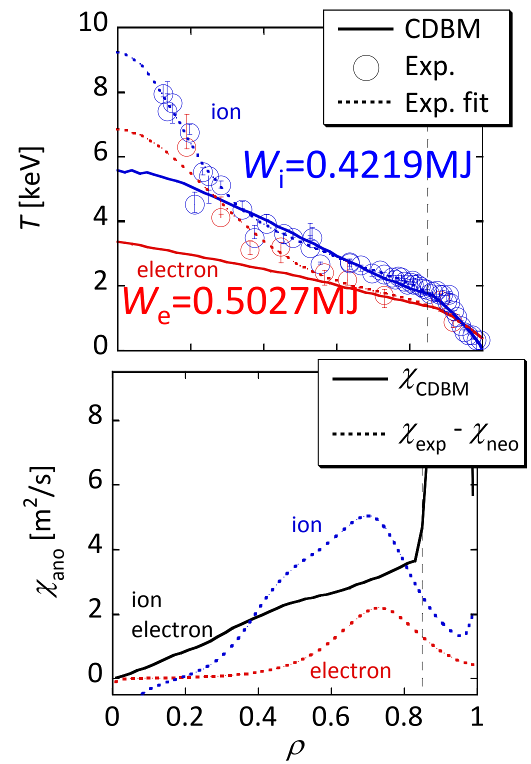
Comparisons between co and ctr

Little difference

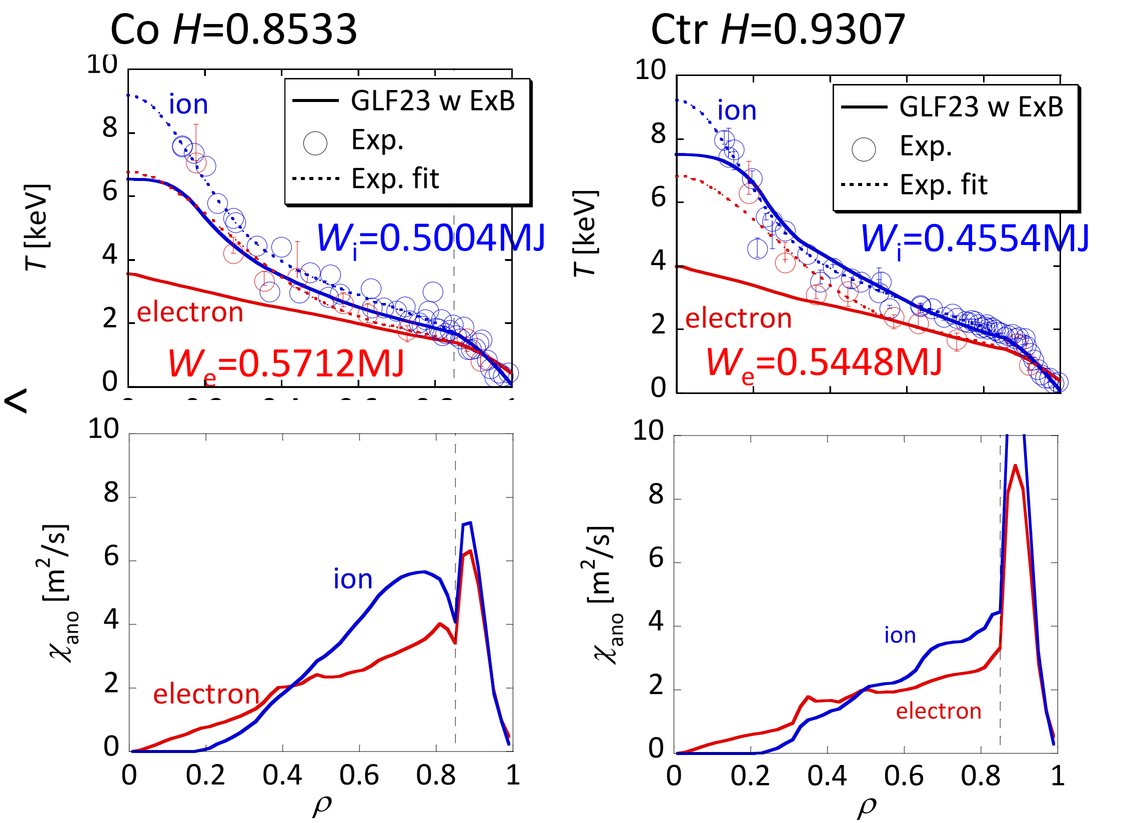
Co H=0.8518



Ctr H=0.8587



Calculations with GLF23 for H-mode shots



Ion

similar T_i profile to exp. for $\rho > 0.2$
Better agreement for ctr case

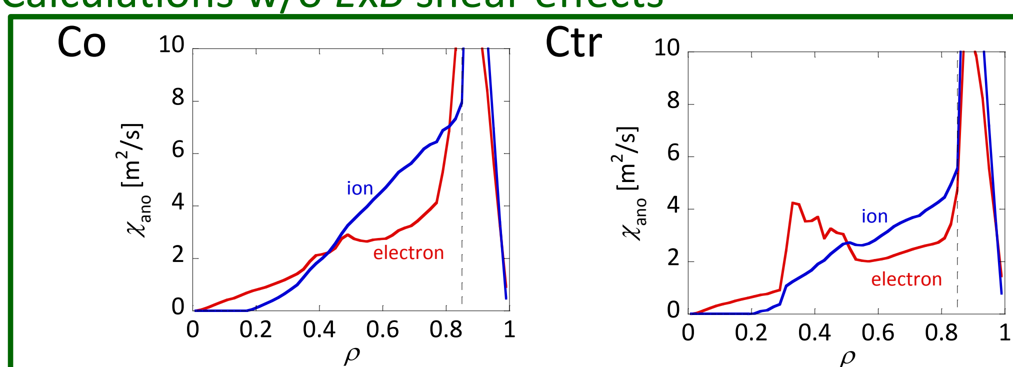
Electron

lower T_e than exp., especially for $\rho <$ 0.5

Comparisons between co and ctr

- Predicted χ_i for co rotation is larger than that for ctr rotation.
- However, the difference in χ_i is not caused by *ExB* shear effect.

Calculations w/o *ExB* shear effects



Calculations with BgB for H-mode shots

Ion

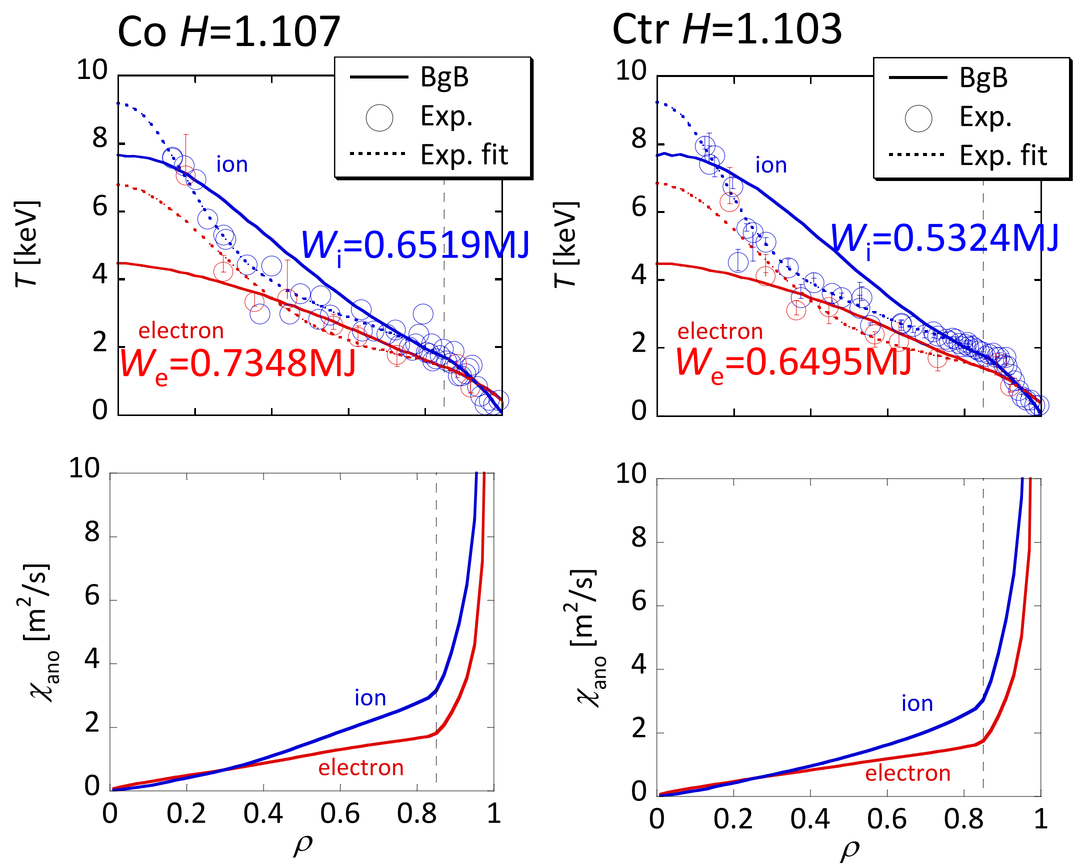
overestimated T_i with much smaller χ_i than exp., especially for $0.4 < \rho < 0.8$

Electron

T_e similar to exp. for $\rho > 0.3$

Comparisons between co and ctr

Little difference



Calculations with CDBM for parabolic ITB shots

Co

I_p=0.9MA

B_t=1.60T

H=1.133

W_e=0.5233MJ

W_i=0.3252MJ

Ctr

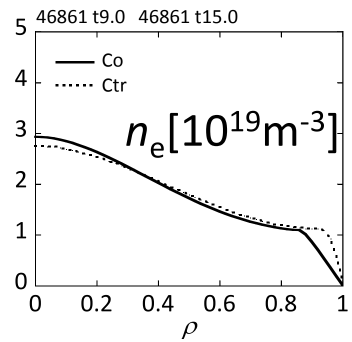
I_p=0.9MA

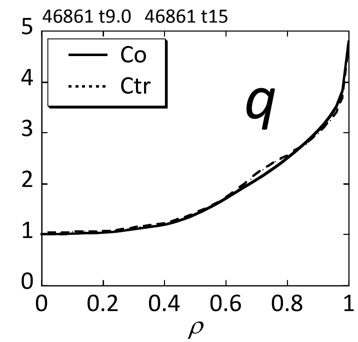
B_t=1.59T

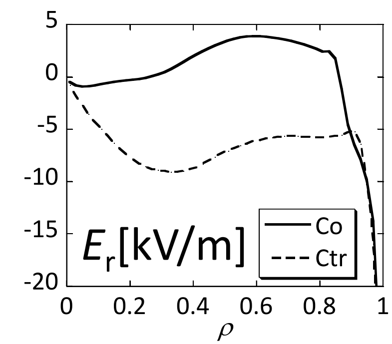
H=0.9128

W_e=0.4698MJ

W_i=0.2268MJ







CDBM model

Ion

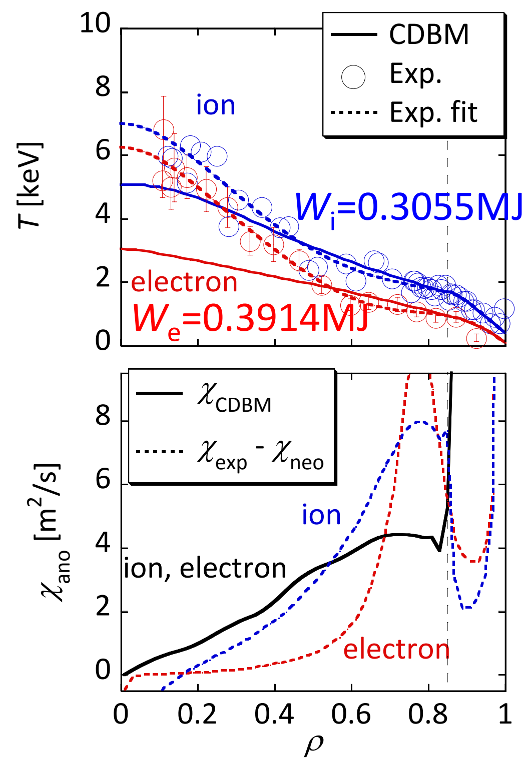
similar to exp. for $\rho > 0.3$

Electron

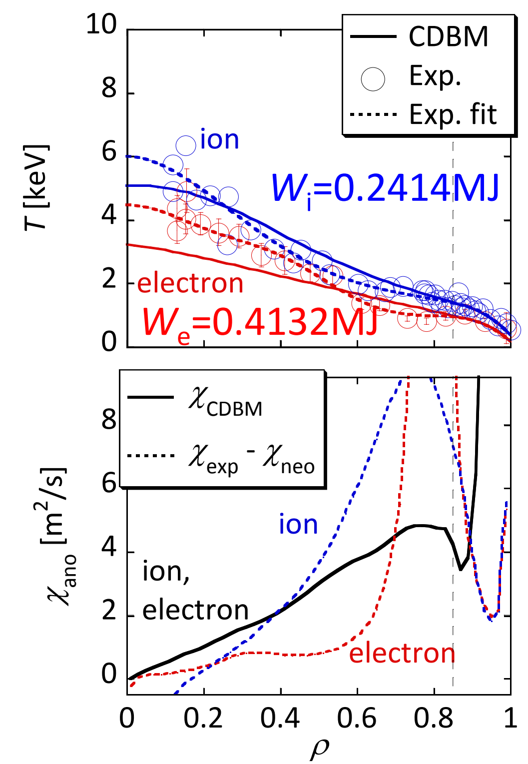
similar T_e for $\rho > \rho_{ITB}$

lower T_e with high χ_e for $\rho > \rho_{ITB}$, especially for co case

Co H=0.9352



Ctr H=0.8642



Calculations with GLF23 for parabolic ITB shots

Ion

similar T_i gradient, but overestimated T_i with much smaller χ_i than exp .

Electron

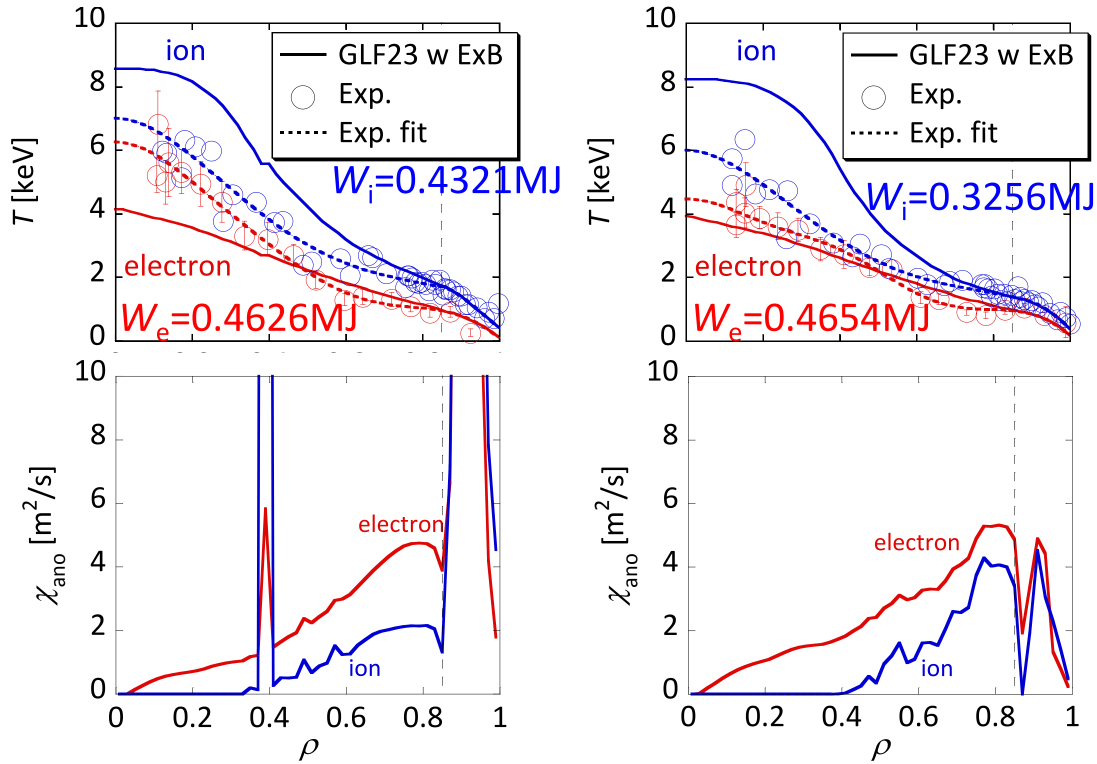
Co: similar T_e for $\rho > \rho_{ITB}$

Ctr: similar T_e

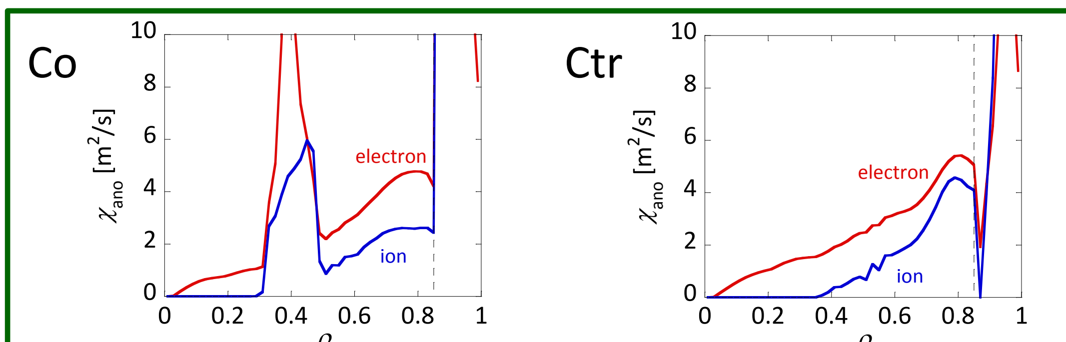
➔ Failure of T_e-ITB reproduction may be due to ETG mode

[cf. J. E. Kinsey PoP2005]

Co H=1.212 Ctr H=1.058



Calculations w/o *ExB* shear effects



Calculations with BgB for parabolic ITB shots

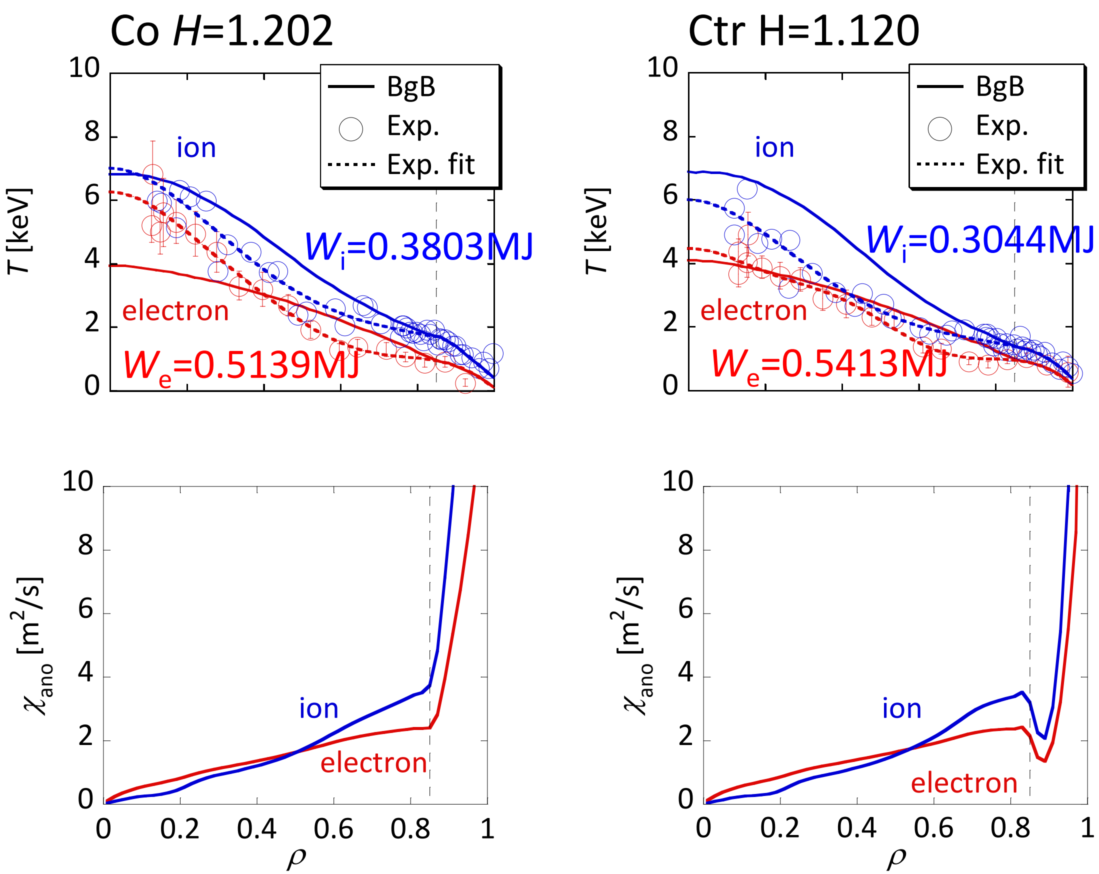
Ion

Co: similar to exp.

Ctr: overestimated

Electron

similar to exp. for ctr case, but no gradient like exp. for both co and ctr cases



GS2 code

GS2 code [M. Kotschenreuther CPC1995, W. Dorland PRL2000] is

- the local flux-tube gyrokinetic code
- solving the gyrokinetic equations for the perturbed distribution functions δf
- able to carry out linear and nonlinear
- able to calculate both electrostatic and electromagnetic cases, including nonadiabatic (kinetic) electrons
- calculating initial value problems using the Lorentz collision operator
- able to work with *s*-α model equilibrium, Miller equilibrium and the equilibrium obtained experiments(G EQDSK)
- incorporating effects of sheared flow by forcing radial wavenumber k_x to depend linearly on time

$$k_x(t) = k_{x0} - \underline{\gamma_{E\times B}} k_y t$$

$$\gamma_{E\times B} = \frac{\rho}{q}\frac{d\omega}{d\rho}$$ — Toroidal angular velocity

$$\gamma_{\mathrm{p}} = (qR/r)\gamma_{E\times B}$$: Parallel flow shear

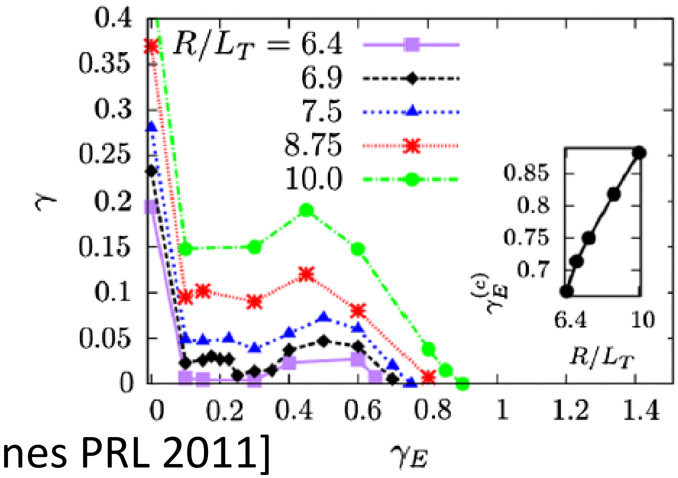
Effects of the flow shear

GS2

- Cyclone base case

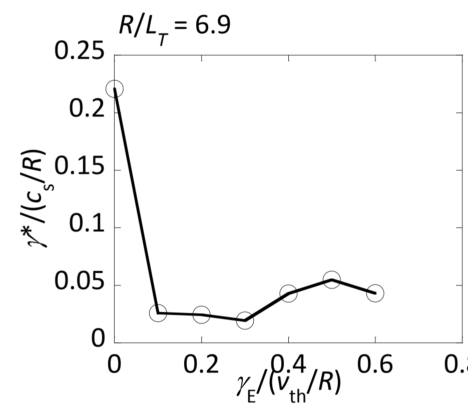
  $$q = 1.4, s = 0.8, r/R = 0.18, R/L_n = 2.2$$

- ITG mode is stabilized by increasing γ_E for $0 < \gamma_E < 0.3$.
- ITG and parallel velocity gradient (PVG) drive for $0.3 < \gamma_E < \gamma_E^{(c)}$.

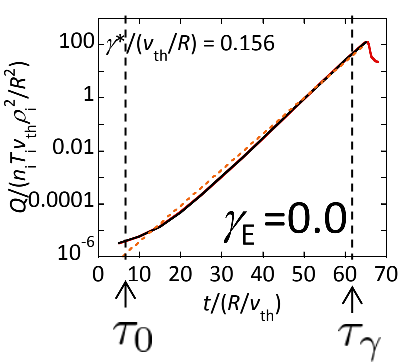


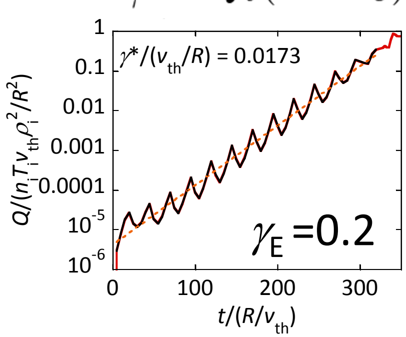
[Barnes PRL 2011]

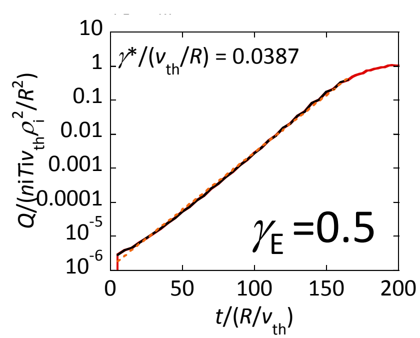
- The effects of the flow shear are confirmed.
- The growth rate is estimated by time dependence of the heat flux at linear phase. [C. M. Roach PPCF2009]



$$\gamma^* = \frac{1}{2\tau_\gamma} \ln \frac{Q_t(t=\tau_\gamma)}{Q_t(t=\tau_0)}$$







Conclusions and future works

Transport models

Conventional H-mode

- Estimated T_i using CDBM and GLF23 is similar to exp.
- CDBM and BgB predict little differences between co and ctr cases.

Parabolic ITB

- CDBM and GLF23 predict similar T_e and T_i for $\rho > \rho_{ITB}$.
- CDBM, GLF23 and BgB do not show the difference in T_e profile between co and ctr cases observed in the experiment.

Gyrokinetic code GS2

- ExB shear stabilization and PVG destabilization are able to investigate with GS2

Future works

- ☐ Calculations using GS2 with the equilibrium obtained experiments
- ☐ Estimation of *ExB* shear effects using the transport model TGLF [G. M. Staebler PoP2005, PoP2007, J. E. Kinsey PoP2008]