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Comprehensive Gyrokinetic Analysis of Fast Ion Effects on Turbulence in KSTAR FIRE Mode Discharge

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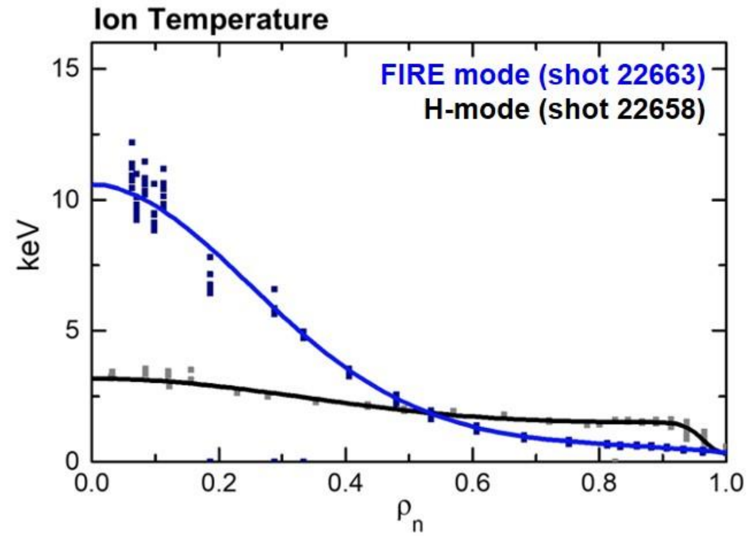
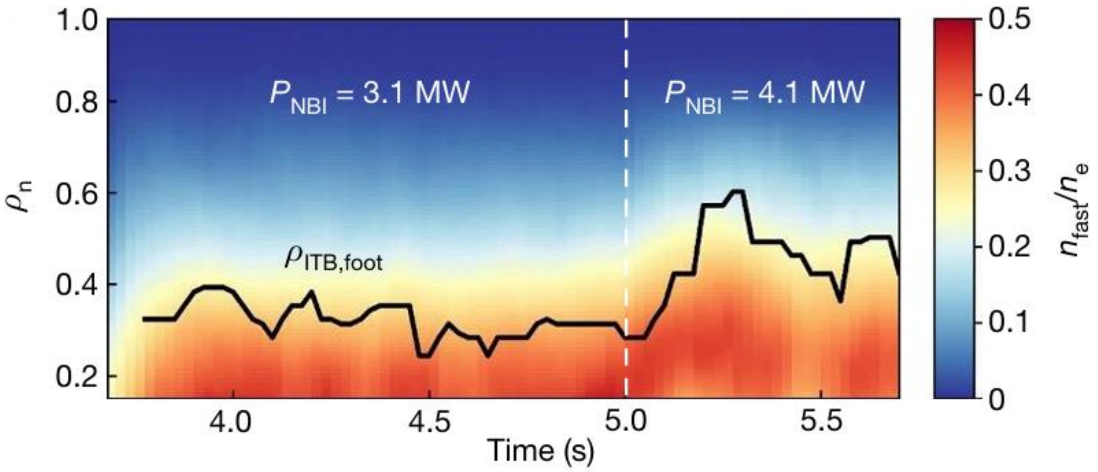
The Role of Fast ions on ITB Operation in the KSTAR FIRE Mode Discharge was Investigated





* ρ_n is the square root of the normalized toroidal magnetic flux

- ITB operation mode having a high fast ion fraction was observed in KSTAR [Han and Park 22]
  - ✓ High performance comparable to hybrid mode (H_{89L}~2)
  - ✓ Can be maintained for ~30s without delicate control
- The correlation between fast ions and ITB region was observed
  - ✓ Fast ions may contribute to confinement enhancement and ITB formation
  - ✓ Therefore, this mode is named **Fast Ion Regulated Enhancement (FIRE) mode**
- This motivated the gyrokinetic analysis for the role of fast ions on ITB operation in KSTAR FIRE mode plasmas
  - ✓ Fast ion effects on electron scale turbulence as well as ion scale turbulence were also investigated

Gyrokinetic Analysis for the Role of Fast Ions on ITB operation in KSTAR FIRE mode Discharge were Performed

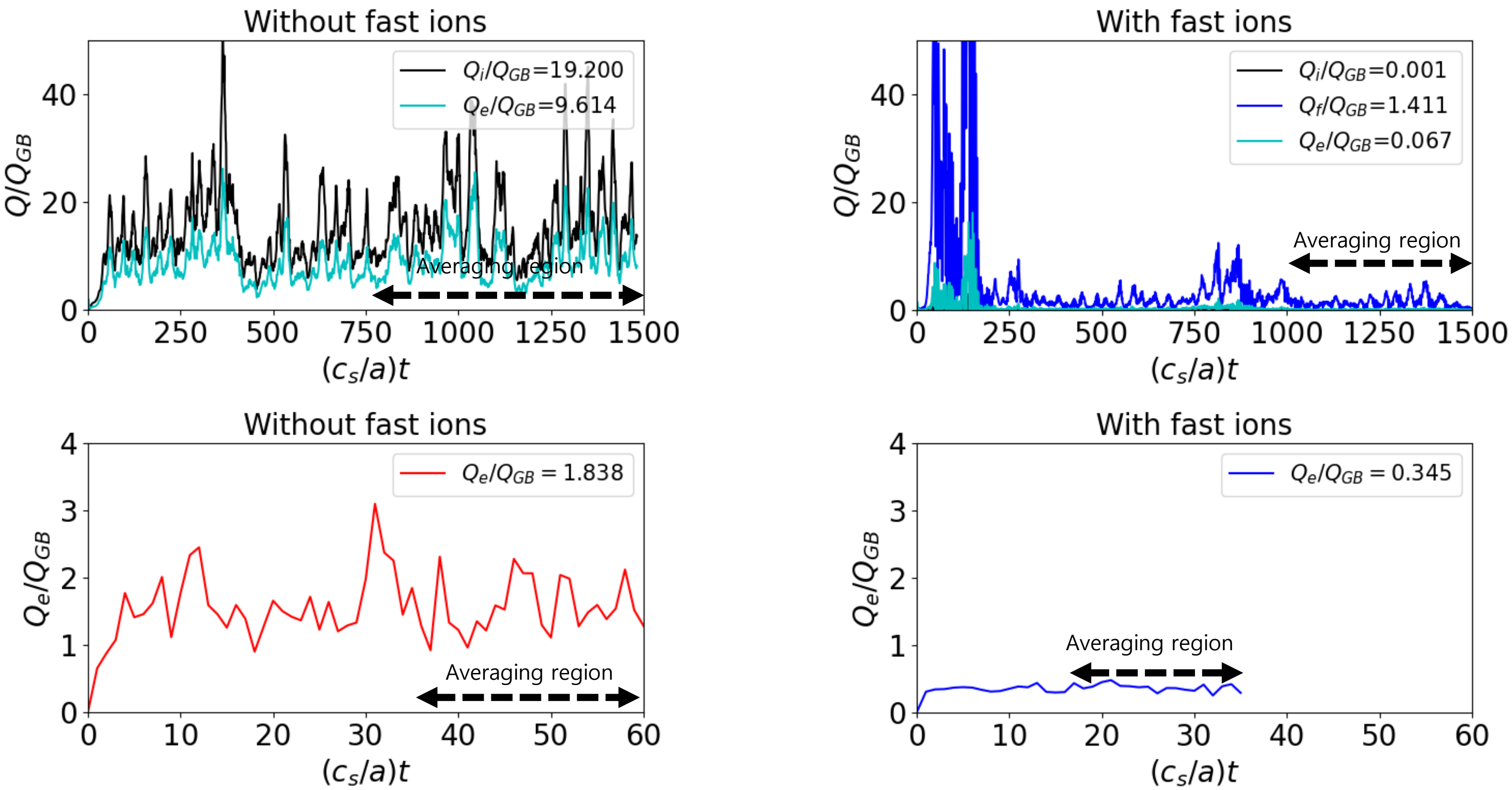
- CGYRO [Candy and Belli 16] was used for gyrokinetic analysis

- Simulation setup
  - ✓Local simulation (flux tube)
  - ✓Simulation location is inside ITB region, r/a=0.47 (ρ=0.4)
    - ρ is the square root of the normalized toroidal magnetic flux
  - ✓Ion scale ($k_y\rho_s \leq \sim 1.0$) and electron scale ($k_y\rho_s \leq \sim 60.0$)
    - k_y is the poloidal wave number, ρ_s is the ion gyro radius
  - ✓Miller geometry parameterization
  - ✓Electromagnetic ($\delta\tilde{\phi}, \delta\tilde{A}_{\parallel}$)
  - ✓Kinetic electrons with collisions
  - ✓Included rotation and ExB shear effects
  - ✓Fast ions were treated as additional ion species
  - ✓$Z_{eff}(\equiv \frac{\Sigma_j Z_j^2 n_j}{n_e}) = 2$ flat profile was assumed
  - ✓Used carbon (Z=6) as a single impurity species

Gyrokinetic Simulations Show the Significant Reduction of Energy Flux with Fast Ions

Ion scale simulation
($k_y \rho_s \leq \sim 1.0$)

Electron scale simulation
($k_y \rho_s \leq \sim 60.0$)



- Thermal energy fluxes predicted by gyrokinetic simulation decreased significantly for both ion and electron scale turbulence when fast ions were included

$Q_{GB} (= n_e c_s T_e (\rho_s/a)^2)$: GyroBohm energy flux
$c_s (= \sqrt{T_e/m_i})$: Ion sound speed, ρ_s: Ion gyro radius

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Possible Turbulence Suppression Mechanisms by Fast Ion Effects

- **Possible mechanisms of turbulence suppression due to fast ions** were investigated through gyrokinetic analysis in the KSTAR FIRE mode discharge [Kim and Sung 23]

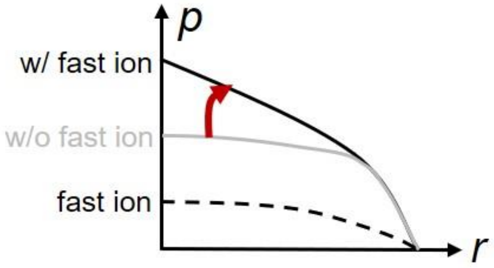
  ✓ **Increased pressure gradient** ($\beta_* \equiv -\frac{8\pi}{B^2}\nabla p$) [Bourdellel 05]

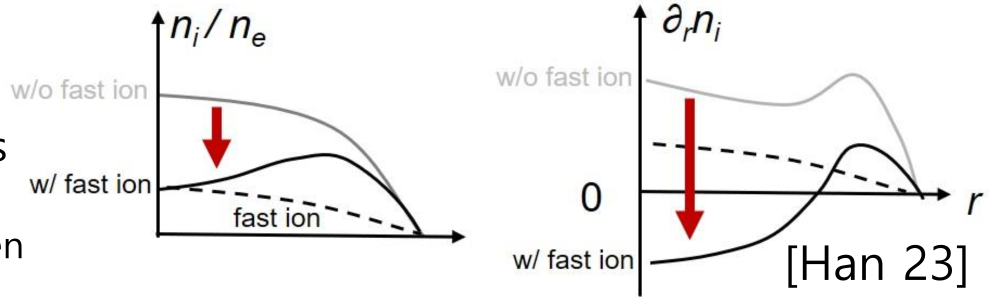
  ✓ **Dilution**
  - Reduced main ion density fraction (n_i/n_e) [Wilkie 18]
  - Inverted main ion density gradient [Hahm 89]

  ✓ **Changes in the zonal shearing rate** [Hahm 23]

  ✓ Resonance interaction between background instabilities and fast ions [Siena 18] is not applicable in this case
  - Turbulence suppression by resonance interaction occurs significantly when $a/L_{Tf} \gg a/L_{nf}$, but $a/L_{Tf} \ll a/L_{nf}$ in this case (a/L_{Tf}~0.56, a/L_{nf}~3.57)

  ✓ Fast ion driven mode [Siena 19, Mazzi 22] (will be discussed later)



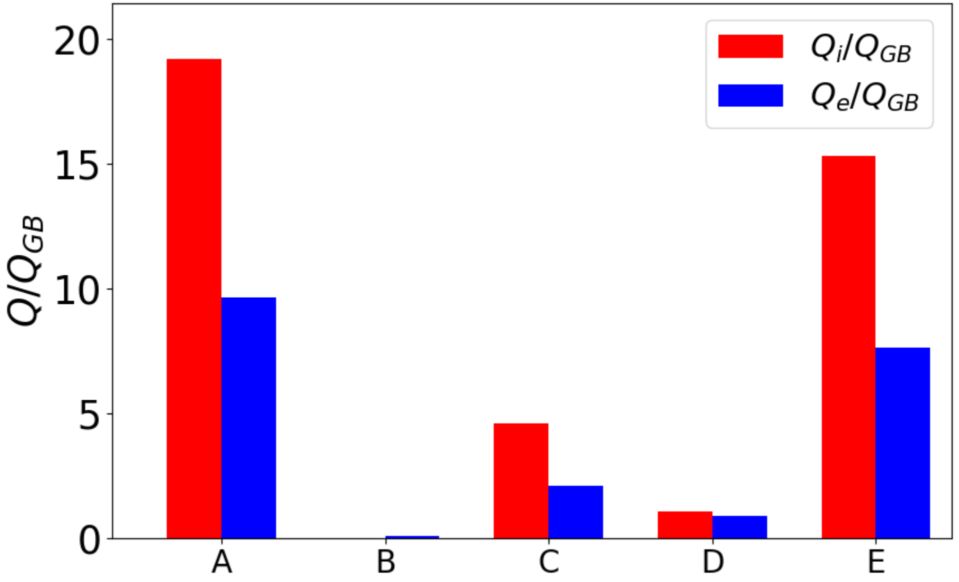


[Han 23]

$a/L_X = -a\nabla X/X$

Reduced Main Ion Density Fraction Effects Can be Responsible for Turbulence Suppression

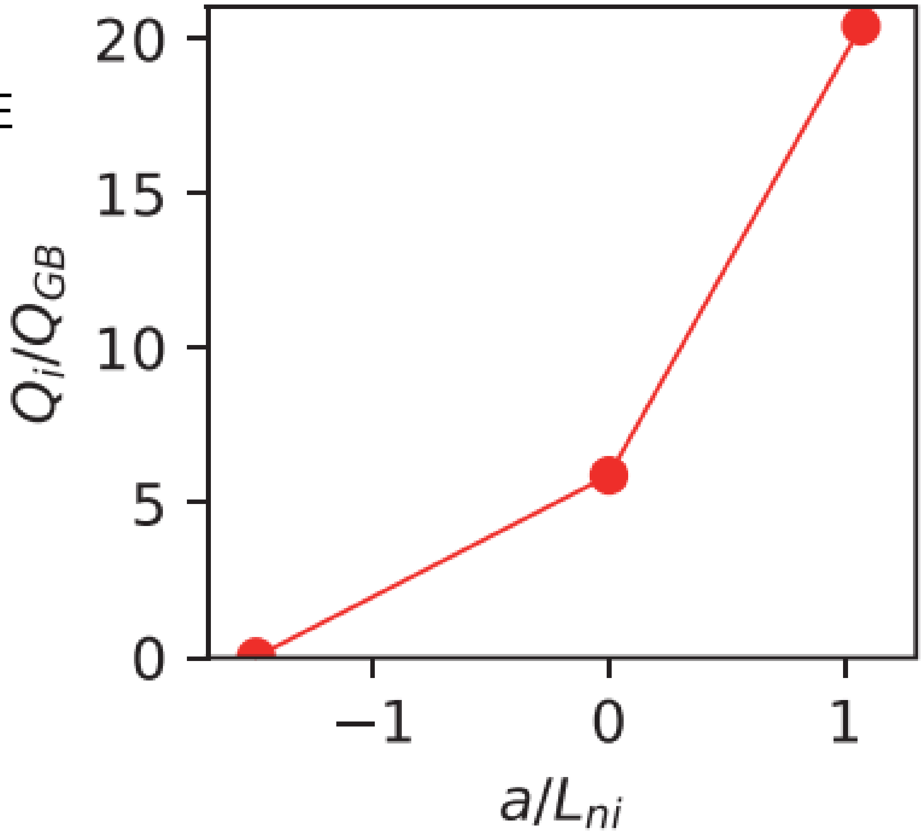
- Possible mechanisms of turbulence suppression due to fast ions were investigated through gyrokinetic analysis in the KSTAR FIRE mode discharge [Kim and Sung 23]
  - ✓ Increased pressure gradient ($\beta_* \equiv -\frac{8\pi}{B^2}\nabla p$) [Bourdellel 05]
    - β_* increased from 0.024 to 0.075 when fast ions were included
    - Increase of $\beta_* \left(\equiv -\frac{8\pi}{B^2}\nabla p\right)$ can suppress the turbulence by reducing the vertical drift motion
  - ✓ Dilution I: Reduced main ion density fraction (n_i/n_e) [Wilkie 18]
    - n_i/n_e decreased from 0.8 to 0.4 when fast ions were included
    - Decrease of main ion fraction can reduce the turbulence driven by the main ion
  - ✓ Changes in the zonal shearing rate [Hahm 23]
    - An increase in zonal shearing rate was observed when fast ions were included (not shown here, detail will be discussed later)
    - Zonal flow shearing can suppress turbulence
- Thermal energy flux reduction due to reduced n_i/n_e effect is larger than increased β_* and zonal shearing rate



A: **Without fast ions**
B: **With fast ions (exp)**
C: **Increased β_*** without fast ions
D: **Reduced n_i/n_e** with fast ions and fixed a/L_{ni}
E: **Increased zonal shearing rate** without fast ions

Dilution Effects are Dominant Turbulence Suppression Mechanisms by Fast Ion Effects on Thermal Energy Flux Reduction

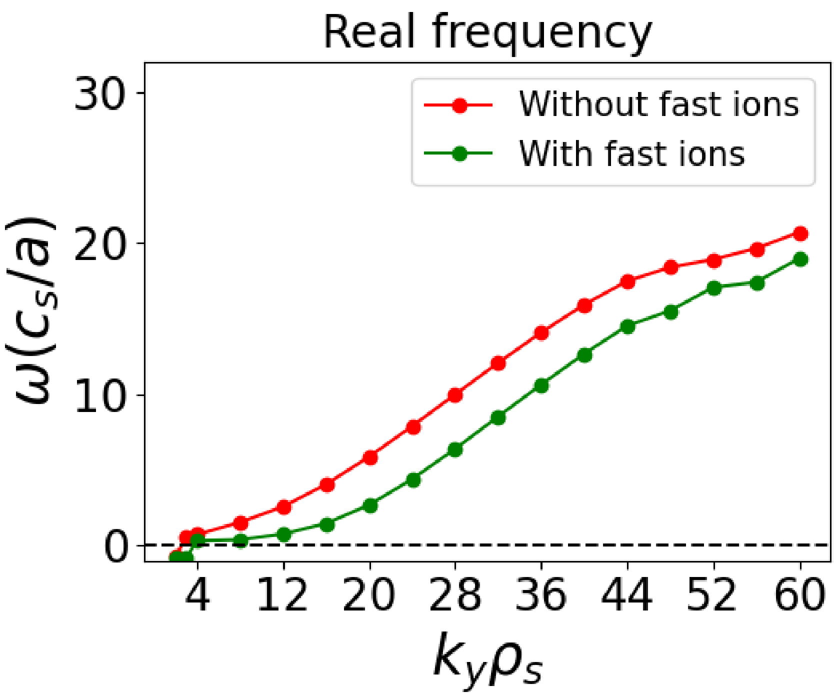
- Possible mechanisms of turbulence suppression due to fast ions were investigated through gyrokinetic analysis in the KSTAR FIRE mode discharge [Kim and Sung 23]
  - ✓ Dilution II: Inverted main ion density gradient [Hahm 89]
    - a/L_{ni} changed from 1.067 to -1.494 when fast ions were included
- As a/L_{ni} is inverted from 1.067 to -1.494 (exp), thermal energy flux decreases significantly
  - ✓ Close to the level in the case with fast ions
- The sole effect of the inverted main ion density gradient on turbulence suppression is sufficient to form ITB
  - ✓ Consistent with studies showing the effects of inverted density profile on turbulence suppression [Hahm 89,90]
- Dilution effects including inverted a/L_{ni} and lower n_i/n_e are mainly responsible for turbulence suppression

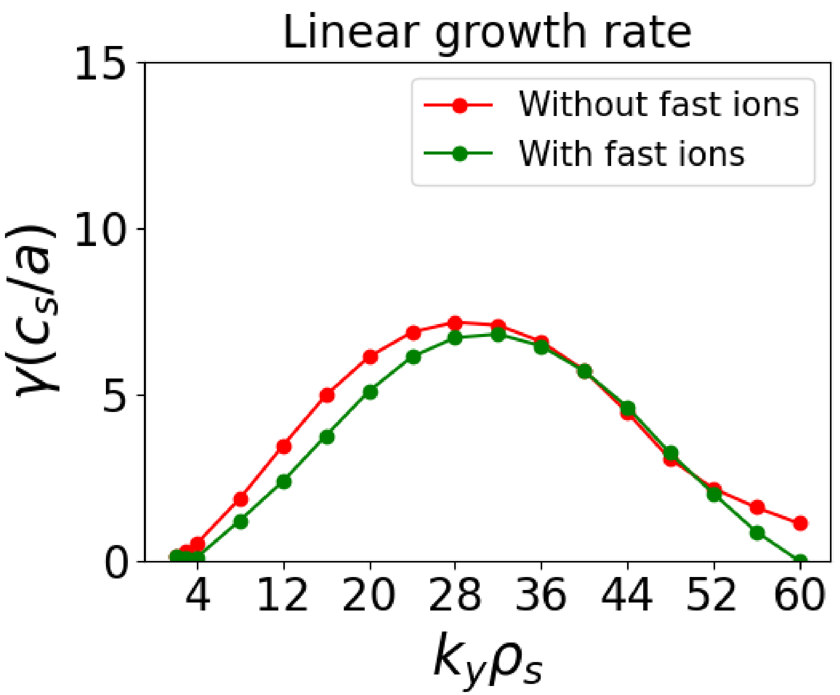


a/L_{ni} was changed with a/L_{nf} for quasi-neutrality condition

To evaluate the sole effect of inverted a/L_{ni} without effect of reduced n_i/n_e and fast ion mode, 1% addition of fast ion (n_f/n_e=0.01) and lower T_f/T_i were used

Fast Ions Affect the Linear Growth Rate in High k_y Region

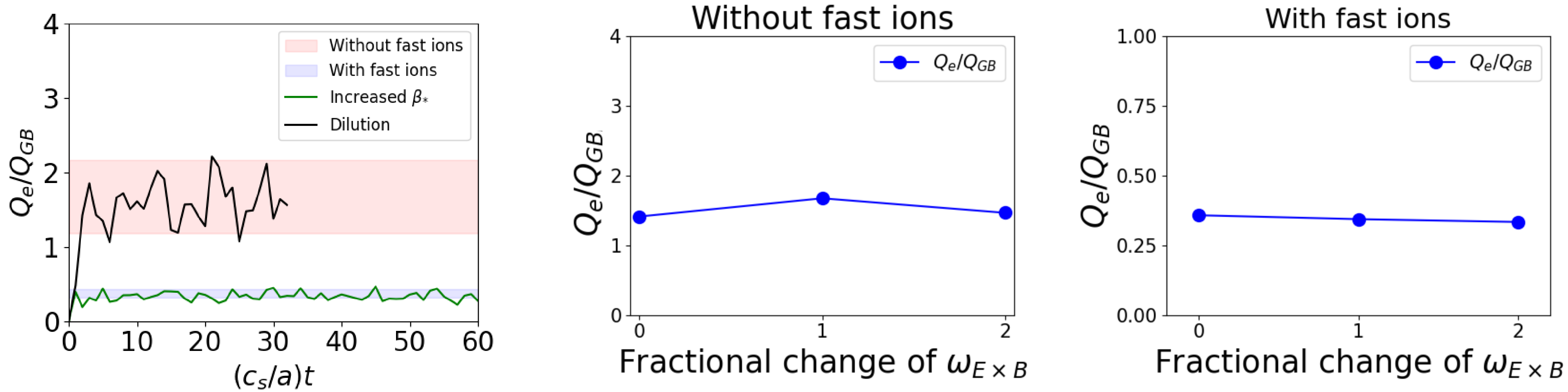




(+) and (-) sign of real frequency denote the most unstable mode propagate to electron and ion diamagnetic direction, respectively

- The most previous studies [Siena 18, Mazzi 22, Citrin 23] focus on fast ion effects on ion scale turbulence
- However, electron scale turbulence can degrade the confinement by increasing the electron energy flux [Mariani 21]
- When fast ions were included, the linear growth rate decreased

The Suppression of Electron Scale Turbulence by Fast Ions is Mainly due to Increased β_*



Dilution effects: reduced main ion density fraction + change of main ion density gradient

- When β_* increased, energy flux decreased to a similar level to the case with fast ions
  - ✓ This is consistent with a previous study [Jian 19] that electron scale turbulence can be suppressed by increased β_*
- Dilution effect seems to be negligible on electron scale turbulence
- For electron scale simulation, changes in shearing rate have negligible effect on turbulence
- The energy flux level of the electron scale simulation is higher than the level of the ion scale simulation
  - ✓ $Q_e[Q_{GB}]{\sim}0.067$ in ion scale simulation, $Q_e[Q_{GB}]{\sim}0.345$ in electron scale simulation
  - ✓ Multi-scale simulations may be required since electron scale turbulence is not negligible

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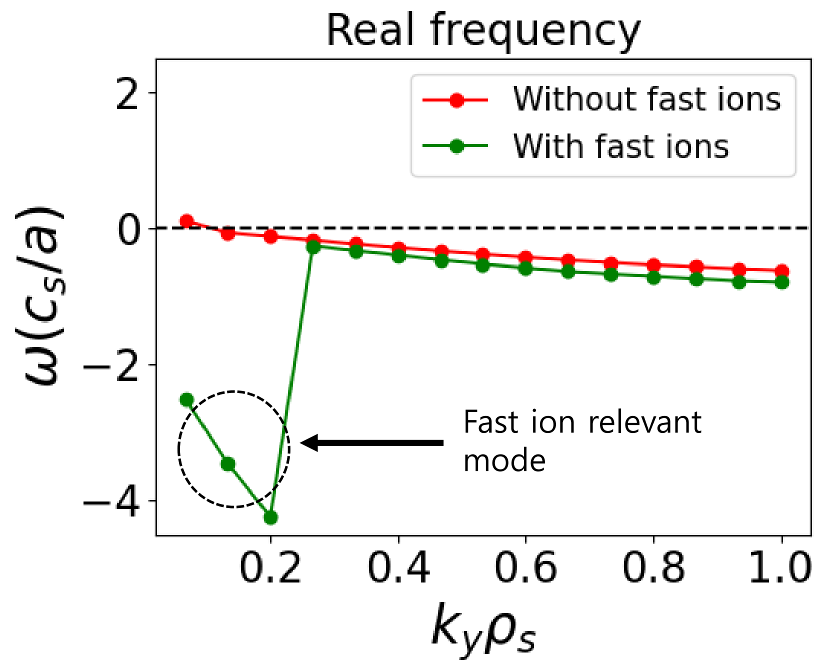
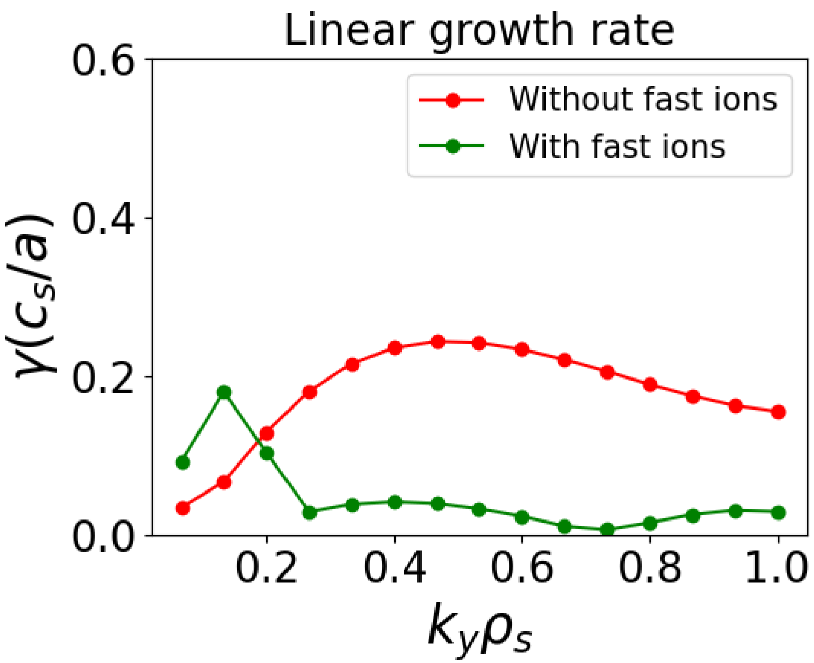
Fast Ion Relevant Mode was Observed When Fast Ions were Included

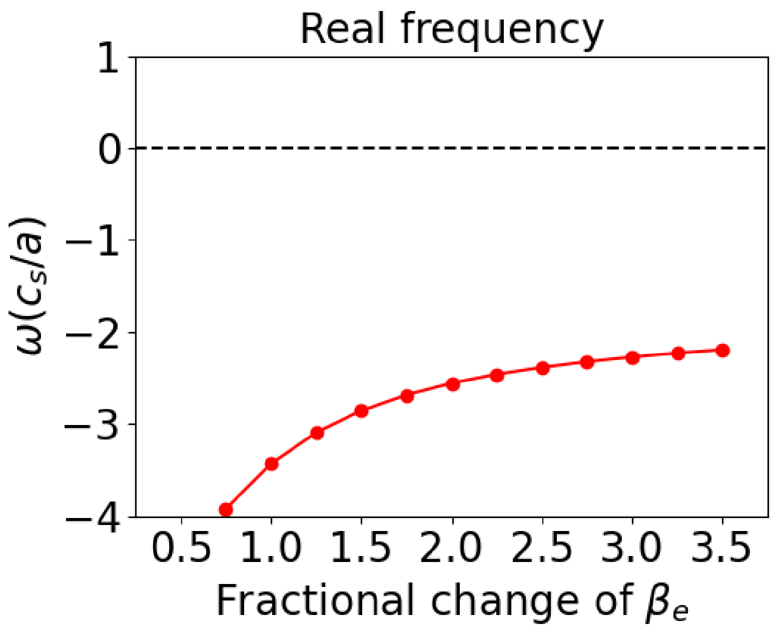


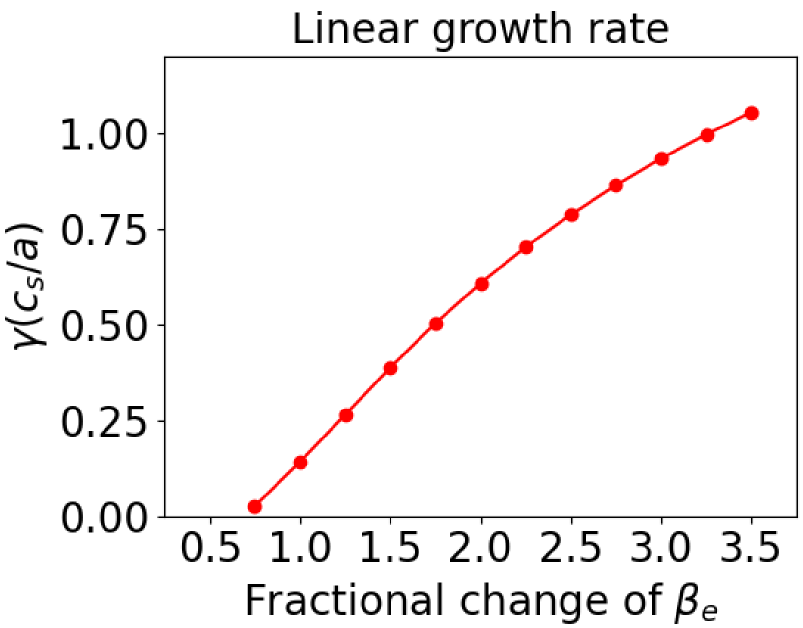


(+) and (-) sign of real frequency denote the most unstable mode propagate to electron and ion diamagnetic direction, respectively

- When fast ions were included, fast ion relevant mode become destabilized at $k_y\rho_s < 0.27$
- Impact of fast ion relevant mode observed in simulations on turbulence should be investigated
  - ✓ It is known that fast ion driven mode can suppress the turbulence by increasing zonal shearing rate [Mazzi 22]
  - ✓ Fast ion driven mode can increase the thermal transport [Bass 10]

The Linear Threshold on β was Observed in the Fast Ion Relevant Mode



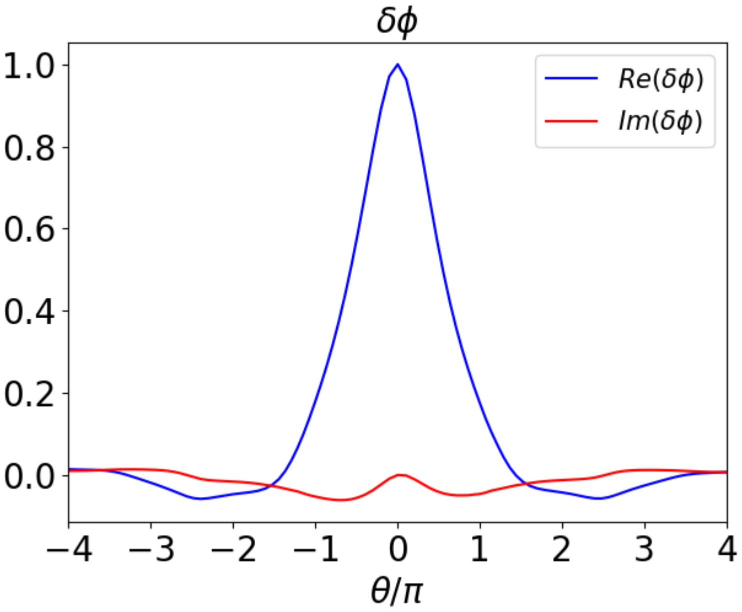


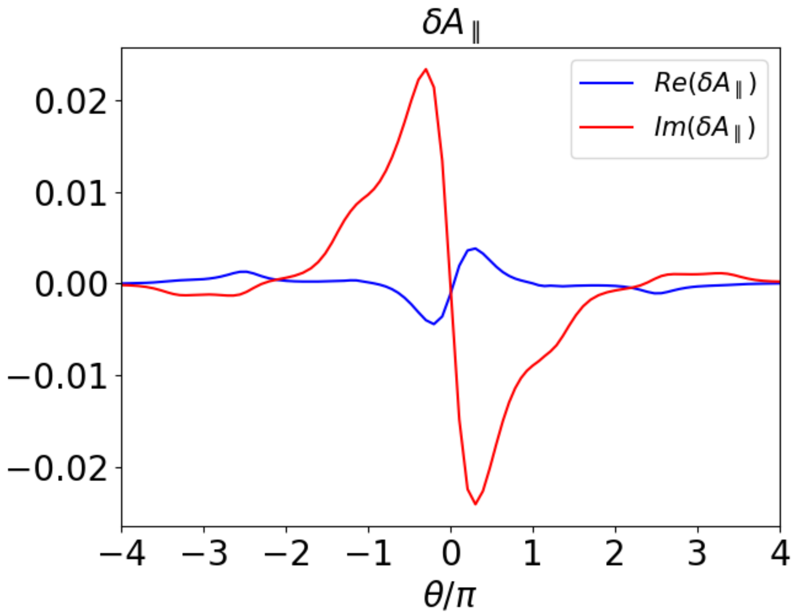
- To identify the fast ion relevant mode, linear simulations for varied β_e were performed
  - ✓ Simulations were performed with varied β_e, but fixed $\beta_* = 0.075$ and a/L_{Ti}, a/L_{Tc}, $a/L_{Te} = 0$ to focus only fast ion relevant mode

- As β_e increased, the real frequency decreased and the linear growth rate increased

- The linear threshold was observed in β
  - ✓ Therefore, this mode is not fast ion driven electrostatic drift wave instability [Kang 25]

The Characteristics of Mode Structure for the Fast Ion Relevant Mode were Investigated

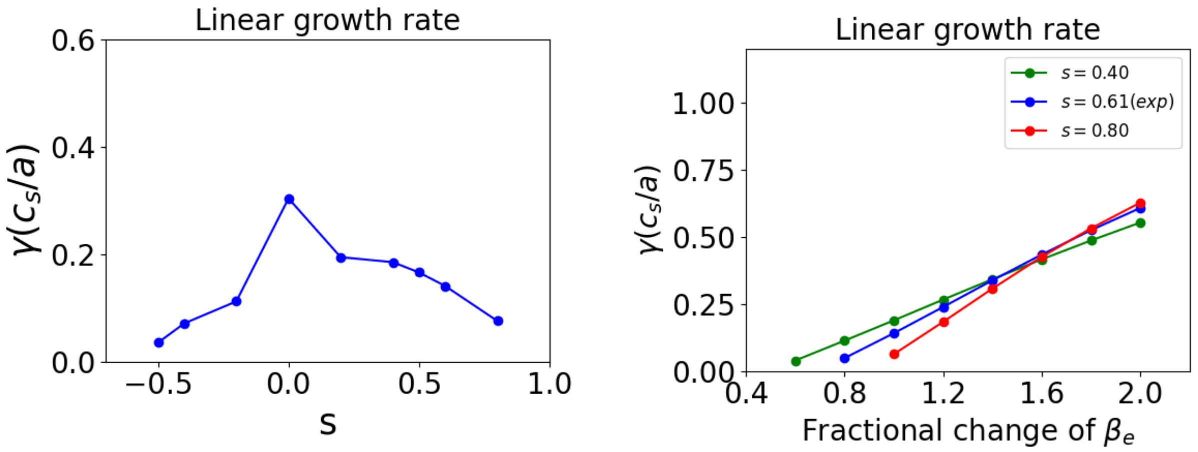




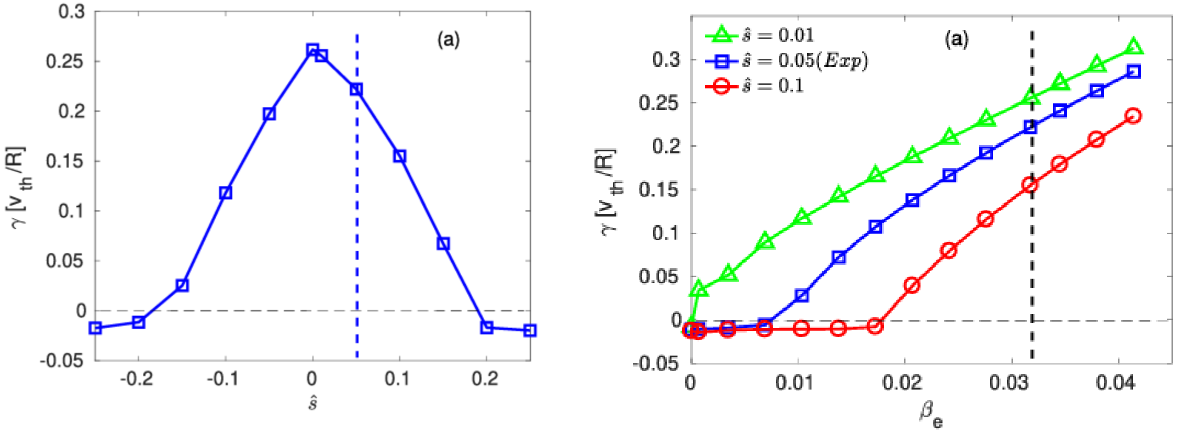
- The eigenfunctions are characterized by even parity in $\delta\phi$ and odd parity in $\delta A_{\parallel}$ with the electrostatic perturbation amplitude higher than the magnetic perturbation amplitude

- Interestingly, clear out of phase symmetry in vector potential ($Re[\delta A_{\parallel}] \propto -Im[\delta A_{\parallel}]$) were observed
  - ✓ This characteristic is a signature of kinetic ballooning mode (KBM) [Belli 10, Mazzi 25]

The Fast Ion Relevant Mode Exhibits a Similar Characteristic to KBM Observed in JET hybrid Scenario



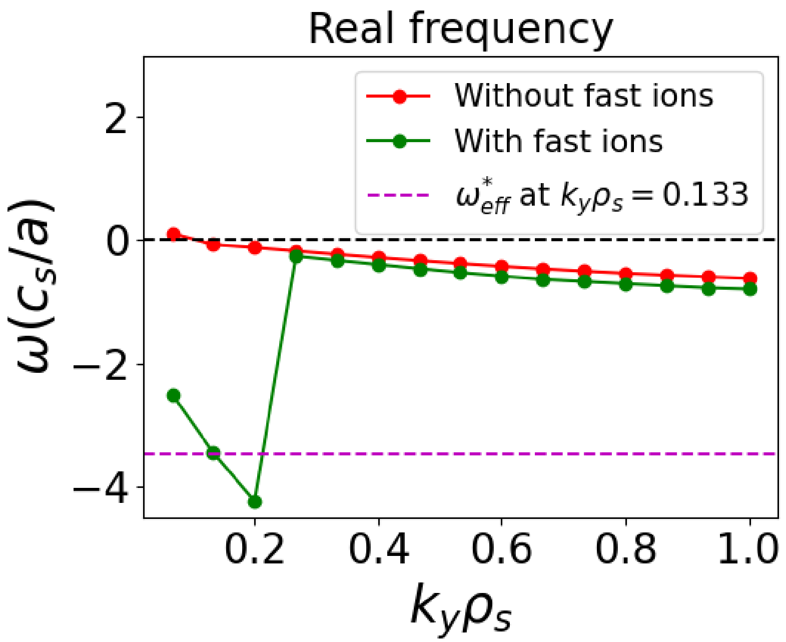
Fast ion relevant mode in FIRE mode discharge

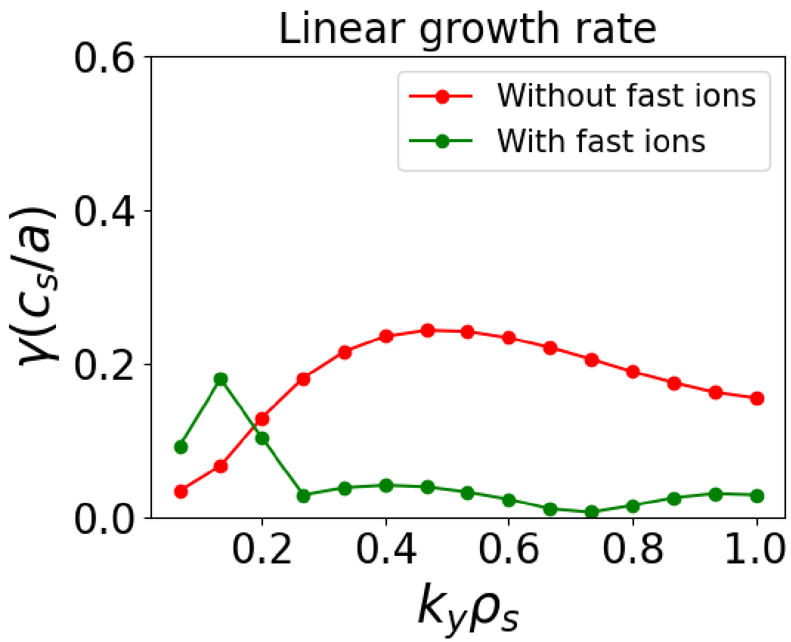


KBM shown in JET hybrid scenario [Kumar 21]

- The linear growth rate decreased with increasing the absolute value of the magnetic shear $|s|$
- Linear threshold in β increased with magnetic shear
- In addition, tendency in linear growth rate depending on safety factor and $\beta^*(\propto \nabla p)$ were also consistent with KBM shown in JET hybrid scenario (not shown here)

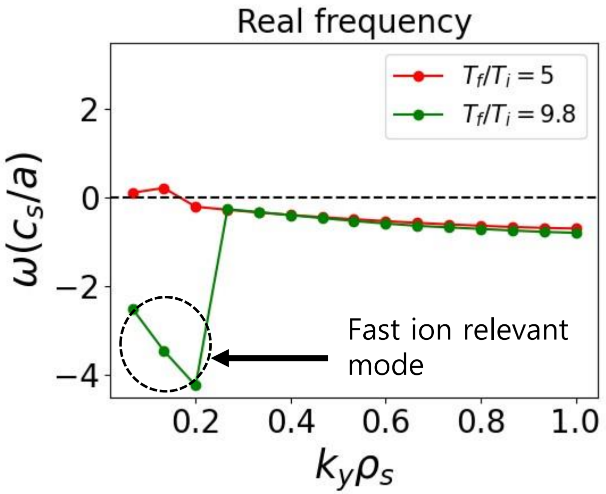
Frequency of Fast Ion Relevant Mode were Matched with Frequency of Kinetic Ballooning Mode



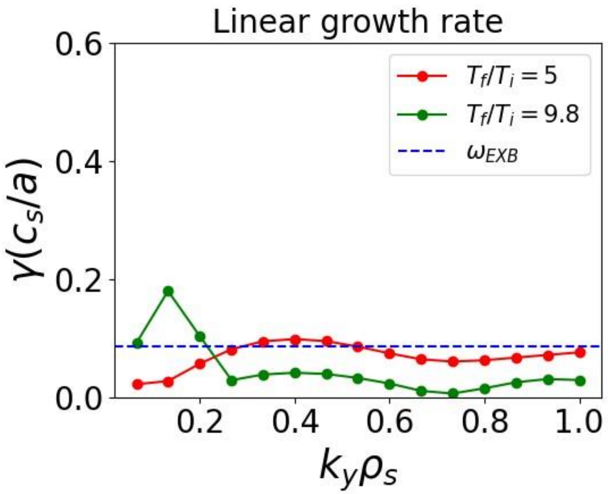


- However, Beta-induced Alfven eigenmode (BAE) can share characteristics as the KBM [Garcia 15, Citrin 15]
- Therefore, Frequency of fast ion relevant mode was compared to frequency of BAE and KBM
  - ✓ BAE: $\omega_{BAE} \sim \omega_{GAM} \sim 2\pi \left[\frac{1}{2\pi^2 m_i R_0^2}\left(T_e + \frac{7}{4}T_i\right)\left(1 + \frac{1}{2q^2}\right)\frac{2}{\kappa^2+1}\right]^{0.5}$ [Van Zeeland 16, Heidbrink 21]
    - – $\omega_{BAE} \sim 0.678\ c_s/a$ at $k_y\rho_s = 0.133$ is much lower than our simulation results ($\omega_r = 3.455\ c_s/a$), so BAE is ruled out
  - ✓ KBM: $\omega_{KBM} \sim \omega^*_{pj} = k_y\rho_s \frac{T_j}{T_e}\frac{a}{L_{pj}}\frac{c_s}{a}$ [Ruirui 22], and effective frequency considering multi-species $\omega^*_{eff} \equiv \Sigma_j f_j \omega^*_{pj}$ where $f_j = Z_j n_j / n_e$ and Z_j is charge for species j [Huang 25]
    - – ω^*_{eff} considering fast ions, $\sim 3.484\ c_s/a$ at $k_y\rho_s = 0.133$, has a similar value (~1% discrepancy) compared to simulation results at $k_y\rho_s = 0.133$
- **Therefore, Fast ion relevant mode is likely to KBM, considering all the above results**

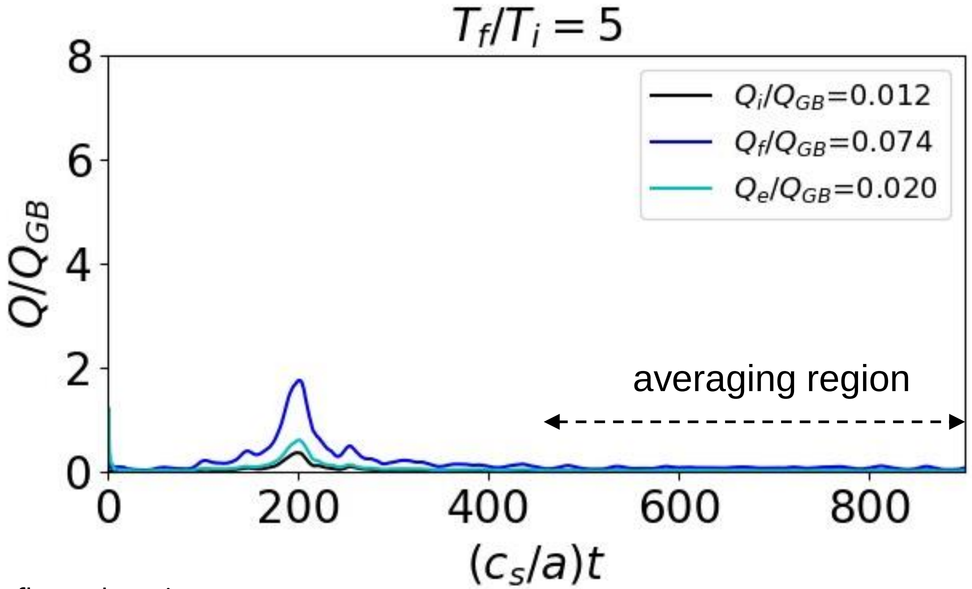
Impact of Fast Ion Relevant Mode is not Mainly Responsible for Thermal Energy Flux Reduction



(+) and (-) sign of real frequency denote the most unstable mode propagate to electron and ion diamagnetic direction, respectively

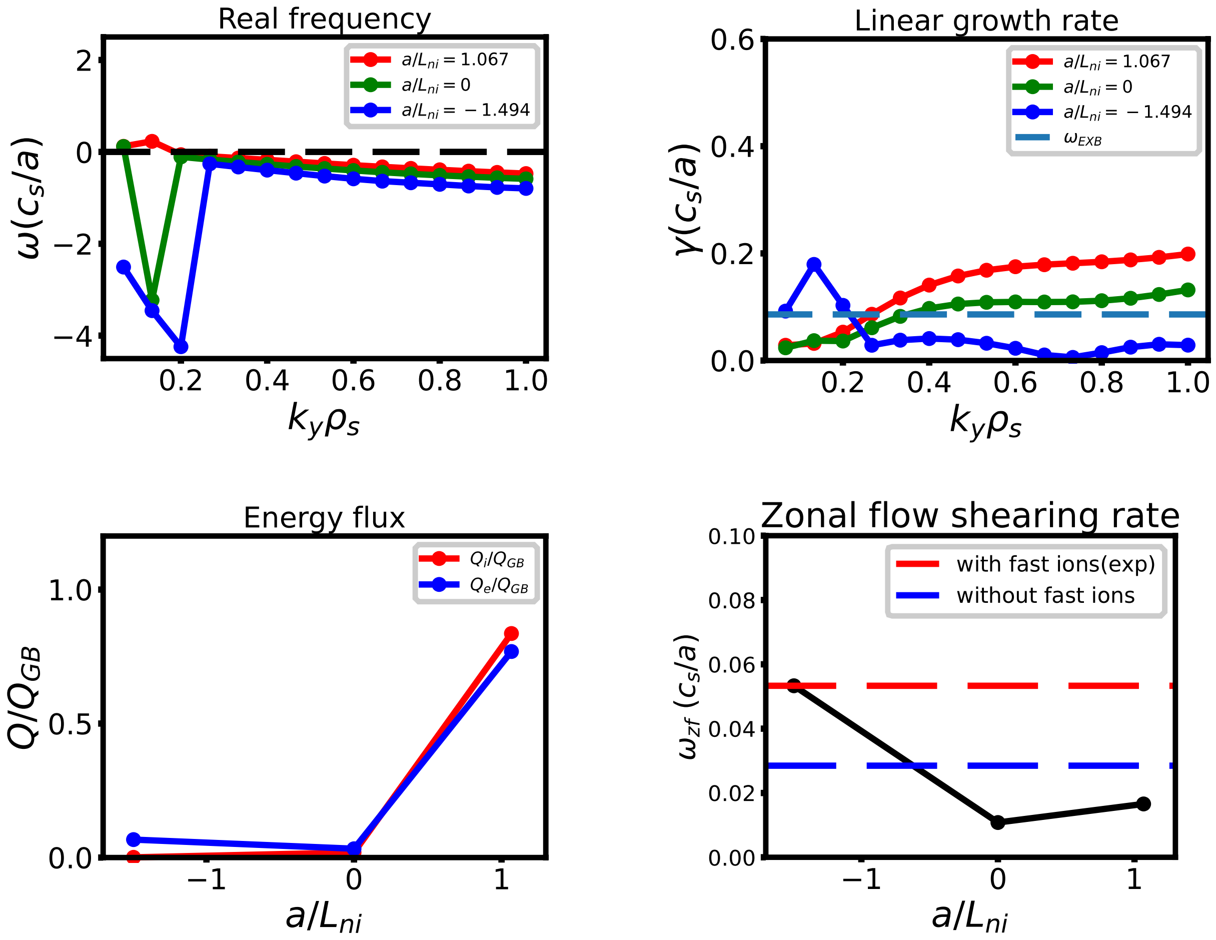


$\omega_{E\times B}$: mean equilibrium $E \times B$ flow shearing rate



- Fast ion relevant mode becomes stabilized when T_f/T_i decrease from 9.8(experimental value) to 5
  - ✓ Fast ion relevant mode exists in T_f/T_i=9.8 case, but not in T_f/T_i=5 case
- Thermal energy fluxes predicted by nonlinear simulation with T_f/T_i=5 is similar level to T_f/T_i=9.8
  - ✓ $Q_i[Q_{GB}]{\sim}0.001, Q_e[Q_{GB}]{\sim}0.067$ for T_f/T_i=9.8
- **Impact of fast ion relevant mode is not significant on thermal energy flux reduction in this study**
  - ✓ Turbulence was already suppressed even without fast ion relevant mode

Fast Ion Relevant Mode can Contribute on Increase in the Zonal Shearing Rate



Simulation were performed with n_f/n_e=0.4, T_f/T_i=9.8, β_*=0.075 while varying a/L_{ni} from -1.494 (experimental level) to 1.067 (= a/L_n) along with a/L_{nf} to satisfy the quasi-neutrality condition

- When a/L_{ni} increases from -1.494 to 1.067, linear growth rate at $k_y\rho_s \leq 0.27$ decreased
  - ✓ Fast ion relevant mode become stabilized
- As the fast ion relevant mode become stabilized, thermal energy flux increases, but zonal shearing rate does not
- Zonal shearing rate was not correlated well with energy flux level
  - ✓ Zonal shearing rate decreased significantly while energy flux was similar with varied a/L_{ni} from -1.494 to 0
  - ✓ Zonal shearing rate slightly increases when energy flux significantly increases from 0 to 1.067
- Zonal shearing rate was correlated well with a linear growth rate of fast ion relevant mode
- Zonal shearing rate can increase to the level for case with fast ions(exp) by fast ion relevant mode
- Fast ion relevant mode can potentially affect turbulence suppression when the dilution effect is reduced

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Conclusion and Future Work

Conclusion

- The fast ion effects on turbulence suppression in FIRE mode plasma were investigated through the gyrokinetic analysis

- Turbulence suppression mechanisms were identified depending on the turbulence scale
  - ✓ Ion scale: Dilution effect
  - ✓ Electron scale: Increased β_* effect

- Fast ion relevant mode is likely to Kinetic ballooning mode
  - ✓ Fast ion relevant mode exhibits consistent characteristics with KBM regarding β, frequency, s, β^*, q, and mode structure

- Fast ion relevant mode is not mainly responsible for thermal energy flux reduction, but it can contribute to the increase in zonal shearing rate
  - ✓ Fast ion relevant mode can potentially affect turbulence suppression when the dilution effect is reduced

Future Work

- Nonlinear simulation for fast ion effects on multi-scale turbulence will be performed since electron scale turbulence is not negligible