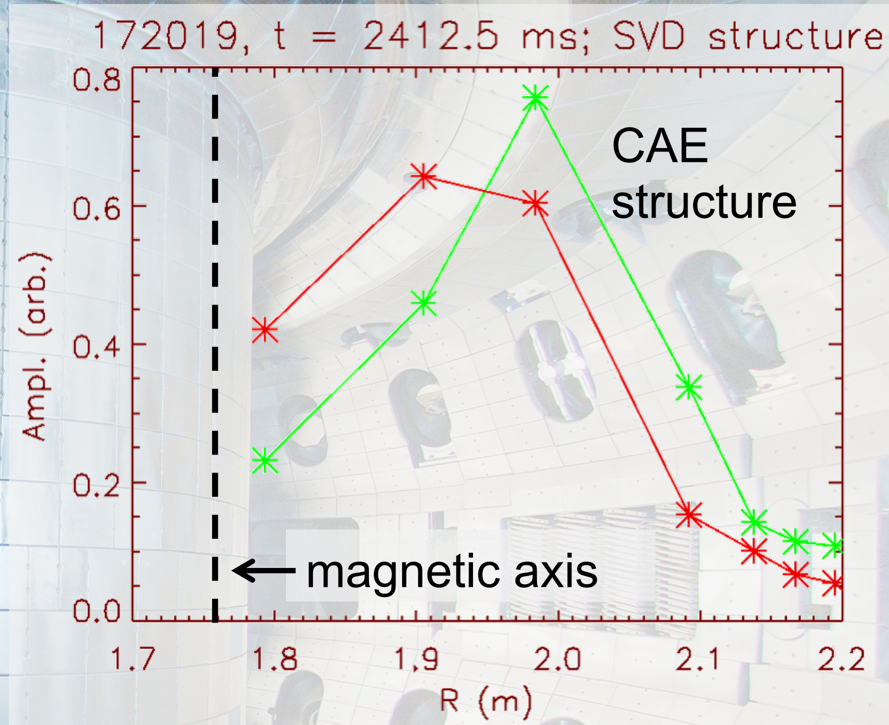
CAE structure measurements in DIII-D



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NSTX-U/Magnetic Fusion Science Meeting

NSTX-U/DIII-D National Campaign

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

GENERAL ATOMICS

Understanding of high frequency Alfvén activity important to transport and fast-ion diagnosis

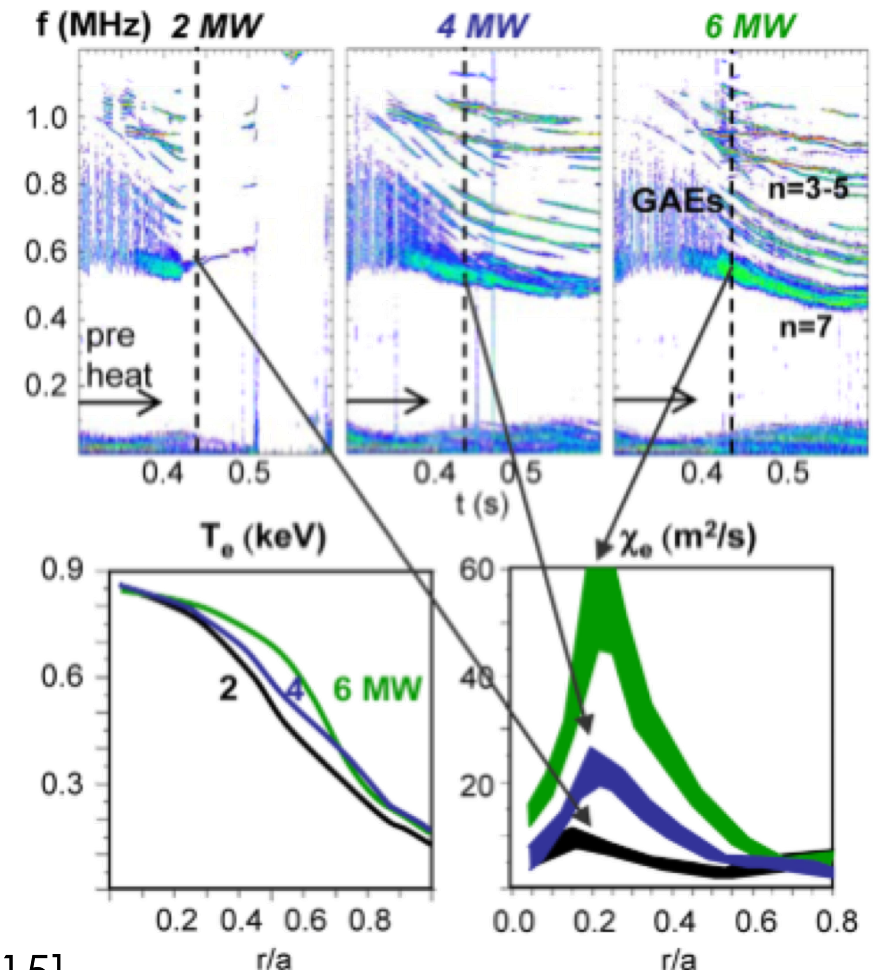
- **Compressional (CAE) and global (GAE) Alfvén eigenmodes linked to enhanced core electron thermal transport (χ_e) in NSTX**

- **CAEs and GAEs are potentially powerful diagnostic for fast-ion population in burning plasma environment**
  - nominally driven by Doppler-shifted cyclotron resonance with fast ions => deeper understanding enables "MHD spectroscopy"

CAE and GAEs linked to enhanced core electron thermal transport in NSTX

- **CAE and GAE activity correlate with enhanced core χ_e in NSTX**

- **Proposed mechanisms:**
  - Resonant orbit stochastization => enhanced χ_e
  - CAEs/GAEs couple to Kinetic Alfvén Waves (KAWs), which channel energy out of the core



[D. Stutman PRL 2009]

[Gorelenkov NF 2010]

[Kolesnichenko PRL 2010], [Belova PRL 2015]

High frequency Alfvén eigenmodes driven unstable by Doppler-shifted cyclotron resonance with fast ions

- **Compressional/Global Alfvén eigenmodes (CAE/GAE) => same instability as coherent Ion Cyclotron Emission (ICE)**
  - For cyclotron resonance, [N.N. Gorelenkov NF 2003]

    $\omega - k_{\parallel} v_{b\parallel} = l\omega_c, l = \cdots, -1,0,1, \ldots$ [Dendy, PoP 1994]
  - $k_{\perp}\rho_b$ stabilizing in some ranges and destabilizing in others
    - Anisotropy important
    - Perpendicular instability condition requires finite orbit widths:

      CAEs: $1 < k_{\perp}\rho_b < 2$

      GAEs: $2 < k_{\perp}\rho_b < 4$
  - For CAEs, $\omega^2 \approx k^2 v_A^2$
  - For GAEs, $\omega^2 \approx {k_{\parallel}}^2 v_A^2$
    - Dispersion relationships modified by finite ω/ω_{ci} - (important to existence of GAEs)

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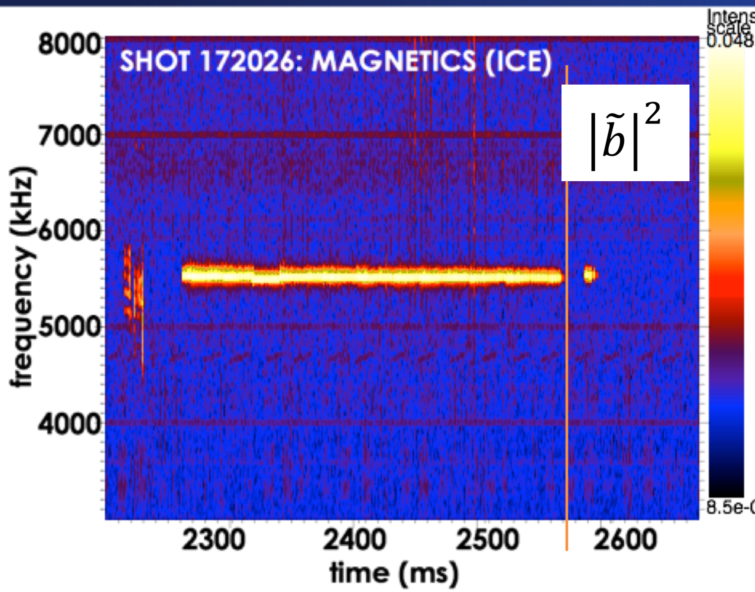
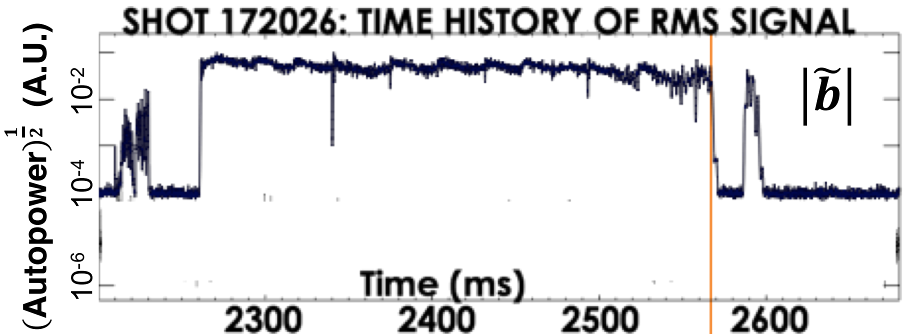
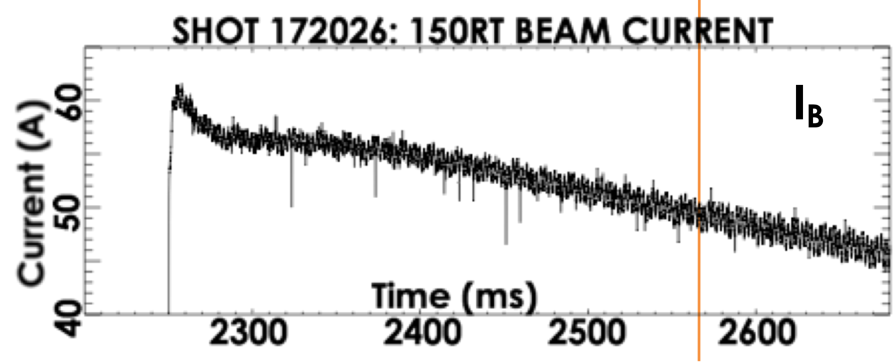
CAE with observed beam current threshold





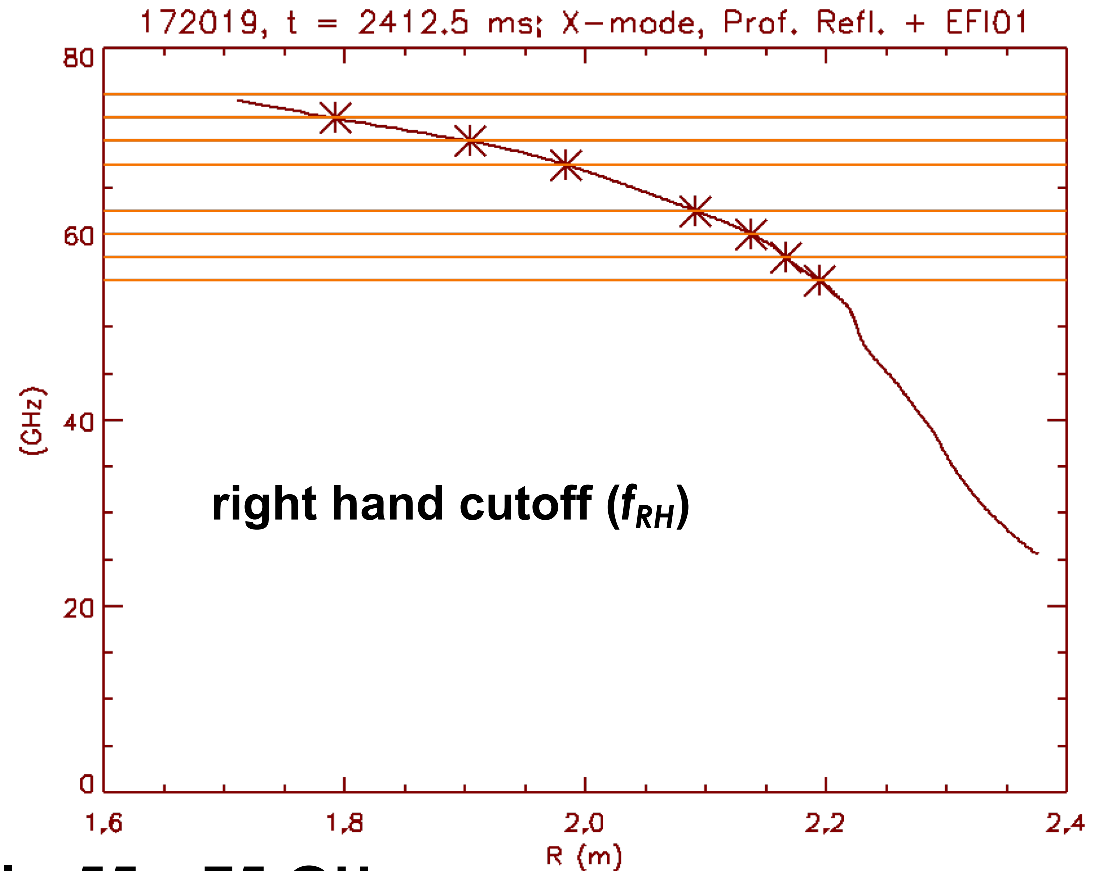


- V_B constant as I_B ramped (variable perveance)
- CAEs abruptly disappears as I_B drops below threshold

<u>caveats:</u>

- delay in CAE start => due to beam density build-up?
- CAE reappears => due to sawtoothing?

Reflectometer array measures CAE $\tilde{n}$ across plasma



- **8 channels: 55 – 75 GHz**
- **X-mode or O-mode => reflection at f_{RH} or f_{pe}**
- **global mode: path length fluctuations ($\tilde{l}$) ~ from $\tilde{n}$ @ cutoff**

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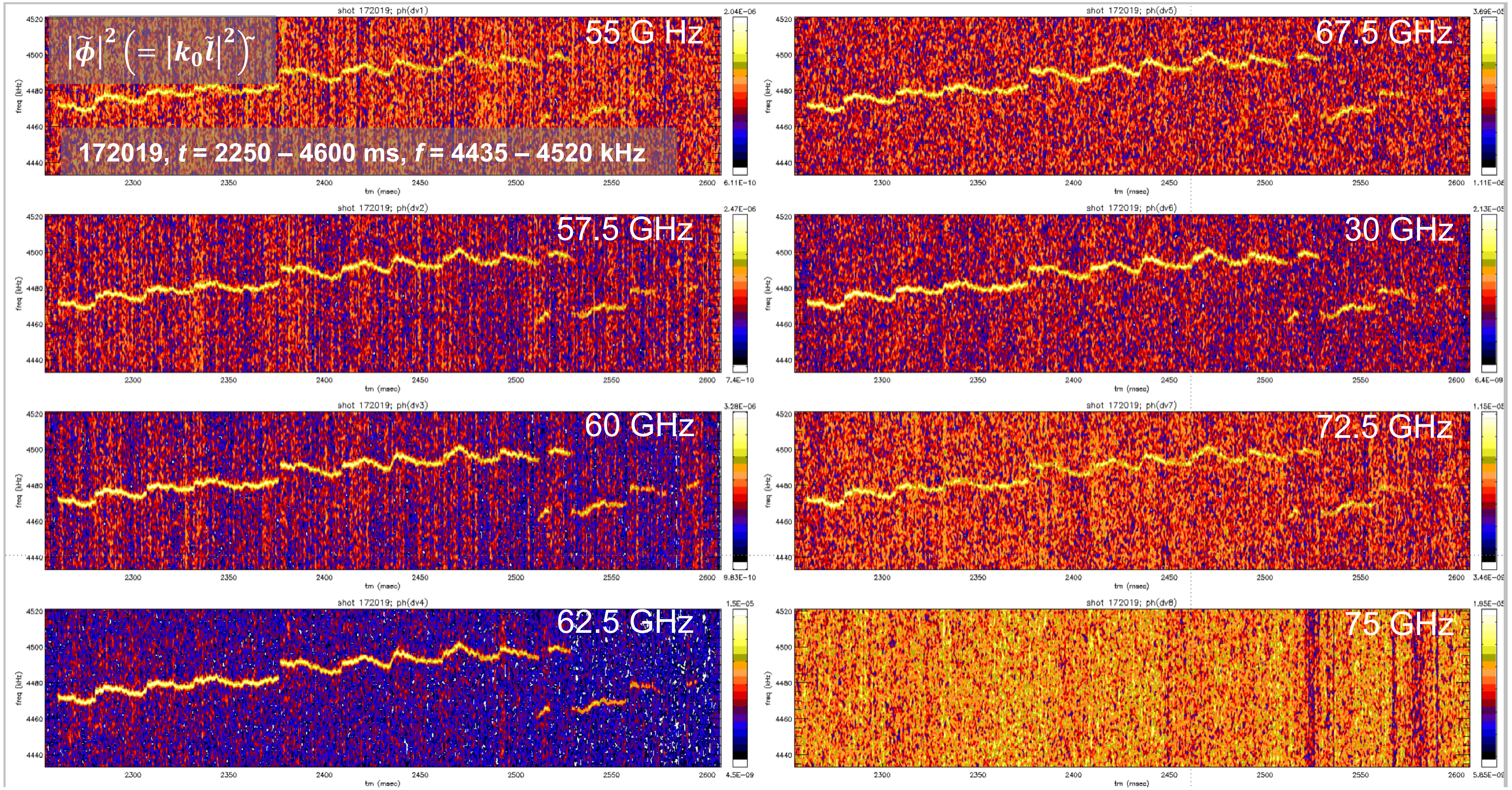
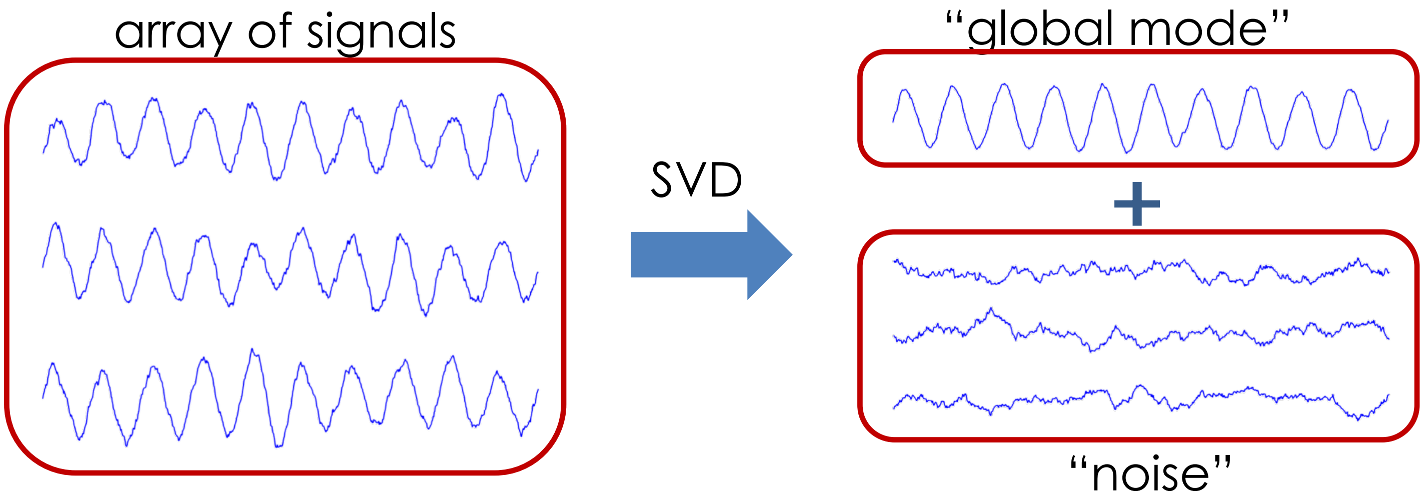
Reflectometer array shows CAE structure is global



- **Global CAE observed with reflectometers in I_B ramp at constant V_B**
- **CAE aliased from *f* ~ 5.5 MHz to ~ 4.5 MHz (10 MHz sampling rate)**

Use singular value decomposition to isolate "global mode" from signal array



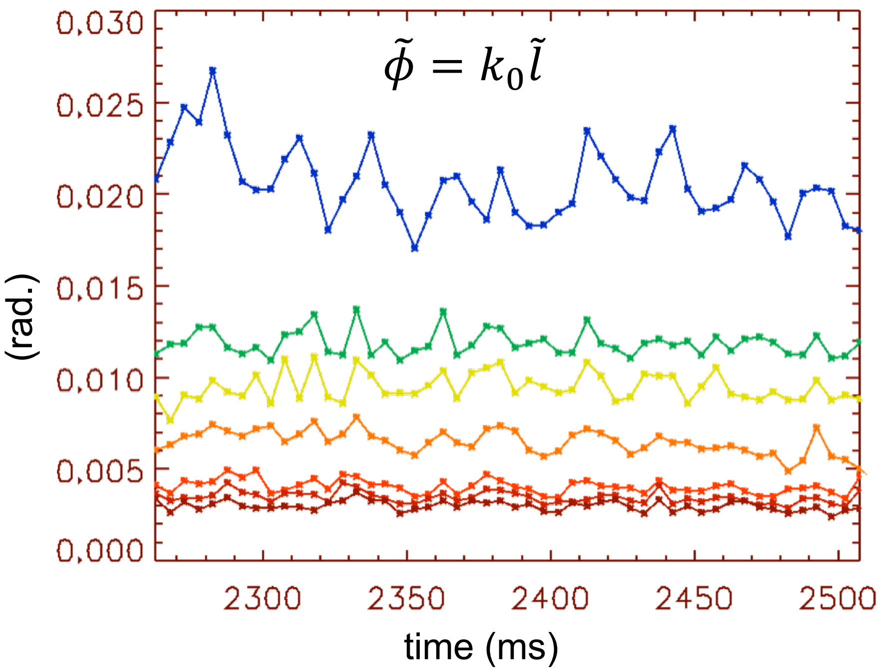
- **array of signals contains global mode + noise/turbulence**
- **SVD separates signal matrix into global modes + noise/turbulence**

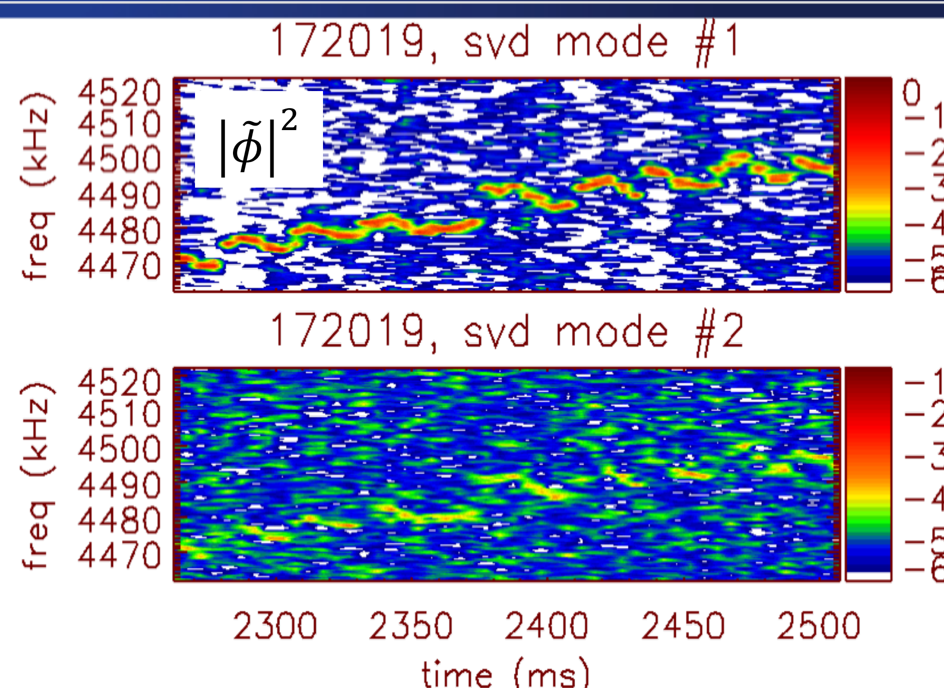
$$\tilde{s}_{jk} = \tilde{s}_j(t_k) \rightarrow \sum_{m \in \text{modes}} \tilde{s}_{m0\,j}\tilde{s}_m(t_k) + \epsilon_j(t_k)$$

- **Steps before SVD …**
  - bandpass filter signals to isolate mode
  - make signals complex ⇒ temporal phase factors out automatically:
    - $\tilde{s}_j(t) = A(t)\cos\big(\theta(t) + \theta_{0j}\big) \rightarrow \hat{\tilde{s}}_j(t) = \frac{1}{\sqrt{2}}A(t)e^{i\left(\left(\theta(t)+\theta_{0j}\right)\right)} =$

$$\frac{1}{\sqrt{2}}\int_0^{\infty} d\omega e^{i\omega t}\int_{-\infty}^{\infty} dt'\tilde{s}(t')e^{-i\omega t'}$$

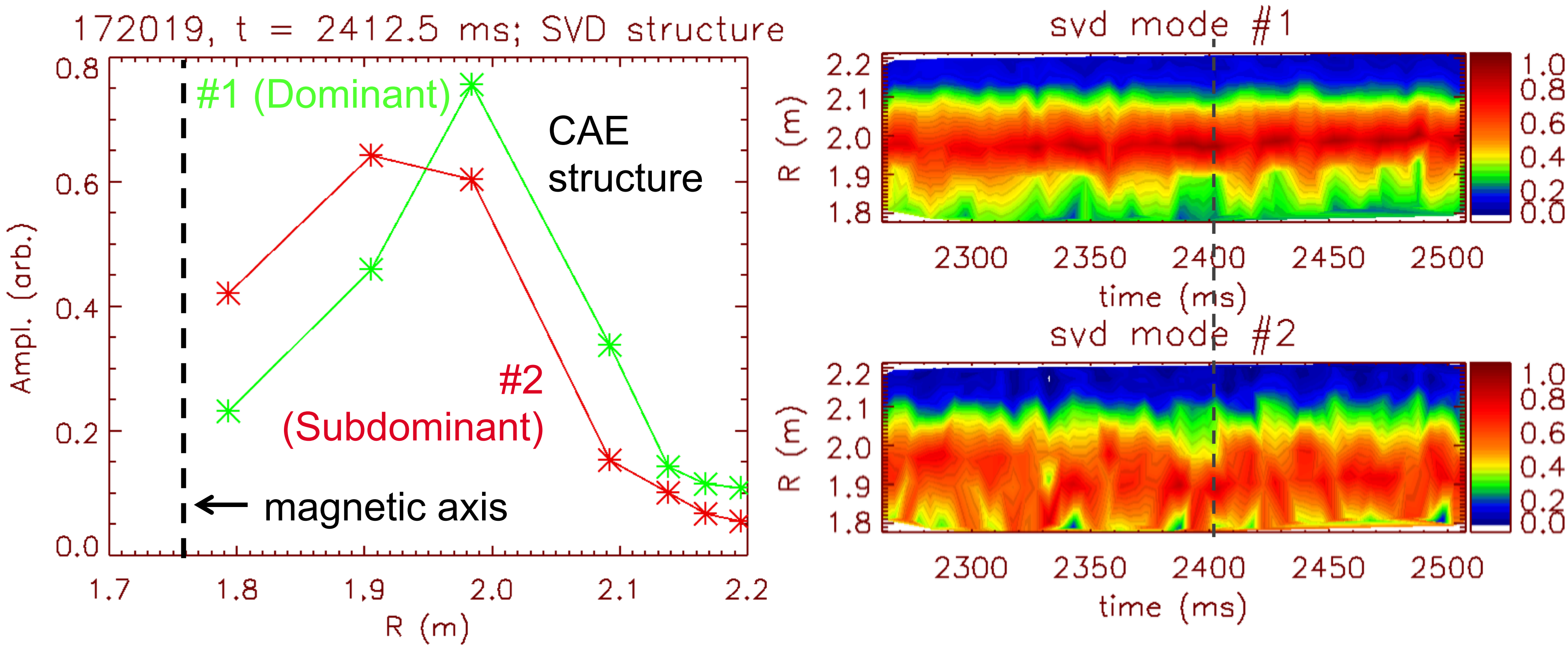
SVD shows one dominant "mode"





- **SVD shows single dominant "mode" (~ 50 % fluctuation power)**
  - 5 ms records (no overlap), 60 kHz bandwidth
  - large amplitude subdominant mode (~ 25 % fluctuation power) @ ~ same frequency => Distinct modes **OR**
    - #1+#2 = single mode w/time-dependent structure (< ~5 ms modulation)?
    - #2 is SVD artifact?
- **Low amplitude components = noise/turbulence**

Dominant SVD modes have global structure



- **Modes have broad structure**
- **Modes peak at mid-radius (R ~ 2 m)**

Conclusions

- **CAEs observed during beam current ramp at constant voltage**
- **Reflectometers observe global structure**
- **Modes peak at mid-radius (R ~ 2 m)**
- **SVD analysis one dominant mode**
  - Subdominant mode @ ~ same frequency => time-dependent CAE structure?

Future Work

- **Toroidal mode numbers from ICE toroidal loops**
- **Comparison with theory/simulation**