Measurement and gyrokinetic simulations of zero-frequency fluctuations generated by coupling between 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 fast ions, Alfvén modes and turbulence?

- Supra-thermal particles will be ubiquitous in upcoming **burning plasmas.**

- Originate in plasma heating, or fusion reaction $(\mathrm{D} + \mathrm{T} \rightarrow \alpha + n)$: very common !!

- Fast ions (FI) can excite MHD/Alfvén instabilities[1].
  ➔ Deleterious for plasma confinement due to large fast particle transport[2]

- Presence of Alfvén eigenmodes (AEs) not always deleterious
  - GK simulations[3] have shown that AEs driven by fast ions can stabilize turbulence
  - Todo NF 2010/2012 (MHD): AEs can generate a zero-frequency zonal perturbation[4]

    TAE+TAE → ZF
    TAE+TAE → sidebands

  → **zero-frequency zonal perturbation could interact with and stabilize turbulence**

- Zero-frequency fluctuation driven by AEs lacks experimental confirmation

[1] Rosenbluth PRL 1975 [2] Heidbrink PoP 2008/2020 [3] DiSiena NF 2019, Biancalani PPCF 2021/JPP 2023, Mazzi Nat Phys 2022
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We show the first experimental confirmation of a zero-frequency fluctuation that is pumped by an Alfvén eigenmode in a magnetically-confined plasma[5]

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Outline

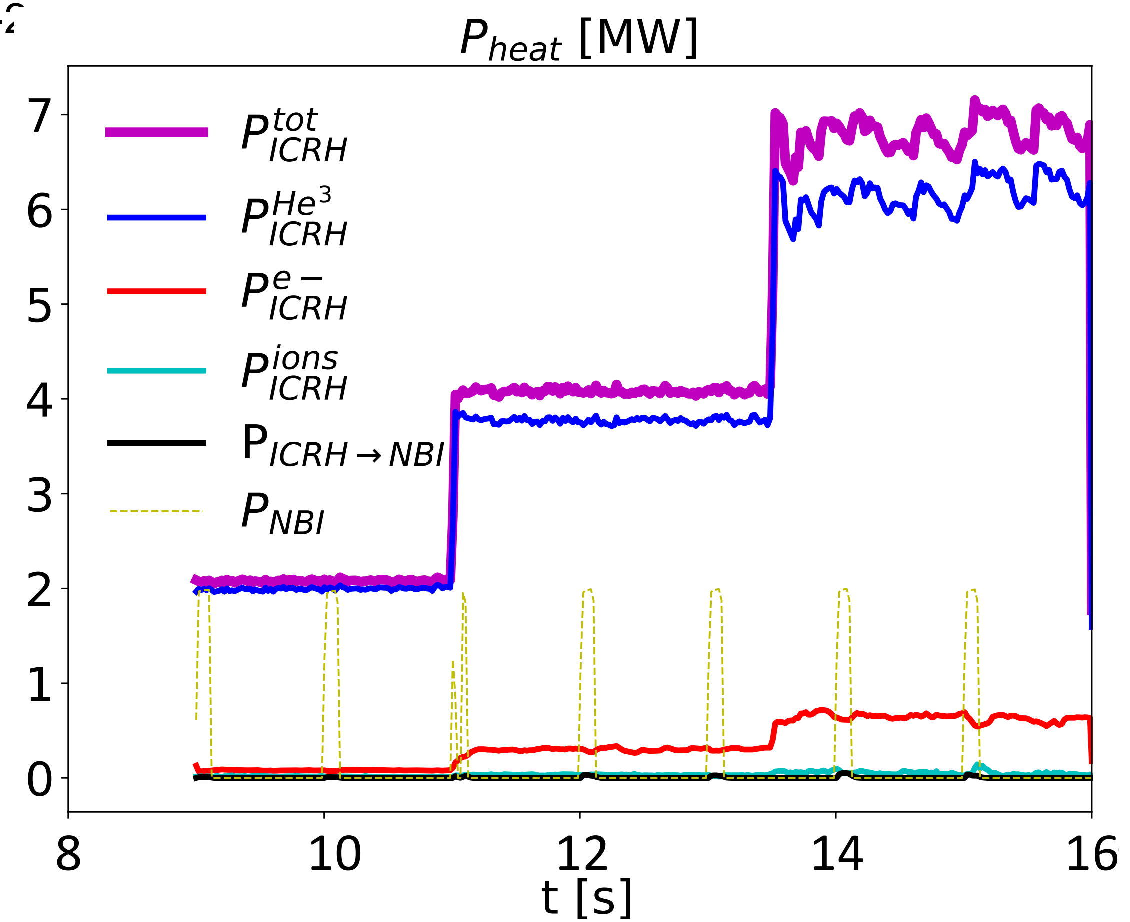
- **Experimental observations**
  - JET plasma with MeV-range ICRF-heated ions
  - Alfvénic activity (TAE)
  - Doppler backscattering (DBS) measurements
    - Power spectrum and bicoherence analysis (Ruiz Ruiz PRL 2025)

- **Gyrokinetic modelling**
  - Local nonlinear simulations (TAE+ITG)
    - Effect on thermal transport
    - Bicoherence analysis

JET 97090 L-mode heated with ICRF 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-2
- ICRF 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)

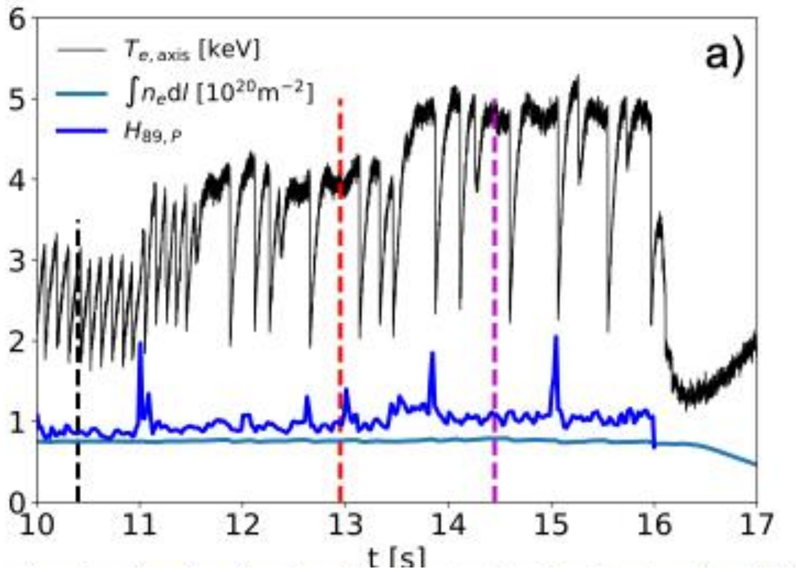
→ Almost pure electron heating plasma via slowing down of 3He – mimic conditions of 3.5 MeV alpha particles in a burning plasma



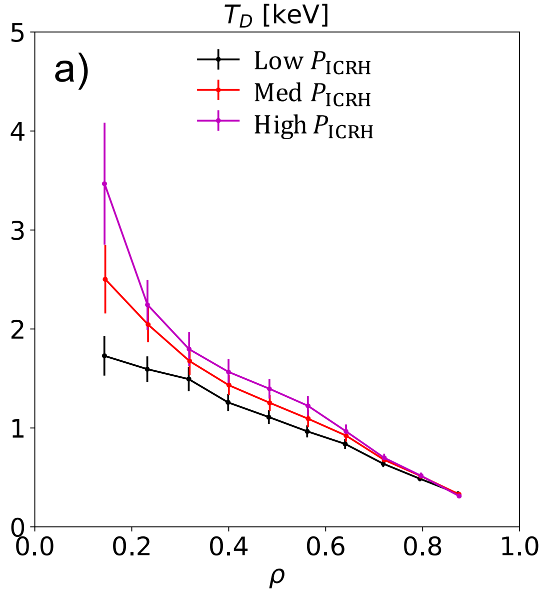
[*] '3-ion ICRH heating', Kazakov NF 2015

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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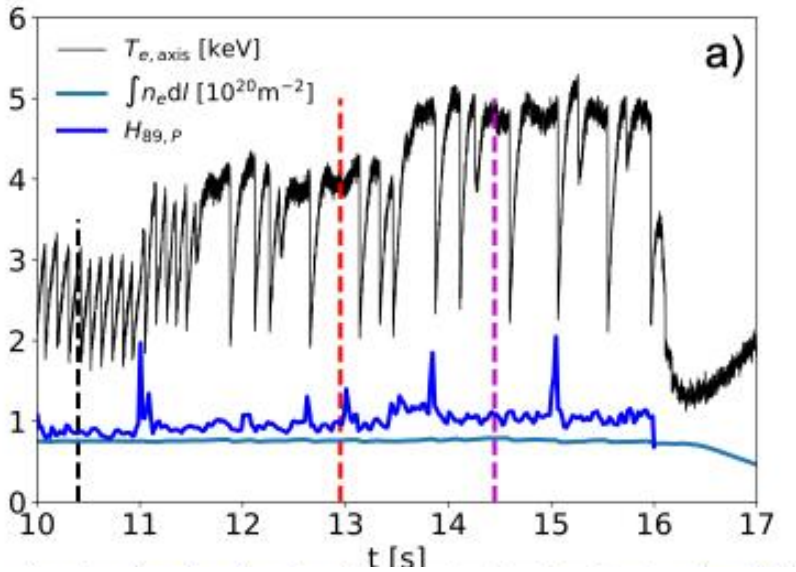

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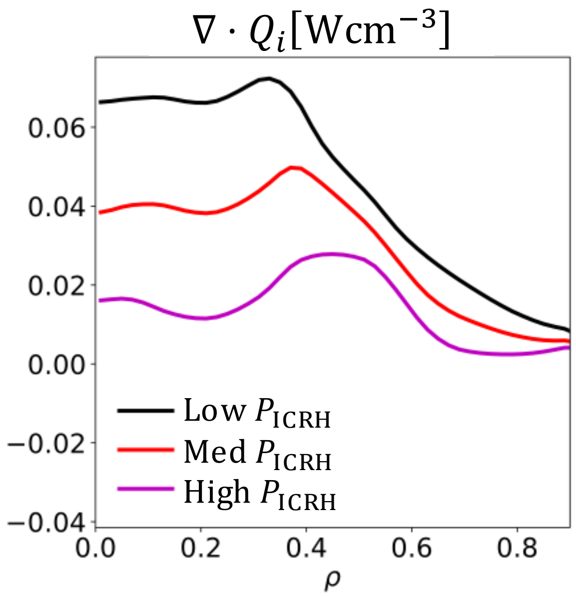
    ➔ Decrease in Q_i ($Q_e > Q_i$, TRANSP)



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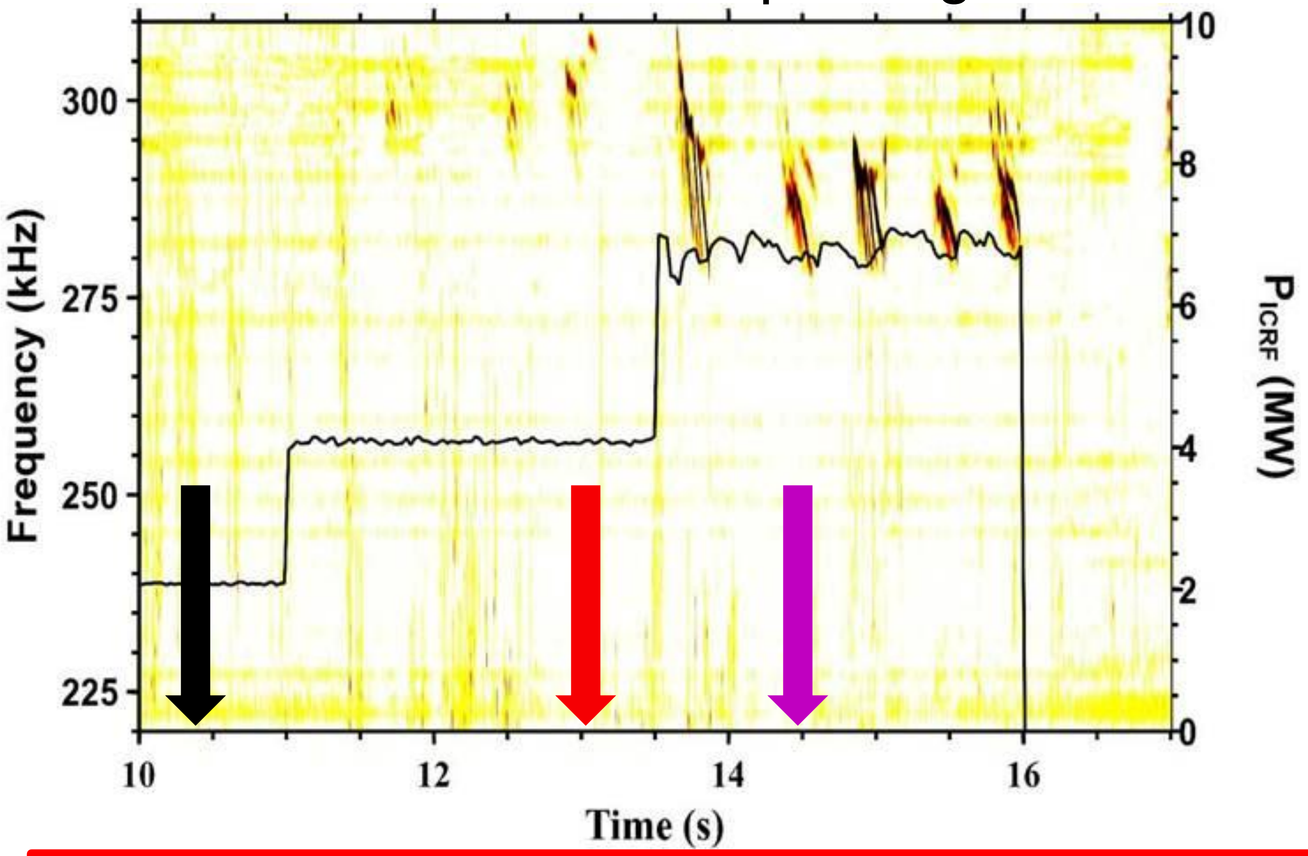
Increase in T_i and thermal confinement is correlated with increased MHD activity observed with increasing ICRH power



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

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

→ Motivate local turbulence measurements via Doppler Backscattering (DBS)

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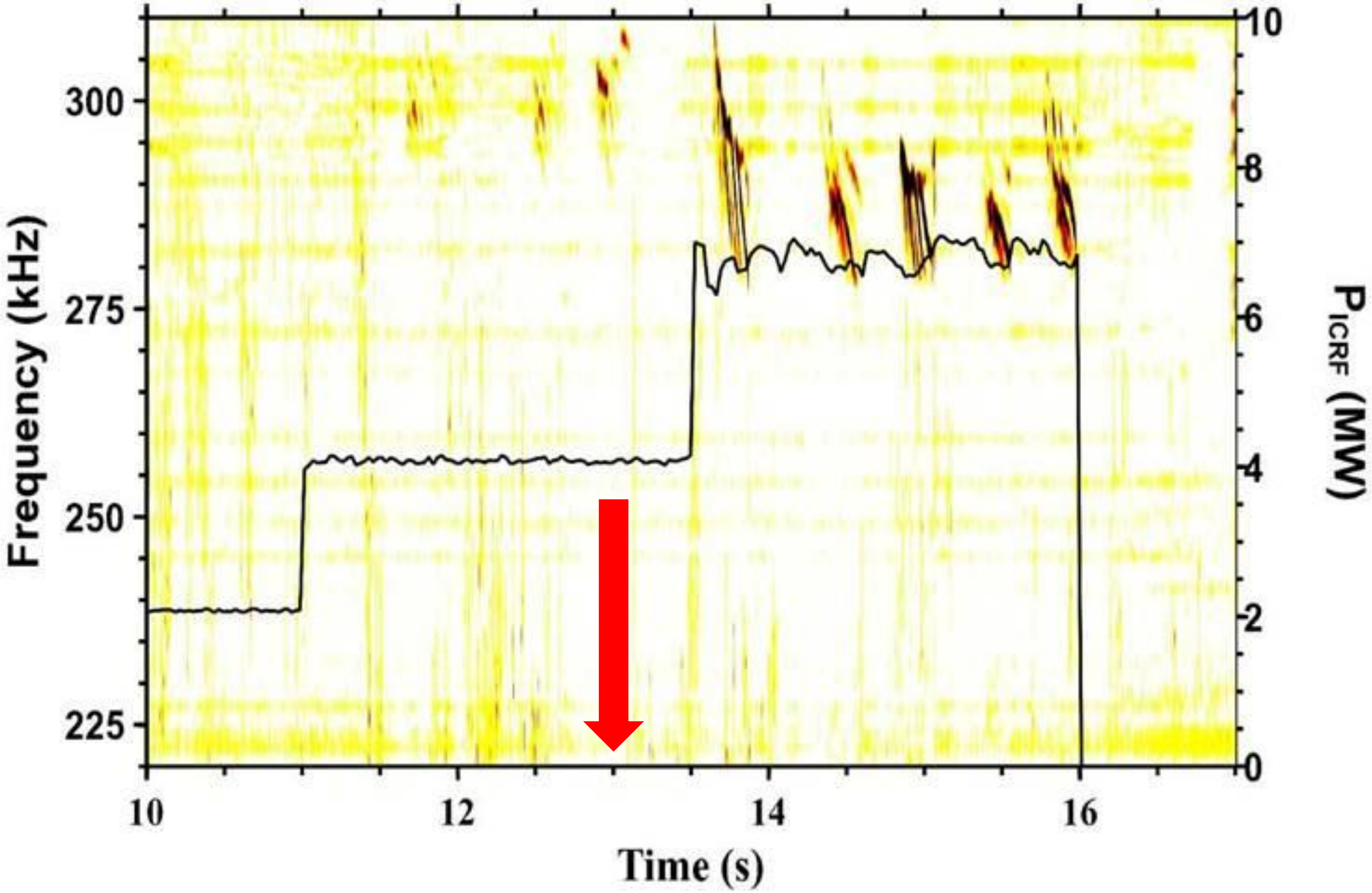
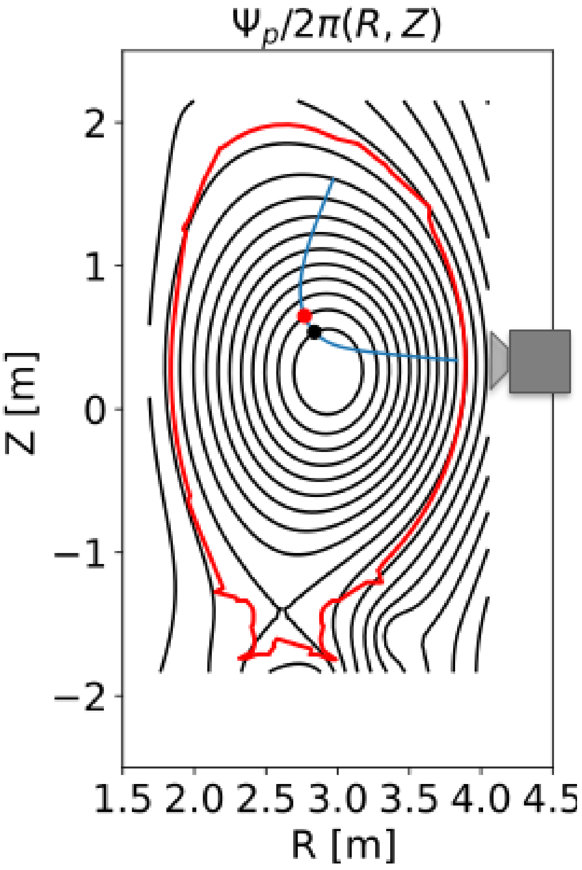
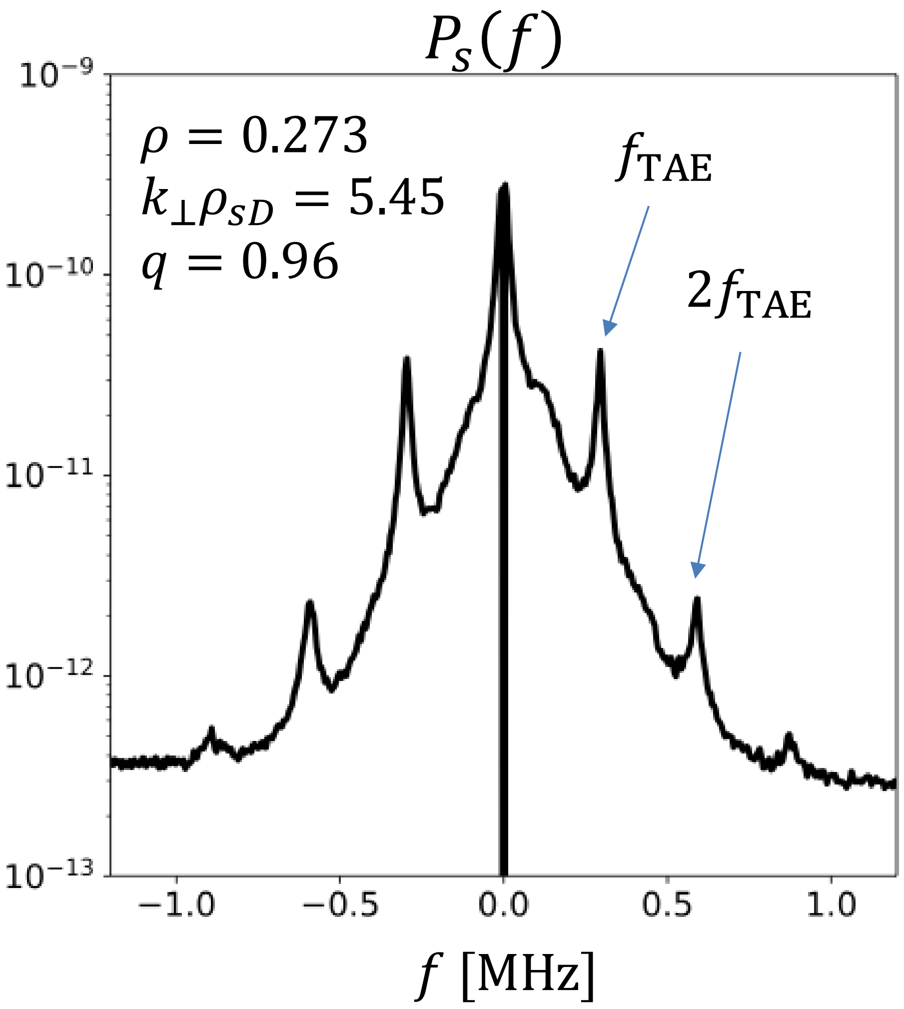
DBS measurements at medium ICRH power



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





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

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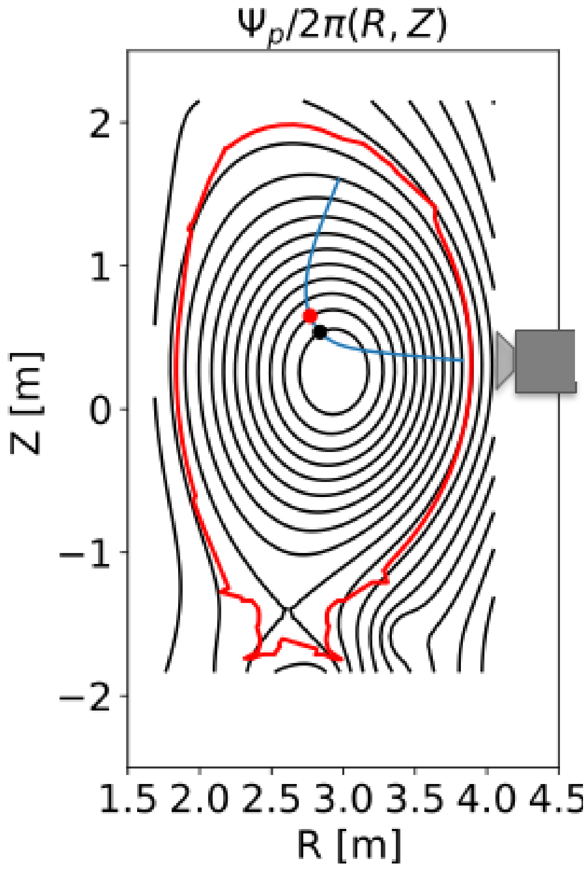

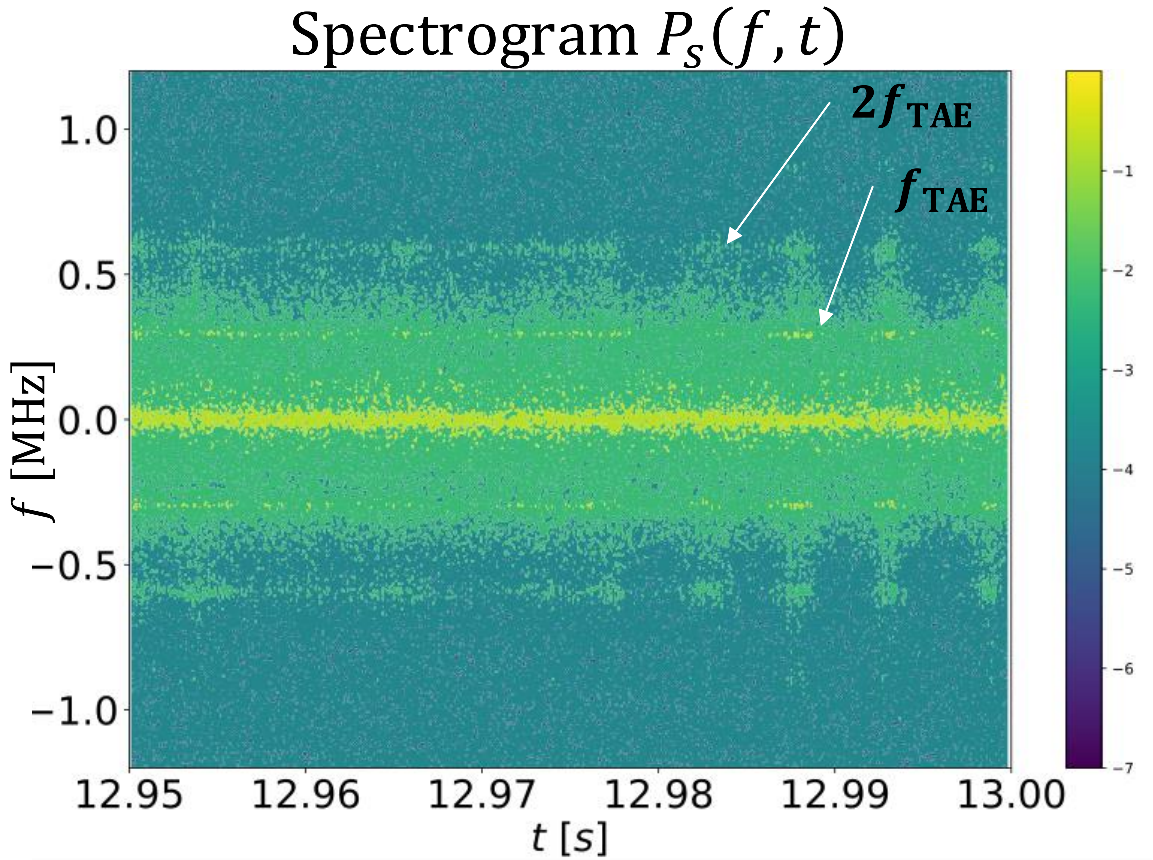

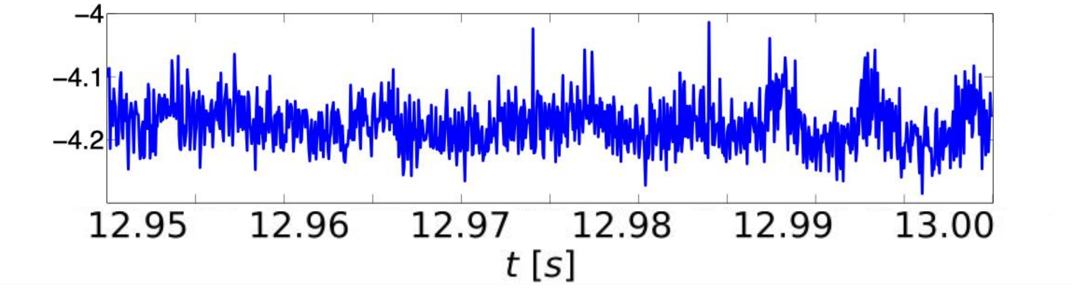

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- Spectral peaks at $f_{TAE}, 2f_{TAE}, 3f_{TAE}$
- Presence of TAEs (near q=1, tornado TAEs [*]) that burst every $\Delta t \approx 6-7$ ms

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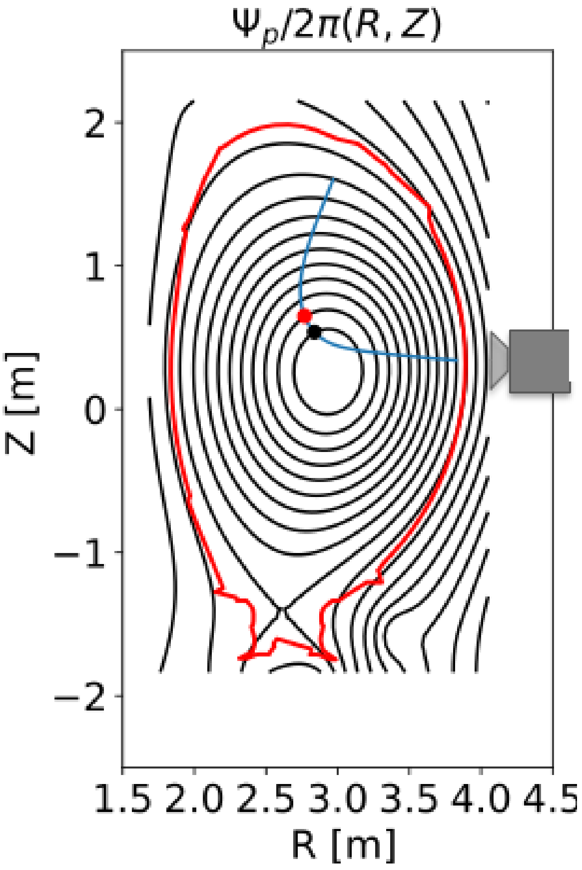

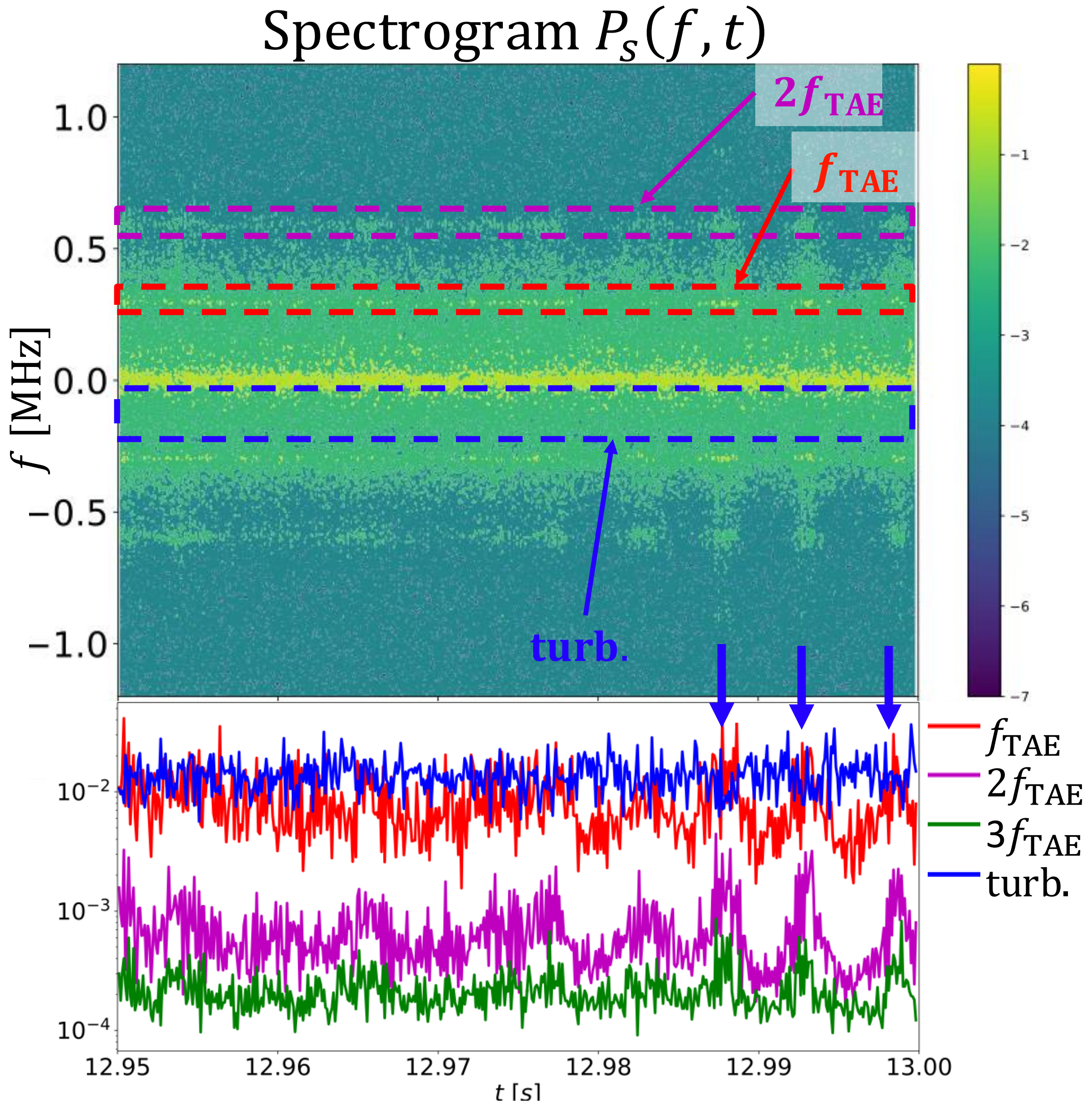

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- Are higher gap modes sidebands?
- Faint effect on turbulence?

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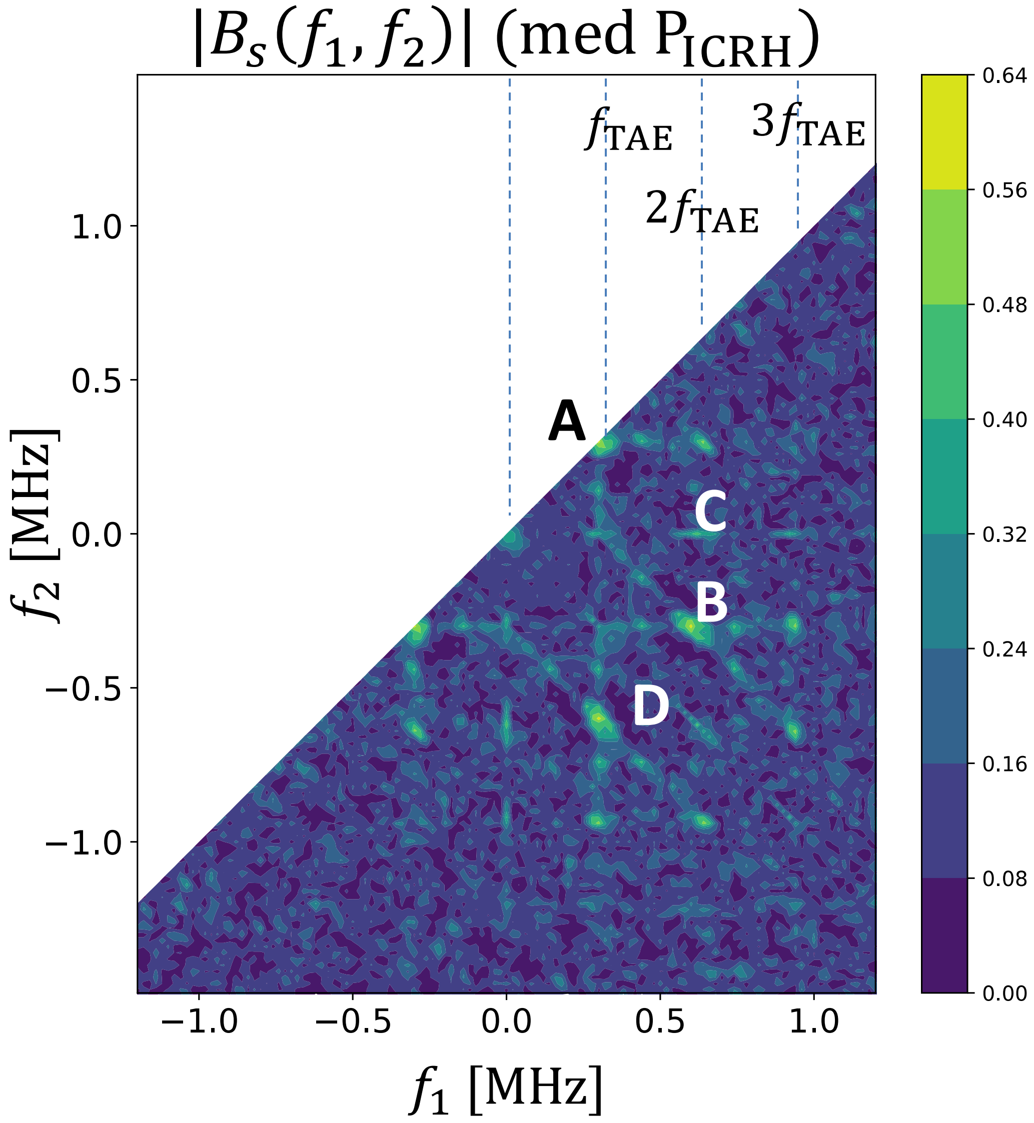
At medium P_{ICRH}, bicoherence exhibits three-wave matching relations at f_{TAE}, $2f_{TAE}$, $3f_{TAE}$ and a zero-frequency fluctuation



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

  → 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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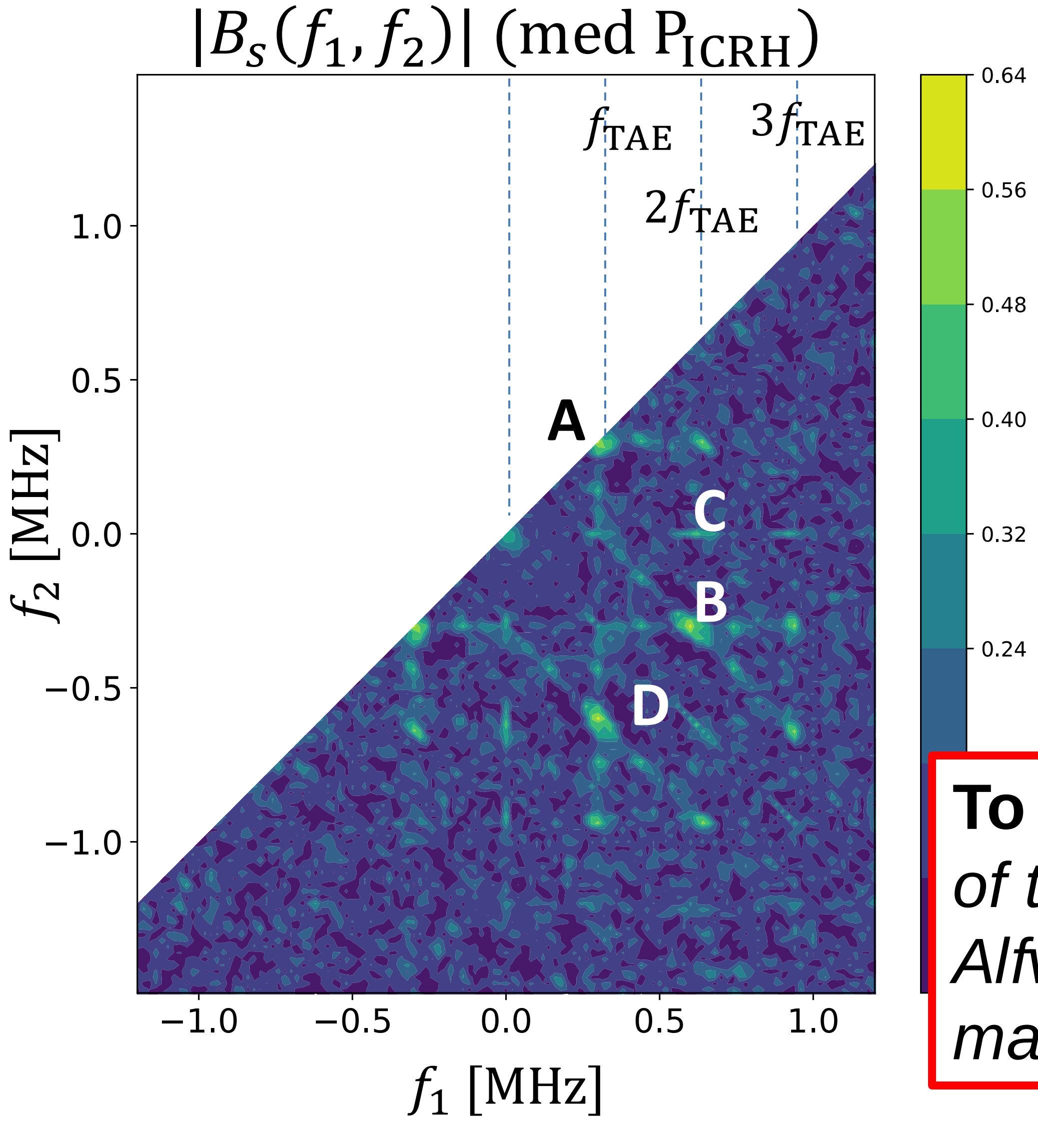

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To our knowledge: *first experimental measurement of three-wave phase matching relationship between Alfvénic modes and a zero-frequency fluctuation in a magnetically confined plasma*

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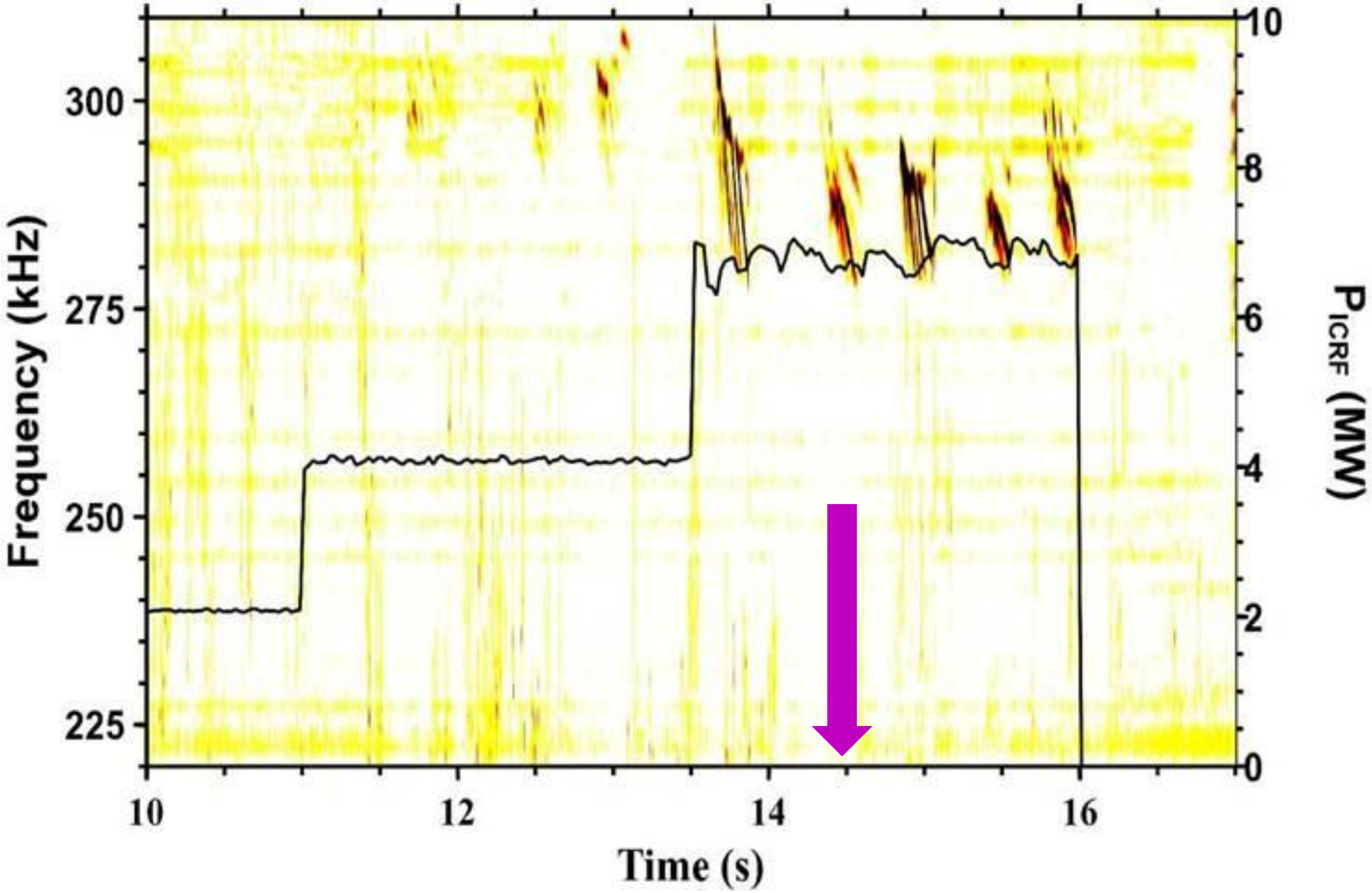
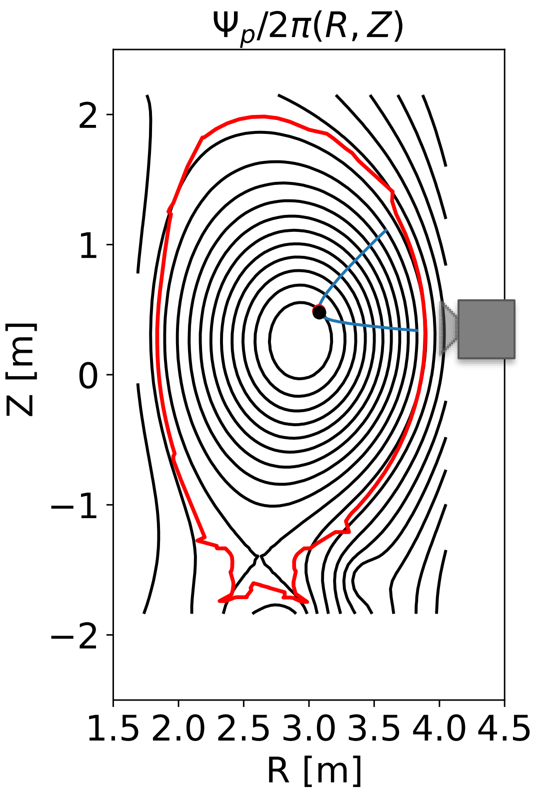
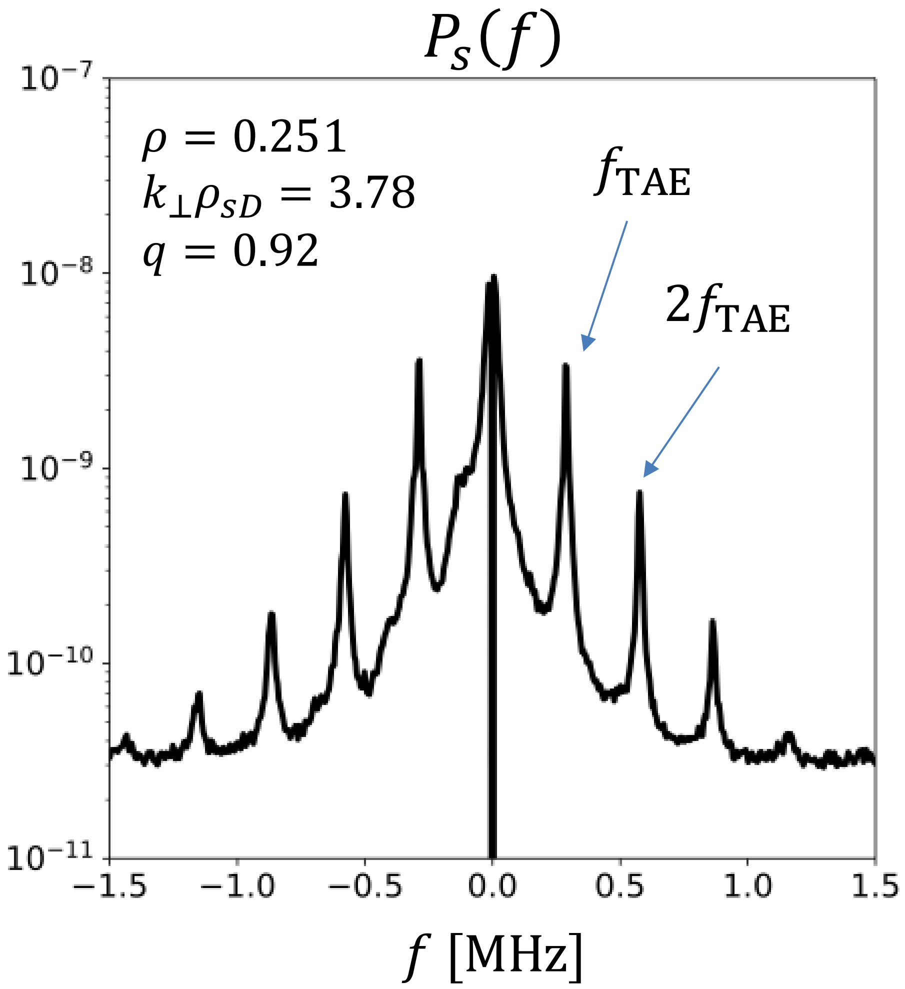
DBS measurements at high ICRH power



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





- Modes in higher gaps (up to $5f_{\mathrm{TAE}}$) inside q=1 surface (and persist outside)

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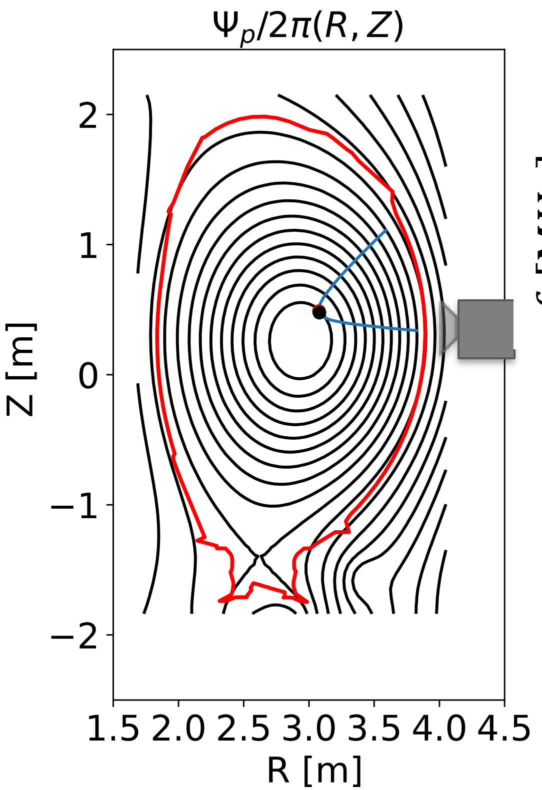

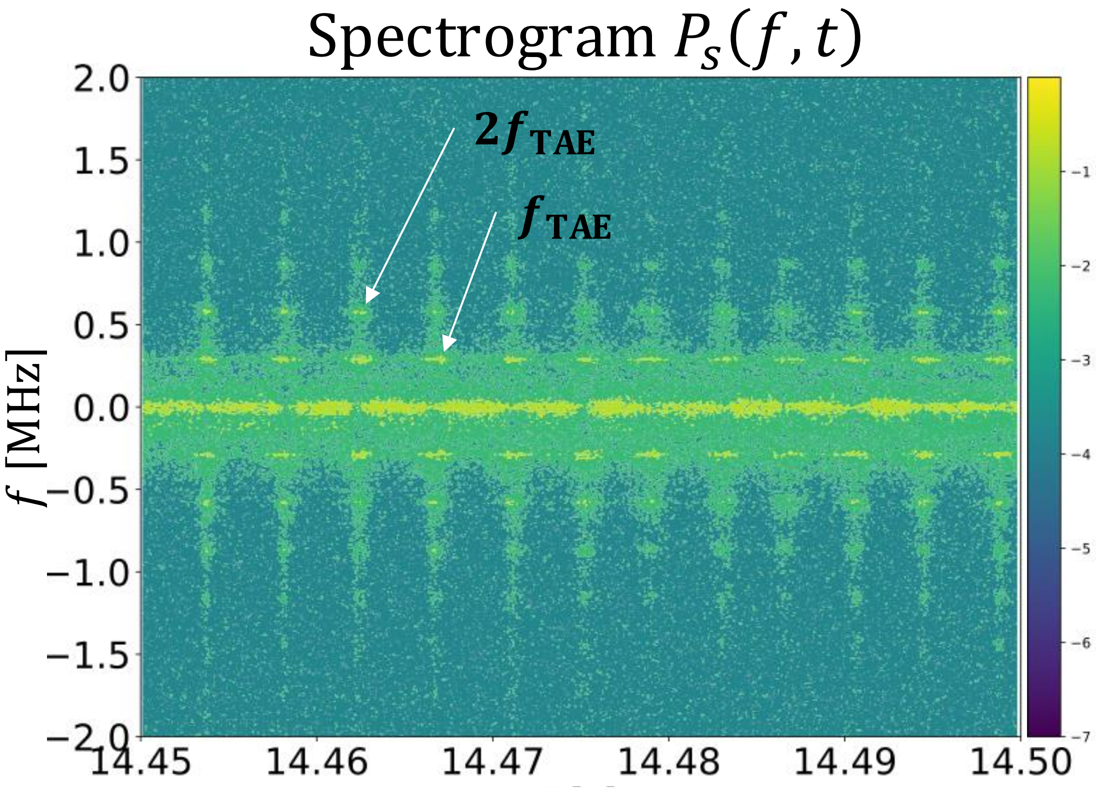

- Modes in higher gaps (up to $5f_{\mathrm{TAE}}$) inside q=1 surface (and persist outside)
- Bursts of the Alfvénic modes ($\Delta t \approx 4$ ms). *Are higher gap modes sidebands?*

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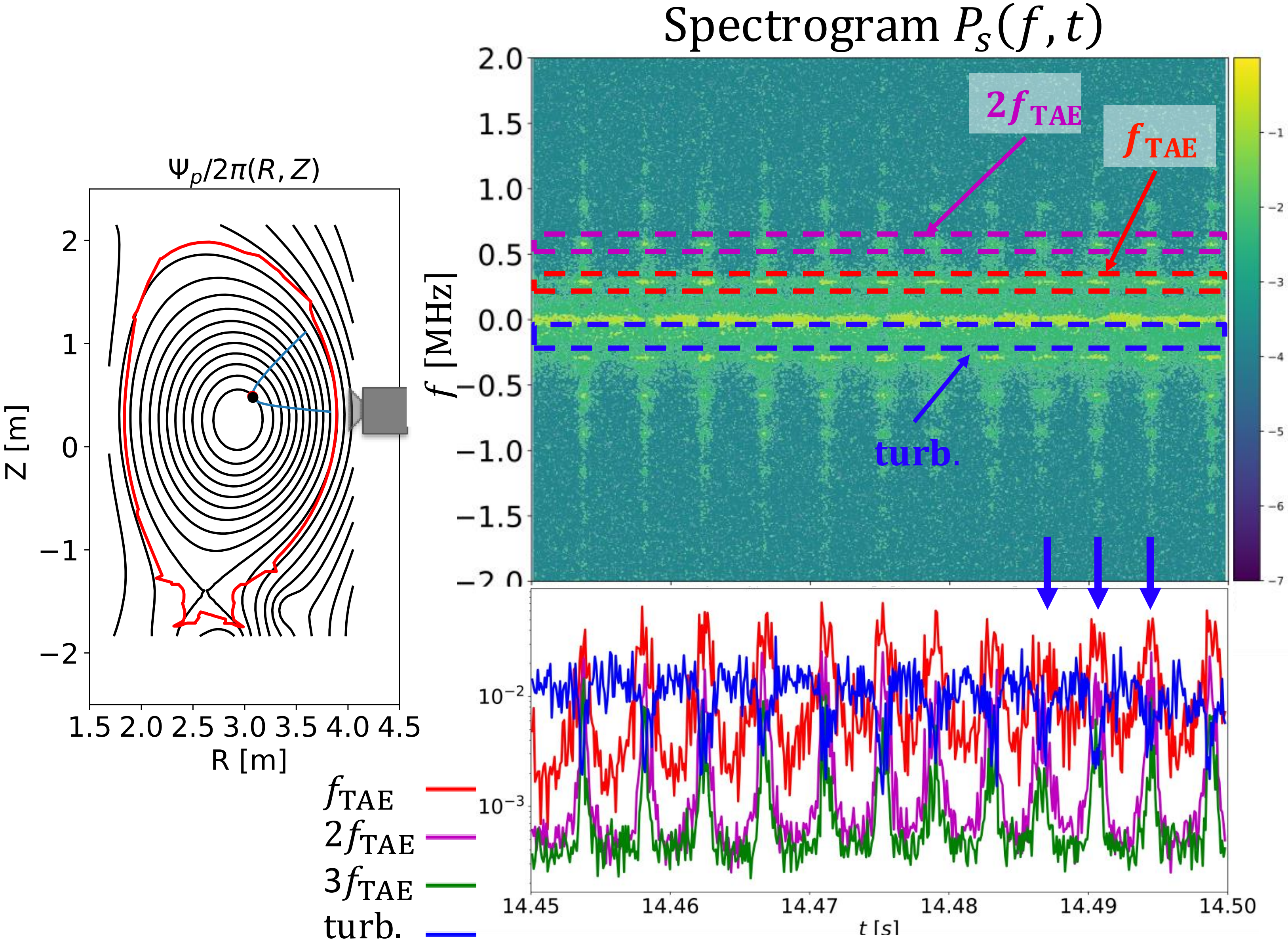

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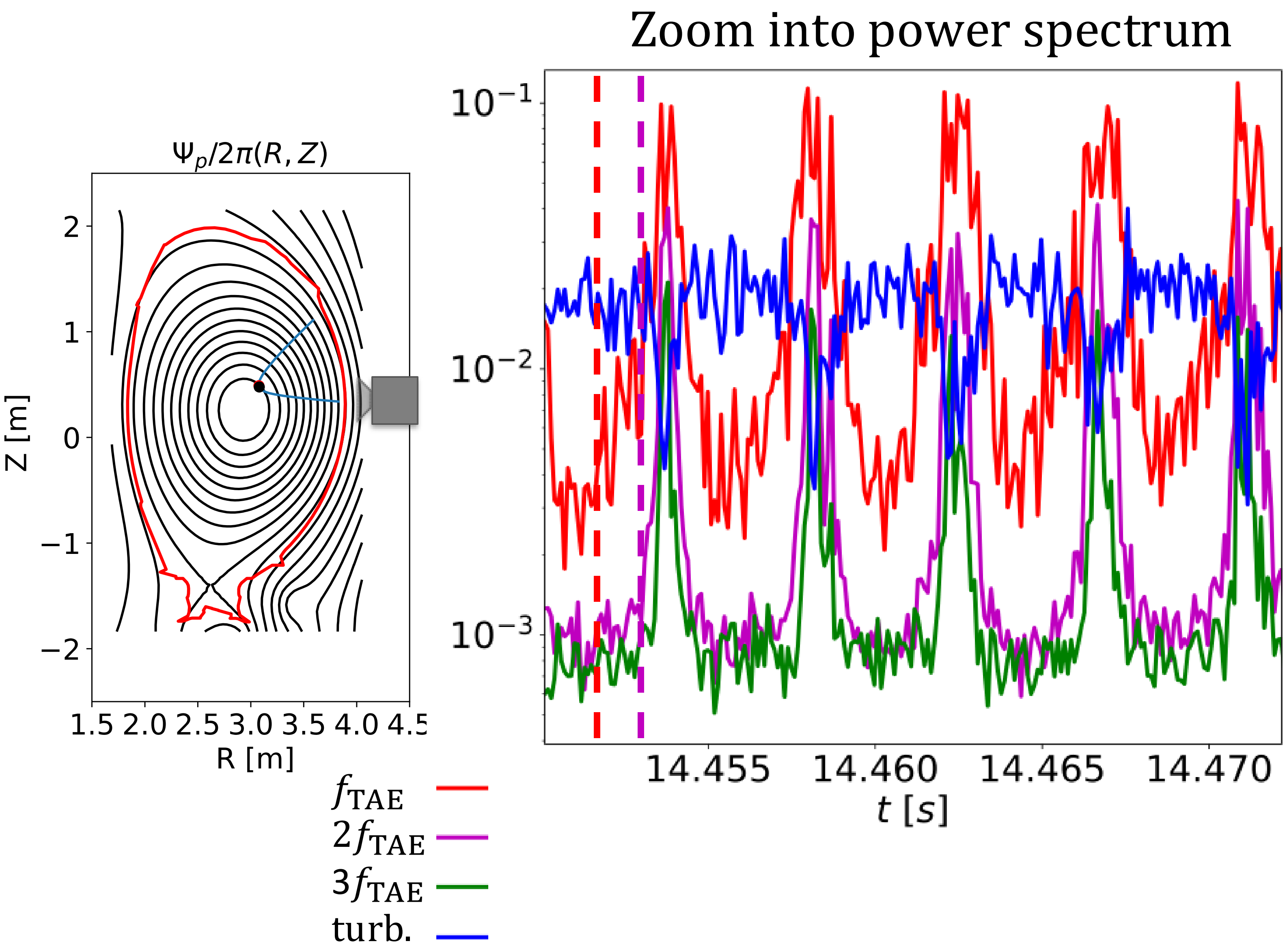

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- Power in **turbulence** frequencies ($f < 200$ kHz) decreases during bursts (predator-prey behavior?)
- ***Causality****: fundamental TAE* ***precedes*** higher gap modes & turb. stabilization

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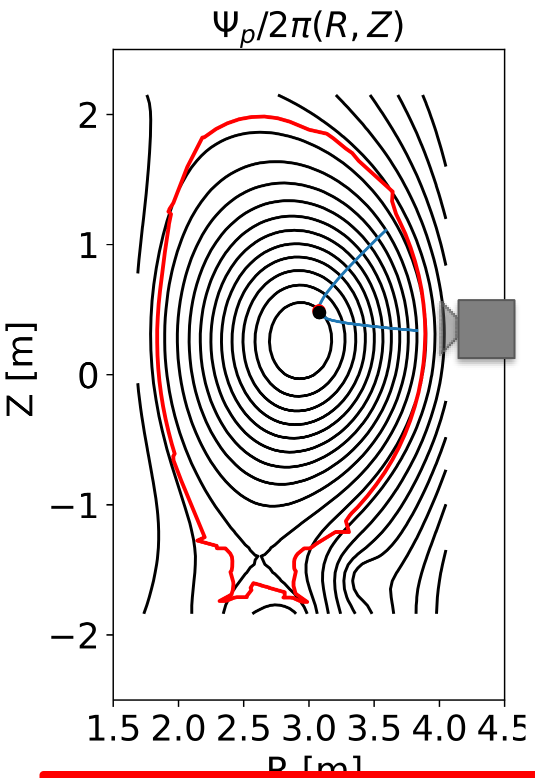

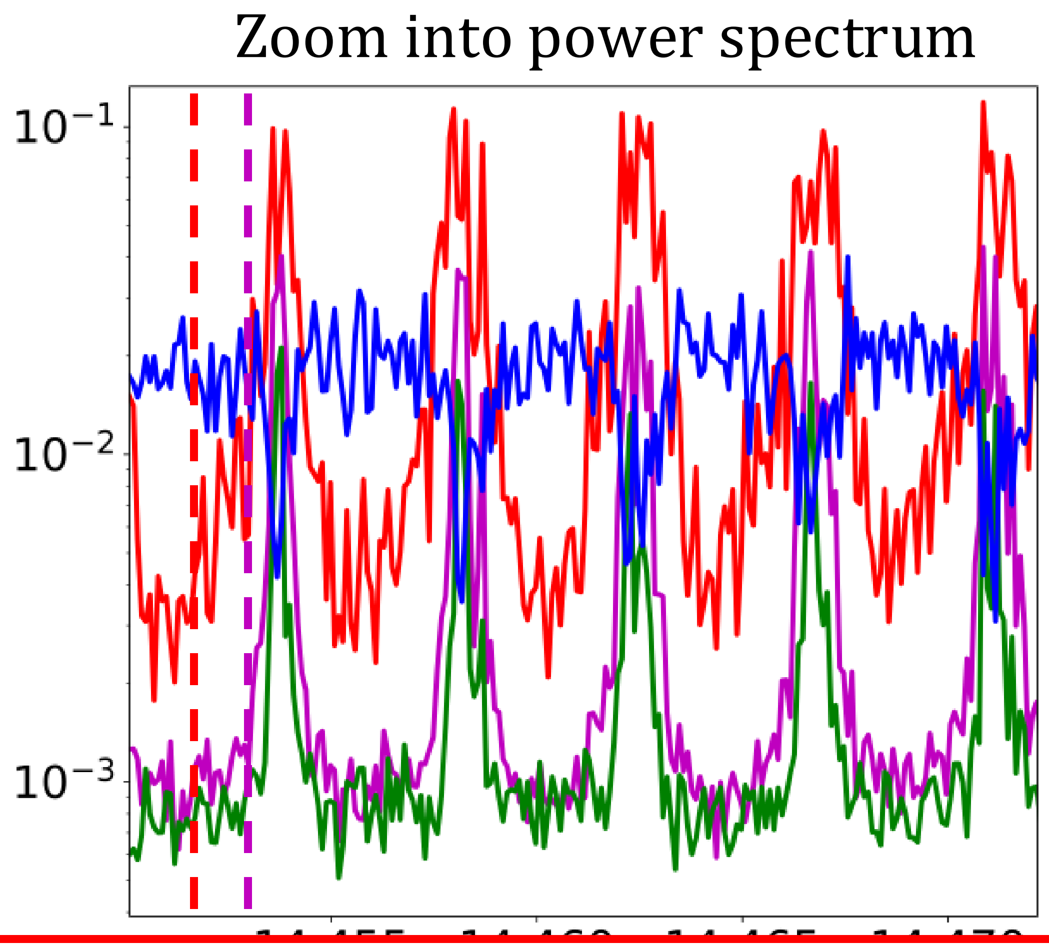

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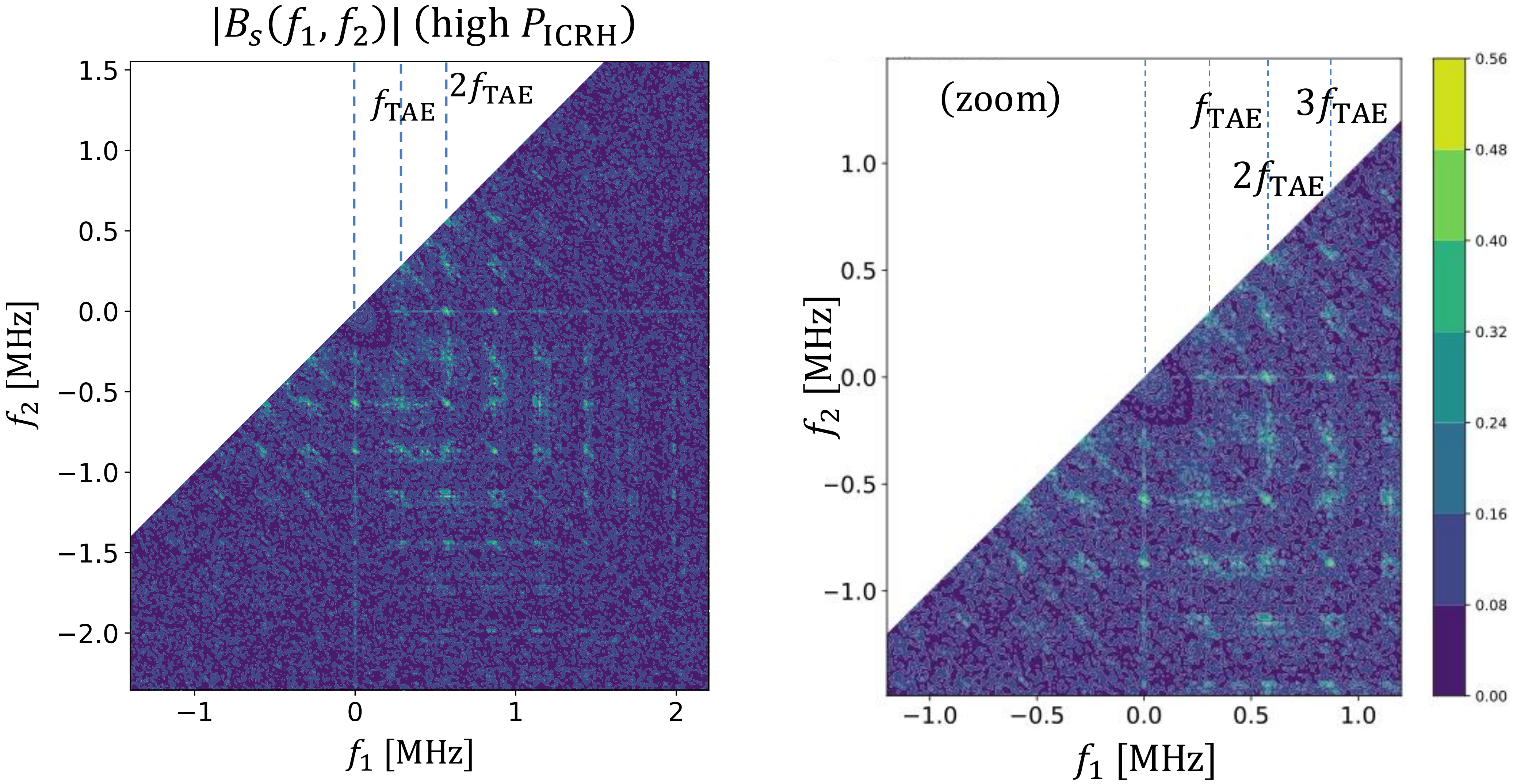
TAE in fundamental gap ***f_{TAE}*** ***precedes*** *modes in higher gaps and turbulence stabilization → suggests predator-prey behavior TAE-turbulence-(zonal flow)*

turb.

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



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

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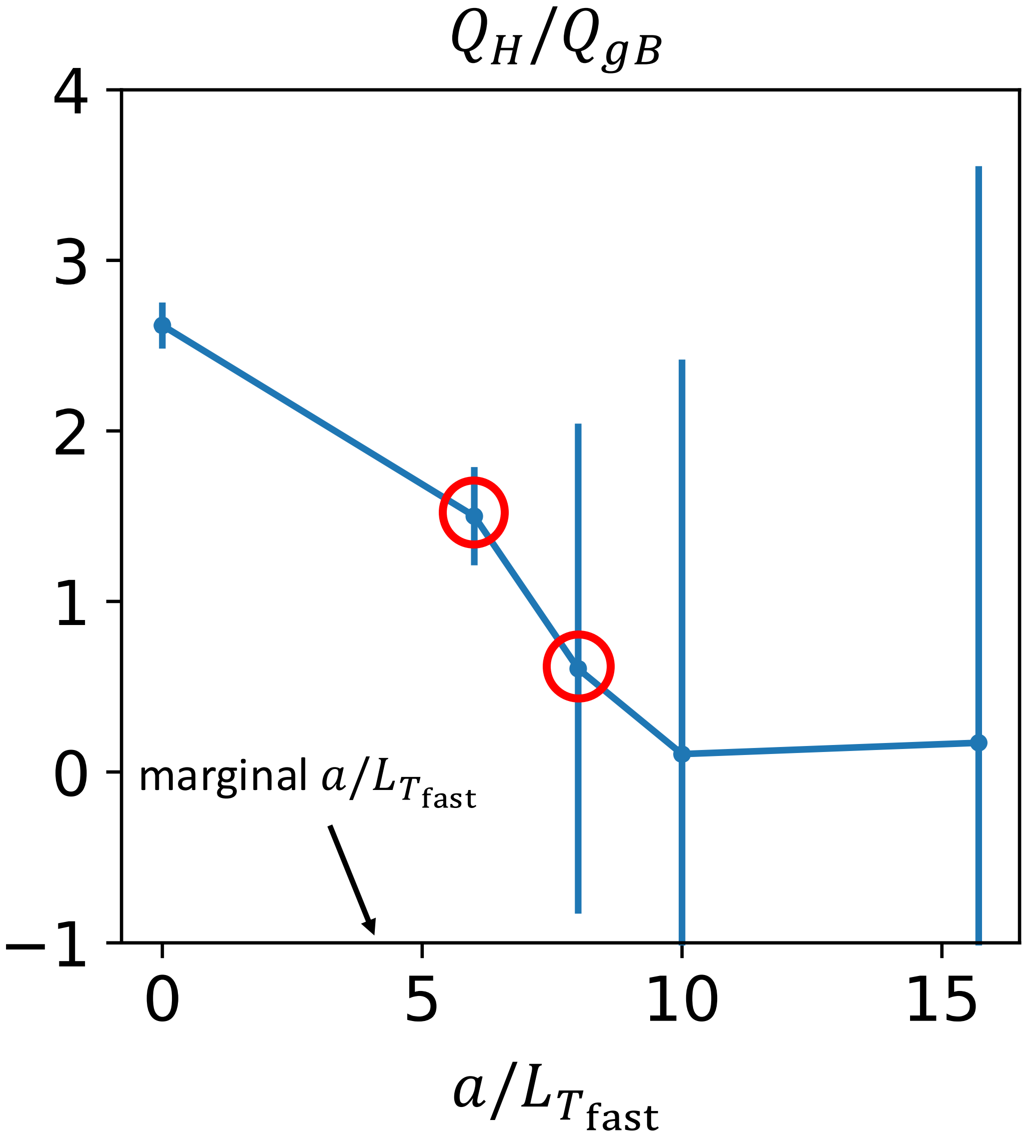
Local nonlinear CGYRO for high P_{ICRH}: turbulence is stabilized when the AE is driven unstable



- 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 $a/L_{T_{\mathrm{fast}}} \gtrsim 4$ (marginal AE instability)

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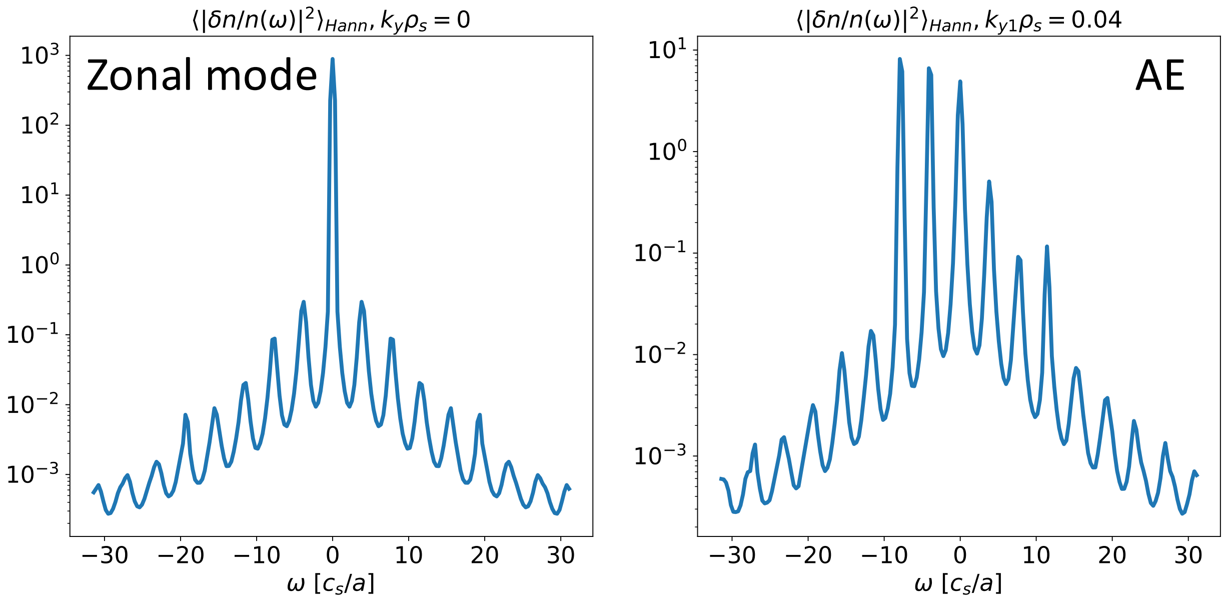
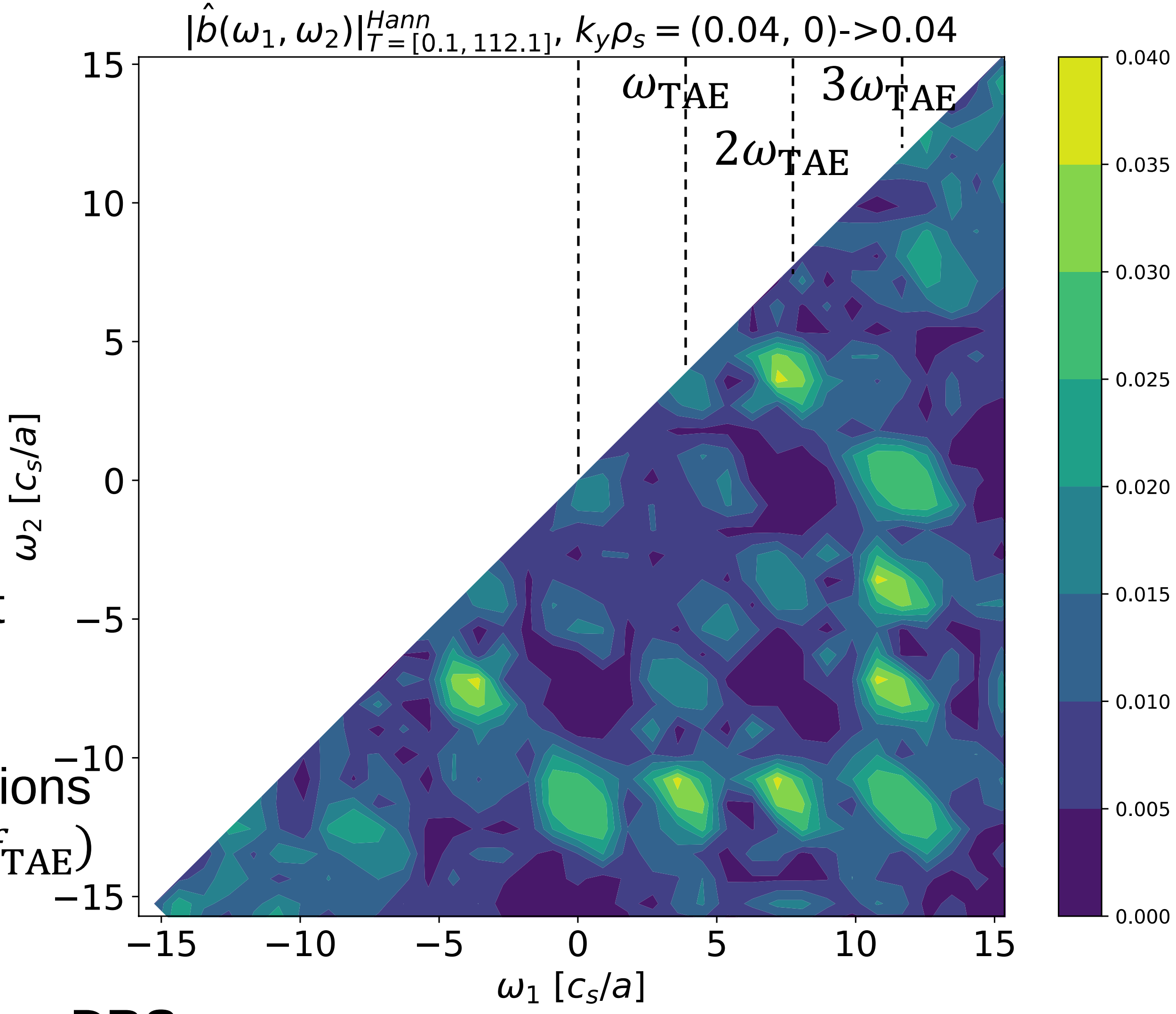
Density power spectrum and bicoherence at $a/L_{Tfast} = 6$ (low drive) exhibits harmonics of f_{TAE} and dominant mode-mode interactions



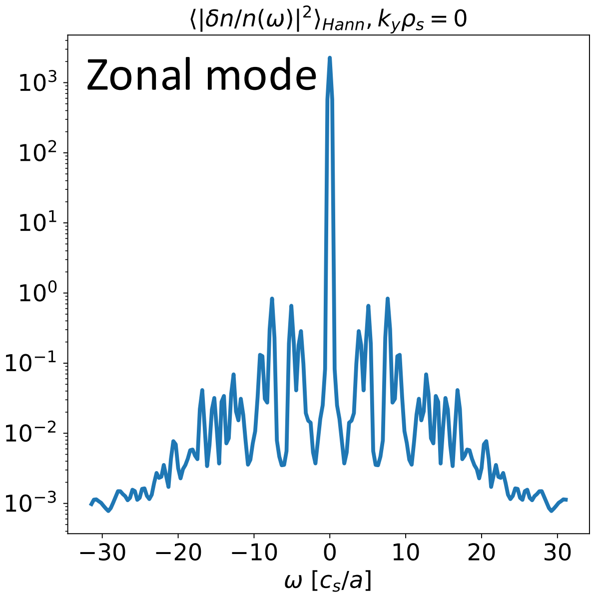
- Zonal δn_e response exhibits large $f = 0$ component
- AE is unidirectional, exhibits harmonics of f_{TAE}

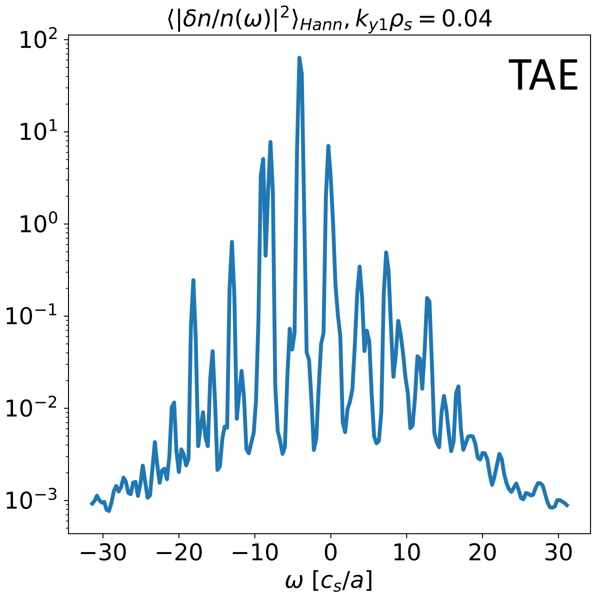
- Bicoherence exhibits dominant mode-mode interactions $(\pm 2f_{\mathrm{TAE}}, \pm f_{\mathrm{TAE}})$, $(\pm 3f_{\mathrm{TAE}}, \mp f_{\mathrm{TAE}})$, and $(\pm 3f_{\mathrm{TAE}}, \mp 2f_{\mathrm{TAE}})$
- Subdominant $(\pm 3f_{\mathrm{TAE}}, 0)$

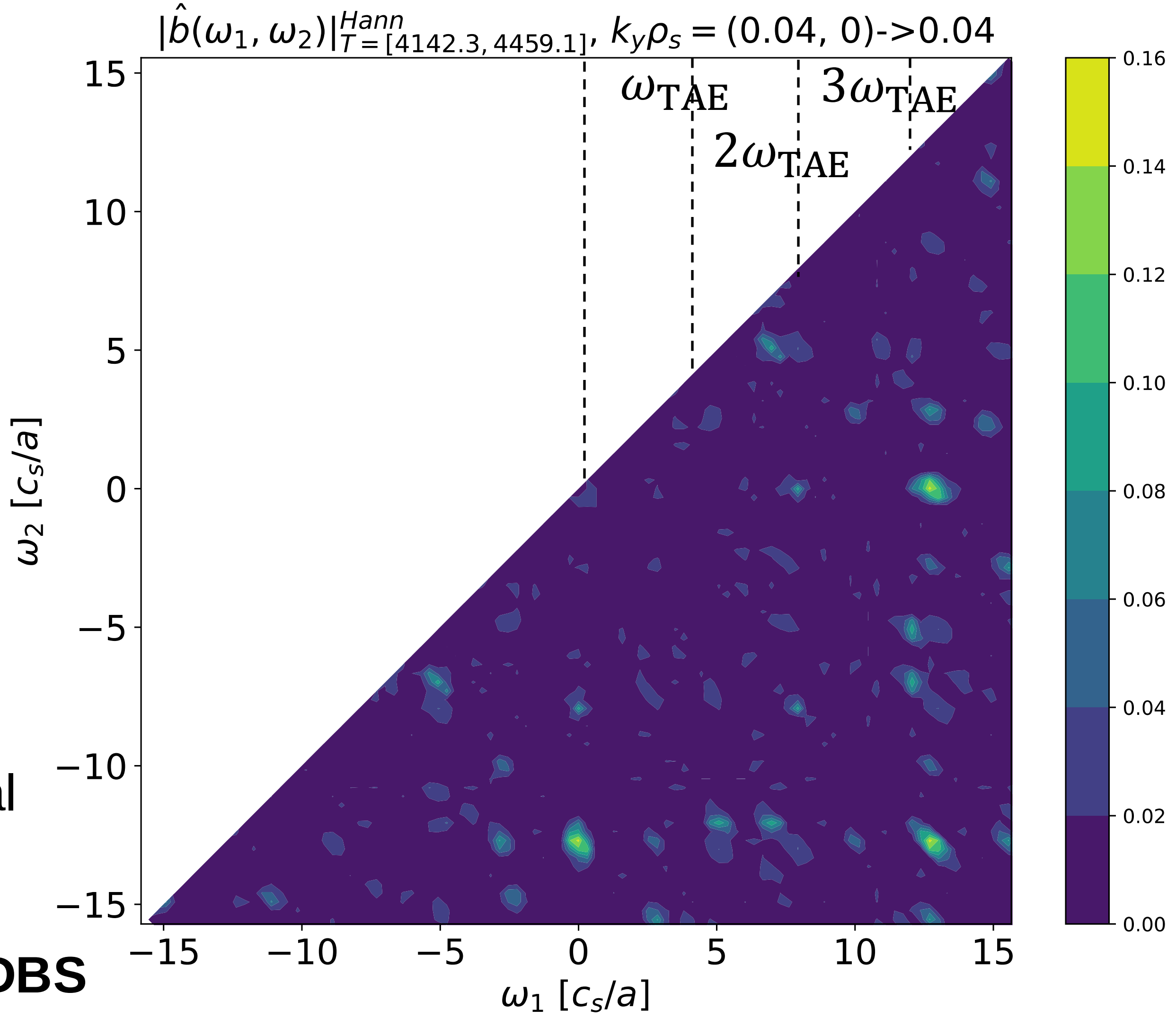
- **Consistent with medium P_{ICRH} measurements from DBS**



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

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 χ_i → **enhanced total 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 AEs*

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