Intense Compressional Instability Driven by Counter Injected Neutral Beam Ions in DIII-D

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in collaboration with
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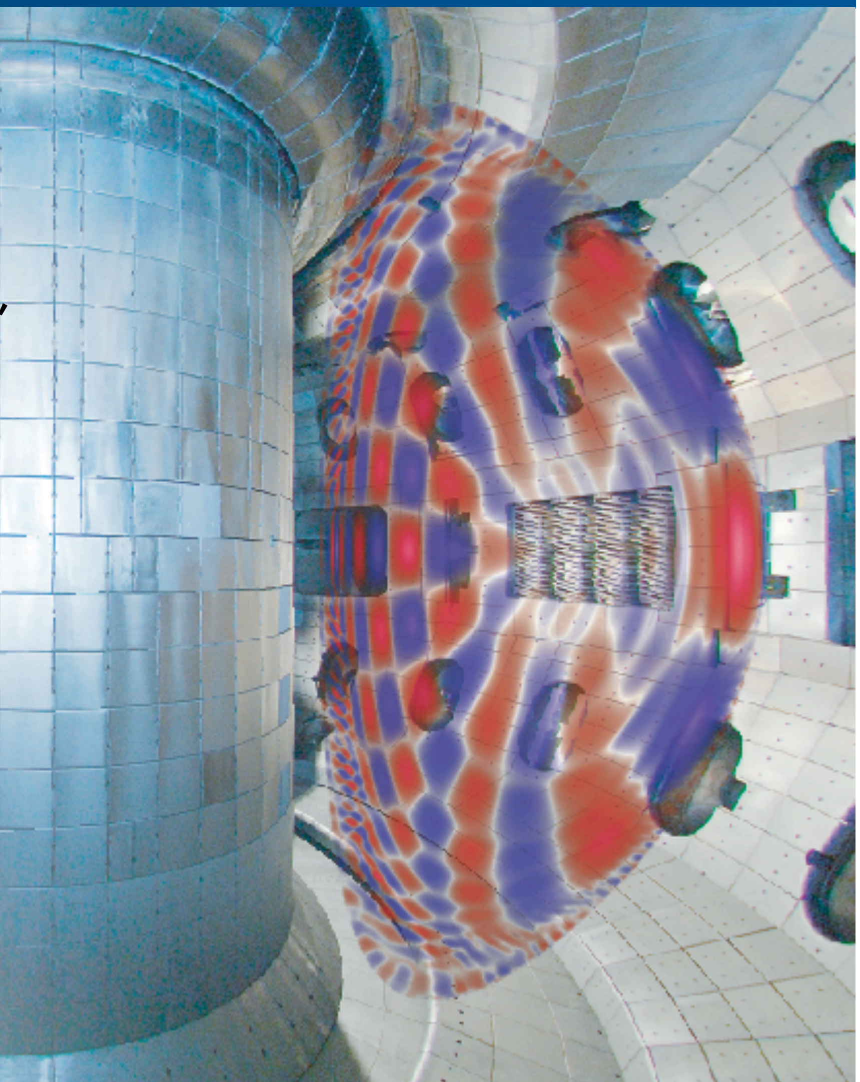

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Is particle direction for passing ions important for Alfvén eigenmode excitation?

- A burning plasma experiment will consist of similar numbers of co and counter going 3.5 MeV alphas, however present experiments mostly focus on co-injectedfast ions

- Passing ion resonance condition for Alfvén eigenmodes has weak or no directional sensitivity in the zero orbit width limit (theory)

  However

- In AT (high q_{min}) regimes, the poloidal orbit wodth can be dramatically different for co and counter passing ions

- Expect quantitative differences in instability drive

  - dominant mode number, growth rate for RSAEs, TAEs, …

Beam Line Reorientation on DIII-D Allowed detailed Test of co/counter drive symmetry in DIII-D AT plasmas

Key differences from past co/counter experiments:

Advances in core fluctuation measurements

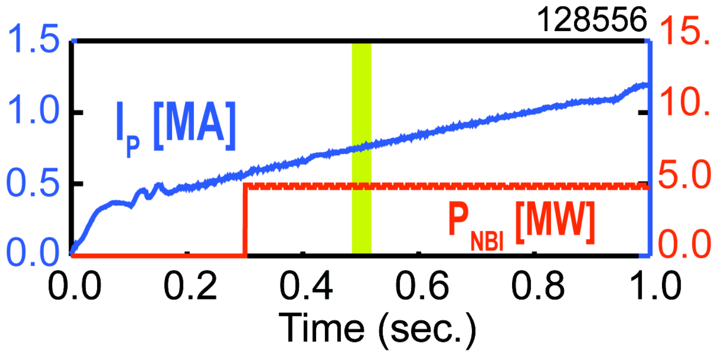
Development of advanced confinement regimes

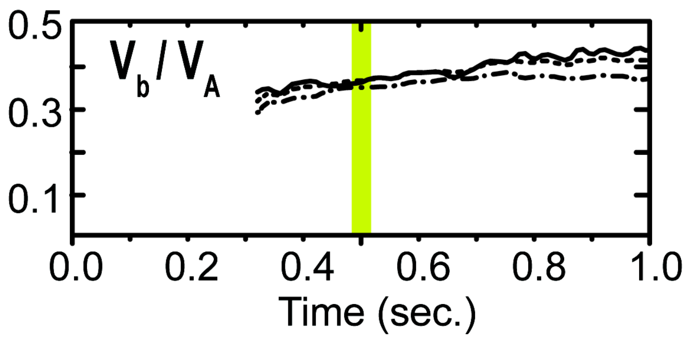
- $q(0) >> 1$ strongly modifies drift orbits and mode drive

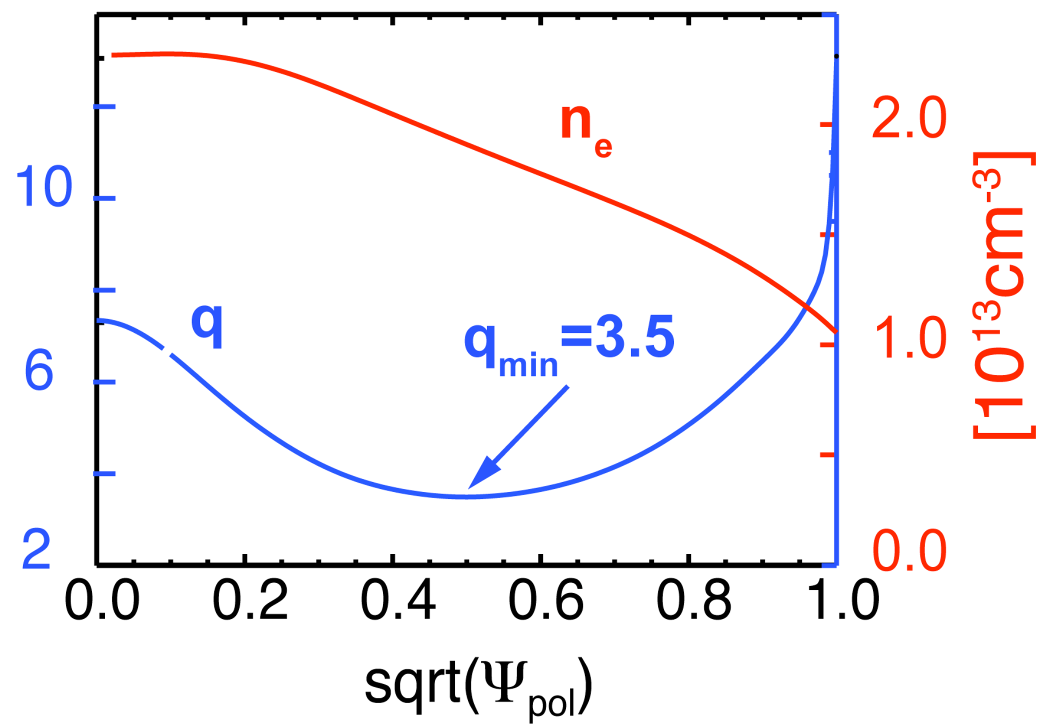
- We did the experiment and Surprise:

A new intense instability is observed for counter beam injection at high q_{min}, not seen in co-beam injection plasmas

DIII-D: Neutral Beam Injection into Current Ramp Generates Reverse Magnetic Shear, high q_{min}

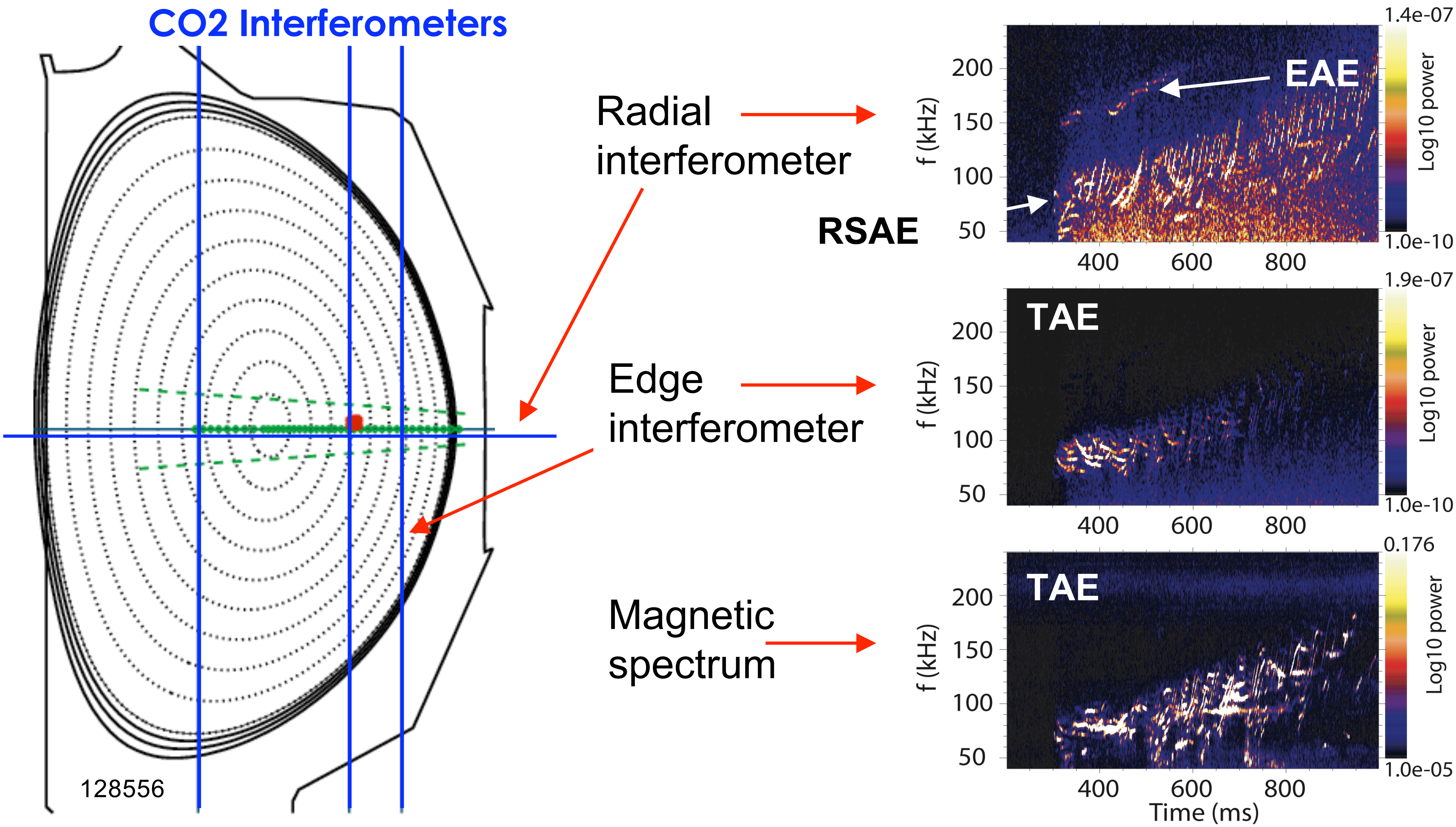




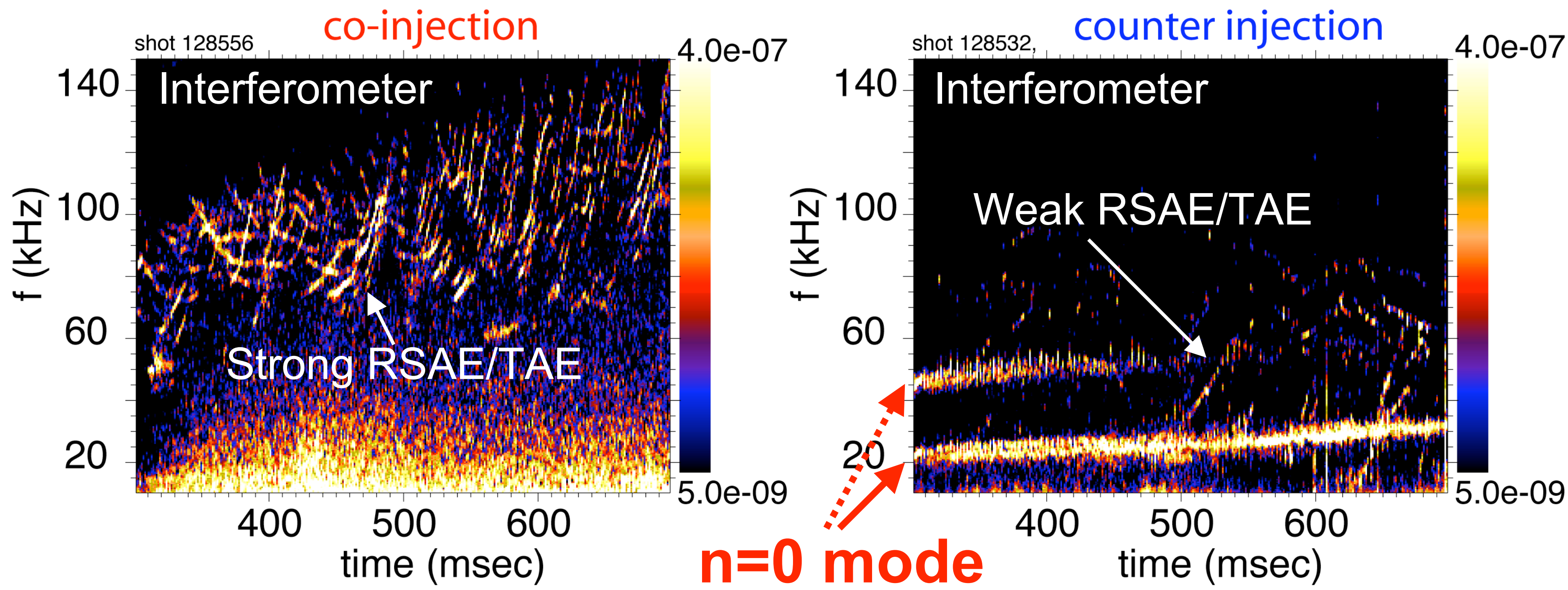


- **Early beam heating is used to delay current penetration and create reverse magnetic shear**
  - relevant to ITER advanced regimes
- **High q_{min} maximizes $k_\perp \rho$ ($k_\perp \approx nq/r$)**

Usual Alfvén Eigenmodes for co-injected 80 keV Deuterium on DIII-D: (RSAE, TAE, EAE)



However, Mode Activity Very Different for Counter Beam Injection in DIII-D



- P_{inj} = 5 MW co/counter injection, starting at 300 ms
- n=0 mode with counter injection only
- n=0 2nd and 3rd harmonics also observed

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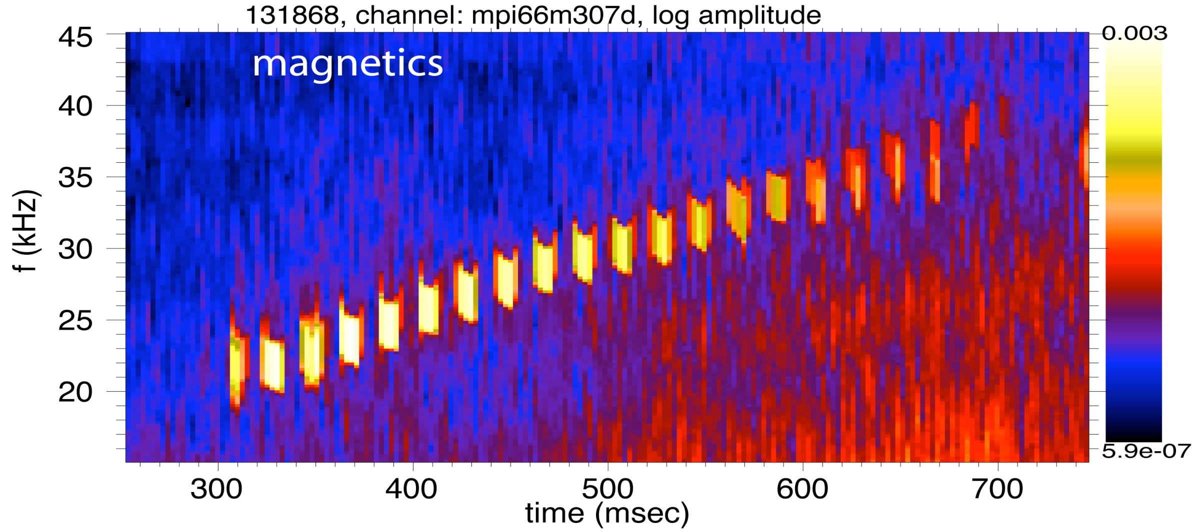
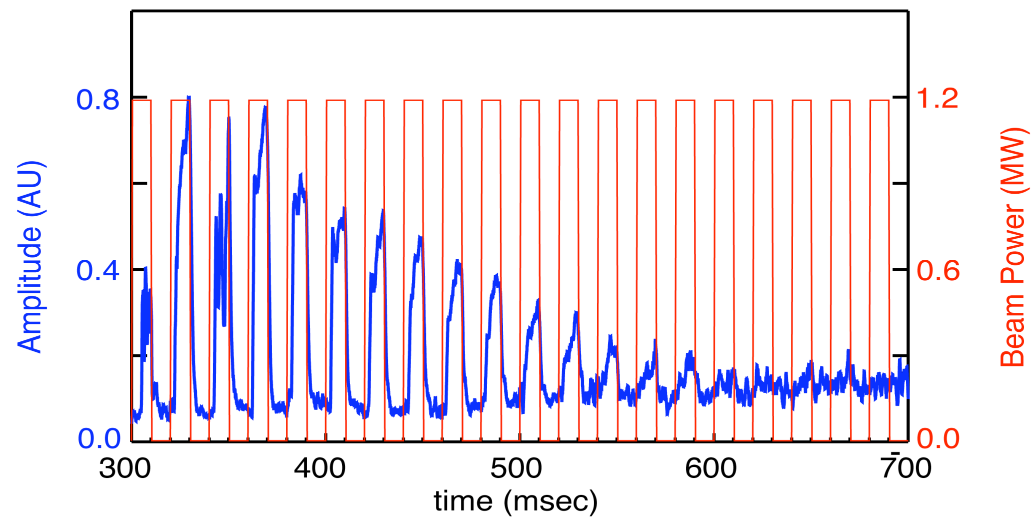
JET :
H.L. Berk, et al., NF 2007

Low Power Beam Blip Perturbations: Mode amplitude plummets with decreasing q_{min}

- 500 kW average power
- mode appears in less than 5 ms after first beam injection
- q_{min}: 4.2 --> 2.3
- f x q_{min} ≈ const.





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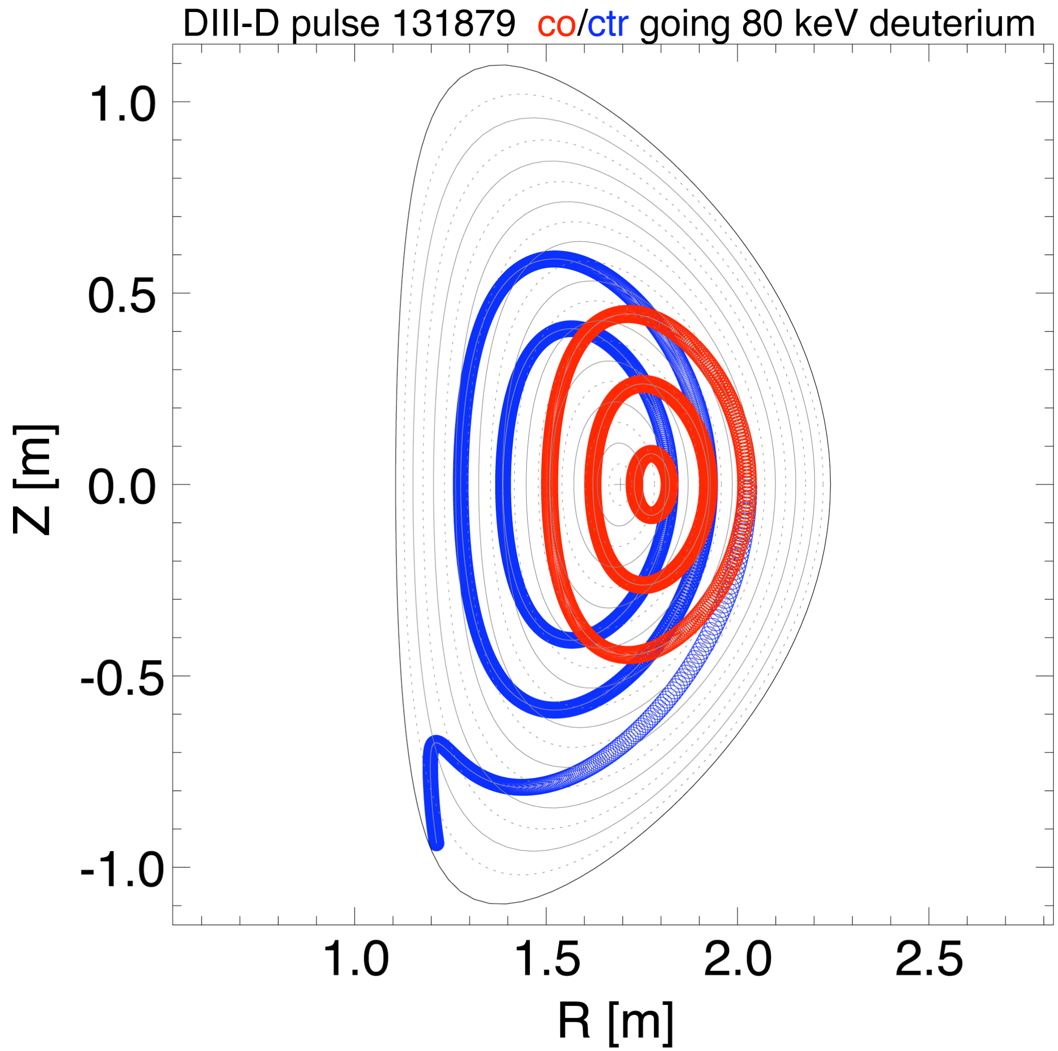
Orbit widths can be very different for co and counter passing ions at high q ($q_{min} \approx 3.5$)

- 80 keV beam ion pitch angle ≈ -/-0.6 at $R_{dep} \approx 200$ cm

- counter orbits close to loss boundary

- only low-n RSAEs observed in counter case, perhaps due to large orbit width

- strong anisotropy at high q_{min}



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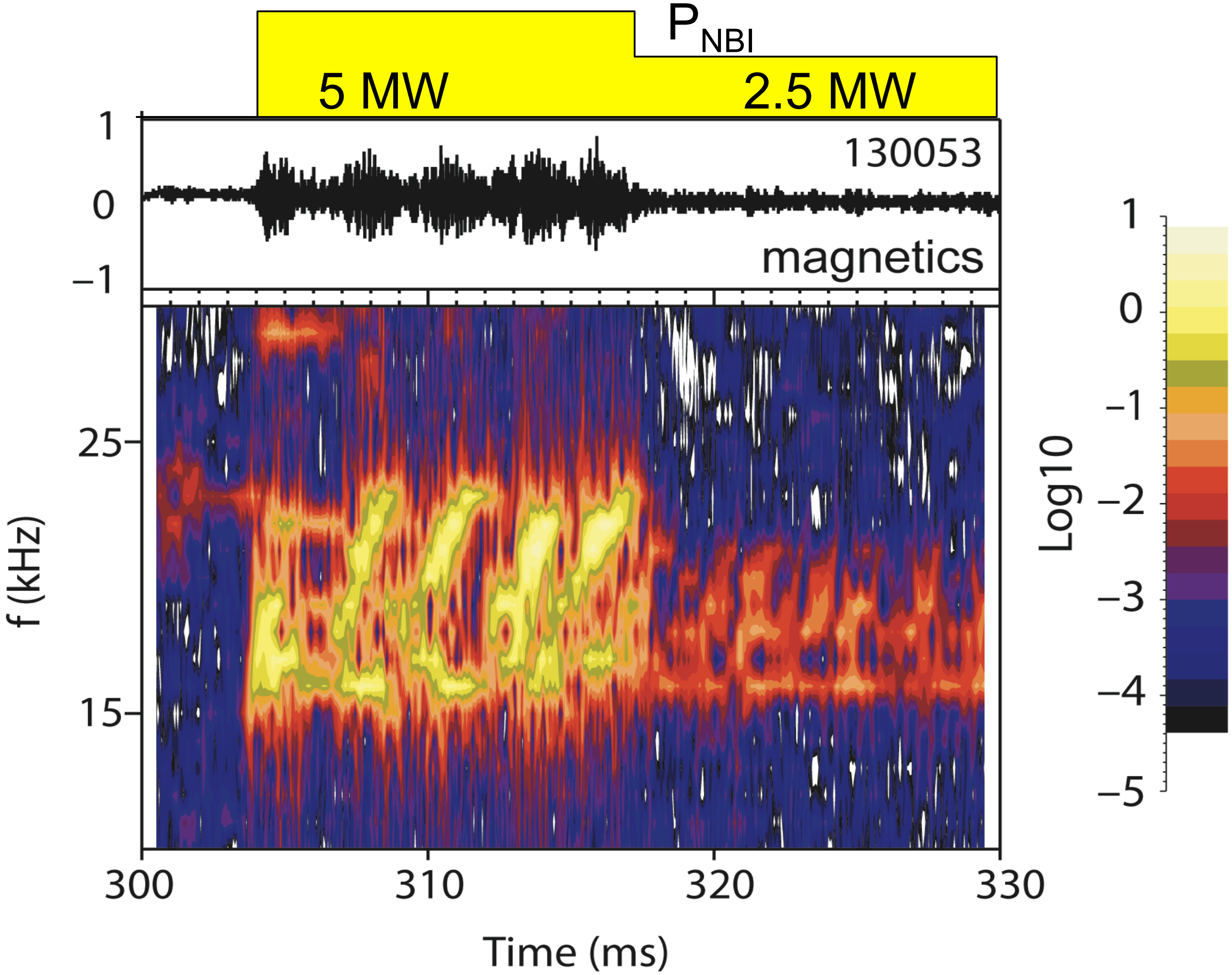
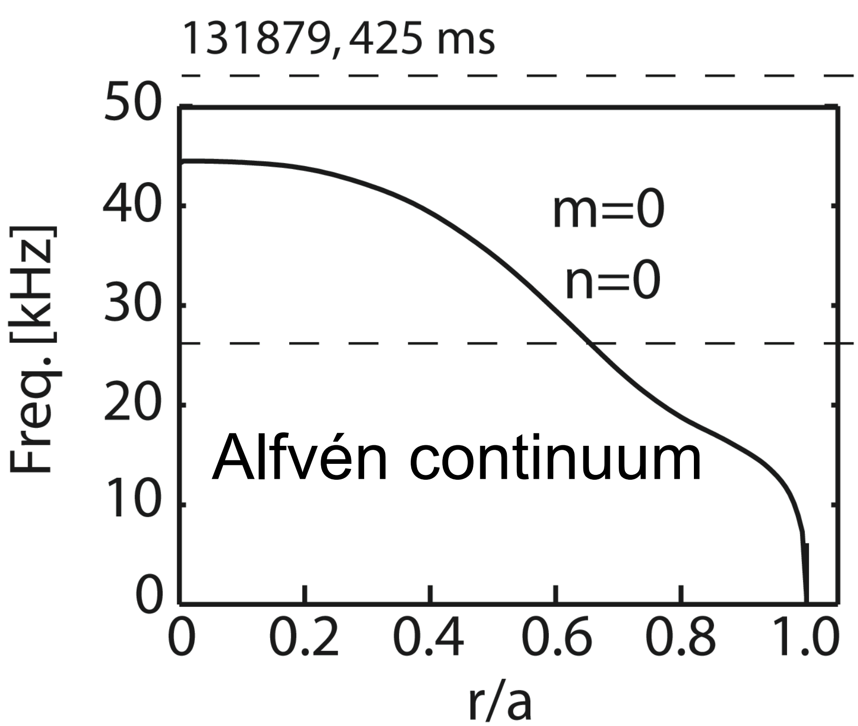
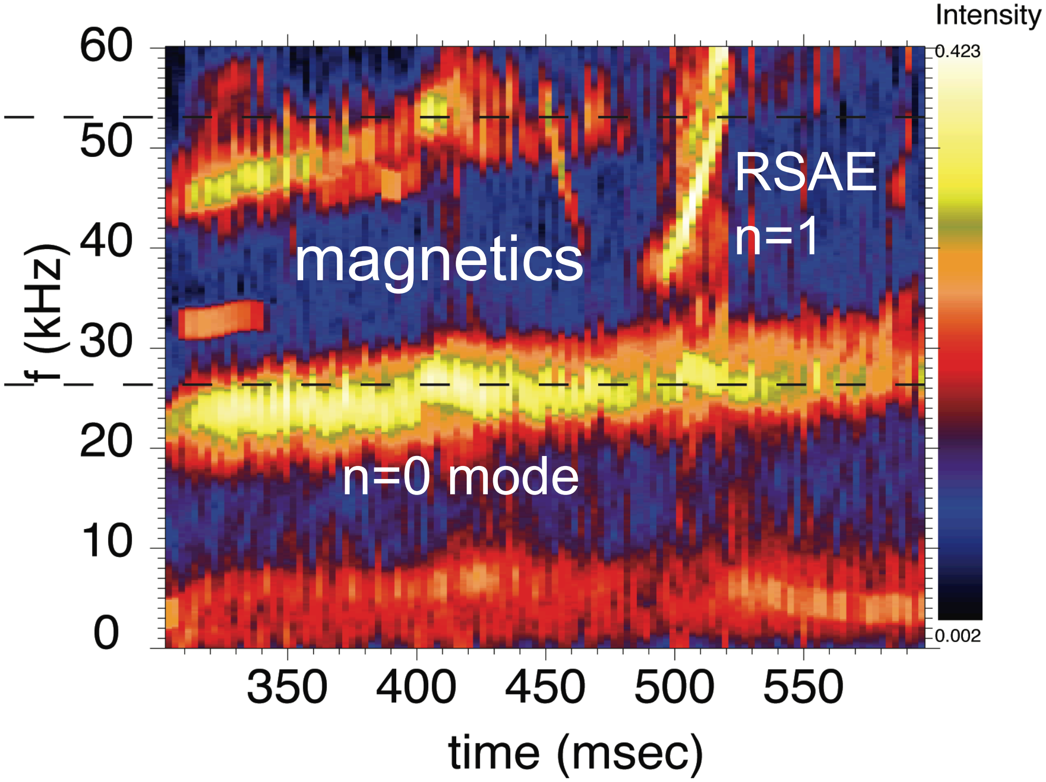
Fast Up-Down Mode Frequency Chirp Indicates Hole-Clump Formation and beam strong interaction



Mode frequency well below GAM frequency , based on NOVA continuum analysis : γ_{eff} = 1.4





- No Doppler shift for n=0.
- NOVA GAM eigenmode does not always exist, not a robust instability
- bispectral analysis needed for harmonics, suspect independent modes
- Mode close to GAM frequency at loss boundary ?????

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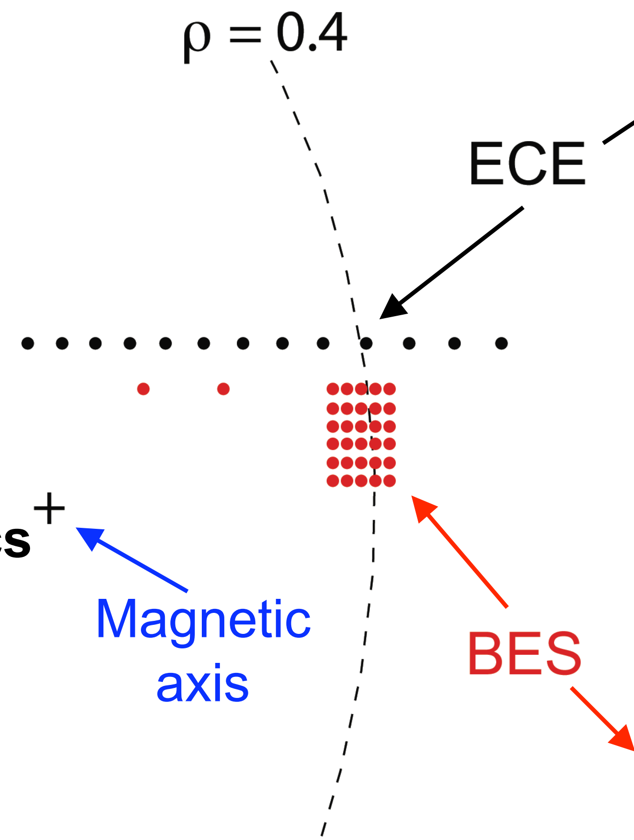
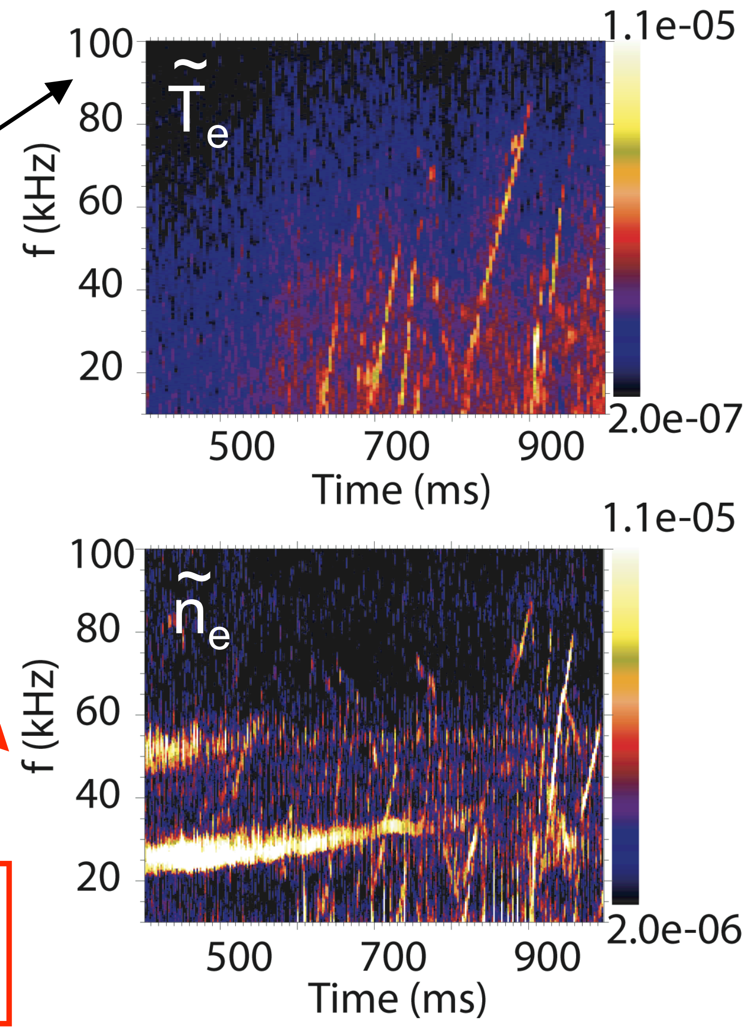
Surprise: Local BES and ECE Measurements Indicate no Electron Temperature Fluctuations for this mode !

- **RSAE seen on BES and ECE**

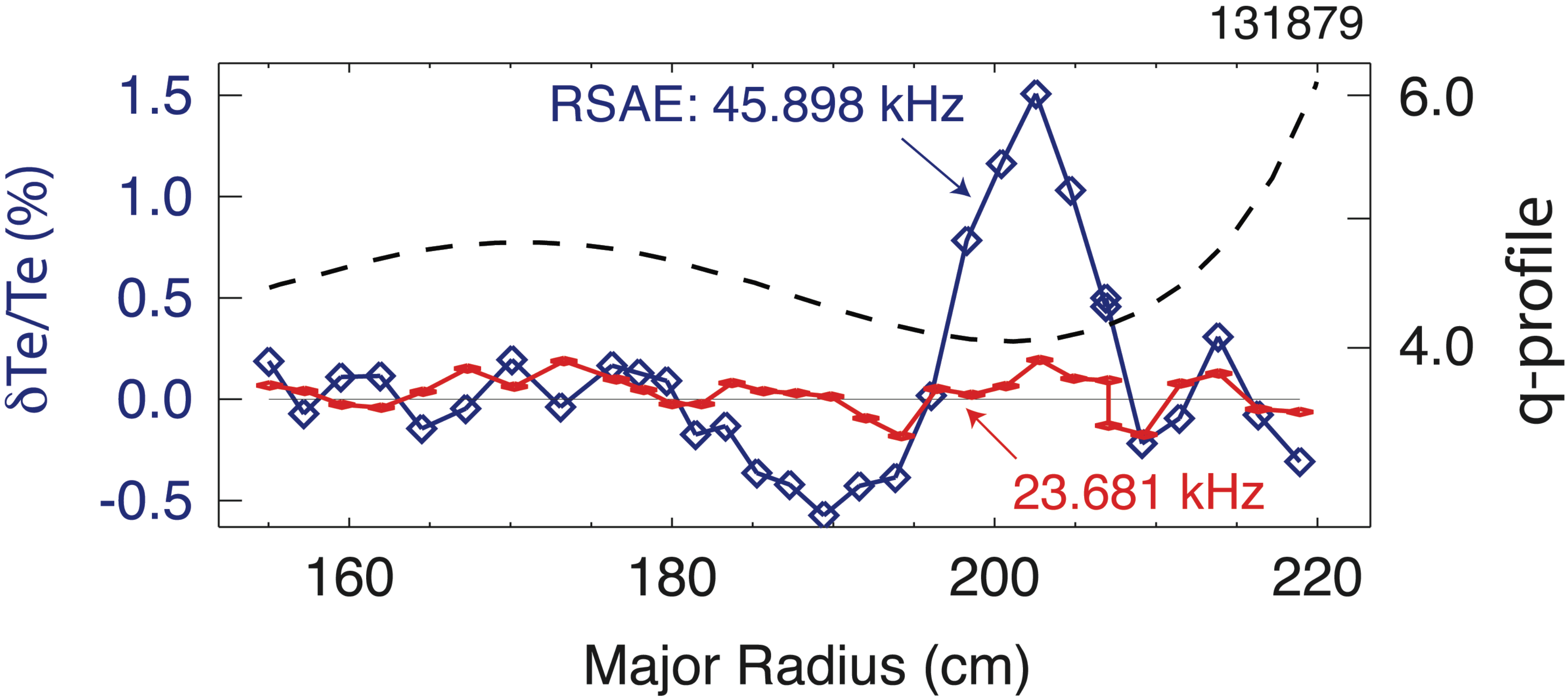
- **n=0 mode only shows up on magnetic and density diagnostics**





$$\tilde{T}_e/T_e \ll \tilde{n}_e/n_e$$

Radial Eigenmode of n=1 RSAE Clearly Resolved using ECE Measurements, Nothing seen for n=0 mode



IS n=0 Mode GAM-like, even if it is the wrong frequency?

- Poor correlation with central GAM frequency

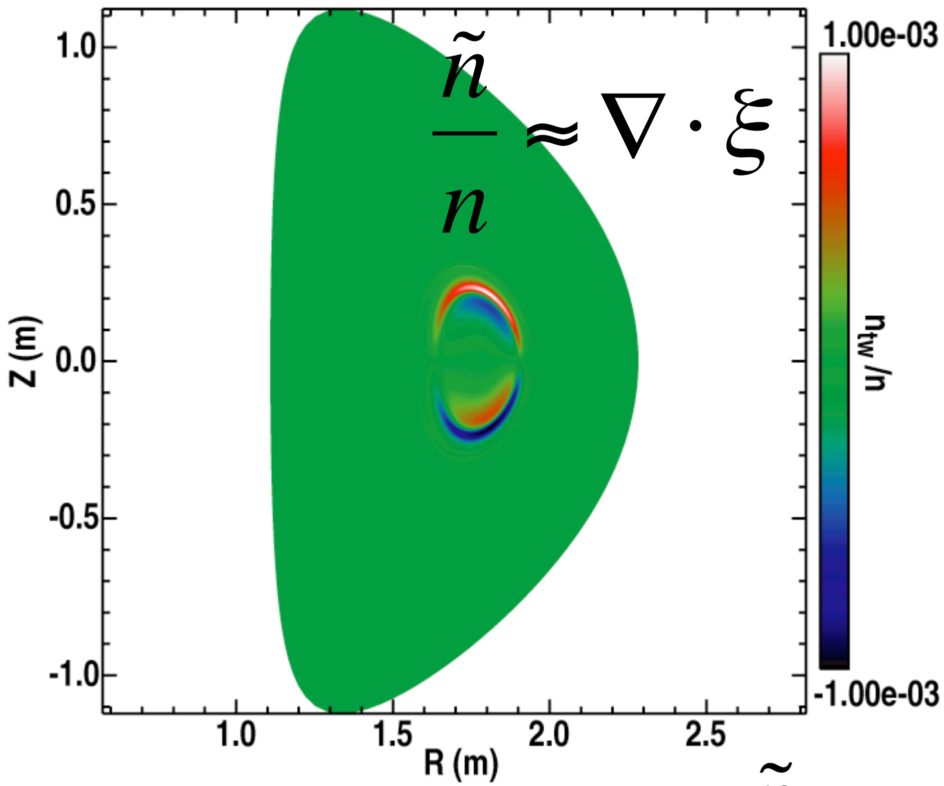
- GAM not ubiquitous in reverse shear plasmas (NOVA)
  mode is always present for counter injection at high q_{min}

- GAM Spatial structure: NOVA predicts

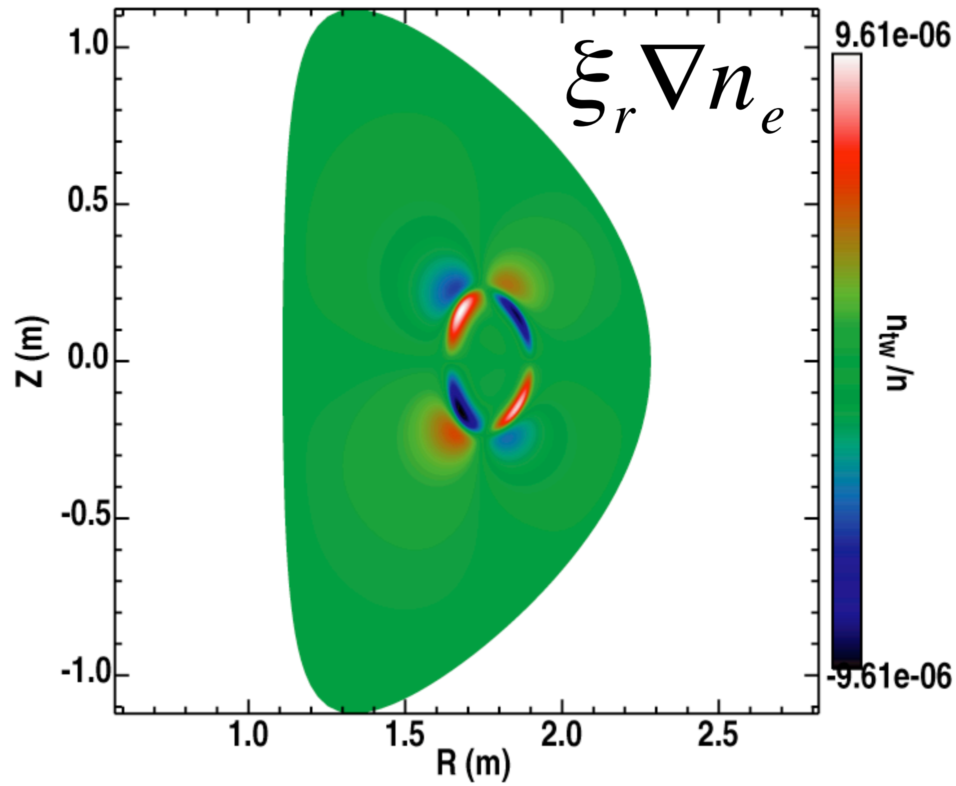
  1. strong core localization
  2. dominant m=0 component that is not observable on the density or temperature
  2. strong m=1 compressional component
  3. much weaker m=2 radial component

GAM solution in NOVA has strong compression term and weak radial displacement contribution to the density

m=1 compression

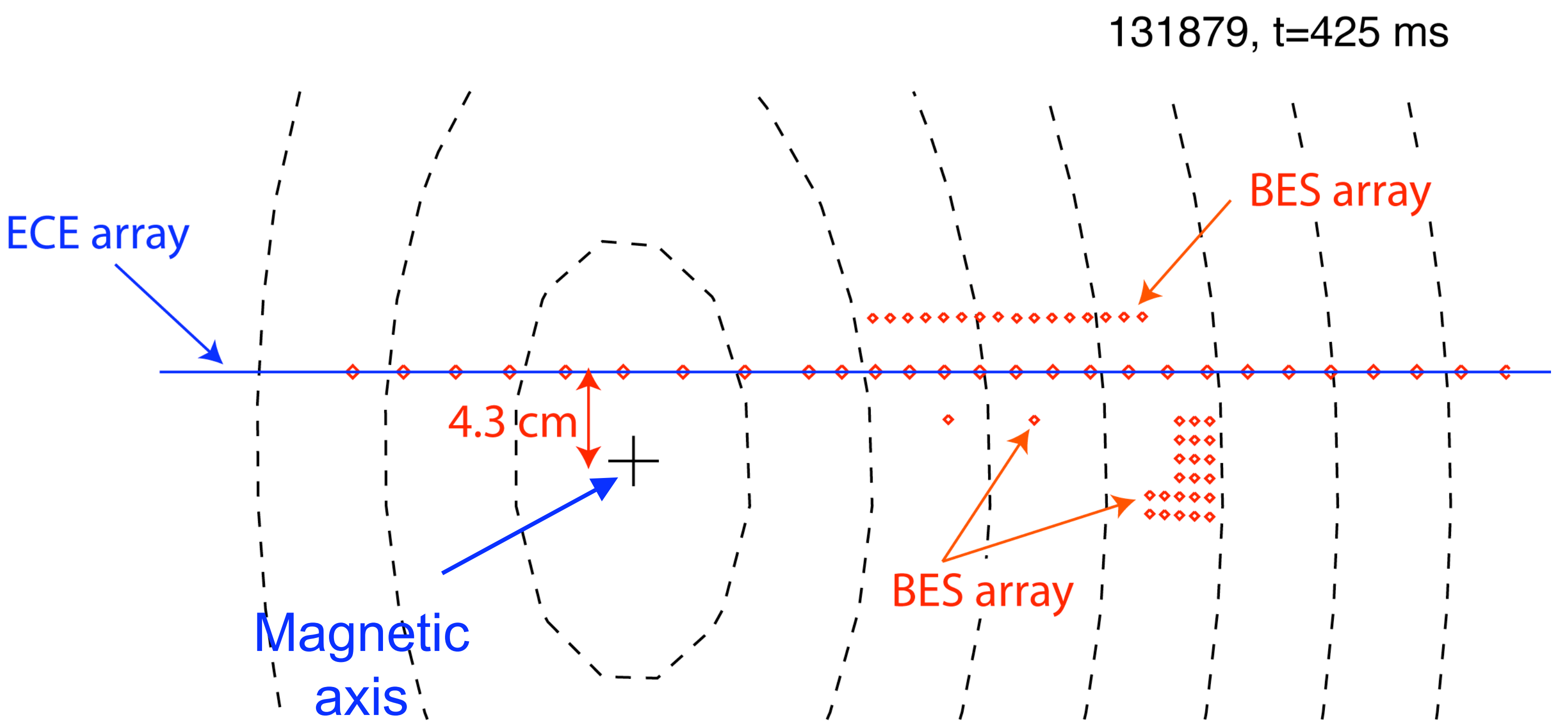


m=2 radial displacement

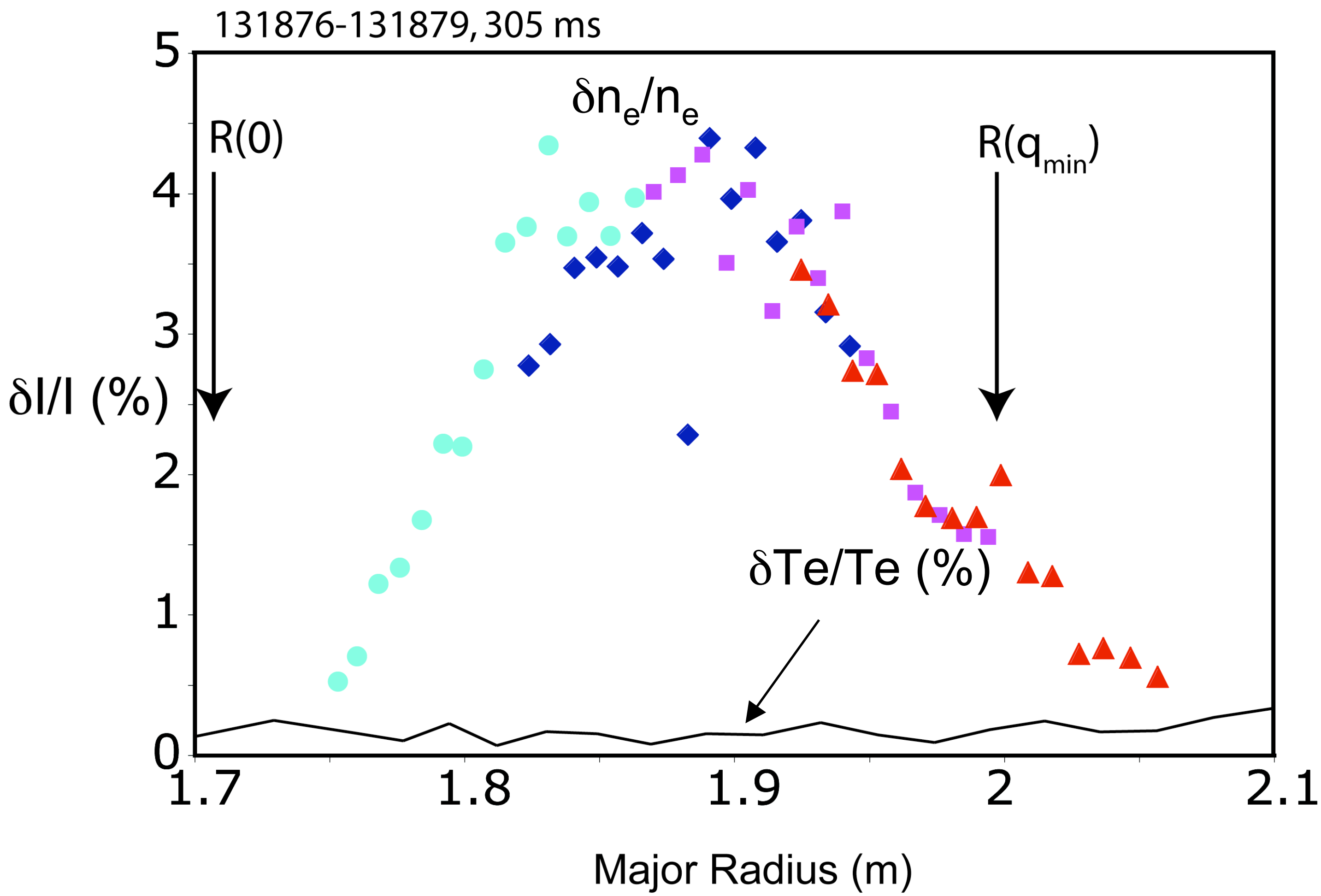


$$\frac{\tilde{n}}{n} >> \xi_r \nabla n_e$$

New Linear Radial BES Array installed to Address Key Issues of Mode Structure



Preliminary: Density fluctuation profile from BES is very broad with no temperature component



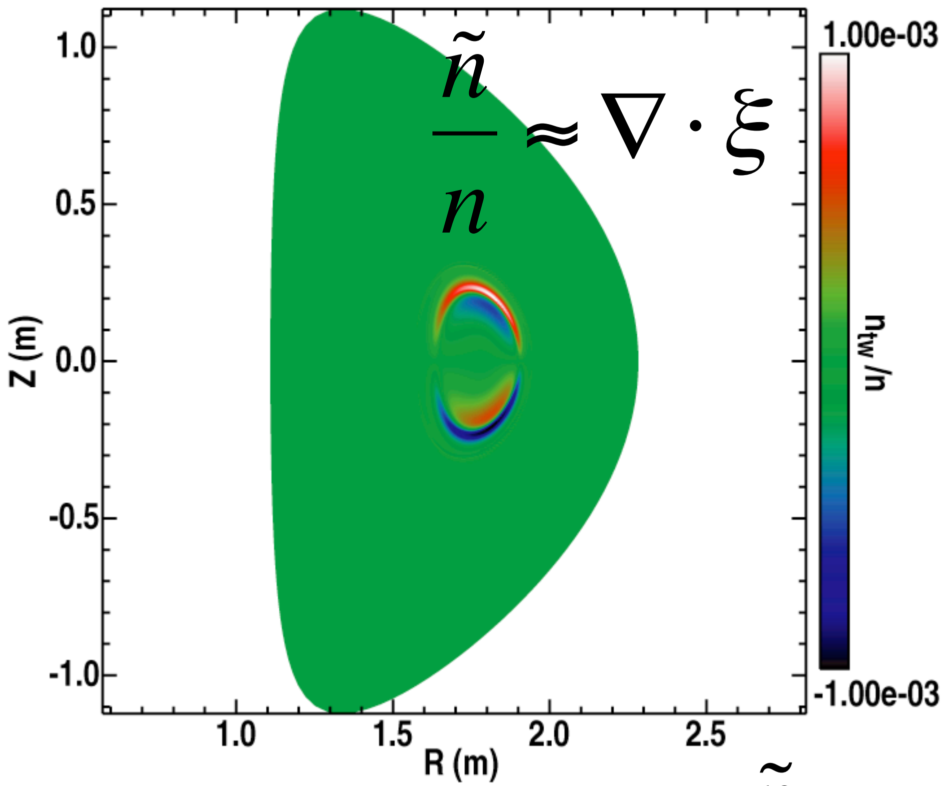
- mode minor radius ≈ 20 cm.

Measurement may grossly underestimate mode amplitude :

Z= + 7 cm.

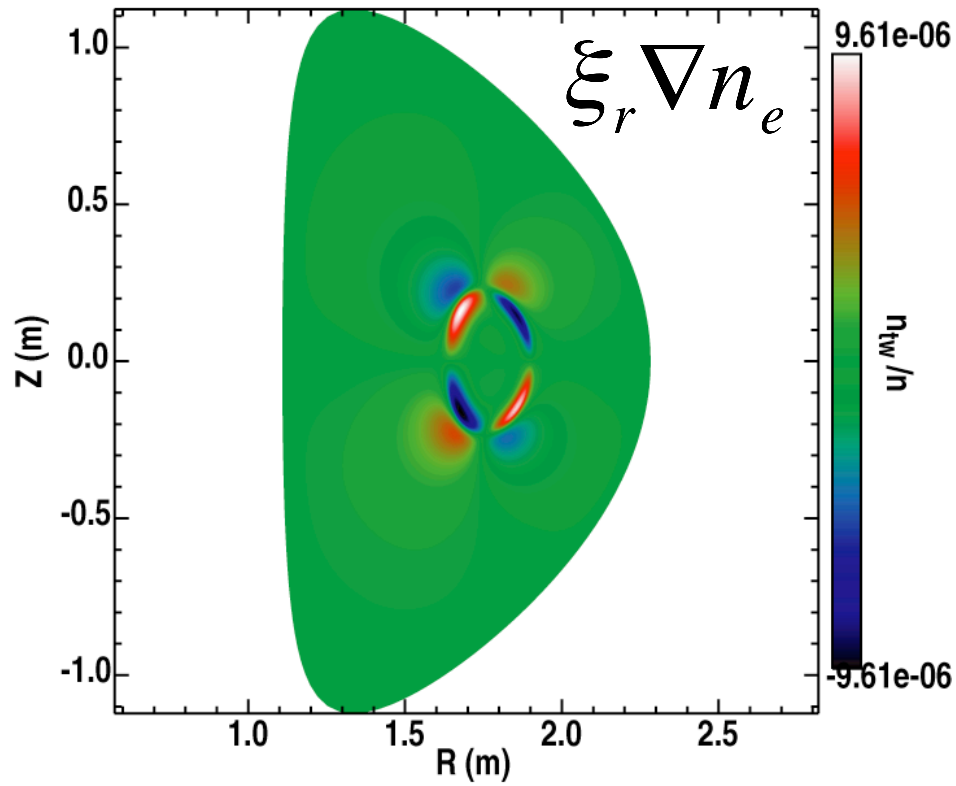
GAM solution in NOVA has strong compression term and weak radial displacement contribution to the density

m=1 compression



$$\frac{\tilde{n}}{n} \approx \nabla \cdot \xi$$

m=2 radial displacement



$$\xi_r \nabla n_e$$

$$\frac{\tilde{n}}{n} >> \xi_r \nabla n_e$$

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WEAK RADIAL COMPONENT MEANS WEAK TEMPERATURE FLUCTUATIONS, CONSISTENT WITH DATA

Ideal MHD closure:

$$Pn^{-\gamma_{eff}} = c$$

$$\Downarrow$$

Density perturbations:

$$\frac{\tilde{n}_e}{n} = \nabla \cdot \xi + \xi_r \nabla n_e$$

Isothermal electrons γ_e=1:

i.e., $\omega_{e\text{-transit}} >> \omega_{MHD}$

$$\frac{\tilde{T}_e}{T_e} = (1 - \gamma_e)\nabla \cdot \xi + \xi_r \nabla T_e$$

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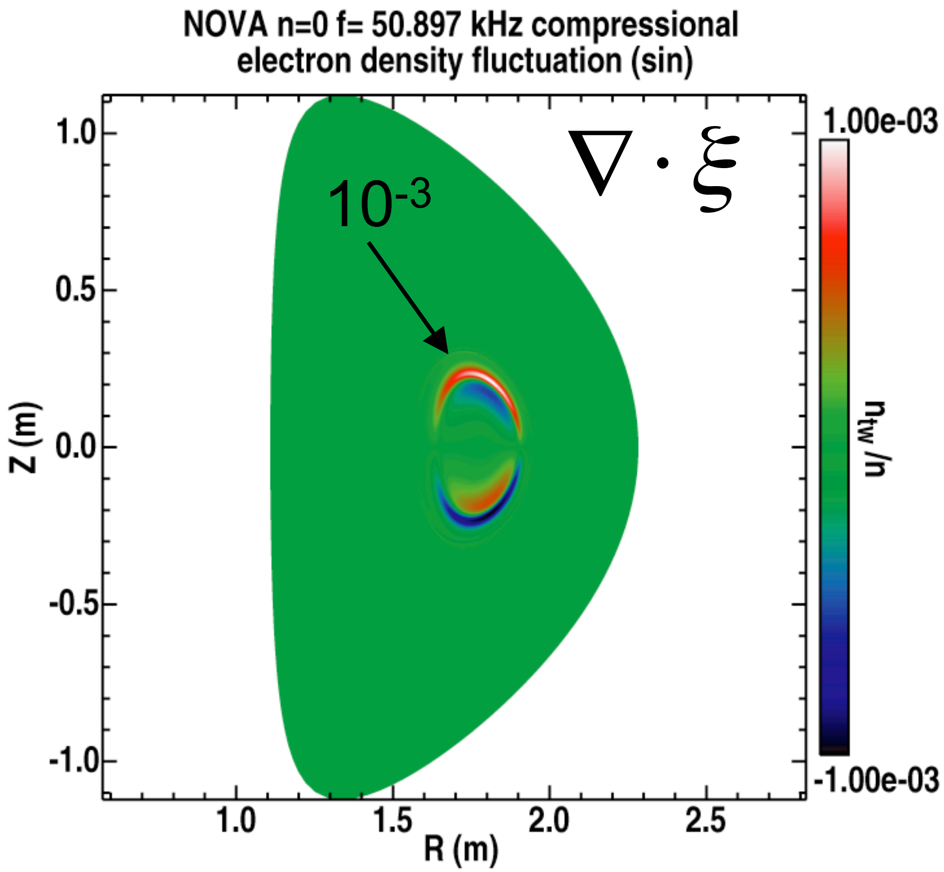
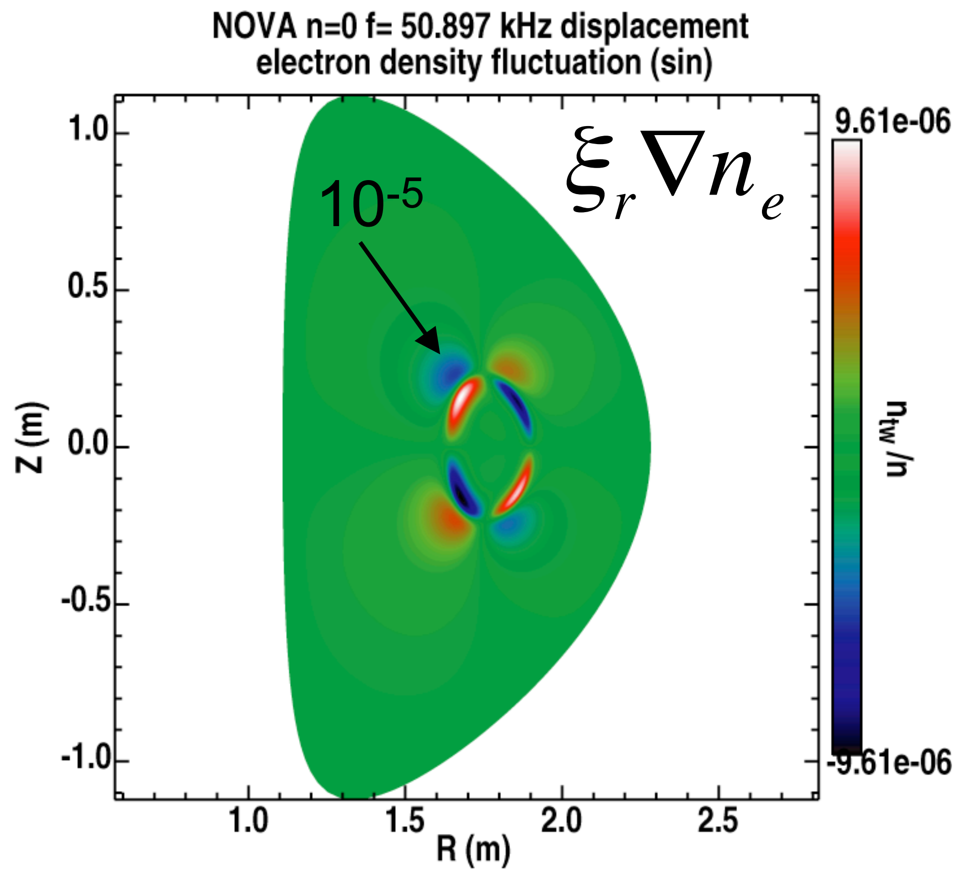
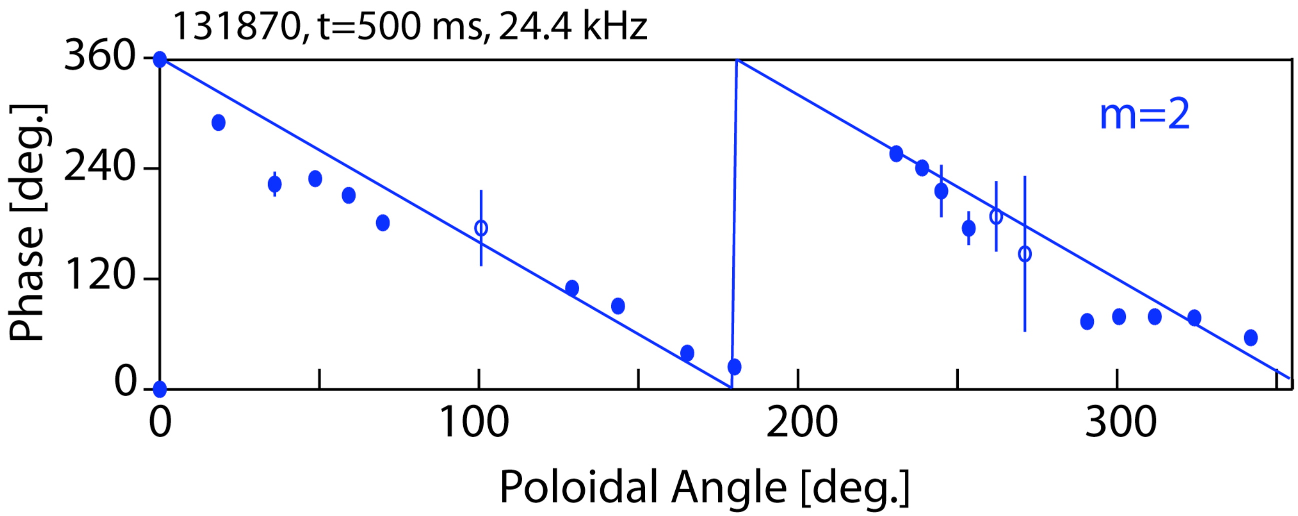
Is there any evidence for weak m=2 radial displacement?





$$\xi_r \nabla n_e \approx 10^{-2} \nabla \cdot \xi$$

For n=0 modes, only the radial displacement contributes to poloidal magnetic field fluctuations

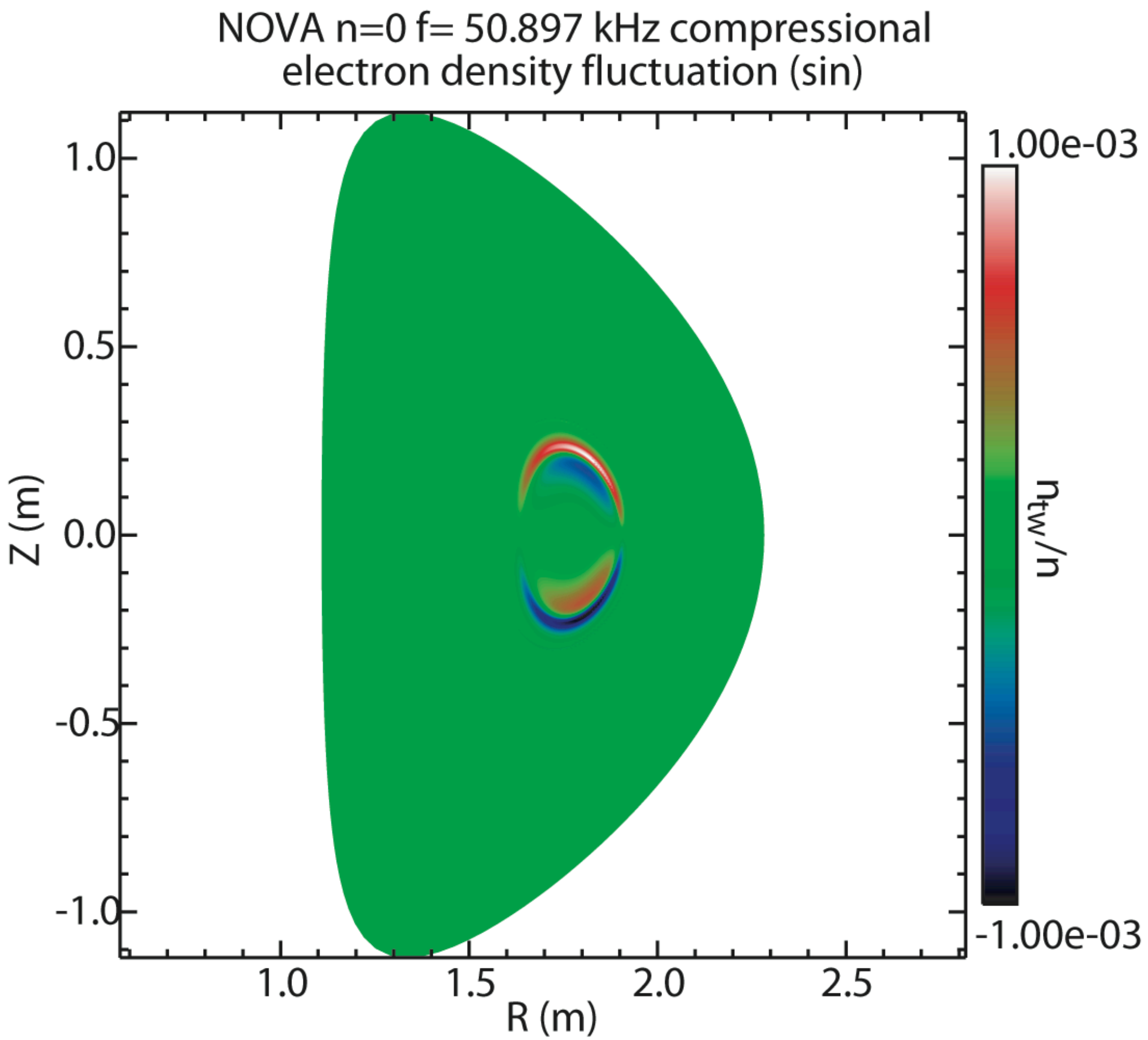


$$\frac{\tilde{B}_\theta}{B} \approx 10^{-5}$$

- Observation of m=2 consistent with lowest order radial component of GAM from NOVA

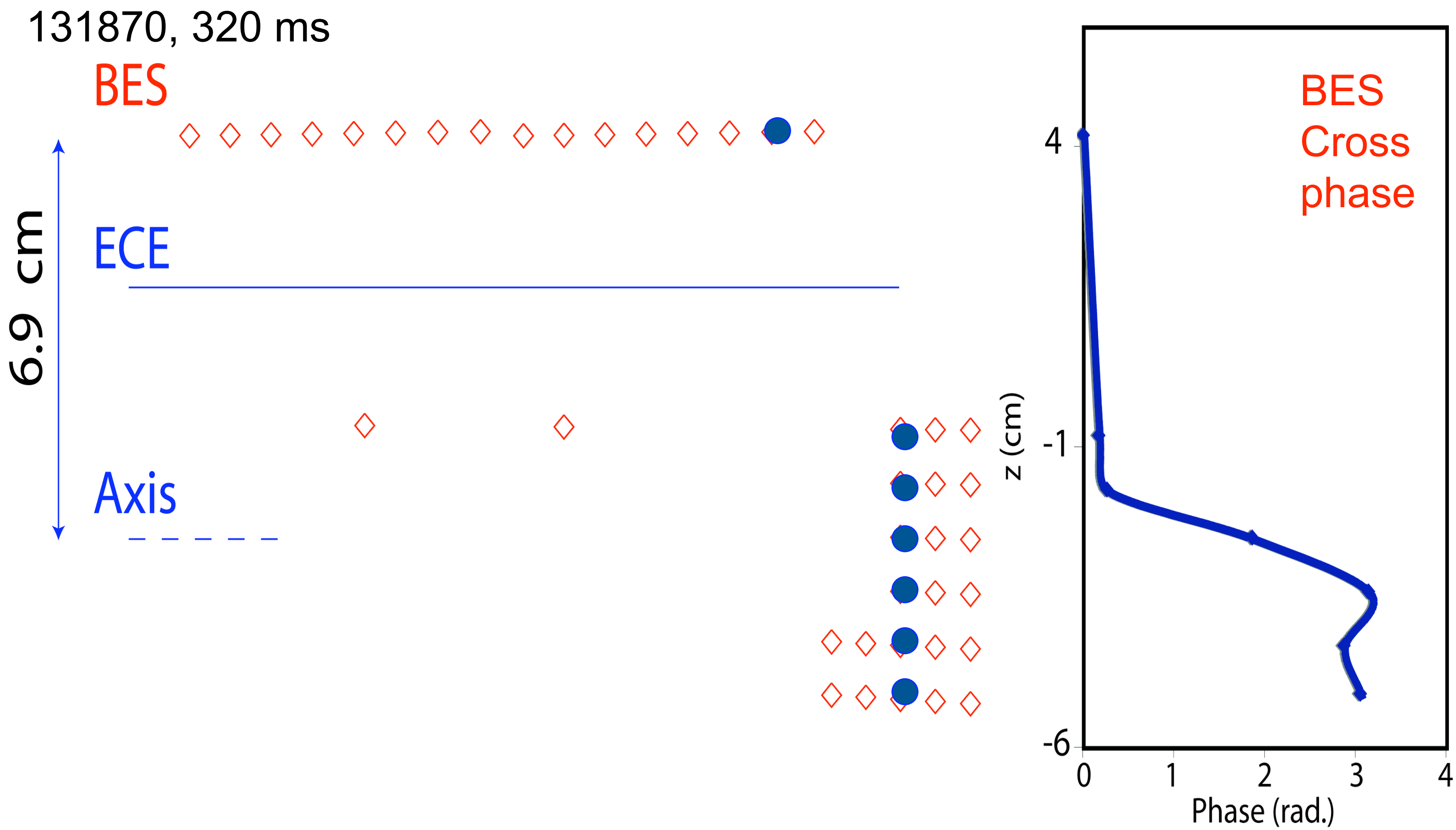
- weak signals consistent with small radial displacement

m=1 density component is a standing wave: expect phase inversion near magnetic axis

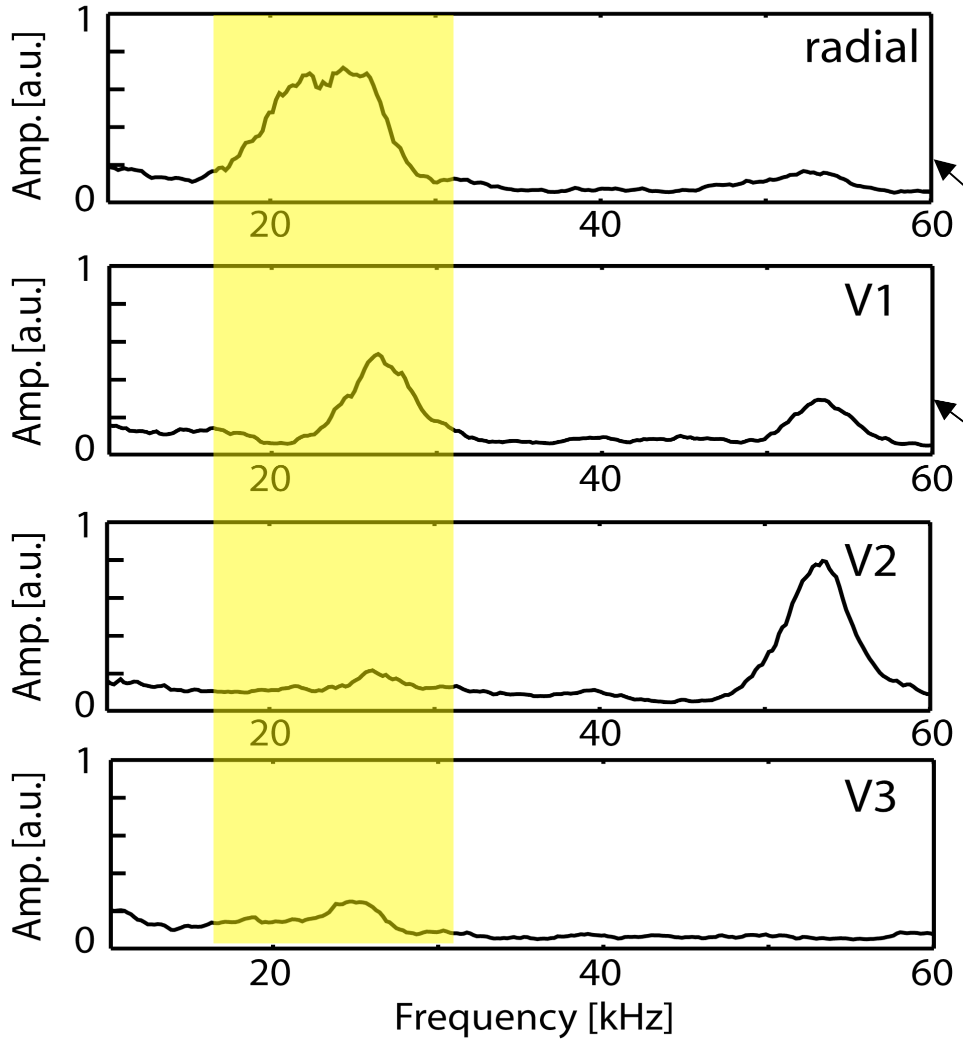


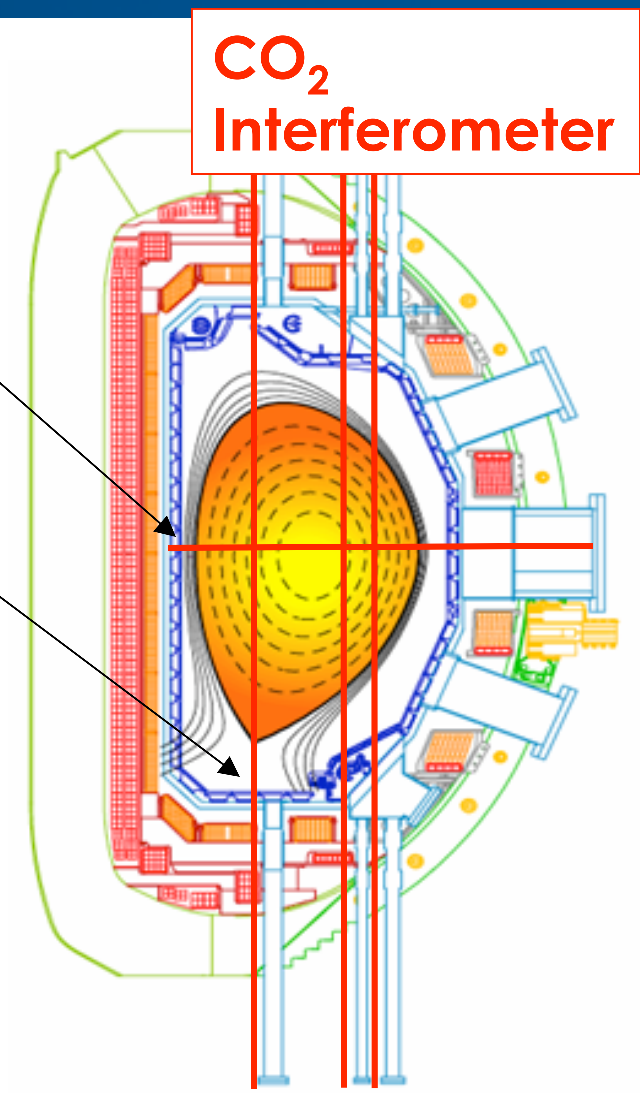
$$\nabla \cdot \xi$$

Phase Inversion Observed Near Magnetic Axis Consistent with m=1 GAM Standing Wave



Vertical and radial CO2 Interferometer measurements confirm opposite up down polarity of mode





Counter beam injection excites new axisymmetric mode well below the GAM frequency in DIII-D

- Robust instability with spatially extended eigenmode is unlike the GAM
  - GAM does not always exist
  - mode frequency too high
- New mode scales better with q_{min} than with f_{GAM}
  - mode amplitude rapidly decays with decreasing q_{min}
- Mode structure consistent with some features of GAM modes
  - large density, weak temperature signals
  - m=2 magnetic signal
  - density inversion below magnetic axis
- chirping and bursting indicates strong interaction with beam ions

Fast Ion Loss detectors needed!!