Zero-frequency zonal flows and predator-prey behavior driven by Alfvén modes in the JET tokamak

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1. Oxford 2. CEA 3. KIPT 4. UKAEA 5. A*STAR 6. Tokamak Energy 7. CFS 8. LPP-ERM/KMS 9. PPPL

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Engineering and Physical Sciences Research Council

Why care about **energetic particles** (EPs) and **turbulence** in magnetic confinement fusion?

- **Energetic particles** (α's) are ubiquitous to fusion energy: D + T → α + n

$$E_\alpha = 3.5\ \text{MeV} \gg T_{\text{plasma}} \sim 20\ \text{keV}$$

- Today's experiments use external EP sources for heating (NBI, ICRH, E~100 keV)[*]
- When the plasma is self-heated by α's, we call it a **burning plasma**

Today's experiments

Burning: No further need of external heat!

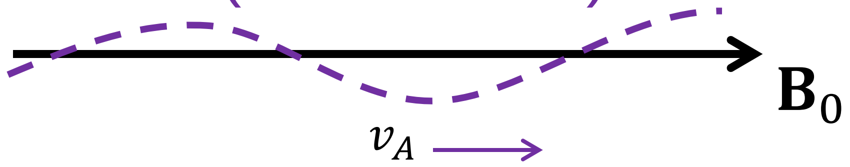
- To produce energy from fusion, need to satisfy Lawson criterion (1955): $\mathrm{n_p}\tau_E \gtrsim \text{const.}$
- Confinement time τ_E is determined by **turbulence**!

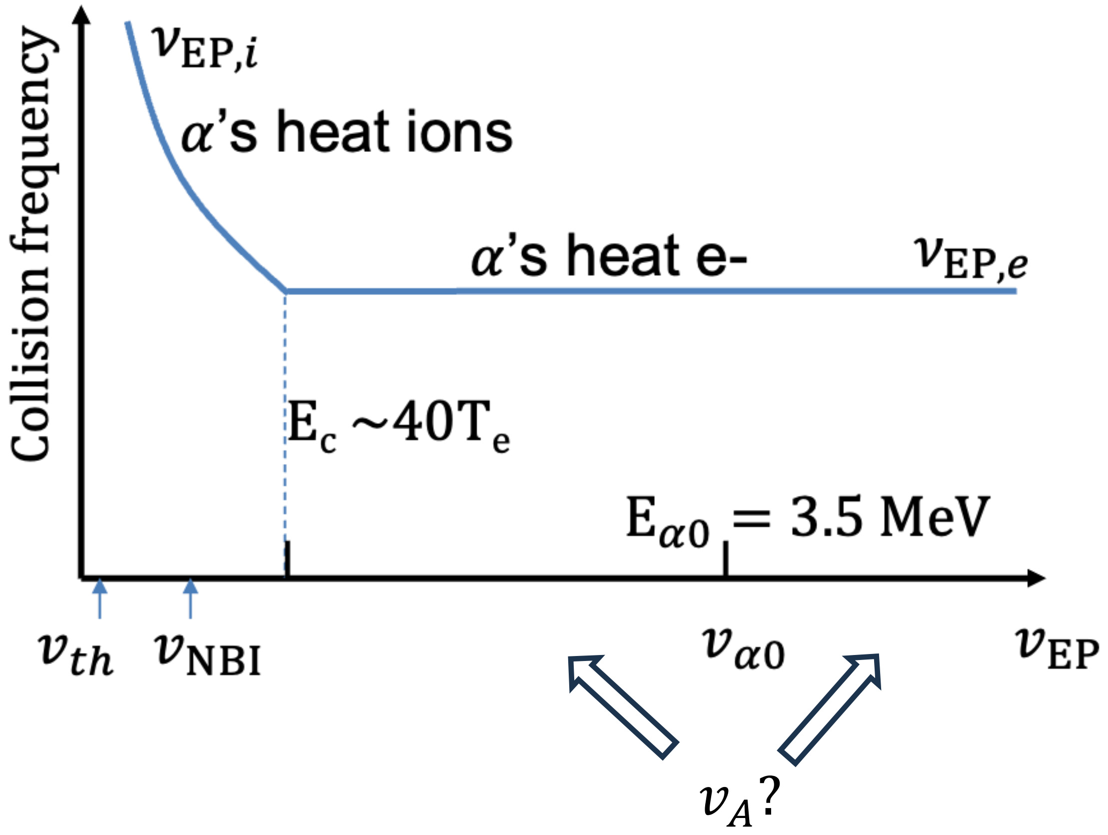
[*] Neutral beam injection / Ion cyclotron resonance heating

1. Critical energy:
    - α’s will heat e- in burning plasma
    - 100 keV EPs heat ions

2. Alfvén speed v_A vs. v_{EP}: $$v_A = \frac{B}{\sqrt{\mu_0 n m_i}}$$

$\delta\mathbf{B}$ (Alfvén wave)





- If $v_{\mathrm{EP}} > v_A$ → EPs can resonate with Alfvén waves as they slow down
- MeV EPs more easily destabilize Alfvén waves (Alfvén eigenmodes AEs)
  ➔ Greatly decreases the confinement of the energetic particles

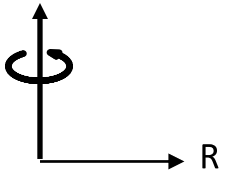
How are MeV energetic particles different from 100 keV (2/2)?

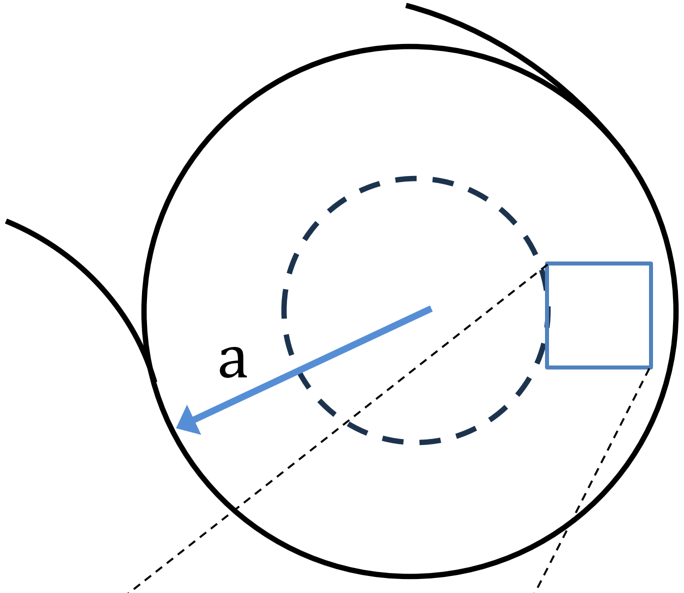
3. Have larger orbits → more difficult to confine

Vertical cross-section of a tokamak

orbit excursion δr in JET $(\mathrm{B} = 3\mathrm{T},\ \mathrm{a} \approx 90\ \mathrm{cm})$:

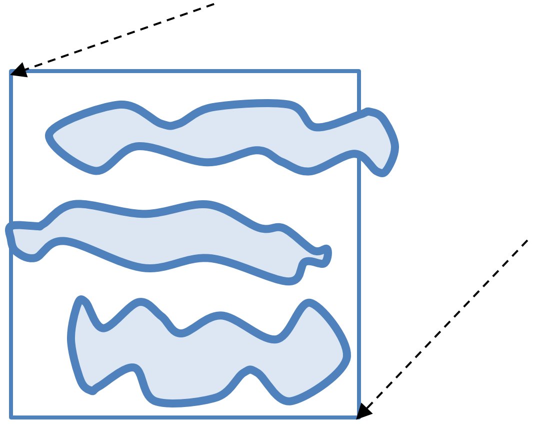
$$\delta r(3.5\ \mathrm{MeV}) \sim\ 10 - 20\ \mathrm{cm}$$
$$\delta r(100\ \mathrm{keV}) \sim 2 - 4\ \mathrm{cm}$$



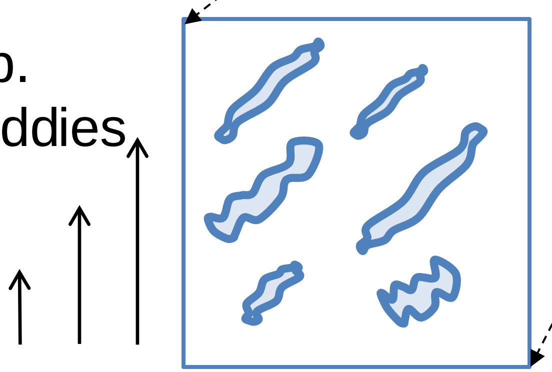


4. Rotation (NBI~100 keV): shears away turbulence [*] but α-particle source is isotropic → no rotation

$\boldsymbol{v = 0\ (\alpha' s)}$
Unsheared turb.



$\boldsymbol{v \neq 0\ (\mathrm{NBI})}$
Sheared turb.
→ Smaller eddies



[*] Terry RMP 2000

Bad news for MeV energetic particles in burning plasmas?

1. Critical energy → e- heating, but need ions hot for fusion! ☹
2. $v_{\alpha 0} > v_A$ → easier to destabilize Alfvén modes : worse confinement ☹
3. Larger orbits → worse confinement of EPs ☹
4. Isotropic α-particle source → no rotation expected in burning plasmas (ITER, SPARC, STEP, DEMO) ☹

EPs can have a positive effect on confinement by affecting the dominant linear micro-instability (ITG) and nonlinearly, the turbulence

1. Dilution:
   - Only background ions contribute to the ion-temperature-gradient driven mode (ITG)
   - Quasineutrality: less resonant ions → stabilize ITG [1]
   - Usually not a dominant effect ($n_{EP} \ll n_i$)

$$Z_i n_i + Z_{EP} n_{EP} = n_e$$

2. Shafranov's shift (β') stabilization:
   - Energetic particles contribute to β'
     → can affect MHD equilibrium & micro-instabilities [2]

$$\beta_s' = \sum \left(\frac{a}{L_{Ts}} + \frac{a}{L_{ns}} \right) \beta_s$$

3. More recently, active linear kinetic effect of energetic particles can stabilize ITG [3]

1,2,3 are ***linear***, and extrapolate to be small in a burning plasma

4. **Nonlinear effects**: "Nonlinear electromagnetic stabilization" [4], presence of EP-driven modes [5], zonal flows …

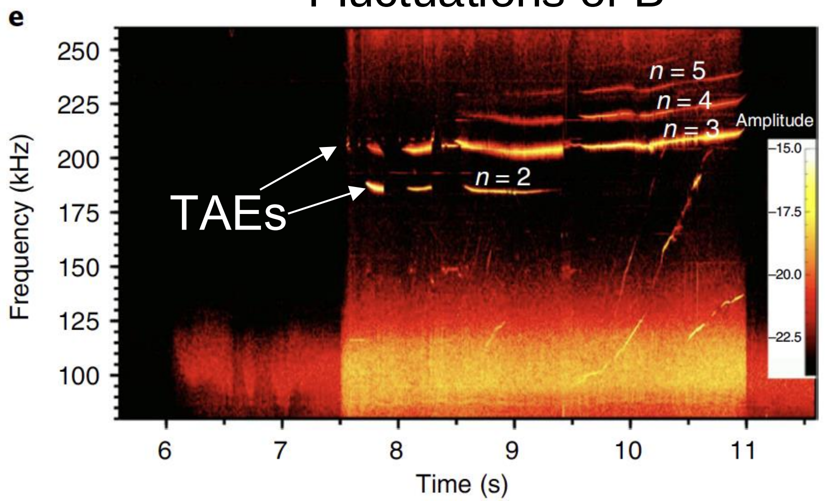
[1] Tardini NF 2007 [2] Bourdelle PoP 2003 [3] Di Siena NF 2018/PoP 2019, Wilkie NF 2018 [4] Citrin PRL 2013 [5] Di Siena NF 2019, Mazzi Nat Phys 2022, Biancalani JPP 2023

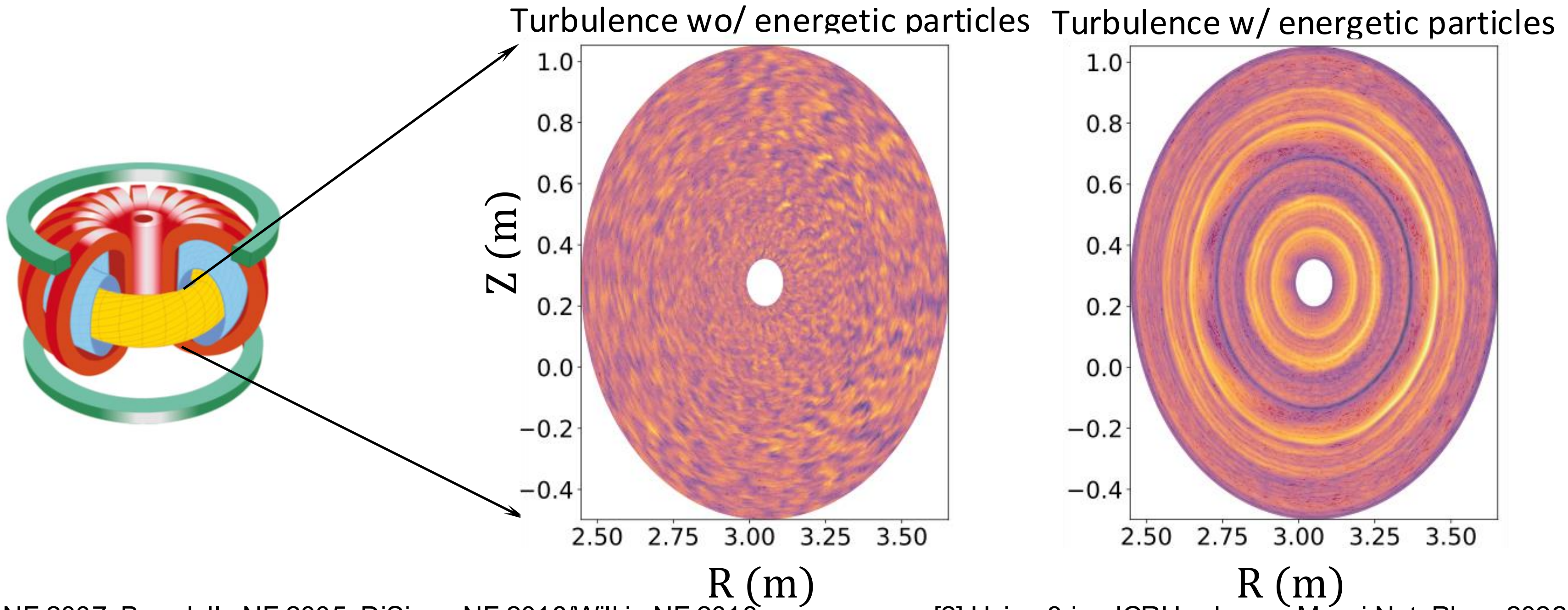
Experiments in JET with MeV ions have exhibited enhanced thermal confinement that could not be explained by linear theories [1]

- Confined MeV ions (ICRH) destabilized Toroidal Alfvén eigenmodes (TAEs). Observed improved confinement [2]

- Nonlinear gyrokinetic (turbulence) simulations showed that TAEs generate zonal flows that stabilize the turbulence
  - ➔ Decrease in the thermal ion heat transport

Fluctuations of B





[1] Tardini NF 2007, Bourdelle NF 2005, DiSiena NF 2018/Wilkie NF 2018

[2] Using 3-ion ICRH scheme: Mazzi Nat. Phys. 2022, Ruiz Ruiz PRL 2025

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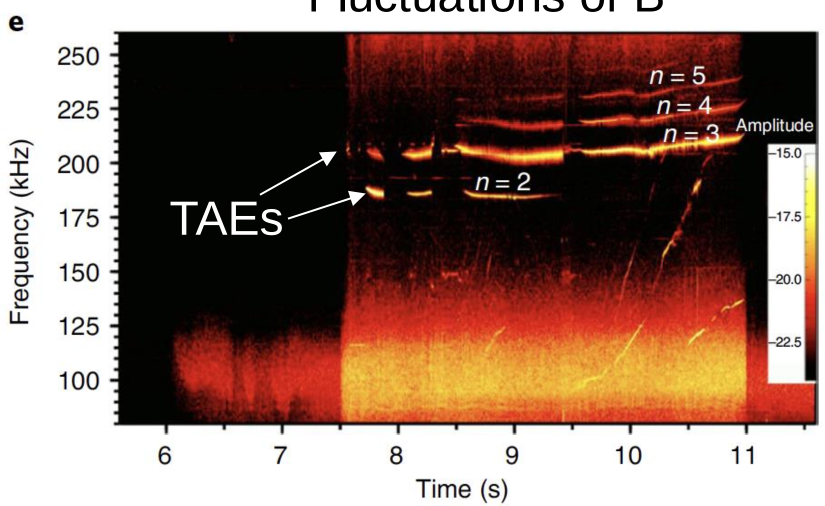
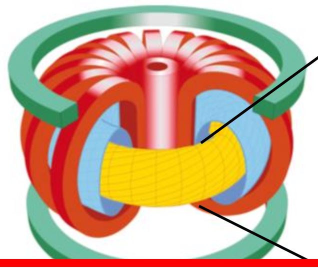
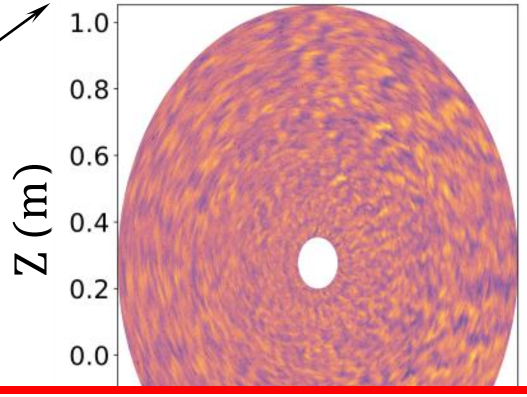




Turbulence wo/ energetic particles



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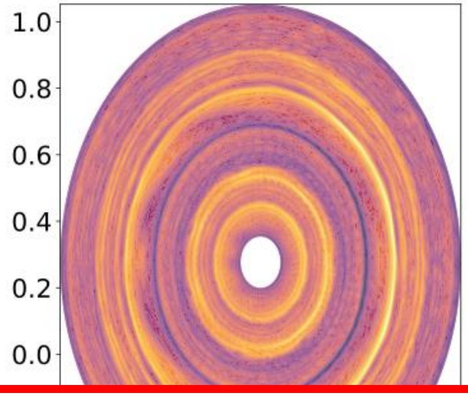

These experiments show that MeV energetic particles can have an *unexpected*, beneficial effect on the thermal plasma 😀

R (m) R (m)

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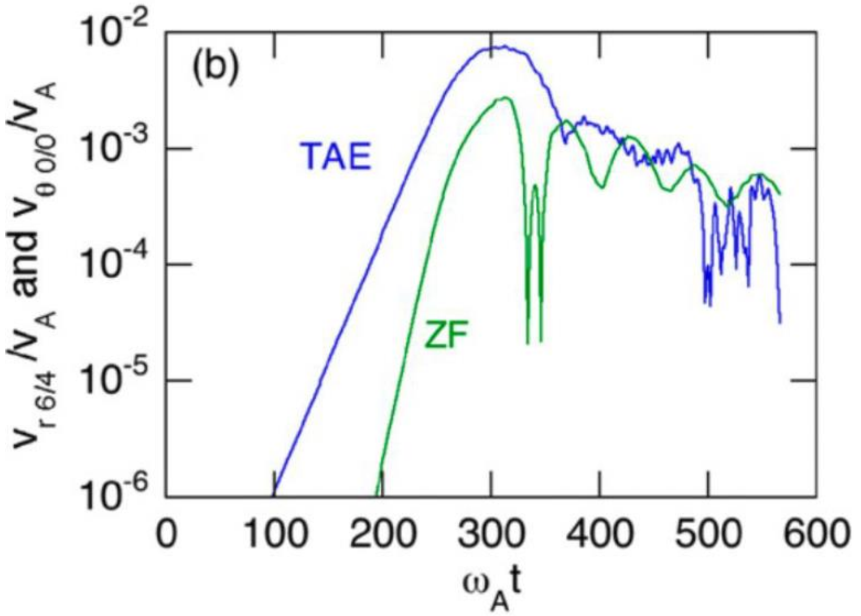
The JET experiments probe close-to-burning plasmas, and exhibit nonlinear interplay between energetic particles and the thermal plasma

- Achieved by the presence of confined MeV ions
  - Provided e- heating
  - Destabilized Toroidal Alfvén eigenmodes (TAEs)
    → improved ion confinement through zonal flow



- Generation of zonal flow by TAEs is a nonlinear process predicted theoretically and numerically [1]

TAE + TAE → ZF (freq~0)
TAE + TAE → sidebands (freq ~ 2x, 3x, ..)

- **Stationary, zero-frequency zonal perturbation** could interact with and stabilize turbulence → consistent with Mazzi Nat Phys 2022 / Ruiz Ruiz PRL 2025

- **Zero-frequency fluctuation driven by AEs lacks experimental confirmation**

We show the first experimental confirmation of a zero-frequency fluctuation that is pumped by an Alfvén eigenmode in a magnetically-confined plasma[3]

[1] Todo NF 2010 (MHD) / Chen PRL 2012, Qiu PoP 2016/NF 2017 [2] Biancalani EPS 2019 [3] Ruiz Ruiz PRL 2025

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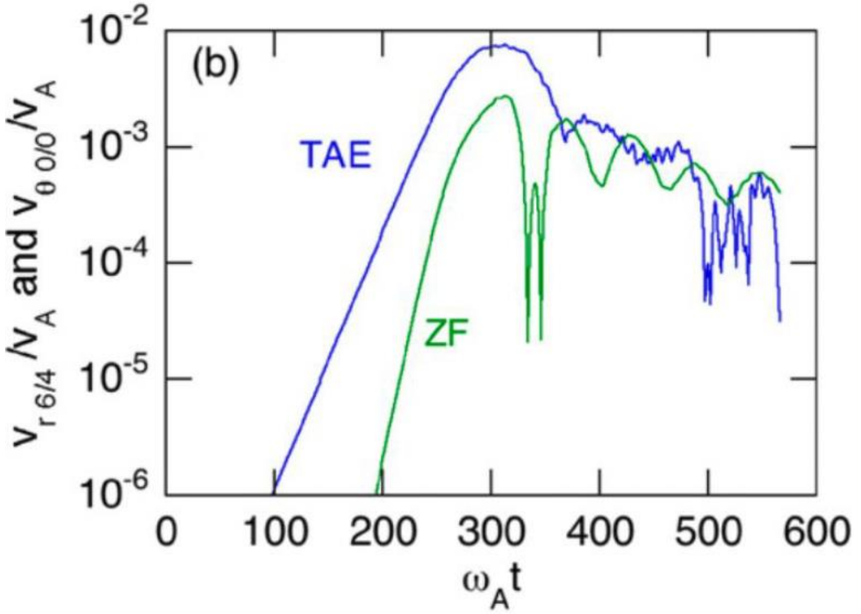

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The effect of α's can be deleterious (☹️) or beneficial (😀) : ***will the overall effect of alpha particles on the thermal plasma be beneficial for fusion performance?***

eigenmode in a magnetically-confined plasma[3]

[1] Todo NF 2010 (MHD) / Chen PRL 2012, Qiu PoP 2016/NF 2017 [2] Biancalani EPS 2019 [3] Ruiz Ruiz PRL 2025

Can the effect of MeV ions be beneficial to global confinement?

- **Experiments probing close-to-burning plasmas in JET**
  - JET plasma with MeV-range ICRH-heated ions
  - Doppler backscattering (DBS) measurements
    - Power spectrum and bicoherence analysis (Ruiz Ruiz PRL 2025)
    - Critical importance of diagnostic interpretation

- **Numerical turbulence modelling (gyrokinetic)**
  - Linear instability
  - Nonlinear turbulence simulations (AE+ITG)
    - Effect on thermal transport
    - Bicoherence analysis

JET 97090 L-mode heated with ICRH produces MeV range 3He that slows down on electrons

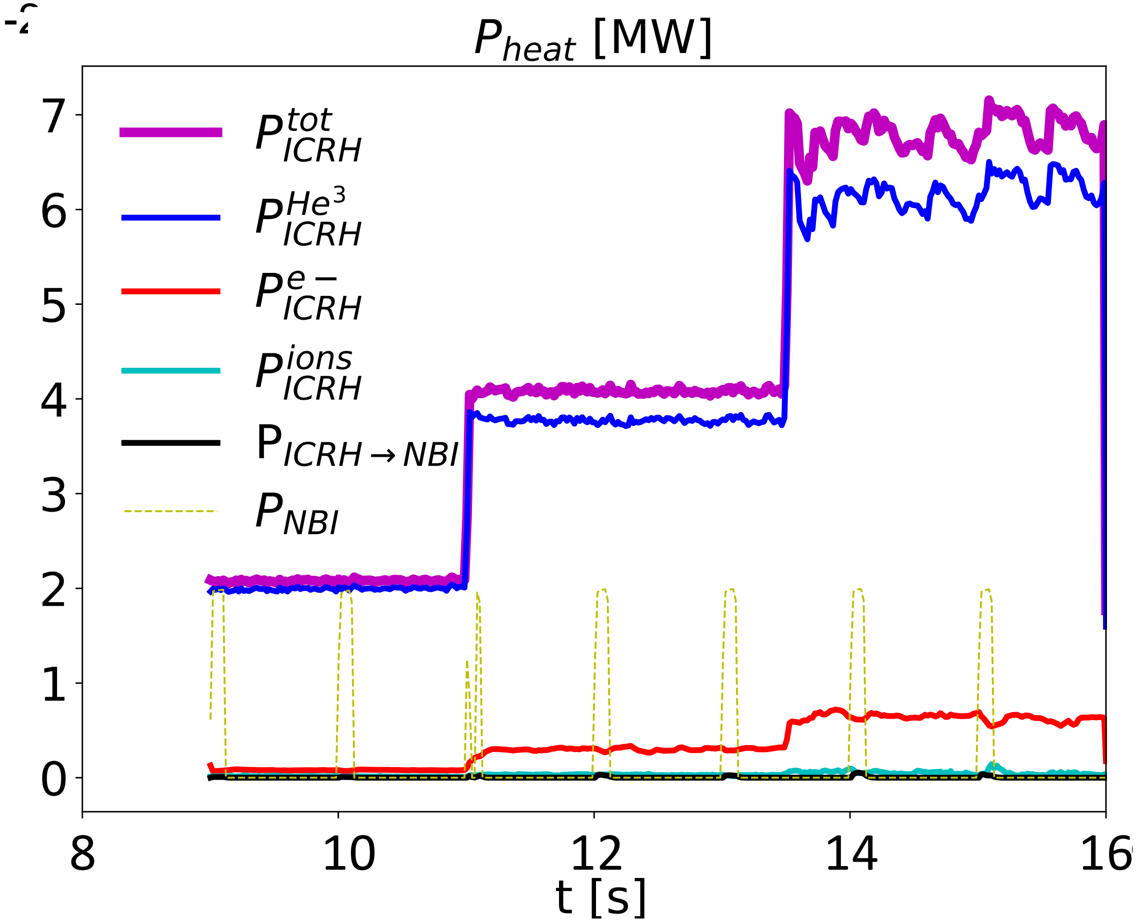
- L mode, I_p=2.4 MA, B_0=3.2 T, $\bar{n}_{e,l} = 7 \times 10^{19}$m-

- ICRH heating (no NBI) steps:
  - 2 MW (low), 4 MW (medium) and 7 MW (high)

- H+D (background), ~0.2% trace 3He → 4-5 MeV [*]

- Fast 3He slows down on e- (>90% heating)

→ Almost pure electron heating plasma via slowing down of 3He – mimic conditions of 3.5 MeV alpha particles in a burning plasma

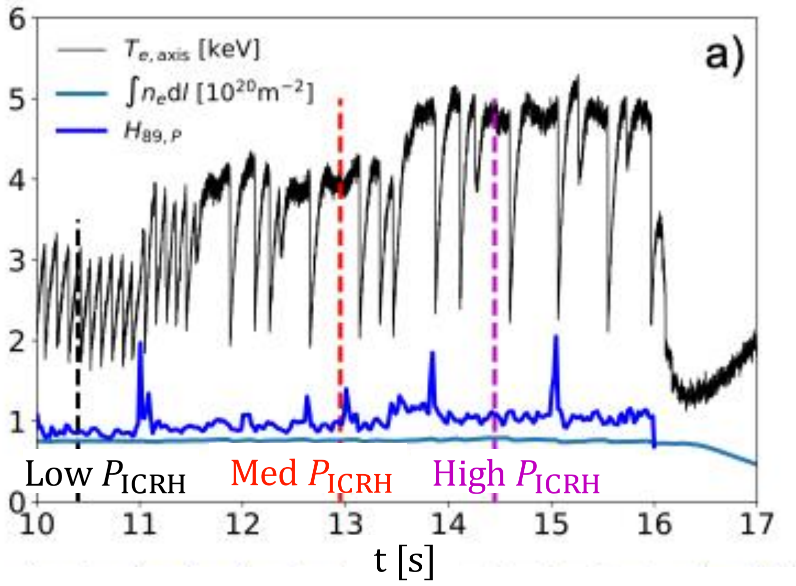


[*] '3-ion ICRH heating', Kazakov NF 2015

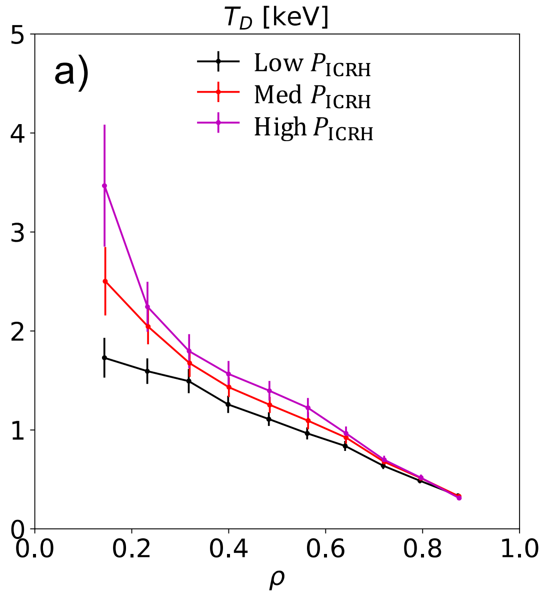
Confinement improves and ion temperature increases with ICRH power

- Core electron temperature T_e increases as expected

- L-mode confinement factor $H_{89,P}$ increases (consistent with [*]) → confinement improvement



- Ion temperature ALSO increases in deep core -- puzzle
  - e- and ions more collisionally decoupled as T_e increases
  - No T_i clamping [**]
  - **Ion turbulence is stabilized?**



[*] Nocente NF 2020, Kazakov PoP 2021, Mazzi Nat Phys 2022 [**] Beurskens NF 2021

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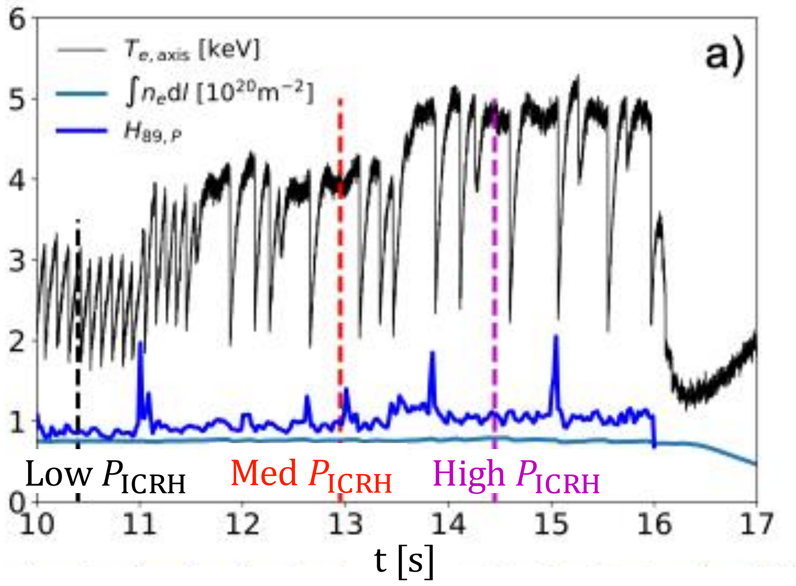

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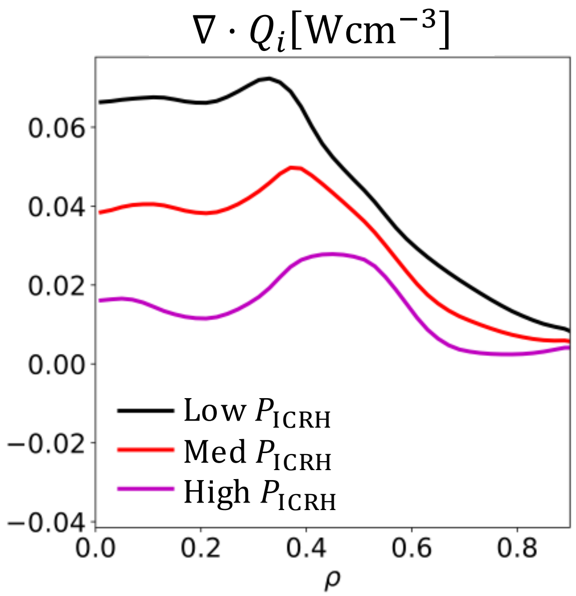
    ➔ Decrease in Q_i ($Q_e > Q_i$, TRANSP)



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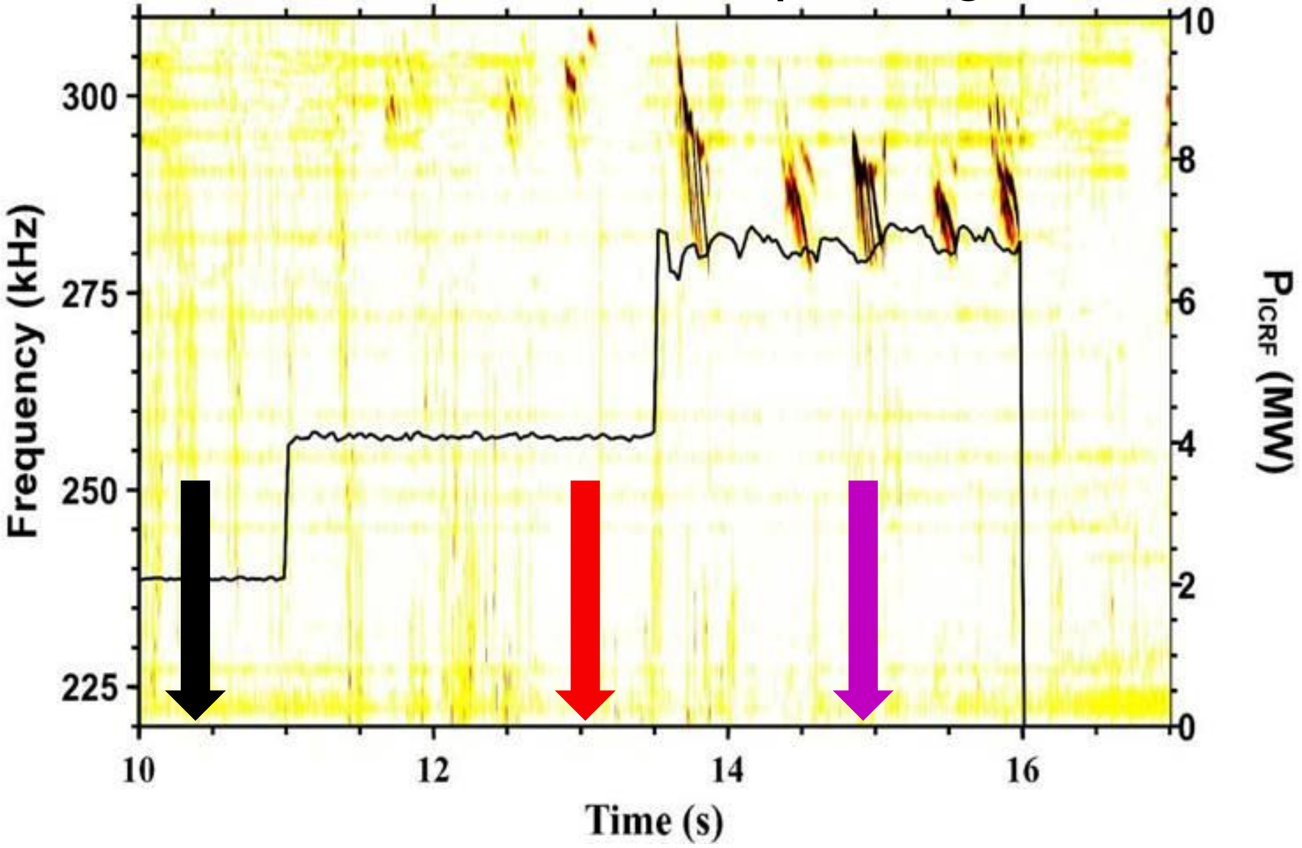
Increase in T_i and thermal confinement is correlated with increased Alfvénic activity observed with increasing ICRH power

Interferometer spectrogram



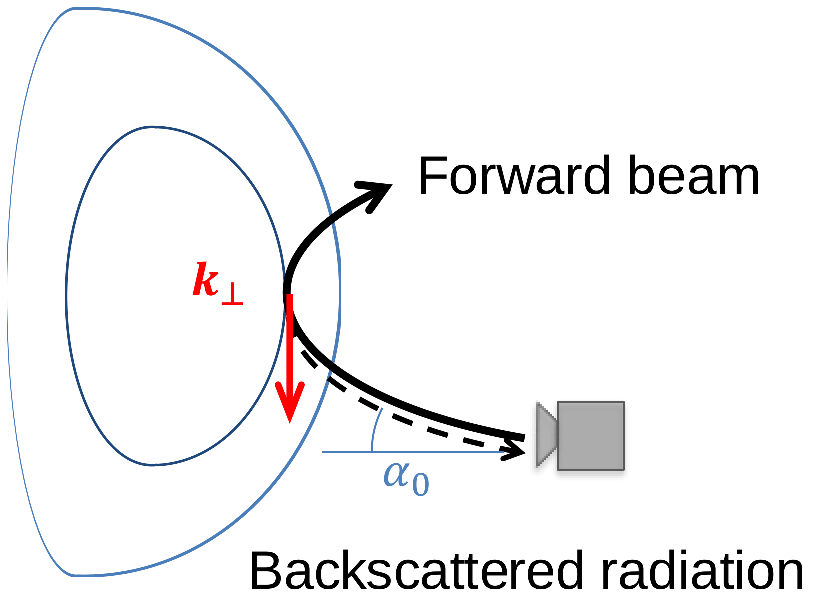
- **Low ICRH power** – similar to Ohmic
- **Medium ICRH power** – close to marginal stability of MHD modes
- **High ICRH power** – MHD activity (TAE)
  - $f \approx f_{\mathrm{TAE}} \approx 270 - 300\ \mathrm{kHz}$
  - $n \approx 4 - 6$

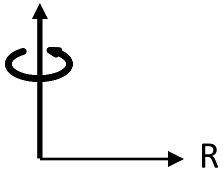
$$f_{\mathrm{TAE}} = v_A / 4\pi q R$$

- Electron heating (MeV-range fast ions)
- Improved ion confinement ($T_i, H_{89,P}$ increase)
- Alfvénic activity

Motivate local measurements of turbulence fluctuations

Perform turbulence measurements using Doppler Backscattering (DBS) diagnostic





- Externally launched microwave beam propagates into plasma until it encounters a **cutoff.**
- Forward beam deviated upwards.
- **Detect** backscattered radiation from turbulence wavenumber $\boldsymbol{k}_\perp$
- Scattered power $P_s \propto \langle |\delta n(\boldsymbol{k}_\perp)|^2 \rangle$
- DBS measures one $\boldsymbol{k}_\perp$ at one location (cutoff) [*].

In what follows: Show local turbulence measurements at $\rho \approx 0.3$ from $k_\perp \rho_s \approx 0.5 - 4$

[*] Hall-Chen PPCF 2022

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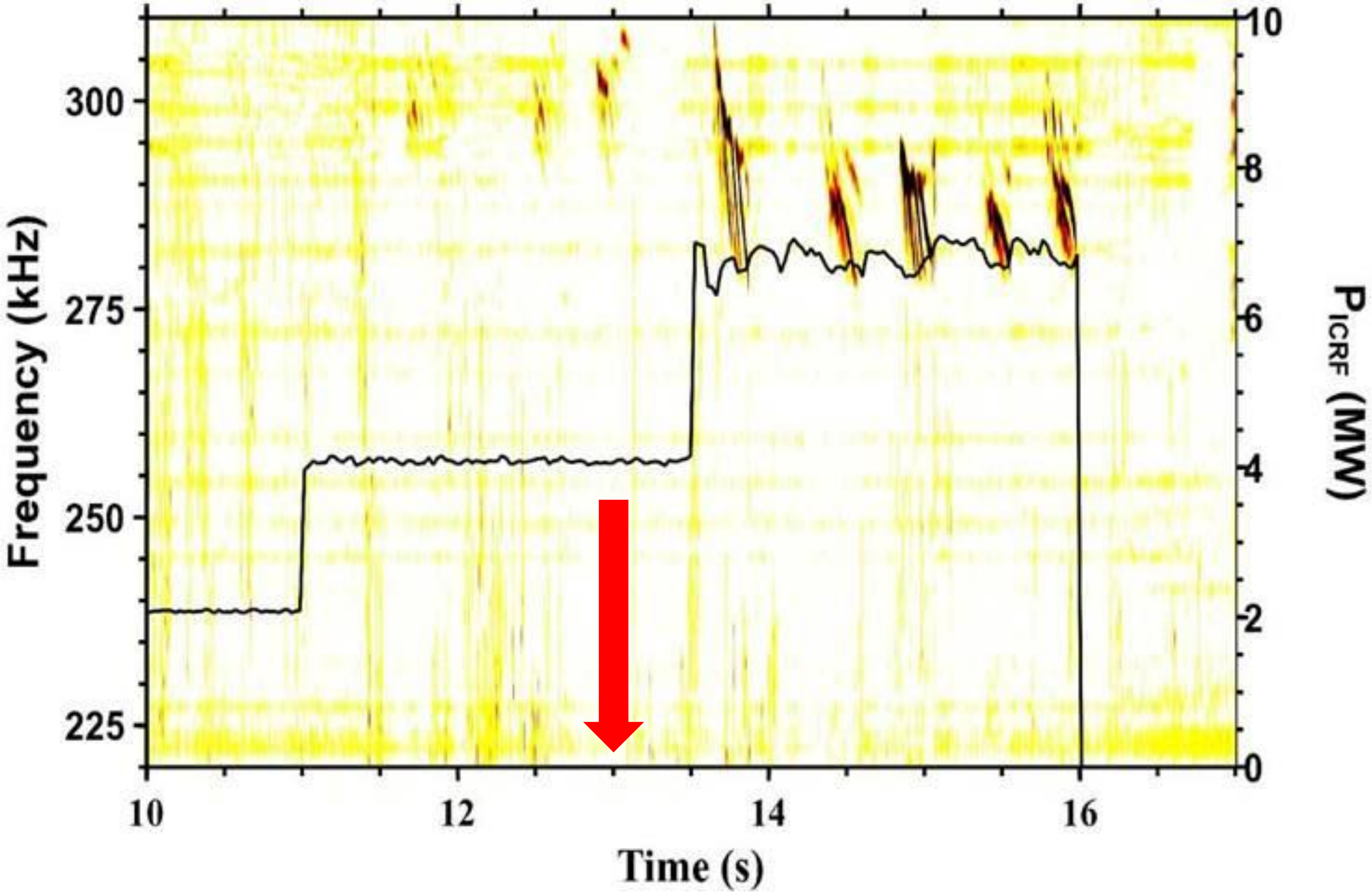
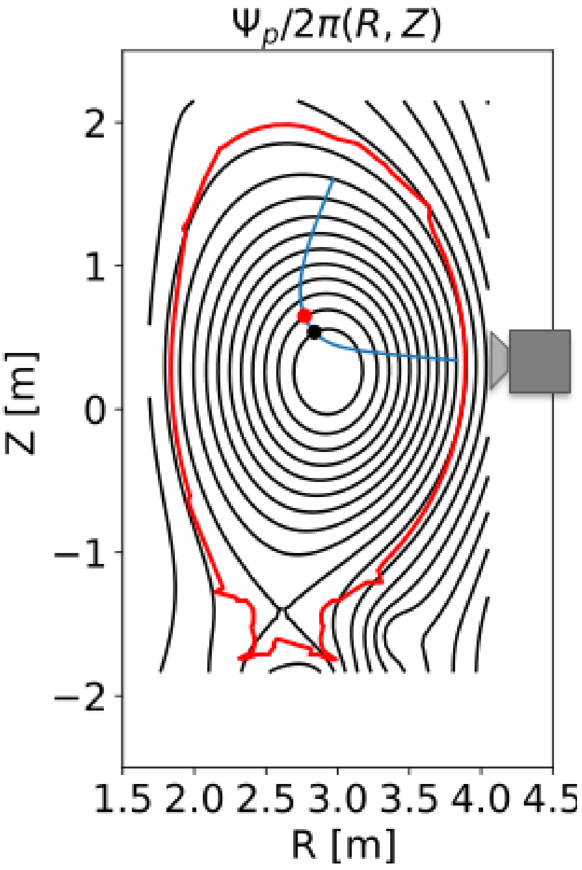
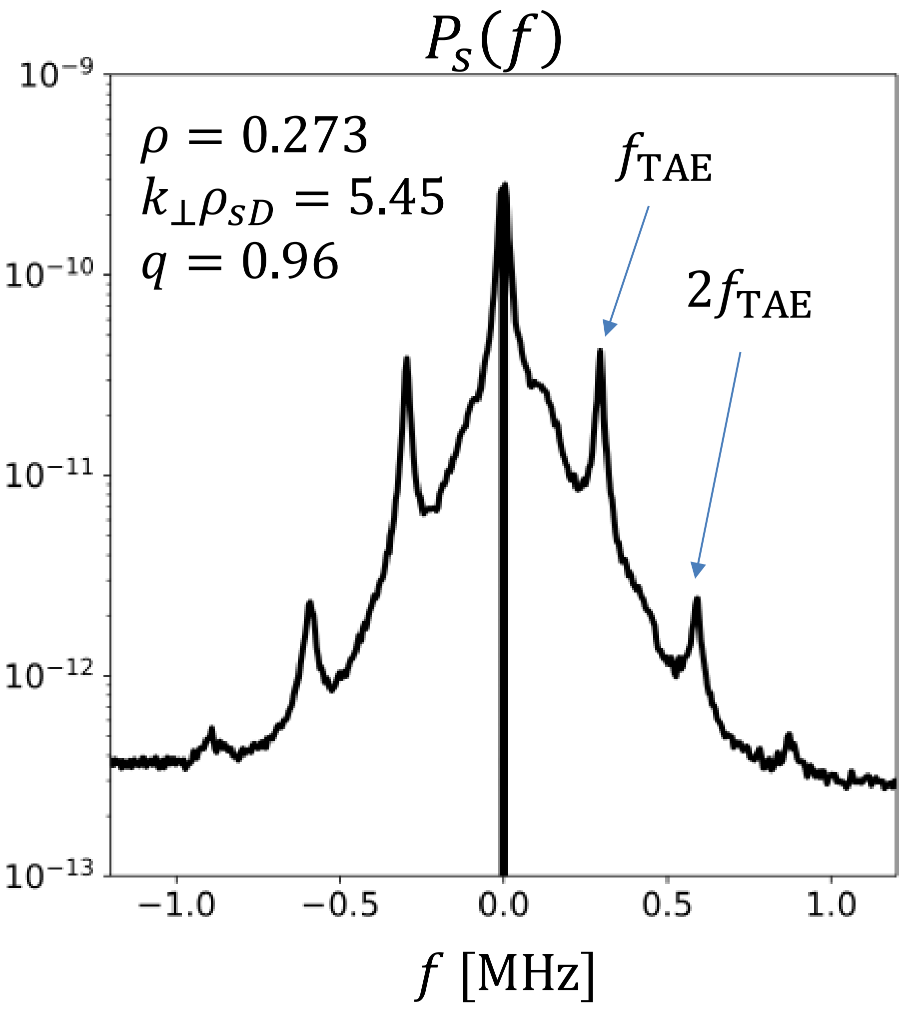
DBS measurements at medium ICRH power



At medium P_{ICRH}, DBS beam reaches deep core, spectrogram exhibits periodic bursts and spectral peaks at gap frequency f_{TAE} and harmonics





- $f_{\mathrm{TAE}} \approx v_A/4\pi q R \approx 270-300$ kHz
- Spectral peaks at $f_{\mathrm{TAE}}, 2f_{\mathrm{TAE}}, 3f_{\mathrm{TAE}}$

[*] Saigusa PPCF 1998

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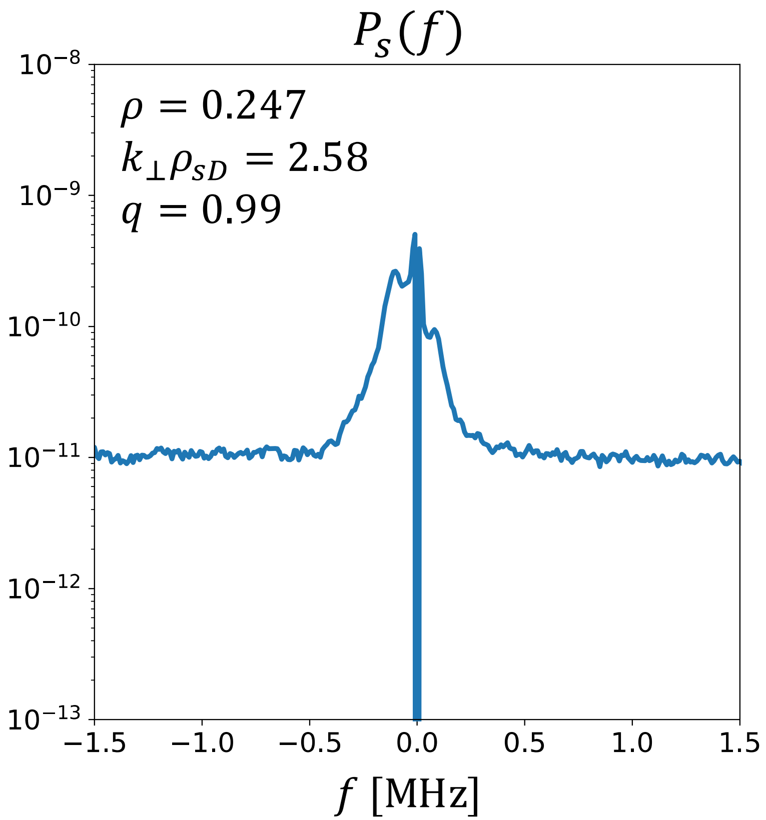
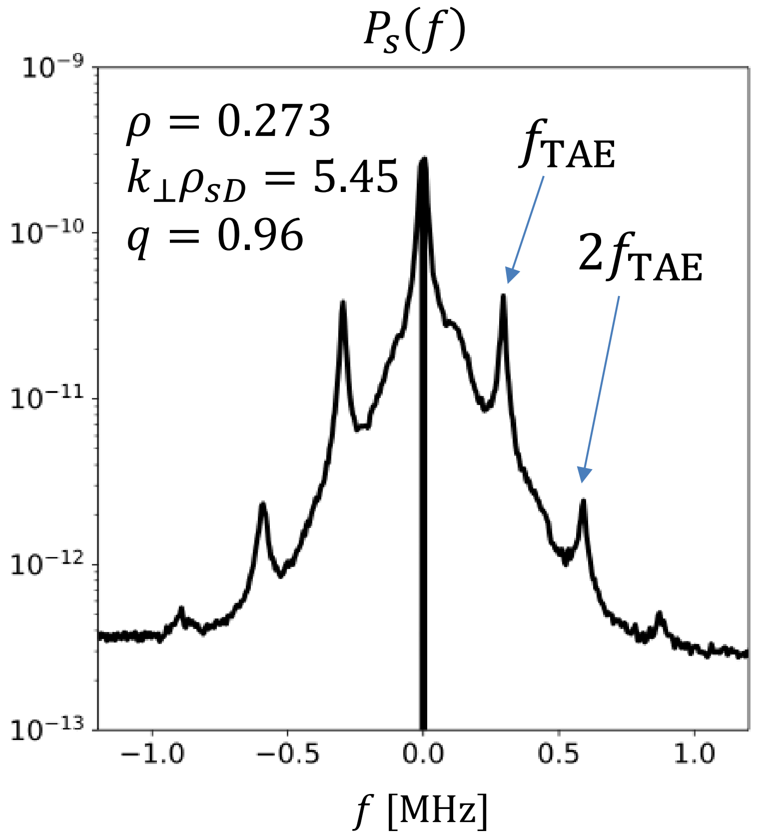


Low P_{ICRH}
Broadband fluctuations (~ITG)



Medium P_{ICRH}
Broadband background + spectral peaks

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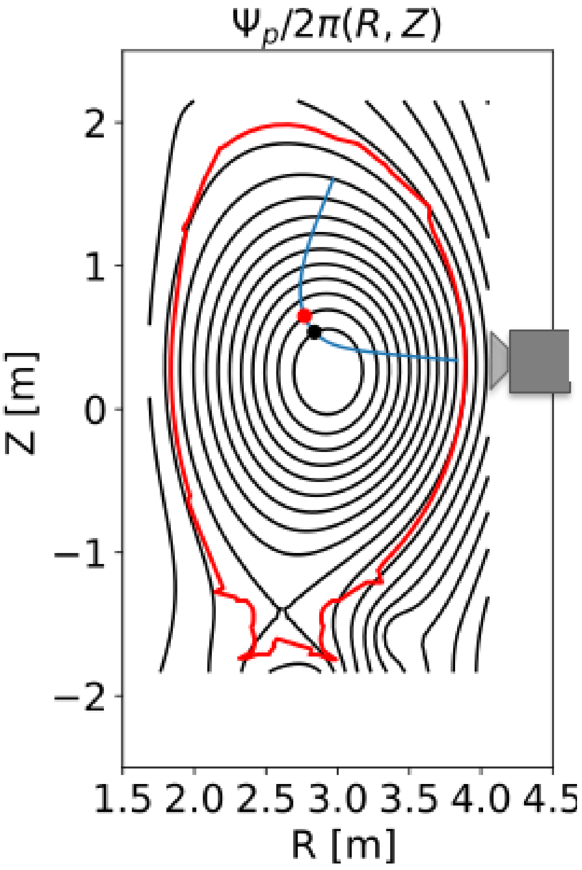

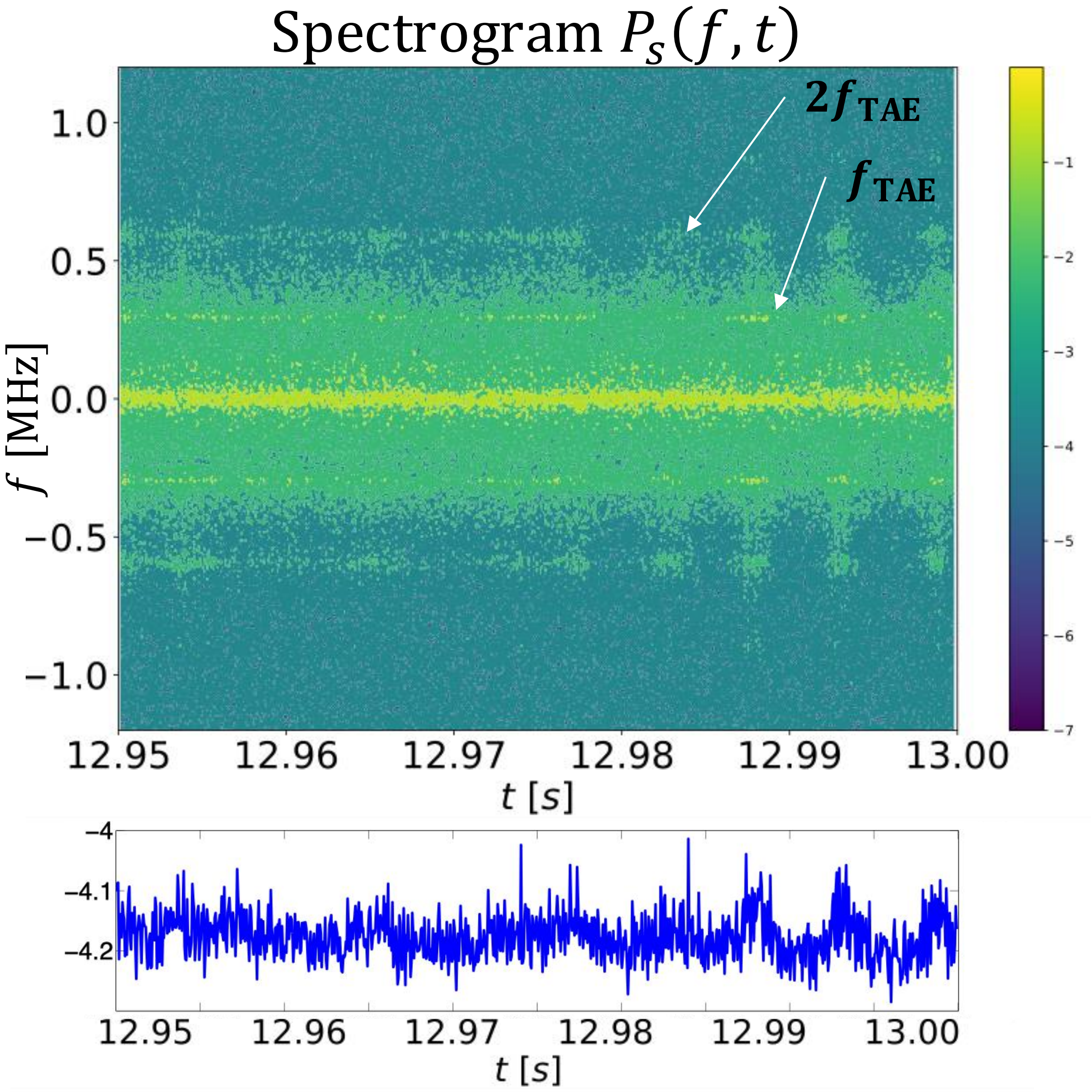

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- Spectral peaks at $f_{\text{TAE}}, 2f_{\text{TAE}}, 3f_{\text{TAE}}$
- Presence of TAEs (near q=1, tornado TAEs [*]) that burst every $\Delta t \approx 6 - 7$ ms

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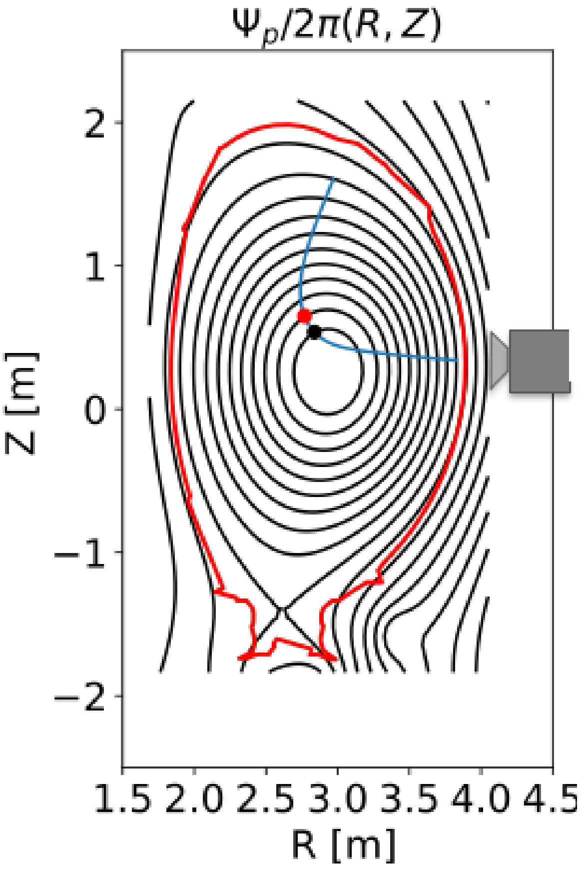

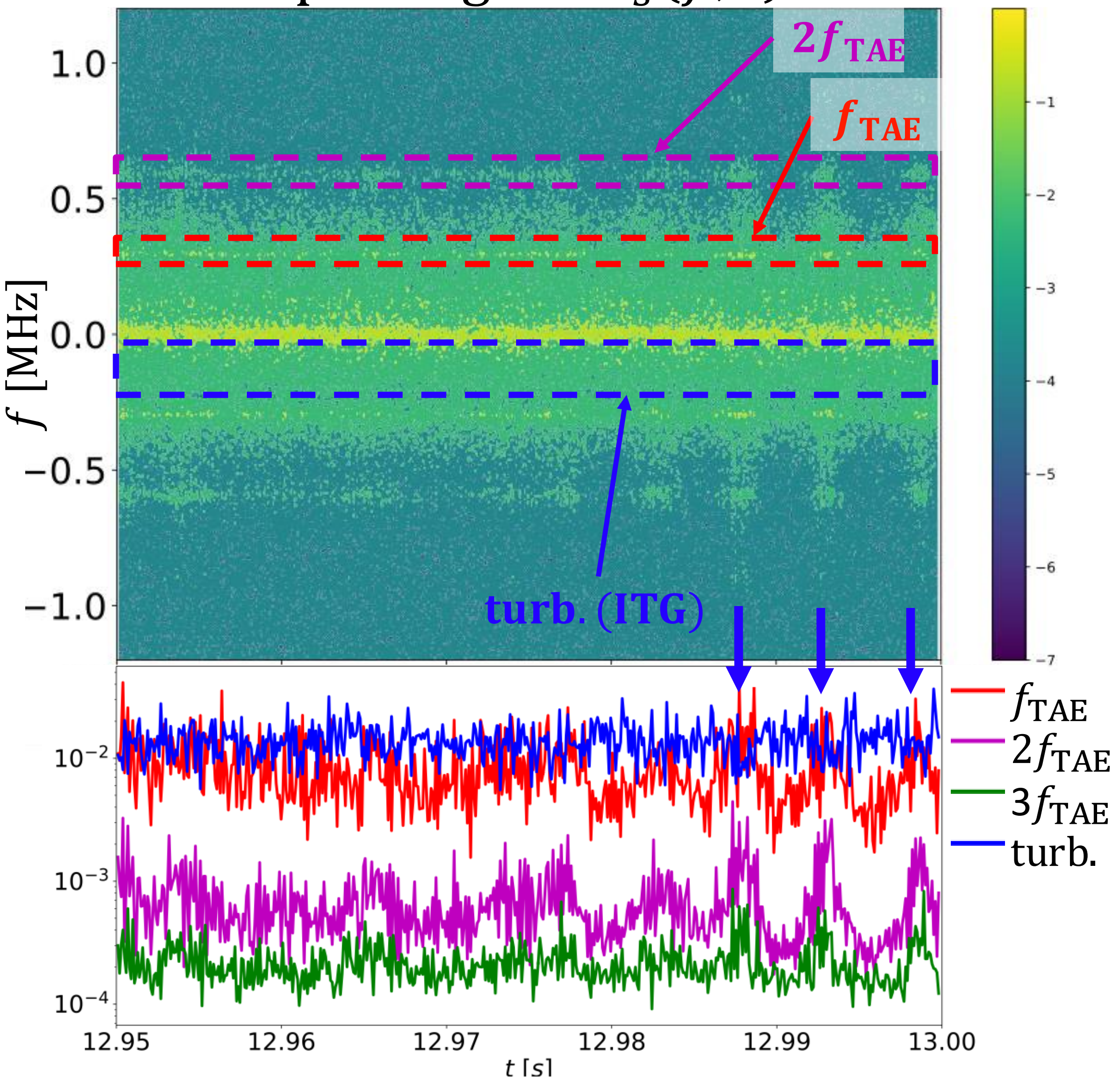

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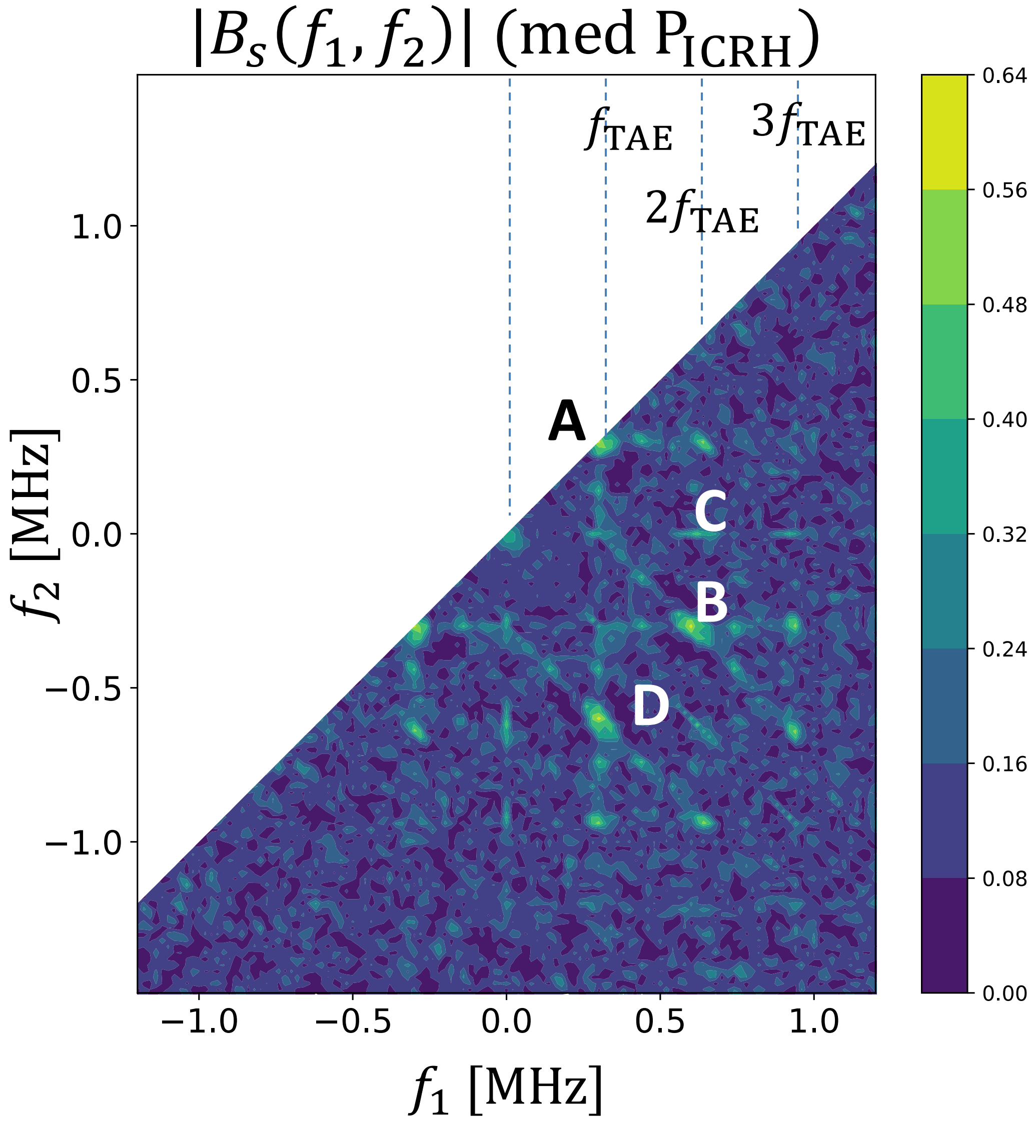
- Presence of TAEs (near q=1, tornado TAEs [*]) that burst every $\Delta t \approx 6 - 7$ ms
- Are higher gap modes sidebands?
- Faint effect on turbulence (ITG)?

[*] Saigusa PPCF 1998

At medium P_{ICRH}, bicoherence exhibits three-wave matching relations at f_{TAE}, $2f_{TAE}$, $3f_{TAE}$ and a zero-frequency fluctuation



$$|B_s(f_1,f_2)| = \frac{\langle \hat{A}_j(f_1)\hat{A}_j(f_2)\hat{A}_j(f_1+f_2)^* \rangle}{\left\langle \left|\hat{A}_j(f_1)\hat{A}_j(f_2)\right|^2 \right\rangle^{\frac{1}{2}} \left\langle \left|\hat{A}_j(f_1+f_2)\right|^2 \right\rangle^{\frac{1}{2}}}$$

→ three-wave phase matching relationship between f_1 and f_2 such that $f_1 \pm f_2 = f_3$ [*]

- Mode-mode interactions (sidebands!):
  $(f_1, f_2) =$ **A**: $(f_{TAE}, f_{TAE}) \rightarrow 2f_{TAE}$
  B: $(2f_{TAE}, -f_{TAE}) \rightarrow f_{TAE}$

- Interaction with a zero-frequency fluctuation:
  $(f_1, f_2) =$ **C**: $(2f_{TAE}, 0) \rightarrow 2f_{TAE}$
  D: $(2f_{TAE}, -2f_{TAE}) \rightarrow 0$

[*] Kim Powers IEEE 1978

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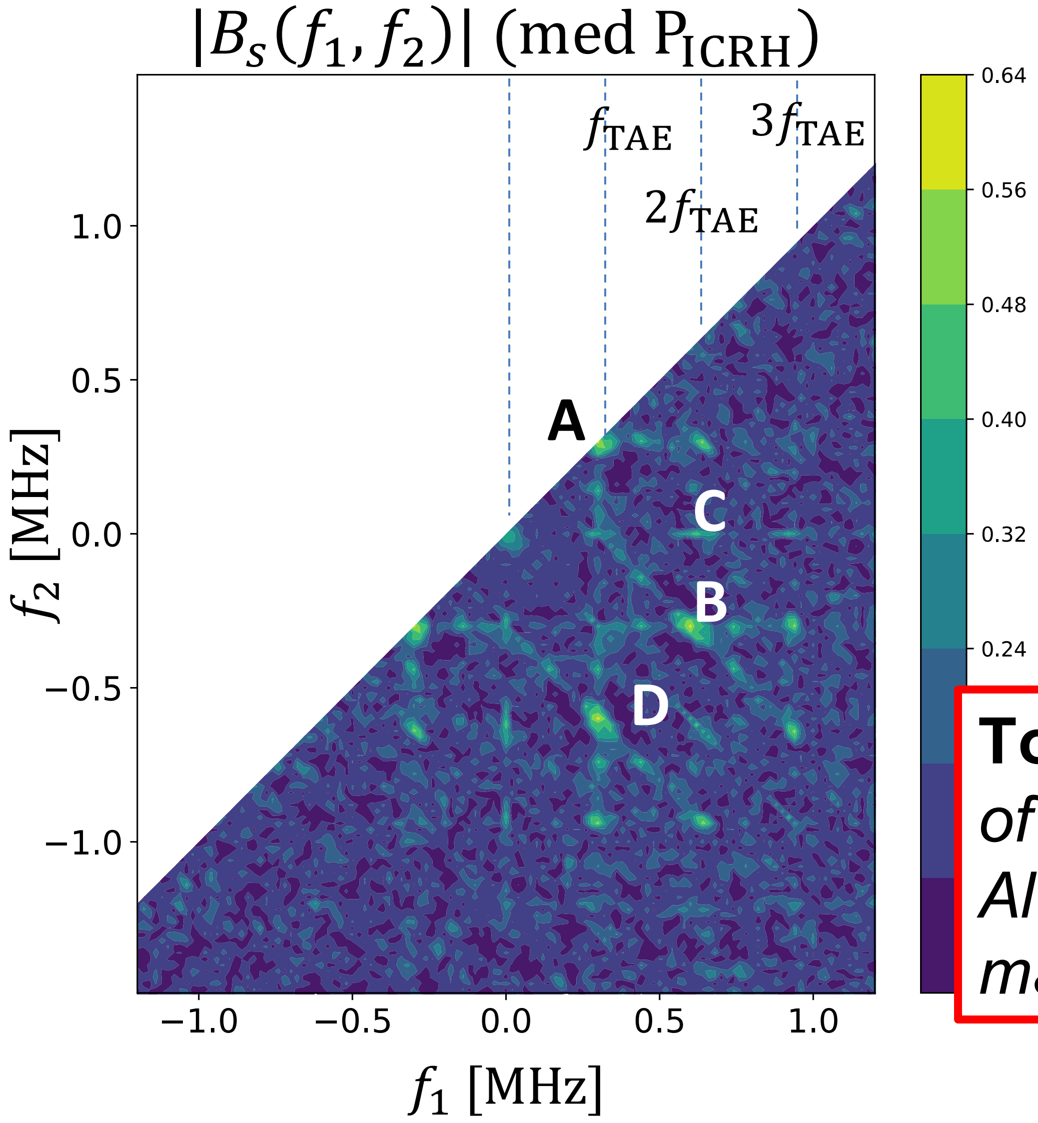

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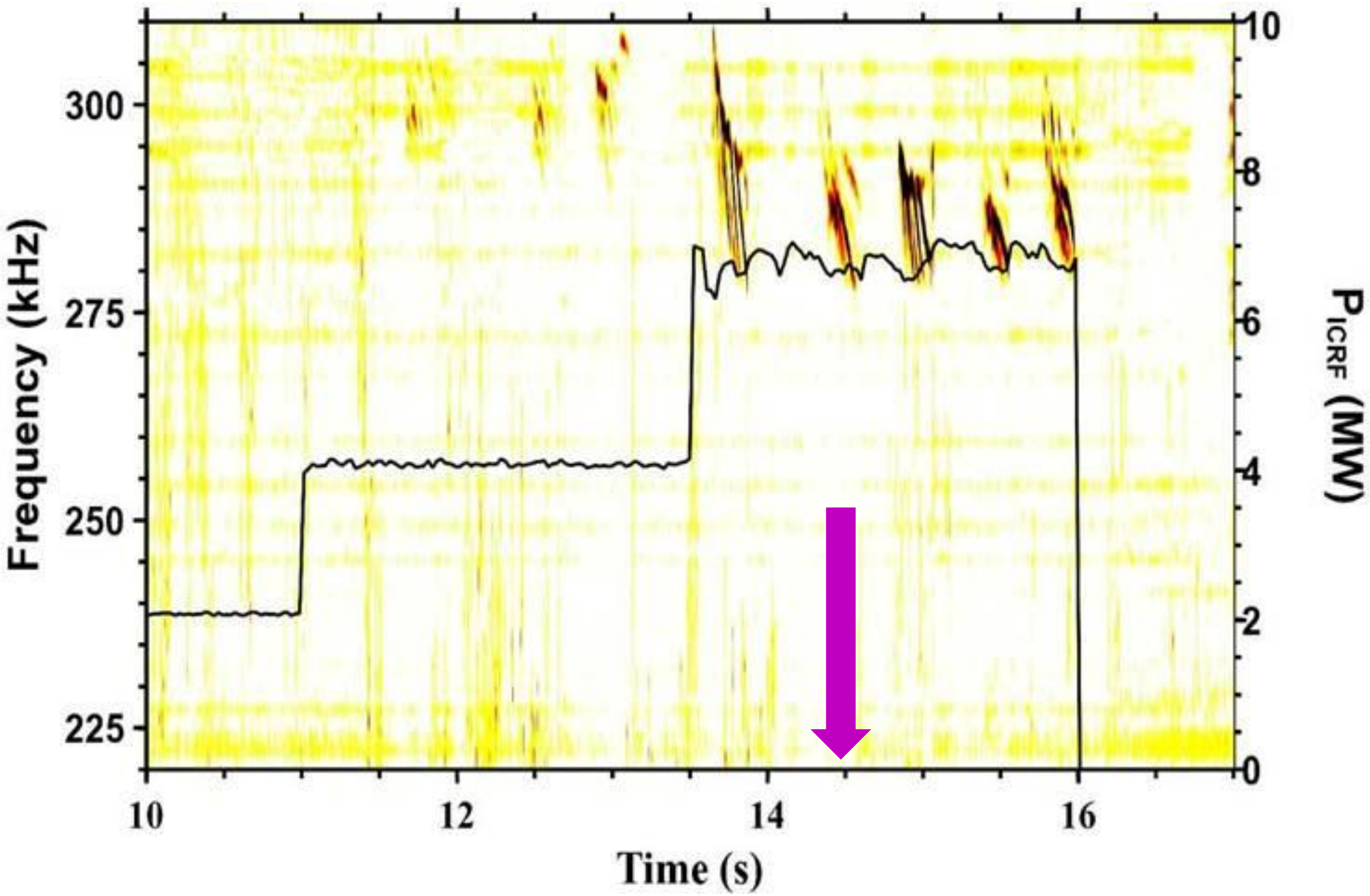
  D: $(2f_{\mathrm{TAE}}, -2f_{\mathrm{TAE}}) \to 0$

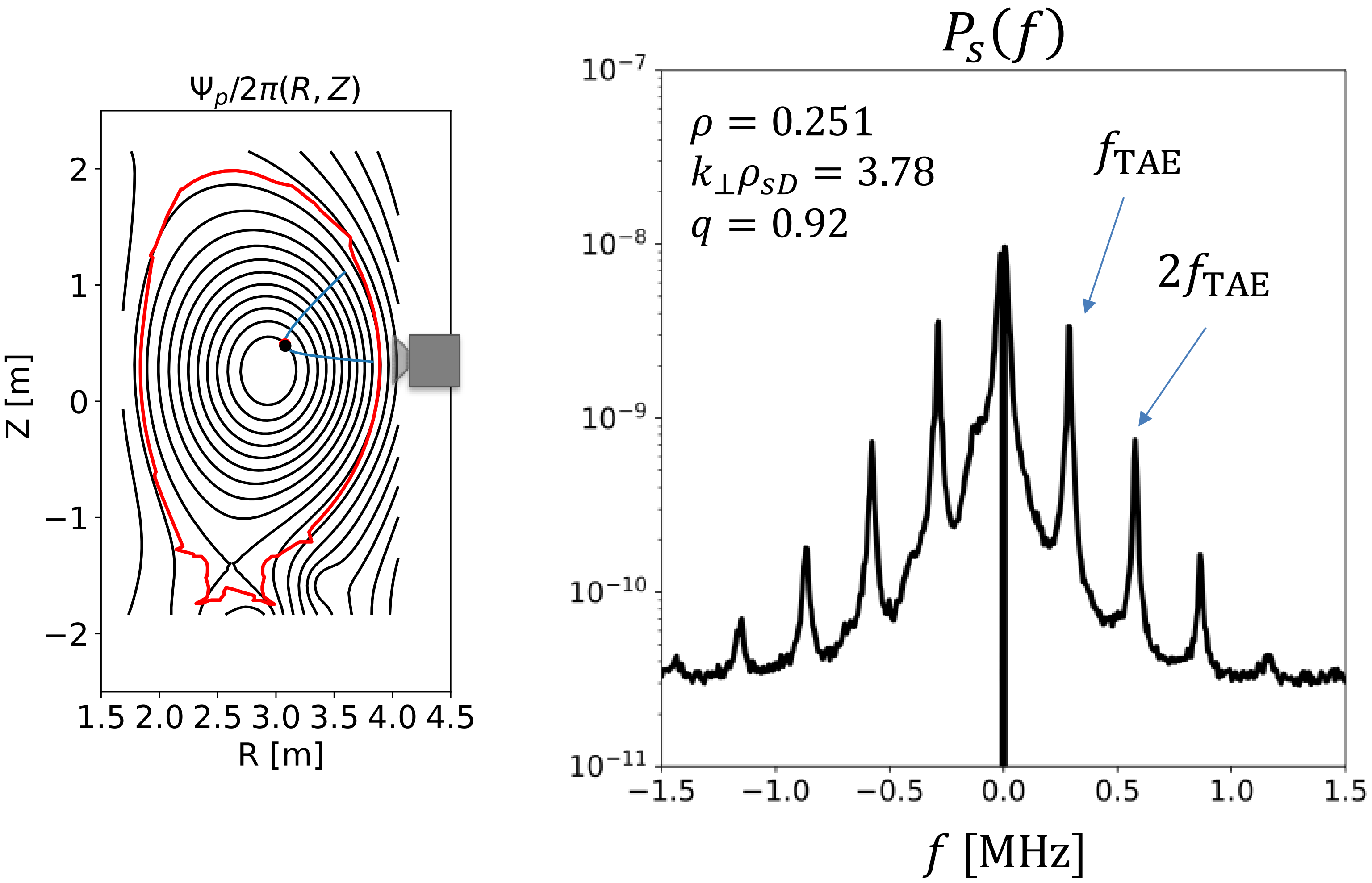
To our knowledge: *first experimental measurement of three-wave phase matching relationship between Alfvénic modes and a zero-frequency fluctuation in a magnetically confined plasma*

[*] Kim Powers IEEE 1978

DBS measurements at high ICRH power



At high P_{ICRH}, the DBS spectrogram in deep core exhibits frequent periodic bursts of Alfvénic modes and multiple harmonics of f_{TAE}



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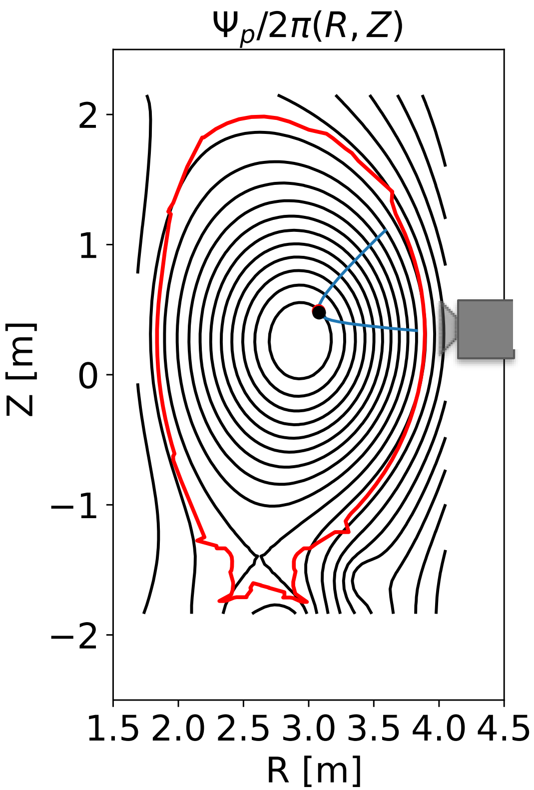

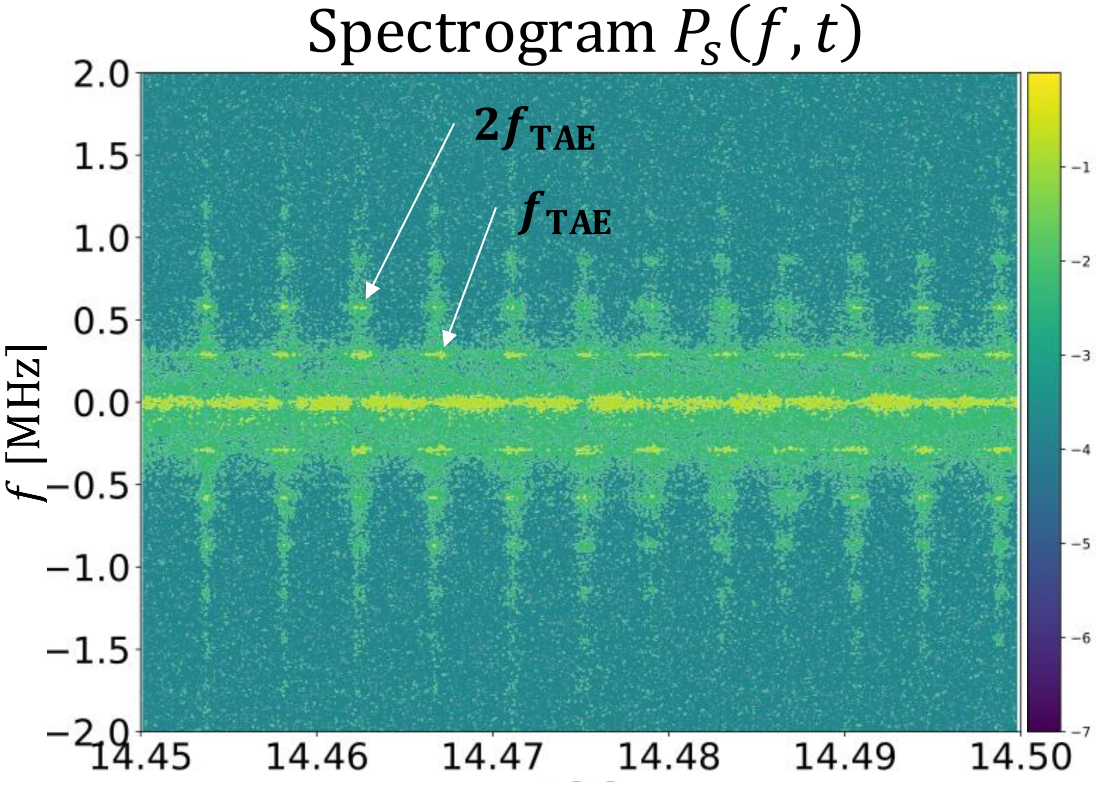

- Modes in higher gaps (up to $5f_{\mathrm{TAE}}$) inside q=1 surface (and persist outside)
- Bursts of the Alfvénic modes ($\Delta t \approx 4\ \mathrm{ms}$). *Are higher gap modes sidebands?*

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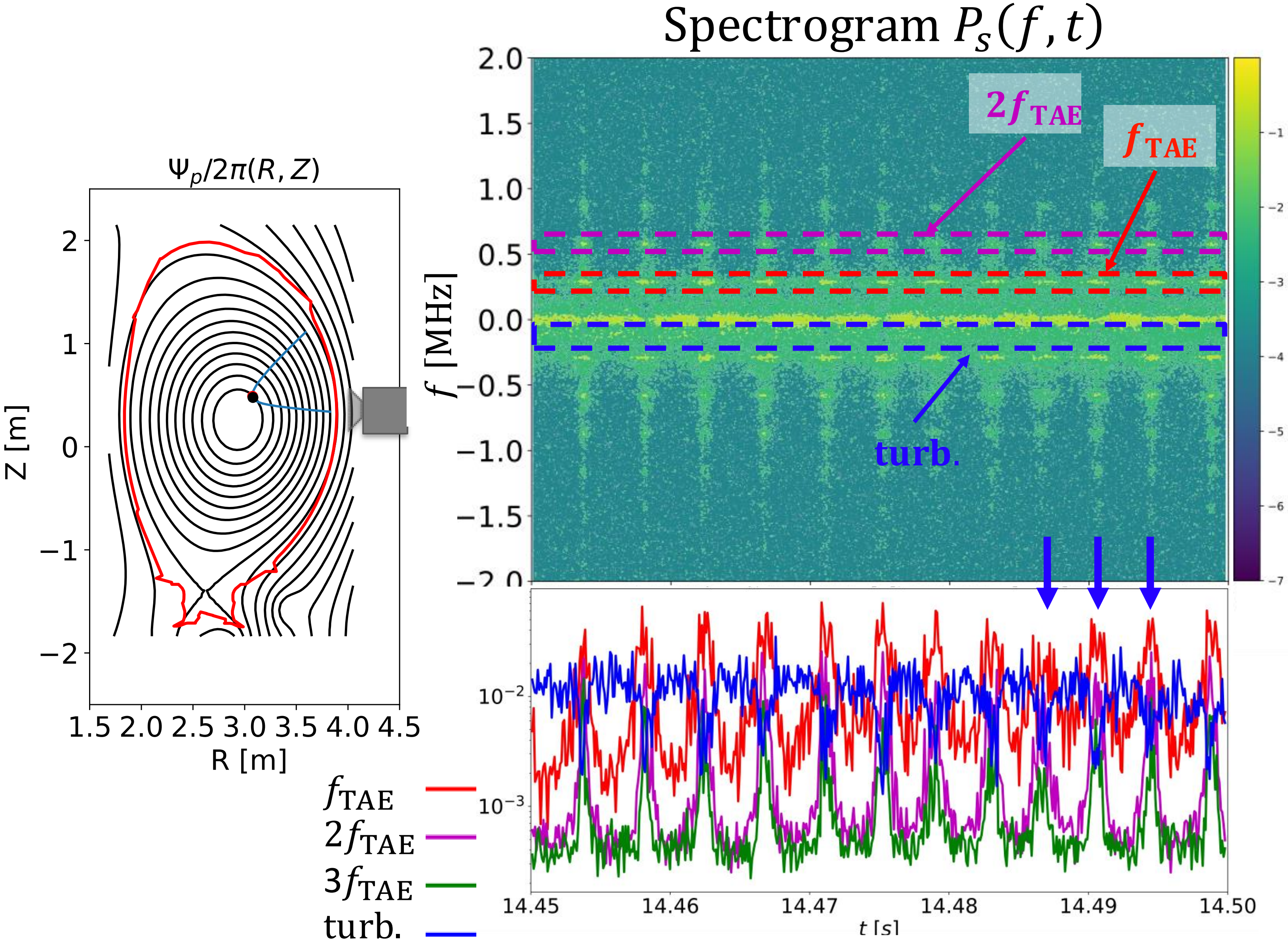

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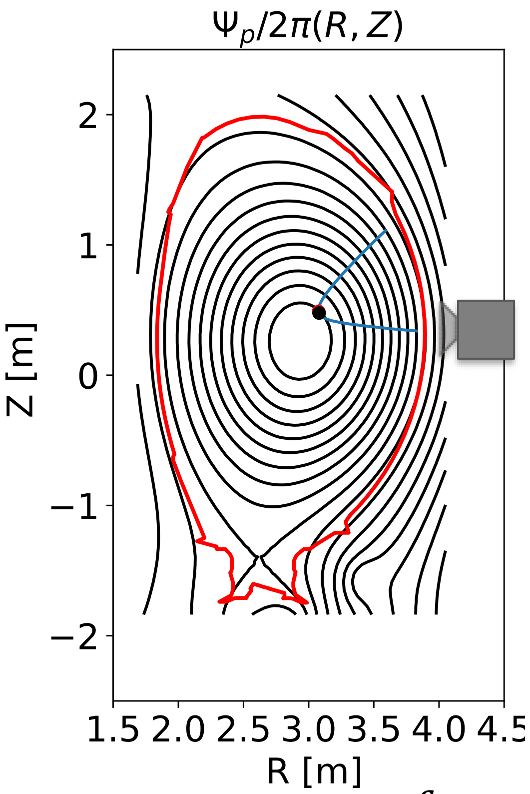

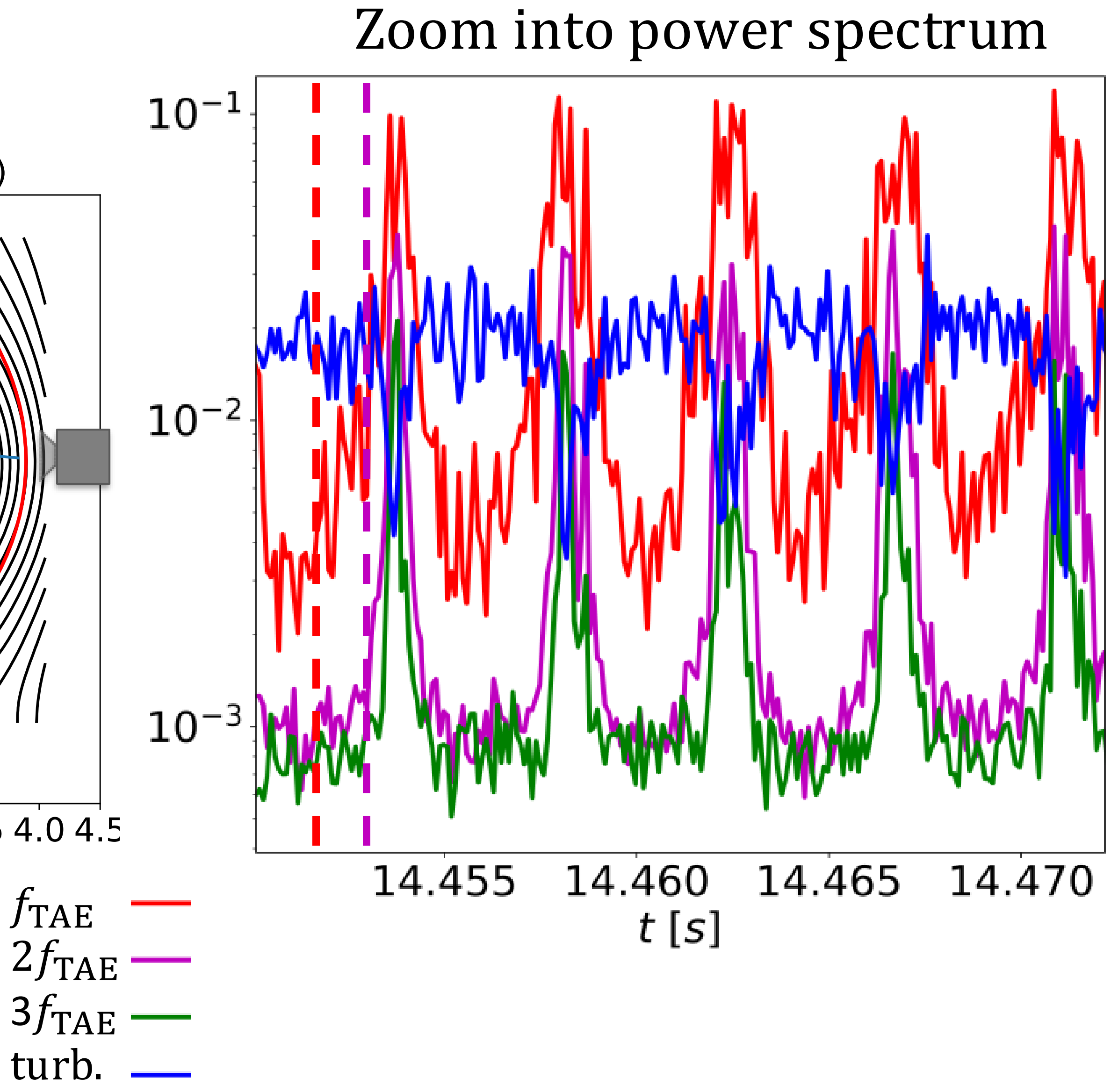

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- ***Causality?***

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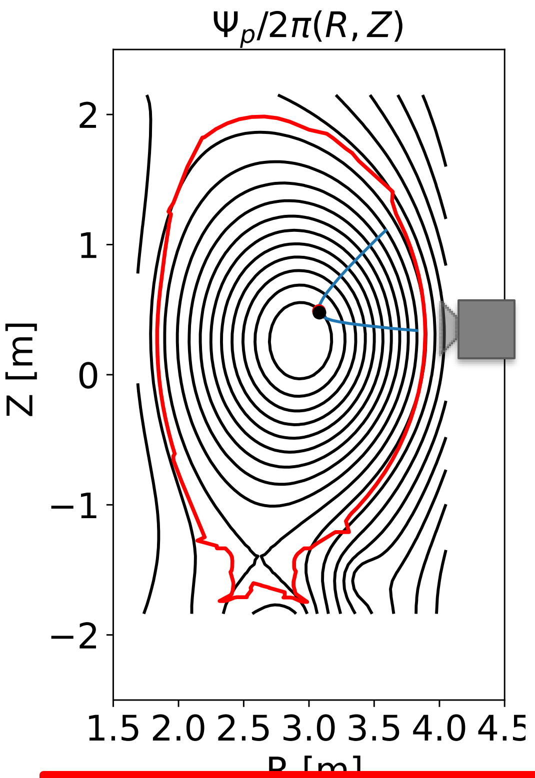

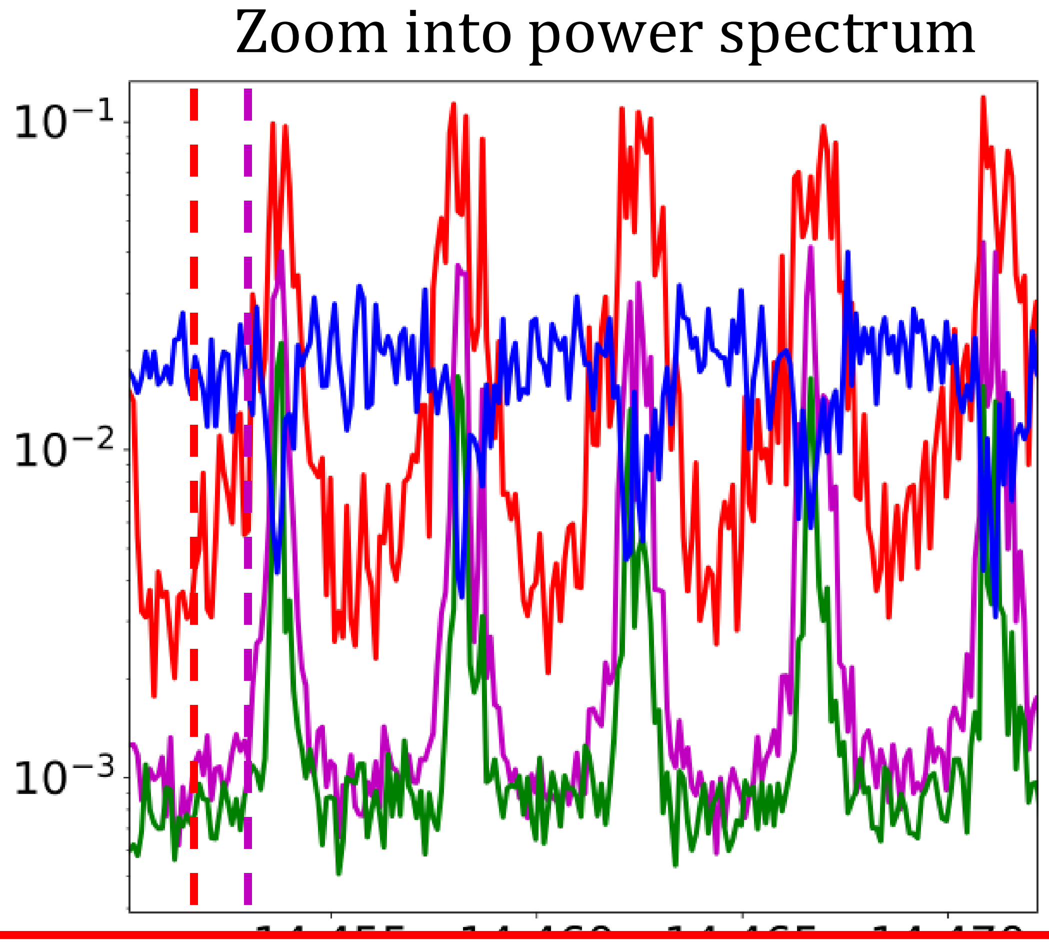

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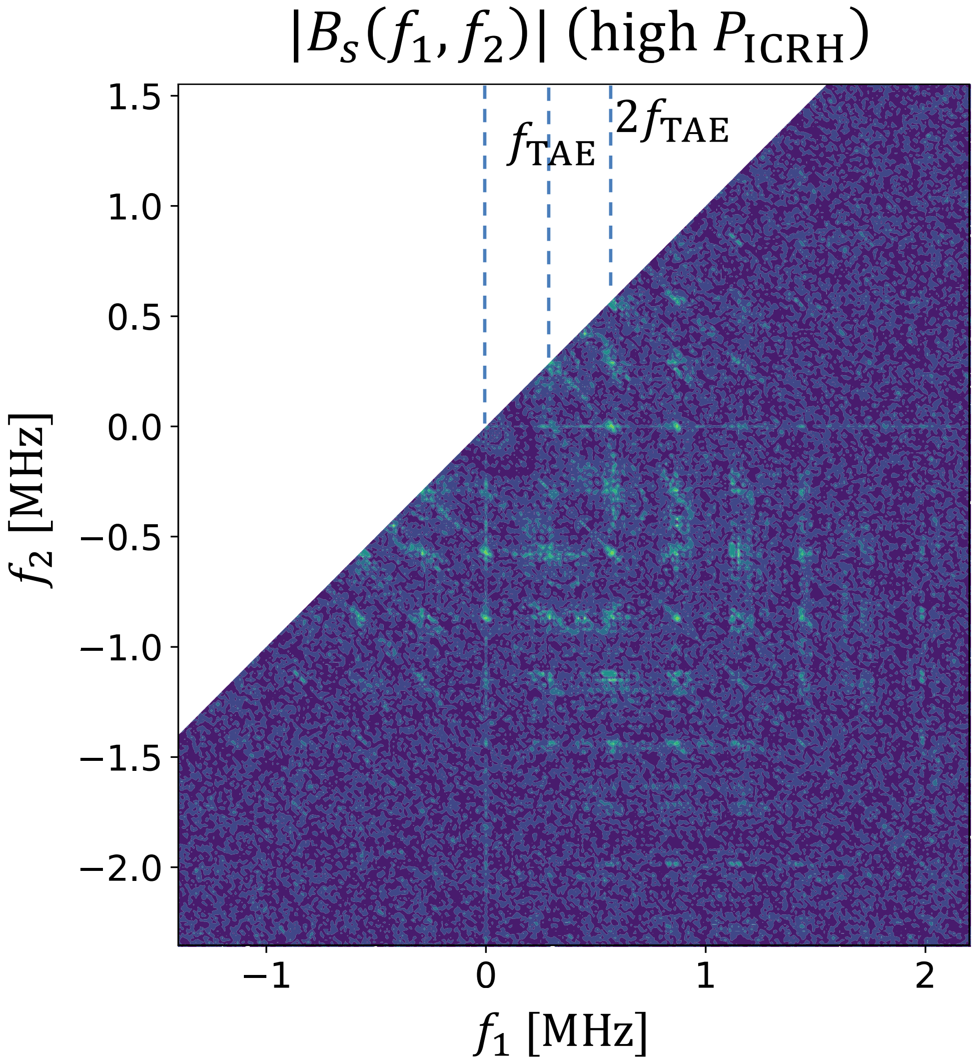
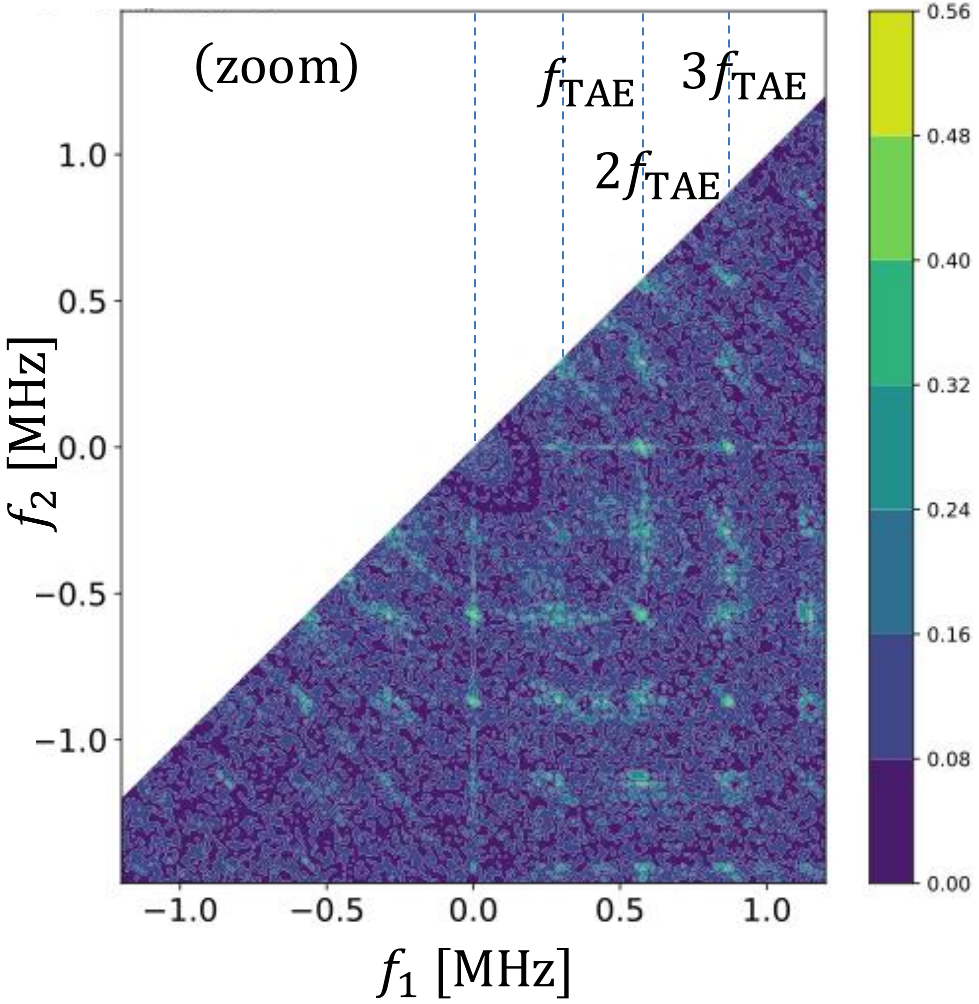
*TAE in fundamental gap f_{TAE} **precedes** modes in higher gaps and turbulence stabilization → suggests that fundamental TAE is the drive of the sidebands, affecting the turbulence (zonal flow?)*

The DBS bicoherence shows that the strongest phase-matching interactions involve $f = 0$. Observe mode-mode interactions up to $7 f_{\mathrm{TAE}}$





- Strongest interactions involve $(2f_{\mathrm{TAE}}, 0)$ and $(3f_{\mathrm{TAE}}, 0)$, not $(f_{\mathrm{TAE}}, 0)$

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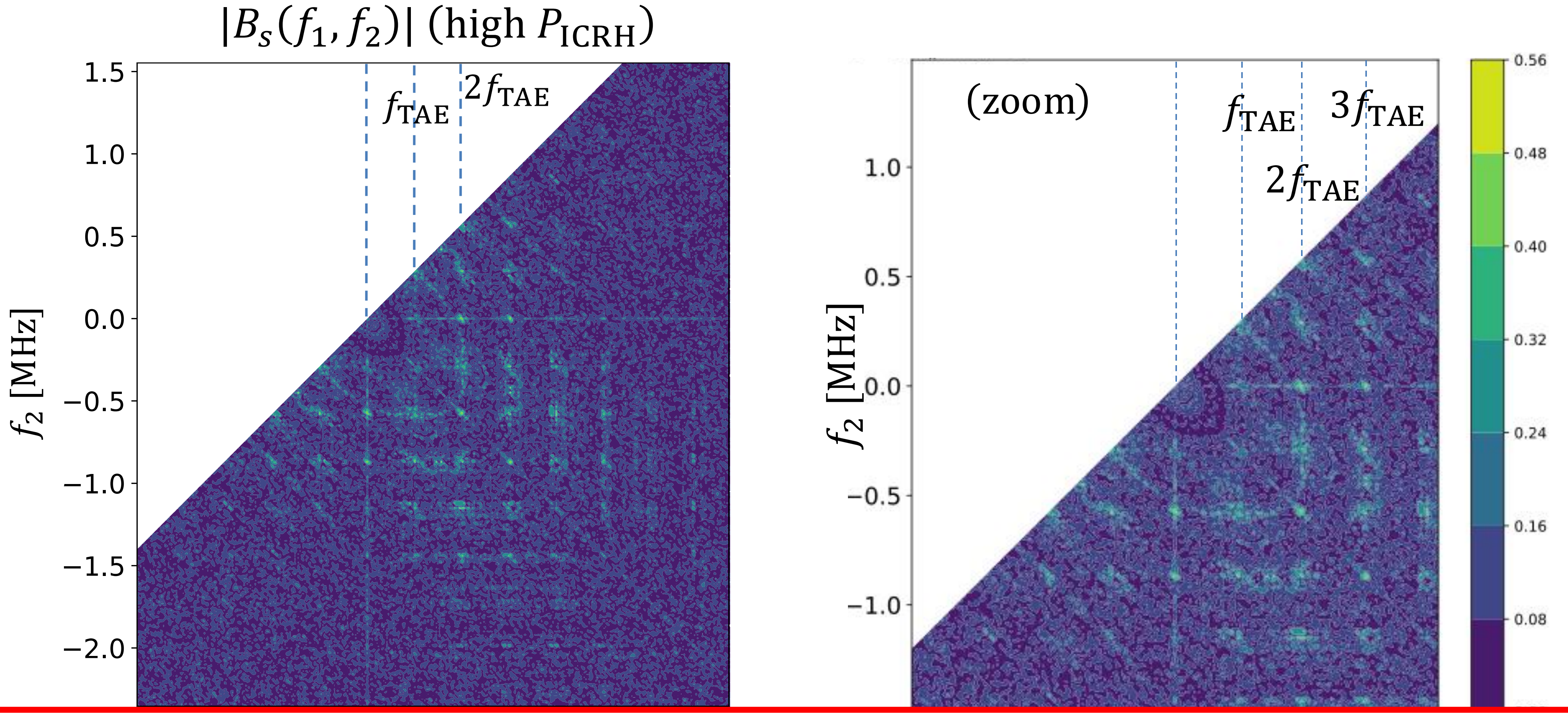


- Strongest interactions involve $(2f_{\mathrm{TAE}}, 0)$ and $(3f_{\mathrm{TAE}}, 0)$, not $(f_{\mathrm{TAE}}, 0)$

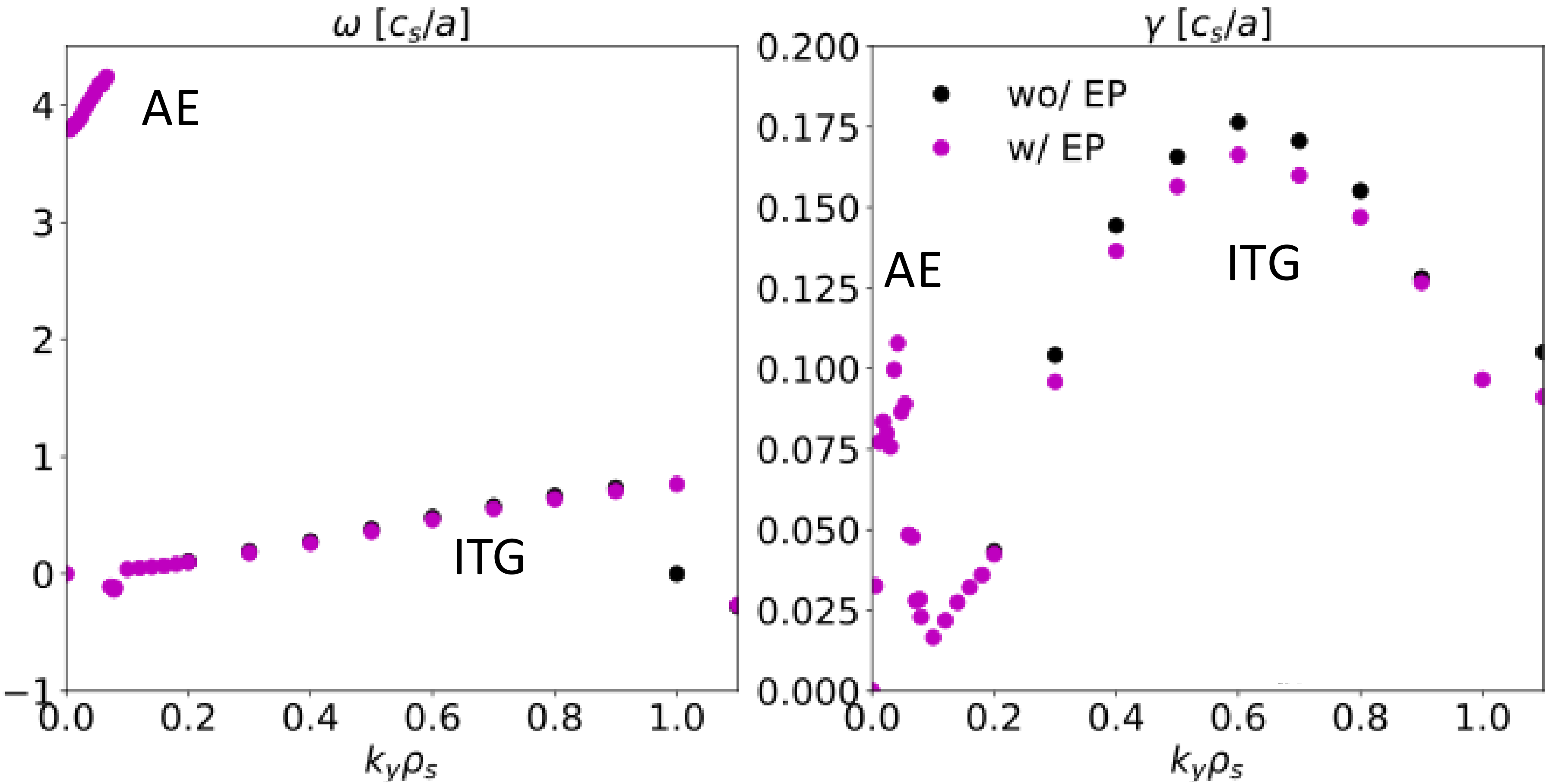
The JET experiments suggest that MeV ions can be ***beneficial*** to the global confinement (via Alfvén eigenmodes and the zero-frequency fluctuation)

Can the effect of MeV ions be beneficial to global confinement?

- **Experiments probing close-to-burning plasmas in JET**
  - JET plasma with MeV-range ICRH-heated ions
  - Doppler backscattering (DBS) measurements
    - Power spectrum and bicoherence analysis (Ruiz Ruiz PRL 2025)
    - Critical importance of diagnostic interpretation

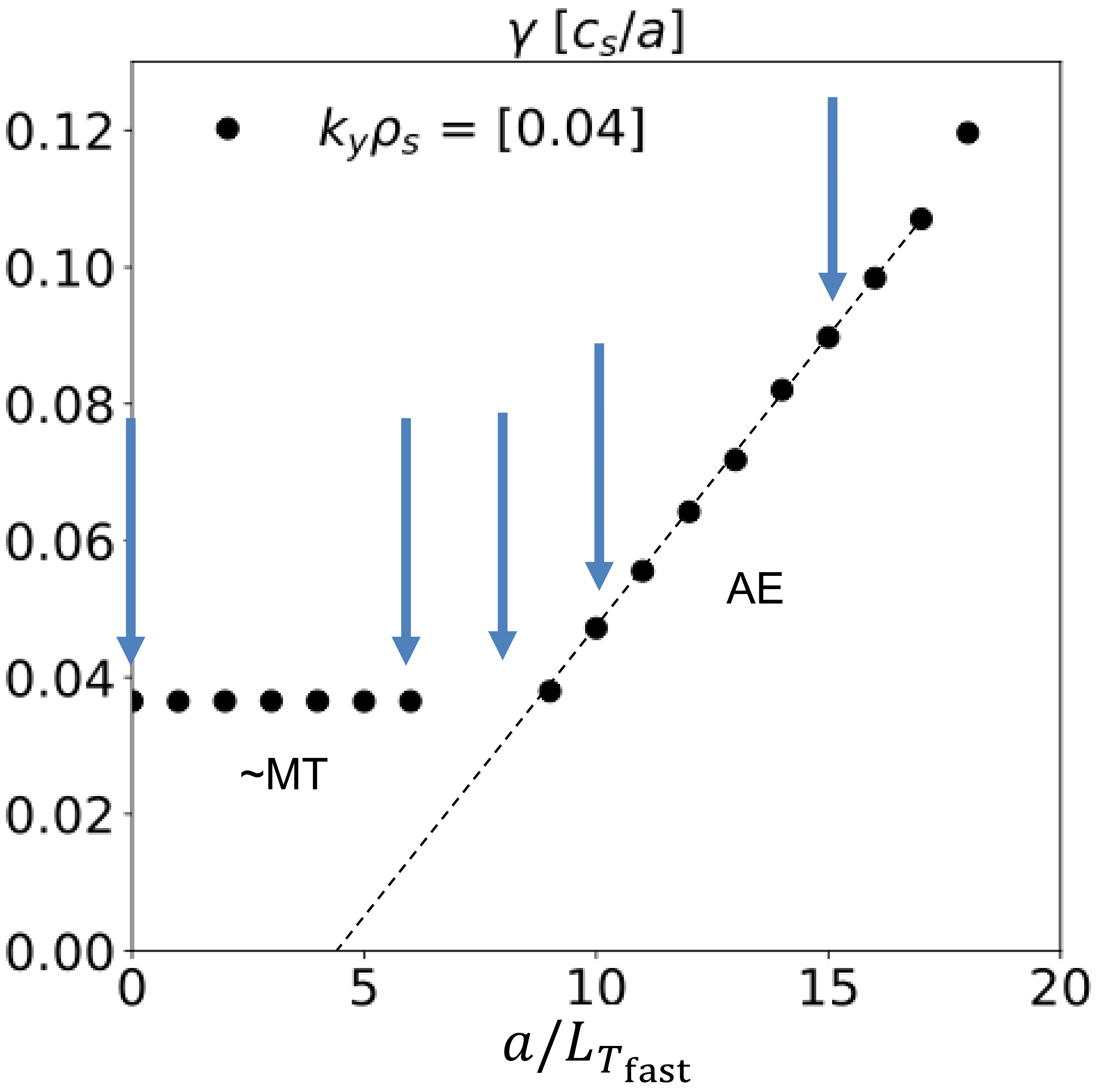
- **Numerical turbulence modelling (gyrokinetic)**
  - Linear instability
  - Nonlinear turbulence simulations (AE+ITG)
    - Effect on thermal transport
    - Bicoherence analysis

Linear CGYRO at high P_{ICRH} shows destabilization of fast-ion-driven instability consistent with AE, and ITG



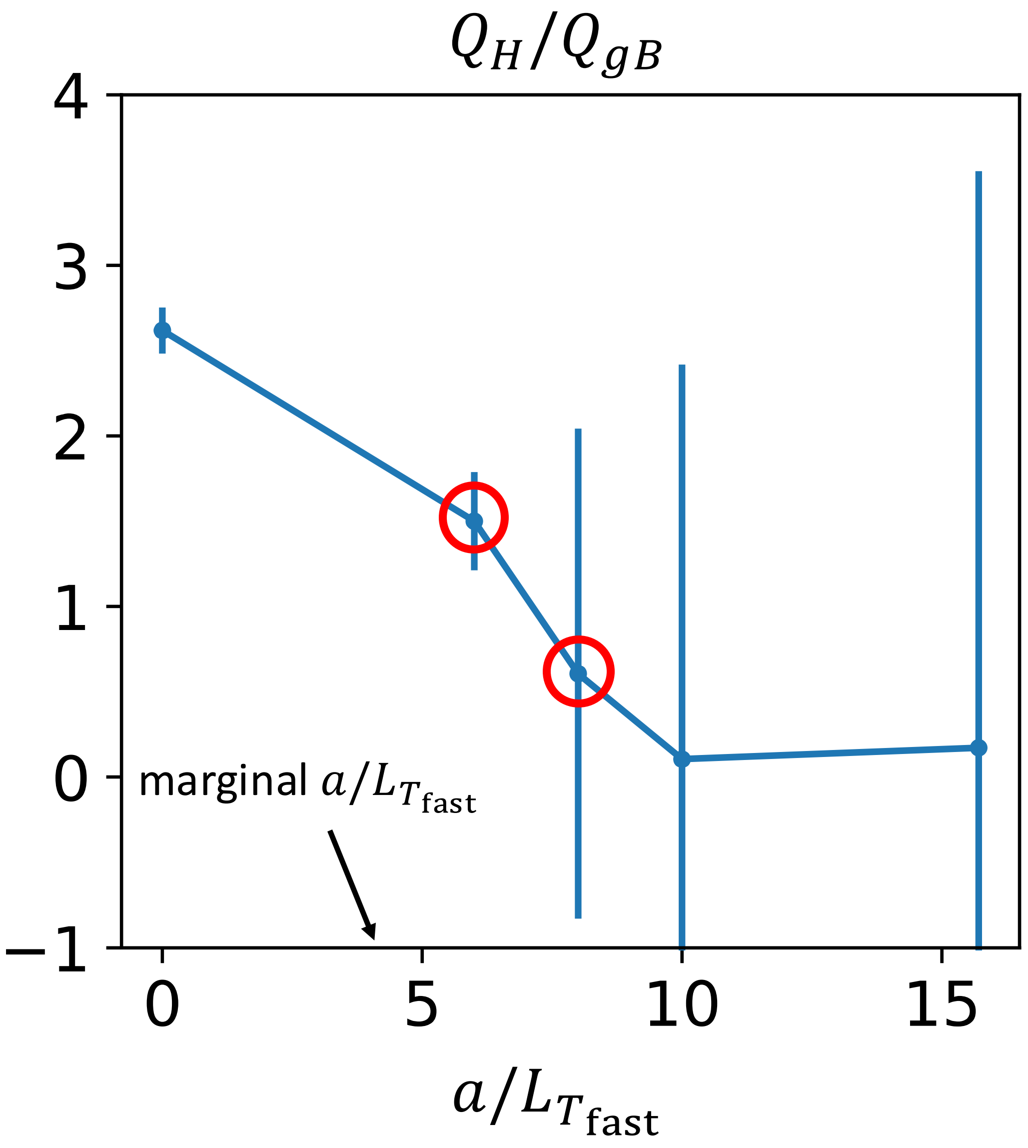
- Highly driven TAE ($k_y\rho_s < 0.1$), ITG ($k_y\rho_s$ $[0.3 - 1]$)
  - CGYRO $\omega_{\mathrm{TAE}} \approx 4\ c_s/a$ matches DBS $f_{\mathrm{TAE}} \approx 270 - 300\ \mathrm{kHz}$, $n \approx 4 - 6$ $(k_y\rho_{sD} \approx 0.04)$
- Negligible effect of EPs on ITG → ***linear*** effects (dilution, β', kinetic stabilization) are negligible
- No low-k_y AE without EP

Low k_y mode (AE) exhibits critical gradient behavior with $a/L_{T_{\mathrm{fast}}}$



- $k_y\rho_{sD} \approx 0.04$ mode (AE) matches:
  - DBS freq. ($f_{\mathrm{TAE}} \approx 260 - 290\ \mathrm{kHz}$)
  - $n \approx 4 - 6$ ($k_y\rho_{sD} \approx 0.04$)
  - $\delta E_{||} = 0$
- $a/L_{T_{\mathrm{fast}}} < 8$: long-tail mode (~MT)
- $a/L_{T_{\mathrm{fast}}} > 8$: AE
- ➔ Probe turbulence without fast particles, at low, medium, and at high $a/L_{T_{\mathrm{fast}}}$ drive of AE.

Local nonlinear CGYRO for high P_{ICRH}: turbulence is stabilized when AE is driven unstable



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

- AE+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 EPs, $Q_i/Q_{gB} \approx 3$

- Stabilization of $Q_{i,e}$ with unstable AE $a/L_{T_{\text{fast}}} \gtrsim 4$ (marginal AE instability)

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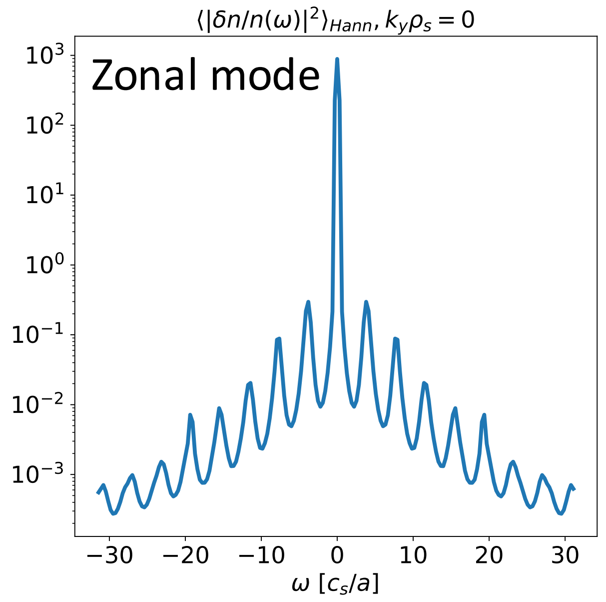
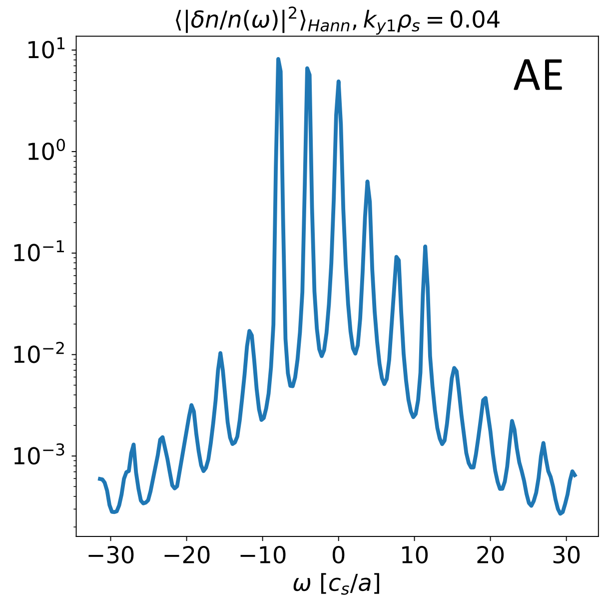
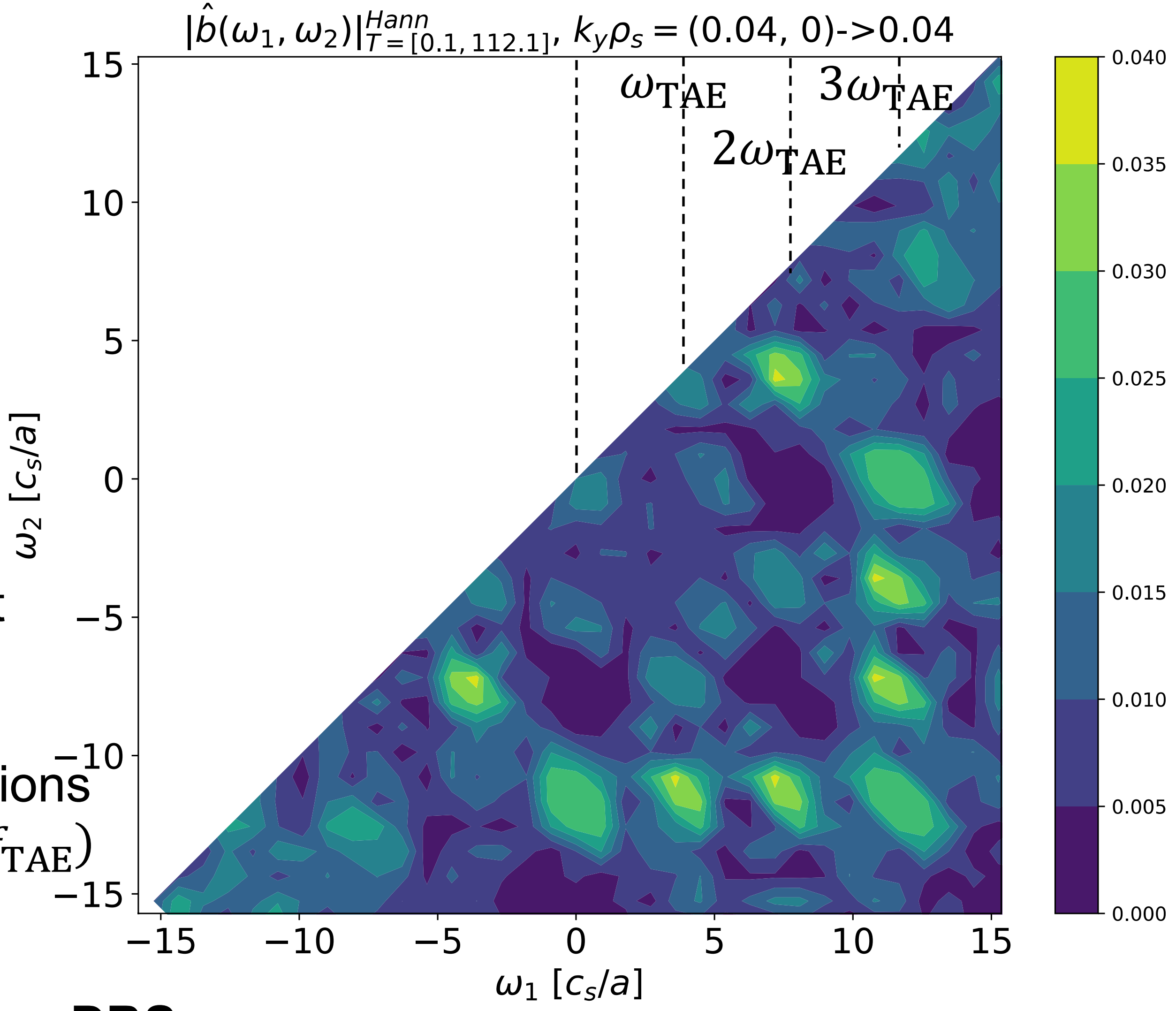
Density power spectrum and bicoherence at a/L_{Tfast} = 6 (low drive) exhibits harmonics of f_{TAE} and dominant mode-mode interactions





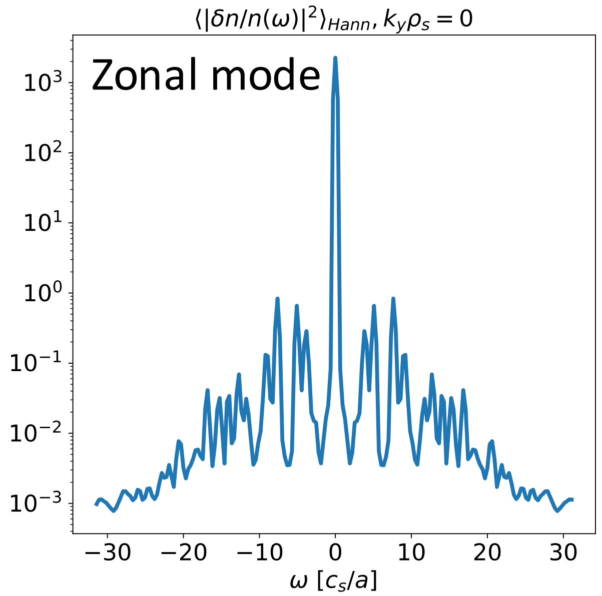


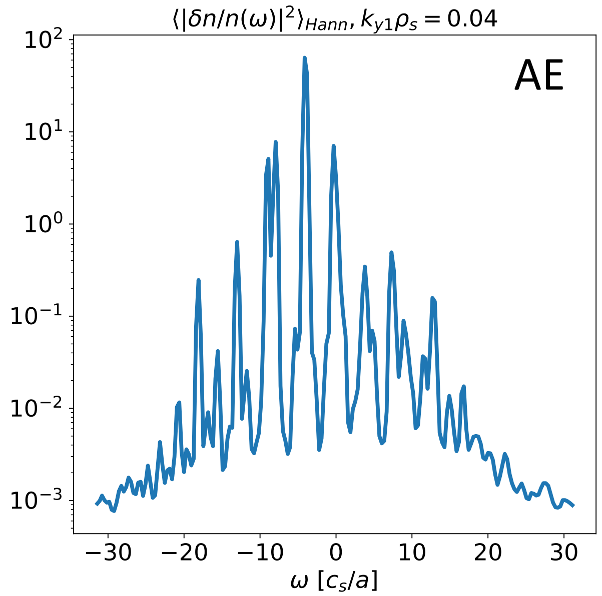
- Zonal δn_e response exhibits large $f = 0$ component
- AE is unidirectional, exhibits harmonics of f_{TAE}

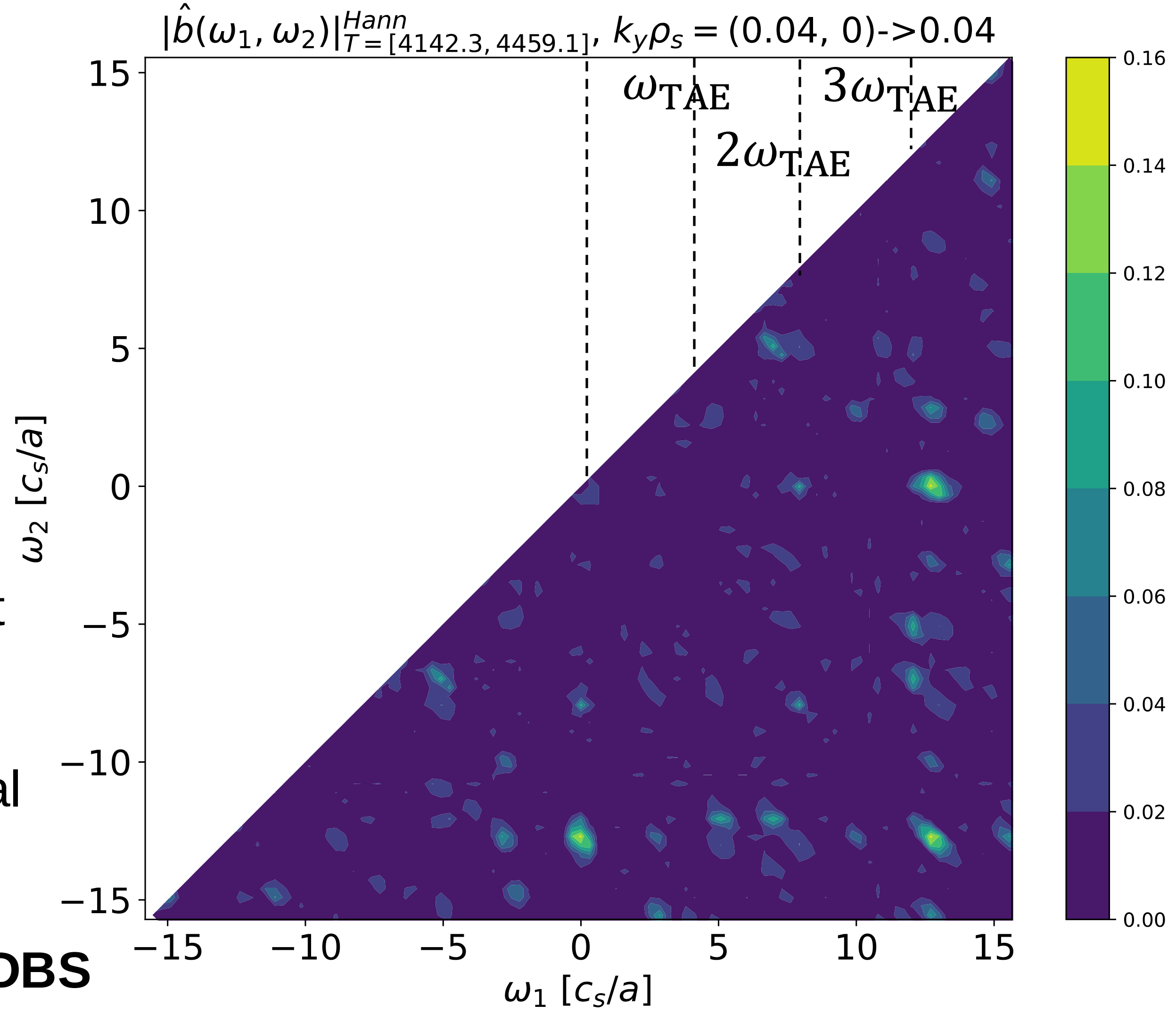
- Bicoherence exhibits dominant mode-mode interactions $(\pm 2f_{\mathrm{TAE}}, \pm f_{\mathrm{TAE}})$, $(\pm 3f_{\mathrm{TAE}}, \mp f_{\mathrm{TAE}})$, and $(\pm 3f_{\mathrm{TAE}}, \mp 2f_{\mathrm{TAE}})$
- Subdominant $(\pm 3f_{\mathrm{TAE}}, 0)$

- **Consistent with medium P_{ICRH} measurements from DBS**

Density power spectrum and bicoherence at a/L_{Tfast} = 8 (med drive) exhibits harmonics of f_{TAE} and dominant interaction with $f = 0$







- Zonal δn_e response exhibits large $f = 0$ component
- AE is unidirectional, exhibits harmonics of f_{TAE}
- Bicoherence exhibits dominant interaction with zonal component $(\pm 3f_{\mathrm{TAE}}, 0)$, subdominant $(\pm 2f_{\mathrm{TAE}}, 0)$
- **Consistent with high P_{ICRH} measurements from DBS**

Conclusions from the research (1/3)

To our knowledge: *the first experimental confirmation of a zero-frequency fluctuation that is pumped by an Alfvén eigenmode in a magnetically-confined plasma* [*]. *Confirmed by local nonlinear gyrokinetic simulations.*

- JET discharge with dominant e- heating (MeV range fast ions) shows T_i and $H_{89,P}$ increase with P_{ICRH}, decrease in Q_i → **enhanced global confinement**.

- Alfvénic modes (tornado TAEs) exhibit nonlinear phase-matching relations with a **zero-frequency fluctuation,** and suggest **predator-prey** behavior TAE-turbulence-zonal flow.

- **Nonlinear CGYRO confirms** nonlinear phase-matching between f=0 and AE mode ➔ *zero-frequency fluctuation could be responsible for enhanced total plasma confinement, could balance deleterious energetic particle transport by the Alfvén eigenmodes.*

[*] Ruiz Ruiz *et al.*, PRL 2025

Discussion of the findings (2/3)

- What this work means
  - **Zero-frequency zonal flow** pumped by Alfvén modes is real [1]. We see a manifestation of it in bicoherence and the predator-prey behavior.
  - Possibly a glimpse of the rich, nonlinear behavior at the heart of next-generation burning plasmas.

- Why has this not been seen before?
  - MeV ions: difficult to generate
  - Most machines do not **confine MeV ions** (except JET, TFTR, JT-60U)
  - NBI can drive Alfvén modes, but also often stabilize them [2]
  - Here, we have analyzed a discharge **exclusively heated by MeV ions**
  - Zonal flow from AEs never really been looked after until very recently

[1] Todo NF 2010/2012, Qiu PoP 2016/NF 2017, Mazzi Nat Phys 2022

[2] eg. rotation, resonance more difficult to realise, damping on beam ions

Important / unresolved questions (3/3)

1. Measure radial structure of zero-frequency zonal flow produced by Alfvén modes: need further measurements!

2. What does this zonal flow depend on? Can it be tailored to our advantage in a future burning plasma? eg. increase Ti?

3. Are Alfvén eigenmodes good or bad overall for fusion performance?

4. Here, MeV ions are controlled externally – what will happen in a burning plasma, where nonlinear effects are expected to be more important?