Study of shaping effect on ITG/TEM instabilities through global gyro-kinetic simulation.

W. Wang,[A] K. Imadera,[B] H. Seto,[A]
Y. Kishimoto[B] and M. Yagi[A]

[A] Rokkasho Fusion Institute, QST, 039-3212, Japan
[B] Kyoto University, Uji, Kyoto 611-0011, Japan

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CONTENT

In this report:

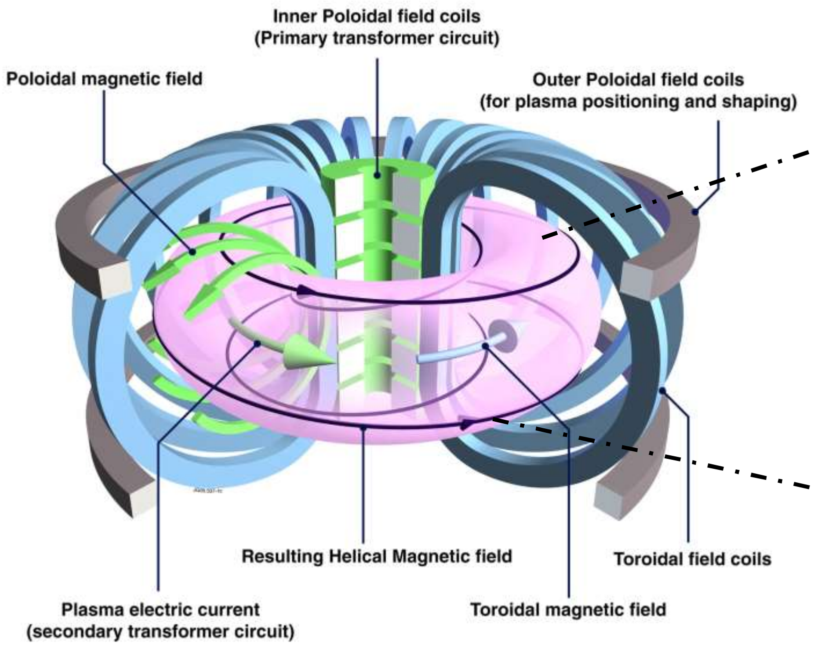
- Introduce of shaping study with gyrokinetic simulation:
  i. Background, and the purpose of this work.
  ii. Workflow by steps, and convergence benchmark tests.

- Shaping effect on linear ITG and TEM instabilities.
  i. Influence of elongation and triangularity on linear ITG instability.
  ii. η_i dependence of ITG/TEM instability, and shaping effect on linear TEM.
  iii. Summary of the shaping effect.

- Discussion: Influence of linear mode structures on heat transport.
  i. Methodology of size-PDF analysis in the real space.
  ii. Size-PDFs of heat flux structures in flux-driven simulation.

- Summary & Future plan.

➢ Introduce of shaping study with gyrokinetic simulation.



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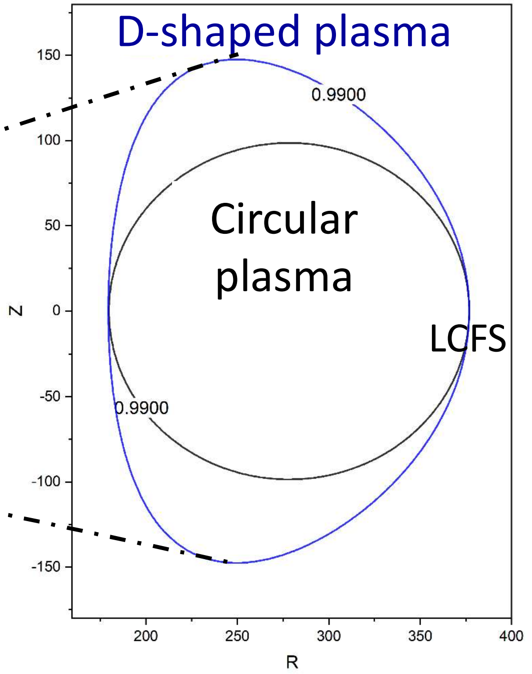


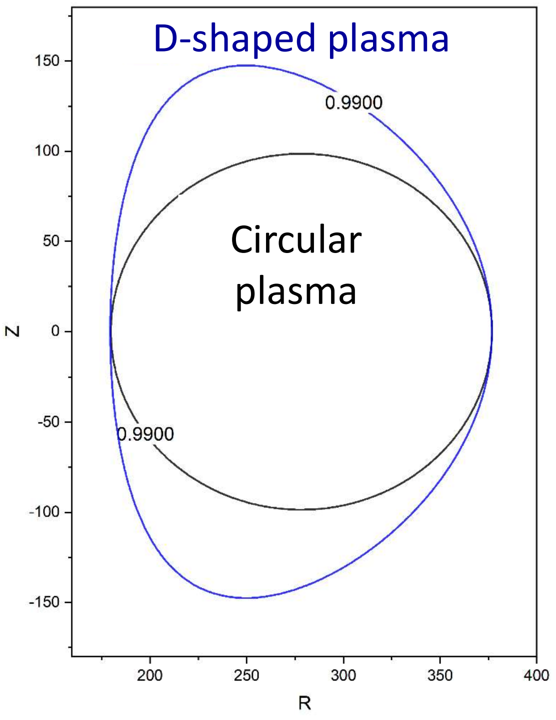
❖ Plasma shaping, and basic properties:

- Plasma equilibrium and shaping: coils and Shafranov shift.
- D-shaped: elongation κ and triangularity δ.
- Scaling law with elongation: $\tau_E \propto \kappa^{0.78}$ (ITER IPB98(y, 2)).
- Negative triangularity.

➢ Introduce of shaping study with gyrokinetic simulation.

❖ Purpose of this work :

- ☐ Employ numerical equilibrium to full-f gyro-kinetic simulation code GKNET.
- ☐ Study the shaping effect on linear ITG/TEM instabilities.



❖ Associated codes:

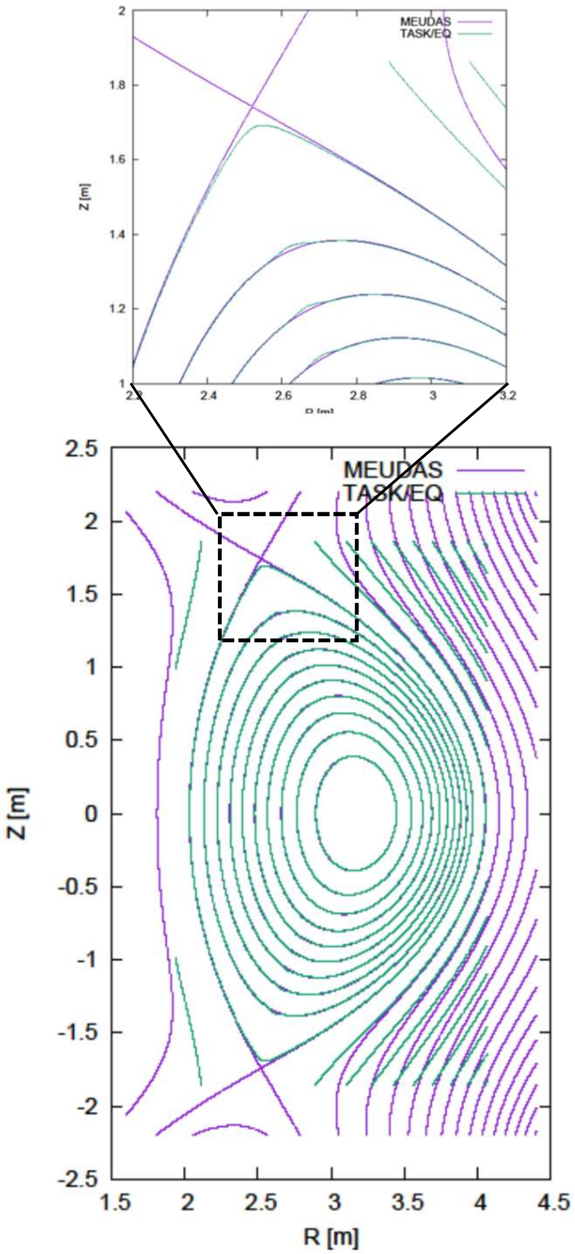
1. **TASK/EQ:** fixed-boundary MHD equilibrium code, developed A. Fukuyama, et al., Kyoto Univ.
2. **IGS:** Interface code for the linkage between several equilibrium codes and gyro-kinetic simulation codes, developed A. Matsuyama, et al., QST. [M. Nakata, et. al., *Plasma and Fusion Research*, 1403029 (2014)]
3. **GKNET:** 5-D gyro-kinetic simulation code, developed by K. Imadera, et al., Kyoto-U.
   [W. Wang, et al, *Nuclear Fusion* (2018).] [O. Kevin, et al., CPC 216: 8-17 (2017).]
   [K. Imadera, *et al.*, TH/P3-3, IAEA-FEC (2016).] [Y. Kishimoto, *et al.,* TH/P3-2, IAEA-FEC (2016)]

Introduce of shaping study with gyrokinetic simulation.

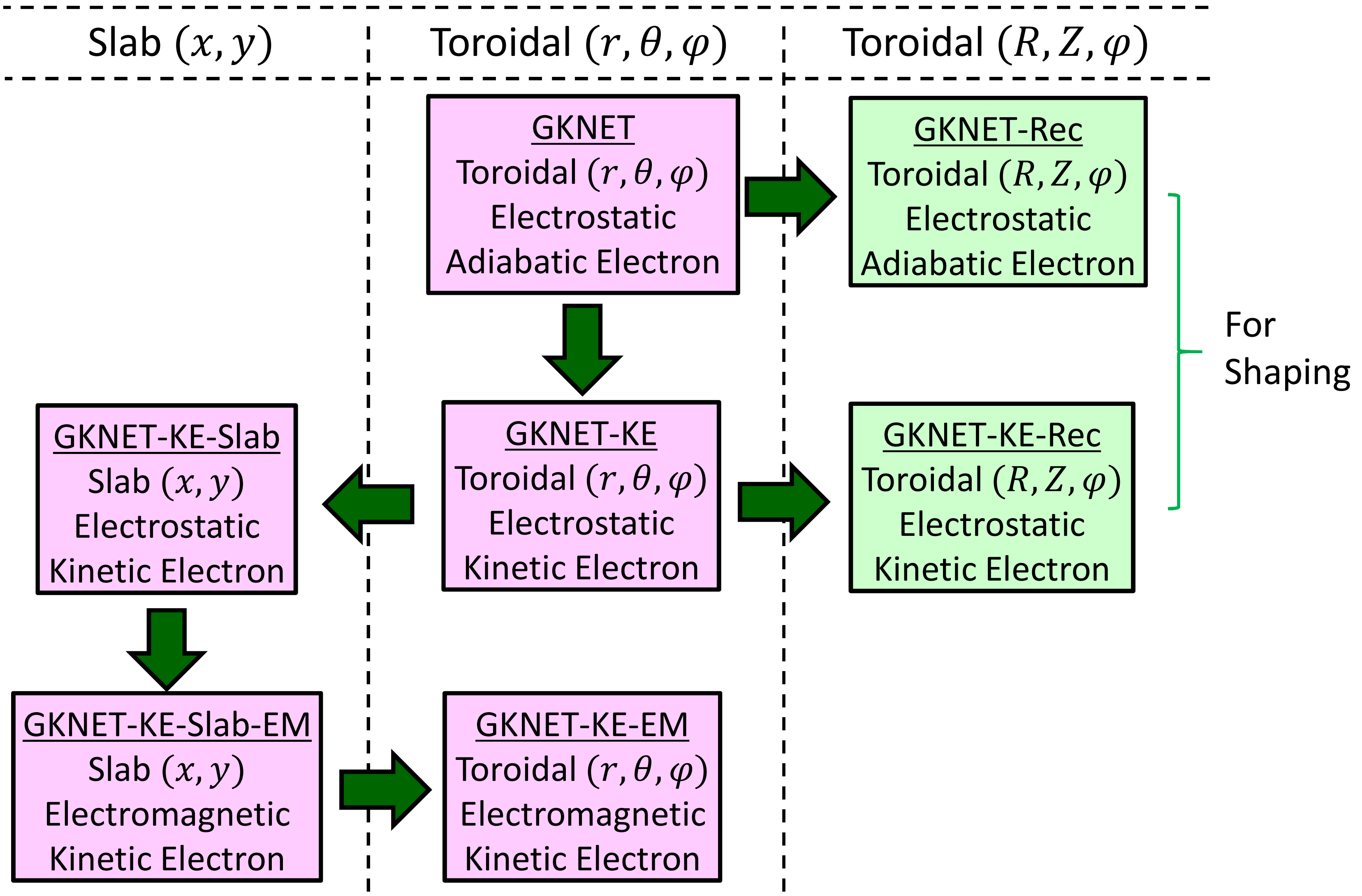
1. TASK/EQ

- Fixed-boundary MHD equilibrium code.
- G-S equation solved for Shafranov shift.
- Input for calculation can be:
  1) pressure p, q
  2) pressure p, $j_{\parallel}$
  3) pressure p, I_θ, I_p

  etc. as functions of flux label ρ.
- Shaping defined by elongation κ and triangularity δ of LCFS.
- Benchmarked with free-boundary equilibrium code.



3. **GKNET** (Gyro-Kinetic Numerical Experimental Tokamak)



Slab (x, y)

Toroidal (r, θ, φ)

Toroidal (R, Z, φ)

GKNET
Toroidal (r, θ, φ)
Electrostatic
Adiabatic Electron

GKNET-Rec
Toroidal (R, Z, φ)
Electrostatic
Adiabatic Electron

For
Shaping

GKNET-KE-Slab
Slab (x, y)
Electrostatic
Kinetic Electron

GKNET-KE
Toroidal (r, θ, φ)
Electrostatic
Kinetic Electron

GKNET-KE-Rec
Toroidal (R, Z, φ)
Electrostatic
Kinetic Electron

GKNET-KE-Slab-EM
Slab (x, y)
Electromagnetic
Kinetic Electron

GKNET-KE-EM
Toroidal (r, θ, φ)
Electromagnetic
Kinetic Electron

Main contributor: K. Imadera (Kyoto-U.), O. Kevin (JAEA), A. Ishizawa (Kyoto-U), etc.

Introduce of shaping study with gyrokinetic simulation.

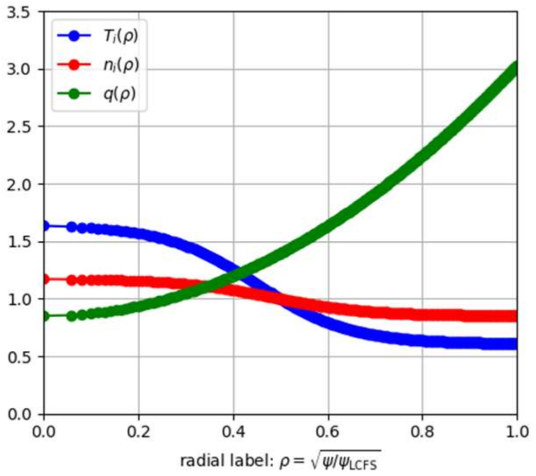
ii. Workflow by steps, and convergence benchmark tests.

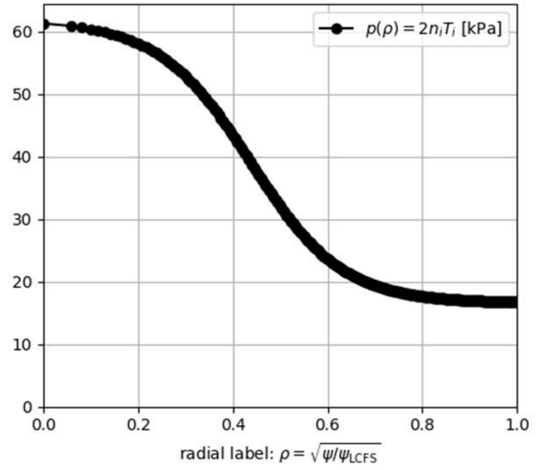
❖ Normalization:

- Flux label: $\rho = \sqrt{\Psi/\Psi_{edge}}$
- Temperature: $T_{\rho=0.5}$
- Density: $n_{\rho=0.5}$
- B field: B_{R_0}
- Scale: ρ_i

❖ Profiles/parameters

- $a = 100, a/R_0 = 0.36$
- $q(\rho) = 0.85 + 2.18\rho^2$
- $T_{eq}(\rho) = \exp\{-(0.2a/l_T) \cdot tanh[(\rho - 0.5)/0.2]\}$
- $n_{eq}(\rho) = \exp\{-(0.2a/l_n) \cdot tanh[(\rho - 0.5)/0.2]\}$
- $R_0/l_T = 6.92, R_0/l_n = 2.22, T_i = T_e$



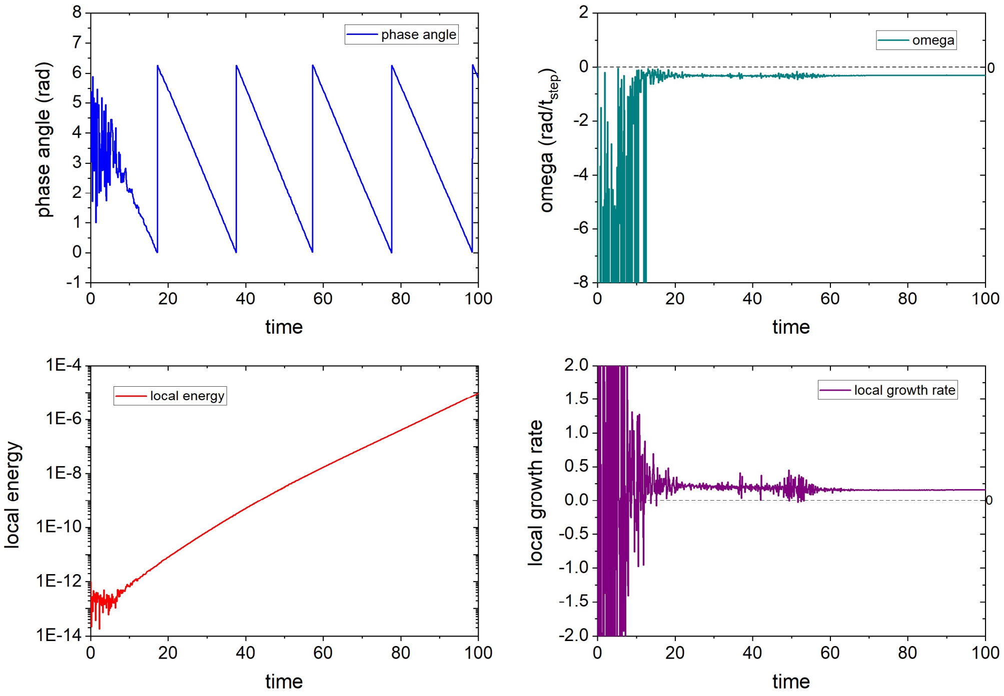


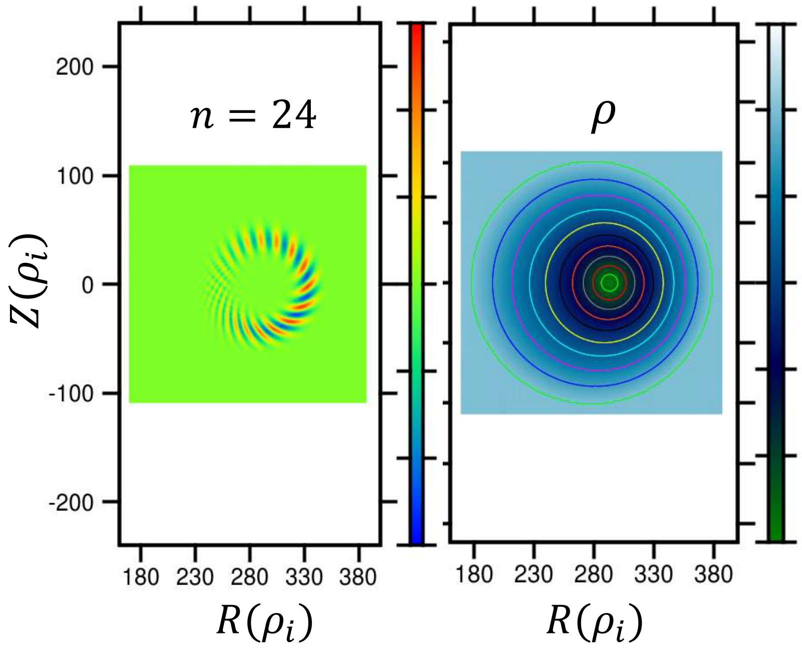
❖ Through $p(\rho) = T_i n_i + T_e n_e, q(\rho)$, equilibrium is obtained by given κ and δ.

Introduce of shaping study with gyrokinetic simulation.

ii. Workflow by steps, and convergence benchmark tests.

- Test run with $\kappa = 1.0$, $\delta = 0$.





- Left: For a local fixed point: (ρ =0.5, Z=0), time evolutions of phase angle, omega, local energy, local growth rate are plotted.
- Right: Linear mode structures shown for n=24 in R-Z coor. And flux label ρ.

➢ Introduce of shaping study with gyrokinetic simulation.

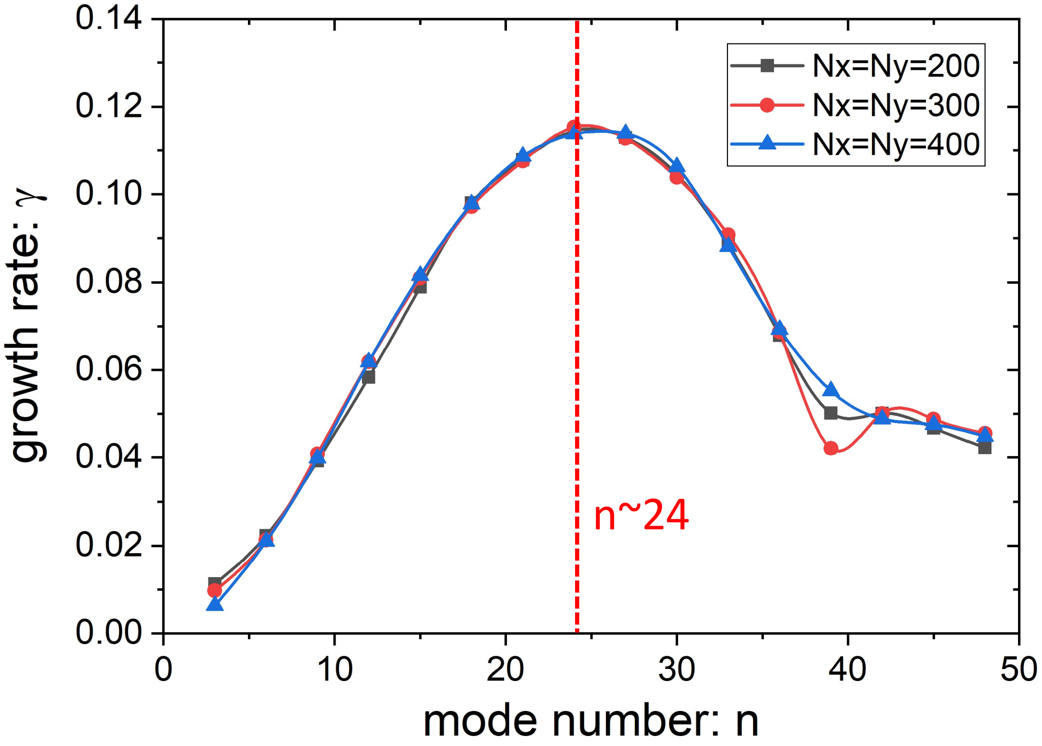
ii. Workflow by steps, and convergence benchmark tests.

❖ With circular shaping ($a = 100\rho_i,\ \kappa = 1.0,\ \delta = 0$), different resolutions on R,Z are tested for a convergence:

1. $N_R = N_Z = 200$
2. $N_R = N_Z = 300$
3. $N_R = N_Z = 400$

Results:

1. Enough resolution for: $dR = dZ \sim \rho_i$.
2. Most unstable mode for ITG instability: n~24 (circular shape).



➢ In the following, shaping study mainly focus on the most unstable mode (n~24), and investigate the influence of shaping effect on the linear growth.

C O N T E N T

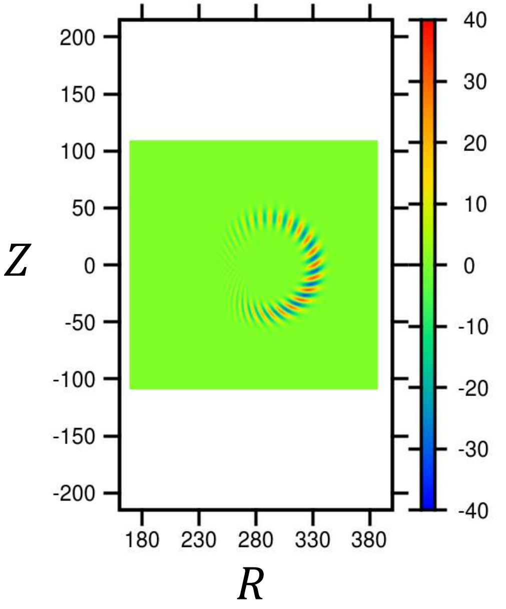
In this report:

Shaping effect on linear ITG and TEM instabilities

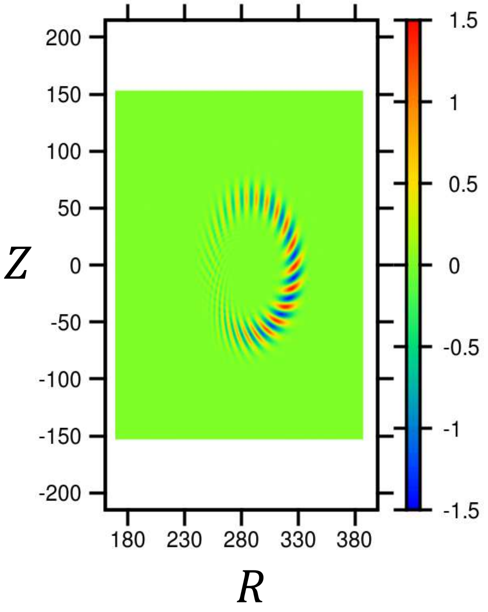
i. Influence of elongation and triangularity on linear ITG instability: elongation κ

- To get a regular mesh with same spacing on R and Z, $N_Z = N_R * \kappa$

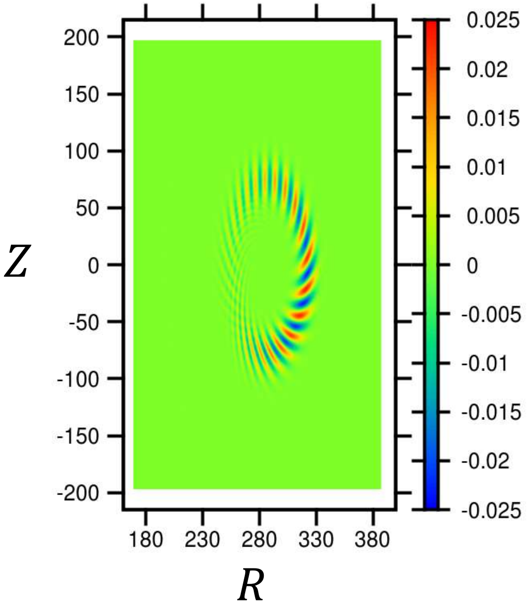
Mesh : N_x=N_y=200
Kappa : 1.0, delta = 0, n=24

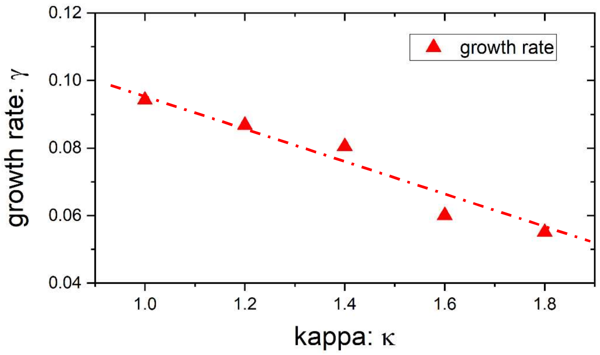


Mesh : N_x2=00, N_y=280
Kappa : 1.4, delta = 0, n=24



Mesh : N_x=200, N_y=360
Kappa : 1.8, delta = 0, n=24





- Elongation shows stabilizing effect to the ITG mode.
- Most unstable region located in the bad curvature region (outer part)

➢ Shaping effect on linear ITG and TEM instabilities

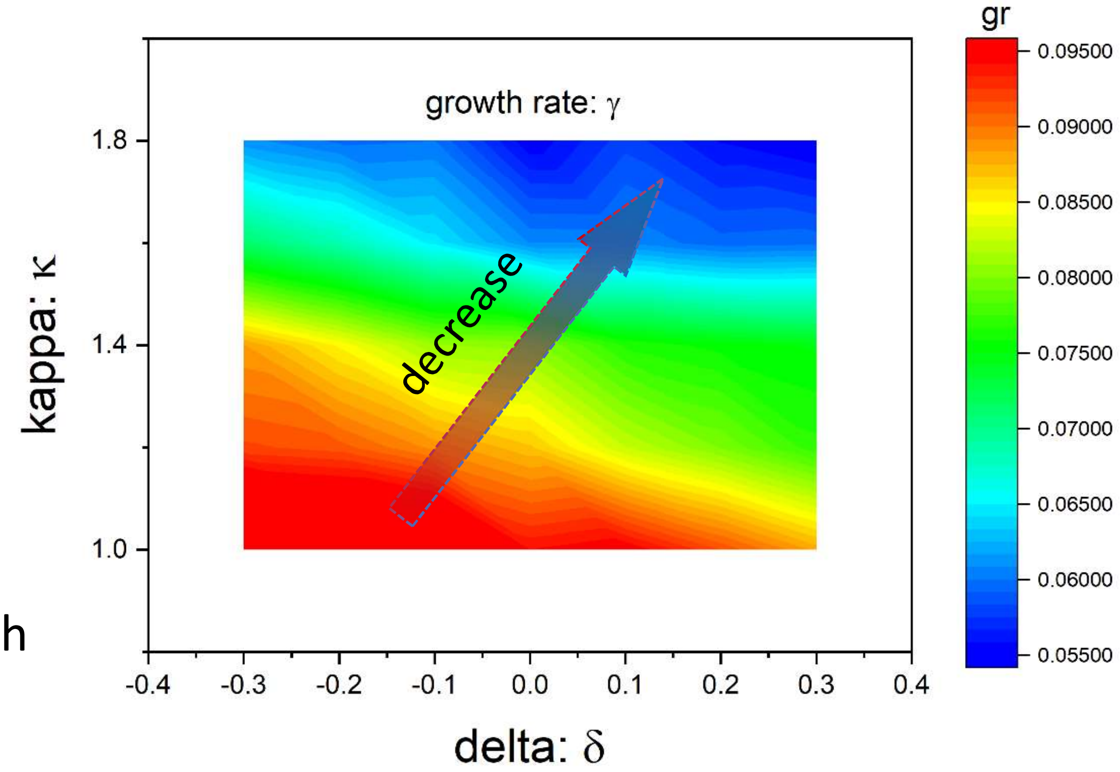
i. Influence of elongation and triangularity on linear ITG instability: triangularity δ

- ○ Shaping scan for the most unstable mode (n~24):

$\kappa =$
1.0, 1.2, 1.4, 1.6, 1.8

$\delta =$
-0.3, -0.2, -0.1, 0, 0.1, 0.2, 0.3

Right fig: contour plot of growth rate γ in the $\delta - \kappa$ space.



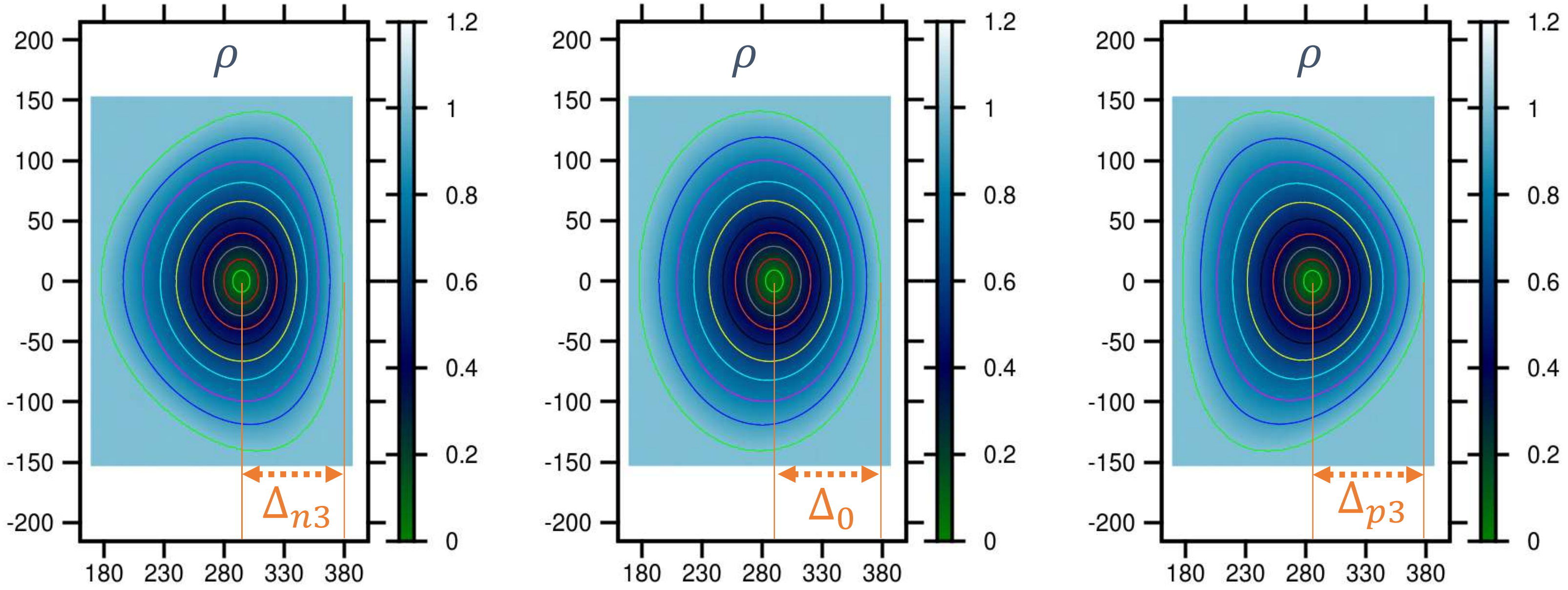
➢ Elongation show stabilizing effect for all triangularity case.

➢ Reversed triangularity shows de-stabilizing effect to linear ITG modes, while positive triangularity always show better stabilizing. (discussed in the following)

Shaping effect on linear ITG and TEM instabilities

i. Influence of elongation and triangularity on linear ITG instability: triangularity δ

$\kappa = 1.4,\ \delta = -0.3$ | $\kappa = 1.4,\ \delta = 0$ | $\kappa = 1.4,\ \delta = 0.3$



$R_{n3}^{axis} = 294\rho_i$ → $R_0^{axis} = 291\rho_i$ → $R_{p3}^{axis} = 285\rho_i$

$\Delta_{n3} \sim 83\rho_i$ → $\Delta_0 \sim 86\rho_i$ → $\Delta_{p3} \sim 92\rho_i$

- Profiles are functions of flux surface label $\rho = \sqrt{\Psi/\Psi_{edge}}$, equilibriums are modified accompanied with the variation of shaping → effective temperature gradient $(R_0/L_T)_{eff}$:

➢ Shaping effect on linear ITG and TEM instabilities

i. Influence of elongation and triangularity on linear ITG instability: triangularity δ

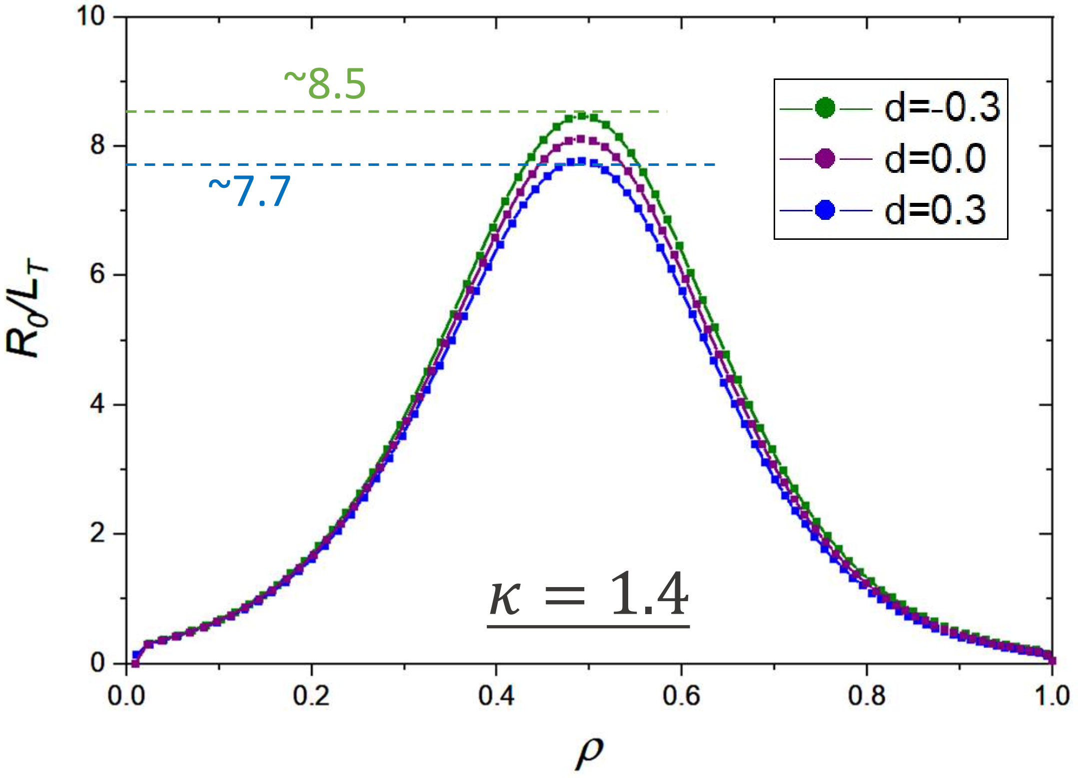


Fig. profiles of effective temperature gradient R/L_T measured for Z=0.

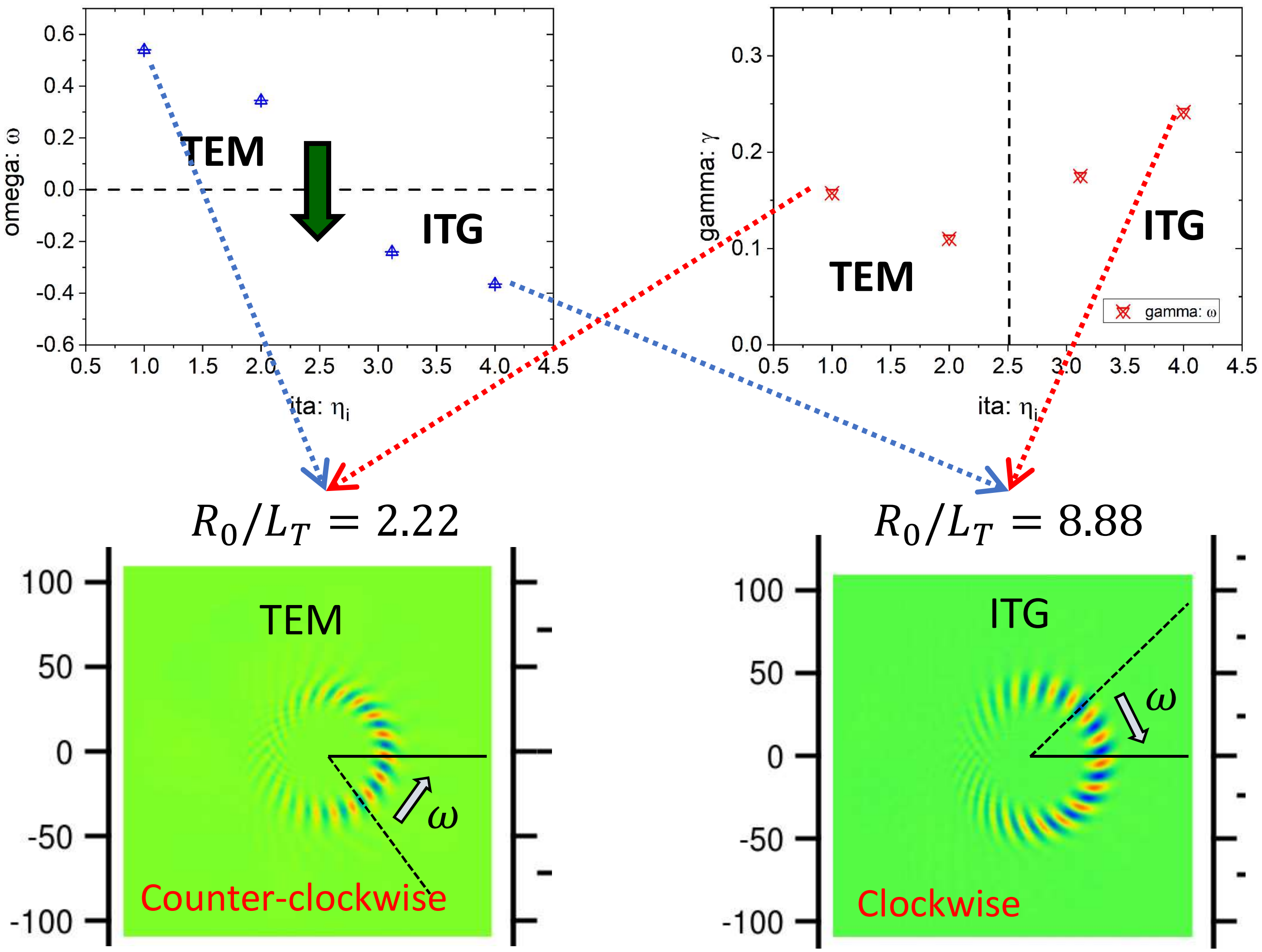
- ➢ Temperature profiles are defined as ρ.
- ➢ $(R_0/L_T)_{d=-0.3}$ is 10% larger than $(R_0/L_T)_{d=0.3}$.

➢ Shaping effect on linear ITG and TEM instabilities

ii. η_i dependence of ITG/TEM instability.

$$R_0/l_{n_i} = R_0/l_{n_e} = 2.22, R_0/l_{T_e} = 6.92$$

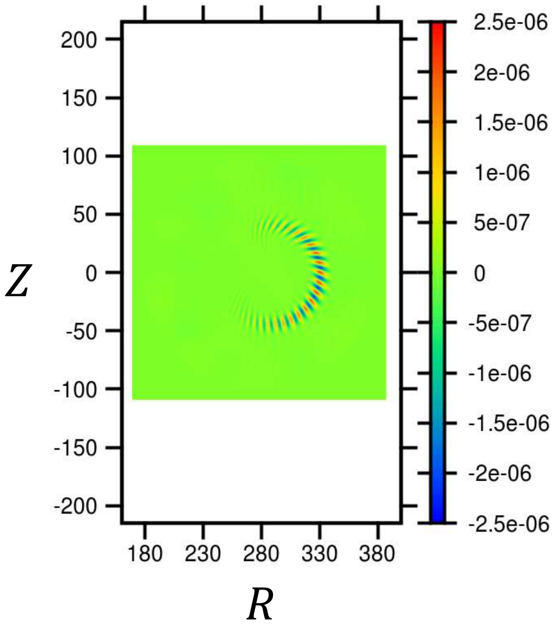
$$R_0/l_{T_i} = 2.22\ (\eta_i = 1),\ 4.44\ (\eta_i = 2),\ 6.92\ (\eta_i = 3.12),\ 8.88\ (\eta_i = 4)$$



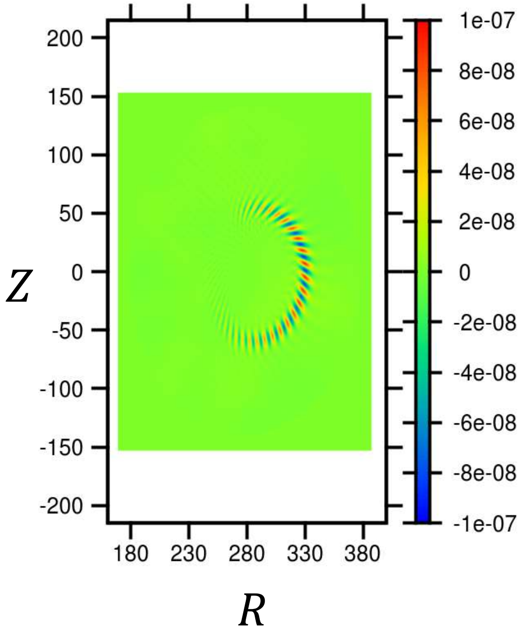
➢ Shaping effect on linear ITG and TEM instabilities

iii. Shaping effect on the linear TEM instability: elongation κ

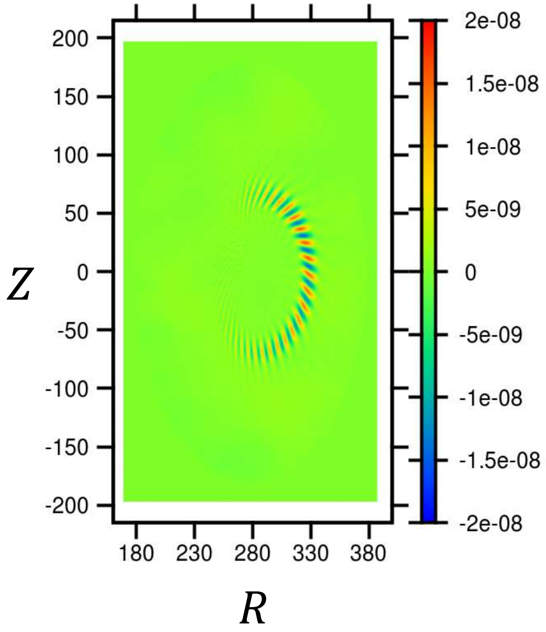
Mesh : N_R=N_Z=200
Kappa : 1.0, delta = 0, n=28

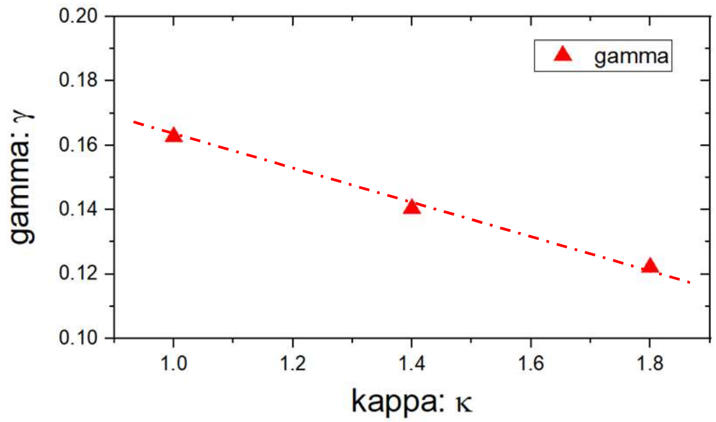


Mesh : N_R=200, N_Z=280
Kappa : 1.4, delta = 0, n=28



Mesh : N_R=200, N_Z=360
Kappa : 1.8, delta = 0, n=28

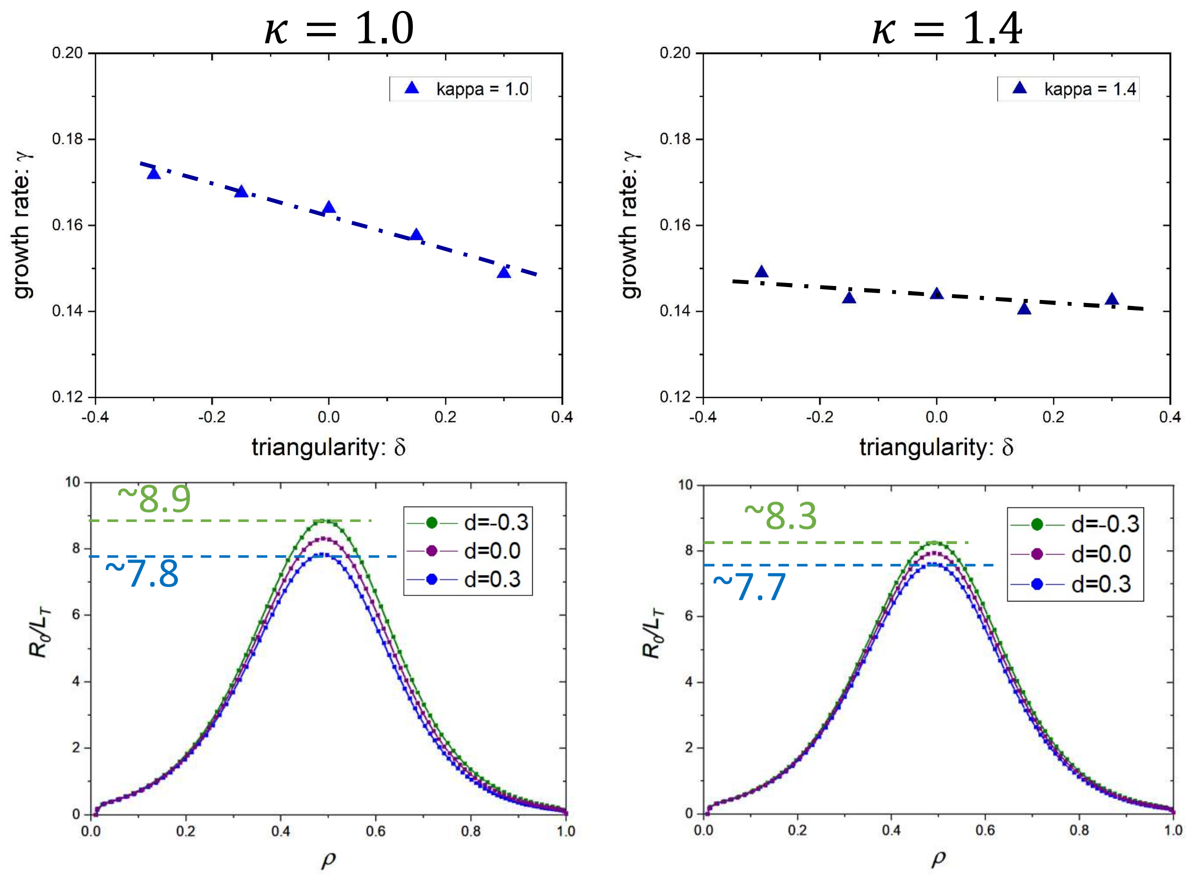




- ➢ Elongation show stabilizing effect to TEM instability, similar to the ITG case with adiabatic electron.
- ➢ Most unstable region located in the bad curvature region (outer part)

➢ Shaping effect on linear ITG and TEM instabilities

iii. Shaping effect on the linear TEM instability: triangularity δ



- ➢ The effect of triangularity is related to the elongation due to effective T gradient.
- ➢ Competition between two effects.

Effect	Low κ	Mid κ
$(R/L_T)_{eff}$	Strong+ ∨	Weak+ ≀
$stabilizing\ TEM$	Weak-	Weak-

➢ Summary of shaping effects on linear ITG/TEM instabilities.

ITG case (adiabatic electron):

1. Employed numerical equilibrium code TASK/EQ and IGS to the gyro-kinetic simulation code GKNET with rectangular coordinate.
2. For the ITG instability, elongation show stabilizing effect. Larger triangularity always show better confinement due to the change of effective T gradient.

TEM case (kinetic electron):

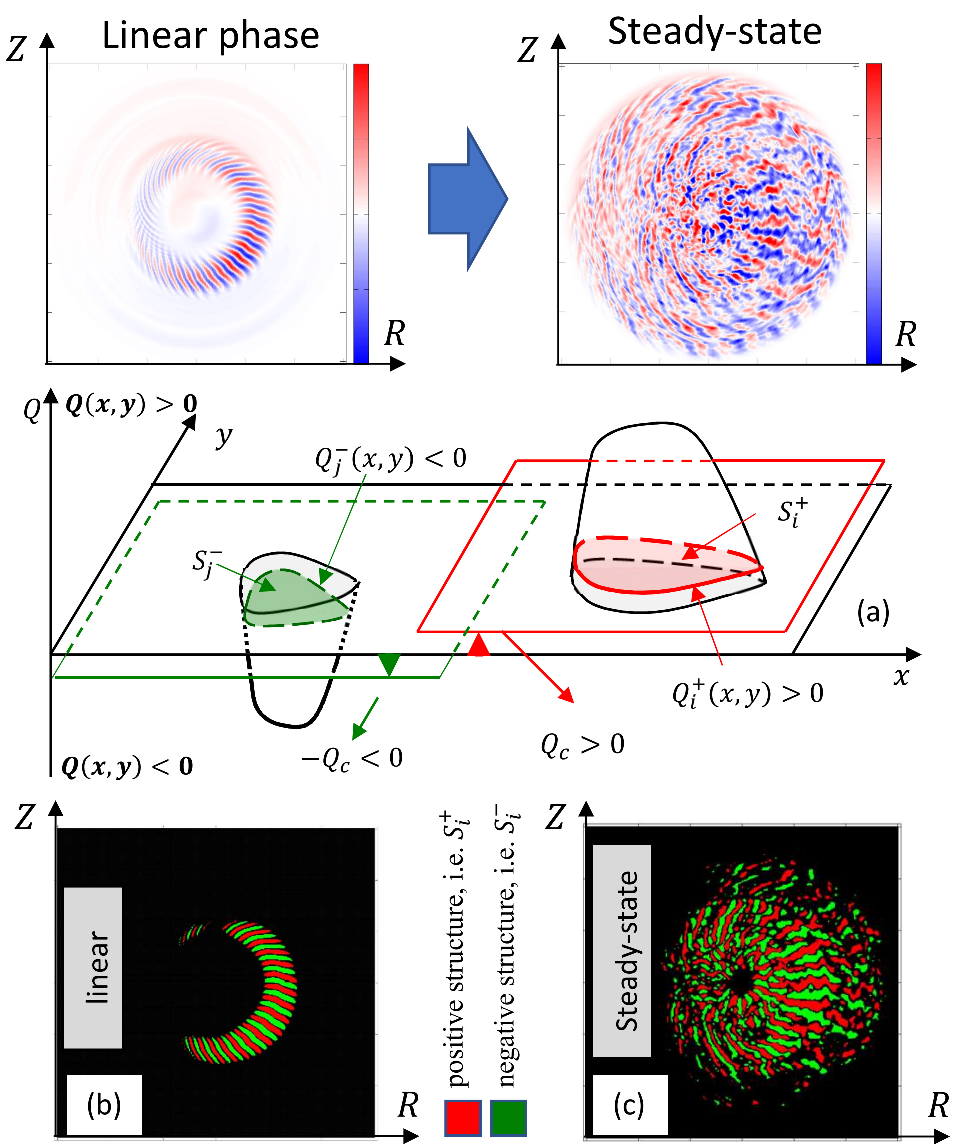
1. Dependence of ITG/TEM is related to η_i value in kinetic electron simulation.
2. For the TEM instability, elongation show stabilizing effect.
3. The effect of triangularity is related to the elongation, which comes from the competition between 1. effective temperature gradient and 2. stabilizing effect to the TEM instability.

CONTENT

In this report:

➢ Discussion: Influence of linear mode structures on heat transport

i. Methodology of size-PDF analysis in the real space.



Definitions in PDF analysis:

- ➢ Heat flux structure is defined by:
  - ➢ +: $Q_i^+(\boldsymbol{r}) \geq Q_c$
  - ➢ - : $Q_j^-(\boldsymbol{r}) \leq -Q_c$
- ➢ Size: $S_{i/j}^{\pm}$
- ➢ Total number: $N^{\pm}$
- ➢ Size PDF:

$$P^{\pm}(S) = \left(N_S^{\pm}/N^{\pm}\right)/dS_{linear}$$

- ➢ Heat flux by size:

$$\delta q^{\pm}(S) = \sum_{S-dS<S_{i/j}<S+d} q_{i/j}^{\pm}$$

- ➢ Total heat flux:

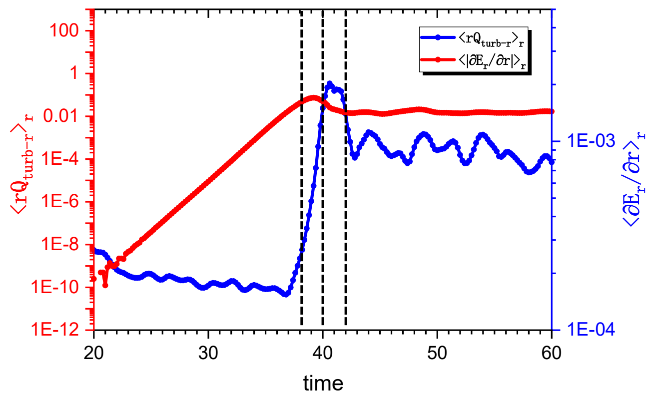
$$q_{total} = \sum_{i=1}^{N^+} q_i^+ + \sum_{j=1}^{N^-} q_j^-$$

- ➢ Total heat flux in $[0, S]$:

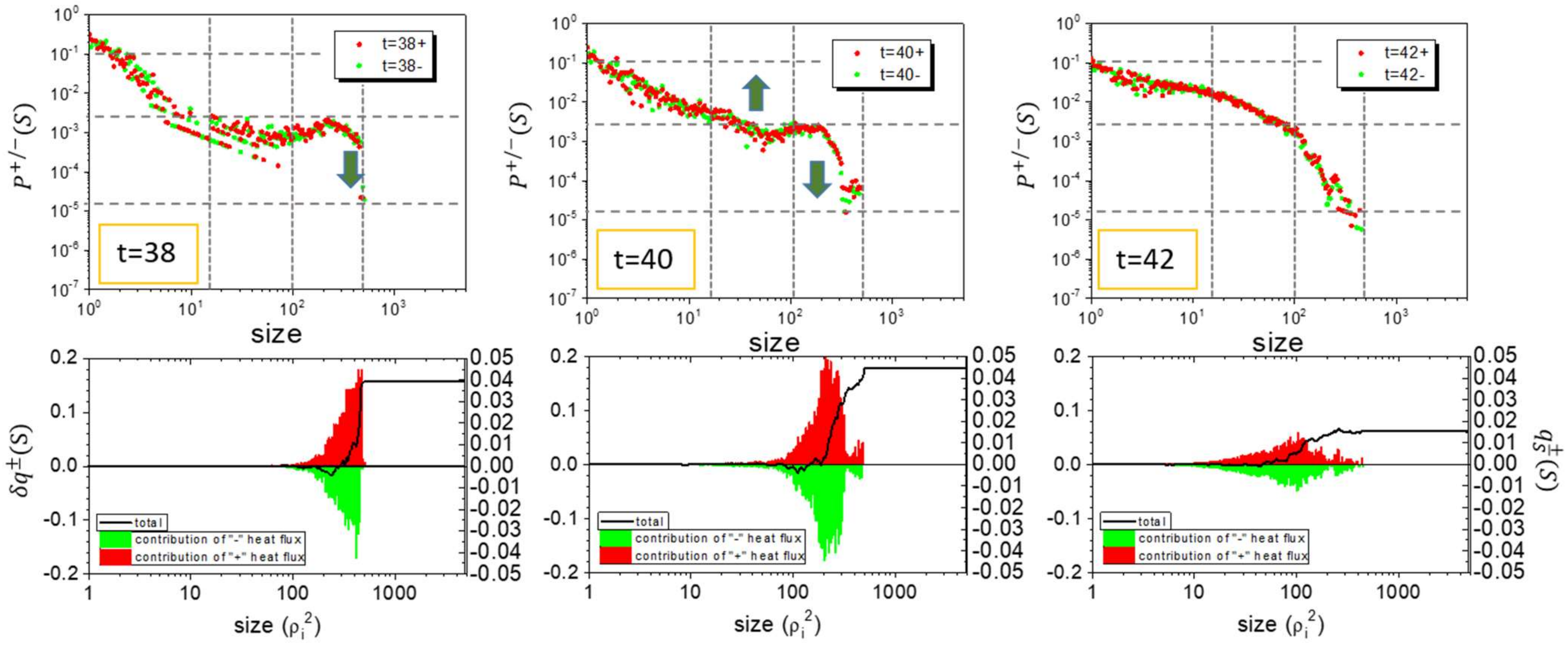
$$q_S^{\pm}(S) = \int_0^S \delta q^{\pm}(S)\,\mathrm{ds} \sim \sum_{0<S_{i/j}<S} q_{i/j}^{\pm}$$

➢ Discussion: Influence of linear mode structures on heat transport

ii. Size-PDF of mode structures in circular simulation: linear → saturation

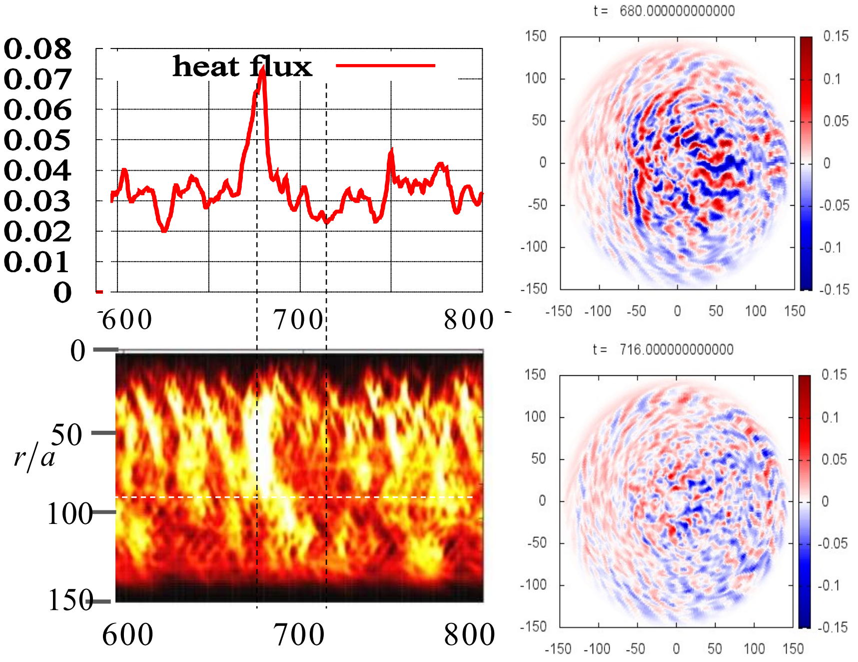


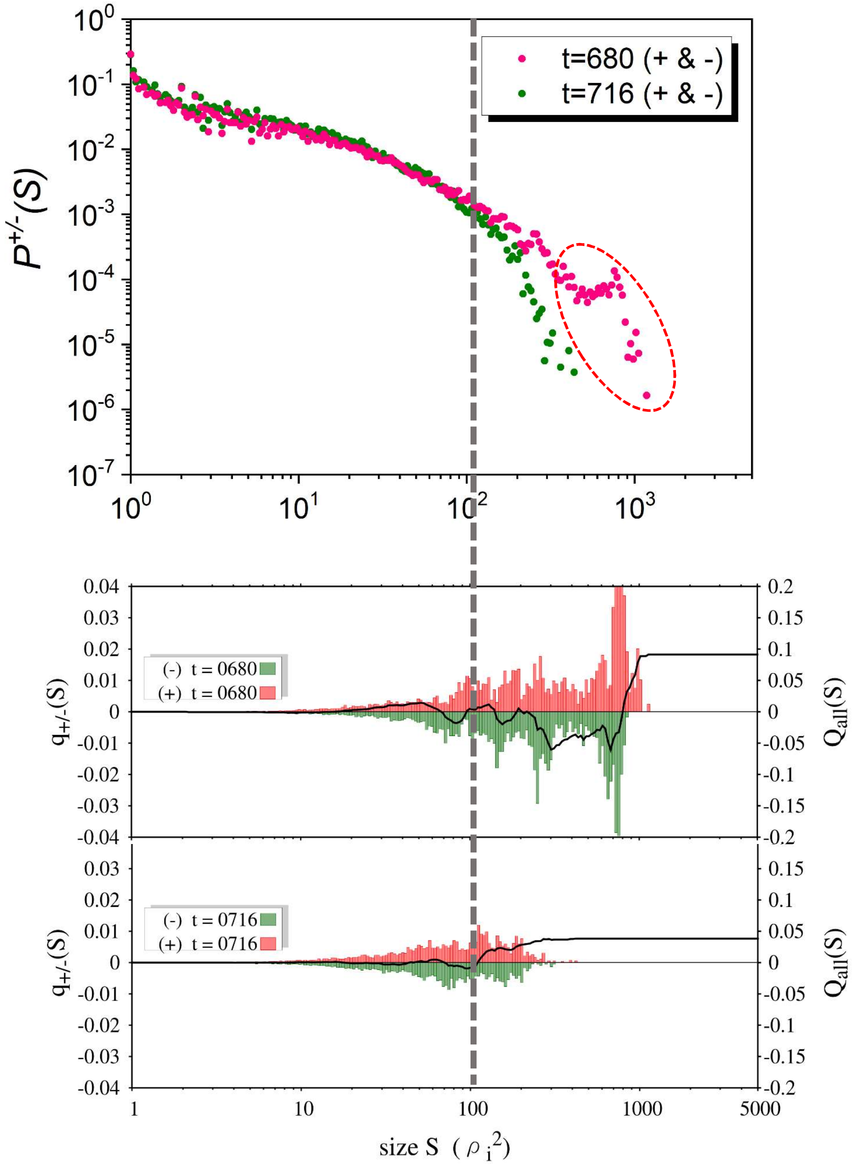
- ❖ Linear: A few number of large linear-mode structures.
- ❖ Saturated due to zonal flow excitation.
- ❖ Size distribution: global structure (S~500) reduced, meso-scale (S~10^2) structures increased.
- ❖ Contribution expanded, net value still comes from S>100



Discussion: Influence of linear mode structures on heat transport

ii. Size-PDF of mode structures in circular simulation: steady-state.





- Global structures at bursting transport.
- Size-PDFs: Irregular tail (S~10^3) for the bursting timing and disappears at bottom.
- Total heat flux is contributed by S>100 eddies, global eddies play an important role in leading to the burst, which likes the linear phase.

➢ Summary & Future plan.

❖ Summary for the size-PDF analysis.

1. By the size-PDF analysis, structures can be studied in the real space.
2. Analysis to the linear phase indicate that the total heat loses are results from a finite number of linear structures.
3. Through size-PDF analysis to the steady-state phase, global streamers shows linear-like radially extended mode structure when bursting happens, indicates that linear mechanisms also play a role in the non-linear phase.

❖ Future.

1. Flux-surface averaged in the rectangular GKNET simulation, investigate the influence of shaping in non-linear phase.

THANK YOU