Observation of fast-ion driven modes in JET and effect on turbulence

J. Ruiz Ruiz[1], J. Garcia[2], M. Barnes[1], C. Giroud[3], M. Hardman[4], J.C. Hillesheim[5], Y. Kazakov[6], S. Mazzi[2], F.I. Parra[7], B. Patel[3]

1. Oxford 2. CEA 3. CCFE 4. Tokamak Energy 5. CFS 6. LPP-ERM/KMS 7. PPPL

20th European Fusion Theory Conference, Padova, Italy, October 2-5, 2023

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

What are fast ions (FI) and why we care?

- Populations of supra-thermal particle species:

$$E_f \gg T_i, T_e$$
$$n_f \ll n_i, n_e$$

- Originate in plasma heating, or in fusion process: very common !!
  ➔ heat the plasma through collisions as they slow down

What are fast ions (FI) and why we care?

$E_f \gg T_i, T_e$

$n_f \ll n_i, n_e$

- Populations of supra-thermal particle species:

- Originate in plasma heating, or in fusion process: very common !!
  ➔ heat the plasma through collisions as they slow down

- Fast ions (FI) can excite **MHD** instabilities [Rosenbluth PRL 1975].
    - can resonate with Alfvén waves as they slow down (need $v_f \gtrsim v_A$)
    - can cause high fast ion transport

What are fast ions (FI) and why we care?

- Populations of supra-thermal particle species:

$$E_f \gg T_i, T_e$$
$$n_f \ll n_i, n_e$$

- Originate in plasma heating, or in fusion process: very common !!
  ➔ heat the plasma through collisions as they slow down

- Fast ions (FI) can excite **MHD** instabilities [Rosenbluth PRL 1975].
  - can resonate with Alfvén waves as they slow down (need $v_f \gtrsim v_A$)
  - can cause high fast ion transport

- Fast ions can also have a **direct** effect on turbulence:
  1. Dilution (through quasineutraliy: $Z_i n_i + \boldsymbol{Z_f n_f} = n_e$)
  2. Modification of equilibrium ($\boldsymbol{\beta}'$ stabilization)
  3. **Active kinetic effect** '*Linear resonance*' between fast ions and ITG [Di Siena NF 2018, PoP 2019] → improved dilution model [Wilkie NF 2018]
  - ➔ these effects are small when extrapolating to a reactor

What are fast ions (FI) and why we care?

$E_f \gg T_i, T_e$

$n_f \ll n_i, n_e$

- Populations of supra-thermal particle species:

- Originate in plasma heating, or in fusion process: very common !!
  ➔ heat the plasma through collisions as they slow down

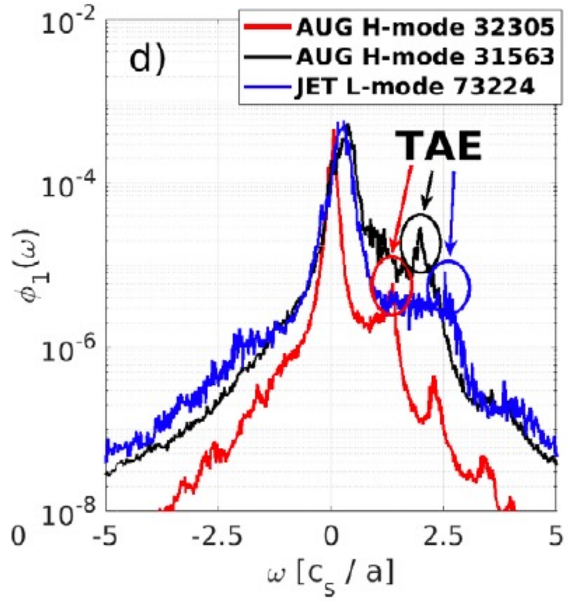
- Fast ions (FI) can excite **MHD** instabilities [Rosenbluth PRL 1975].
    - can resonate with Alfvén waves as they slow down (need $v_f \gtrsim v_A$)
    - can cause high fast ion transport

- Fast ions can also have a **direct** effect on turbulence:
  1. Dilution (through quasineutraliy: $Z_i n_i + \boldsymbol{Z_f n_f} = n_e$)
  2. Modification of equilibrium ($\boldsymbol{\beta}'$ stabilization)
  3. **Active kinetic effect** '*Linear resonance*' between fast ions and ITG [Di Siena NF 2018, PoP 2019] → improved dilution model [Wilkie NF 2018]
  - ➔ these effects are small when extrapolating to a reactor

- **Recent**: Fast-ion driven modes can interact with (and stabilize!) turbulence

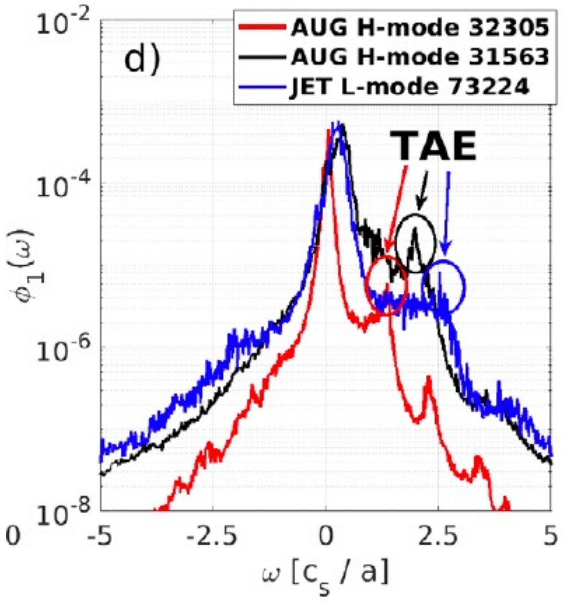
Indirect effect: Fast-ion driven Alfvén eigenmodes can nonlinearly interact with (and stabilize!) turbulence

- JET, AUG-U [Di Siena NF 2019]
    - High-freq. feature in the potential
      → toroidal Alfvén eigenmodes (TAEs)
    - Live at low $k_y \rho_i \sim 0.1$
    - TAEs drive ZF → stabilizes turbulence
    - No TAEs observed in experiment

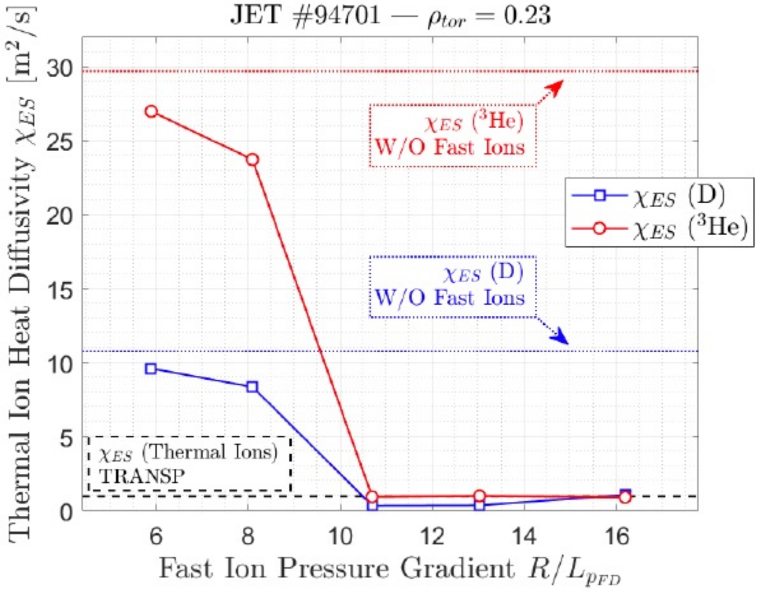


Indirect effect: Fast-ion driven Alfvén eigenmodes can nonlinearly interact with (and stabilize!) turbulence

- JET, AUG-U [Di Siena NF 2019]
  - High-freq. feature in the potential → toroidal Alfvén eigenmodes (TAEs)
  - Live at low $k_y\rho_i \sim 0.1$
  - TAEs drive ZF → stabilizes turbulence
  - No TAEs observed in experiment

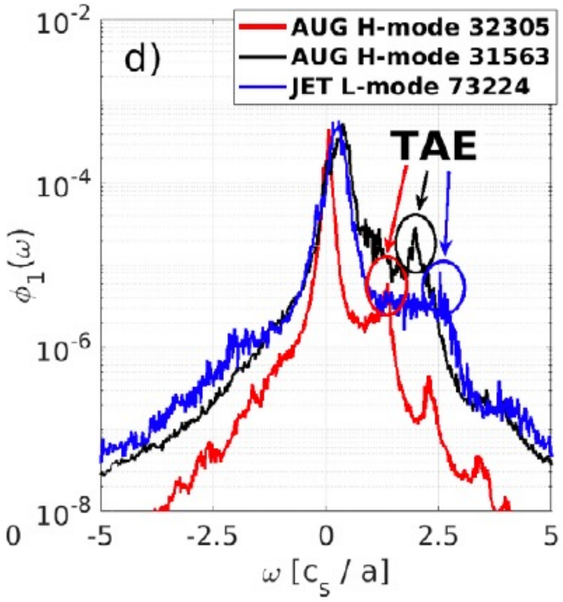


- JET. [Mazzi Nat. Phys 2022]:
  - Unstable AEs (exp & sim).
  - Increase of ZF activity with TAE drive R/L_{PFD}
  - Decrease in χ_{ES}

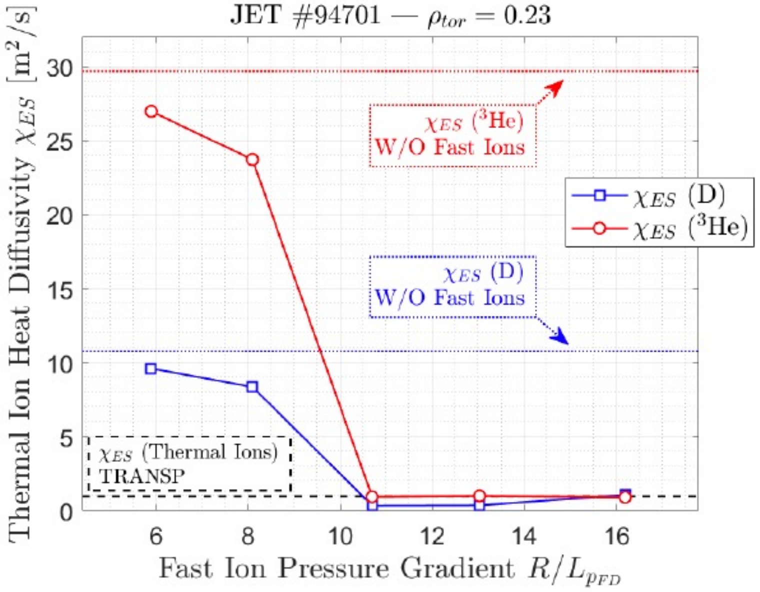


Indirect effect: Fast-ion driven Alfvén eigenmodes can nonlinearly interact with (and stabilize!) turbulence

- JET, AUG-U [Di Siena NF 2019]
  - High-freq. feature in the potential → toroidal Alfvén eigenmodes (TAEs)
  - Live at low $k_y \rho_i \sim 0.1$
  - TAEs drive ZF → stabilizes turbulence
  - No TAEs observed in experiment



- JET. [Mazzi Nat. Phys 2022]:
  - Unstable AEs (exp & sim).
  - Increase of ZF activity with TAE drive R/L_{PFD}
  - Decrease in χ_{ES}

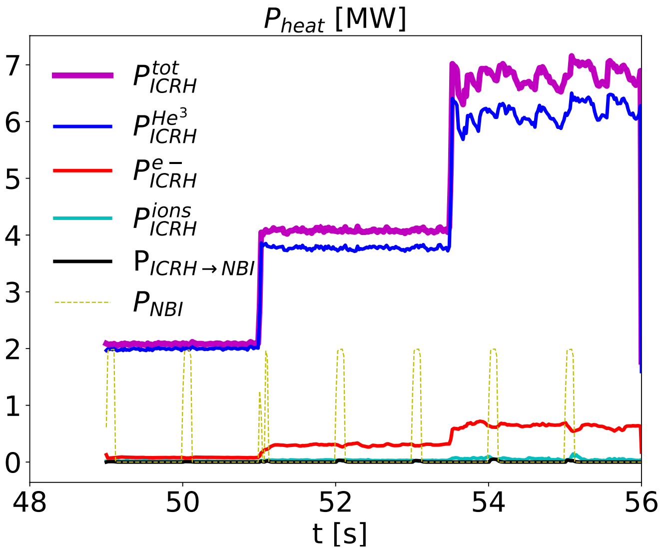


Open questions that motivate this work:

- **Generation of ZFs by AEs** (and zonal fields $A_{||}$!)
- **Electron transport** with ion-scale turbulence is stabilized by AEs?

‘Anomalous’ ion-heating generated via MeV-range ICRH fast ions **in JET?**

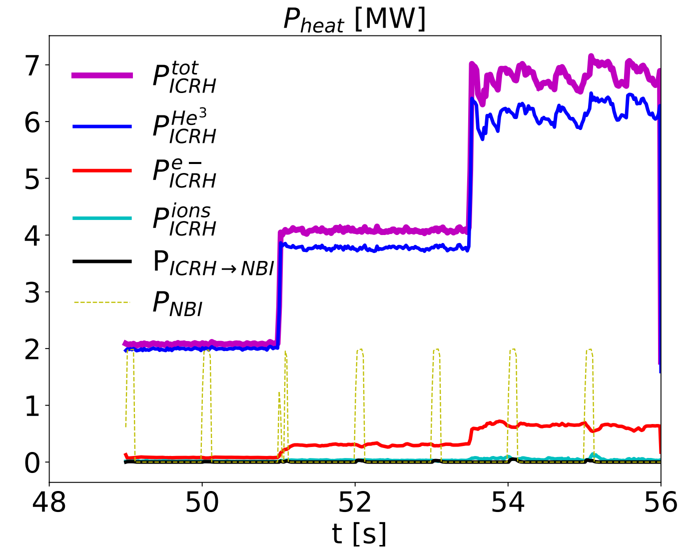
- **L mode, ICRH heating (no NBI) generates MeV range He^3 [*] → dominant e- heating!**
  - H+D (background) + He^3 (fast)
  - Most heating to He^3 (4-5 MeV) → slows down on e-



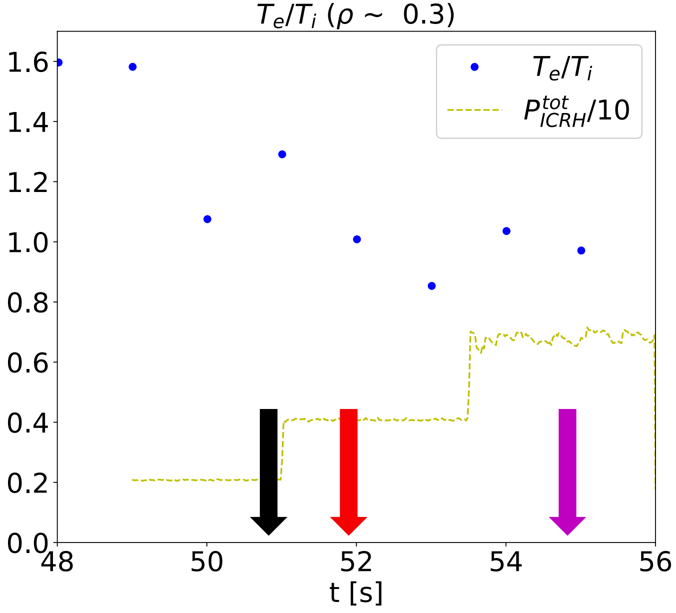
[*] ‘3-ion ICRH heating’, Kazakov NF 2015

‘Anomalous’ ion-heating generated via MeV-range ICRH fast ions **in JET?**

- **L mode, ICRH heating (no NBI) generates MeV range He^3 [*] → dominant e- heating!**
  - H+D (background) + He^3 (fast)
  - Most heating to He^3 (4-5 MeV) → slows down on e-



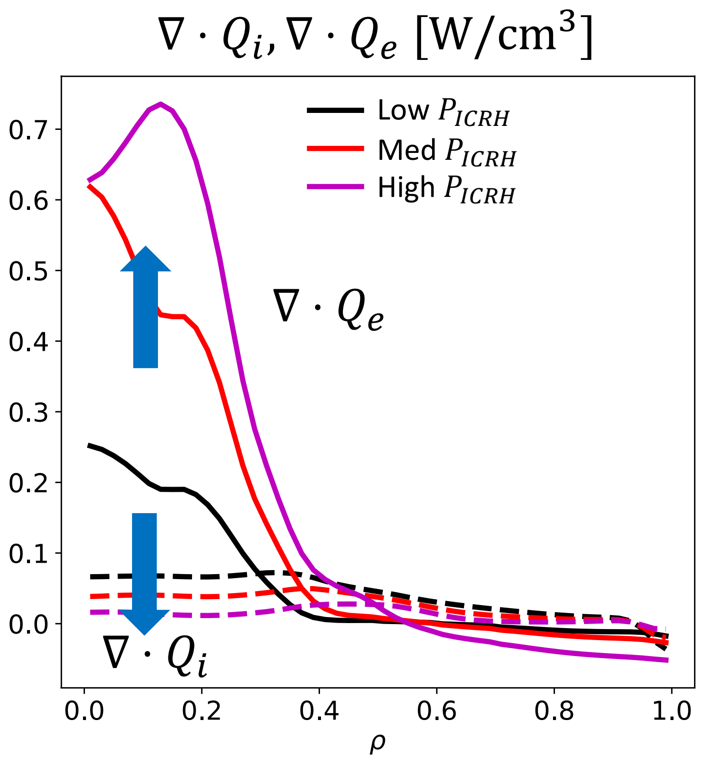
- **T_e increases, but T_e/T_i decreases → 1!**
  - P^{coll}_{ei} decreases with T_e
  - Alpha channeling?
  - Turbulent energy exchange P^{turb}_{ei}?
  - Ion turbulence is stabilized?

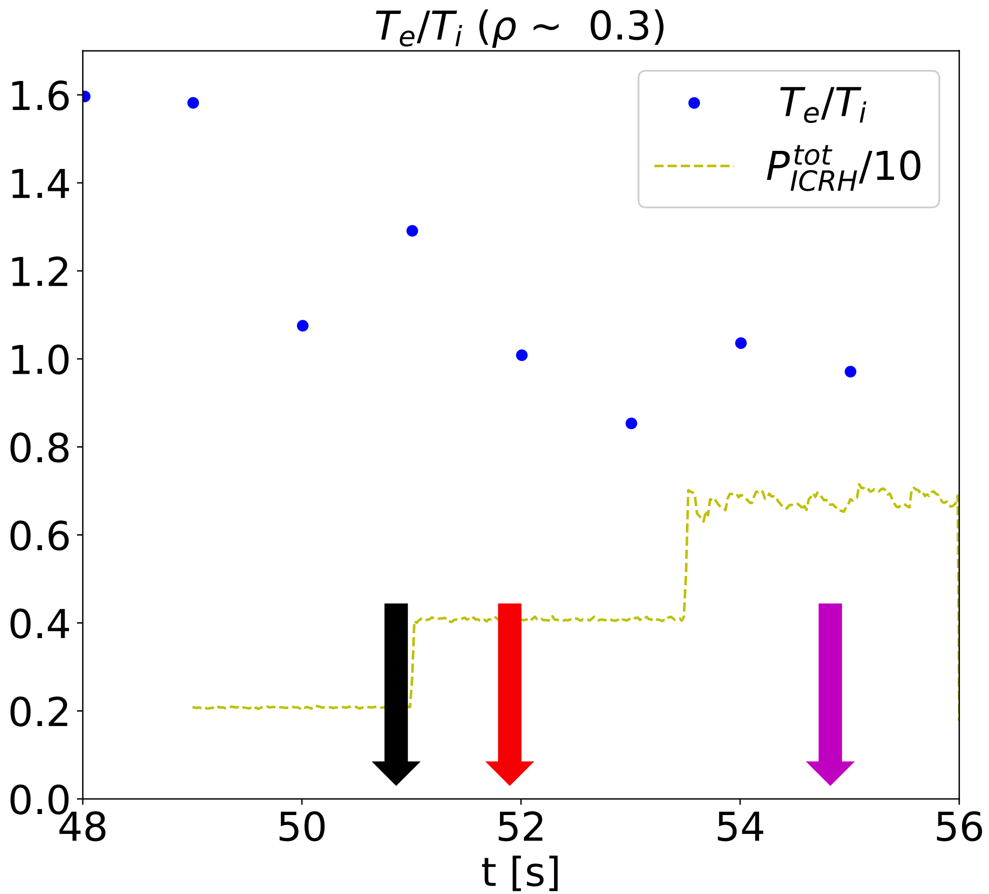


[*] ‘3-ion ICRH heating’, Kazakov NF 2015

TRANSP shows that ion thermal transport approaches NC levels, dominant electron transport in deep core

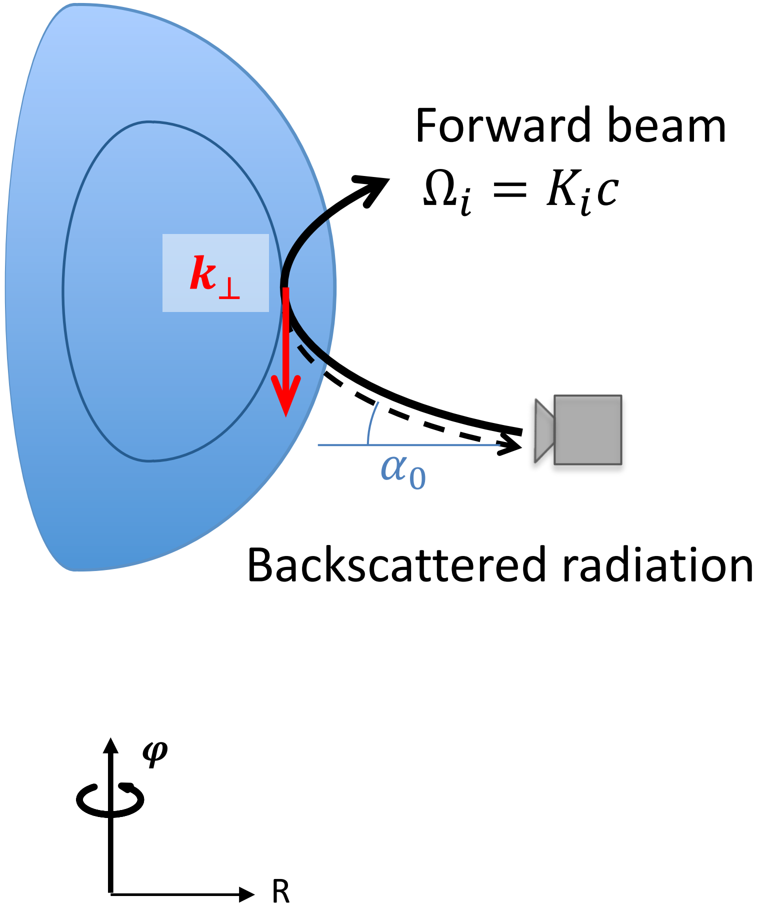
- $\nabla \cdot Q_i$ dominates in outer core and Ohmic phase
- $\nabla \cdot Q_e$ dominates inside $\rho \approx 0.4$
- P_i decreases with P_{ICRH}, P_e increases
  - Suggests changes in ion turbulence
  - How is heat exhausted via e-?





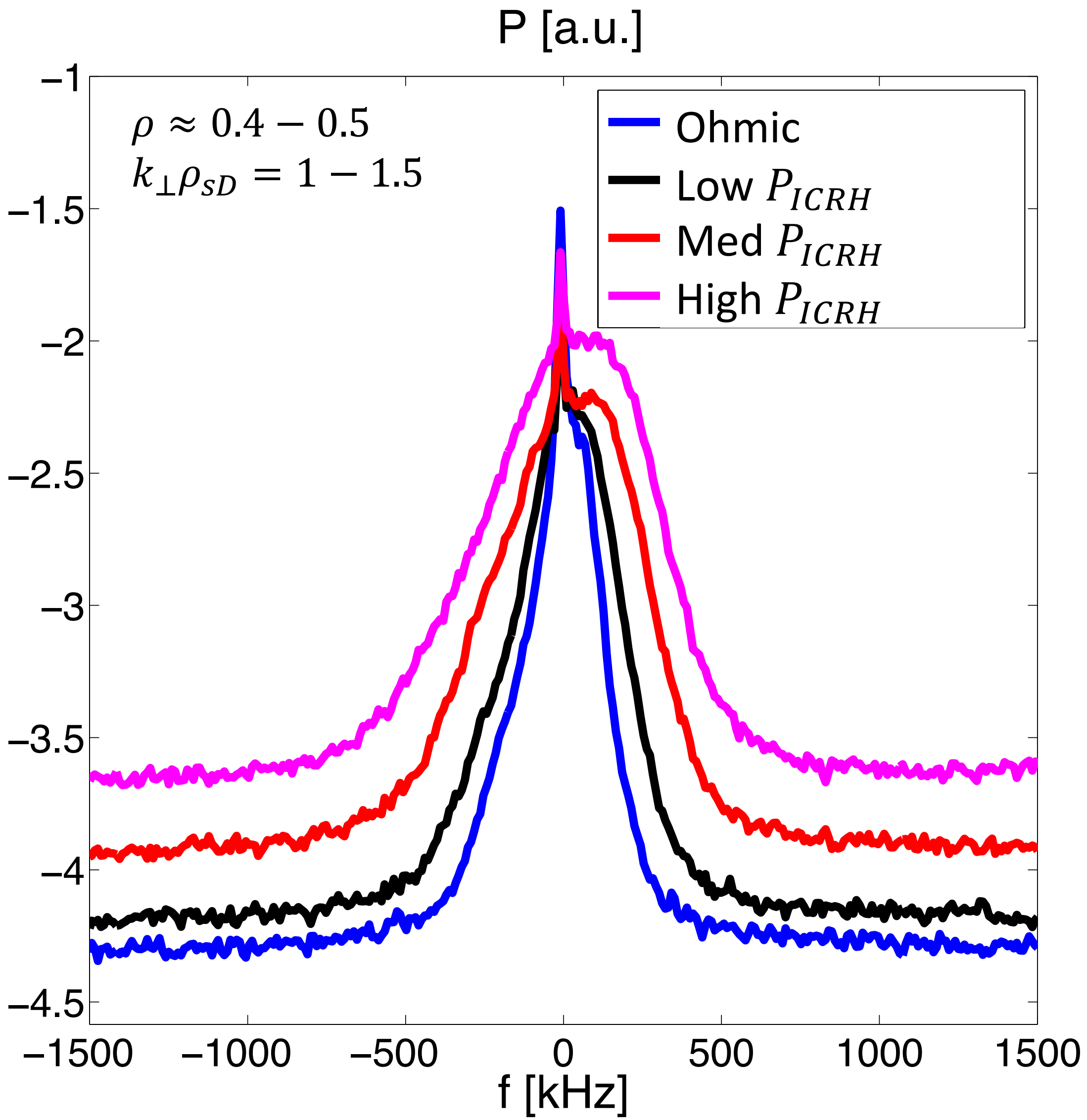
Hypothesis is that fast ions stabilize ion turbulence & drive e- turbulence

Perform turbulence measurements using Doppler Backscattering (DBS) diagnostic



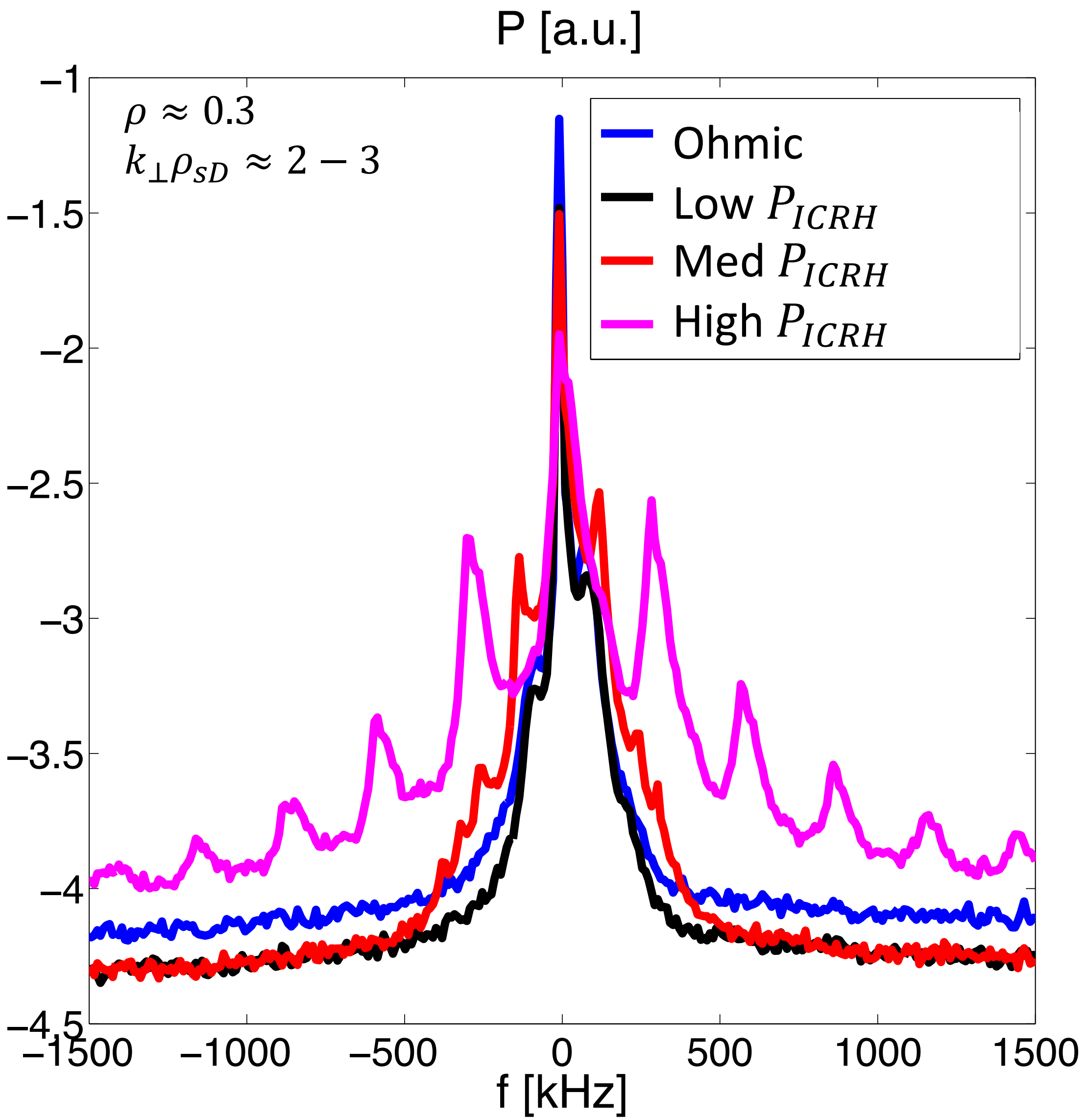
- Launch microwave beam at an angle α_0 wrt. horizontal ($\lambda_i \sim 1 - 3$ mm).
- Beam propagates into plasma until it encounters a **cutoff.**
- Forward beam deviated upwards.
- Bragg condition: Detect backscattered radiation from turbulence wavenumber $\boldsymbol{k}_\perp = -2\boldsymbol{K_i}$
- Scattered power $P_s \propto \left\langle \left| \delta n \left(\vec{\boldsymbol{k}}_\perp \right) \right|^2 \right\rangle$
- DBS measures one $\vec{\boldsymbol{k}}_\perp$.

Mid-core DBS measurements show low-f, broadband turbulence increases with P_{ICRH}



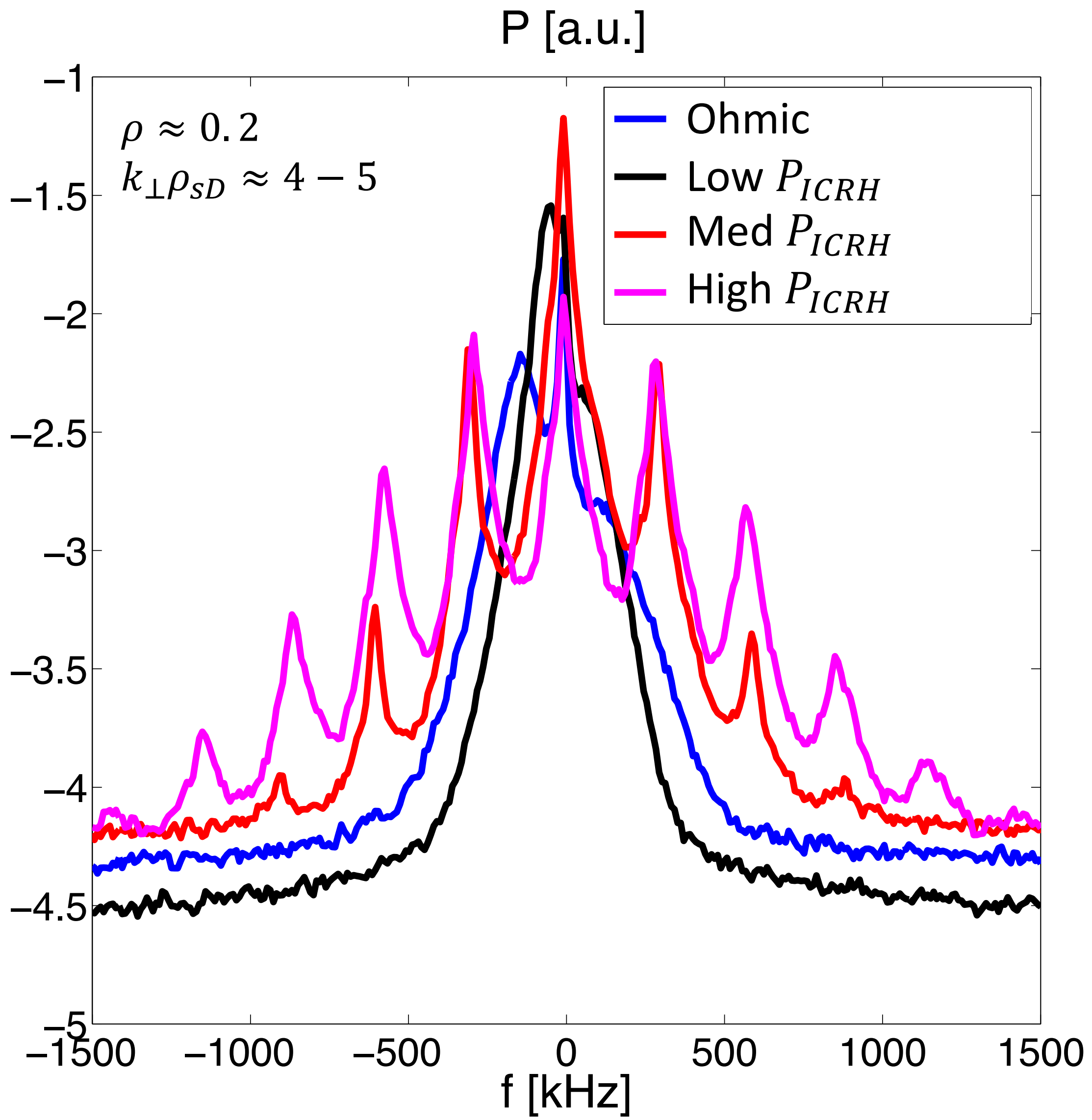
- **Mid-core** Radial location $\rho \approx 0.4 - 0.5$ typically characterized by ITG turbulence in similar JET discharges
- Measured turbulence wavenumber $k_\perp \rho_{sD} = 1 - 1.5$ is intermediate ion-to-electron scale
- Low-f, broadband spectrum ($f \approx 100$ kHz) increases with P_{ICRH}.
- Increase in turbulence fluctuation power is consistent with increase in Q_e.

Fast-ion driven AEs observed in the deep core by DBS as P_{ICRH} increases



- **Deep-core**: low-f turbulence disappears in favor of TAEs at med+high P_{ICRH}
  - What happens to the low-f turbulence in presence of TAEs ($\Delta f \approx 260-290$ kHz)? Indications it might stabilize in deepest channels
  - Why are we measuring TAEs (low $k_y\rho_s \sim 0.1$) at high $k_y\rho_s$ with DBS?

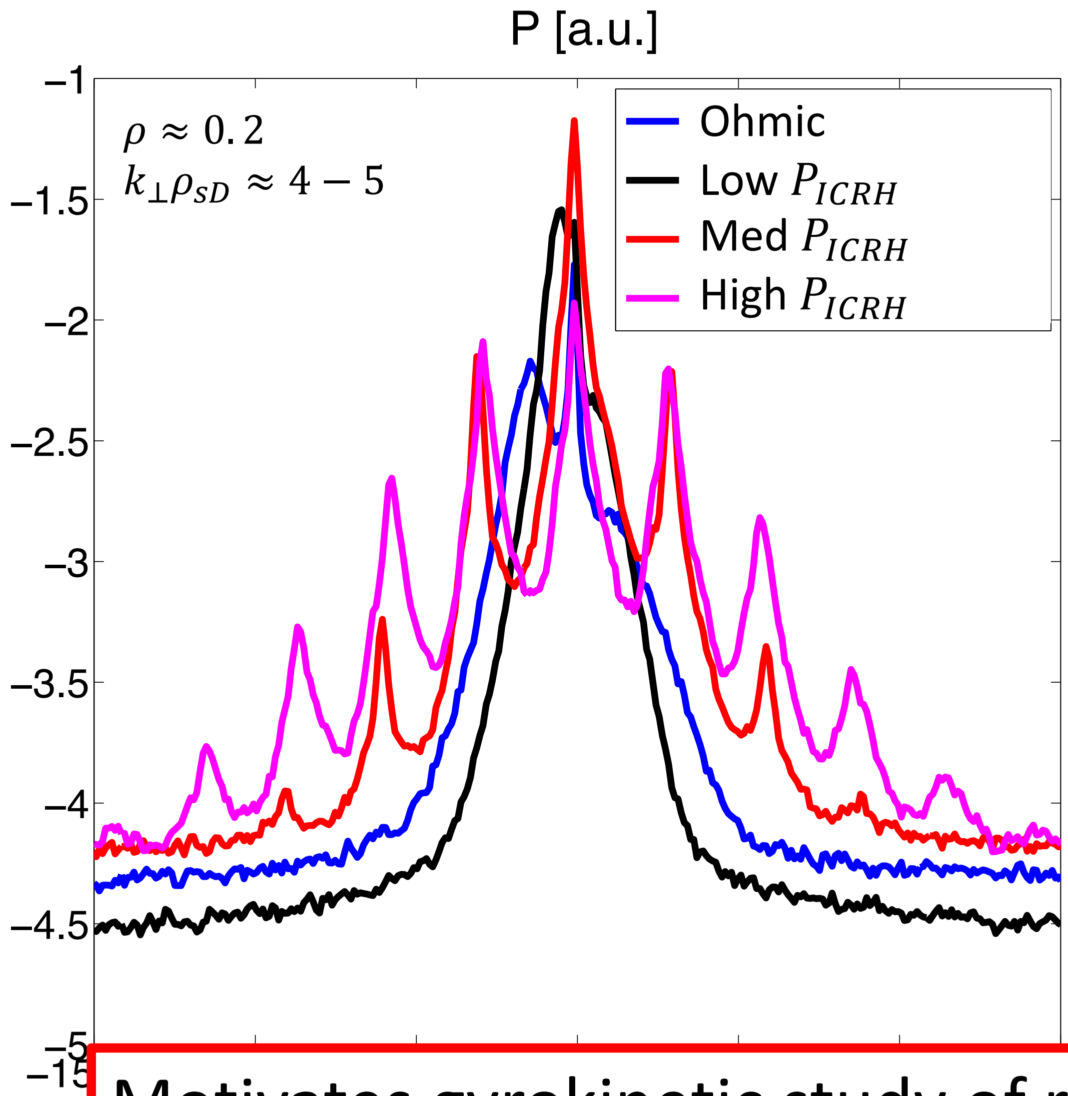
Fast-ion driven AEs observed in the deep core by DBS as P_{ICRH} increases



- **Deep-core**: low-f turbulence disappears in favor of TAEs at med+high P_{ICRH}
  - What happens to the low-f turbulence in presence of TAEs ($\Delta f \approx 260 - 290$ kHz)? Indications it might stabilize in deepest channels
  - Why are we measuring TAEs (low $k_y \rho_s \sim 0.1$) at high $k_y \rho_s$ with DBS?

- Similar spectrum deeper in the core for even higher $k_y \rho_s$

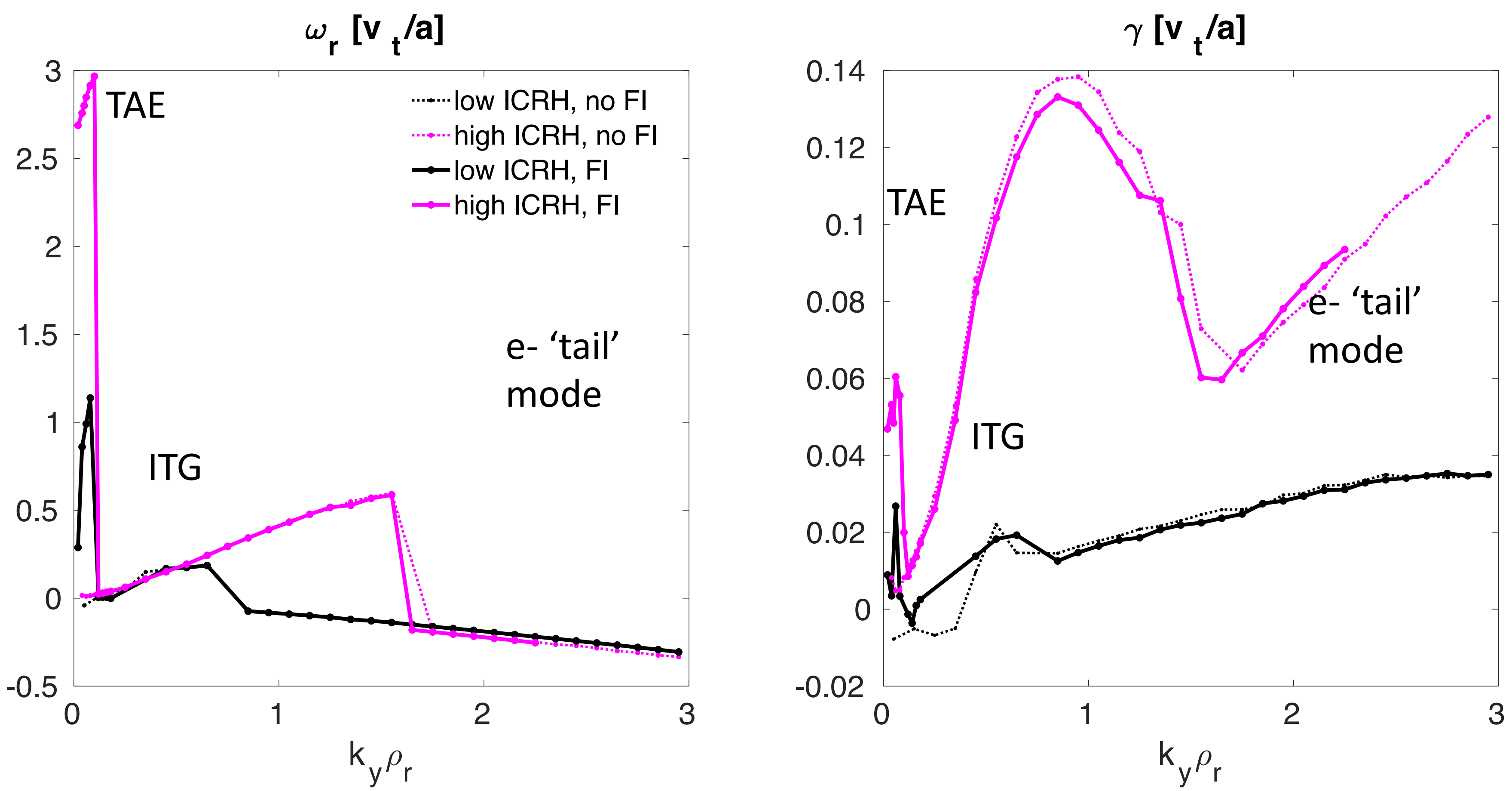
Fast-ion driven AEs observed in the deep core by DBS as P_{ICRH} increases



- **Deep-core**: low-f turbulence disappears in favor of TAEs at med+high P_{ICRH}
  - What happens to the low-f turbulence in presence of TAEs ($\Delta f \approx 260 - 290$ kHz)? Indications it might stabilize in deepest channels
  - Why are we measuring TAEs (low $k_y \rho_s \sim 0.1$) at high $k_y \rho_s$ with DBS?
- Similar spectrum deeper in the core for even higher $k_y \rho_s$

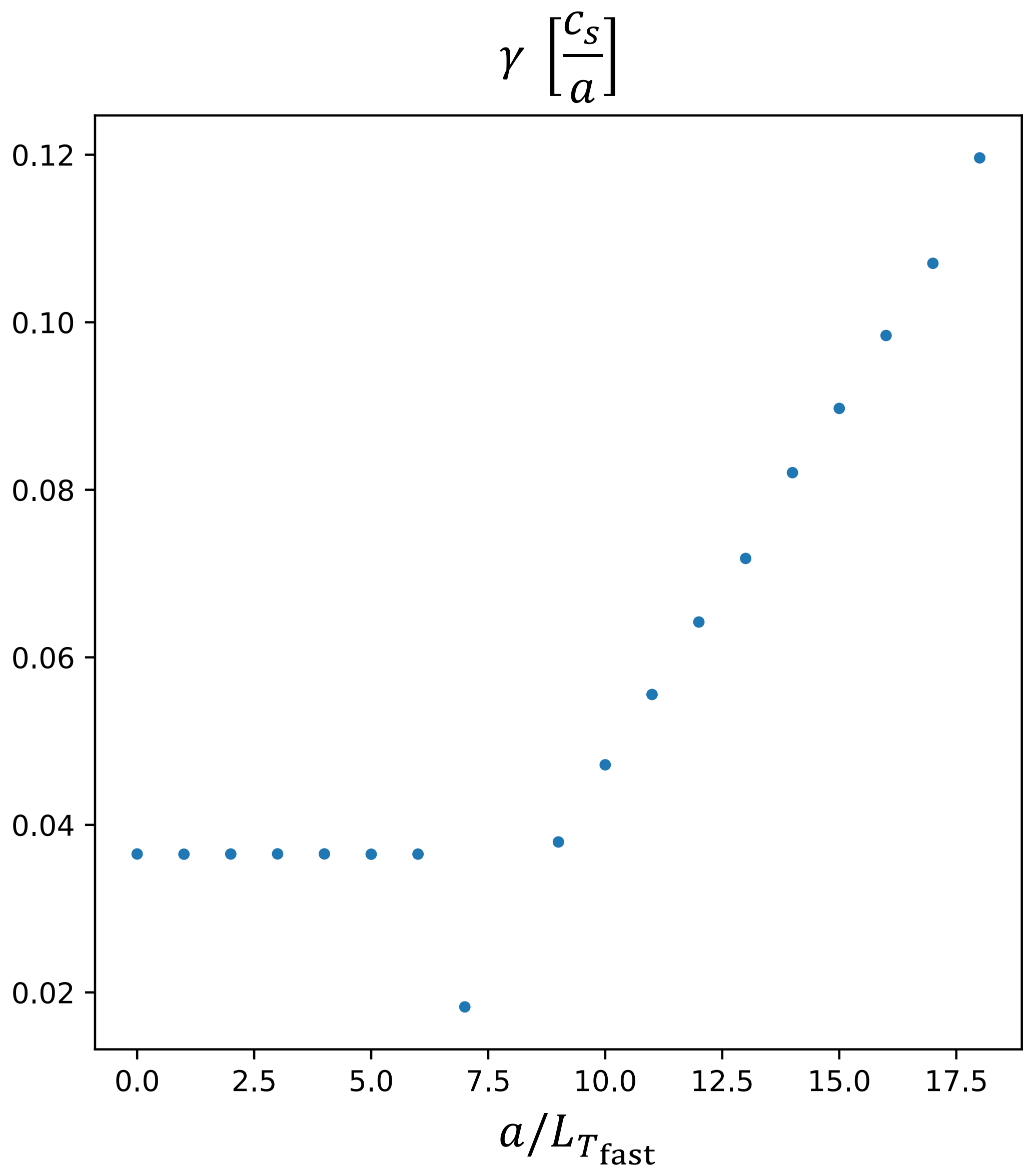
Motivates gyrokinetic study of role of TAEs in determining Q_i, Q_e

Linear GS2 shows destabilization of low k_y TAE (by fast He^3), ITG and electron-driven 'long-tail' mode



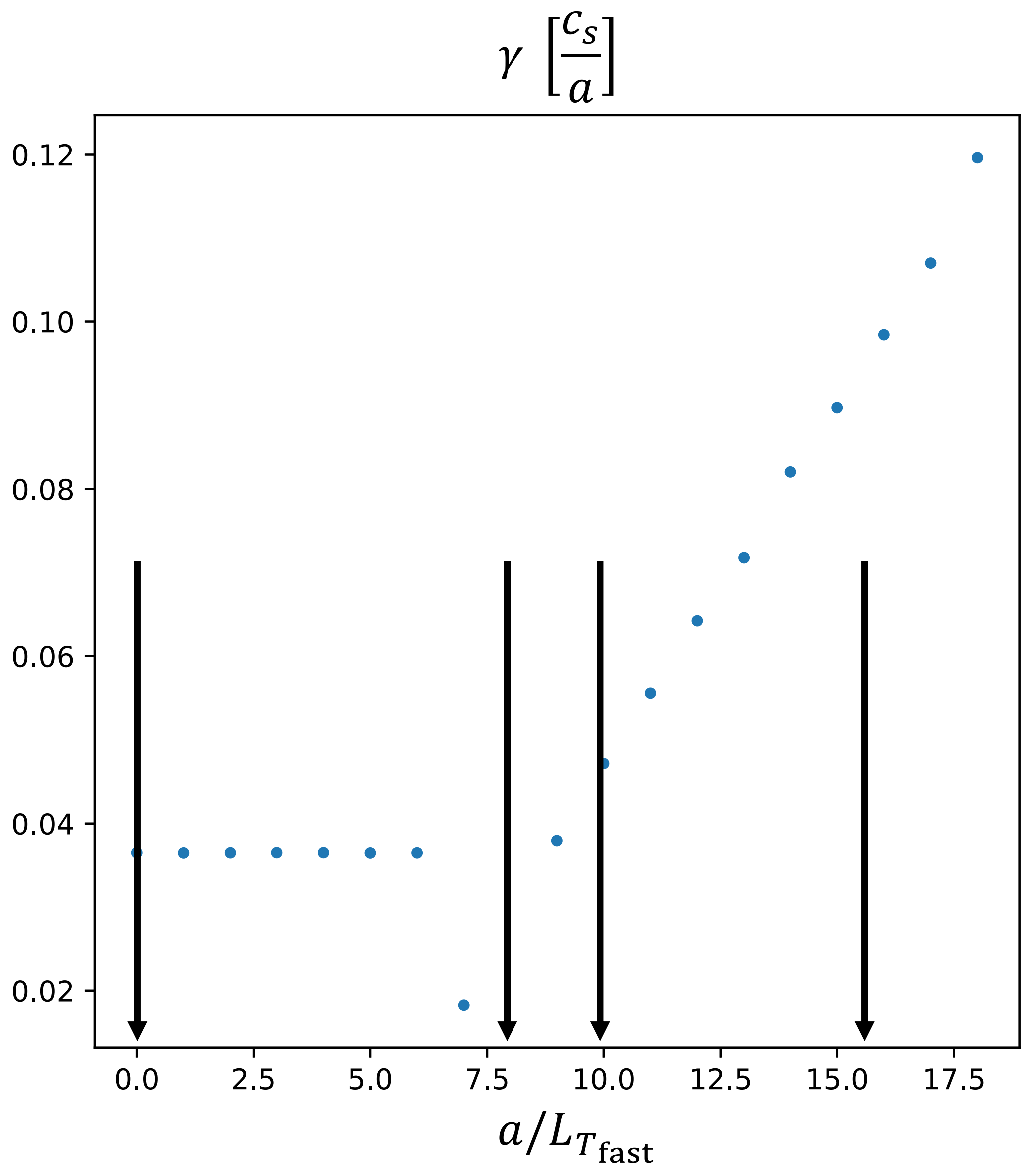
- **Low ICRH**: Weakly unstable TAEs, ITG & e- tail mode (~ Ohmic)
- **High ICRH**: Highly driven TAE, ITG and e- tail mode
  - TAE matches measured DBS freq. ($f \approx 260 - 290$ kHz), $n \approx 4 - 6$ ($k_y \rho_{sD} \approx 0.04$)
- No low-k_y TAE without FI

Linear CGYRO for high P_{ICRH} shows critical gradient behavior with a/L_{Tfast} at low $k_y\rho_{sD}$ (TAE)



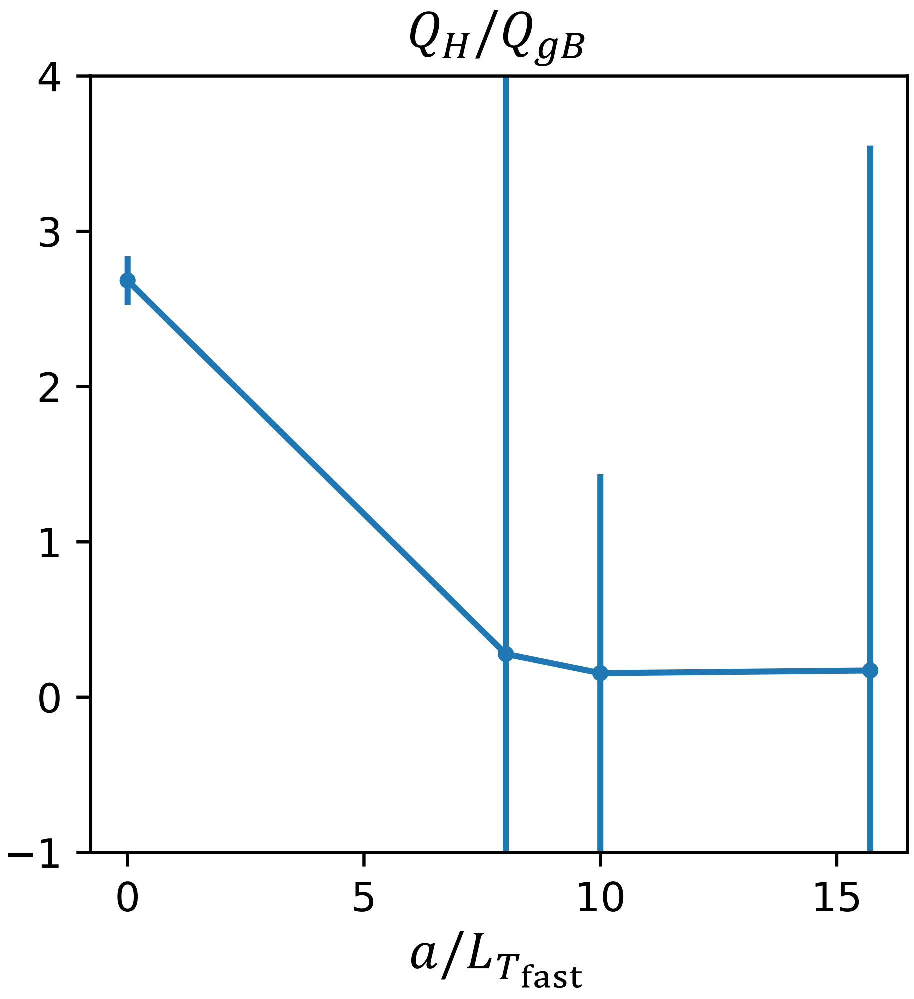
- $k_y\rho_{sD} \approx 0.04$
- $a/L_{T_{\mathrm{fast}}} < 8$: long-tail mode (~MT)
- $a/L_{T_{\mathrm{fast}}} > 8$: TAE

Linear CGYRO for high P_{ICRH} shows critical gradient behavior with a/L_{Tfast} at low $k_y\rho_{sD}$ (TAE)



- $k_y\rho_{sD} \approx 0.04$
- $a/L_{T_{\mathrm{fast}}} < 8$: long-tail mode (~MT)
- $a/L_{T_{\mathrm{fast}}} > 8$: TAE
- ➔ Probe turbulence without fast particles, near marginal, and at high $a/L_{T_{\mathrm{fast}}}$ drive of TAE.

Nonlinear CGYRO for high P_{ICRH}: turbulence stabilization for a/L_{Tfast} > linear TAE marginal stability

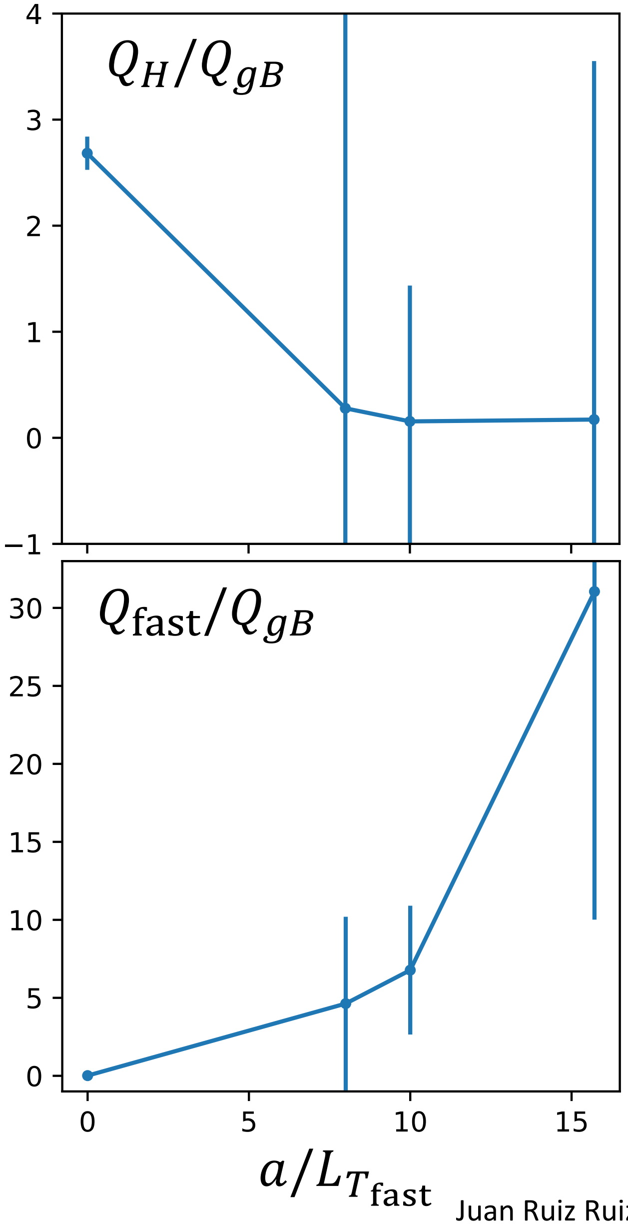


- Electromagnetic ($\phi, A_{||}$), fast-Maxwellian He^3 ($T_f \approx 168\, T_i$)
- TAE+ITG scales:

$k_y\rho_{sD} = [0.02, 1.26],\ L_y = 314\rho_{sD}$
$k_x\rho_{sD} = [0.015, 2.93], L_x = 410\rho_{sD}$

- Heat flux dominated by ions for no FI, $Q/Q_{gB} \approx 3$
- Stabilization of $Q_{ion/e-}$ with $a/L_{T_{\mathrm{fast}}} \geq \mathrm{marginal}$

Nonlinear CGYRO for high P_{ICRH}: turbulence stabilization for a/L_{Tfast} > linear TAE marginal stability



- Electromagnetic $(\phi, A_{||})$, fast-Maxwellian He^3 $(T_f \approx 168\, T_i)$

- TAE+ITG scales:

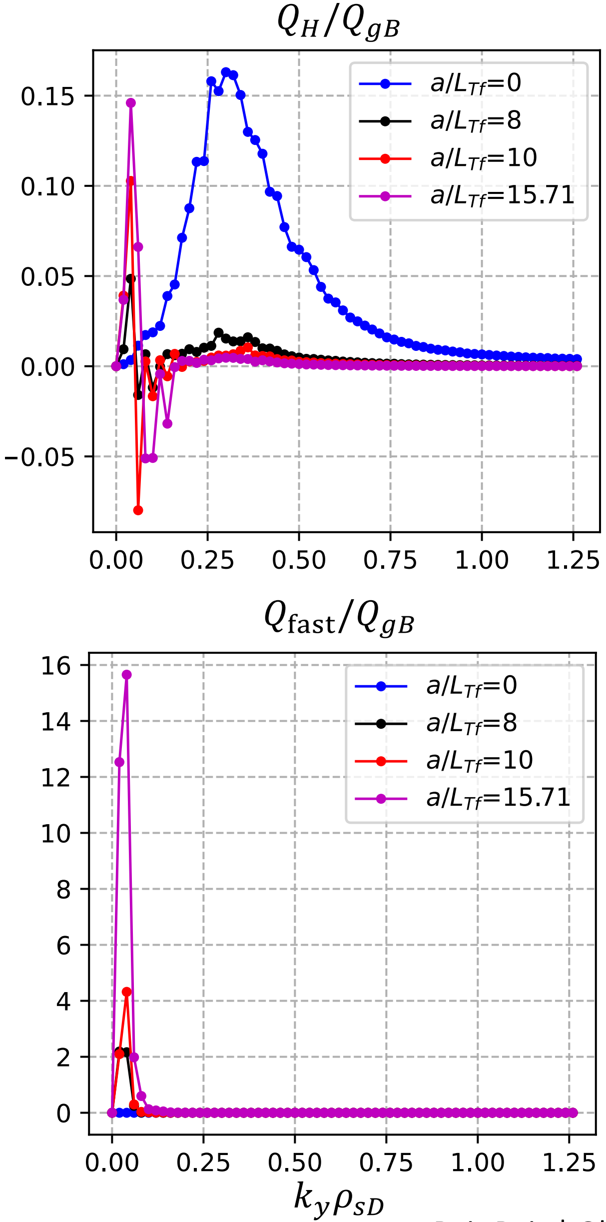
$k_y\rho_{sD} = [0.02, 1.26],\ L_y = 314\rho_{sD}$
$k_x\rho_{sD} = [0.015, 2.93], L_x = 410\rho_{sD}$

- Heat flux dominated by ions for no FI, $Q/Q_{gB} \approx 3$

- Stabilization of $Q_{ion/e-}$ with $a/L_{T_{fast}} \geq$ marginal

- Fast ion fluxes dominate for $a/L_{T_{fast}} \geq$ marginal ➔ exp. near marginal TAE stability

Turbulent wavenumber ITG spectrum is stabilized, driven at $k_y\rho_{sD} < 0.1$ in presence of fast particles

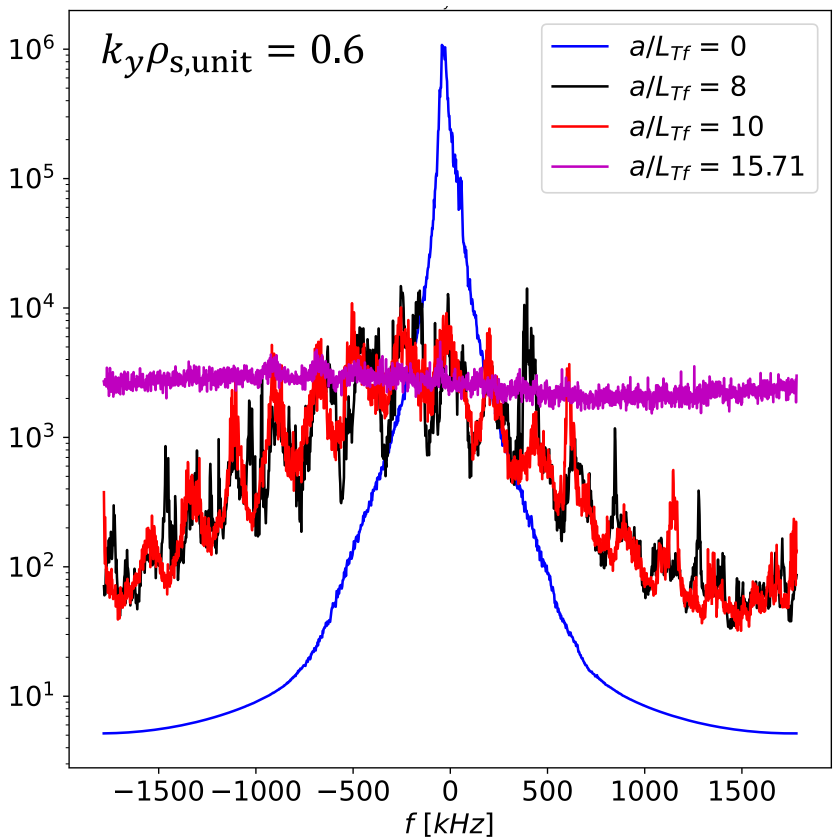


- **No FI**: ITG at $k_y\rho_{sD} \approx 0.3$
  - Positive AND negative fluxes!

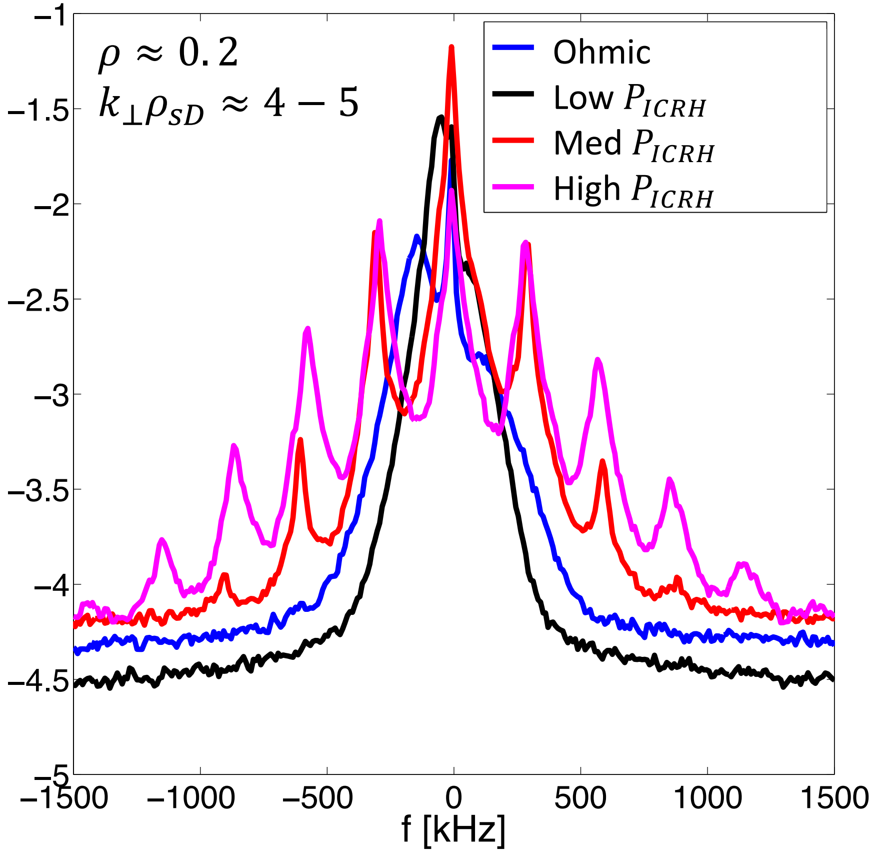
- **With FI**:
  - Thermal fluxes stabilized at $k_y\rho_{sD} \approx 0.3$
  - Dominant Q_{fast} at $k_y\rho_{sD} < 0.1$

Comparison with DBS spectra shows qualitative agreement with turbulent $|\delta n_e|^2$ for near marginal a/L_{Tf} = 8

$|\delta n_e|^2$ CGYRO

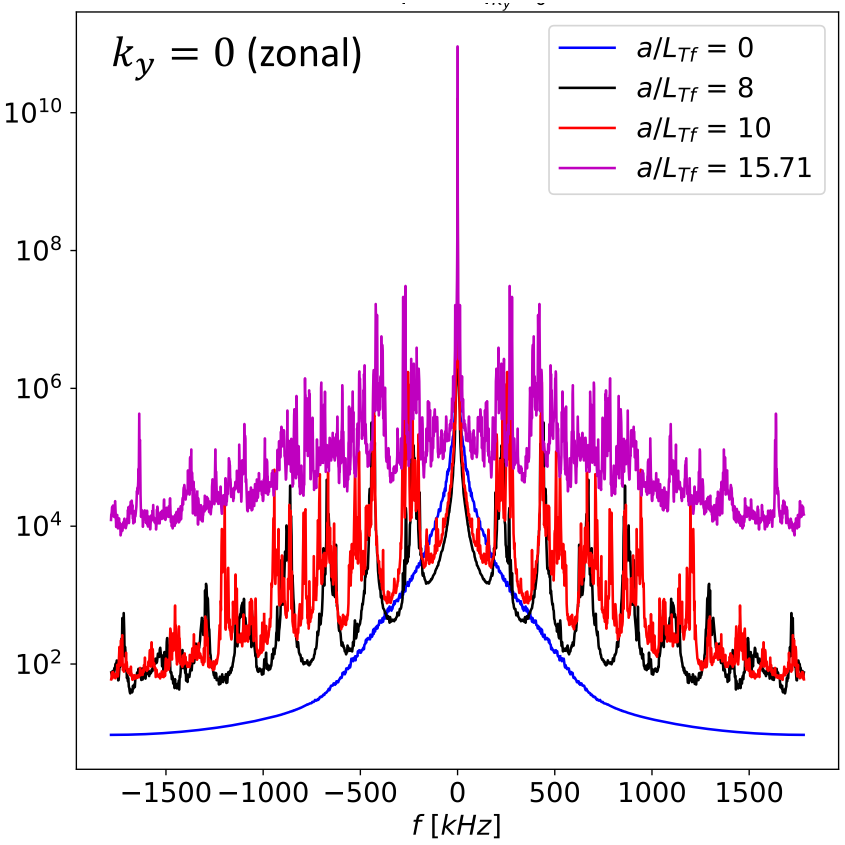


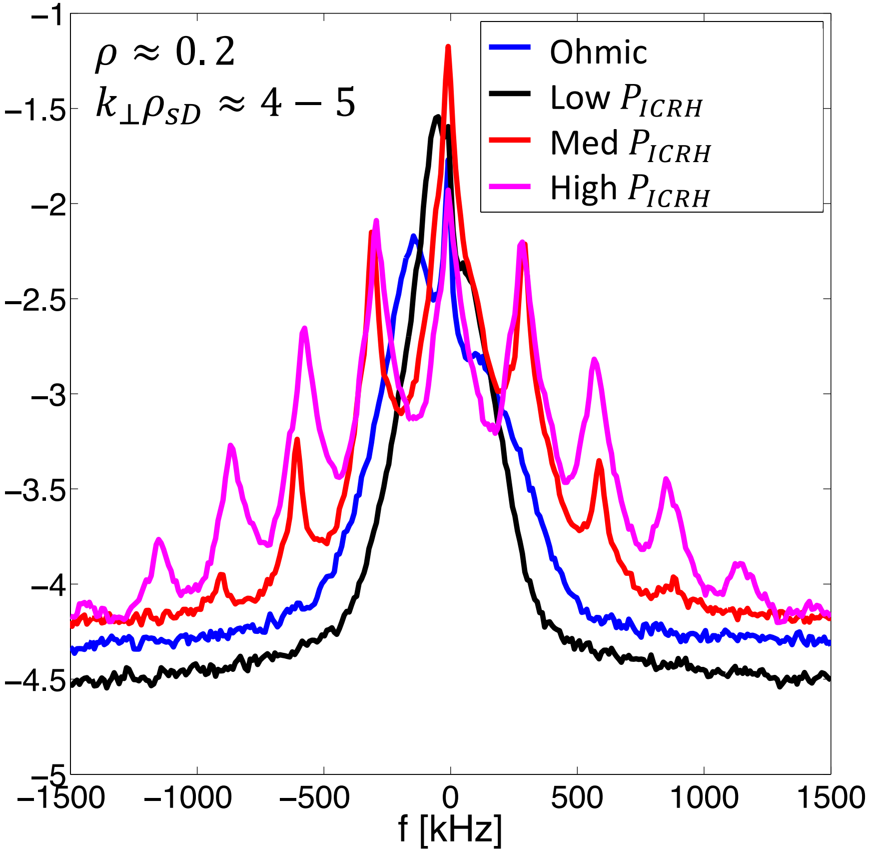
PDBS [a.u.] (exp.) ∝ $|\delta n_e|^2$



- CGYRO $|\delta n_e|^2(\omega)$ exhibits peaks at f_{TAE} (and harmonics) for $k_y\rho_{s,\text{unit}} = 0.6$, similar to exp.
- Peaks disappear at highest drive.
- Comparison $k_y\rho_{sD} = 4-5$ requires large comp. resources (ongoing).

Agreement improves when compared with zonal component $|\delta n_e|^2$ rather than $k_y\rho_{s,unit} = 0.6$





- CGYRO $|\delta n_e|^2(\omega)$ exhibits peaks at f_{TAE} (and harmonics) for $k_y\rho_{s,\text{unit}} = 0.6$, similar to exp.
- Peaks disappear at highest drive.
- Comparison $k_y\rho_{sD} = 4 - 5$ requires large comp. resources (ongoing).
- DBS spectrum agrees better with ***zonal*** rather than $|\delta n_e|^2$ from $k_y\rho_{sD} = 4 - 5$

Conclusions & next steps

Experimental evidence:

- JET discharge with dominant e- heating (via MeV range fast ions) shows T_e increases with P_{ICRH}, but T_e/T_i decreases → 1 ('anomalous' ion heating?)
- $\nabla \cdot Q_i$ decreases with P_{ICRH}, $\boldsymbol{\nabla \cdot Q_e}$ **increases & becomes dominant**
- Deep-core, low-f turbulence disappears in favor of higher-f TAEs

Gyrokinetic simulations:

- Linear GS2/CGYRO shows destabilization of low-k_y, high-f TAE
- NL CGYRO
  Thermal ion/e- fluxes stabilized by increasing a/L_{tfast}
  Fluxes dominated by Q_{fast} even for marginal a/L_{tfast}
  CGYRO $|\delta n_e|^2(\omega)$ spectrum exhibits peaks near f_{TAE} for $k_y \rho_{s,\mathrm{unit}} = 0.6$, similar to DBS measurement, but zonal component agrees better

Next steps:

- Analyze DBS propagation + synthetic diagnostic to understand TAE measurement by DBS.
- Effect of ∇T_i on thermal/fast ion transport.
- Develop a reduced model for the TAE/ITG interaction → fundamental understanding

Backup slides

Details about JET 97090 and NL GK sim [*]

I_p [MA]	
B_T [T]	3.18
P_{NBI} [MW]	0
P_{ICRH} [MW]	0/2/7
fueling	
β_N	
a [m]	0.93/0.94/0.95
rho	0.3
ω [m/s]	14294.175/18191.62/16931.99

etae ~ etai > 10!!
For Ohmic + 2MW

$\rho^*_{s,\mathrm{unit}} = 1/520$

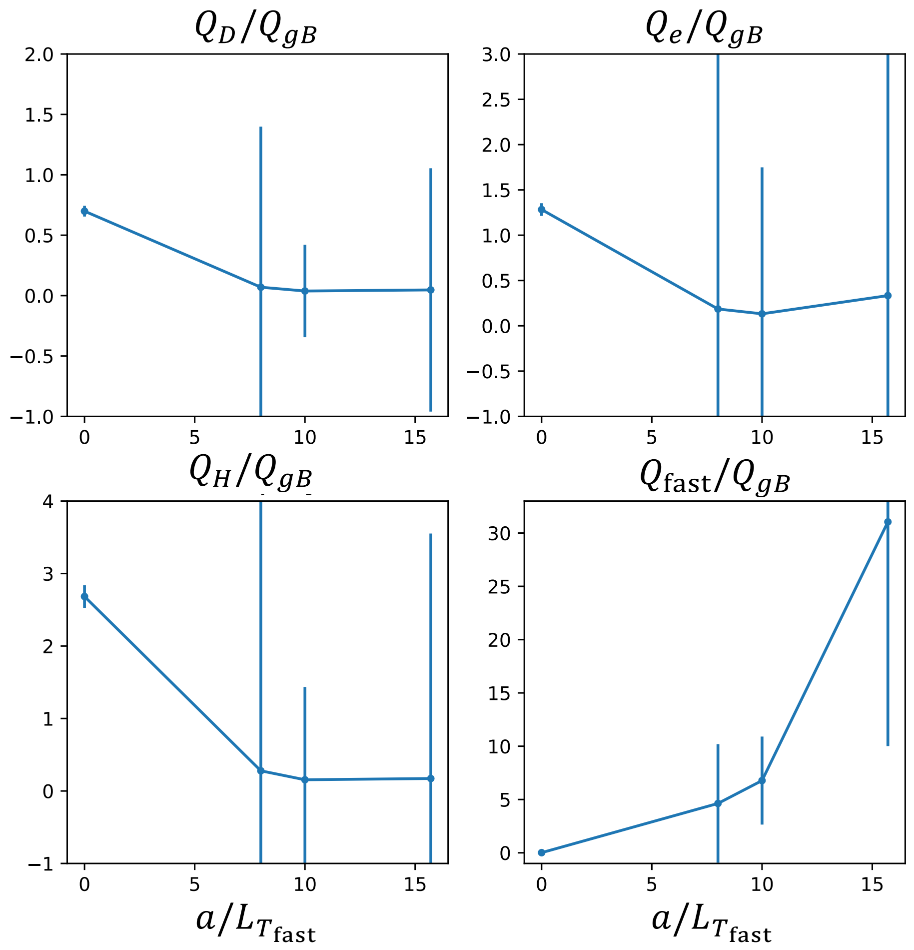
$Q_{gB,\mathrm{unit}} = 21\,\frac{\mathrm{kW}}{\mathrm{m}^2}$

	OH	2MW	7MW
v_A [m/s]			1.04 10^7
$\omega_A = v_A/2q_0R_0\left[\frac{v_t}{a}\right]$			2.9 / 3.8 (Bunit)
v_{tref} [m/s] / c_s			5.09 10^5 / 3.75 10^5
v_f [m/s]			5.37 10^6
$k_y\rho_r = 0.04$			$n = 5$ (GS2)
$k_y\rho_{s,\mathrm{unit}} = 0.02$			$n = 3$ (CGYRO)

	OH	2MW	7MW
R_0 [m]	3.14	3.09	3.06
a/L_{Te}	1.305	1.381	2.775
a/L_{ne}	0.23	0.12	0.695
q	1.372	1.303	1.1122
s	0.113	0.0667	0.244
M	0.039	0.043	0.0319
γ_E			
β_e	0.00193	0.00239	0.003795
β'	-0.00583	-0.01096	-0.0475
ν_{ee}	0.0876	0.0646	0.0325
Z_{eff}	1.1	1.155	1.457
κ	1.337	1.315	1.2685
δ	0.0473	0.0421	0.03764
T_e [keV]	1.57	1.84	2.65
n_{e19}	3.1	3.29	3.58
B_{ref} [T]	3.18	3.19	3.17
T_f [keV]	0	110	447
a/L_{Tf}	0	14.8	15.7
a/L_{nf}	0	0.12	0.7

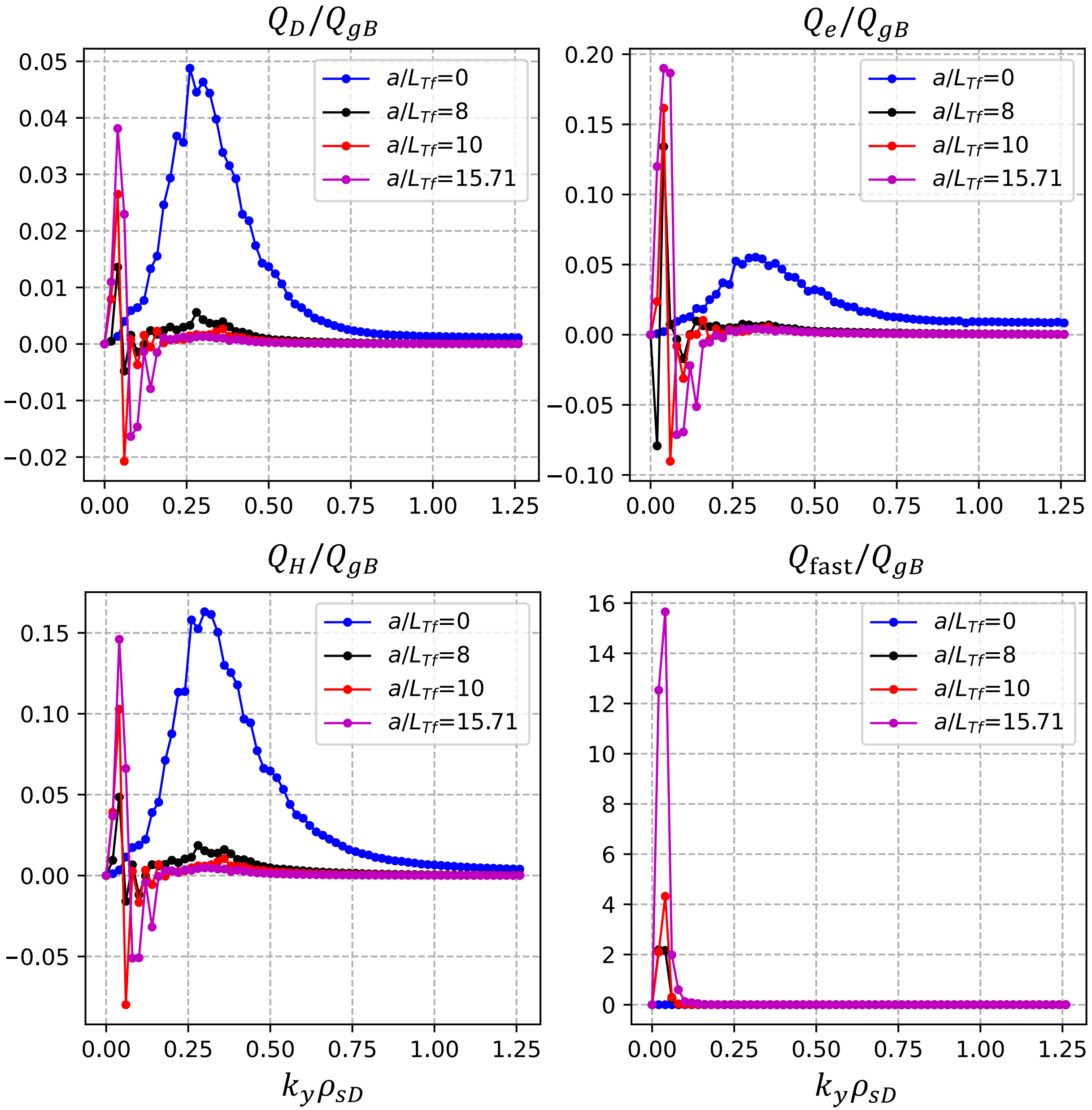
Nonlinear CGYRO for high P_{ICRH}: turbulence stabilization for a/L_{Tfast} > linear TAE marginal stability

- Electromagnetic $(\phi, A_{||})$, fast-Maxwellian He^3 $(T_f \approx 168\, T_i)$
- TAE+ITG scales:



- Heat flux Q dominated by ions for no FI, subdominant Q_e.
- Decrease in $Q_{ion/e-}$ with $a/L_{T_{\mathrm{fast}}}$.
- Fast-ion fluxes stiff, dominate for $a/L_{T_{\mathrm{fast}}} > 8$ (TAE marginal stability).

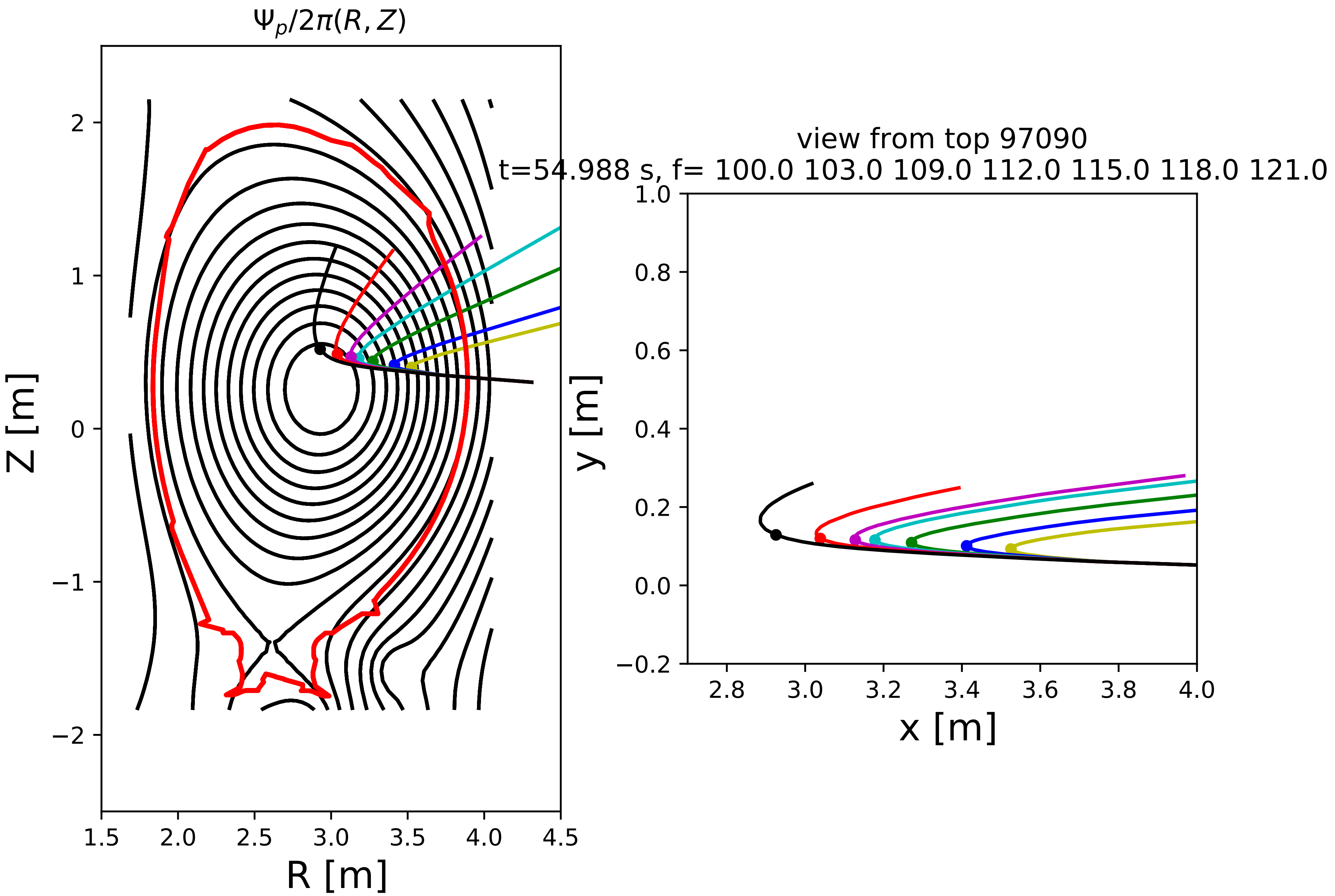
Turbulent ITG spectrum is stabilized, driven at $k_y \rho_{sD} < 0.1$



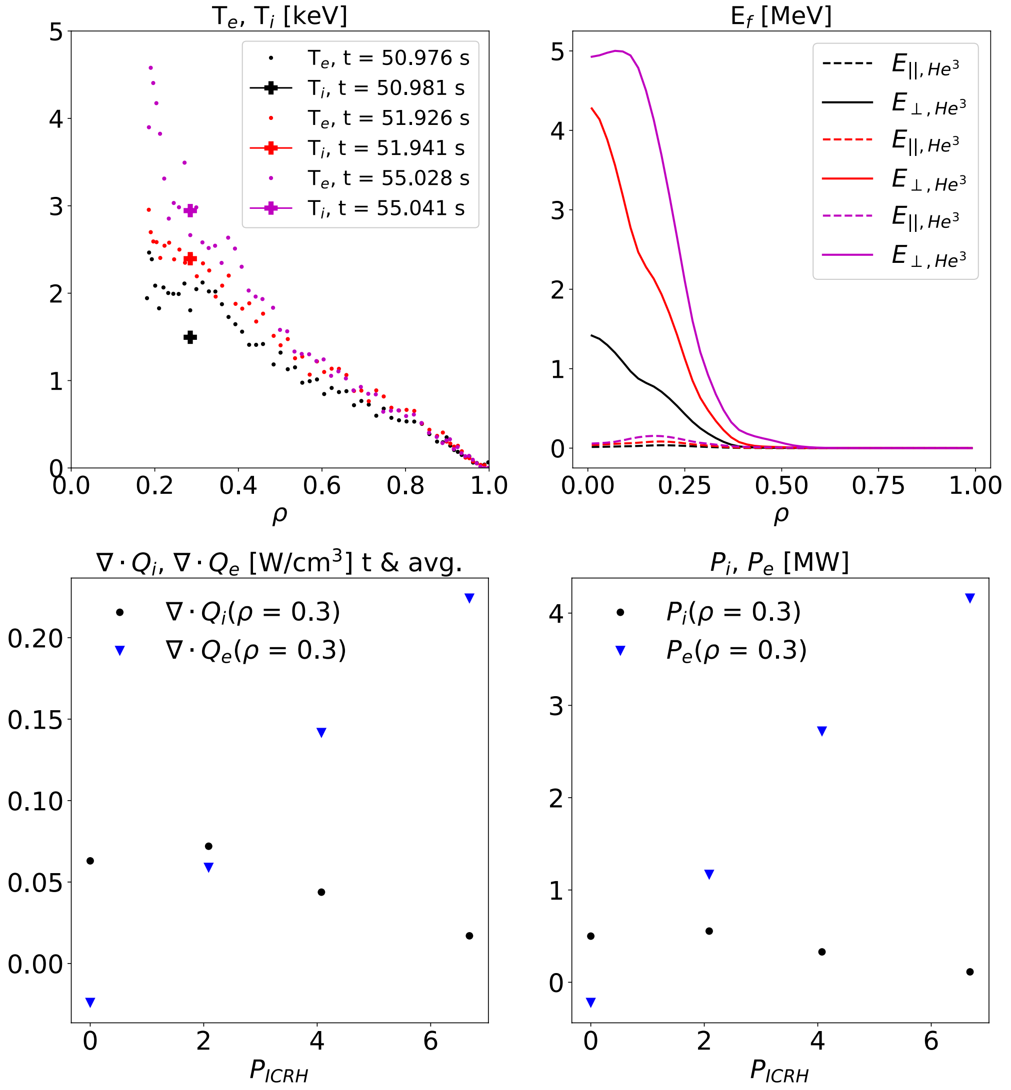
- Numerical resolution:
  $k_y \rho_{sD} = [0.02, 1.26]$,
  $L_y = 314 \rho_{sD}$

  $k_x \rho_{sD} = [0.015, 2.93]$,
  $L_x = 410 \rho_{sD}$
- **No FI**: ITG at $k_y \rho_{sD} \approx 0.3$
- **With FI**:
  - Thermal fluxes stabilized at $k_y \rho_{sD} \approx 0.3$
  - Dominant Q_{fast} at $k_y \rho_{sD} < 0.1$

Torbeam simulations of DBS beam propagation



Experimental profiles and fluxes



- T_e increases, T_i increses more!
- $E_\perp$ dominant energy into He^3

- P_e(rho=0.3) increases with P_{ICRH}
- P_i(rho=0.3) decreases when TAEs unstable (med, high P_{ICRH})

Frequency spectrum for different ky