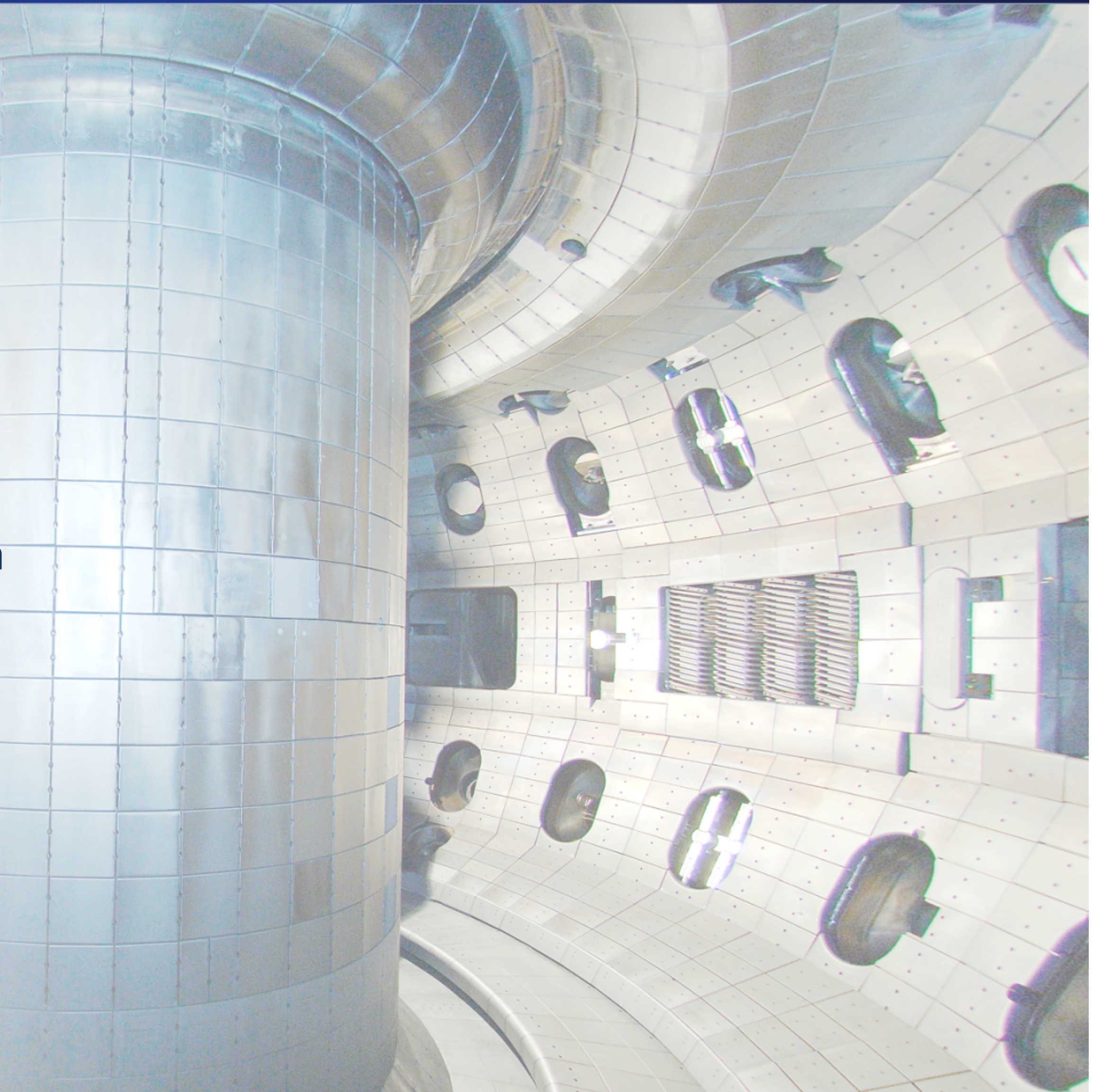
Experimental Investigation of Stability, Frequency and Toroidal Mode Number of Compressional Alfvén Eigenmodes in DIII-D



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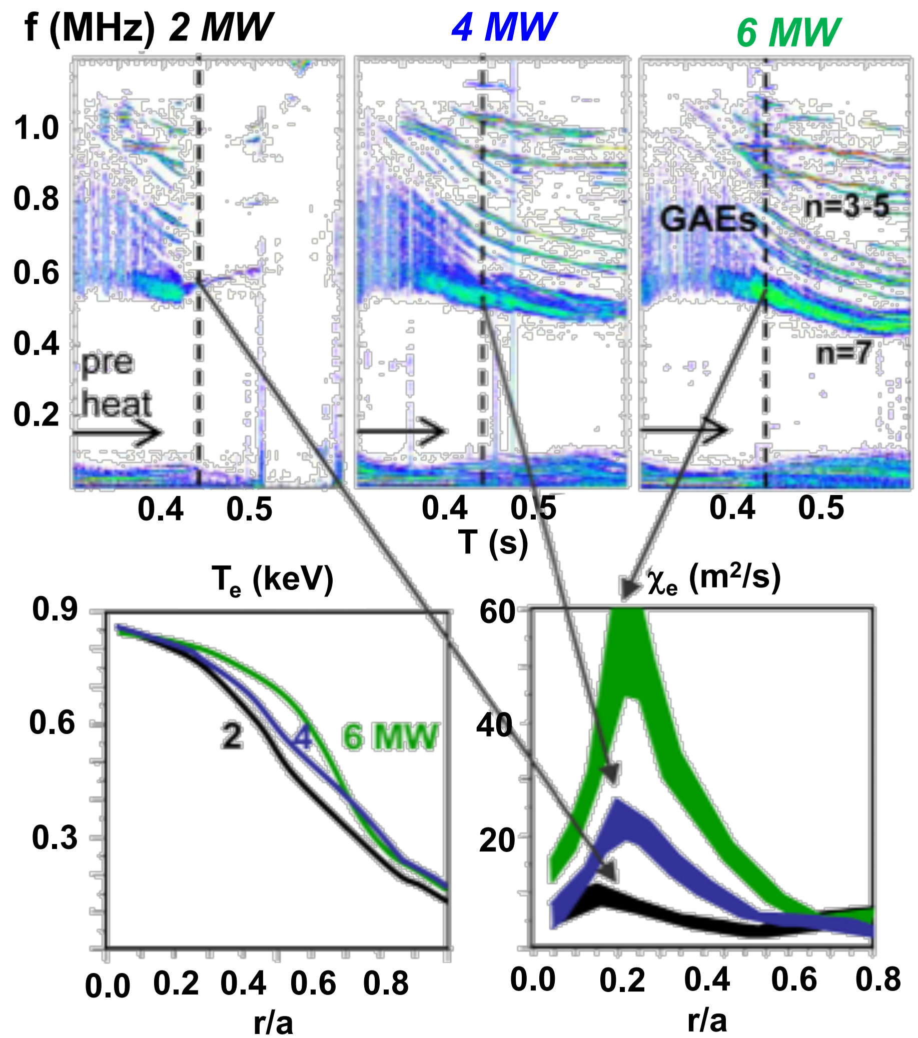
High Frequency Alfvén Activity Linked to Enhanced Core Electron Thermal Transport in NSTX

- **Compressional (CAE) and global (GAE) Alfvén eigenmodes correlate with enhanced core χ_e in NSTX**
- **Proposed mechanisms:**
  - Resonant interaction of modes with electron guiding center orbits, causing enhanced thermal transport
  - CAEs/GAESs couple to Kinetic Alfvén Waves (KAWs), which channel energy out of the core

[Gorelenkov NF 2010]

[Kolesnichenko PRL 2010], [Belova PRL 2015]



[D. PRL 2009]

High Frequency Alfvén Eigenmodes Driven Unstable by Doppler-shifted Cyclotron Resonance with Fast Ions

- **Compressional/Global Alfvén eigenmodes (CAE/GAE) /coherent Ion Cyclotron Emission (ICE)**

[N.N. Gorelenkov NF 2003]

[Dendy, PoP 1994]

  – For cyclotron resonance,

$$\omega - k_{\parallel} v_{b\parallel} = l\omega_c, l = \cdots, -1,0,1, \ldots$$

  – $k_{\perp}\rho_b$ 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)

Experiment Designed on DIII-D to Test High Frequency Alfvén Eigenmode Theory

- **Experiment performed to test dependence of HFAEs on broad range of plasma and beam parameters**
  - Exploit beam capabilities of DIII-D to separate beam density and velocity dependences of modes
- **CAEs observed by many diagnostics, including the Ion Cyclotron Emission (ICE) diagnostic**
- **Beam density threshold consistent with theory**
- **Magnetic field and plasma density threshold observed for onset of CAEs**
- **Mode frequency scales as Alfvén velocity for single mode**

New High Speed Measurement Capability Creates Opportunity to Test CAE/ICE Theory

- **CAE frequency is $f < f_{ci}$, typically f ~1-10MHz range in DIII-D**
- **Previous magnetic fluctuation measurements limited to < 1MHz**
- **Ion Cyclotron Emission (ICE) diagnostic measures high speed toroidal magnetic fluctuations**
  - High bandwidth: up to 200MHz
  - High speed acquisition: 200MHz, 8GB/shot
  - Coil pairs separated by 10-15 degrees allowing for toroidal mode number measurement
- **ICE digitizers allow exploitation of full bandwidth of other fluctuation diagnostics (e.g. CO2 interferometer)**

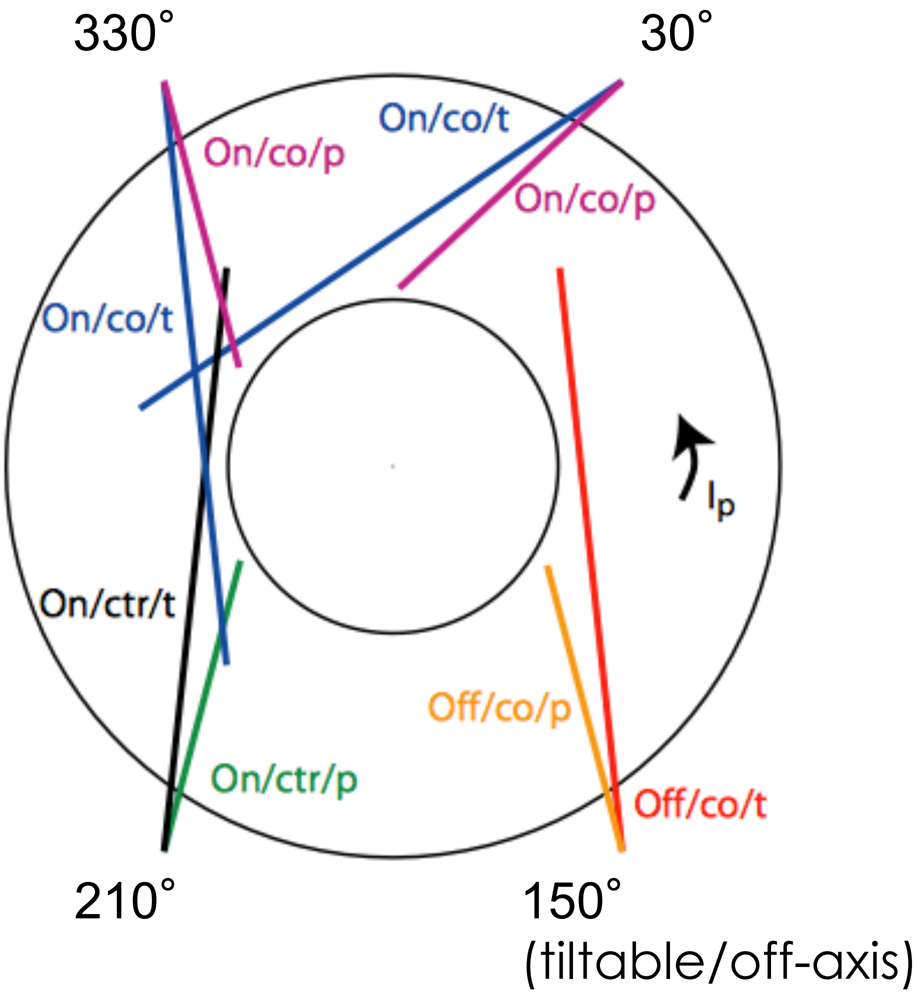
RF Loop
Refurbished 2017
232-248°

Experiment Designed to Test High Frequency AE Theory

- **Extend previous study of CAEs on DIII-D** [Heidbrink NF 2006]
  - Systematically vary beam pitch angle and injection direction
  - Extensive diagnosis with most current diagnostics for simulation validation
- **Opportunity to identify GAEs on DIII-D for the first time (future work)**
- **Verify parallel resonance condition, perpendicular instability condition, and dispersion relation**
  - Vary injection geometry → Pitch angle/direction
  - Beam velocity scan (at constant beam density, n_b)
  - B_T scans at constant n_e → vary ω_c
  - n_e scans at constant B_T → vary v_A
- **Establish stability threshold: vary beam density (n_b) at constant velocity, pitch angle**
  - Use variable perveance → vary beam current at constant voltage

See NI3.6 (Wed 9:30) for more info on variable perveance

Flexible DIII-D Beam Geometry and Capabilities Give Wide Range of Directions/Pitch Angles



[Heidbrink, NF 2012]

- **8 available sources inject at 6 different injection angles**
- **Co/counter injection**
- **Tangential/perpendicular injection (left/right)**
- **Off-axis beam**
  - Source at 150 can be tilted down → more perpendicular at normal BT, IP
- **Every beam up to ~ 80keV, ~2MW**
- **Beams can vary current and voltage independently**

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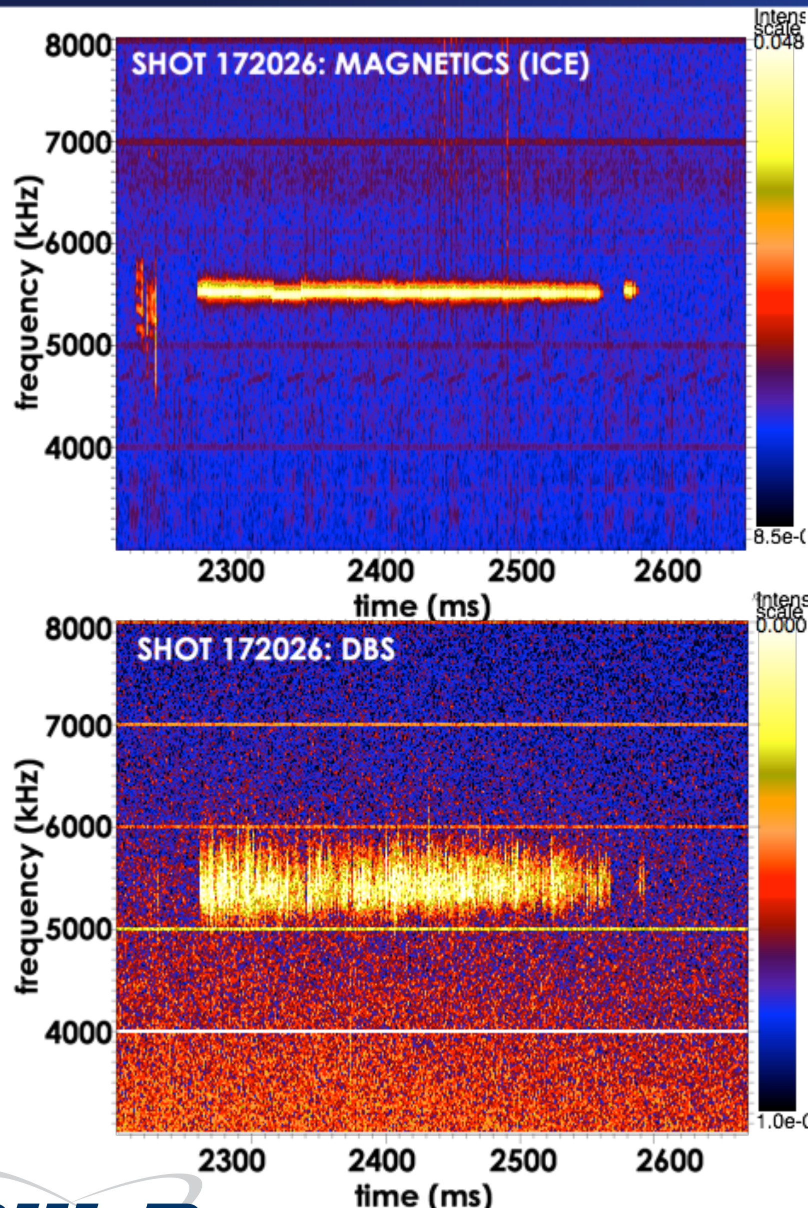
Beam Modulation Important Tool in Experiment

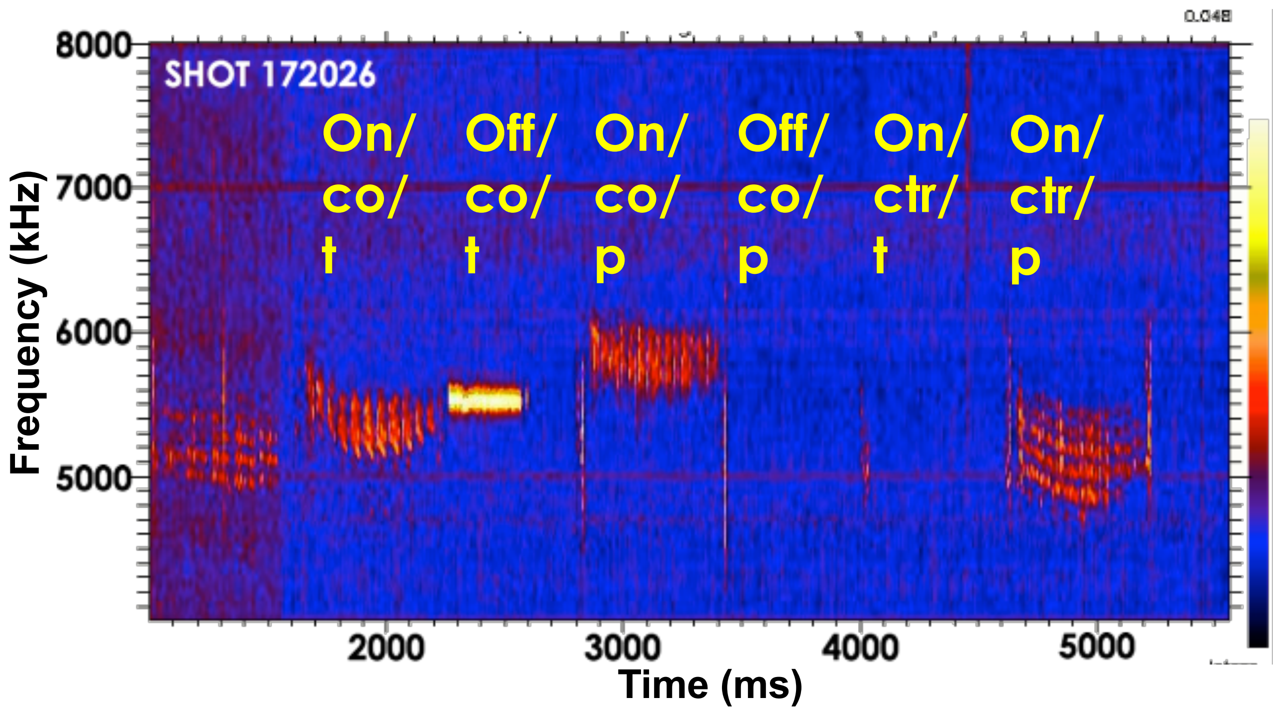
- **Perveance Scans: cycle through each injection geometry once while holding B_T, n_e constant**
  - Beam current varied at constant voltage, and vice versa
  - Separately control energetic ion density and velocity
  - Energetic ion velocity control tests resonance condition
  - Energetic ion density control tests stability threshold
- **Parameter Ramps: cycle through all injection geometries rapidly during ramp**
  - Ramps reveal thresholds for activity related to resonance condition

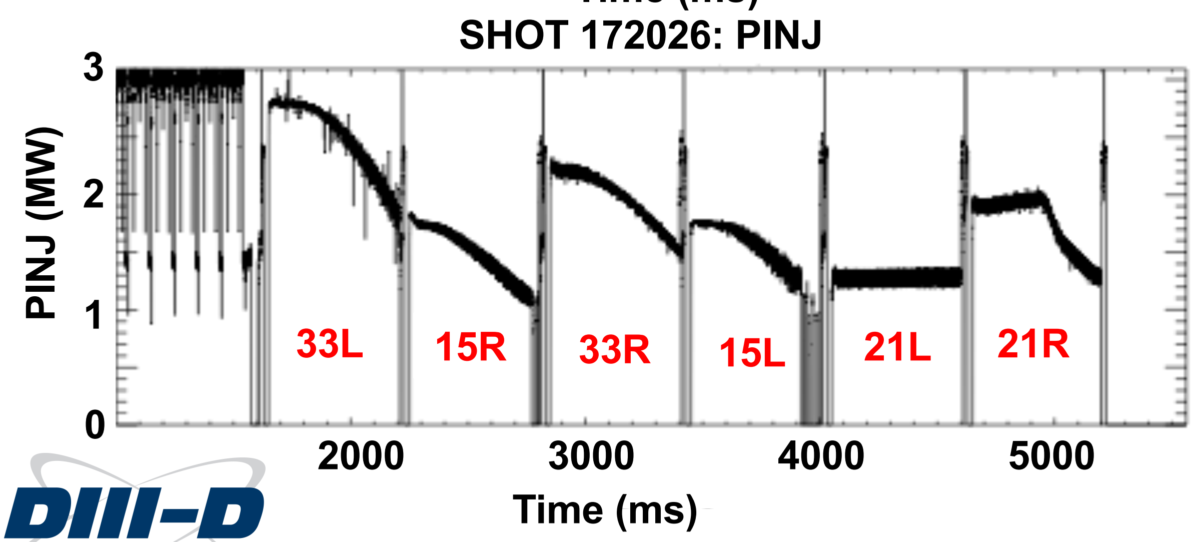
CAEs Observed with Magnetic and Density Fluctuation Diagnostics



- **Magnetic fluctuation (ICE) diagnostic observed CAEs**
- **Internal diagnostics also see CAEs**
  - Doppler backscattering (DBS) (δn)
- **Example: beam density scan at constant voltage**

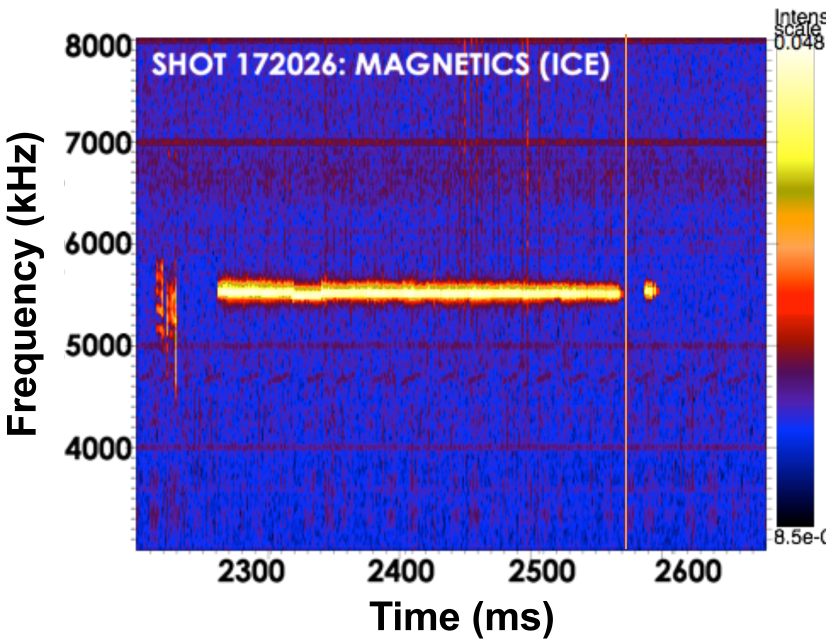
Injection Geometry Plays Important Role in Activity

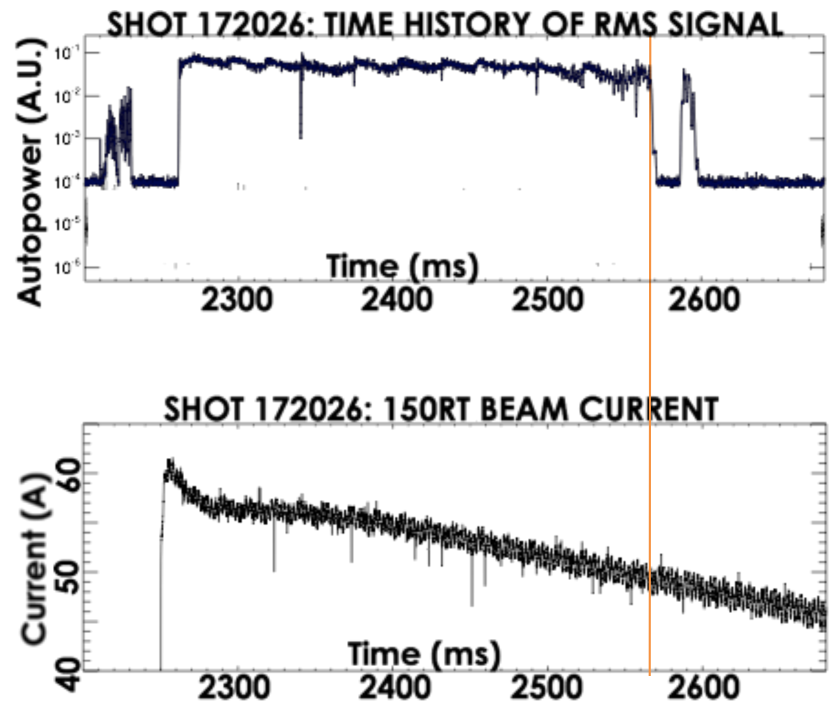




- **Different beams excite at different frequencies**
- **At low field (1.3T), highest beam voltage (~80keV), CAEs are excited by 4 of the 6 geometries**
  - Beam current scan at constant high source voltage
  - Not all beams operating at full voltage
  - Bursting due to sawteeth which varied with injection geometry

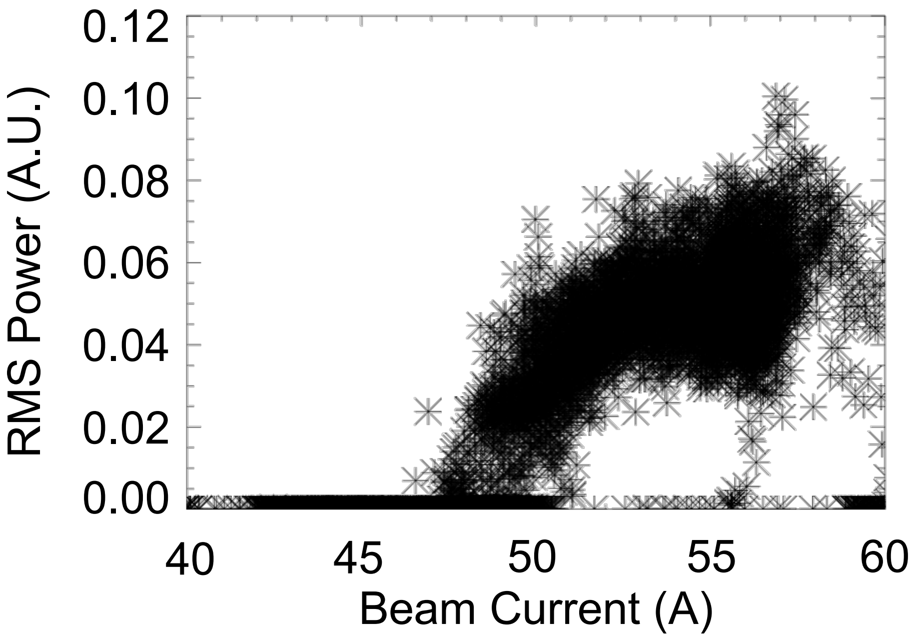
Beam Density Threshold Observed

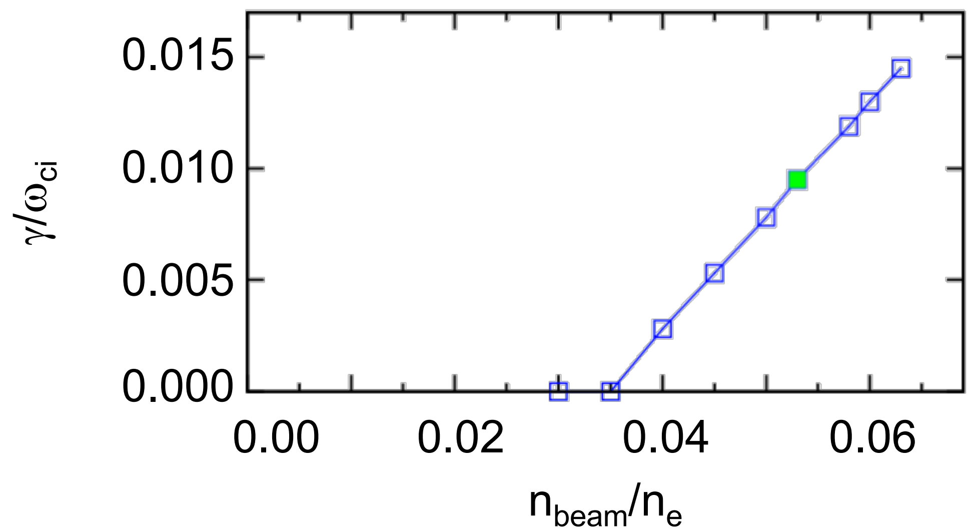




- **Voltage held constant as current is ramped**
- **Mode abruptly disappears as beam current drops below a threshold**

Beam Density Threshold Consistent with Simulation

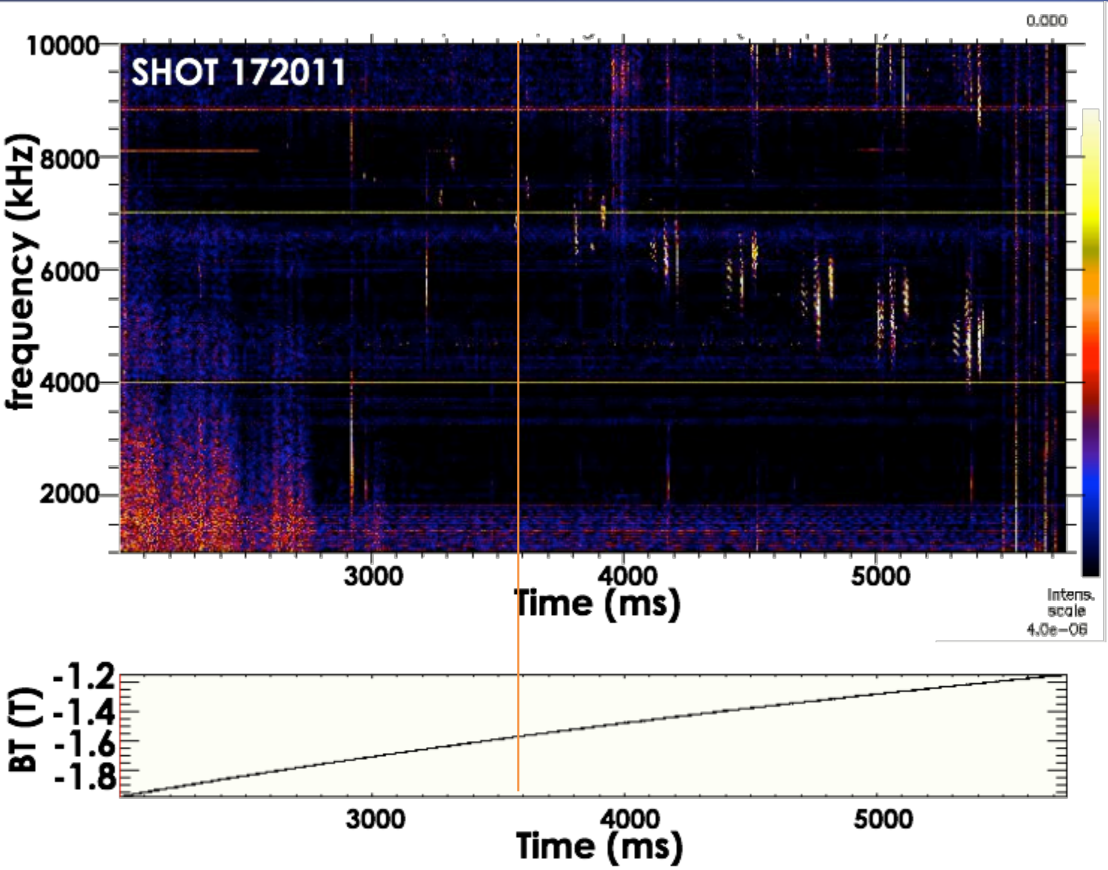




[Belova, PoP 2017]

- **Mode power drops to zero when beam current crosses threshold of <~47A**
- **Simulation predicts CAE growth rate to be positive above a threshold, below which CAE is stable**

BT Ramp Shows Onset of CAEs Expected from Resonance Condition



- **CAEs are observed to be unstable at around BT ~ 1.65T**
  - Corresponds to $v_A = 3.5e6\ \mathrm{m/s}$ (using n_{eL}), $v_b = 2.8e6\ \mathrm{m/s}$
- **BT threshold expected because of resonance condition**

$$\omega - k_{\|} v_{b\|} = \omega_c$$

$$\omega = k v_A$$

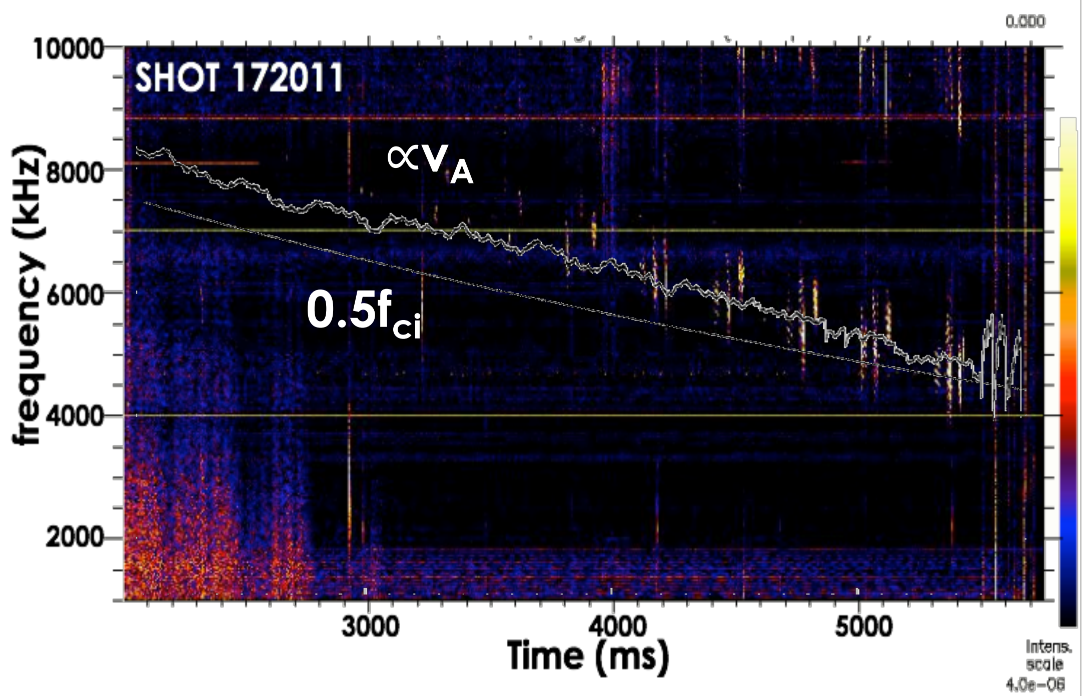
$$\left|\frac{\omega_c}{\omega} - 1\right| < \frac{v_b}{v_A}$$

$$\left|\frac{\omega_c}{\omega} - 1\right| \sim 1 \text{ observed}$$

- **→ Beam ions Alfvénic to hit velocity for resonance**

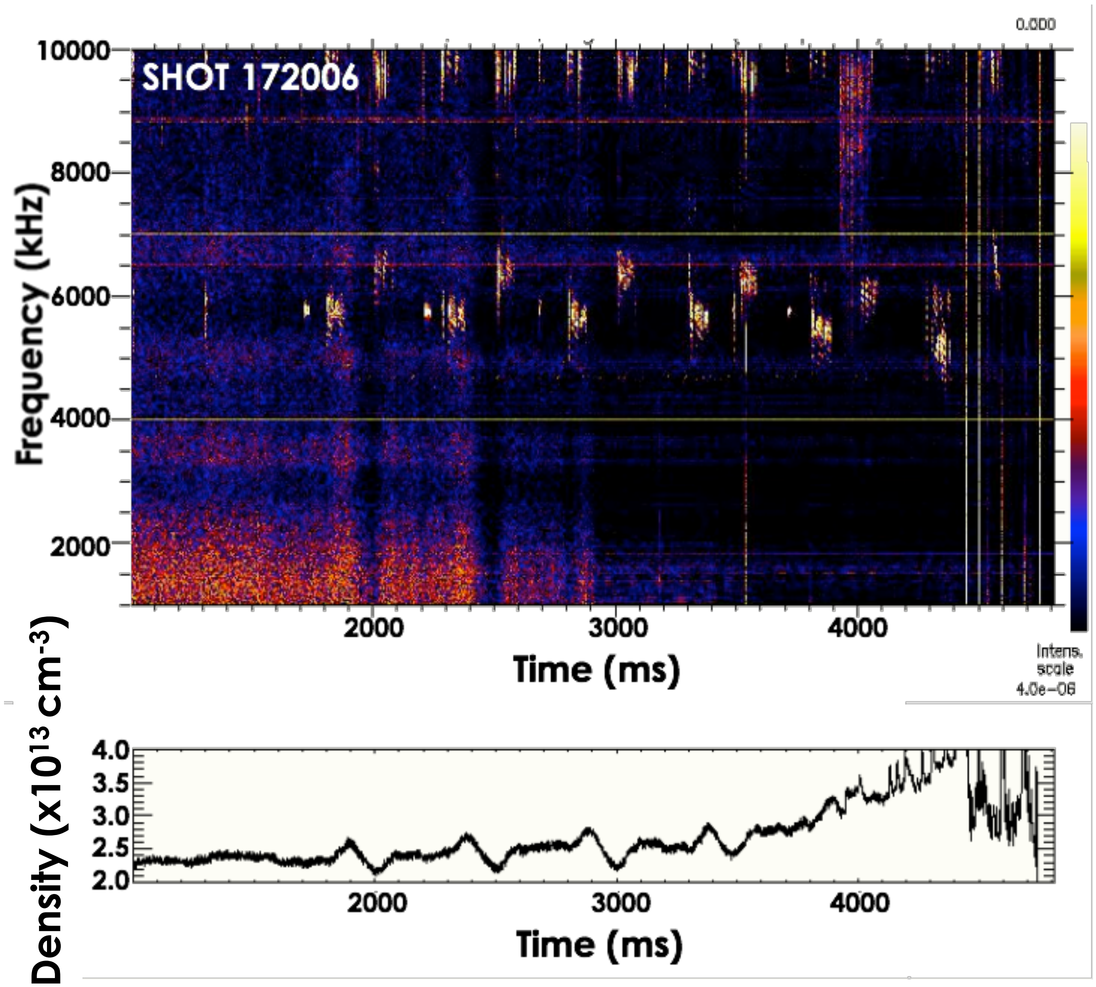
Mode Frequency Not Proportional to Cyclotron Frequency During BT Ramp

- **Frequency consistent with perpendicular instability condition, taking into account finite ω/ω_c effects: expect $\omega/\omega_c > 0.5$**
  - Use cold dispersion relation
- **During BT ramp, f is not proportional to f_c**
  - Different from ICE
- **However, $f \propto v_A$**
  - Expected if all bursts have same k (future work)

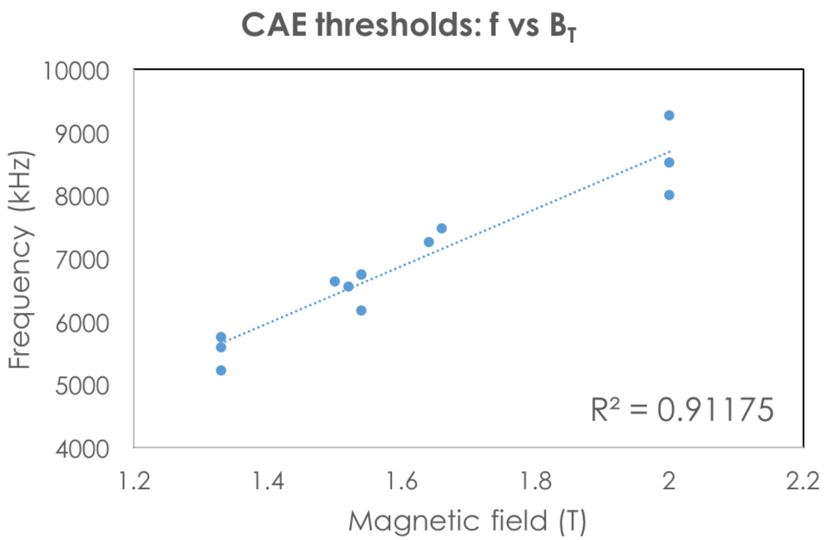


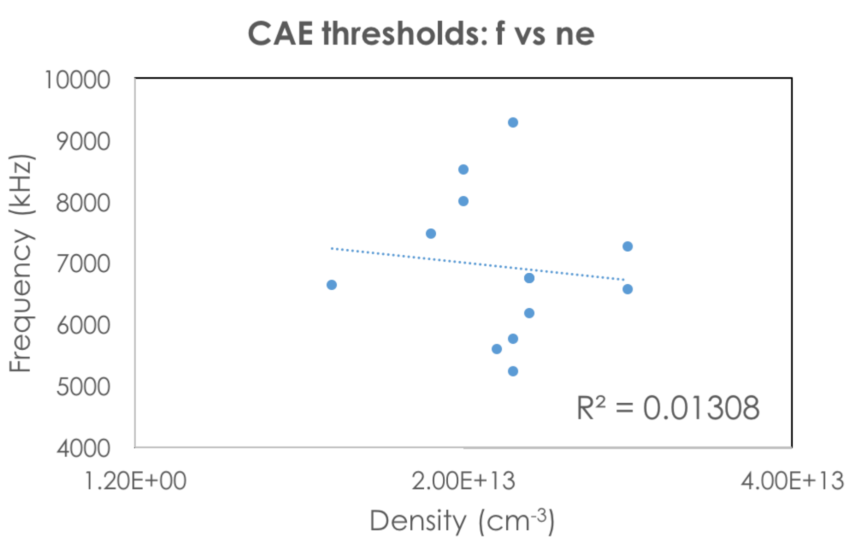
Density Ramp Shows Onset Consistent with Parallel Resonance Condition

- **CAEs are observed to be unstable around n_{eL} > 2.4e13 cm^{-3}**
  - Consistent with threshold
    $$\left|\frac{\omega_c}{\omega} - 1\right| < \frac{v_b}{v_A}$$
- **Frequency not proportional to v_A**
  - Density rises by a factor of ~2, but frequency does not drop by $\sqrt{2}$



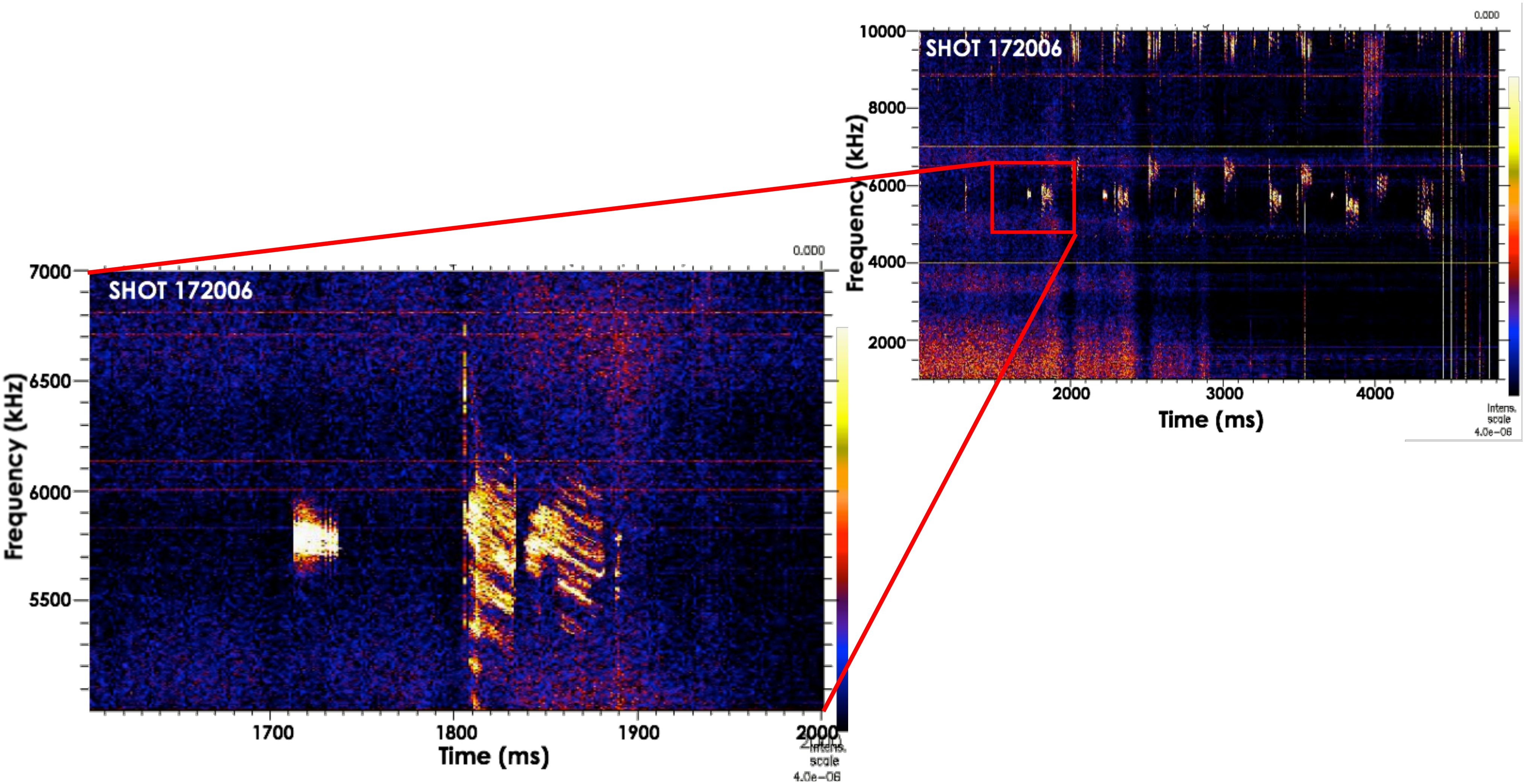
Onset Frequency Strongly Correlated with BT, No Correlation with n_e



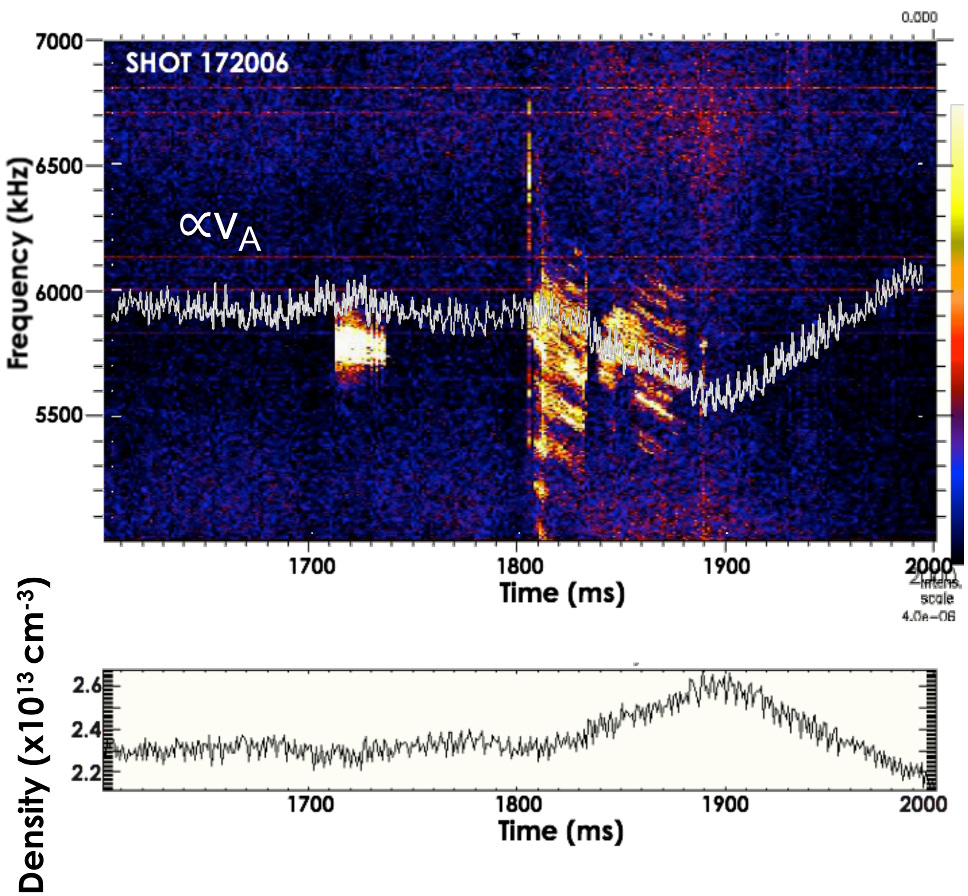


- **Onset frequency of modes shows a strong linear correlation with BT**
  - No correlation observed with density
- **All onsets occur at around f/fc~0.57**
- **Future investigation needed to understand this**

For Single Mode, Frequency Scales with Alfvén Velocity

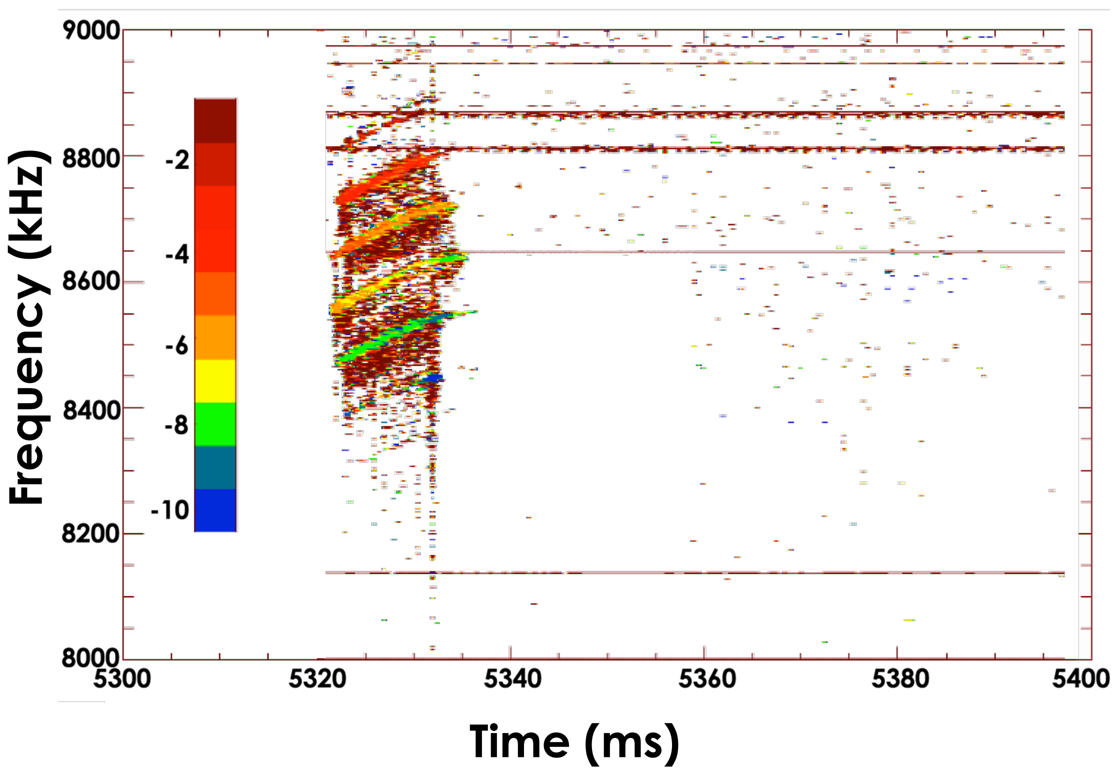


For Single Mode, Frequency Scales with Alfvén Velocity



- As density ramps upwards, possibly driven by the beam, frequency sweeps down
- As density increases, v_A decreases, so frequency decreases
- $f \propto v_A$ within each burst, but not during the ramp → mode number is changing with each burst? (future work)

Preliminary Analysis Shows *f* Increases as |*n*| Decreases



- **Toroidal mode number measured by pair of toroidally separated edge coils**
  - Path length difference → calibration required for best n
- **n < 0 consistent with Doppler shifted cyclotron resonance**
  - Modes propagating against beams
- **Same trend of *f*, |n| seen in NSTX** [Tang TTF 2017] **and MAST** [Sharapov PoP 2014]

Conclusions

- **Observed CAEs consistent with many aspects of theory**
  - Frequency dependent on beam injection geometry
  - Beam density threshold observed
  - Observed BT & n_e thresholds consistent with resonance condition
  - f increases with v_A as expected
- ***f* increases as |*n*| decreases**
  - Calibration needed for exact mode number measurement
- **n < 0 consistent with Doppler shifted cyclotron resonance**

Future Work

- **Calibrate path length to coil pairs**
- **Investigate toroidal mode numbers**
  - Are there GAEs?
  - Explain f during density ramp?
  - Frequency scaling with mode numbers (compare with NSTX)
- **Further investigate conditions for mode onset**
- **Further understand implications of finite f/fc**
- **Validate HYM**
  - TRANSP runs needed for beam populations