High-energy fast ions drive BAEs unstable but not BAAEs

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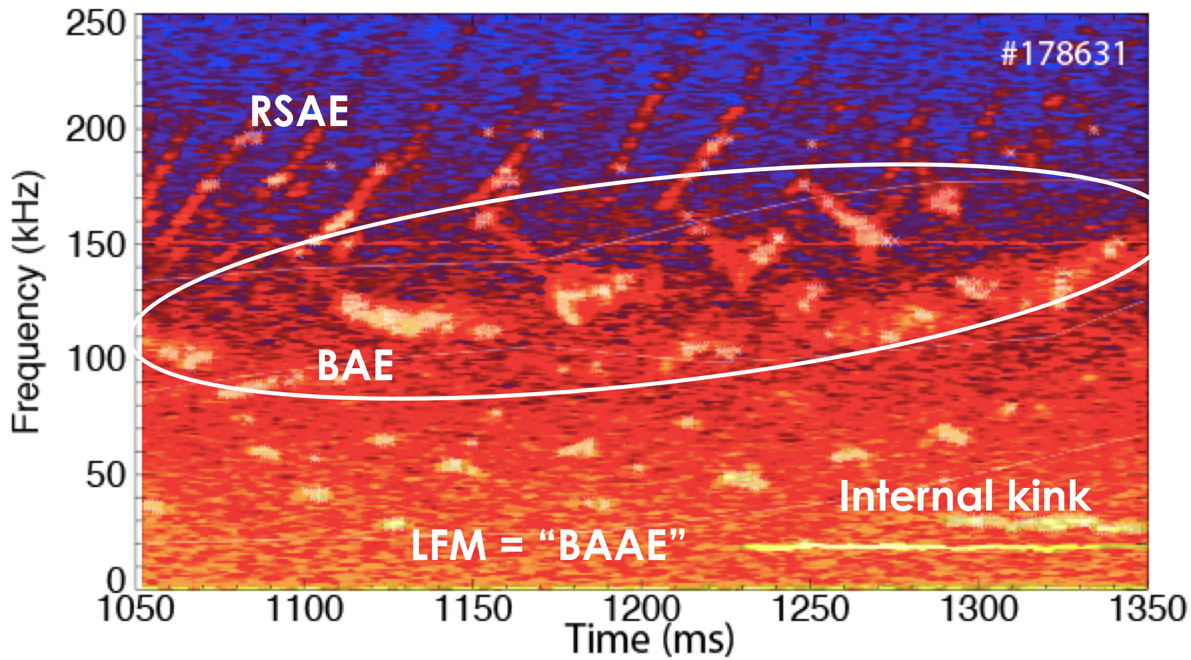

1. Heidbrink et al., *'BAAE' instabilities observed without fast ion drive*, NF 61 (2021) 016029
2. Heidbrink et al., *Stability of beta-induced Alfvén eigenmodes (BAE) in DIII-D*, NF 61 (2021) submitted.
3. Gyungjin Choi et al., *Gyrokinetic simulation of low-frequency Alfvénic modes in DIII-D tokamak*, NF 61 (2021) in press.

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Conclusions

1. Beta-induced Alfvén eigenmodes (BAE) are driven unstable through resonances with high-energy (~ 80 keV) beam ions
2. BAEs are more unstable near rational values of qmin
3. The modes previously called Beta-induced Alfvén-acoustic eigenmodes (BAAE) were misidentified—we now call them low frequency modes (LFM)
4. LFMs are <u>not</u> driven by high-energy fast ions
5. LFMs occur near rational values of qmin in plasmas with high electron temperature but low beta
6. BAE mode properties are adequately described by established theory
7. LFMs are probably a low frequency reactive instability of predominately Alfvénic polarization
8. BAEs & LFMs are as unstable in hydrogen plasmas as deuterium plasmas

Fast-ion driven low frequency modes are dangerous

- Modes with frequencies below RSAEs are often unstable on existing devices
- Empirically, they are correlated with substantial fast-ion transport
- Theoretically, $\boxed{n\Delta E = \omega \Delta P_\phi}$

n toroidal mode number
ΔE energy exchanged with the wave
ω wave frequency
ΔP_ϕ change in toroidal canonical angular momentum

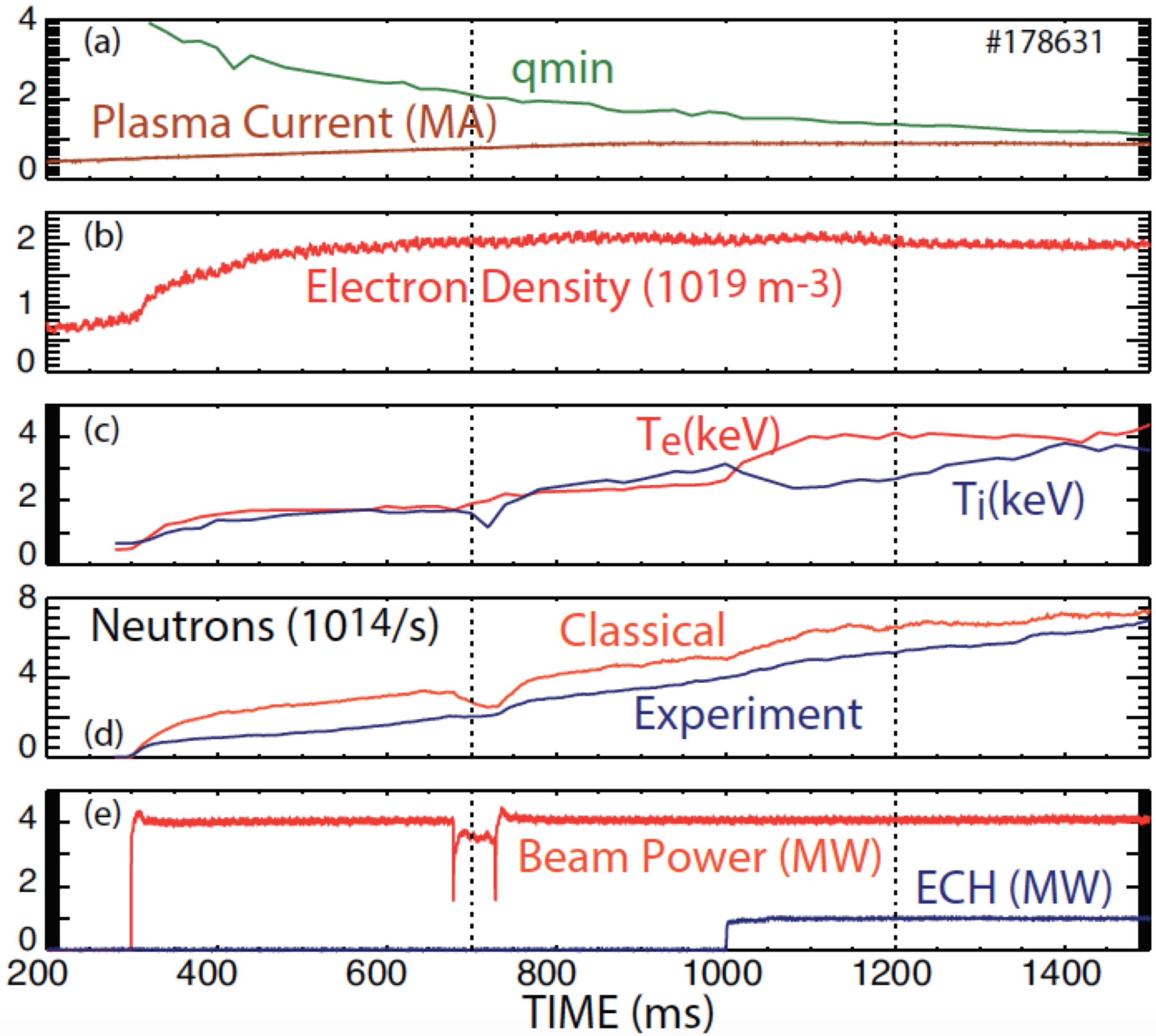
→ if a low-frequency mode effectively resonates with a fast ion, the spatial transport is large.

Goal of Dedicated Experiment

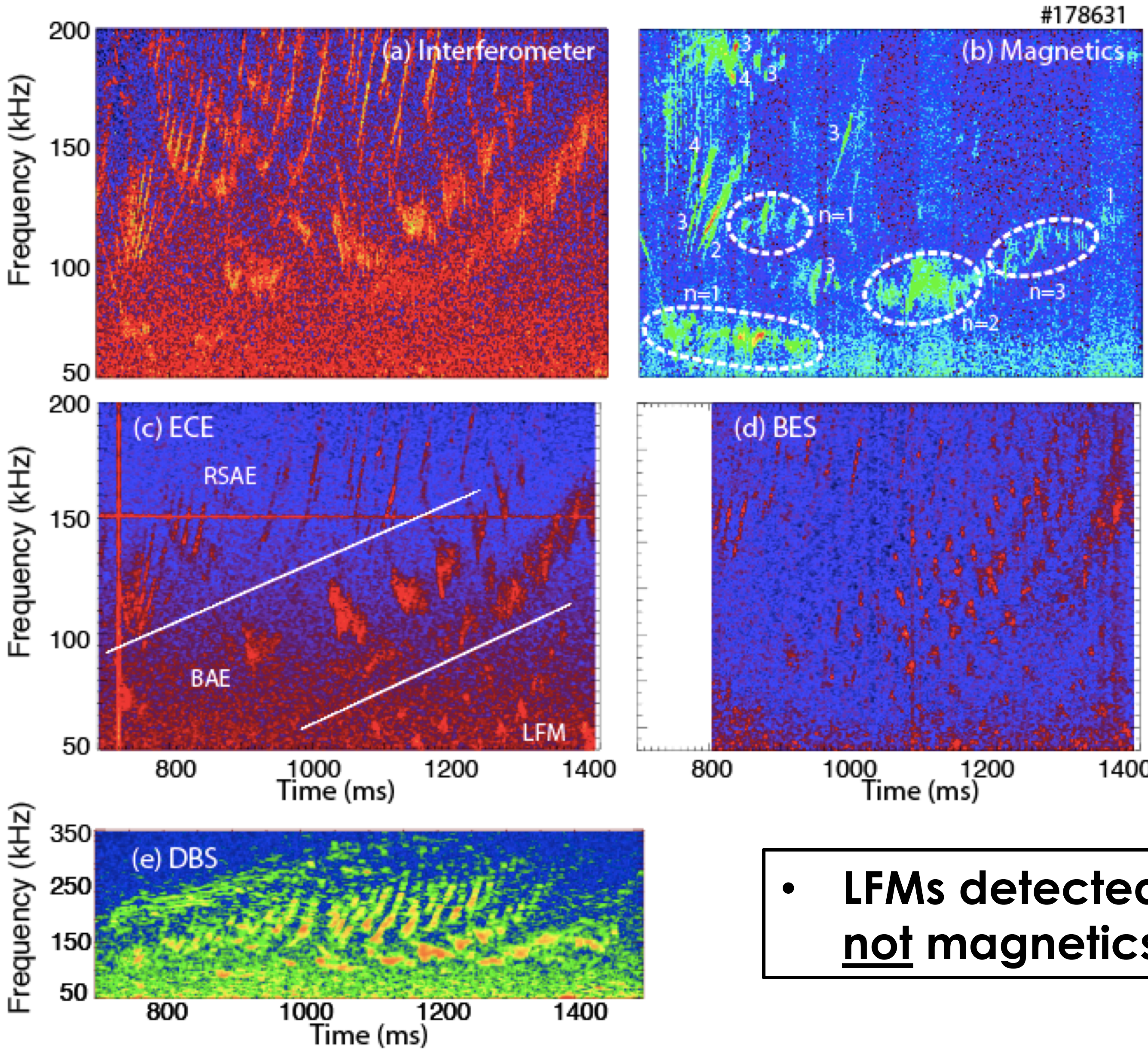
Understand the stability of beta-induced Alfvén-acoustic eigenmodes (BAAE) and beta-induced Alfven eigenmodes (BAE)

The current ramp phase of the discharge scans q_{min}

- **Two deuterium co-tangential beams throughout except for brief periods**
- **Reproducible qmin evolution**



Multiple fluctuation diagnostics detect the BAEs



ECE=electron cyclotron emission

BES=beam emission spectroscopy

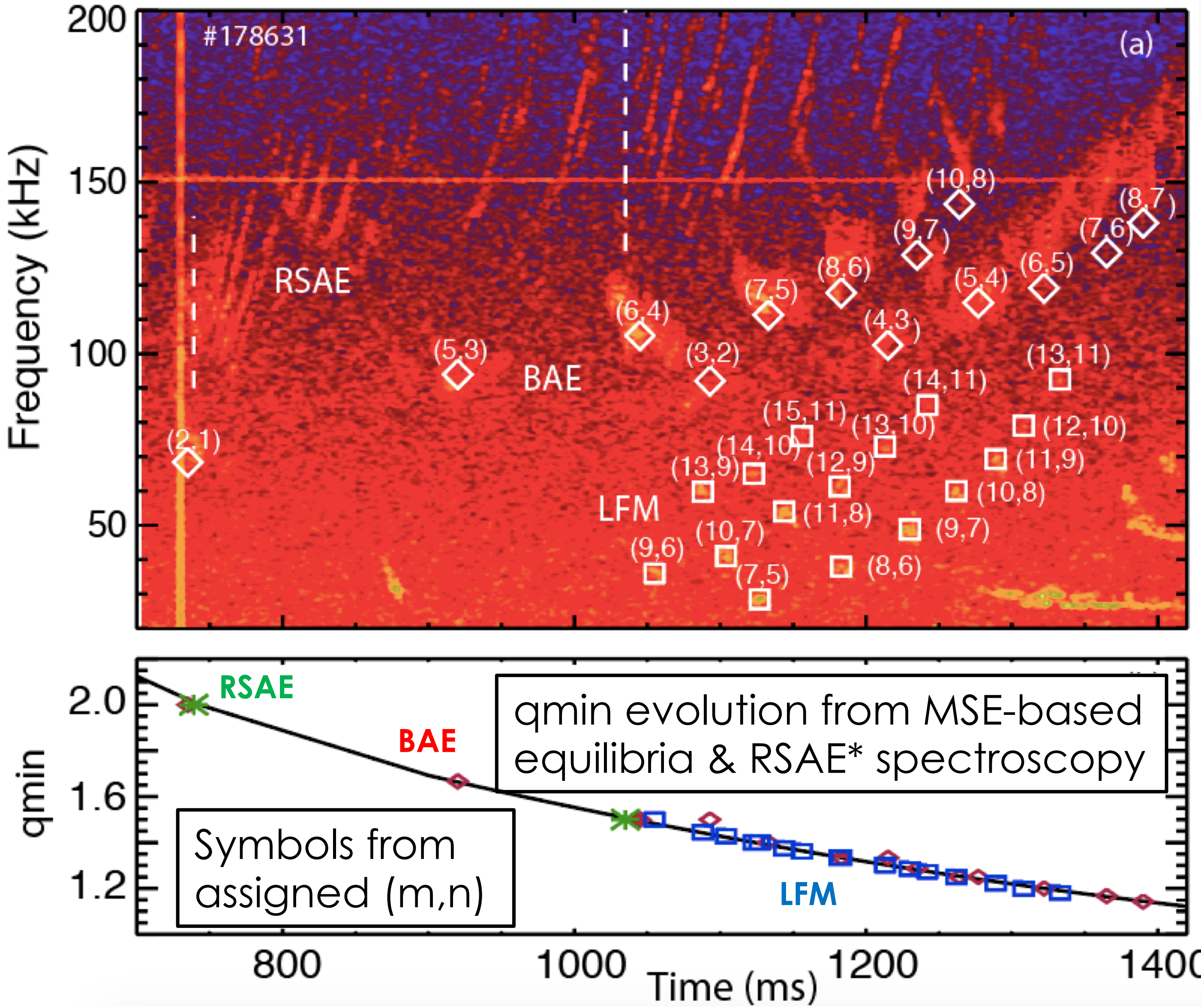
DBS=Doppler backscattering

- **BAEs chirp rapidly in frequency**

- **LFMs detected by ECE & BES but <u>not</u> magnetics**

BAEs & LFMs occur near rational values of qmin

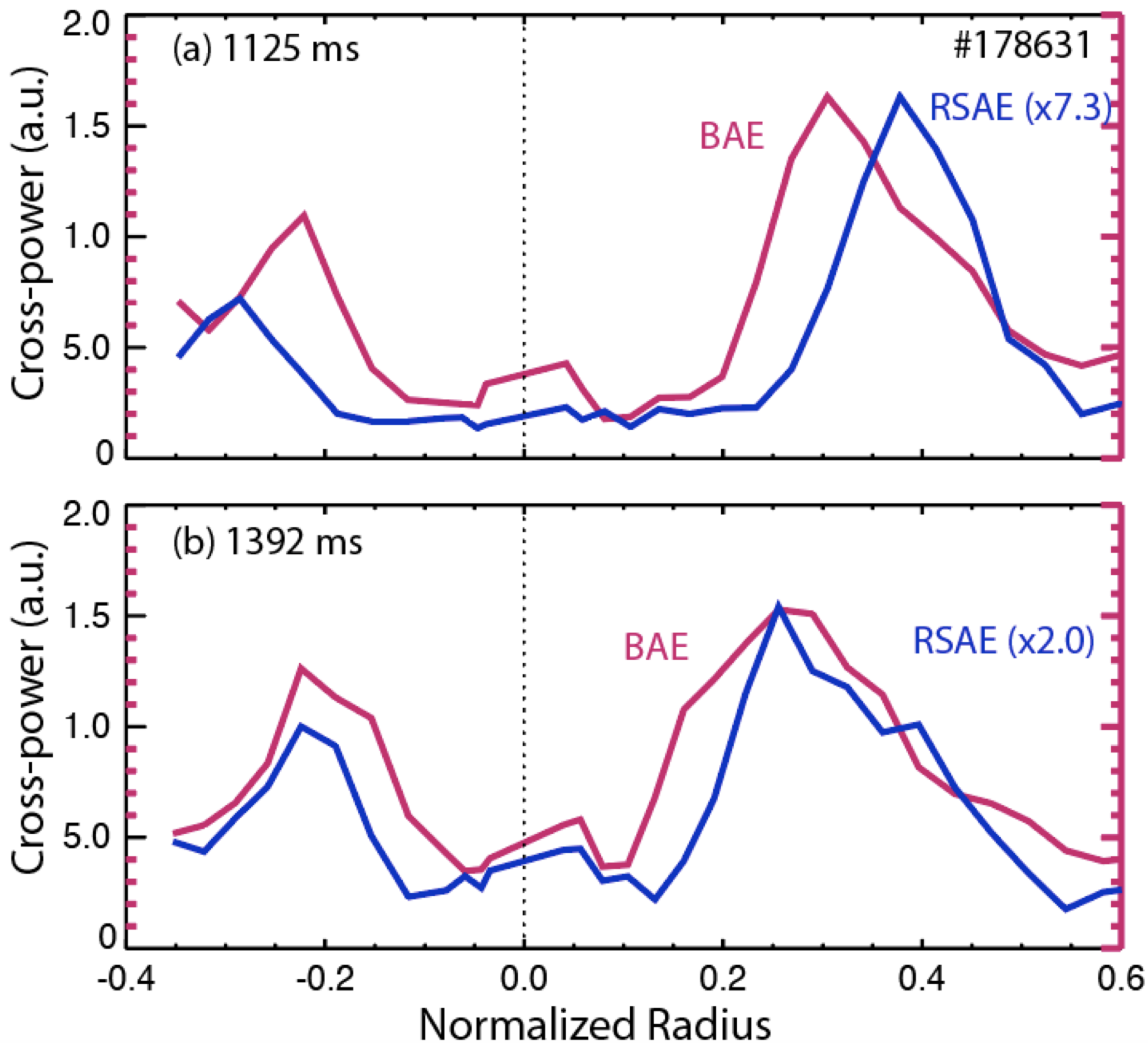
- BAE frequencies near BAE accumulation frequency
- LFM frequency near zero (in plasma frame)
- BES data confirm poloidal mode numbers *m* for LFMs
- Magnetics data confirm toroidal mode numbers *n* for BAEs



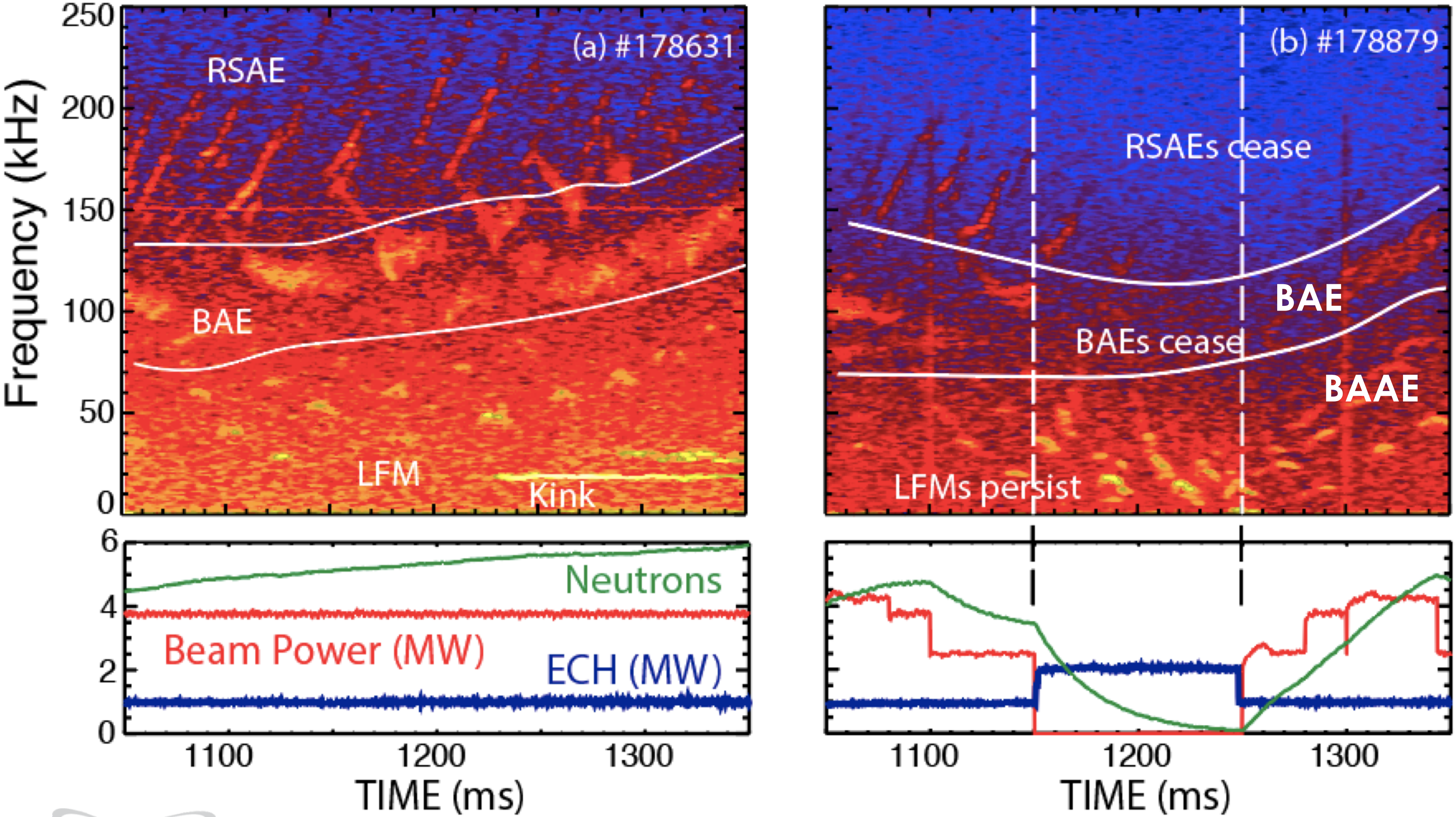
*RSAE = Reversed shear Alfven eigenmode

The eigenfunctions peak near qmin

- **The eigenfunction often peaks closer to the magnetic axis than the RSAEs and LFMs (but not always)**
- **LFMs peak near RSAEs**
- **Mode amplitude $\delta T_e \approx 10$ eV**

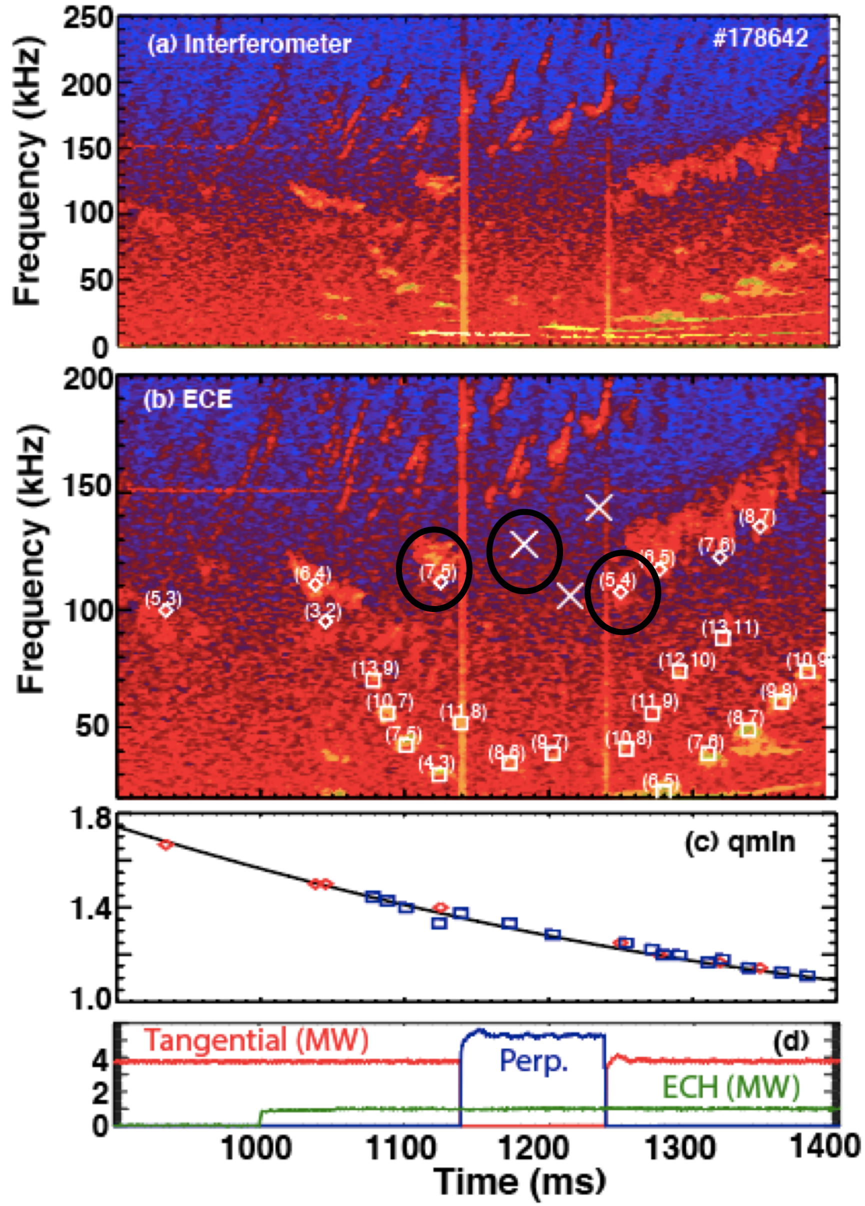


Turning off beams stabilizes BAEs but not LFMs

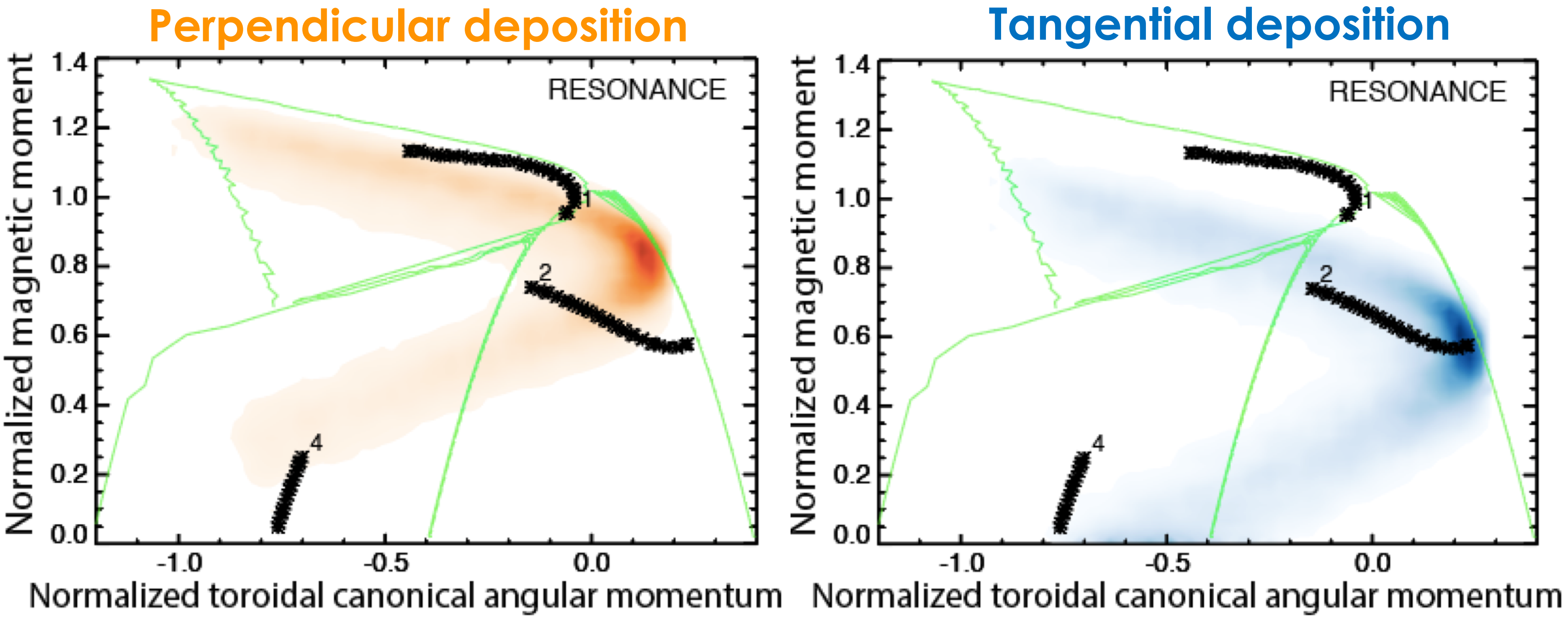


Substitution of perpendicular beams for tangential beams stabilizes BAEs

- LFMs & RSAEs remain unstable
- Slowing-down time: ~100 ms
- The same thing happens for beam substitution earlier in the discharge



Beam-angle dependence of BAEs consistent with resonant condition



- **87 kHz n=2 mode resonates* with few ⊥ beam ions**
- **12 out of 13 unstable BAEs in the reference shot look similar**

*Resonance when:
1) $\omega = n\omega_\phi - p\omega_\theta$
2) Orbit traverses eigenfunction

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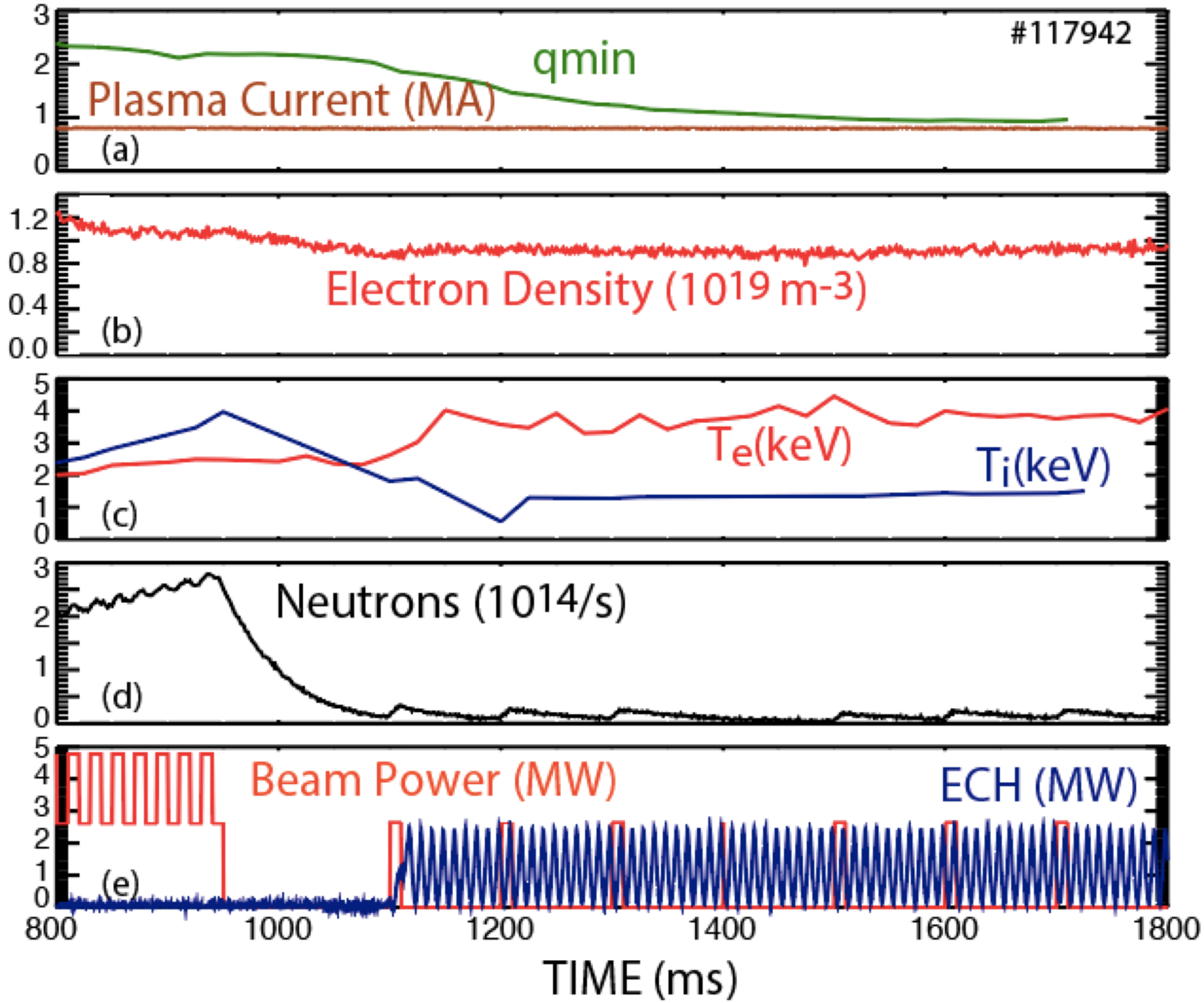
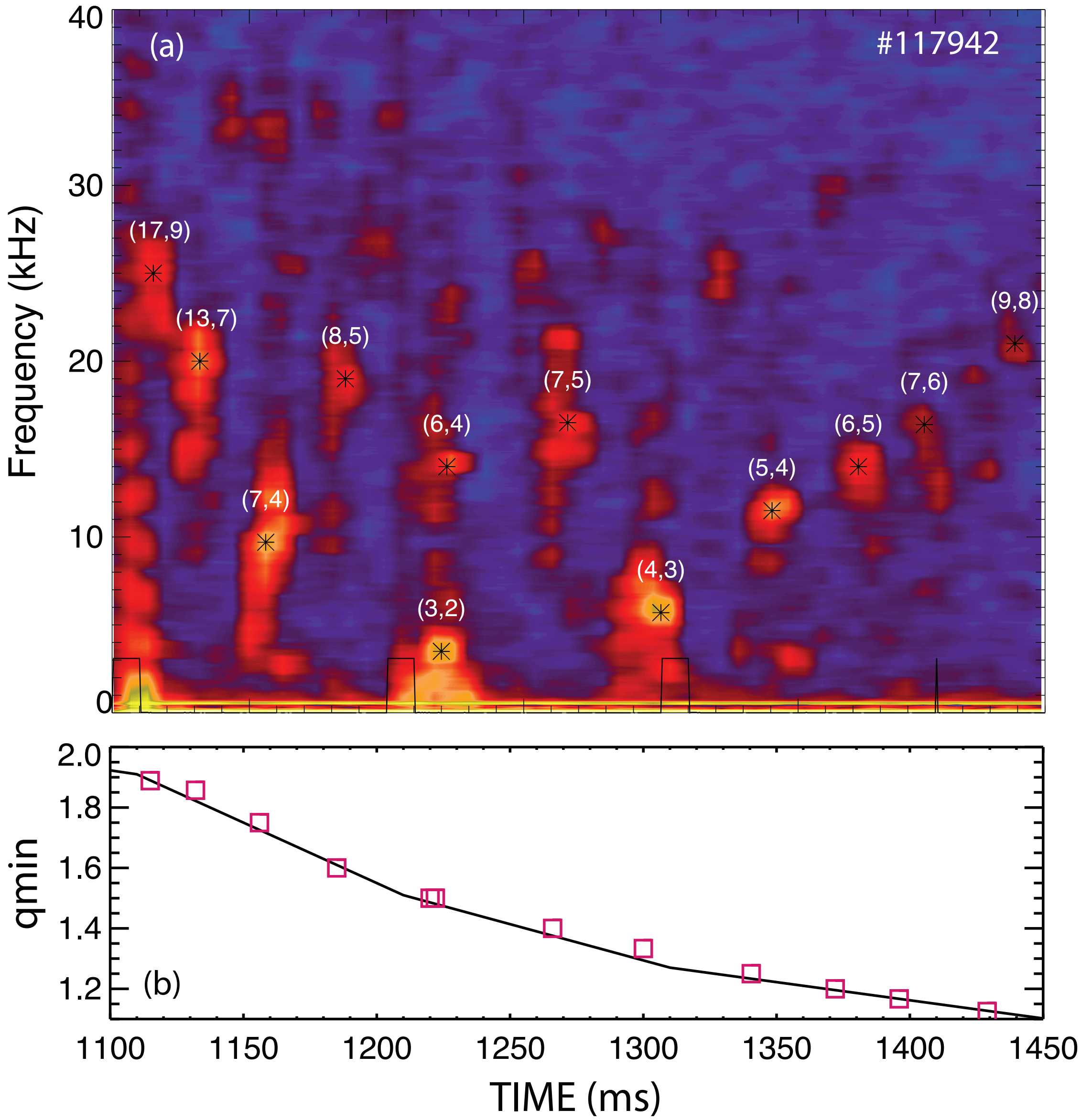
LFMs are observed in archival discharges with little or no beam power

- **Early beams establish weakly reversed q profile**

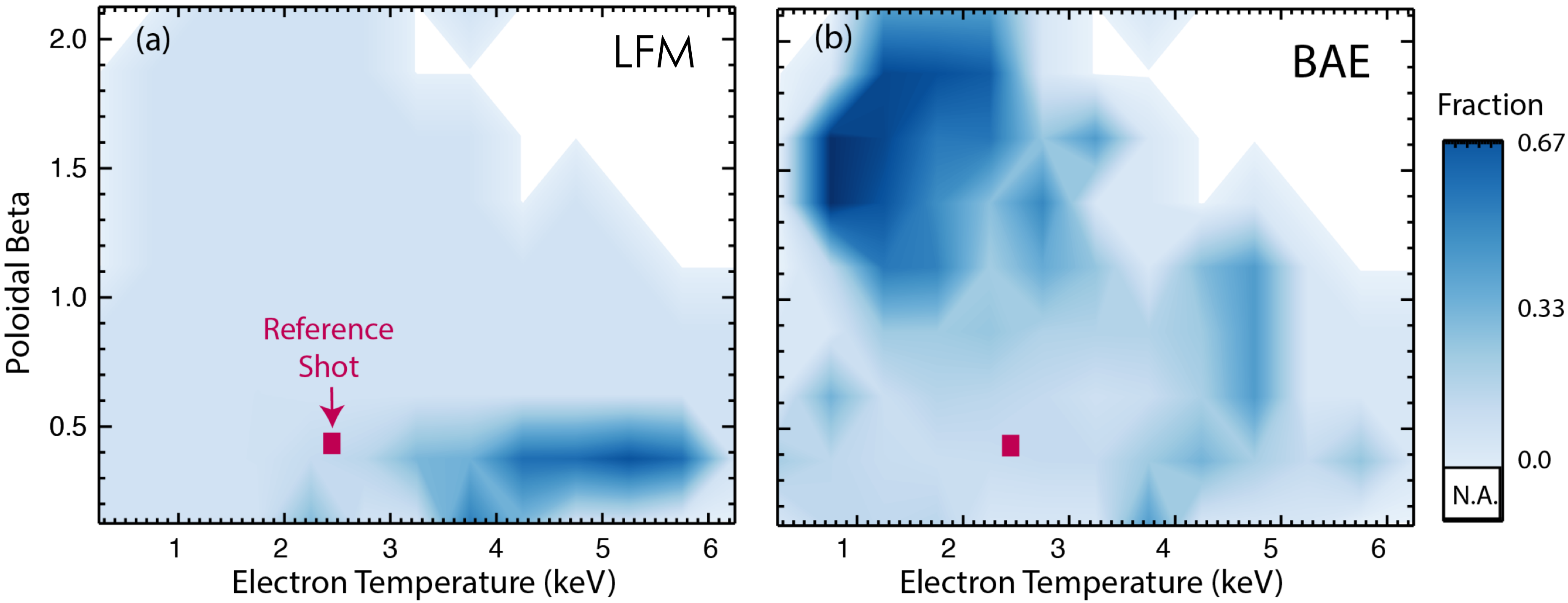


An LFM "Christmas light" pattern is observed in shots without beams

- Beam blips have no visible impact on modes
- Also occurs in shots without beam blips



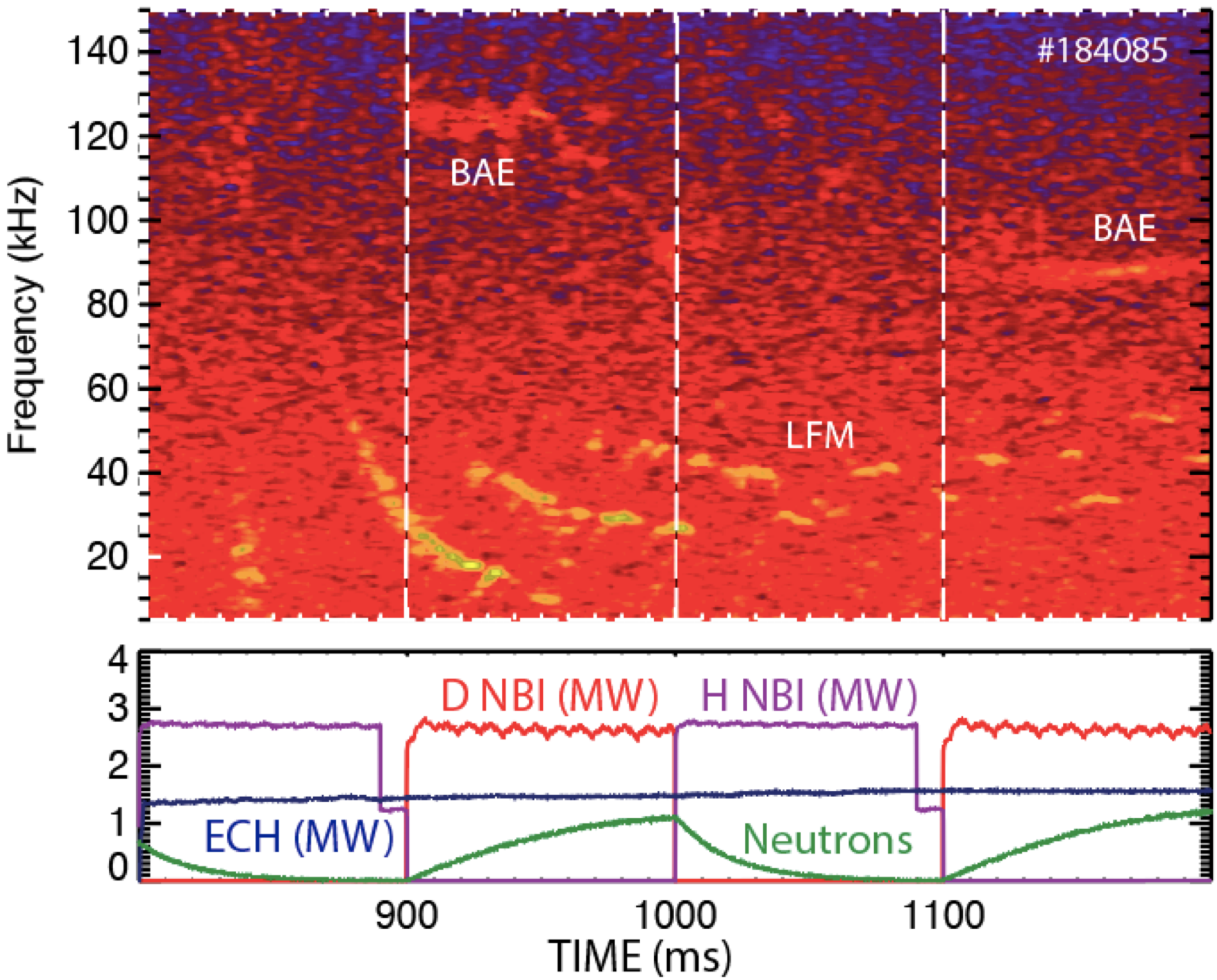
Unstable LFMs occur at high T_e but low β; BAEs favor high β



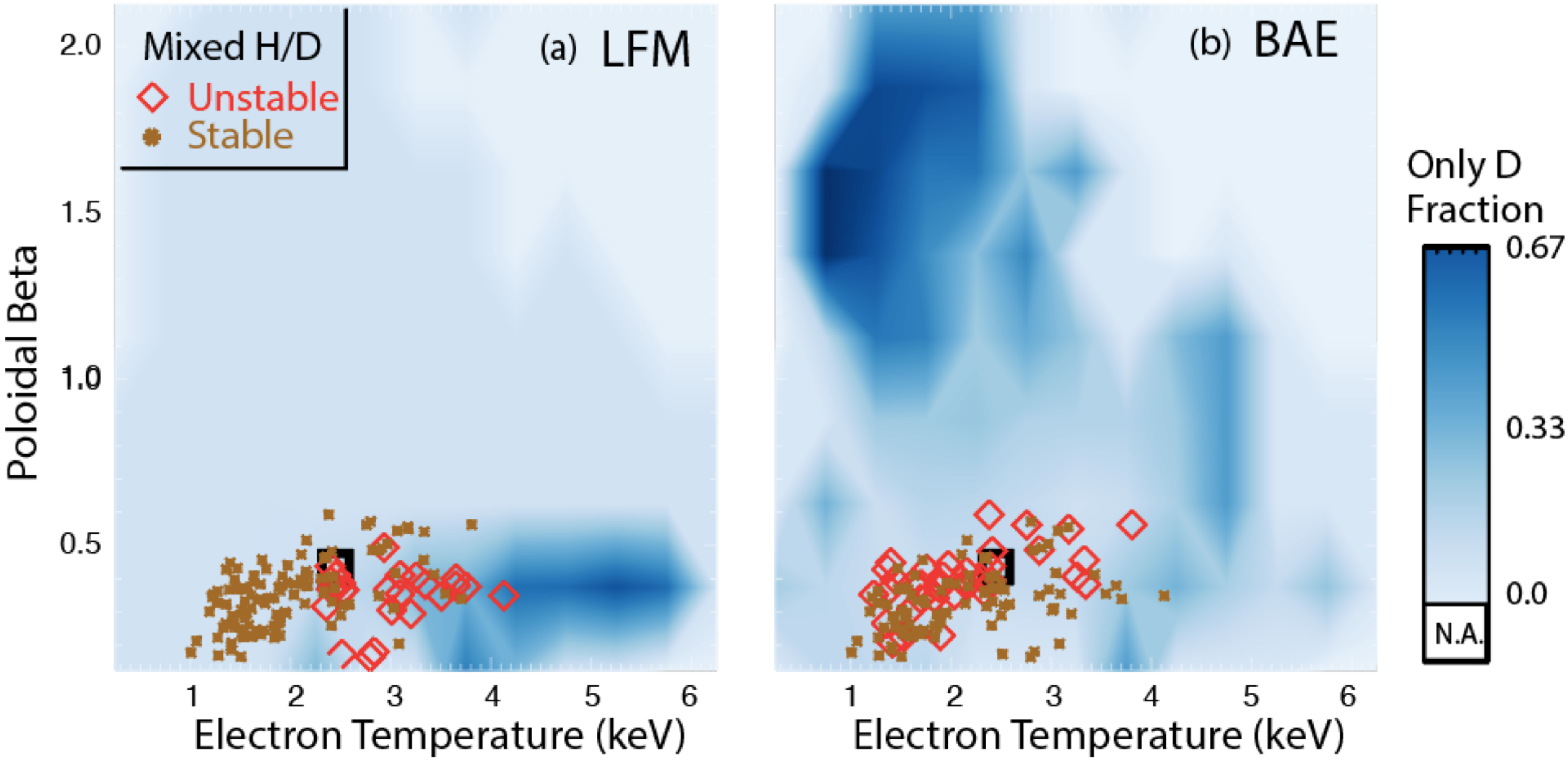
- **Large database of over 1000 discharges**
- **Restricted to deuterium beam heated discharges w/ evolving qmin**

Plasmas with substantial hydrogen concentrations are equally unstable

- **Similar conditions to dedicated experiment**



Plasmas with substantial hydrogen concentrations are equally unstable



Analytical theory* predicts a reactive LFM mode with properties consistent with observations

- Reactive instability (frequency near zero in plasma frame)
- Weak coupling to fast ions (modes observed without beams)
- Dominant thermal electron drive when $T_e \gg T_i$ (instability at large T_e but low beta)
- Mode in weak shear region near qmin (as observed)

Simulation

- GTC, FAR3d, LIGKA find unstable modes similar to BAE
- GTC & FAR3d find unstable modes similar to LFM
- Future work: realistic distribution function to reproduce observed stability threshold
- Future work: Apply validated code to ITER cases

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