Physics of Confinement enhancement in KSTAR FIRE mode

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Outline

- Introduction: Fast Ion Regulated Enhancement (FIRE) mode

- Physics of confinement enhancement in FIRE mode
  - Gyrokinetic simulation of microturbulence
  - Theory development on zonal flow with fast ions

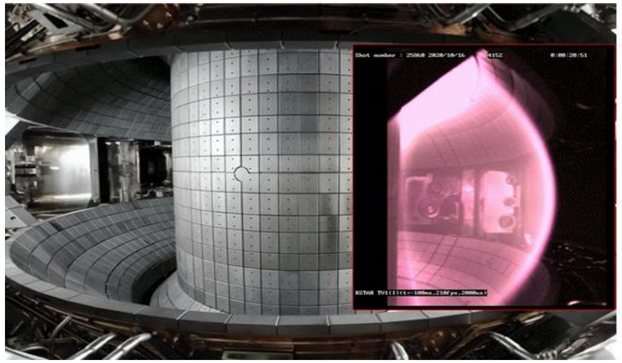
- Ongoing Works on FIRE mode
  - Experimental analysis of FIRE mode edge
  - Fast ion-driven electrostatic and Alfvenic modes
  - NBI control, Higher density

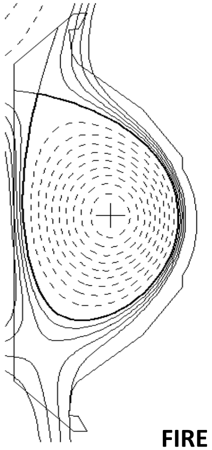
Fast Ion Regulated Enhancement (FIRE)

- **In KSTAR, a stationary ITB** was established in NB (+optional ECH) heated plasmas at q_{95} ~ 4–5.
- L-H transition was avoided by keeping low density ($\bar{n}_e \sim 1.5 \times 10^{19}\ m^{-3}$) and unfavorable ∇B USN.
- Fast ions play crucial roles to this new enhanced confinement regime, so it is coined to "**Fast-Ion-Regulated Enhancement** (**FIRE**)."
- No Alfvenic activity during the transition and early phase of FIRE: **Direct Impact of Fast Ions.** (vs JET, DIII-D mediated by AE)

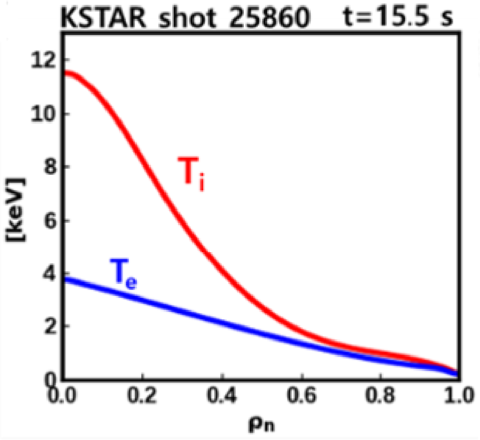
Courtesy: Y.-S. Na

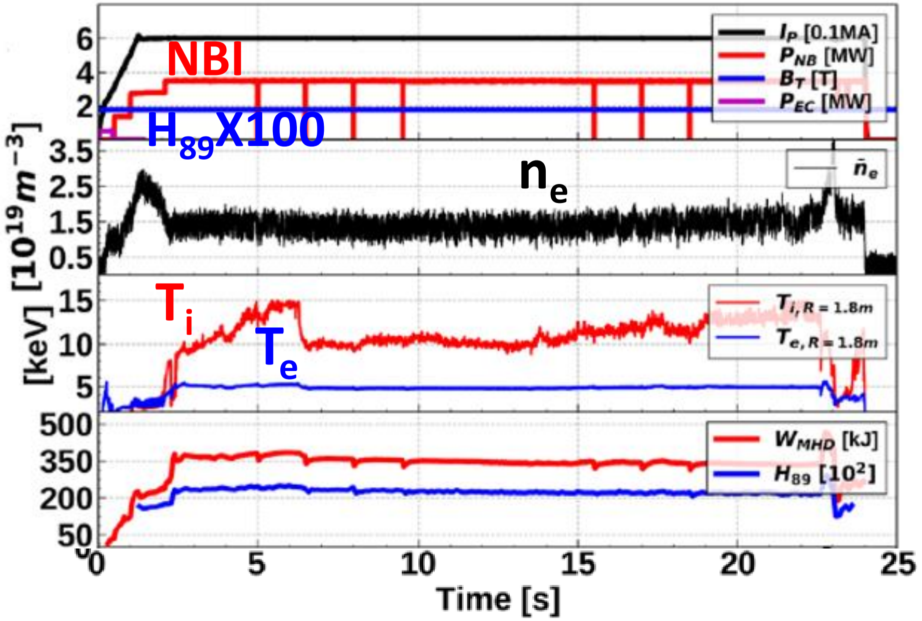
<Camera Image of KSTAR FIRE mode >





FIRE #25860
EFIT construction at 20 s





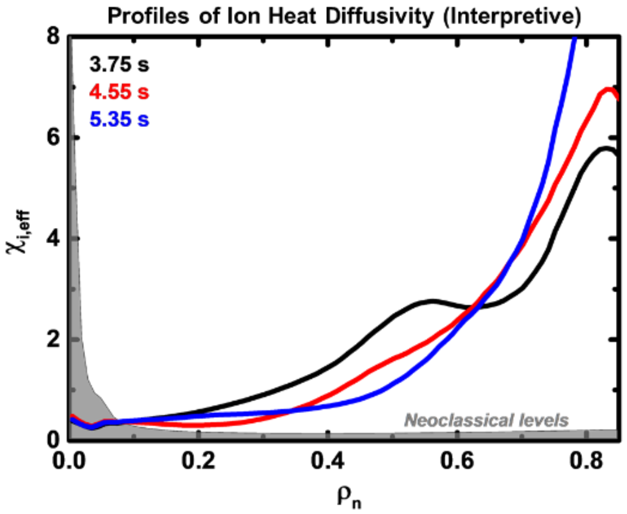
[H. Han, S.J. Park and Y.-S. Na *et al.*, *Nature* **609**, 269 (2022)] [H. Han *et al.*, *Phys. Plasmas* **31**, 032506 (2024)]

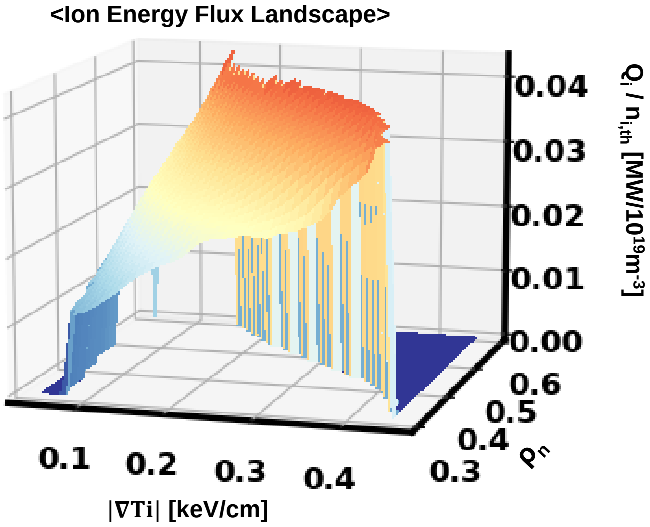
ITB Characteristics of FIRE mode

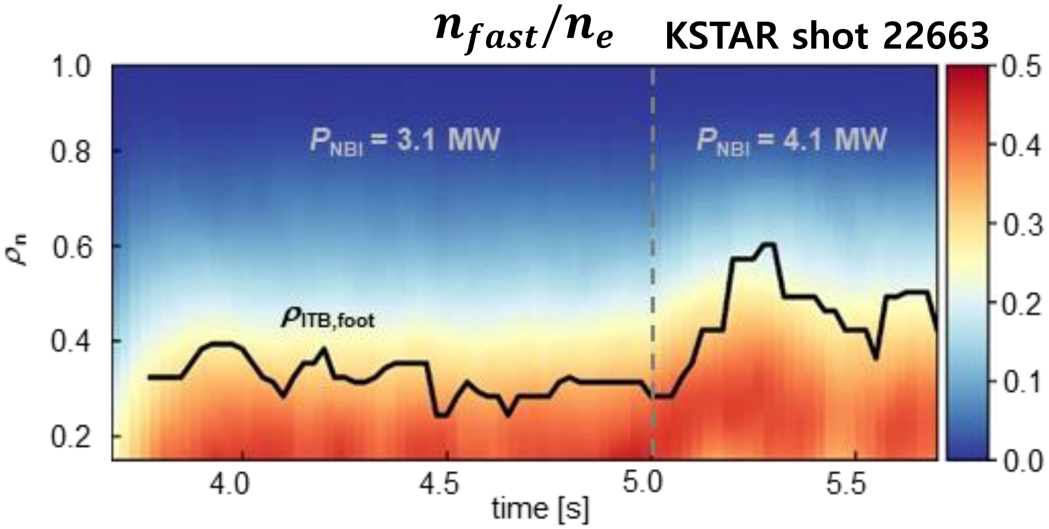
- **Thermal Ion Heat Diffusivity and S-curve**

Courtesy: Y.-S. Na

- The time evolution of the ion heat diffusivity was calculated from the power balance analysis.
- The **thermal ion heat diffusivity reduces** in time correlated **with the expansion of ITB**.
- The relation between the **ion energy flux** and the **ion temperature gradient** shows that there is a "**S-curve**" in the 3D landscape* [P.H. Diamond *et al*., PRL '97] implying a transport bifurcation.
- **ITB foot is correlated with fast ion population!**





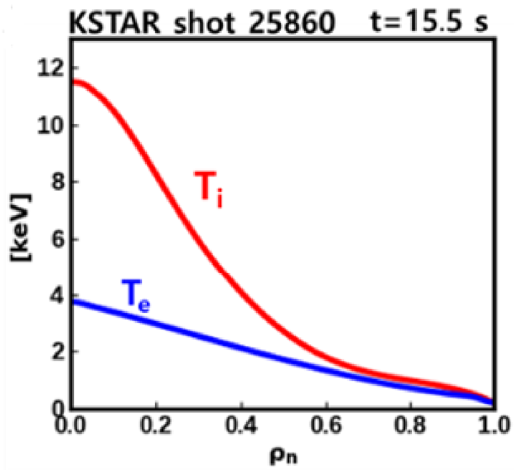


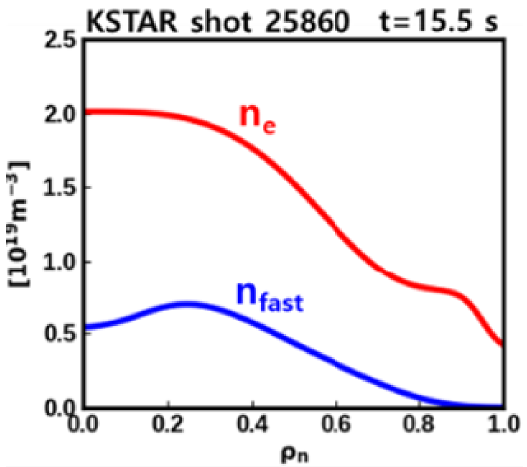
[H. Han, S.J. Park and Y.-S. Na *et al.*, *Nature* **609**, 269 (2022)] [H. Han *et al.*, *Phys. Plasmas* **31**, 032506 (2024)]

FIRE mode as a New ITB Scenario

Courtesy: Y.-S. Na

Conventional ITB		FIRE mode
Difficulty in sustainment	⇨	Stationary up to 50 s
Severe instabilities	⇨	No severe instabilities with high l_i
ELMs and heat load	⇨	No ELMs and reduced heat load
Impurity accumulations	⇨	No clear impurity accumulations
Sophisticated profile control	⇨	Self-organized





- High performance (β_N,H_{89L}) even comparable to Hybrid mode
- Almost **non-inductive current** drive ($V_{loop} < 0.1\ V$)
- High thermal ion temperature $\sim 10\ keV$

➡ **Worth to analyze the physical mechanism of the confinement enhancement in FIRE mode**

[Y.-S. Na *et al*., submitted to *Nucl. Fusion* (2024)]

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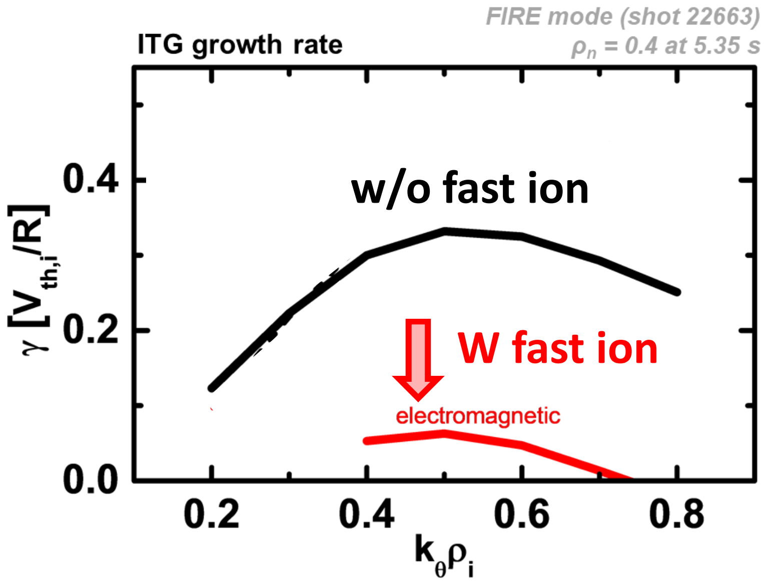
Gyrokinetic Simulation of FIRE mode

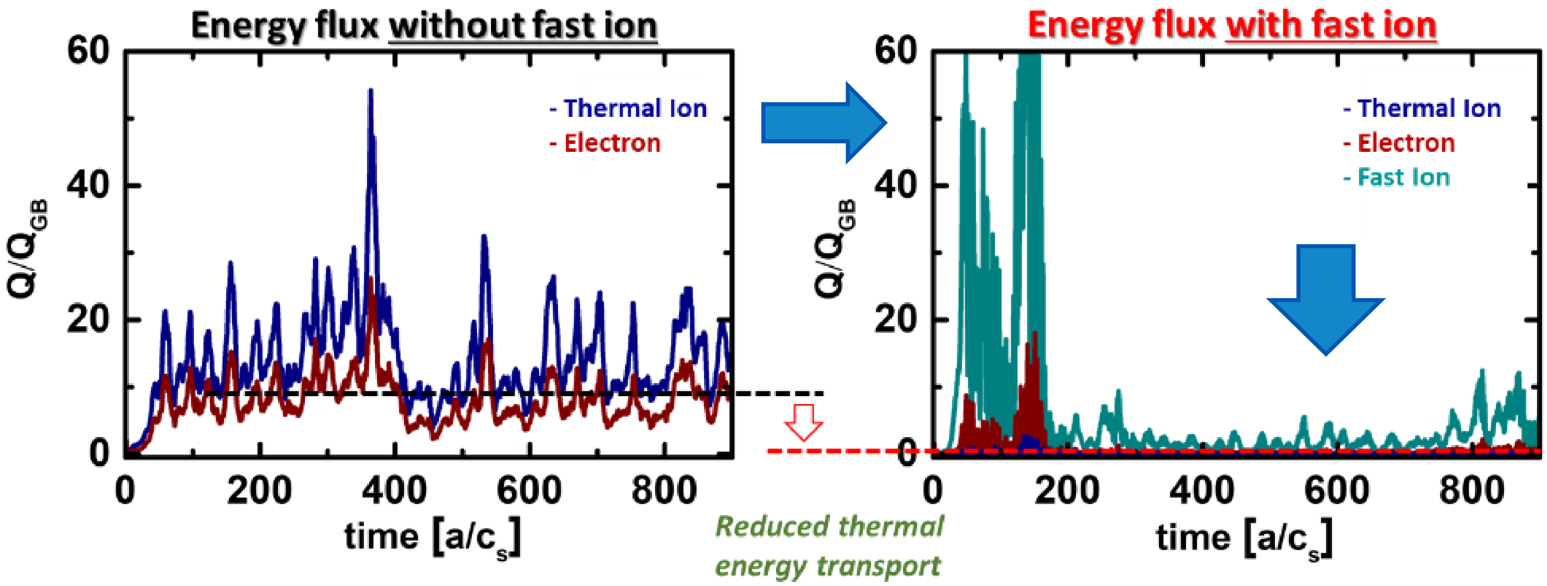
- **Local electromagnetic (EM) gyrokinetic simulations at just inside ITB foot**
  - Significant linear stabilization of microturbulence (ITG mode)
    + Further nonlinear suppression of turbulent transport
  - Candidates: EM (finite-β) effect, Dilution, Wave-particle interaction, E×B shear flow

Courtesy: Y.-S. Na

GKW linear simulation



CGYRO non-linear simulation

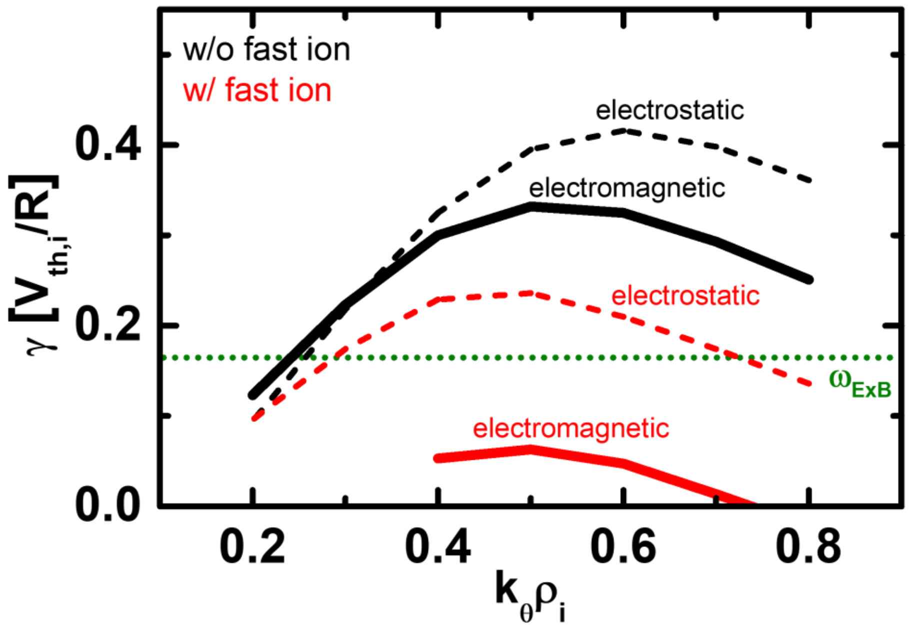


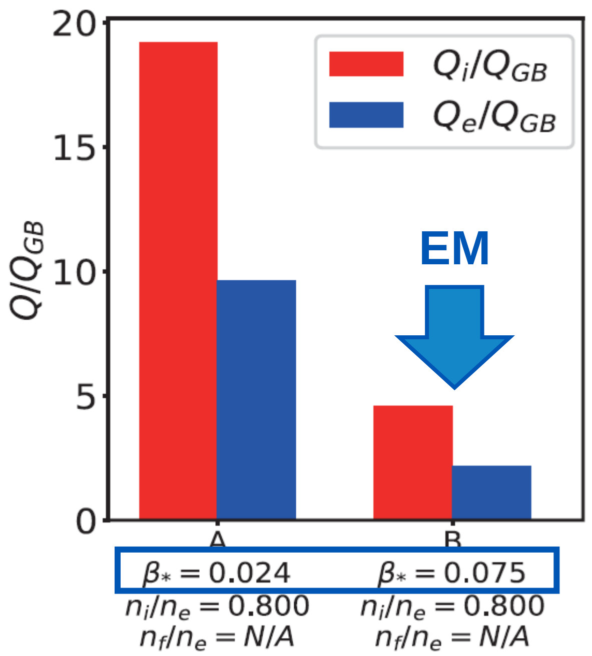
[D. Kim *et al*., *Nucl. Fusion* **63**, 124001 (2023)] [Y.-S. Na *et al*., submitted to *Nucl. Fusion* (2024)]

EM (finite-β) Stabilization

- Electromagnetic (finite-β) effect reduces both the linear growth rate γ of ITG turbulence [B.G. Hong *et al*., PPCF '89] and the nonlinear turbulent heat flux Q [M.J. Pueschel *et al.*, PoP '08].
- In FIRE mode, fast ion contribution to total β is profound, so that both γ and Q reduces by $\sim 1/4$ by the inclusion of fast ions. (cf. [J. Critin *et al*., PRL '13])

Courtesy: S.J. Park



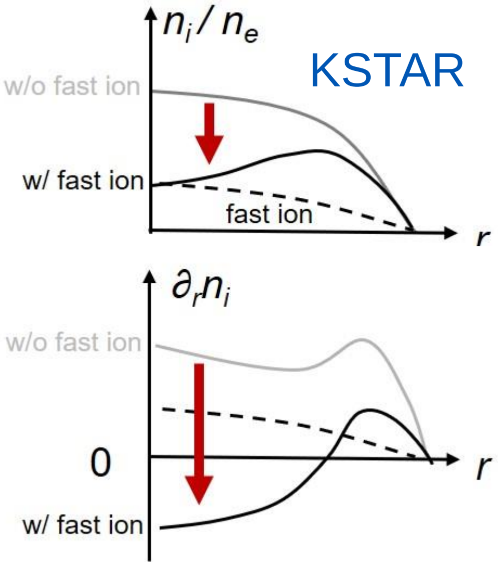


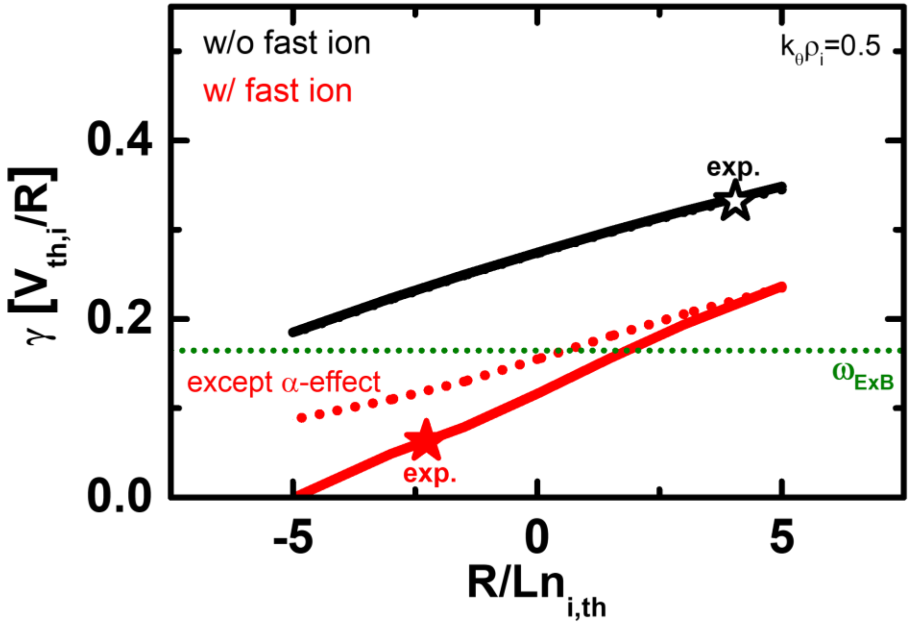
[D. Kim *et al*., *Nucl. Fusion* **63**, 124001 (2023)]

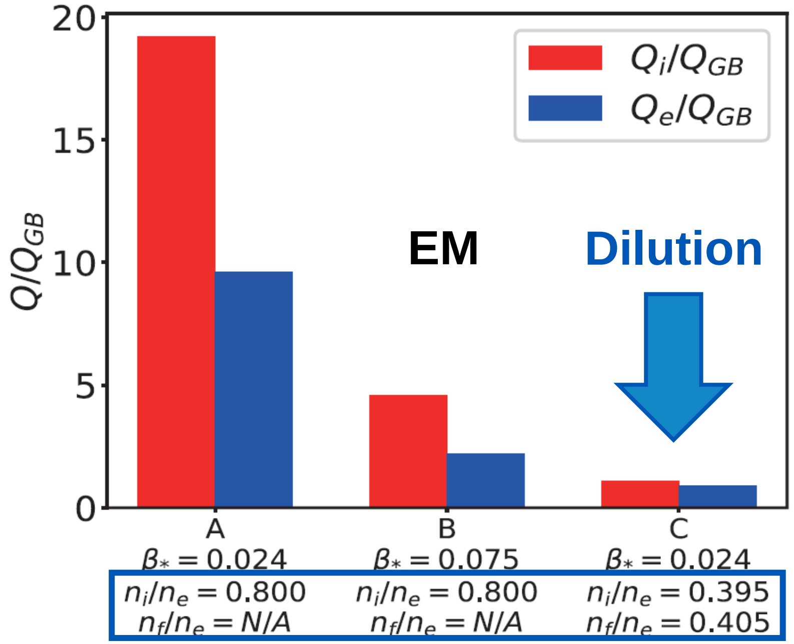
Fast Ion-induced Dilution

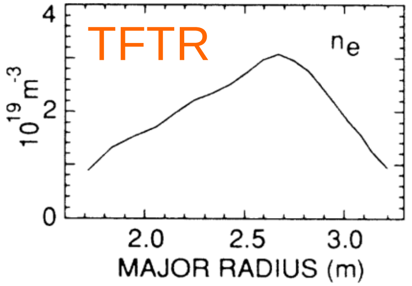
- **Dilution**: due to significant fast ion population (i.e., density n_f), thermal ions n_i are diluted because of quasi-neutrality $n_e = n_i + n_f$. "*Fast ion as a different ion species*"
- It has appeared as **the primary contributor** of transport reduction in FIRE mode.
- Note the featured inverted thermal ion density in KSTAR FIRE mode vs. inverted electron density in TFTR hot ion mode

Courtesy: C. Sung









[S. Scott *et al.*, PRL '90]

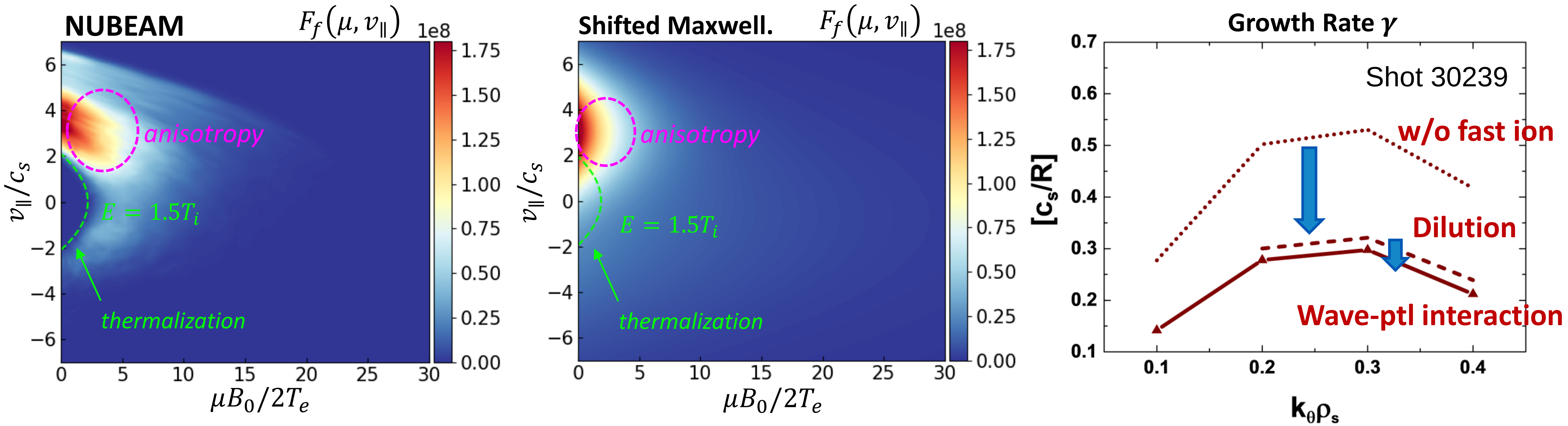
[D. Kim *et al.*, *Nucl. Fusion* **63**, 124001 (2023)] [H. Han *et al.*, *Phys. Plasmas* **31**, 032506 (2024)]

Wave-particle Interaction

- While the dilution is the essential and thus simplest effect of fast ion as a different ion species, wave-particle interaction b/w fast ion and ITG turbulence could give more complicated effect. [A. Di Siena *et al*., PoP '18]
- In FIRE mode, NUBEAM-based modelled non-Maxwellian fast ion yields only small difference in linear stability of ITG mode, compared to the case with Maxwellian fast ion.

  ⇒ Linear ITG-fast ion interaction seems to give only minor impact on ITG stability.

Courtesy: Y.-S. Na

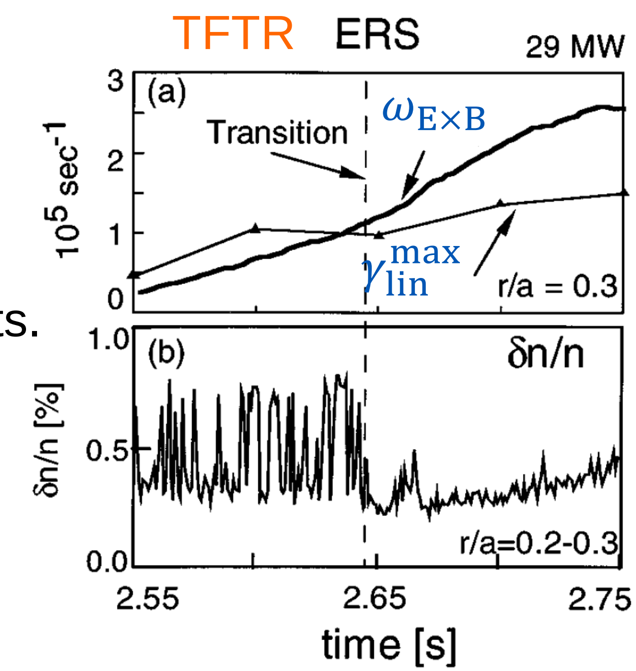


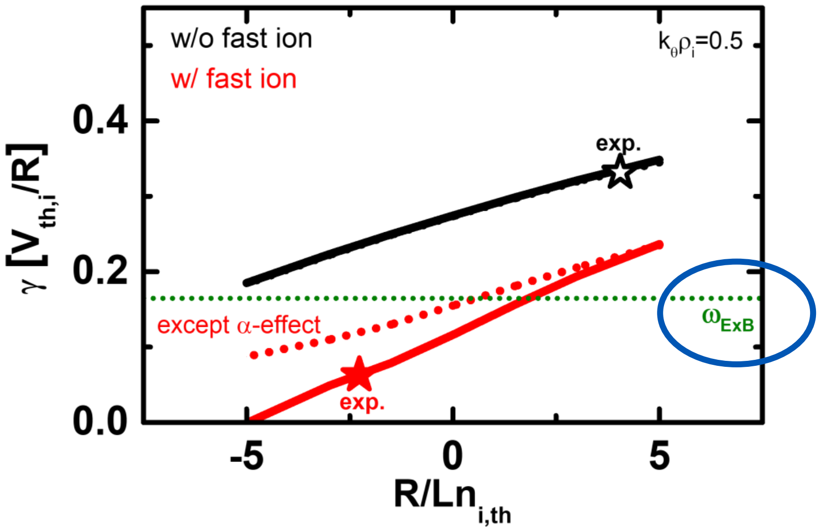
[Y.-S. Na *et al*., submitted to *Nucl. Fusion* (2024)]

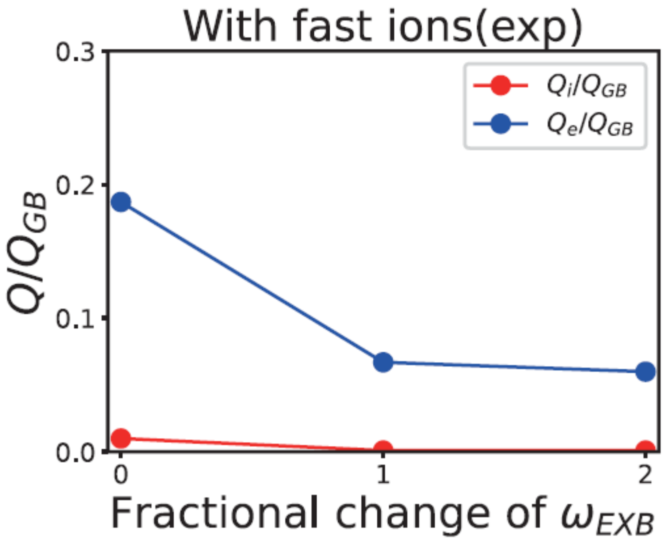
E×B Flow Shear Suppression

- The most widely-accepted, universal mechanism for transport barrier formation is the E×B flow shear suppression of turbulence. [K.H. Burrell, PoP '97, '20]
- "Rule-of-thumb criterion" for the E×B shear suppression:
  $\omega_{\mathrm{E\times B}} > \Delta\omega_{\mathrm{T}} \sim \gamma_{\mathrm{lin}}$ [T.S. Hahm-K.H. Burrell, PoP '95], [R. Waltz *et al*., PoP '94]
- In FIRE mode simulations, suppression of turbulent transport by the equilibrium E×B flow shear is notable, yet not dominant compared to EM and dilution effects.

[E.J. Synakowski *et al*., PoP '97]



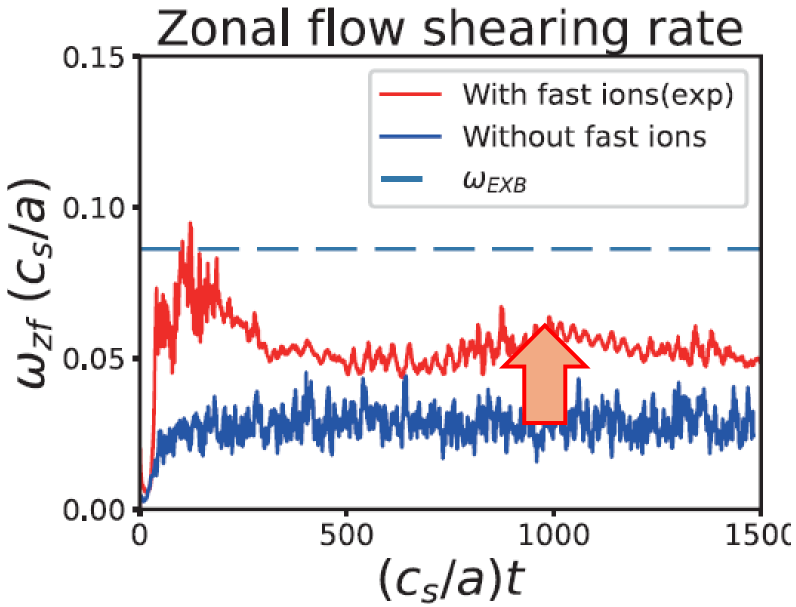


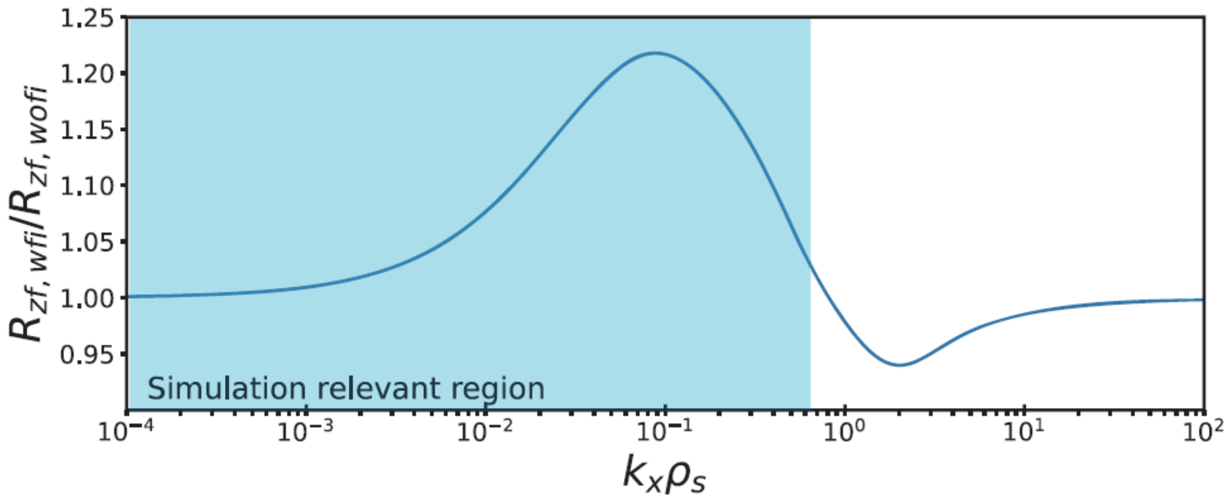


[D. Kim *et al*., *Nucl. Fusion* **63**, 124001 (2023)] [Y.-S. Na *et al*., submitted to *Nucl. Fusion* (2024)]

Self-generated Zonal Flow

- At the meantime, FIRE mode simulations show significant increase of self-generated zonal flow by fast ions.
- Zonal flow self-generation by taking energy from turbulence is ubiquitously observed in gyrokinetic simulations [Z. Lin *et al*., Science '98], and is well-known to trigger transition to an enhanced confinement regime [P.H. Diamond *et al*., PPCF '05]. ⇒ "Rule-of-thumb criterion" → Energetics
- In FIRE mode, fast ions give only moderate change in residual zonal flow level [Y.W. Cho-T.S. Hahm, NF '19] (i.e., response), indicating significantly enhanced zonal flow generation (i.e., source).





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Derivation of Hasegawa-Mima Equation

- The modified Hasegawa-Mima equation [A. Hasegawa-K. Mima, PoF ‘87] is the paradigm equation to study zonal flow generation from drift wave turbulence. It can be naturally derived from the gyrokinetics.

$$\delta N_i + \delta n_{i\mathrm{pol}} = \delta n_e$$

Quasi-neutrality [A.J. Brizard-T.S. Hahm, RMP ’07]

$$\Rightarrow \delta N_i + N_{i0}\rho_s^2\nabla_\perp^2\frac{e\phi}{T_e} = n_{e0}\frac{e\tilde{\phi}}{T_e}$$

Ion polarization density (long-wavelength limit expression)
Adiabatic electron response

$$\Rightarrow \frac{\delta N_i}{n_{e0}} = \frac{e\tilde{\phi}}{T_e} - \rho_s^2\nabla_\perp^2\frac{e\phi}{T_e}$$

Ion gyrocenter density δN_i is the gyrokinetic realization of the Potential Vorticity (PV)!

$$\frac{\partial N_i}{\partial t} - \frac{1}{B}\nabla\phi \times \hat{z}\cdot\nabla N_i = 0$$

Ion gyrocenter continuity equation (= PV equation)

$$\Rightarrow \frac{\partial}{\partial t}\left(\tilde{\phi} - \rho_s^2\nabla_\perp^2\phi\right) + \rho_s c_s\left[\phi, \tilde{\phi} - \rho_s^2\nabla_\perp^2\phi\right] + \rho_s c_s\frac{1}{n_{e0}}\left(\frac{\partial N_{i0}}{\partial x}\right)\frac{\partial\phi}{\partial y} = 0$$

[T.S. Hahm *et al*., *Phys. Plasmas* **30**, 172501 (2023)]

Simple Fast Ion Response to Drift Wave

- For drift waves (DWs), with $\omega, \omega_{*f} \ll k_\parallel v_{T_f}$ and Maxwellian fast ion F_{f0}, the linearized gyrokinetic equation

  $$-i\left(\omega - k_\parallel v_{\parallel f}\right)\delta\tilde{F}_f - i\left(\omega_{*f} - k_\parallel v_{\parallel f}\right)\frac{e\tilde{\phi}}{T_f}J_0\left(k_\perp \rho_f\right)F_{f0} = 0$$

  yields a fast ion gyrocenter density response

  $$\frac{\delta\tilde{N}_f}{N_{f0}} = -\Gamma_0\left(k_\perp^2\rho_{Tf}^2\right)\frac{e\tilde{\phi}}{T_f}$$

  which together with fast ion polarization density

  $$\frac{\delta n_{f\mathrm{pol}}}{N_{f0}} = -\left[1 - \Gamma_0\left(k_\perp^2\rho_{Tf}^2\right)\right]\frac{e\phi}{T_f}$$

  gives adiabatic fast ion response

  $$\frac{\delta\tilde{n}_f}{N_{f0}} = -\frac{e\tilde{\phi}}{T_f}.$$

- Therefore, fast ion response to DW $\delta\tilde{n}_f$ is negligible compared to the electron response due to $T_f \gg T_e$.

[T.S. Hahm *et al*., *Phys. Plasmas* **30**, 172501 (2023)]

Simple Fast Ion Response to Zonal Flow

- Meanwhile, for the fast ion response to zonal flows (ZFs), since we have $\langle \delta N_f \rangle = 0$,

$$\frac{\langle \delta n_f \rangle}{N_{f0}} = \frac{\langle \delta n_{f\text{pol}} \rangle}{N_{f0}} = -\left[1 - \Gamma_0\left(k_\perp^2 \rho_{Tf}^2\right)\right] \frac{e\langle \phi \rangle}{T_f} \rightarrow -k_\perp^2 \rho_s^2 \frac{e\langle \phi \rangle}{T_e} \quad \text{for} \quad k_\perp \rho_f \ll 1$$

The same with $\frac{\langle \delta n_{i\text{pol}} \rangle}{N_{i0}}$

- As a result, in the long-wavelength limit $k_\perp \rho_f \ll 1$, the potential vorticity with fast ions becomes

$$\frac{\delta N_i}{n_{e0}} = \frac{\delta n_e}{n_{e0}} - \frac{\delta n_{i\text{pol}}}{n_{e0}} - \frac{\delta n_f}{n_{e0}}$$

(e.g. KSTAR FIRE mode : T_f / T_e ~ 10)

$$= \frac{e\tilde{\phi}}{T_e} - (1 - f)\rho_s^2 \nabla_\perp^2 \frac{e\tilde{\phi}}{T_e} - \rho_s^2 \nabla_\perp^2 \frac{e\langle \phi \rangle}{T_e}$$

where $f \equiv \frac{n_{f0}}{n_{e0}}$ fast ion population

DW vorticity reduced by fast ion-induced dilution

ZF vorticity unchanged by fast ions

[T.S. Hahm *et al*., *Phys. Plasmas* **30**, 172501 (2023)]

Hasegawa-Mima Equation with Fast Ions

- Substituting δN_i to the continuity equation, we obtain the modified Hasegawa-Mima equation as follows.

$$\frac{\partial}{\partial t}\{\tilde{\phi} - (1-f)\nabla_\perp^2\tilde{\phi} - \nabla_\perp^2\langle\phi\rangle\} + [\phi, \tilde{\phi} - (1-f)\nabla_\perp^2\tilde{\phi} - \nabla_\perp^2\langle\phi\rangle] - \eta_n \frac{\partial\phi}{\partial y} = 0 \quad \text{where} \quad \eta_n \equiv \frac{L_{ni}}{L_{ne}}$$

$$\left(\text{Normalization:} \quad \frac{e\phi}{T_e} \to \phi, \quad \partial_t \to \Omega_i \partial_t, \quad \nabla \to \rho_s \nabla. \right)$$

- E×B nonlinearity is unchanged; Hasegawa-Mima nonlinearity (⟷ Reynolds stress) is reduced by $(1-f)$.

- After linearization we obtain the electron DW eigenfrequency

$$\omega = \frac{(1-f)\eta_n}{1+(1-f)k_\perp^2}\omega_* \quad \Downarrow$$

is **considerably decreased** by thermal ion dilution $(1-f)$ and profile gradient reduction $\eta_n < 1$.

[T.S. Hahm *et al*., *Phys. Plasmas* **30**, 172501 (2023)]

Dilution Effect on Zonal Flow Generation

- As a consequence, with fast ions, the modulational zonal flow growth rate Γ becomes

$$\Gamma^2 = \underline{\gamma_{\text{mod}}^2} - \underline{\Delta_{\text{mm}}^2}$$

from Reynolds Stress Drive   from Frequency Mismatch

where

$$\gamma_{\text{mod}}^2 \cong 2(1-f)k_y^2 q_x^2 \left|\tilde{\phi}_0\right|^2$$

Reynolds stress drive is reduced

$$\Delta_{\text{mm}}^2 \equiv \left\{\frac{1}{2}\Big((\omega_0 - \omega_+) + (\omega_0 + \omega_-)\Big)\right\}^2 \cong (1-f)^4 \eta_n^2 k_y^2 q_x^2$$

Frequency mismatch is reduced much more strongly!

- Therefore, we have significant reduction of threshold for zonal flow growth by fast ions.
  In other words, we have an **easier zonal flow generation** with fast ions!

[T.S. Hahm *et al*., *Phys. Plasmas* **30**, 172501 (2023)]

ZF Generation from Broadband Turbulence

- Using wave-kinetic equation and zonal flow vorticity equation, a standard calculation with fast ions yields

$$-i\Omega = -(1-f)^2 q^2 \eta_n \sum_{\mathbf{k}} \frac{k_y^2 \omega_*}{\left[1+(1-f)k_\perp^2\right]^2} R_q k_x \frac{\partial \langle N \rangle}{\partial k_x}, \qquad R_q^{-1} \simeq -i\left(\Omega - q v_{gx}\right) + 2\gamma$$

where $N(\mathbf{x}, \mathbf{k}, t) = \frac{\mathcal{E}_{\mathbf{k}}}{\omega_{\mathbf{k}}} = \frac{\left[1+(1-f)k_\perp^2\right]}{\omega_{\mathbf{k}}} \left|\tilde{\phi}_{\mathbf{k}}\right|^2$ Wave action density

Likely relevant to core confinement enhancement

- We have two limiting forms of the zonal flow dispersion relation as follows.

1. Strong turbulence (resonant) regime

$$\Gamma \simeq -(1-f)^2 q^2 \eta_n \sum_{\mathbf{k}} \frac{k_y^2 \omega_*}{\left[1+(1-f)k_\perp^2\right]^2} \frac{1}{2\gamma} k_x \frac{\partial \langle N \rangle}{\partial k_x}$$

2. Weak turbulence (non-resonant) regime

$$\Omega \simeq (1-f)^2 q^2 \eta_n \sum_{\mathbf{k}} \frac{k_y^2 \omega_*}{\left[1+(1-f)k_\perp^2\right]^2} \frac{1}{\Omega - q v_{gx}} k_x \frac{\partial \langle N \rangle}{\partial k_x}$$

⇒ **Recover the 3+3-wave calculation with**

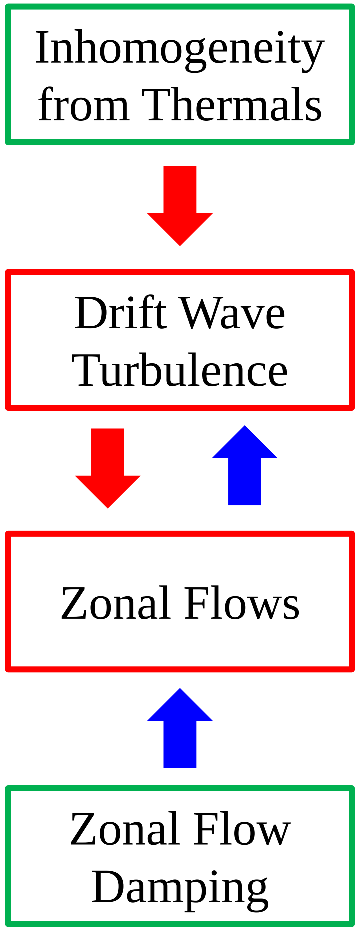
$$q v_{gx} = -\frac{2(1-f)^2 \eta_n \omega_* q k_x}{\left[1+(1-f)k_\perp^2\right]^2}$$

Continuum version of Frequency Mismatch

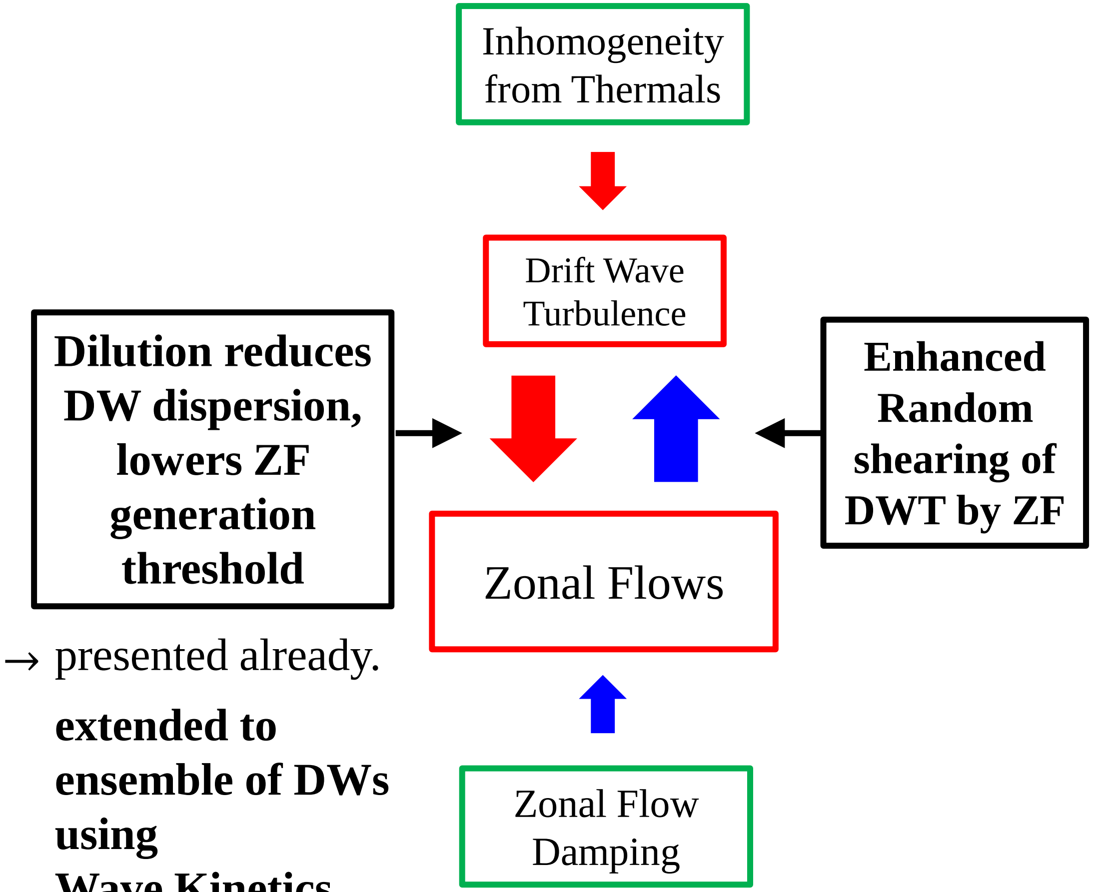
[G.J. Choi, P.H. Diamond and T.S. Hahm, *Nucl. Fusion* **64**, 016029 (2024)]

Dilution Effect on Turbulence-ZF System

Usual Story without Fast Ions



With Dilution from Fast Ions

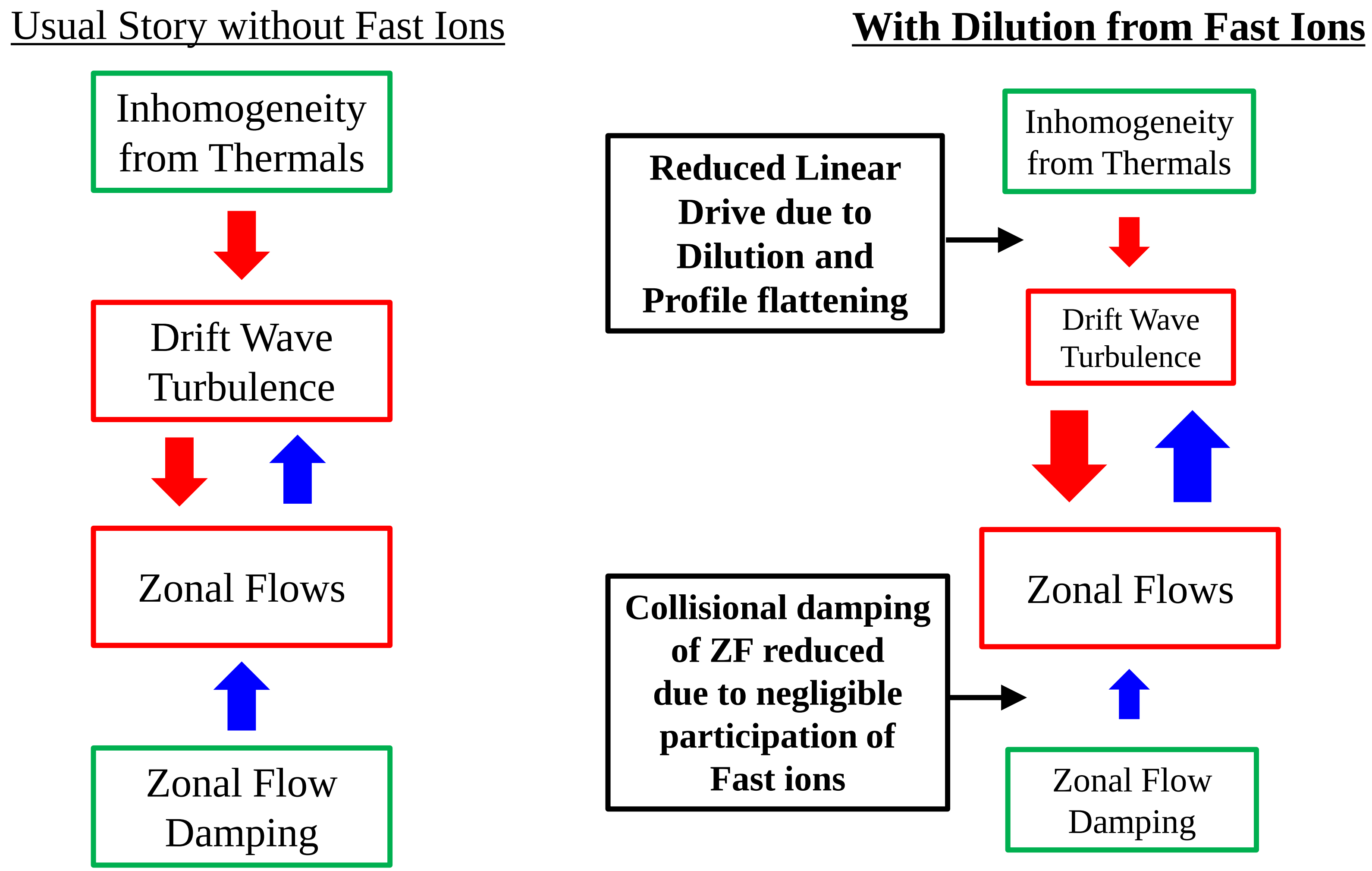


→ presented already.

extended to ensemble of DWs using Wave Kinetics.

[G.J. Choi, P.H. Diamond and T.S. Hahm, *Nucl. Fusion* **64**, 016029 (2024)]

Dilution Effect on Turbulence-ZF System



[G.J. Choi, P.H. Diamond and T.S. Hahm, *Nucl. Fusion* **64**, 016029 (2024)]

Predator-Prey model with Dilution Effect

- Put everything together, for weak turbulence regime relevant to core turbulence,

ZF : $\partial_t u^2 = \sqrt{\gamma_{\rm mod}^2 - \Delta_{\rm mm}^2} H(\gamma_{\rm mod} - \Delta_{\rm mm}) u^2 - (1-f)\gamma_{d(0)} u^2$

DWT : $\partial_t \mathcal{E} = 2\gamma\mathcal{E} - \sqrt{\gamma_{\rm mod}^2 - \Delta_{\rm mm}^2} H(\gamma_{\rm mod} - \Delta_{\rm mm}) u^2 - (1-f) B\mathcal{E}^2$

- The general expression for the nontrivial fixed point : $\boxed{\gamma_{\rm mod}^2 = \Delta_{\rm mm}^2 + \gamma_d^2}$

  That is, either DW frequency mismatch or collisional ZF damping provide the threshold for ZF generation.

⇒ **Collisionless limit relevant to core confinement enhancement**:

$$\mathcal{E} \approx \frac{(1-f)^3 \eta_n^2 \Delta_{\rm mm(0)}^2}{A'}$$

⬇ **Significant reduction by fast ion-induced dilution** $\sim 1/3$ for $f \sim 1/3$

which is determined by a balance between

$\gamma_{\rm mod}^2 = (1-f) A' \mathcal{E}$: modulational zonal flow drive

$\Delta_{\rm mm}^2 = (1-f)^4 \eta_n^2 \Delta_{\rm mm(0)}^2$: frequency mismatch

[G.J. Choi, P.H. Diamond and T.S. Hahm, *Nucl. Fusion* **64**, 016029 (2024)]

Outline

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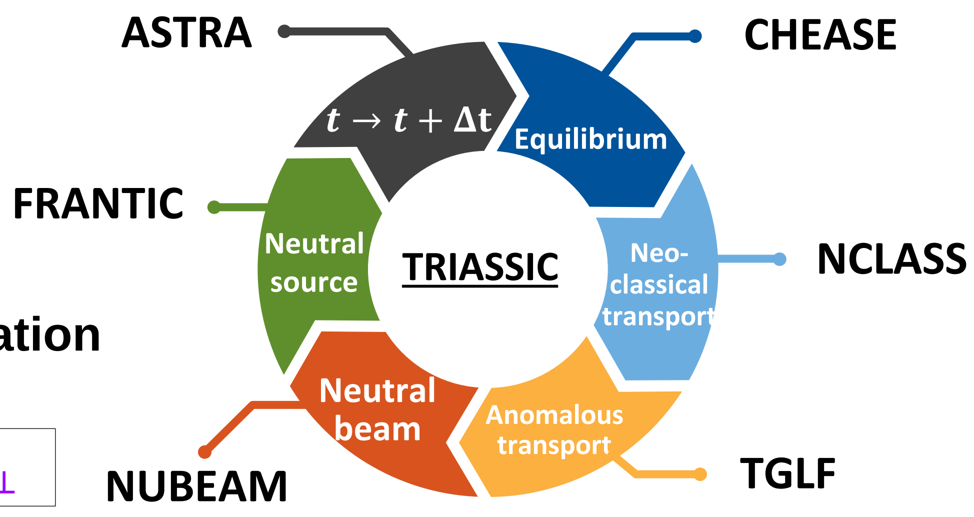
  - NBI control, Higher density

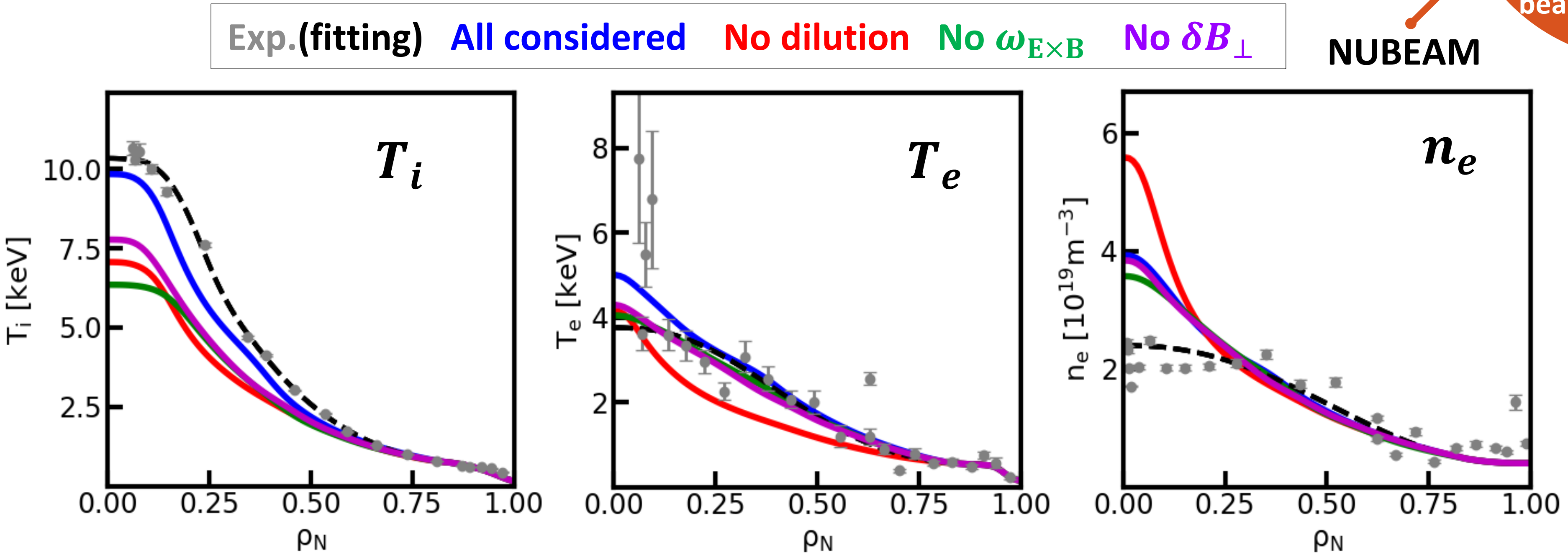
Predictive Modelling of FIRE mode

- A FIRE mode, #26043 @4.3s
- Integrated suite of code, TRIASSIC used
- Several effects evaluated with TGLF
  : Dilution effect, ExB shearing effect, electromagnetic fluctuation



[C.Y. Lee *et al*., Nucl. Fusion **61**, 96020 (2021)]

Courtesy: Y.-S. Na



$\theta_{trapped} = 0.5$ used to match the growth rate of ion-scale turbulence from GKW

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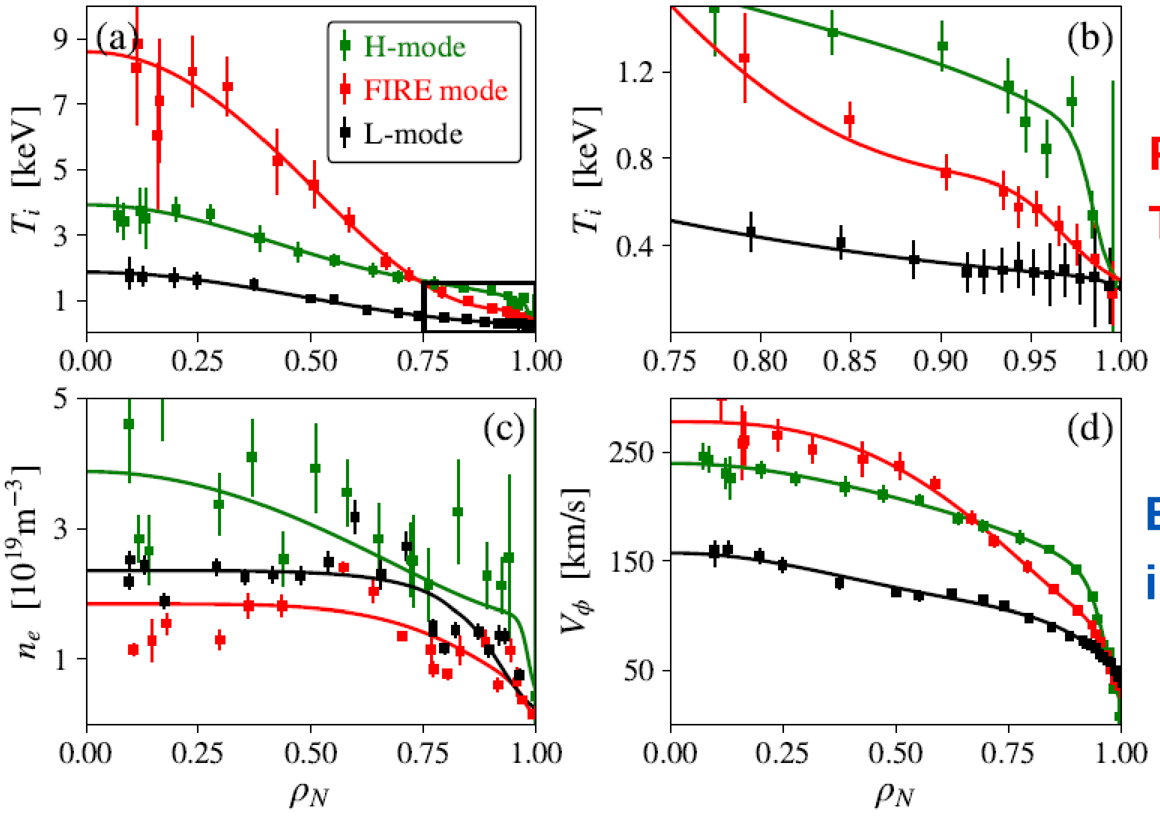
FIRE mode Edge shows I-mode-like feature

KSTAR FIRE mode

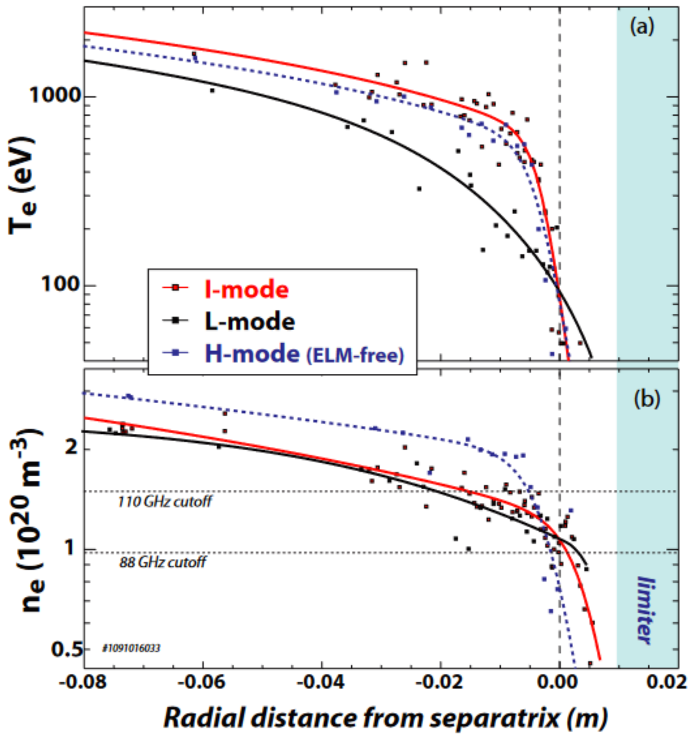
Courtesy: C.H. Heo



Formation of Temperature Pedestal

Edge Density remain in the L-mode level

C-Mod I-mode



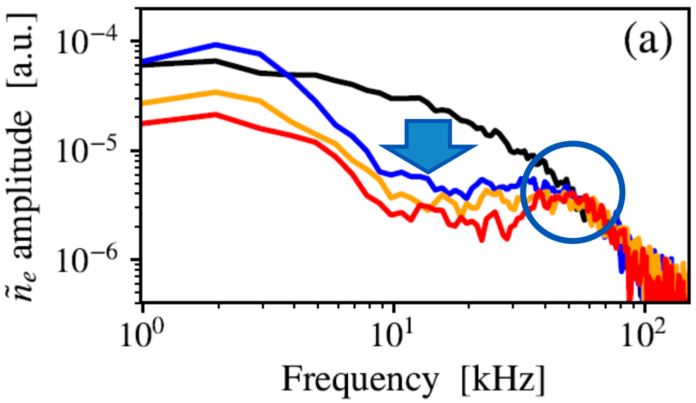
[D.G. Whyte *et al.*, NF '10]

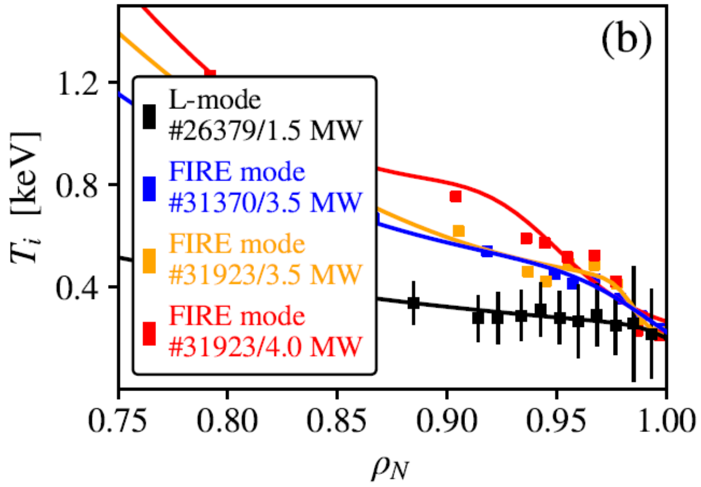
[C.H. Heo *et al.*, submitted to *Nucl. Fusion* (2024)]

WCM observed in FIRE mode

- Broadband turbulence of L-mode is replaced by the **WCM (Weakly Coherent Mode)**-like fluctuation!

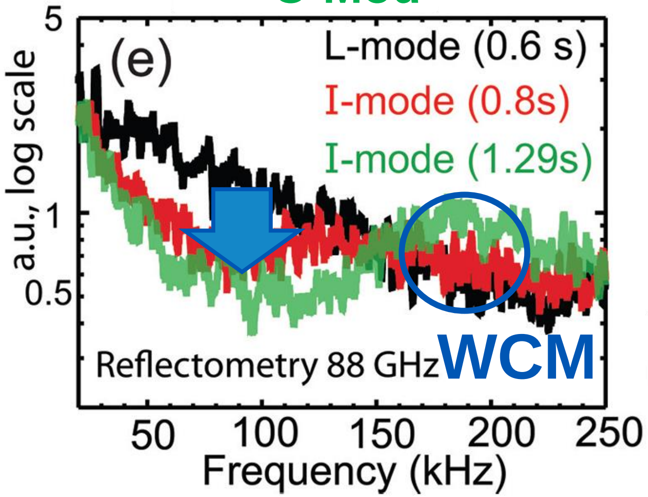
KSTAR



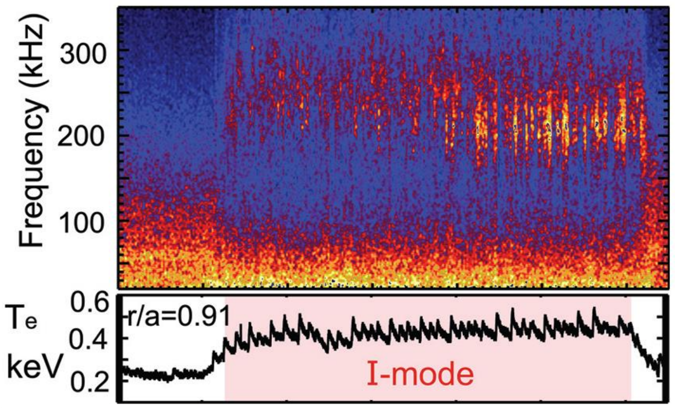


[C.H. Heo *et al.*, submitted to *Nucl. Fusion* (2024)]

C-Mod

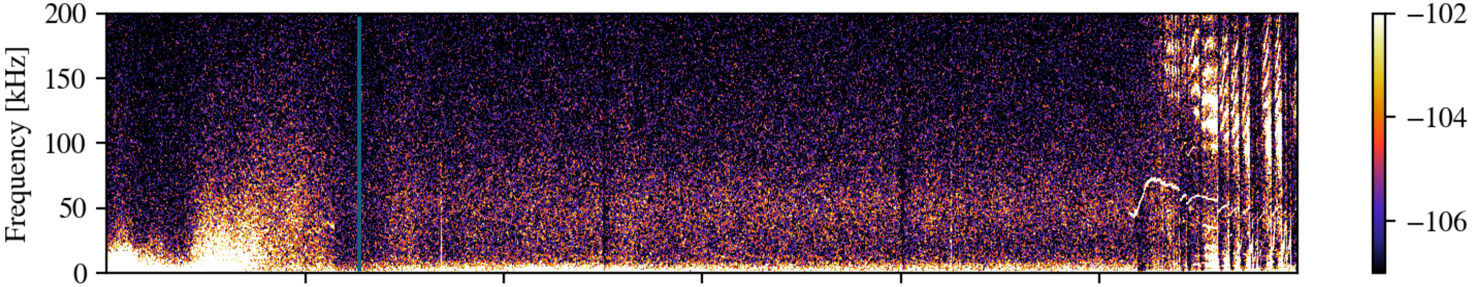


C-Mod



[A.E. Hubbard *et al.*, PoP '11]

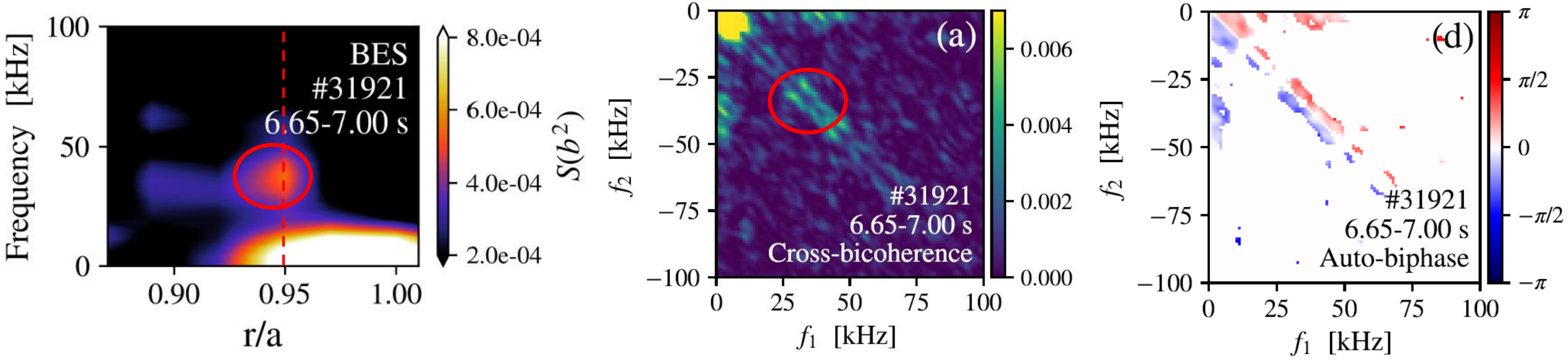
KSTAR **31923** $r/a = 0.95$ BES_0206



Courtesy: C.H. Heo

Nonlinear WCM-Zonal Flow Interaction

- Cross-bicoherence analyses of FIRE mode have revealed the existence of zonal flow ($2 - 4$ kHz) which nonlinearly interact with WCM at the location where WCM is the strongest.
- The zonal flow consistently shows phase delay with respect to the WCM, manifesting predator (ZF)-prey (WCM) relation between the two.
- Ongoing effort to measure zonal flow velocity: so far, what we have observed is zonal density, to be precise.



[C.H. Heo *et al.*, submitted to *Nucl. Fusion* (2024)]

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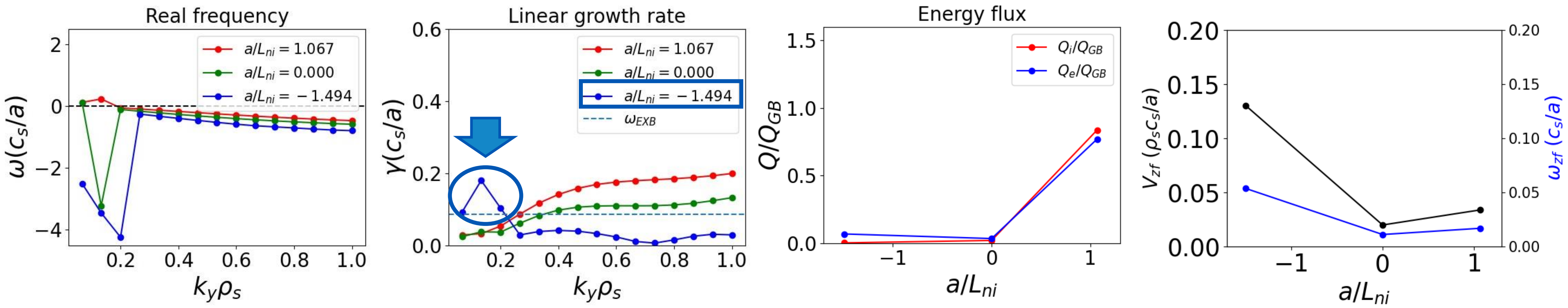
Fast Ion-Driven Electrostatic Mode

- CGYRO simulations of FIRE mode have found a long-wavelength fast ion-driven **electrostatic** mode, which significantly contributes to both zonal flow generation and transport.

- Ongoing collaboration with NIFS on theory & simulation to identify its characteristics and fully understand its impact. (cf. [B.J. Kang-T.S. Hahm, *Phys. Plasmas* **26**, 042501 (2019)], [B.J. Kang *et al*., submitted to *Phys. Lett. A* (2024)] on theory of fast ion-driven electrostatic mode)

Courtesy: C. Sung



[D. Kim *et al*., *Nucl. Fusion* **64**, 066013 (2024)]

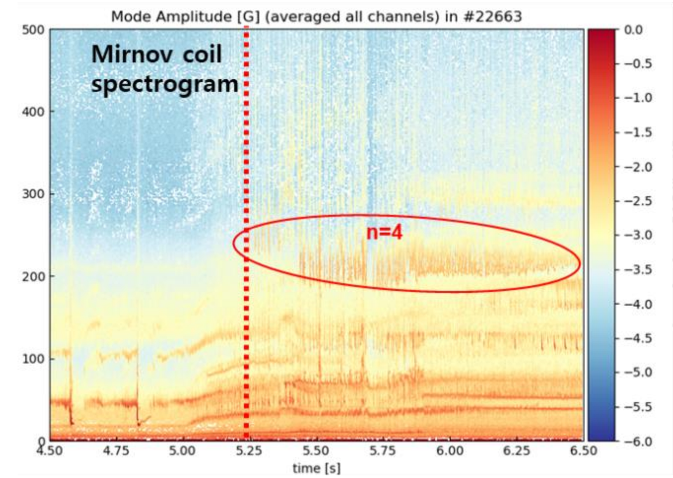
Fast Ion-Driven Alfvenic Mode

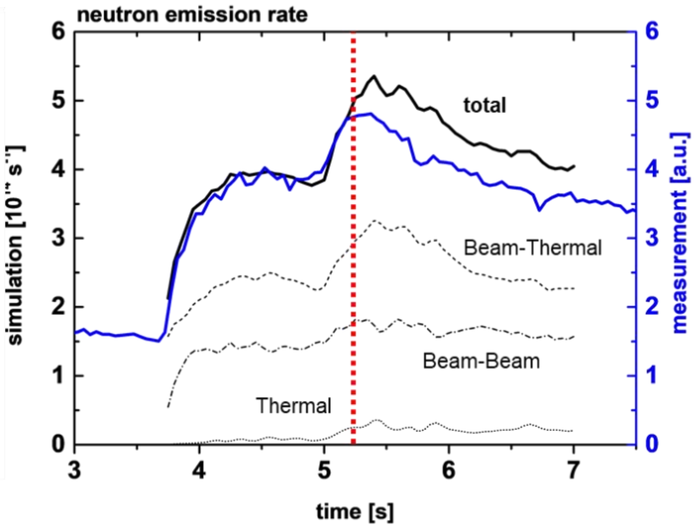
- In the later phase of FIRE mode, we sometimes observe fast ion-driven AE which degrade plasma performance.

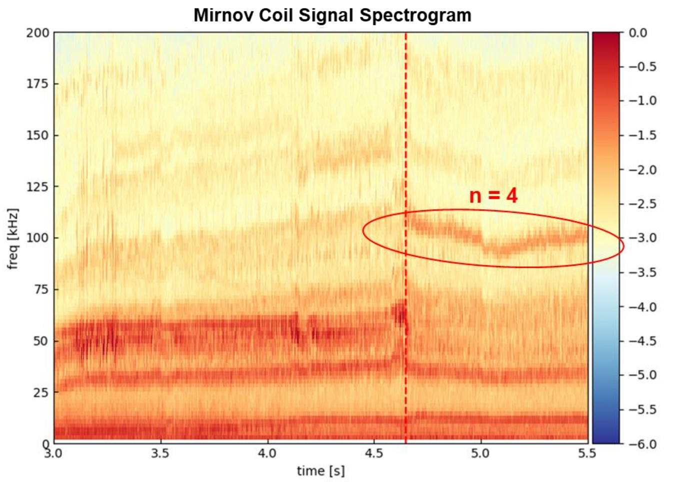
- In addition, core-localized lower-frequency Alfvenic mode is often observed, of which frequency $\sim \omega_{*pi,\mathrm{th}} \Rightarrow$ LFAM?

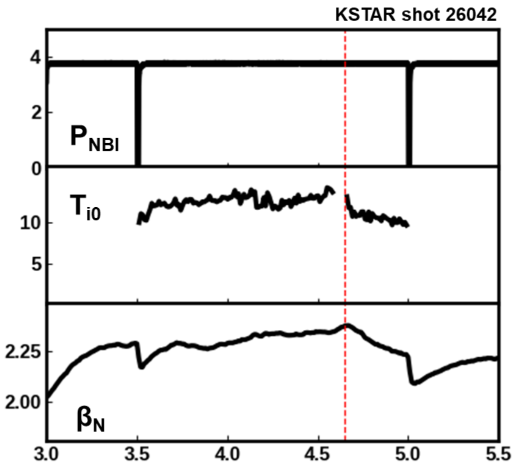
- It has weak impact on performance for weaker $B_T = 1.8\ \mathrm{T}$, whereas the impact is quite significant for higher $B_T = 2.5\ \mathrm{T}$.

- Ongoing global gyrokinetic simulations on these Alfvenic modes.





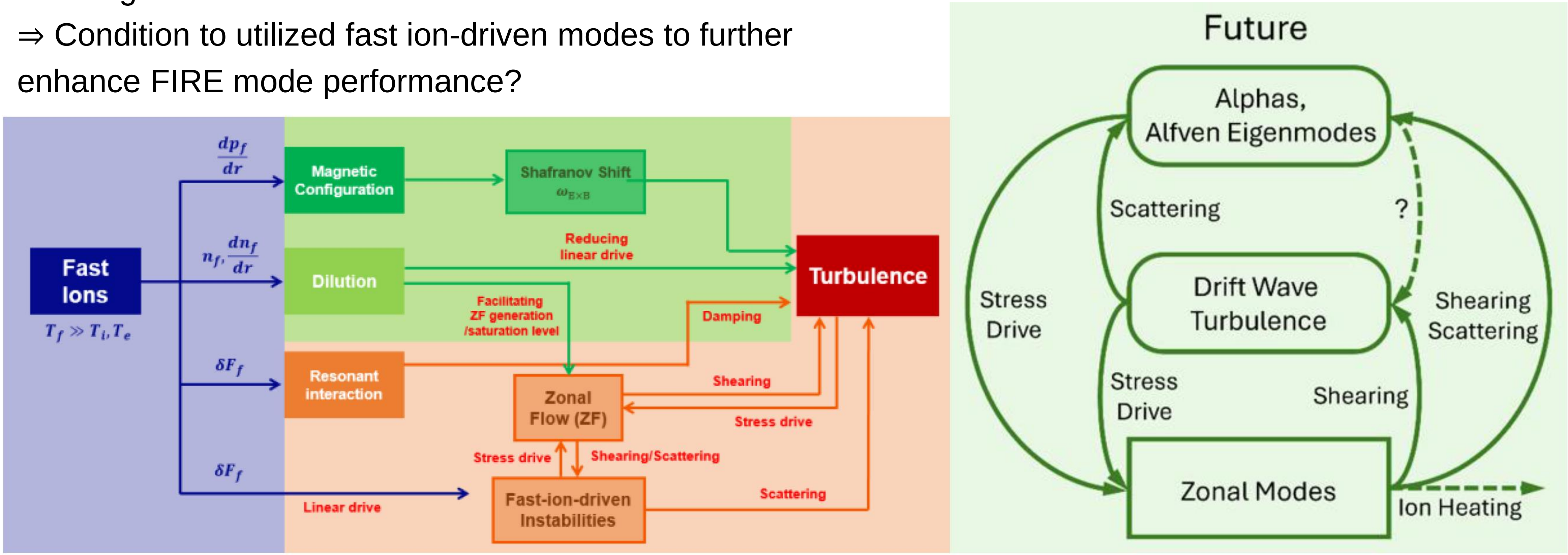




[Y.-S. Na *et al*., submitted to *Nucl. Fusion* (2024)]

Fast Ion-Driven Alfvenic Mode

- Heading to understand 3-animal interactions in FIRE mode
  ⇒ Condition to utilized fast ion-driven modes to further enhance FIRE mode performance?



[Y.-S. Na *et al*., submitted to *Nat. Rev. Phys.* (2024)]

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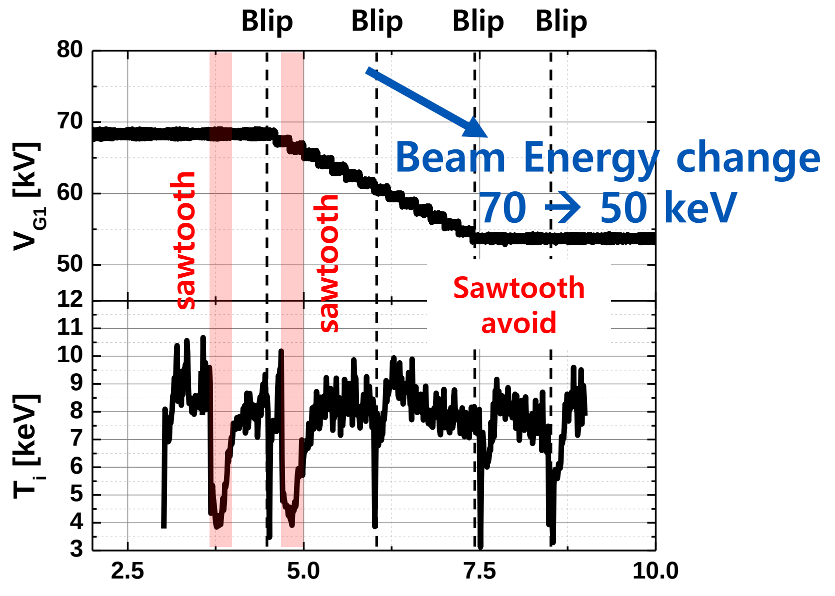
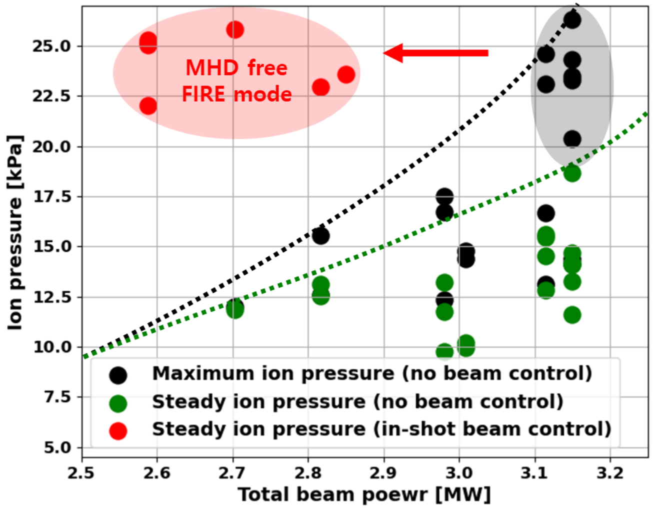
Advanced NBI Control for FIRE mode

Main features of the "Advanced NBI Control System"	Application to "FIRE mode"
1. Decoupling beam power and energy control	Avoid n=1 mode while sustain ion temperature (Operation window expansion)
2. In-shot continuous control	MHD-free state access (sustaining high Ti level)

Courtesy: S.C. Hong



In-shot beam control operation



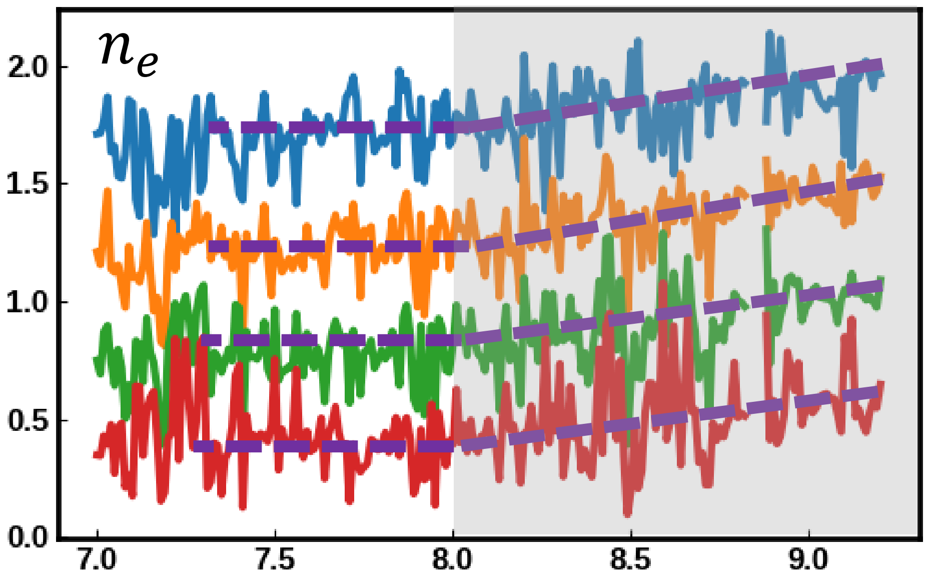
Extension toward Higher Density

- In 2024 KSTAR campaign, we attempt to extend FIRE mode to higher electron density n_e by increasing I_p + actively using gas puffing, SMBI and pellet injection.
- In addition, ITB broadening will be investigated by controlling NBI (P_{NBI}, V_{NBI}).

30242, FIRE mode, gas puffing

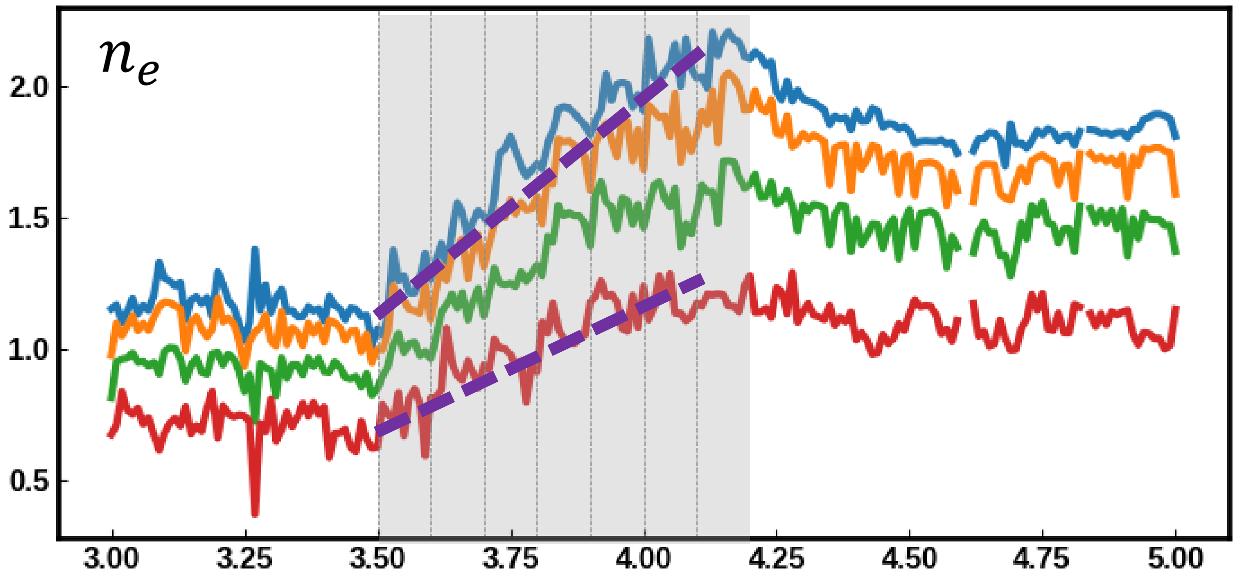
26381, L-mode, SMBI

Courtesy: S.J. Park



Core

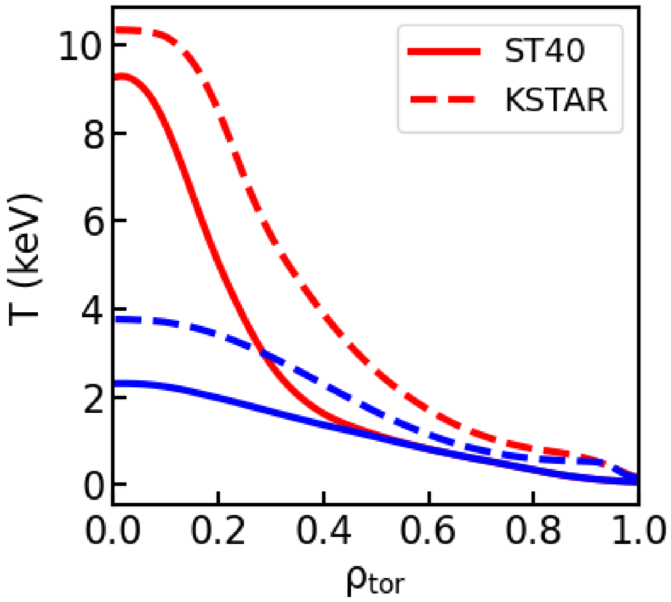
Edge

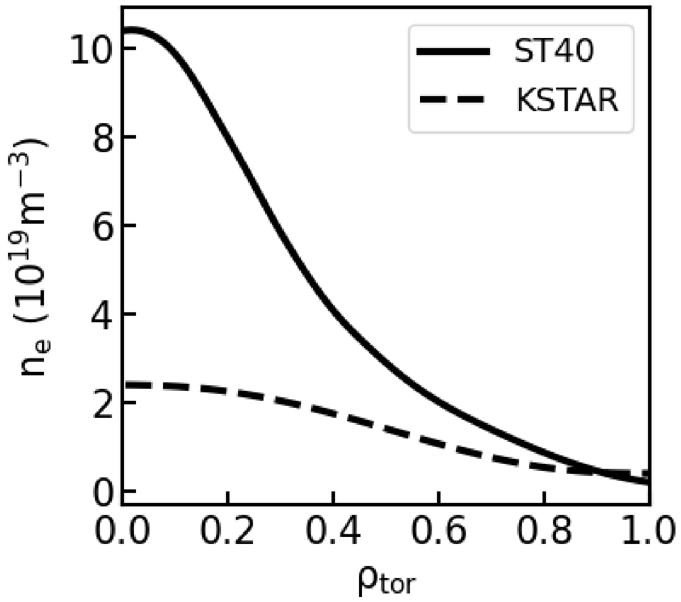


Comparative Physics Study with ST40

- Recent collaboration with ST40 toward establishment of novel operation strategy to burning plasma.

- As ST40 fast ion mode has higher n_e & lower $T_{i,e}$ than KSTAR FIRE mode, comparative physics study and mutual benchmarking are ongoing.





	KSTAR #26043 FIRE mode	ST40 #10009 Hot Ion mode
R/a (m)	$\sim 1.8/0.45\ m$	$\sim 0.4/0.25\ m$
κ	~ 1.7	~ 1.5
δ	0.6 (up) 0.25 (lower)	0.4 – 0.5 (symmetric)
I_p	$\sim 600\ kA$	$\sim 600\ kA$
B_T (T)	$1.8\ T$	$1.9\ T$
q_{95}	4.2	9
E_{nb} (kV)	$90\ /\ 70\ /\ 90\ kV$	$24\ /\ 55kV$
P_{nbi} (MW)	$1.4\ /\ 1.6\ /0.7\ MW$ (Total 3.7 MW)	$\sim 0.7\ /\ \sim 0.9\ MW$ (Total 1.6 MW)
Configuration	Diverted (USN, Unfavorable)	Limited
Coil	Superconductor	Copper
First Wall	Graphite	Graphite

Courtesy: J.H. Lee

Conclusion

- Electromagnetic (finite-β) effect, dilution and ExB flow shear work together leading to core confinement enhancement in KSTAR FIRE mode.
- In FIRE mode, dilution of thermal ion due to fast ion population appears to be the representative fast ion effect on confinement.
  - Linear stabilization of ITG turbulence
  - Enhancement of zonal flow self-generation & suppression of transport fluxes
- Ongoing works on physics study of I-mode-like feature of FIRE mode edge and fast ion-driven electrostatic/Alfvenic modes.
- Attempts to maximize performance and extend to higher density by advanced NBI control, together with gas puffing, SMBI, and pellet injection.