18th Technical Meeting on Energetic Particles in Magnetic Confinement Systems

Verification of Fast Ion Effects on Turbulence through Comparison of GENE and CGYRO for the Beam-heated Discharge in KSTAR

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KFE KOREA INSTITUTE OF FUSION ENERGY

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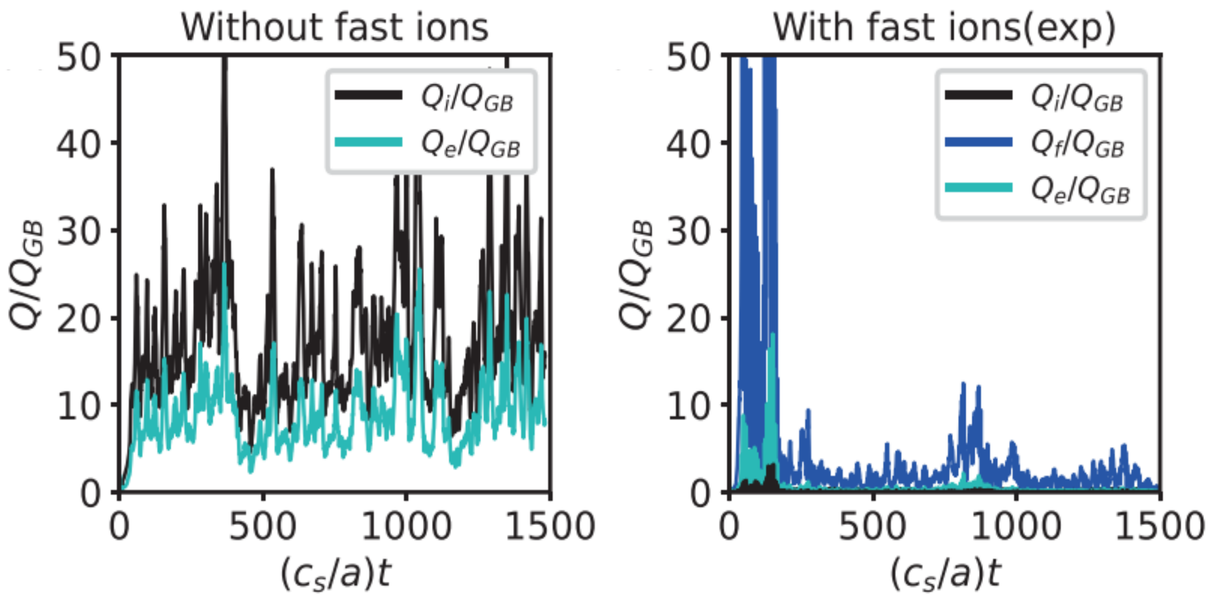
GENERAL ATOMICS

We Need to Verify Fast ion Effects on Turbulence Described by Gyrokinetics



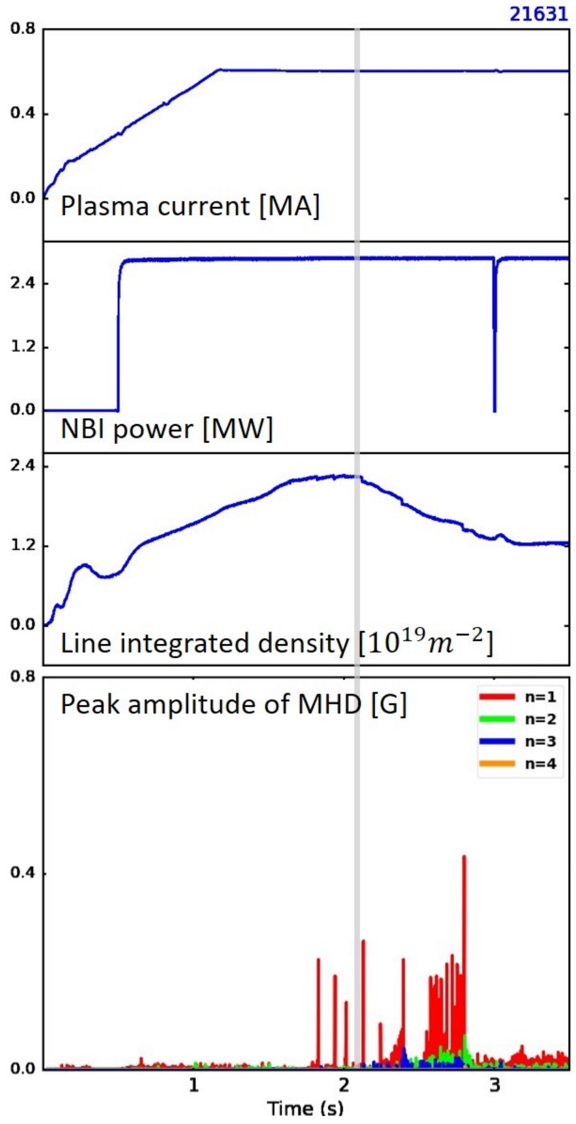
- Fast ions, generated by external heating or fusion reactions, are essential for fusion energy production
- These ions draw more attention these days because of their effects on turbulence
  - Gyrokinetics has been utilized to investigate fast ions' effects on turbulence [Wilkie18,Bonanomi18, di Siena18,19,21, Mazzi22, Garcia22, Kim23, 24]
- However, fast ion effects described by gyrokinetics had not been verified

- **Cross-verification study for fast ion effects on turbulence is performed by comparing the simulation results from two popular gyrokinetic codes, CGYRO [Candy and Belly 16] and GENE [Jenko 00]**

Verification Target : Flux Tube Run for Neutral Beam Heated Discharge in KSTAR

- Target discharge
  - Neutral beam heated L-mode discharge in KSTAR (Shot 21631, t=2050ms)
  - Weak MHD activity (<0.3G) suitable for verification, used in verification and validation studies in the past [Kim22, Yi24]

- Simulation setup
  - Local simulation at r/a=0.5
  - Ion scale ($k_y \rho_s \leq \sim 1.0$)
  - Included electromagnetic ($\delta\tilde{\phi}, \delta\tilde{A}_{\parallel}$), kinetic electrons, and collisions
  - Used carbon (Z=6) as a single impurity species
    - ✓ Z_{eff}=2.0, flat Z_{eff} profile *Z_{eff} : effective charge ($= \sum_j Z_j^2 n_{i,j} / n_e$)
  - Included rotation effects
    - ✓ Experimental toroidal rotation and neoclassical poloidal rotation are used
  - Fast ions are treated as additional ion species
    - ✓ n_f/n_e~ 0.12 and T_f ~ 23.72 keV (T_i, T_e ~ 1.5 keV)
  - Performed extensive convergence test for numerical parameter setup



Verification was Performed by Varying Two Input Conditions

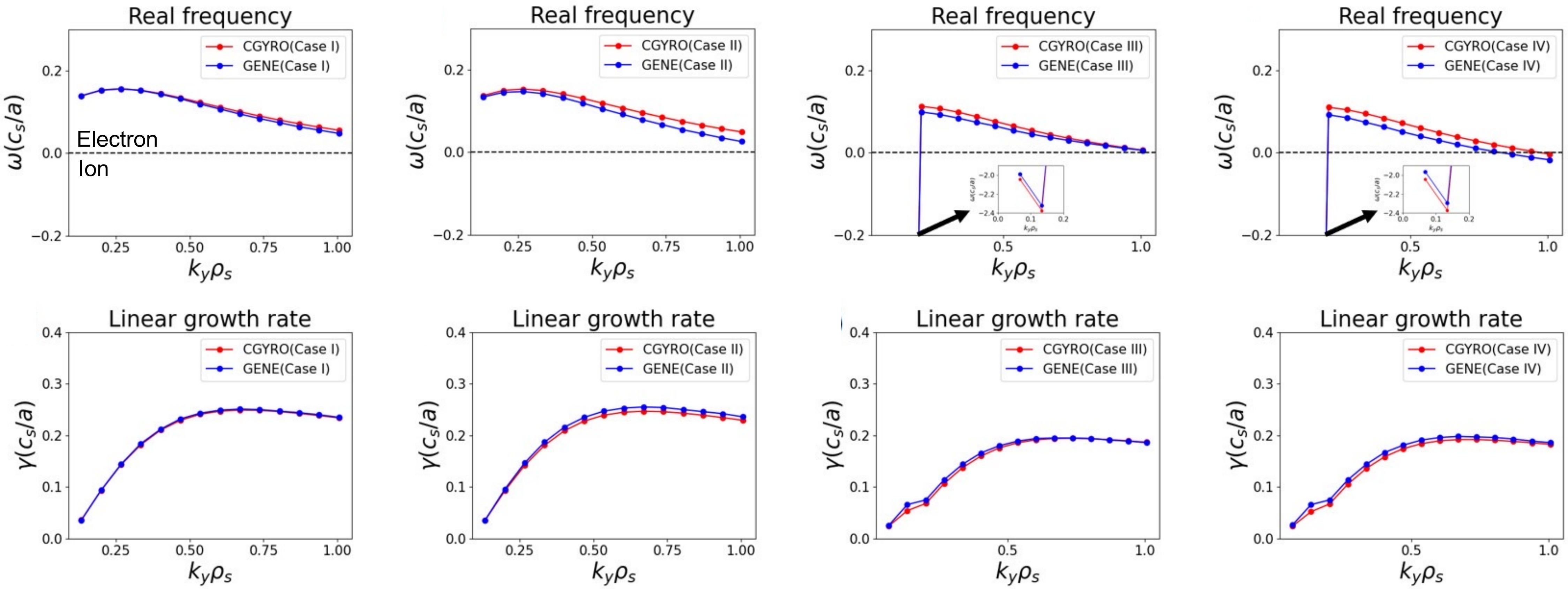
- Cases for verification study
  - Varied two input conditions
    - ✓ Fast ion species
    - ✓ Rotation effects (motivated by the discrepancy between GENE and GYRO due to rotation [Mikkelsen18])
    - ✓ Note that fast ions were not included in [Mikkelsen 18]

	Case I	Case II	Case III	Case IV
Fast ion species	X	X	O	O
Rotation Effects	X	O	X	O

- Parameters used in the verification
  - Real frequency and linear growth rate of the most unstable mode
  - Energy flux level
  - Distribution of energy flux and fluctuations in k space
  - Zonal shearing rate

Linear Simulation Results Show Overall Good Agreement

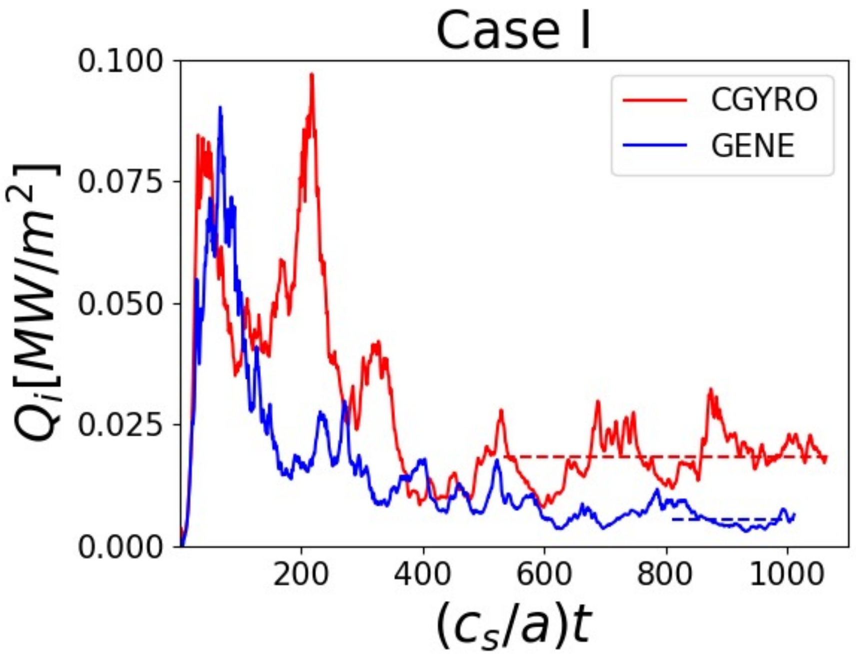
Case I (w/o rotation, w/o fast ions) | **Case II (w/ rotation, w/o fast ions)** | **Case III (w/o rotation, w/ fast ions)** | **Case IV (w/ rotation, w/ fast ions)**

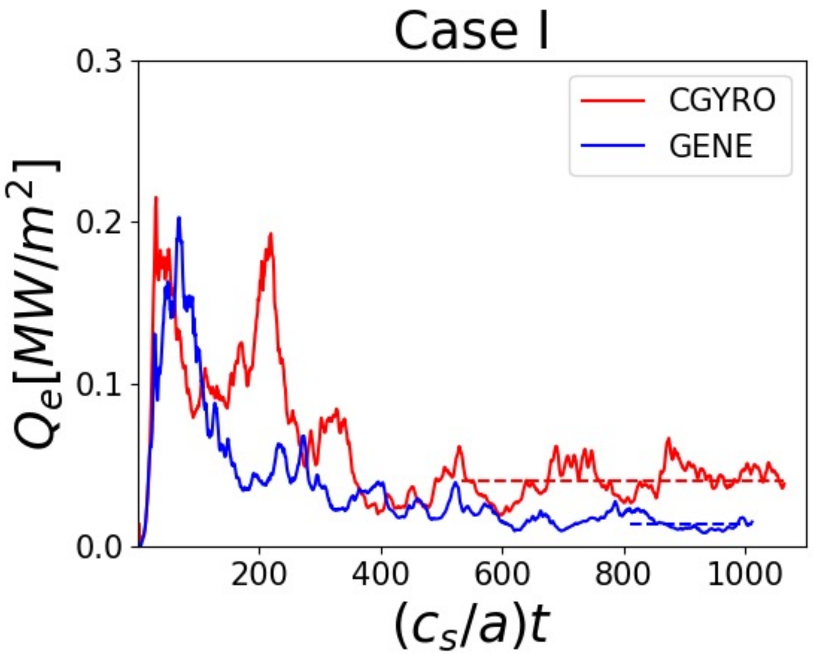


- Overall results from CGYRO and GENE are well agreed
- Both codes show that linear growth rate decreases as fast ions added while no significant changes with rotation
- The ion mode at low k_y is observed as fast ions are included from both codes

Observed Large discrepancy in the energy flux level between two codes

✓ Reminder, Case I : w/o rotation, w/o fast ions



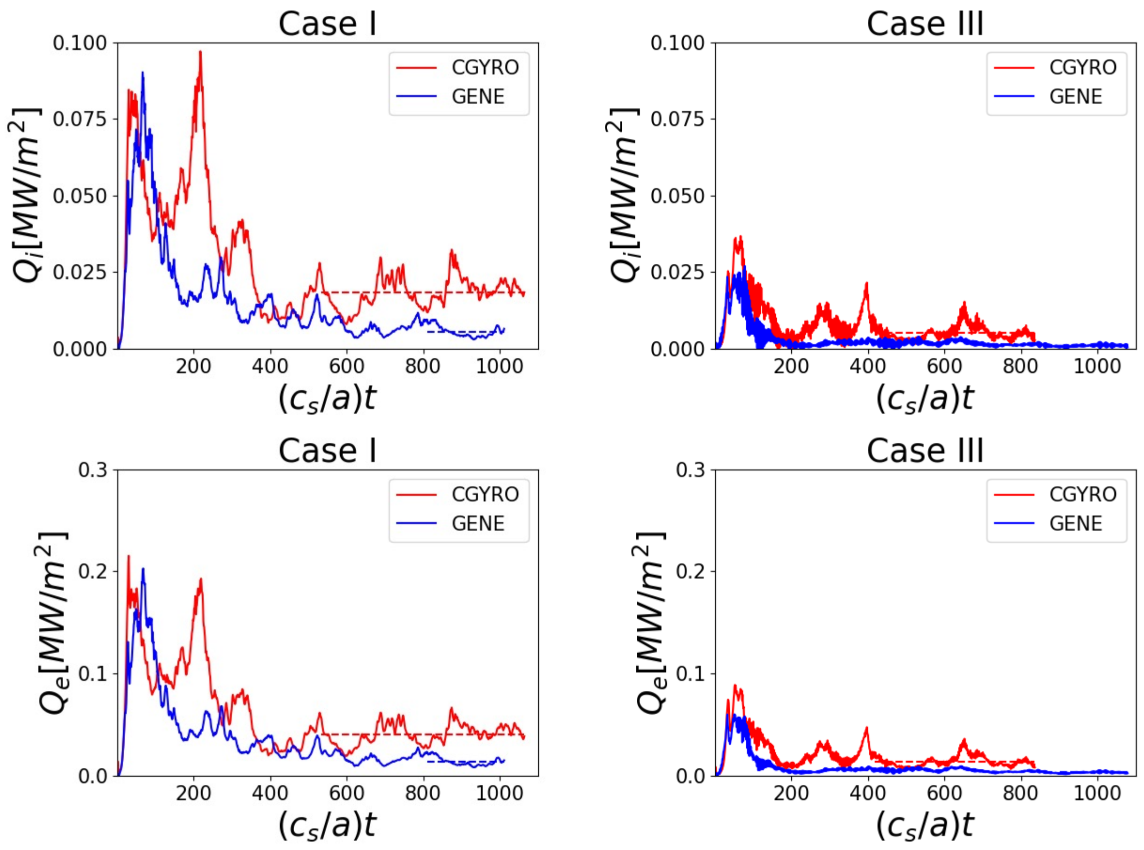


*Q_i includes both main thermal ion and impurity

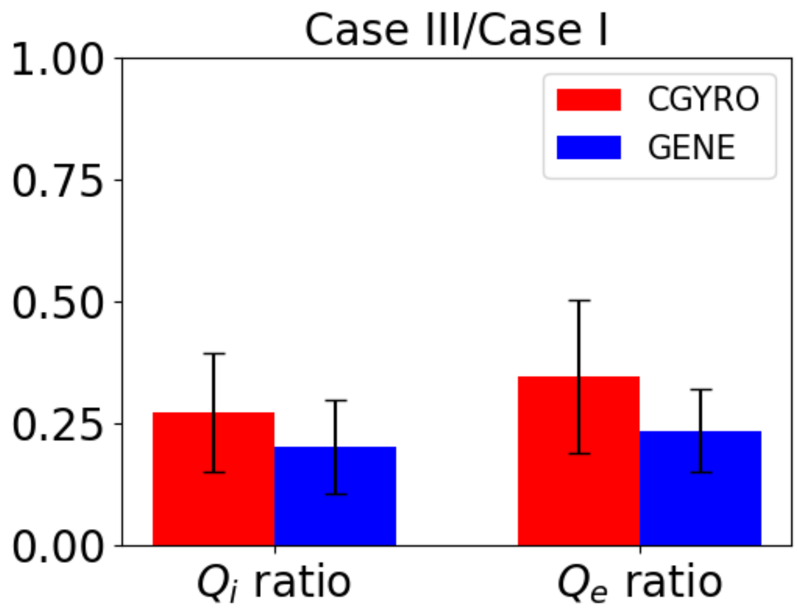
- CGYRO predicts the tripled energy flux levels in the saturated region compared to GENE in Case I
  - $Q_i[MW/m^2]{\sim}0.018 \pm 0.0043$ (CGYRO), ~0.0055 ± 0.0017 (GENE)
  - $Q_e[MW/m^2]{\sim}0.041 \pm 0.0099$ (CGYRO), ~0.014 ± 0.0040 (GENE)
- Note that neither rotation effects nor fast ions are considered in Case I
  → This discrepancy is not due to either fast ions or rotations
  (numerical convergence in some dimensions a possible reason but prohibitively expensive)
  → We will look at the fractional change among cases in this verification study

Thermal Energy Flux Level Comparison without Rotation Effects

Thermal Energy Flux Levels are Reduced by Adding Fast Ions w/o Rotation

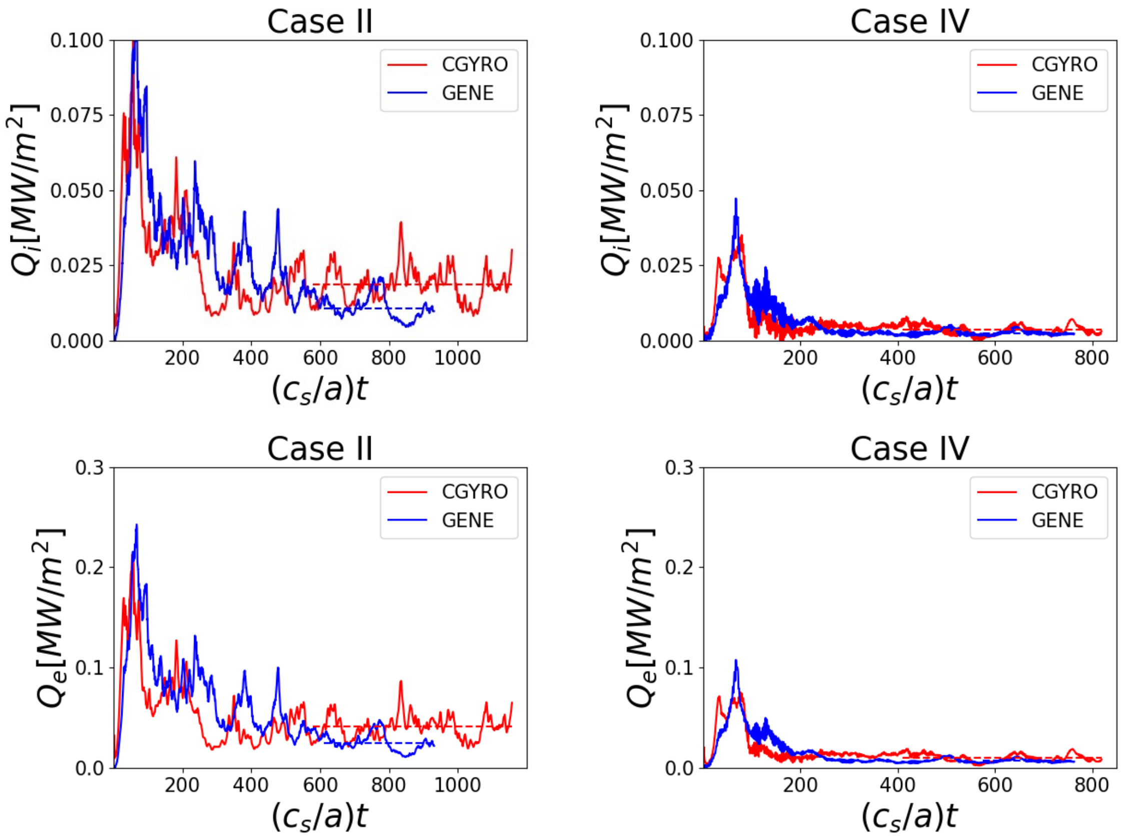


✓ Reminder, Case I : w/o rotation, w/o fast ions
Case III : w/o rotation, w/ fast ions

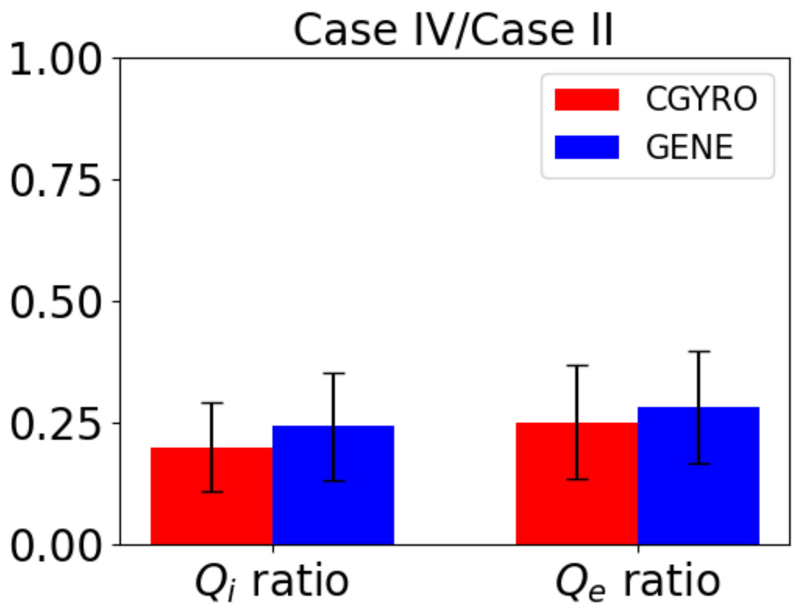


- Both codes predict significant reduction (>~65%) of thermal energy flux due to addition of fast ions (Case I → III)
- GENE predicts larger (~80%) reduction than CGYRO (~70%), but $Q_{Case\ III}/Q_{Case\ I}$ levels are agreed within their uncertainties between CGYRO and GENE

Consistent Fast Ion Effects are Observed in the Cases with Rotation Effects



✓ Reminder, Case I : w/o rotation, w/o fast ions
Case III : w/o rotation, w/ fast ions

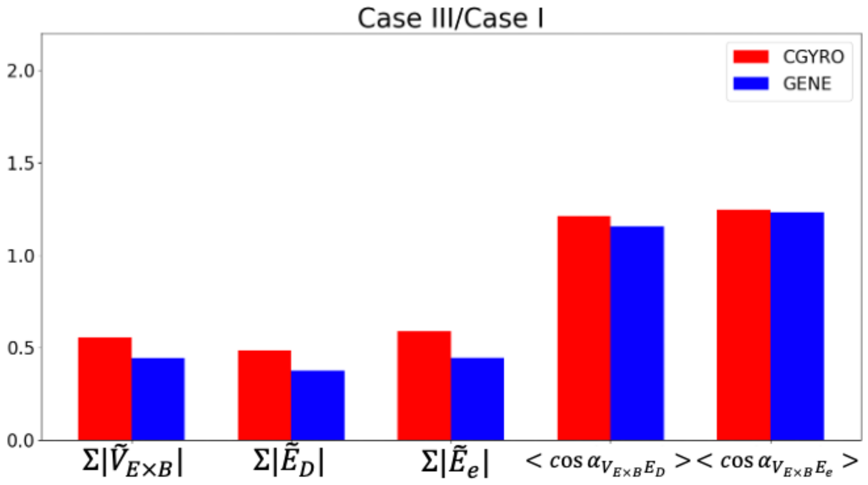


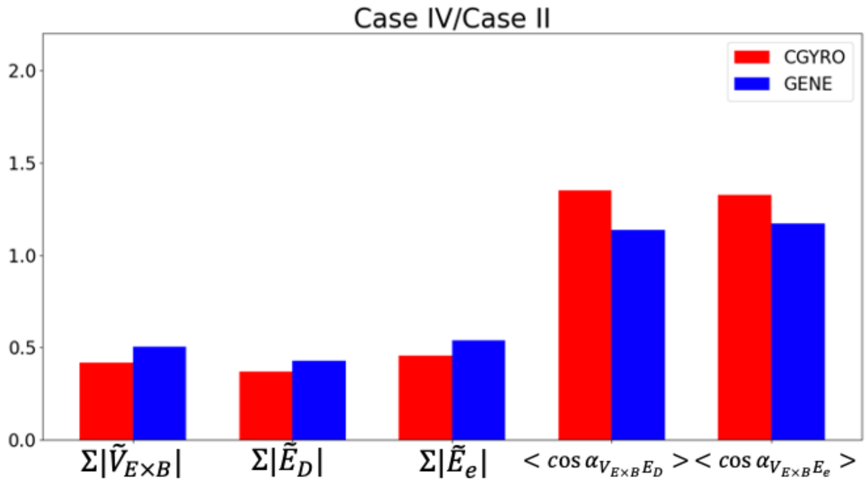
➢ Both codes predict significant reduction (~70-80%) of thermal energy flux with fast ions when rotation is considered (Case II → IV)

- The difference in fractional change by fast ions between two codes is decreased with rotation effects

Both Codes Predict the Consistent Changes in Fluctuations due to Fast Ions

- In this study, most energy flux comes from electrostatic turbulence
- Thus, energy flux can be expressed as,
  - ✓ $\tilde{Q}_j \sim Re[\tilde{V}_{E\times B}\tilde{E}_j^*] = |\tilde{E}_j||\tilde{V}_{E\times B}|\cos\alpha_{V_{E\times B}E_j}$
  - with fluctuations of energy of species j, $\tilde{E}_j$, fluctuations of radial ExB velocity $\tilde{V}_{E\times B}(\equiv \frac{ik_y\tilde{\phi}}{B})$, and their phase angle, $\alpha_{V_{E\times B}E_j}$
- The changes in each components are also compared





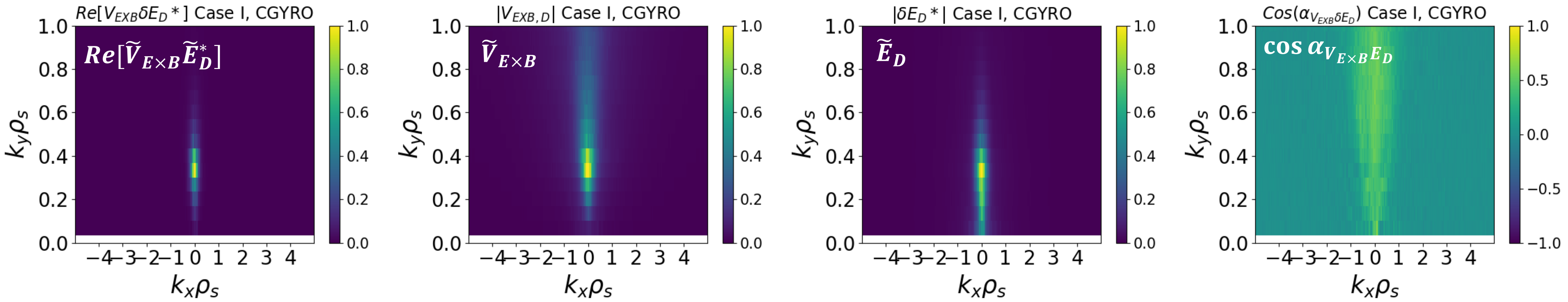
*Considered in $-0.51 \le k_x\rho_s \le 0.51, 0.2 \le k_y\rho_s \le 0.6$

- Both codes consistently predict the reduction of energy flux is mainly attributed to reduced amplitude of fluctuations not due to phase angle

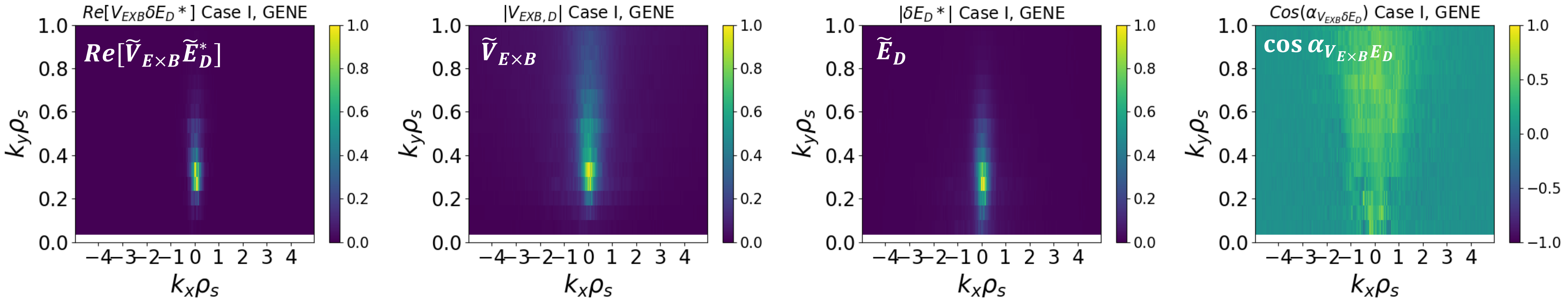
Overall Distribution of Energy Flux and Fluctuations are Agreed

✓ Reminder, Case I : w/o rotation, w/o fast ions

Case I - Main thermal ion (CGYRO)



Case I - Main thermal ion (GENE)

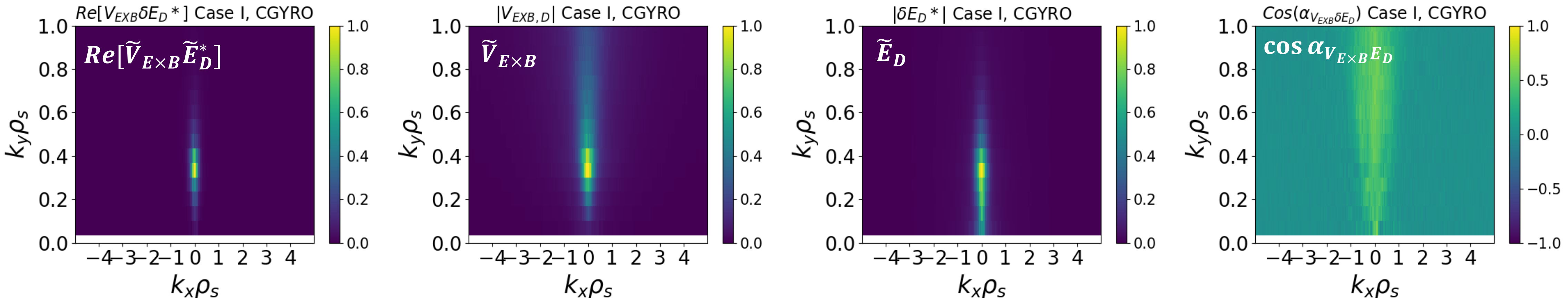


➢ Both codes predict a peaked distribution of energy flux and fluctuations at $0.2 \leq k_y\rho_s \leq 0.4$ & $|k_y\rho_s| \leq 0.51$

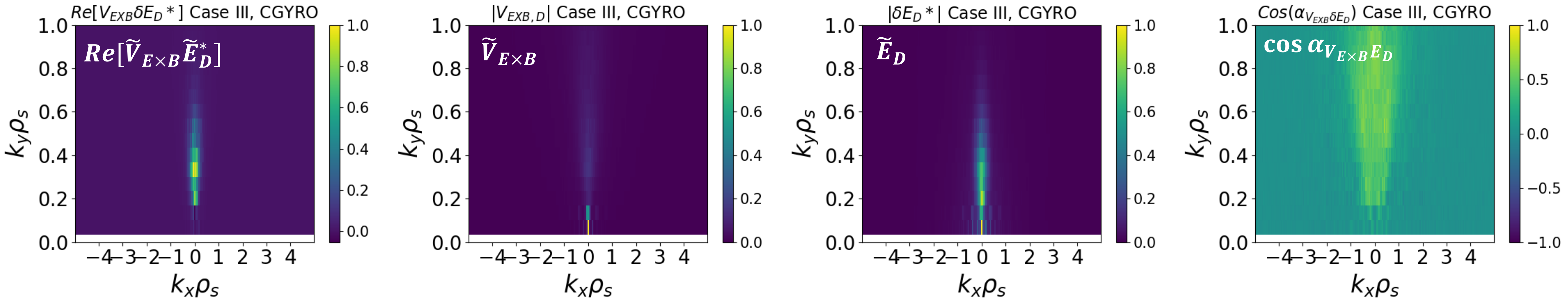
CGYRO Predicts the increase in Long Wavelength Fluctuations but not in Flux

✓ Reminder, Case I : w/o rotation, w/o fast ions
Case III : w/o rotation, w/ fast ions

Case I - Main thermal ion (CGYRO)



Case III - Main thermal ion (CGYRO)

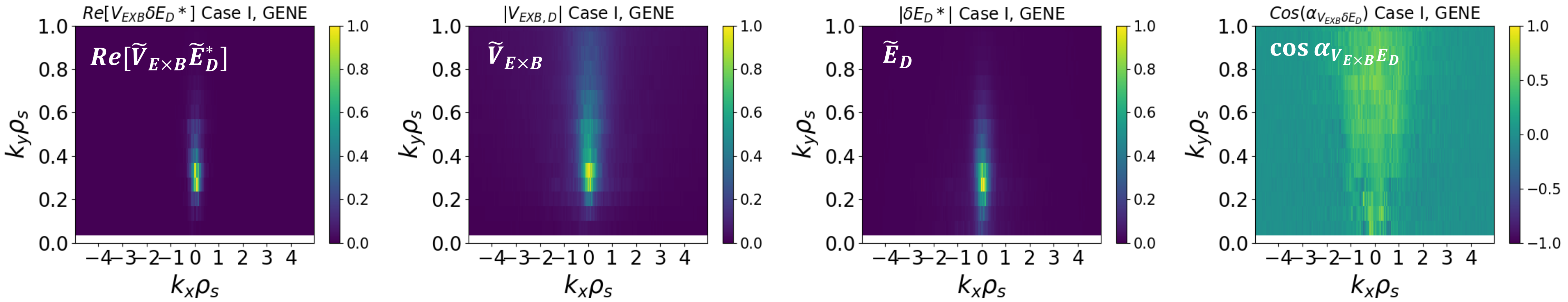


➢ Long wavelength ($k_y\rho_s < 0.2$) $\tilde{V}_{E\times B}$ and $\tilde{E}$ increase with fast ions but not in $\tilde{Q}$ since they are out phase

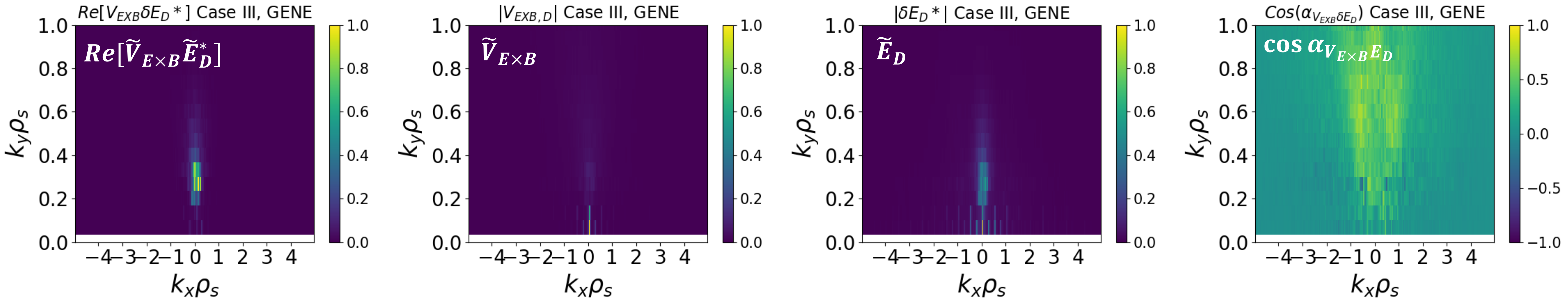
GENE also Predicts Qualitatively Consistent Changes with Fast Ions

✓ Reminder, Case I : w/o rotation, w/o fast ions
Case III : w/o rotation, w/ fast ions

Case I - Main thermal ion (GENE)



Case III - Main thermal ion (GENE)

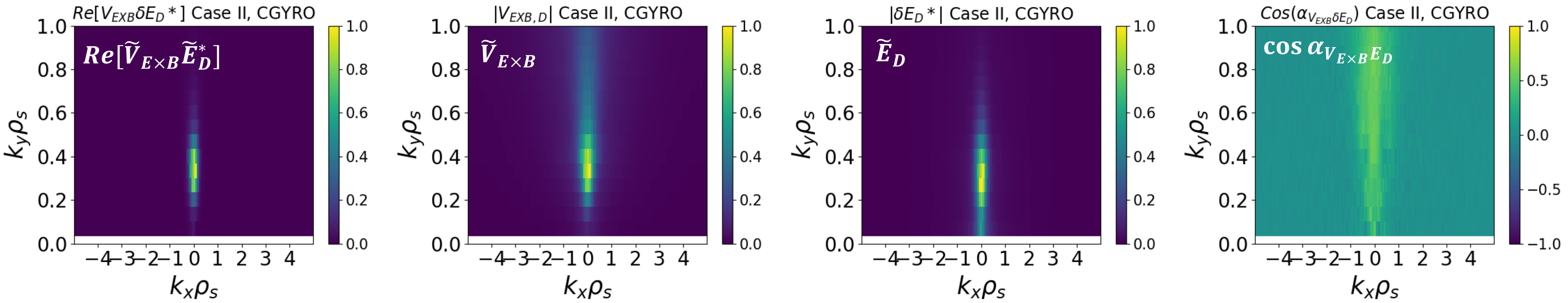


➢ GENE also predicts increase in long wavelength fluctuations not in flux due to phase, similar to CGYRO

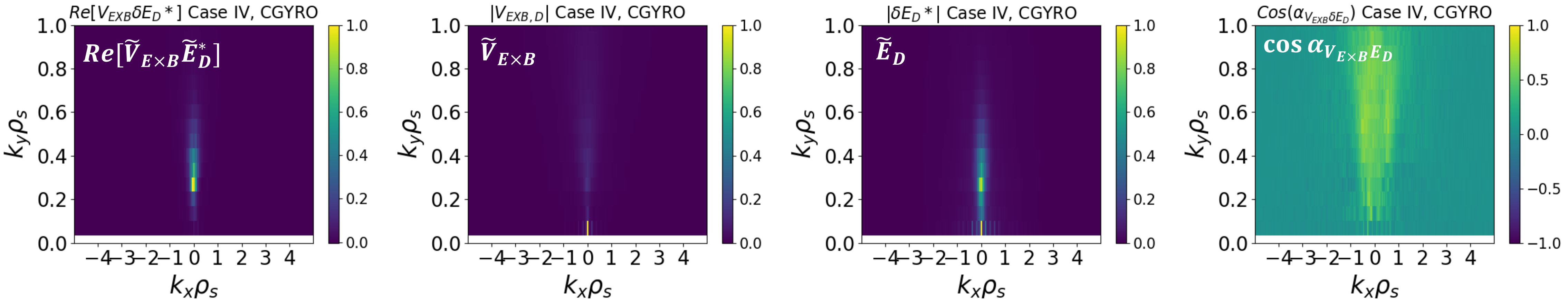
Consistent Changes were Observed in the Cases Considering Rotation Effects

✓ Reminder, Case II : w/ rotation, w/o fast ions
Case IV : w/ rotation, w/ fast ions

Case II - Main thermal ion (CGYRO)



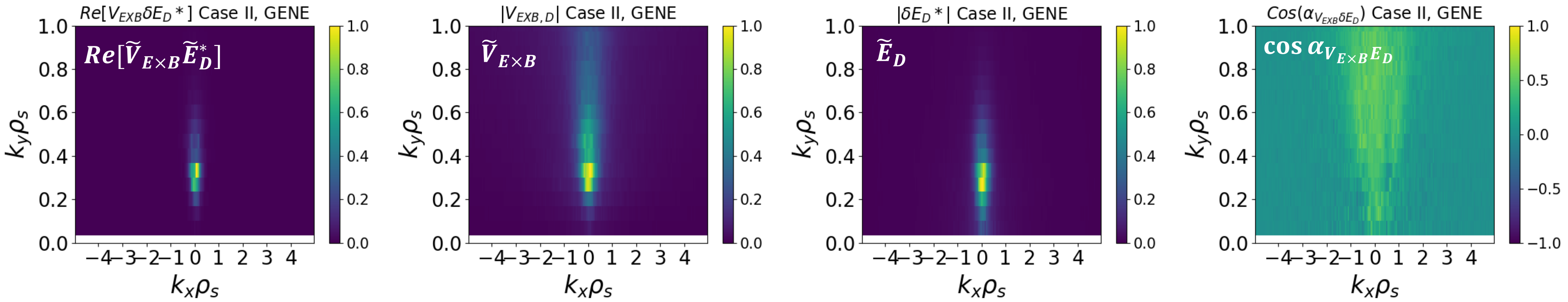
Case IV - Main thermal ion (CGYRO)



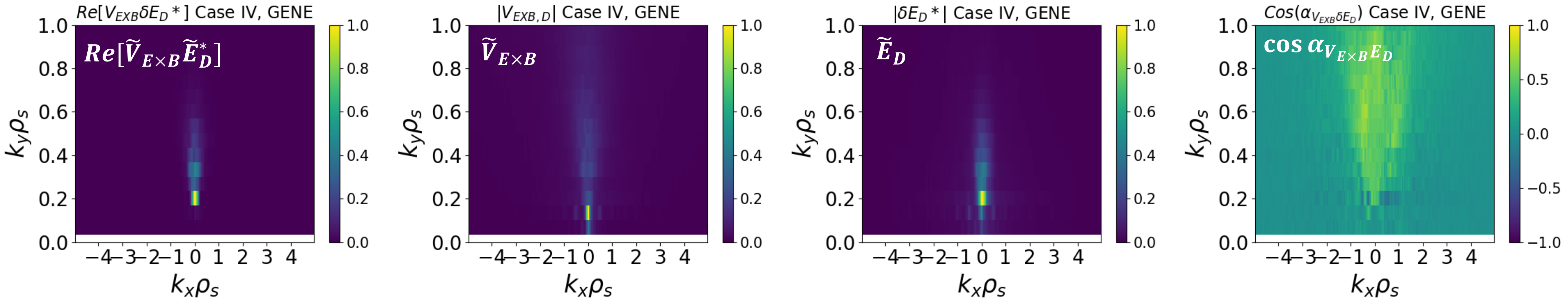
Consistent Changes were Observed in the Cases Considering Rotation Effects

✓ Reminder, Case II : w/ rotation, w/o fast ions
Case IV : w/ rotation, w/ fast ions

Case II - Main thermal ion (GENE)

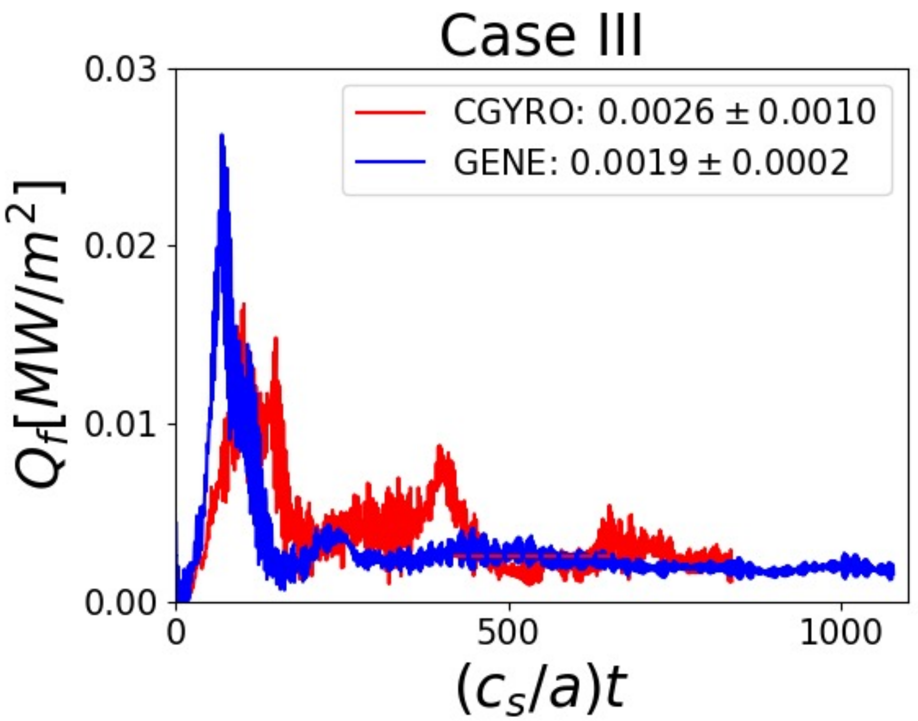


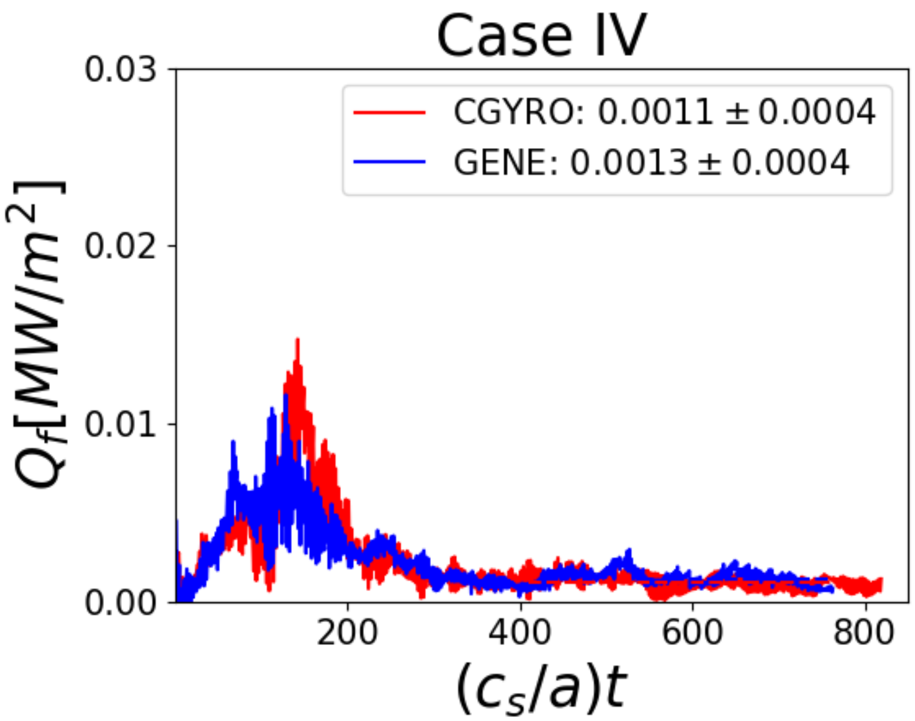
Case IV - Main thermal ion (GENE)



Fast Ion Energy Flux Levels are Quantitatively Matched between Two Codes

✓ Reminder, Case III : w/o rotation, w/ fast ions
Case IV : w/ rotation, w/ fast ions



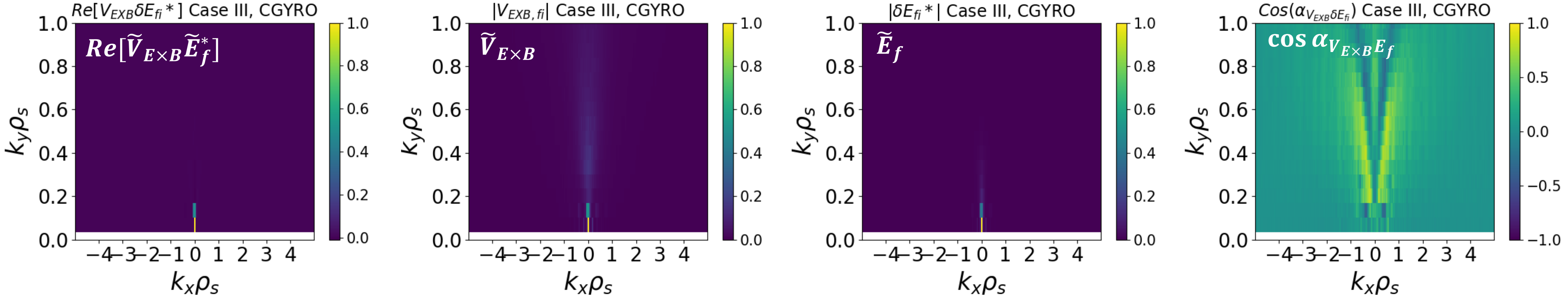


- Fast ion energy flux levels are agreed within their uncertainties between two codes in both Case III and Case IV
- Consistent with the agreed fractional change in thermal energy flux levels due to fast ions

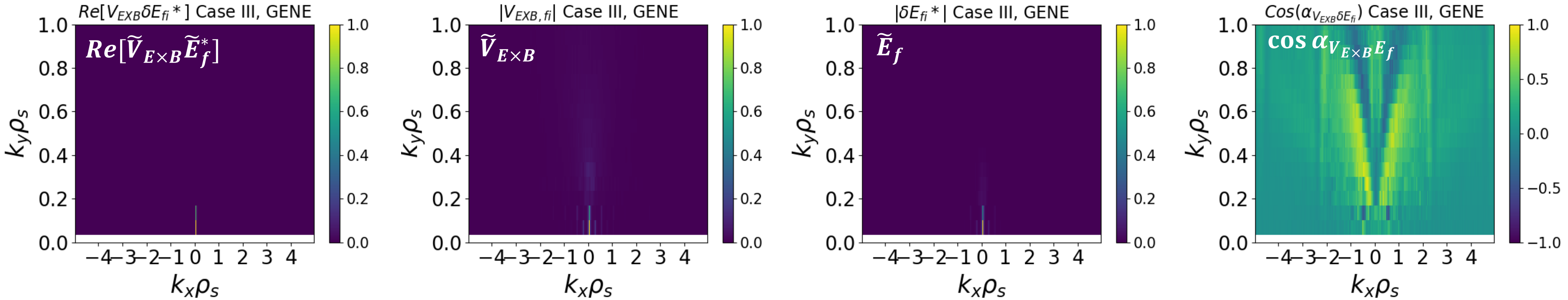
Two Codes Predict Similar $k_x - k_y$ Distribution of Fast Ion Energy Flux

Case III - Fast ion (CGYRO)

✓ Reminder, Case III : w/o rotation, w/ fast ions



Case III - Fast ion (GENE)

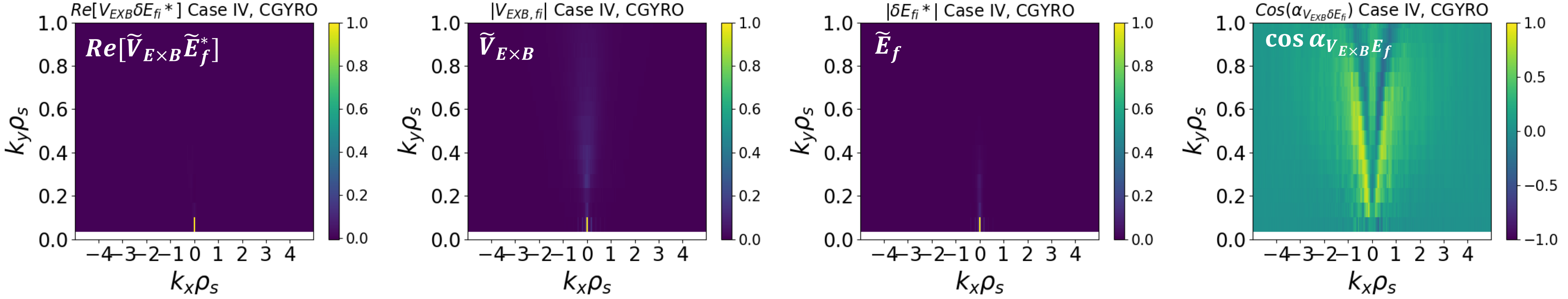


- Dominant mode was appeared at low k_y region ($k_y\rho_s \lesssim 0.2$)
- Nearly symmetric structure was observed in the phase angle distribution

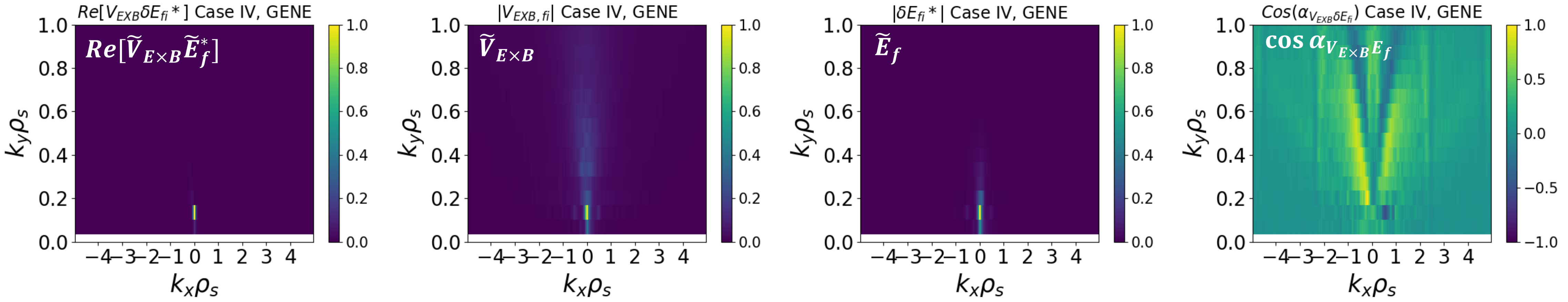
Consistent Features was Found in the Cases with Rotation Effects

✓ Reminder, Case IV : w/ rotation, w/ fast ions

Case IV - Fast ion (CGYRO)

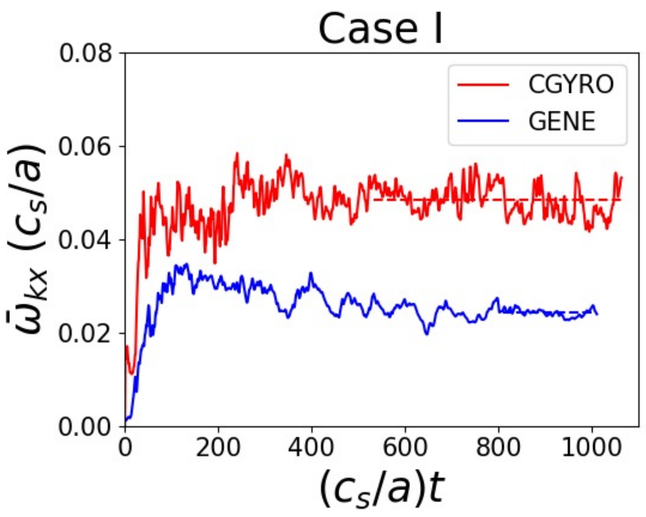


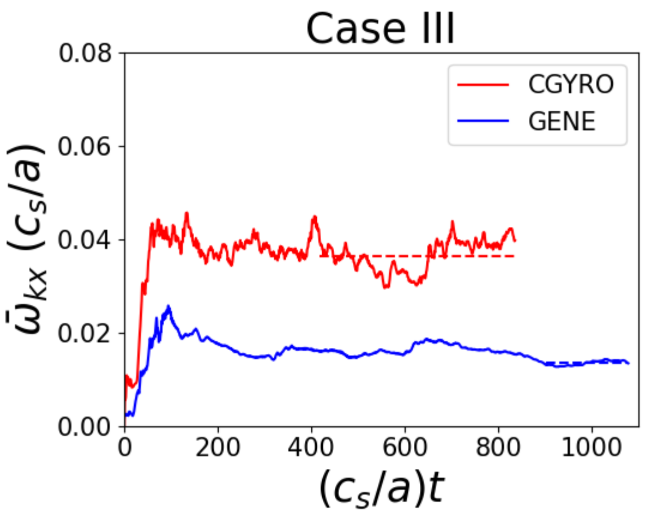
Case IV - Fast ion (GENE)



Discrepancy was Found in Fractional Change in Zonal Shearing due to Fast Ions

✓ Reminder, Case I : w/o rotation, w/o fast ions
Case III : w/o rotation, w/ fast ions





- Zonal shearing rate in the saturated phase

	Case I		Case III		Case III / Case I	
	CGYRO	GENE	CGYRO	GENE	CGYRO	GENE
$\bar{\omega}_{kr}$ $[c_s/a]$	0.048 ±0.0032	0.024 ±0.0008	0.036 ±0.0033	0.013 ±0.0005	0.75 ±0.085	0.56 ±0.028

- Zonal shearing rate defined in [Howard 16] is utilized in this analysis
  - $\bar{\omega}_{kr} = \frac{1}{N}\sum_{-\rho_s^{-1}}^{\rho_s^{-1}} \omega_{kr}$

    w/ $\omega_{kr} = \sqrt{\frac{k_r^4}{B^2}\left|\tilde{\phi}(k_r, k_\theta = 0)\right|^2}$

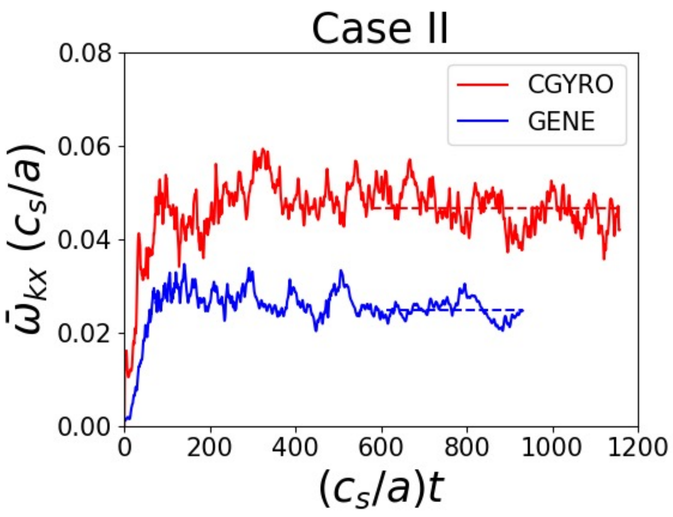
- Zonal shearing in CGYRO is higher than GENE

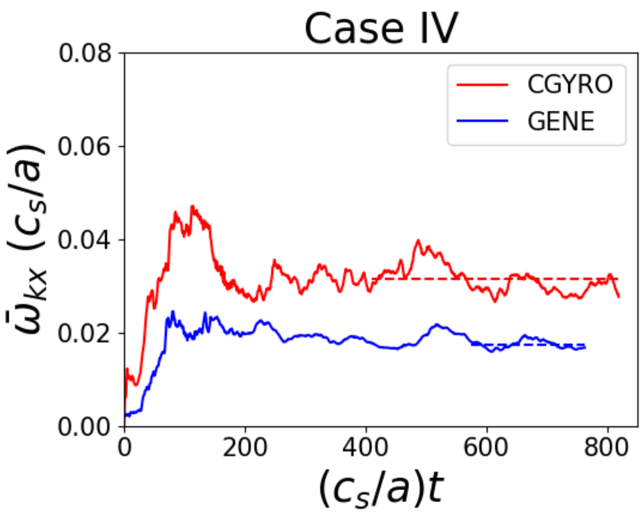
- Both codes predict lower zonal shearing with fast ions, but quantitatively different
  - $\bar{\omega}_{kr,Case\ III}/\bar{\omega}_{kr,Case\ I}$ ~ 0.75 (CGYRO)

    ~ 0.56 (GENE)

Zonal Shearing Predictions Become More Consistent with Rotation

✓ Reminder, Case I : w/o rotation, w/o fast ions
Case III : w/o rotation, w/ fast ions





- ➢ Zonal shearing rate in the saturated phase

	Case II		Case IV		Case IV / Case II	
	CGYRO	GENE	CGYRO	GENE	CGYRO	GENE
$\bar{\omega}_{kr}$ $[c_s/a]$	0.047 ±0.0039	0.025 ±0.0020	0.031 ±0.0029	0.017 ±0.0009	0.68 ±0.084	0.70 ±0.067

- ➢ The fractional reductions in zonal shearing rate are well matched between two codes

- ➢ GENE predicts smaller change in zonal shearing rate by fast ions with rotation while similar change was predicted by CGYRO
  - $\frac{\bar{\omega}_{kr,fi}}{\bar{\omega}_{kr,no\ fi}}$ ~ 0.56 (GENE, w/o rotation)
    ~ 0.7 (GENE, w/ rotation)
  - $\frac{\bar{\omega}_{kr,fi}}{\bar{\omega}_{kr,no\ fi}} \sim 0.68 - 0.75$ regardless of rot. (CGYRO)

- ➢ Zonal shearing is reduced with fast ions, different from previous studies [Mazzi 22…]

Summary

- Using CGYRO and GENE, cross verification for fast ion effects on turbulence and energy transport predicted by gyrokinetic codes is performed

- Overall fast ion effects are agreed between CGYRO and GENE
  - Linear simulation results, reduction of thermal energy flux, changes in fluctuations and flux distribution in k space, fast ion energy flux level
  - Found importance of phase angle in the gyrokinetic analysis of fast ion effects on turbulence

- We also found some discrepancies between two codes
  - Absolute levels of thermal energy flux
    - ✓ not due to fast ions, but should be resolved
  - Fractional change in zonal shearing without rotation

- Need efforts to resolve the observed discrepancies in the future