Alfvén Eigenmodes in DIII-D

M.A. Van Zeeland[1]

In Collaboration With:

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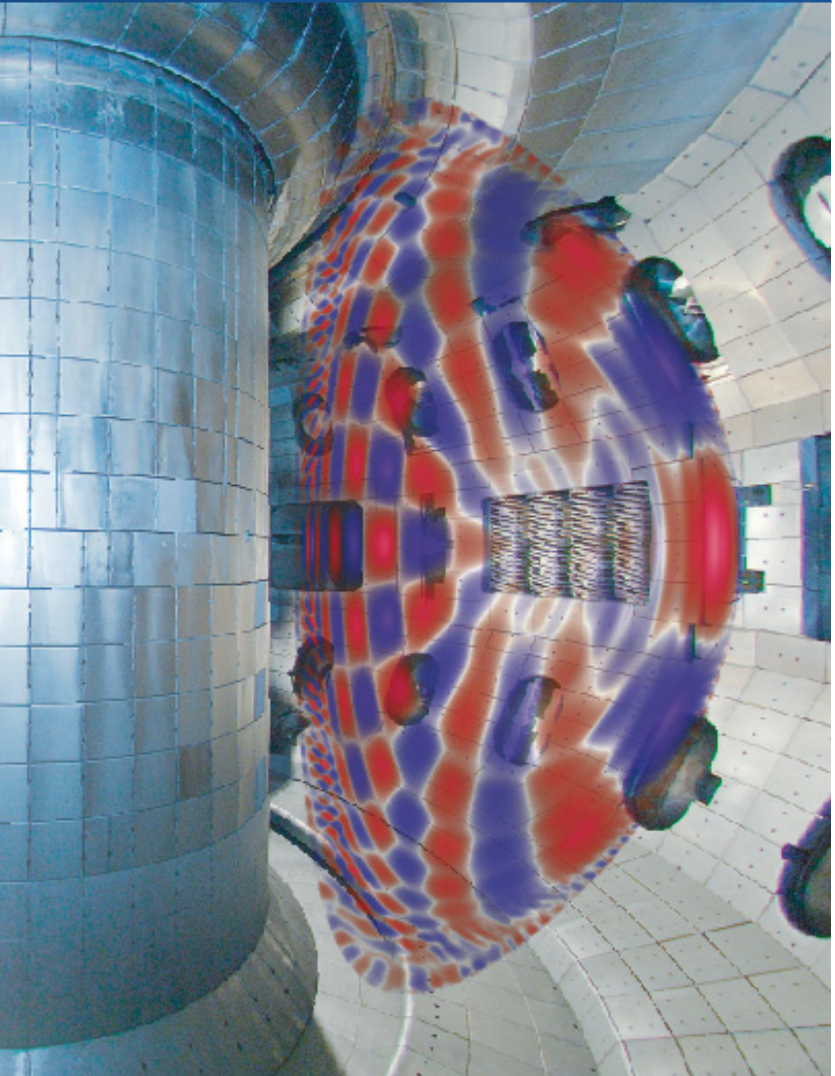

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GENERAL ATOMICS

Why Look at Alfvén Eigenmodes (AEs)?

Standard Story - A variety of AEs in tokamaks can be destabilized by energetic particles. Measurements show AE activity is correlated with transport of fast ions

This increased transport can cause:

- **Reductions in fusion performance***
- **Damage to first-wall components****
- **Potentially advantageous modifications to the current profile†**

Understanding the properties of AEs through modeling and experimental observation is essential in order to have confidence in predictions for their impact on future devices

*GY Fu and JW Van Dam, *Phys. Fluids B*, **1**, 1949 (1989)
HH Duong *et al.*, *Nucl. Fusion* **33, 749 (1993)
†KL Wong *et al.*, *Phys. Rev. Lett.* **93**, 085002-1 (2004)

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Why Look at Alfvén Eigenmodes (AEs)? (cont.)

Recent breakthroughs in the use of core-fluctuation diagnostics are helping to provide:

1) Detailed comparison between theory and experiment — in particular, eigenmode structure and stability
2) Measurements of the impact AEs have on fast ions
3) Information about the q-profile from AE frequencies (Alfvén Spectroscopy)*, †

*H.L. Berk et al., *Phys. Rev. Lett.* **87**, 1085002 (2001)

†MF Nave *et al.*, *Rev. Sci. Instrum.* **75**, 4274 (2004)

Outline

I. Reversed Shear Alfvén Eigenmode (RSAE) and Toroidicity Induced Alfvén Eigenmodes (TAE) — simple model, relevant diagnostics, and experimental observations

II. ECE observations of Alfvén Eigenmodes (AE) and modeling of the measurements using ideal MHD - AE structure

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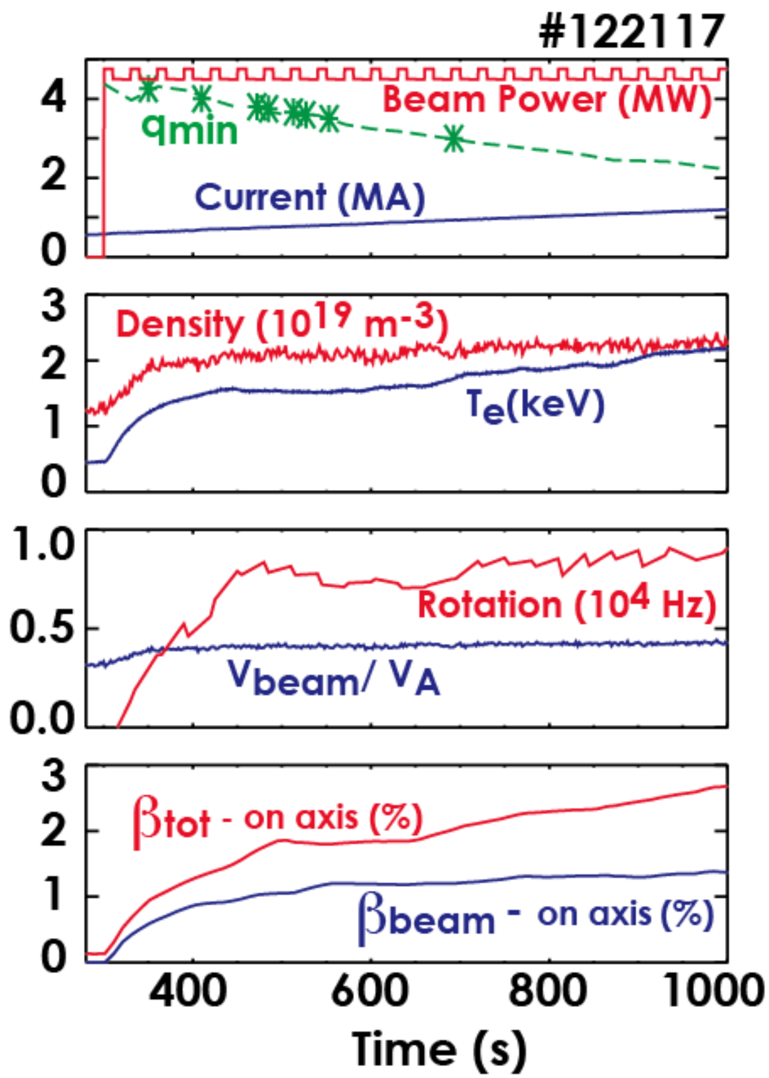
IV. Impact of the measured Alfvén Eigenmodes on the fast ion population

Alfvén Modes Are Usually Unstable in AT Plasmas



In this talk the plasmas have…

- Reversed central magnetic shear
- Co-injected 80 keV deuterium neutral beams
- Large beam beta to drive modes
- Fast-ion speed > $V_A/3$ → circulating fast ions resonate with TAEs

Qualitatively similar conditions in many plasmas make Alfvén modes common in DIII-D

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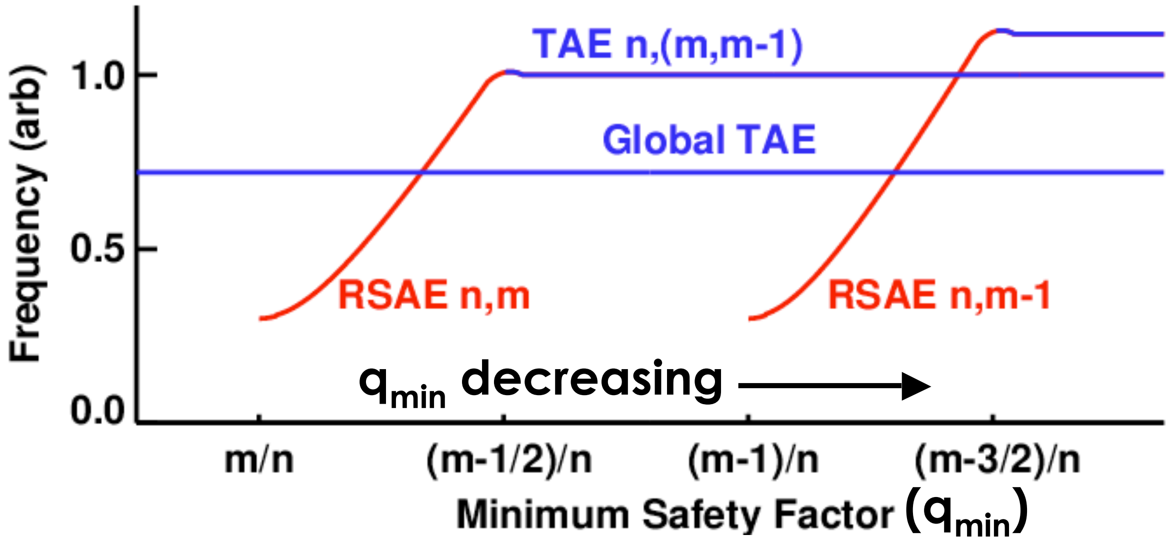
RSAEs and TAEs - Background



n = Toroidal mode number

m = poloidal mode number

Reversed Shear Alfvén Eigenmodes (RSAE)*

- **RSAEs also called *Alfvén Cascades***
- **Can exist in tokamak plasmas with non-monotonic safety factor (q) profiles**
- **Localized near q_{min}**
- **Transition to TAE with a frequency sweep sensitive to q_{min}****

* A. Fukuyama *et al.*, IAEA 2002 TH/P3-14

** H.L. Berk *et al.*, Phys. Rev. Lett. **87** (2001) 185002

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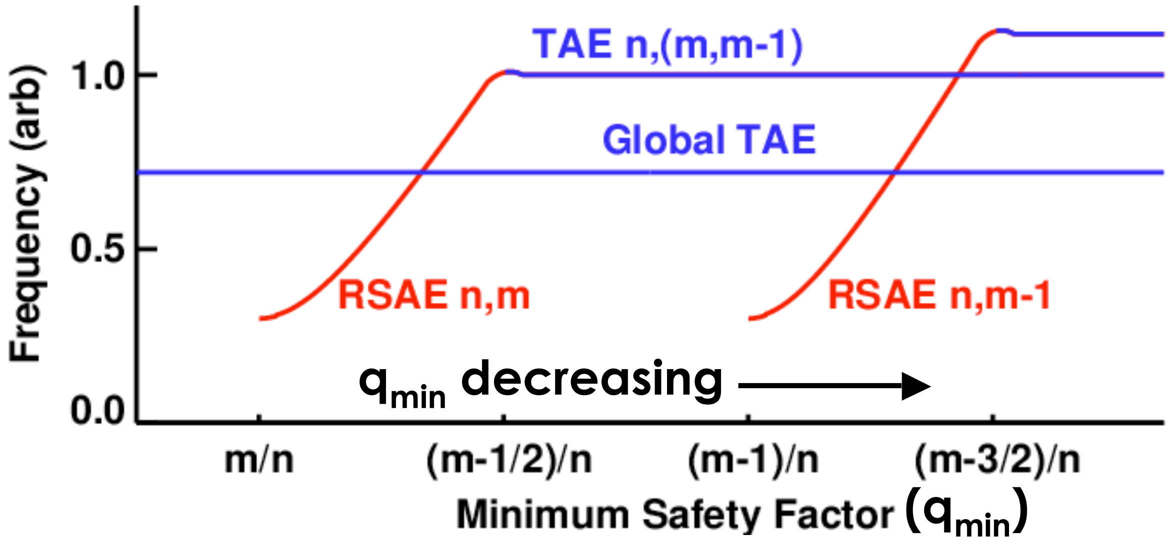
RSAEs and TAEs - Background



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Toroidicity-induced Alfvén Eigenmodes (TAEs)

- Global modes, more than one poloidal harmonic
- Frequency changes gradually
- $f_{TAE} \sim V_A/4\pi qR$ (50-200 kHz in DIII-D)

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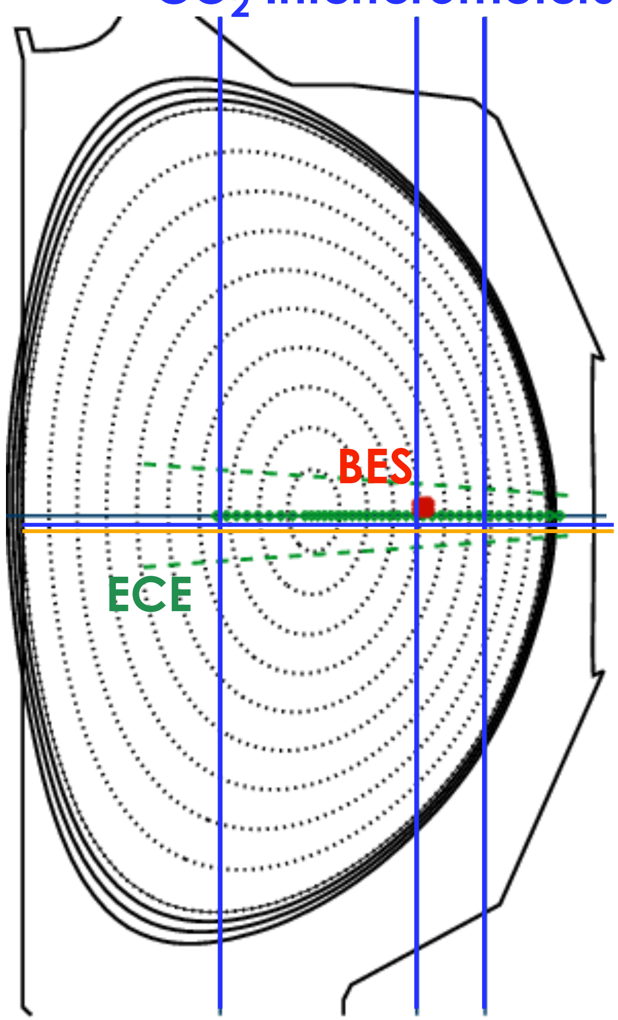
Multiple Diagnostics Provide Data on Different Aspects of Alfvén Eigenmodes in DIII-D



ECE - Electron Cyclotron Emission Radiometer (local, δT_e)

BES - Beam Emission Spectroscopy (local, δn_e)

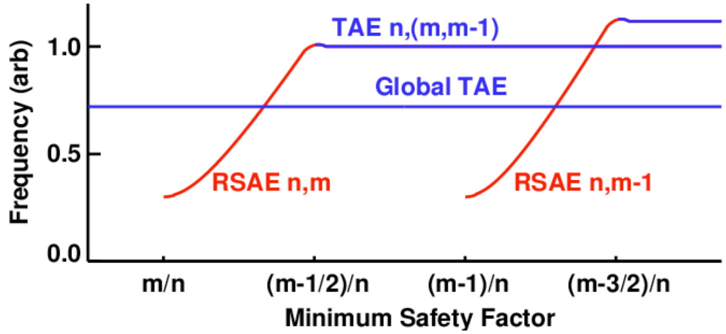
CO2 Interferometer and FIR scattering (line-integrated, δn_e)

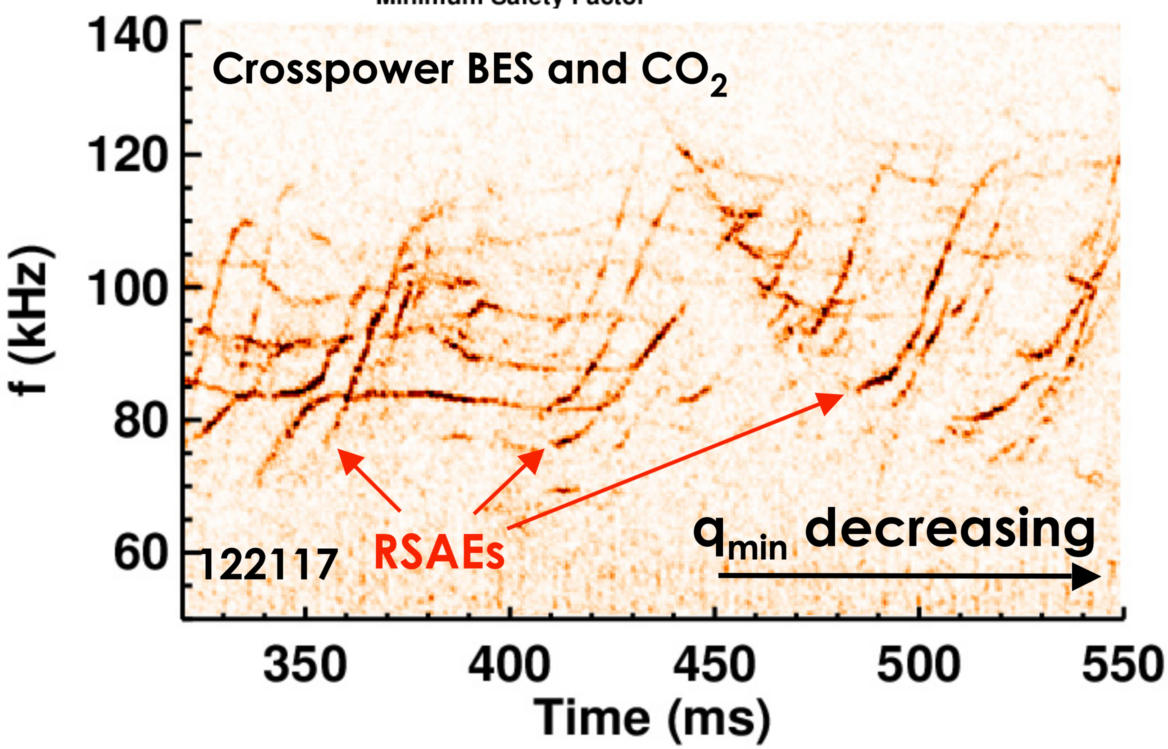
Reflectometer (local, δn_e)

Mirnov Coils (δB at wall)

All are able to resolve typical AE frequencies including Doppler shifts due to rotation! ($f < 1$ MHz)

TAEs and RSAEs are Both Observed in DIII-D Plasmas





Reversed Shear Alfven Eigenmodes (RSAE)

- **Localized near q_{min}**
- **Frequency sweeps upward as q_{min} decreases**

Frequencies are Doppler shifted by:

$f_{Lab} \sim f + n\, f_{rot}$

f_{rot} = *toroidal rotation freq.*

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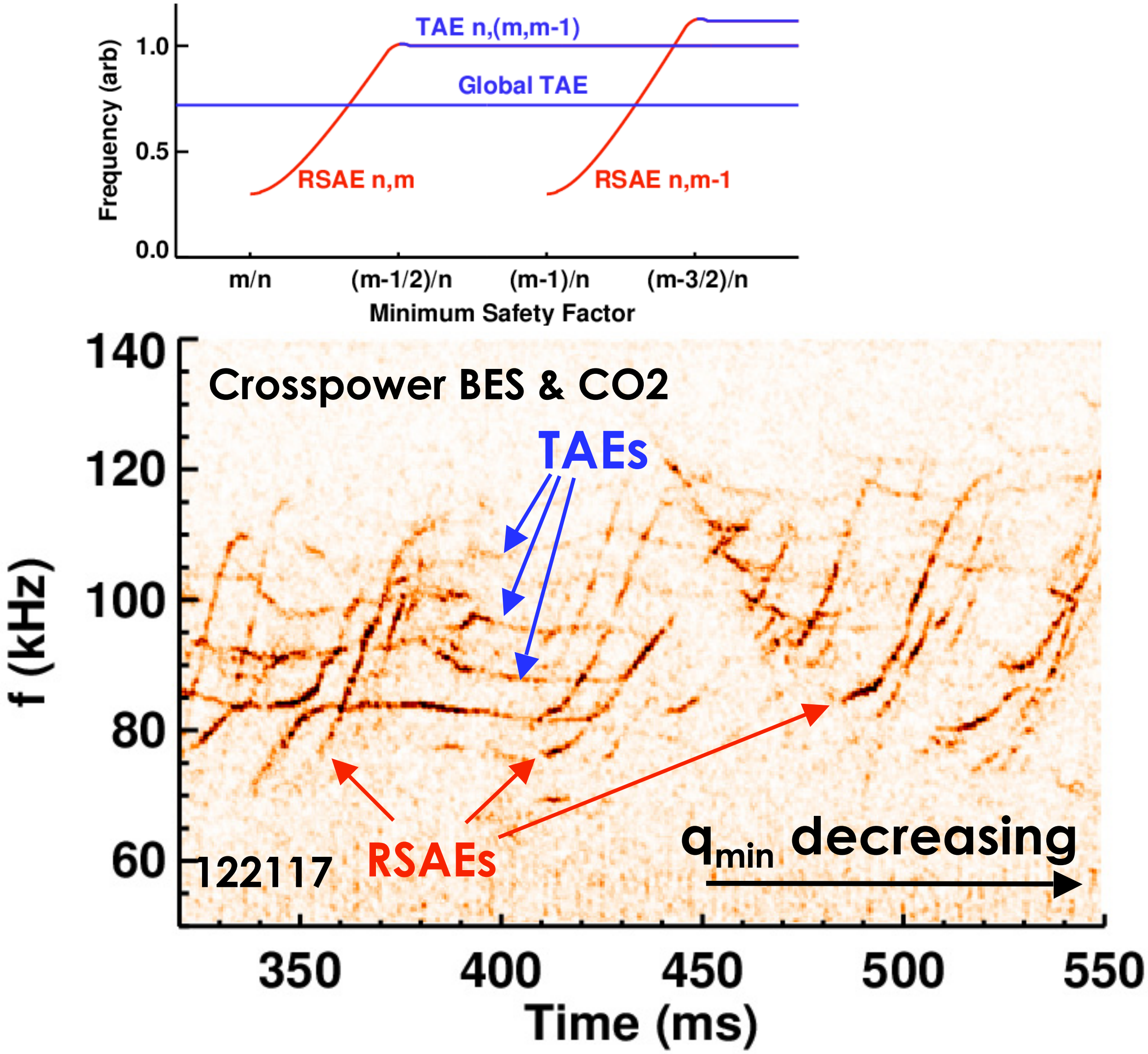

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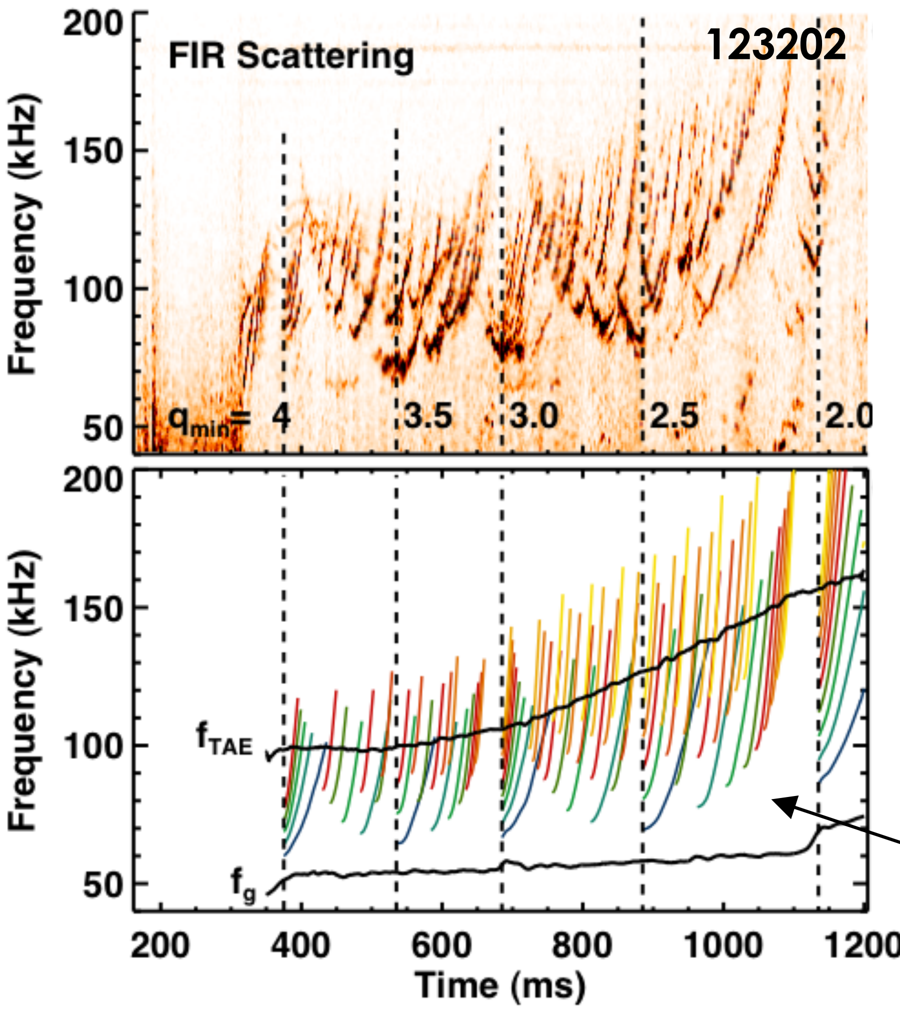
Simple Model for RSAE Frequency Evolution Fits Data Well



$$f = (f_c^{\,2} + f_g^{\,2})^{1/2} + nf_{rot}$$

$$2\pi f_c \approx k_{\|} V_A = \frac{(m - nq_{\min})V_A}{q_{\min} R}$$

$$2\pi f_g \approx \left[\frac{2}{M_i R^2}\left(T_e + \frac{7}{4} T_i\right)\right]^{\frac{1}{2}}$$

V_A = Alfven speed *f_{rot} = toroidal rotation*
T_e = electron temp. *M_i = ion mass*
T_i = ion temp. *R = major radius*
(All quantities evaluated near q_{min})

* B.N. Breizman, et al., Phys. Plasmas **12,** 112506 (2005)

n = 2 - 10 (toroidal mode number)
m = n+l , where l = 0-18

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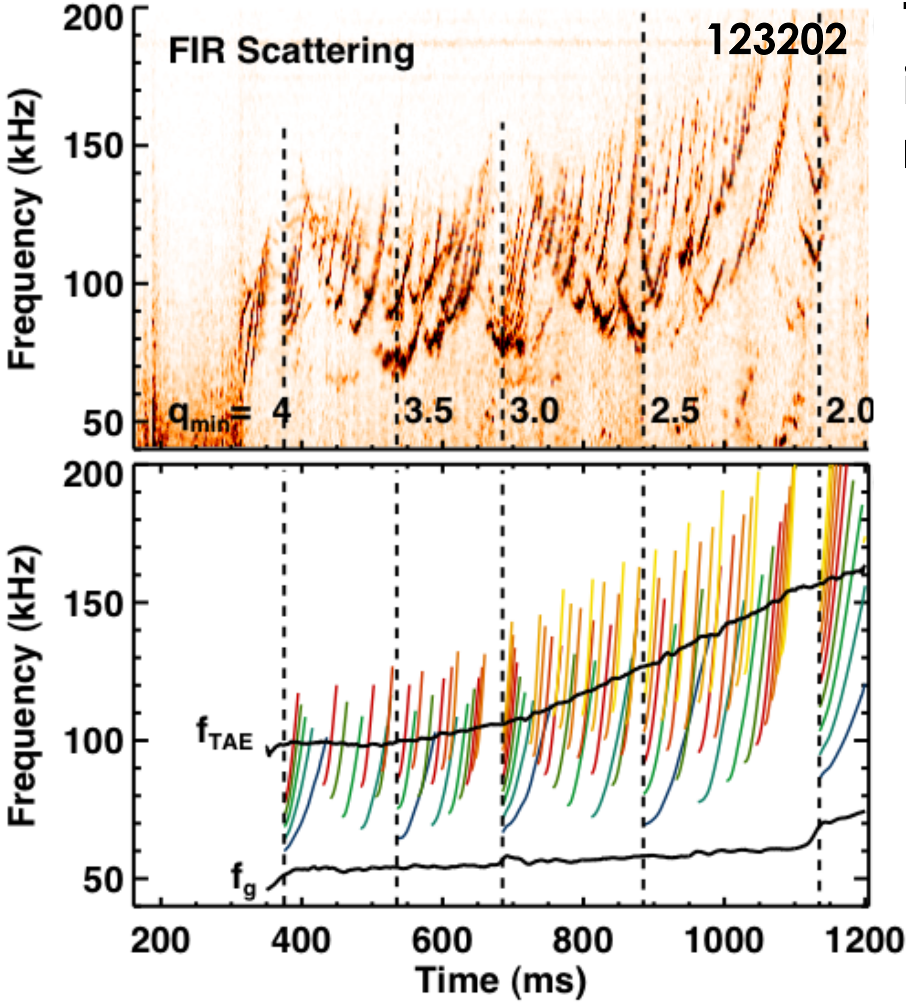
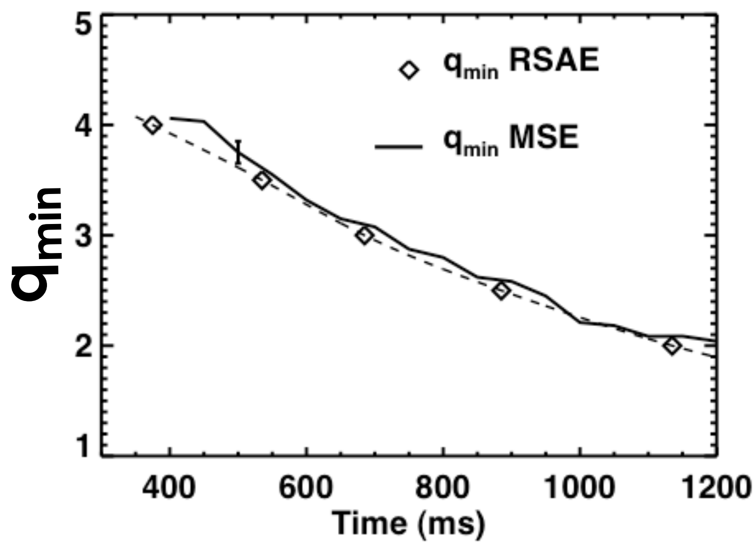
Through Modeling, $q_{min}(t)$ Can Be Obtained



The temporal evolution of q_{min} inferred from RSAE activity accurately reproduces that measured with motional Stark effect (MSE)

***Precise knowledge of q_{min} is very important for more detailed MHD analysis of eigenmode**



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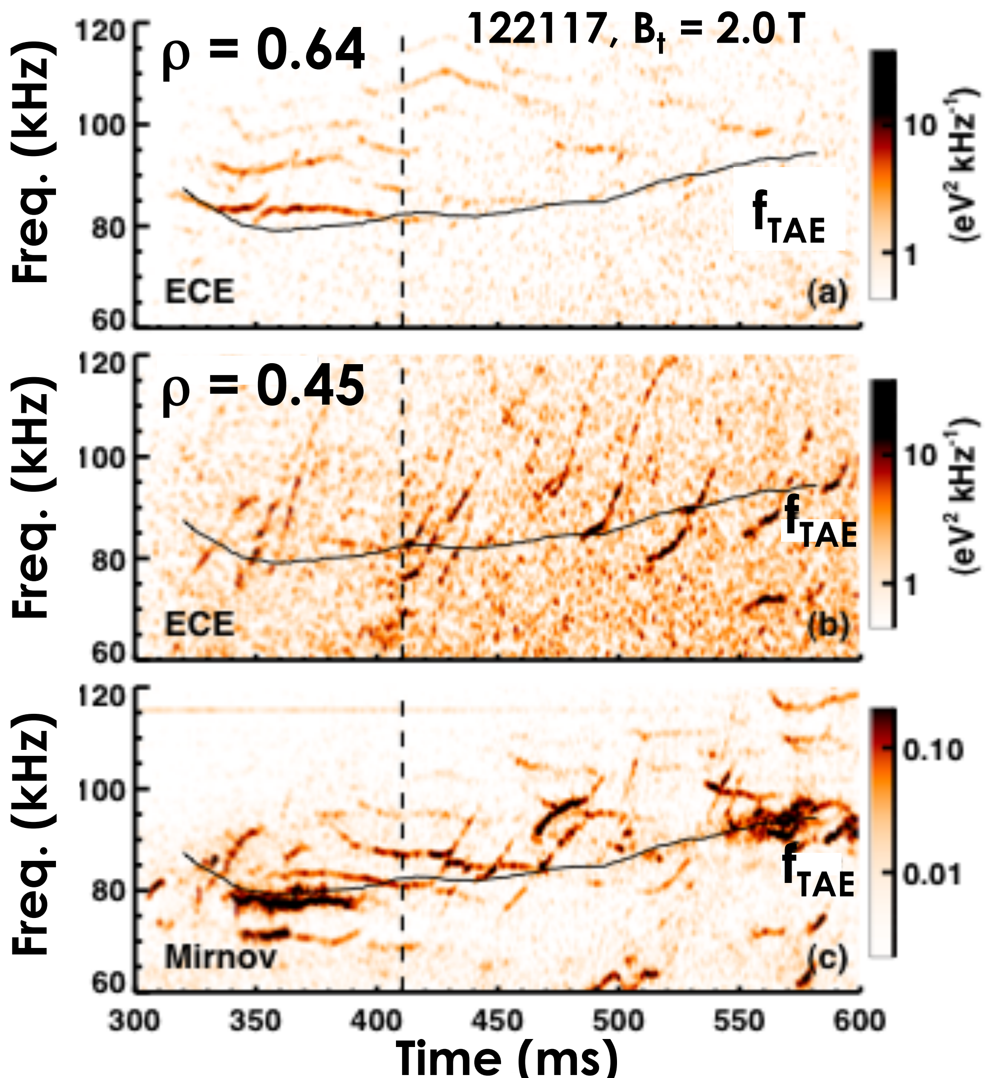
Alfvén Eigenmodes Are Observed by ECE Diagnostic

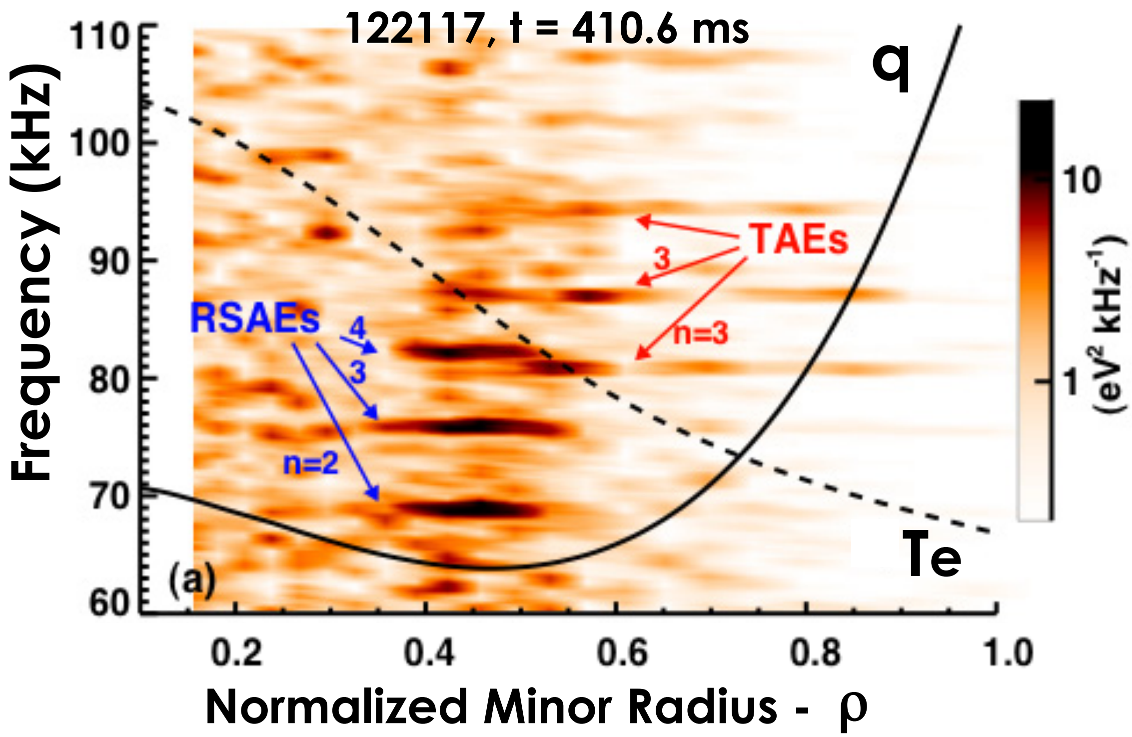


ECE gives local measurement of δT_e at 40 locations along midplane

For this discharge:

- Outer radii ECE channels see mostly TAE
- Inner radii ECE channels see RSAE
- Mirnov coil sees a combination of both RSAE and TAE

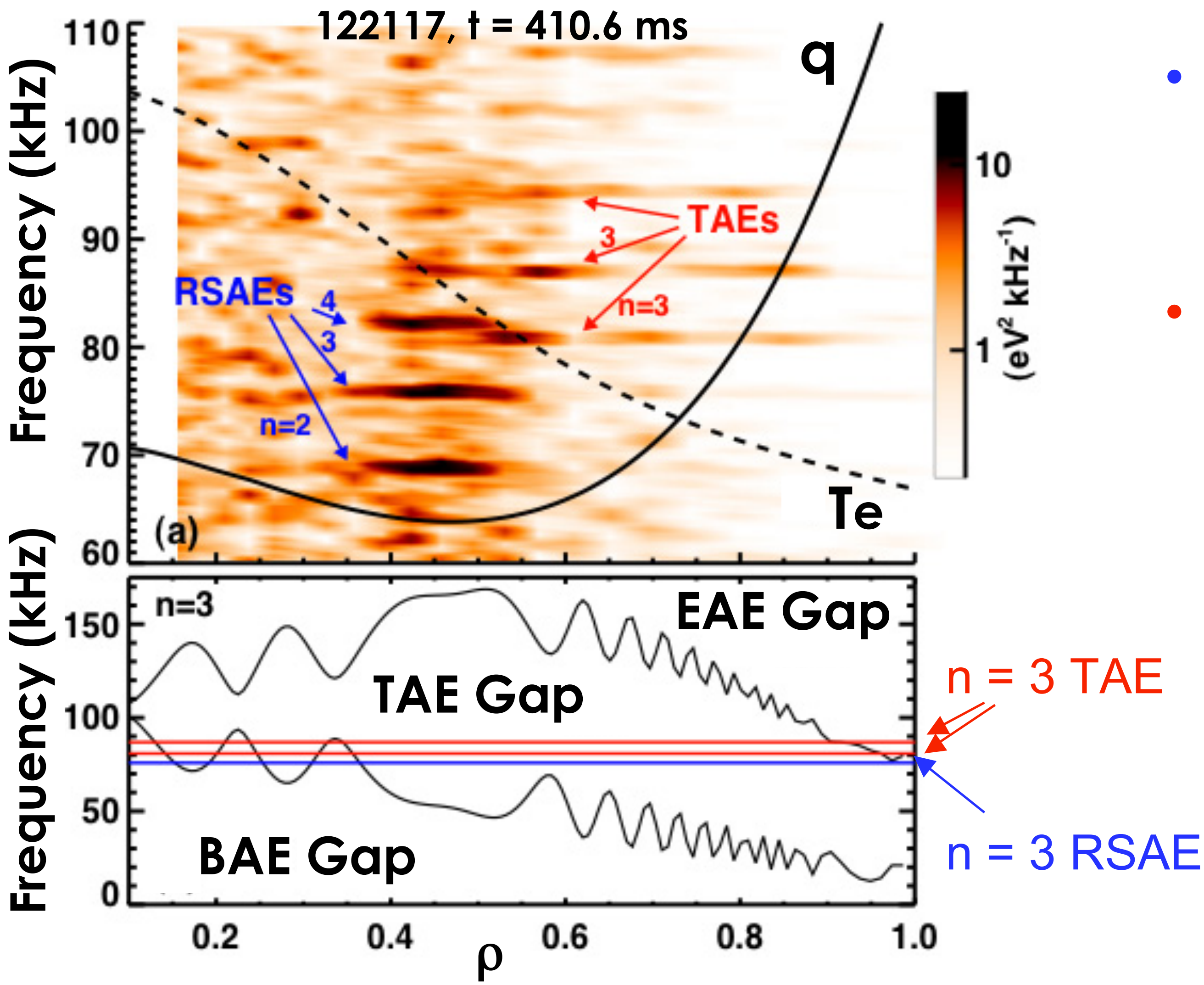
Analysis of Many ECE Channels Reveals AE Structure



- RSAEs are peaked near q-min as expected
- TAEs are more global and extend to the edge

Radial profile of ECE radiometer power spectra

Analysis of Many ECE Channels Reveals AE Structure



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n=3 **Alfvén continuum consistent with modes being RSAEs and TAEs**

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NOVA and NOVA-K Are Used to Investigate AEs in DIII-D

NOVA* uses ideal MHD theory to calculate eigenmodes of the tokamak plasma

Inputs include:

- Full plasma geometry
- Experimental profiles (pressure, q, density, temperature)
- Toroidal mode number

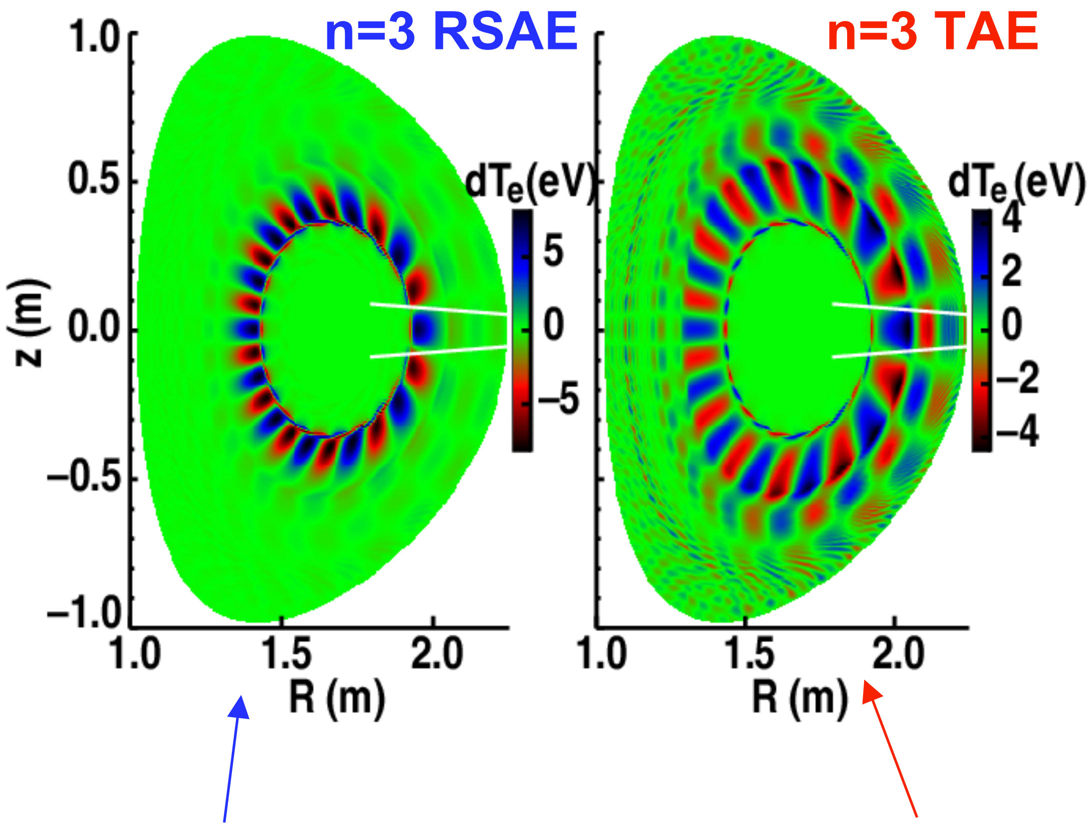
Outputs include:

- Spectrum of eigenfrequencies of the modes
- Radial structure of the eigenmodes
- Density and temperature perturbation due to eigenmode

NOVA-K** includes kinetic extensions for stability analysis

*C.Z. Cheng, *Phys. Rep.* **211**, 1 (1992)
C.Z. Cheng and M.S. Chance, *J. Comput. Phys.* **71, 1124 (1987)

Electron Temperature Perturbation Predictions Can Be Compared to ECE Measurements

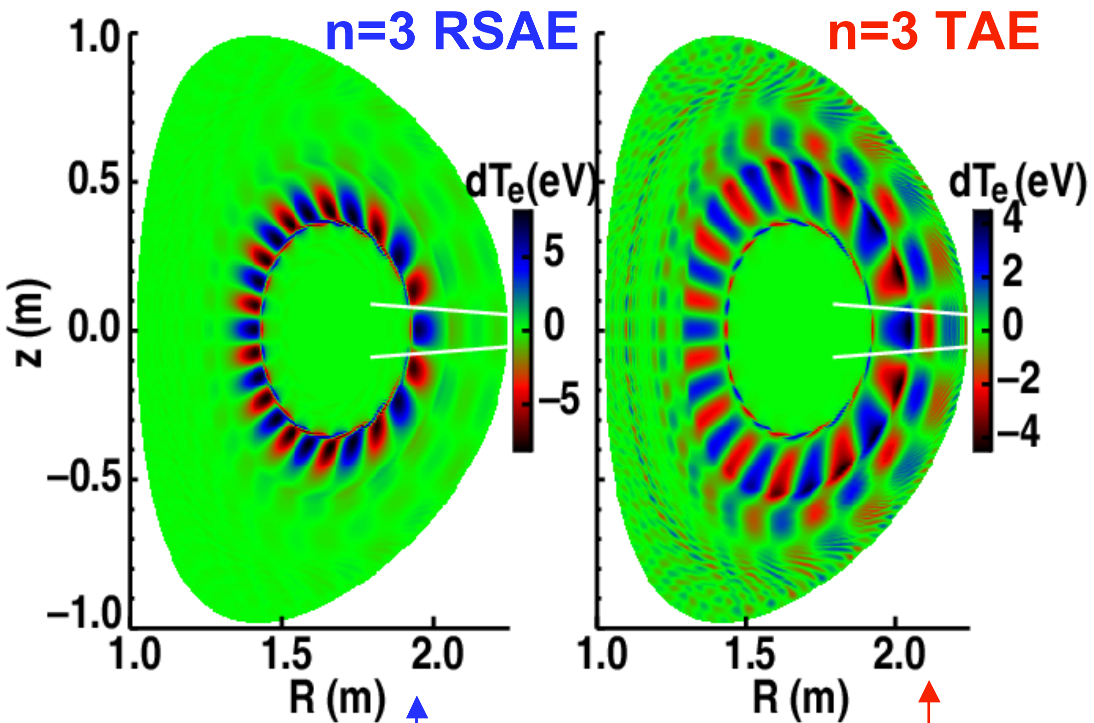


Predicted electron temperature perturbation for two of the *n*=3 modes shown previously

n = 3 RSAE
f_{exp} = 75.8 kHz
f_{NOVA} = 72.3 kHz

n = 3 TAE
f_{exp} = 80.8 kHz
f_{NOVA} = 73.5 kHz

Electron Temperature Perturbation Predictions Can Be Compared to ECE Measurements



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n = 3 TAE
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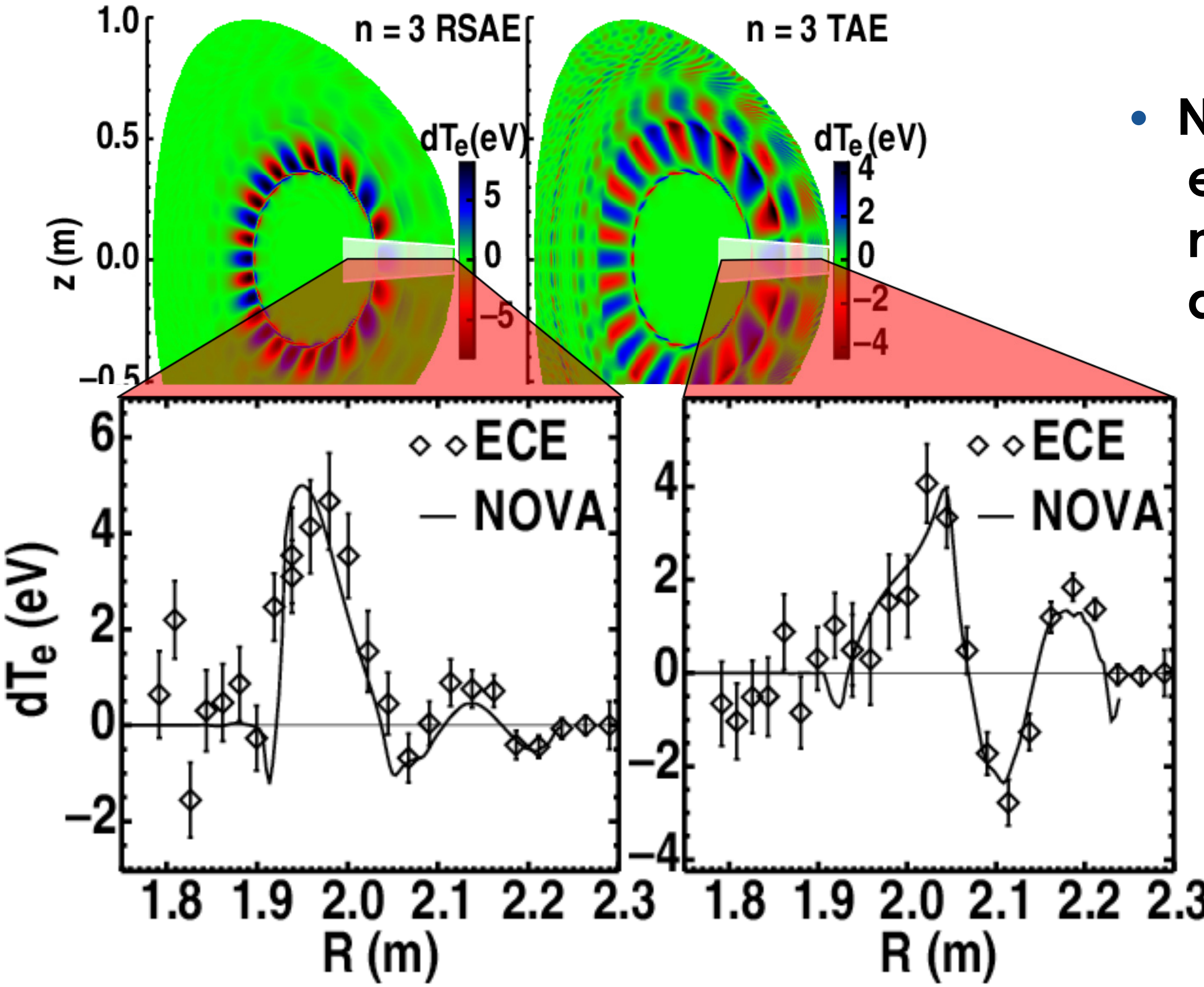
Predicted electron temperature perturbation for n=3 modes on previous slides

For comparison to ECE channels, the finite collection volume must be incorporated into the predictions - *synthetic diagnostic*

- **The ECE antenna pattern is approximated by a Gaussian in the toroidal and poloidal directions (beam waist shown - white lines)**
- **The finite RF filter width defines the radial spot size**
- **A weighted average of the NOVA prediction is taken over the collection volume**

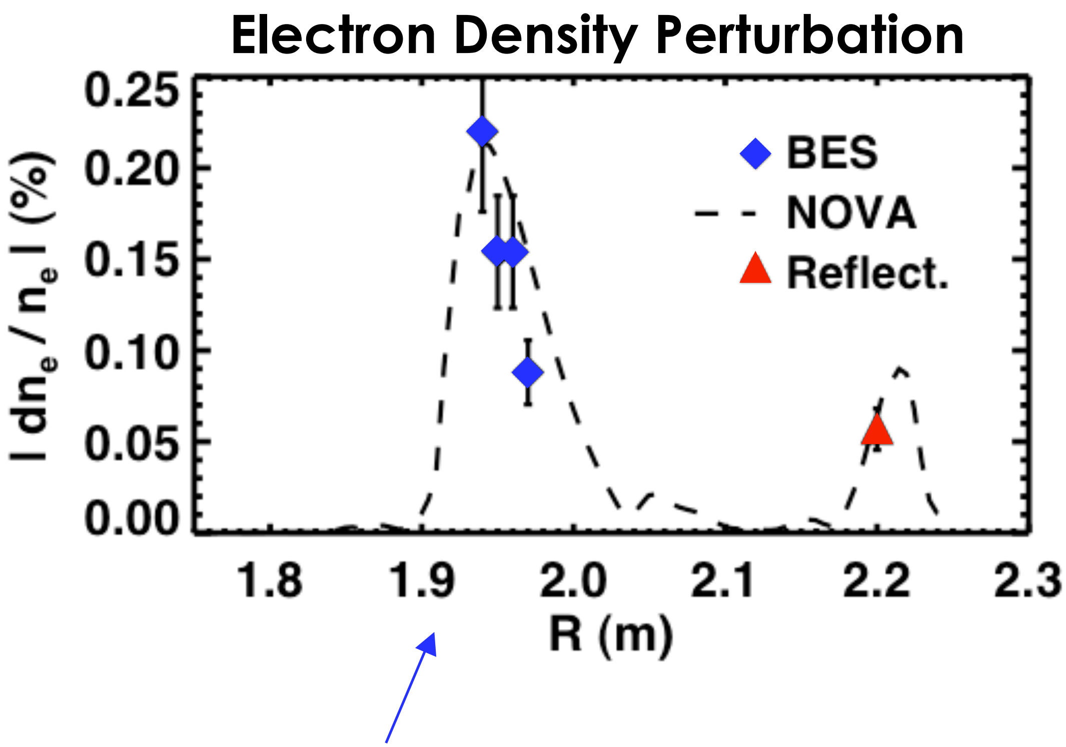
Predicted Electron Temperature Perturbation Structure Agrees Well With ECE Measurements



- NOVA solves for linear eigenmodes and does not predict actual mode amplitude

- Predicted eigenmode scaled using least-squares fit to ECE data

Density Fluctuation Diagnostics Make Self-consistent Check on Inferred Mode Amplitude and Shape



Same n = 3 RSAE from previous slide

k_{pol} BES = 0.22 ± 0.03 cm^{-1}
k_{pol} NOVA = 0.23 cm^{-1}

- *No more adjustable parameters once mode amplitude is fixed by comparison with ECE data*
- BES and reflectometer data provide multiple diagnostic check on mode amplitude and predicted structure

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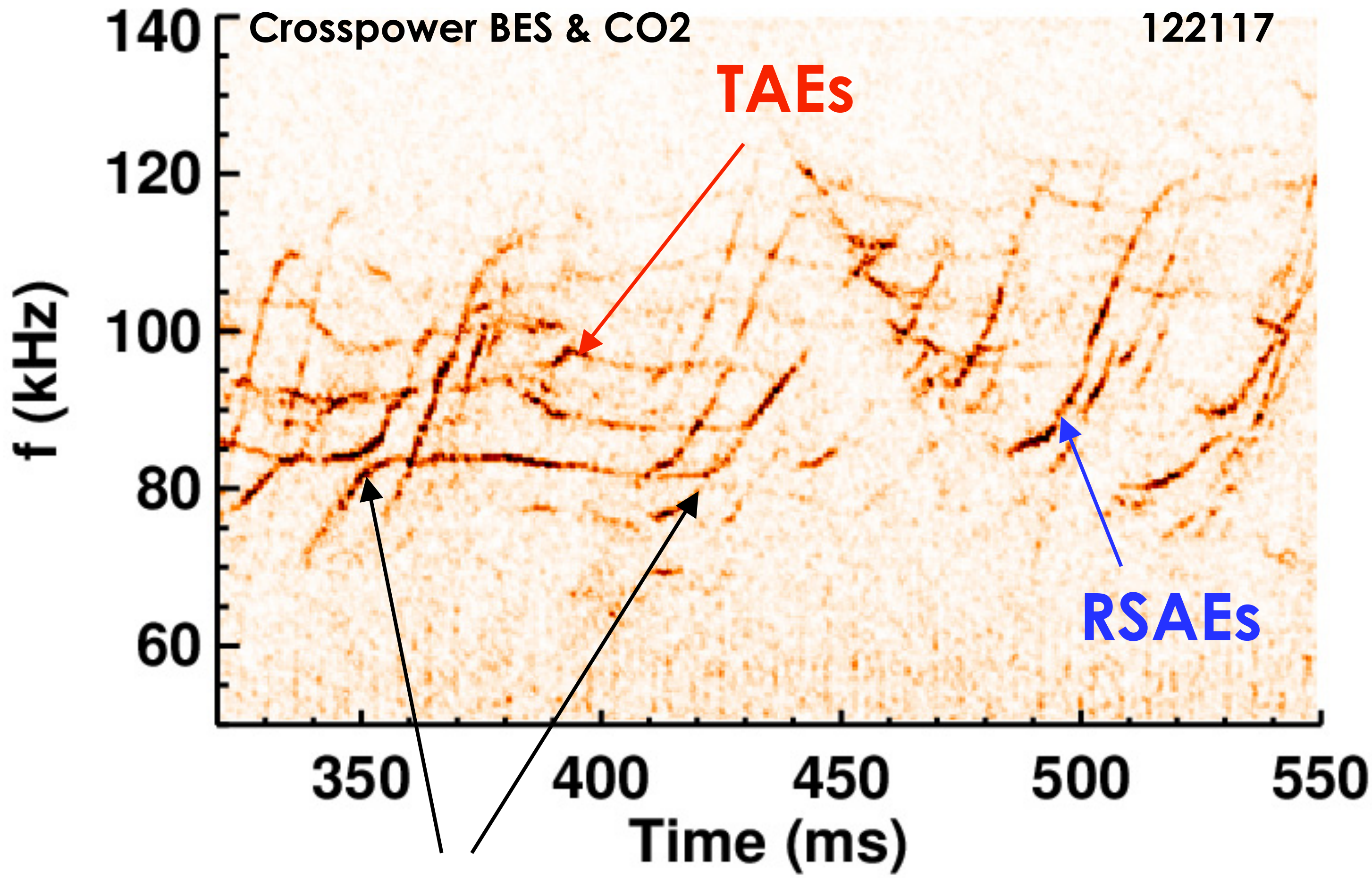
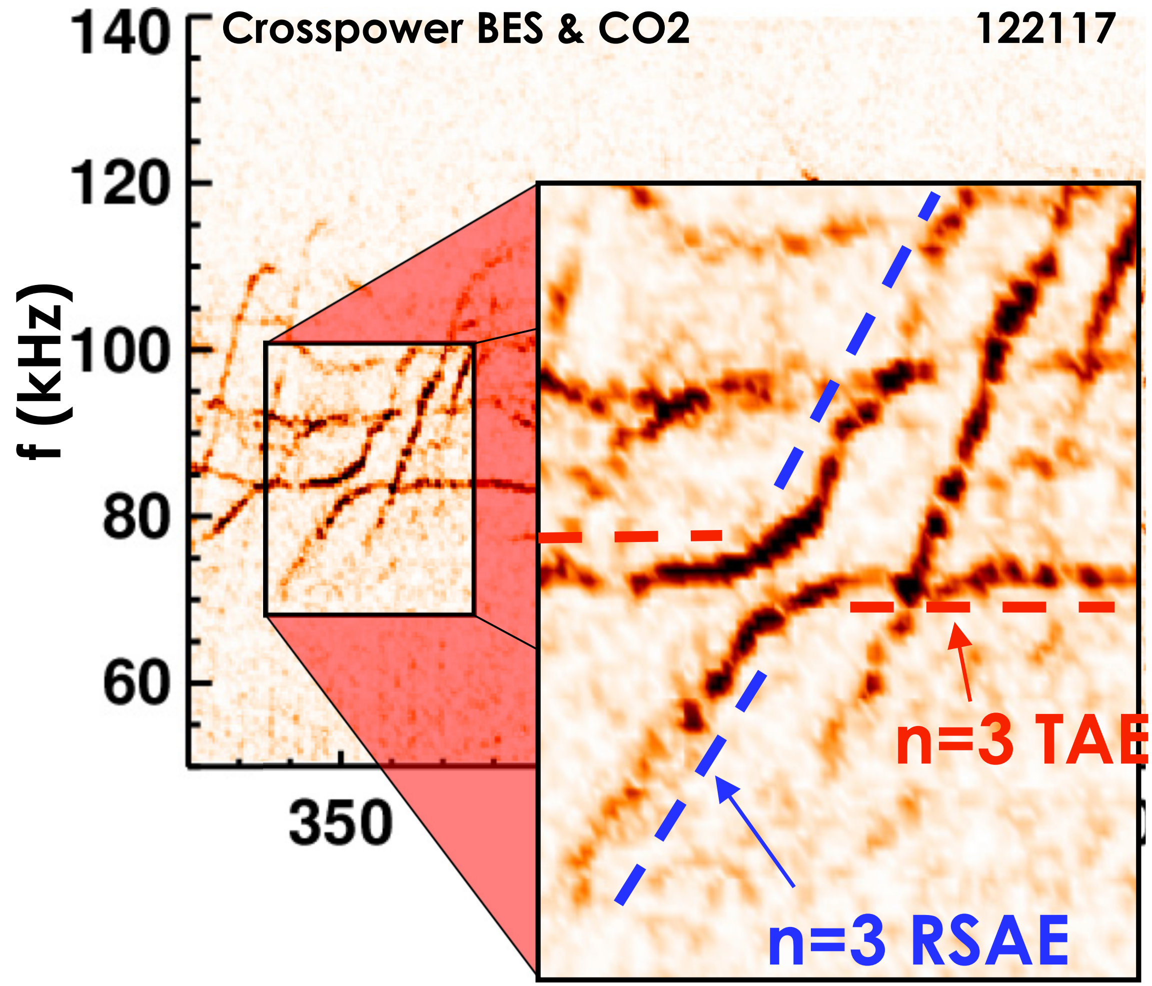
Data Exhibit Behavior Not Taken Into Account by Simple RSAE Model



Occasional breaks in the frequency evolution of both RSAEs and TAEs are observed

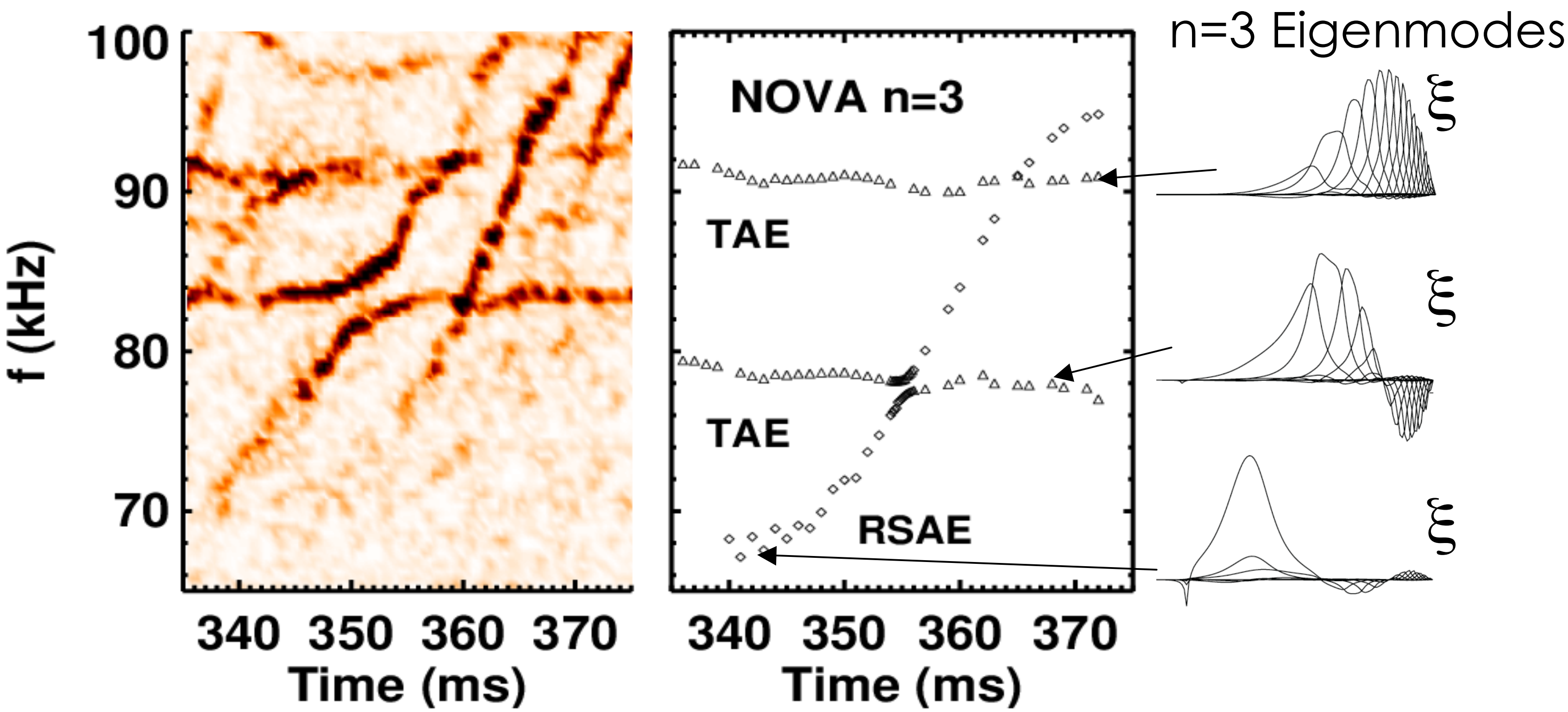
Data Exhibit Behavior Not Taken Into Account by Simple RSAE Model



- Similar phenomena reported on JT60-U
- The coupling of a core localized TAE and a global TAE were inferred from a combination of MHD modeling and magnetic measurements
- It was speculated that this may have implications for fast ion confinement

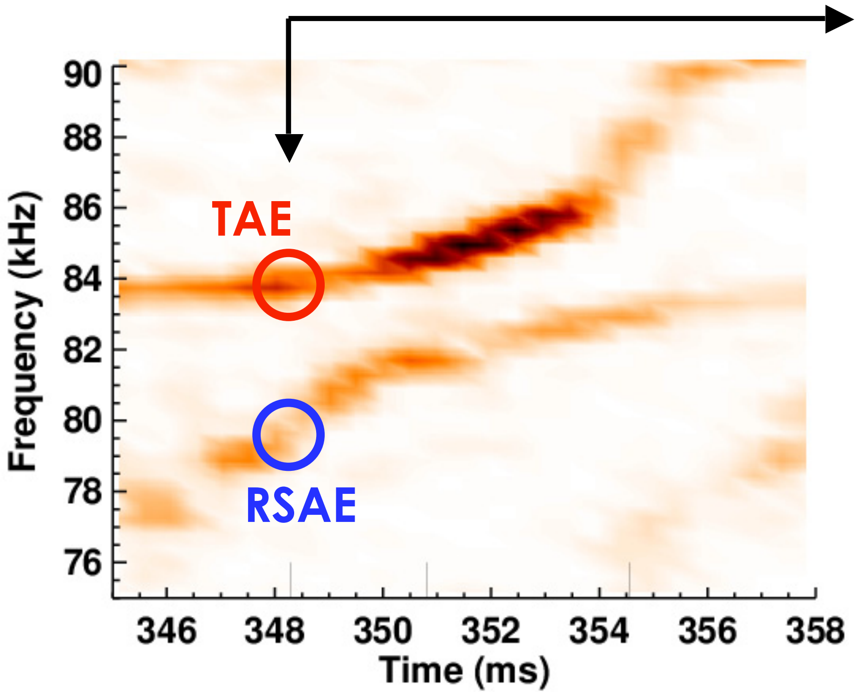
G.J. Kramer *et al.*, *Phys. Rev. Lett.* **83** (1999)

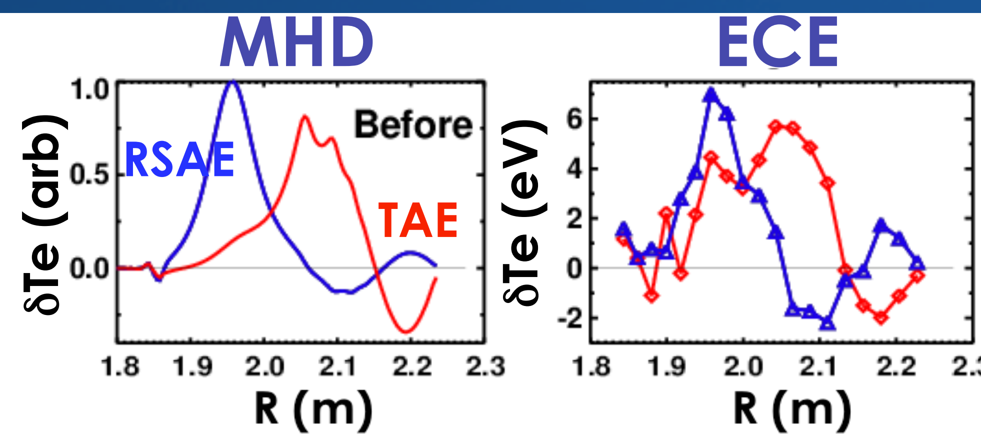
Ideal MHD Calculations Reproduce the Observed Coupling/Frequency Gap



- Simulations point to many coupling events as RSAE chirps through stable and unstable TAEs
- Frequency gap is similar between experiment (2.9 kHz) and theory (1.1 kHz)

Eigenmodes Throughout Coupling Change Structure



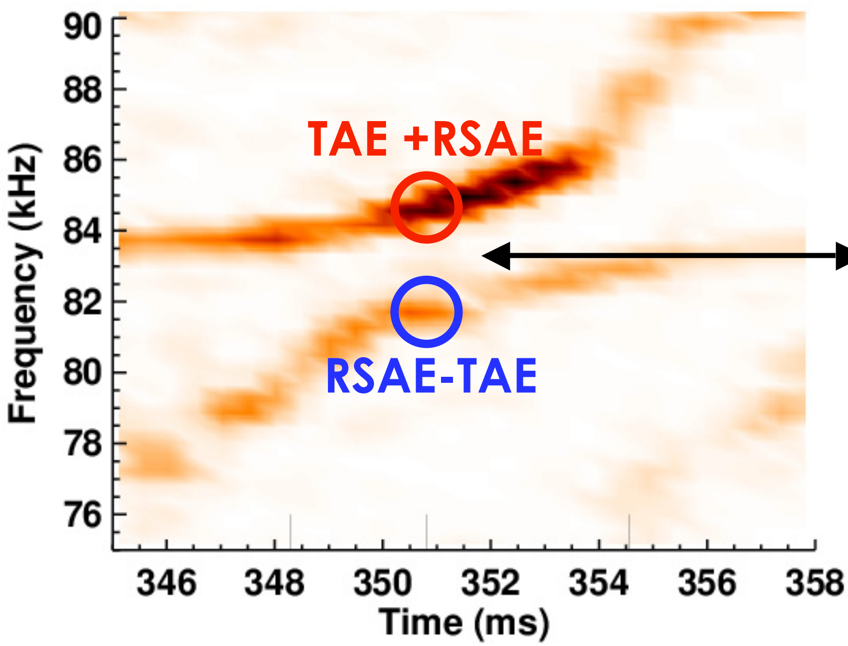


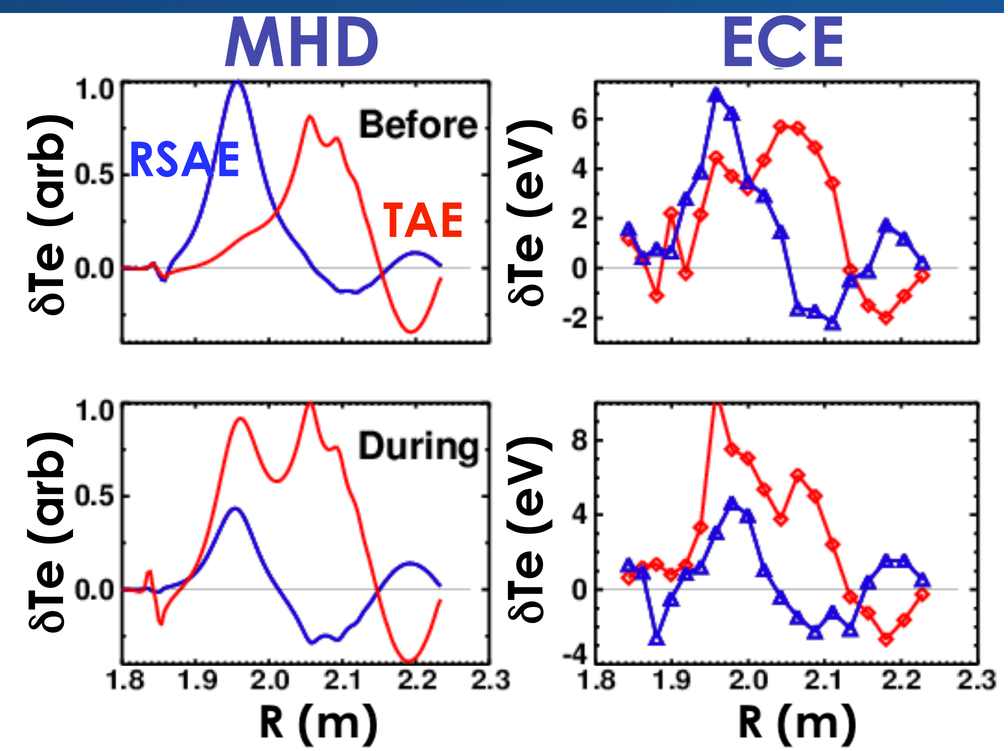
MHD predicted eigenmode amplitudes scaled by ratio derived from ECE data

Before coupling, **eigenmodes are consistent with RSAE and TAE shown previously**

Eigenmodes Throughout Coupling Change Structure

During coupling, modes are odd/even parity combinations of the TAE and RSAE



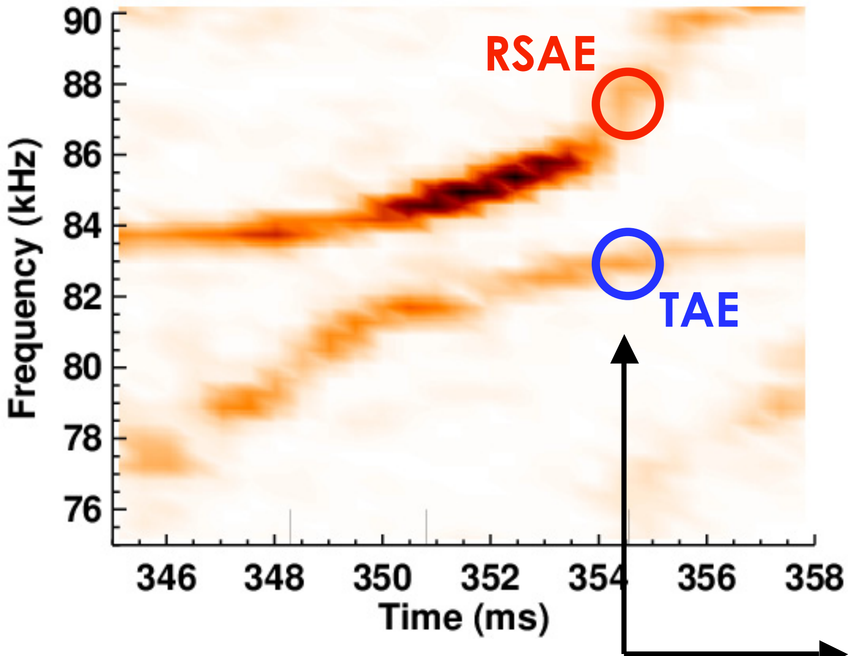


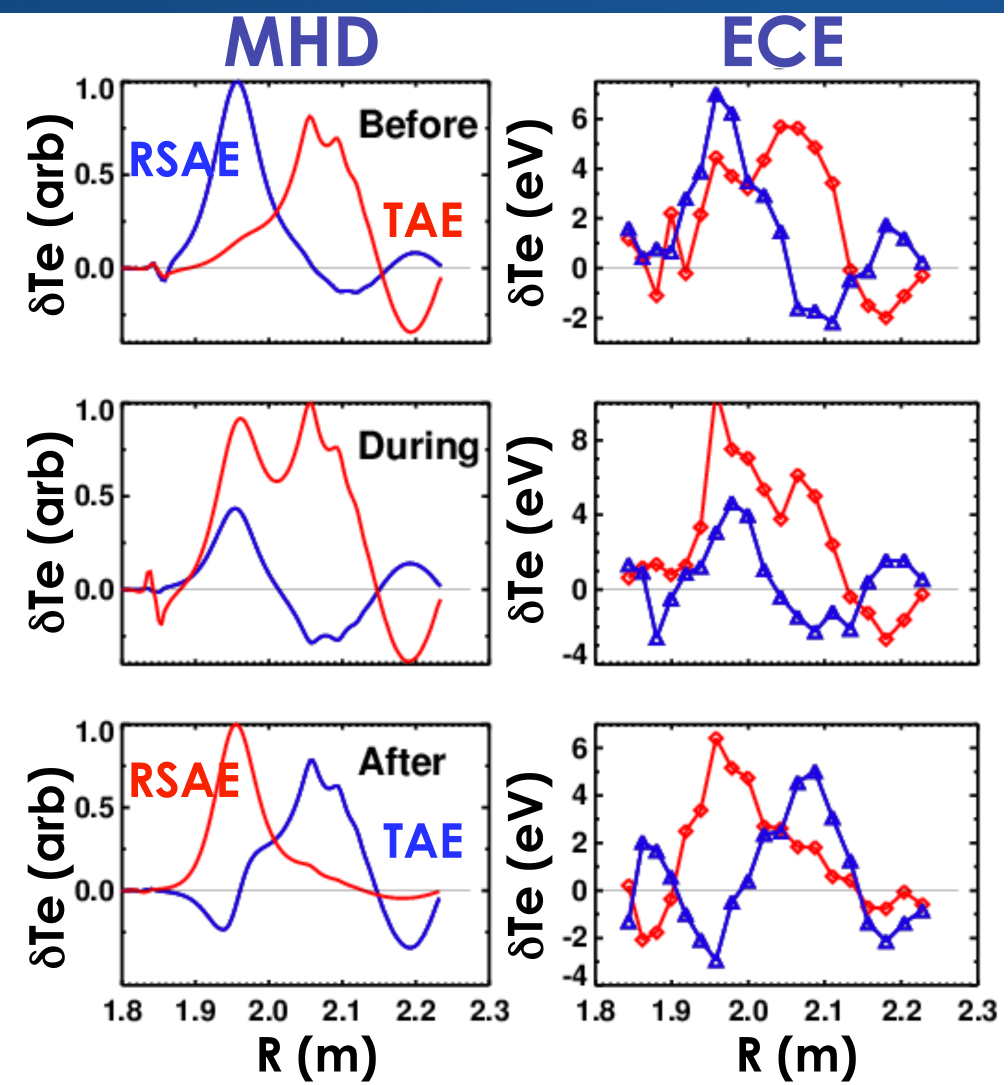
Similar to the quantum mechanics problem of two adjacent potential wells with solutions coupled by tunneling.*

*N. Gorelenkov, L. Chen 2006

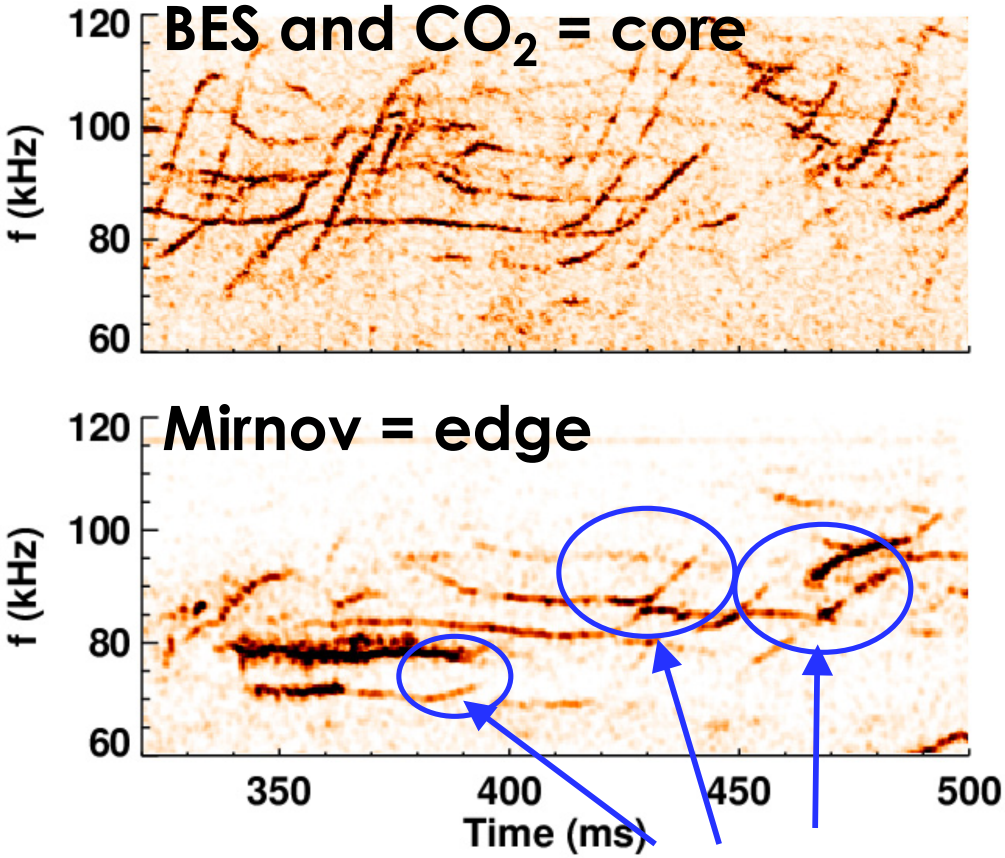
Eigenmodes Throughout Coupling Change Structure

After crossing, modes return to original structure





Mode Structure Mixing Allows Mirnov Loops to See RSAE More Clearly at Crossings



* This temporary global structure may have implications for RSAE ability to cause fast ion transport

At crossing points with TAEs, the RSAEs become more visible on magnetic pickup loops because their eigenfunctions extend closer to the wall

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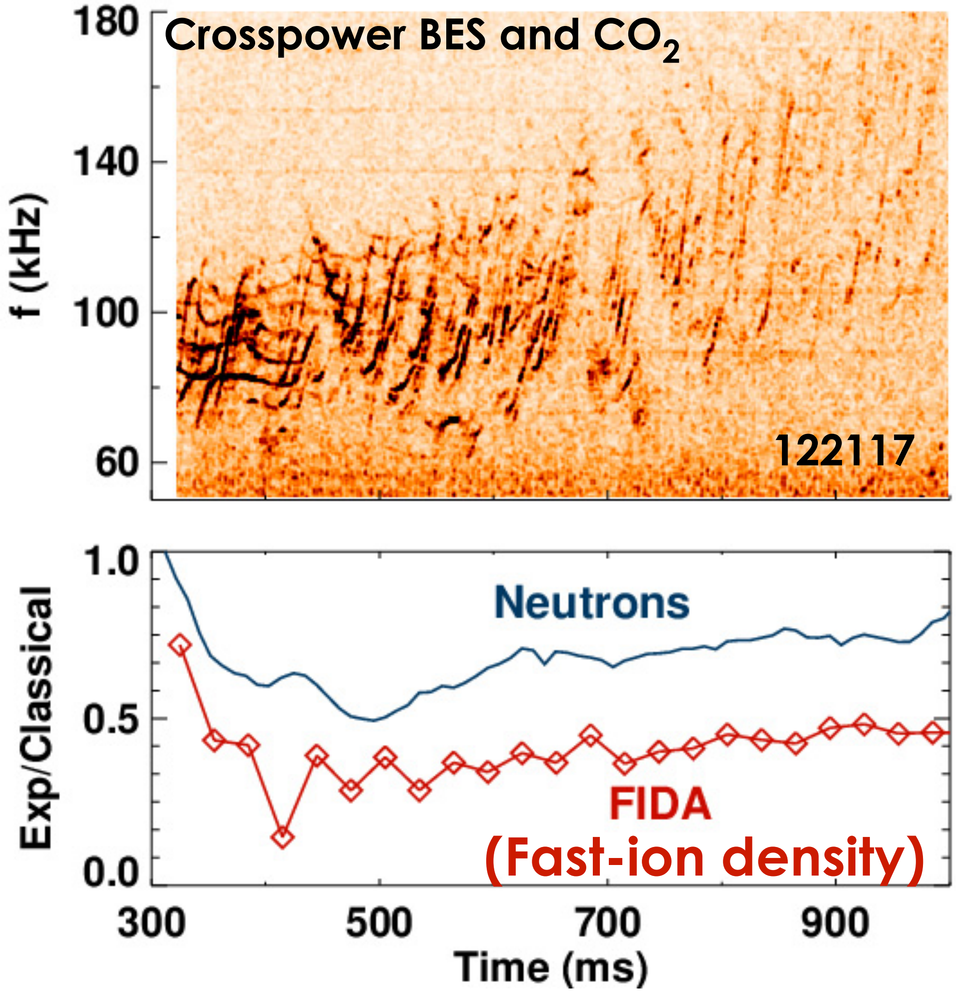
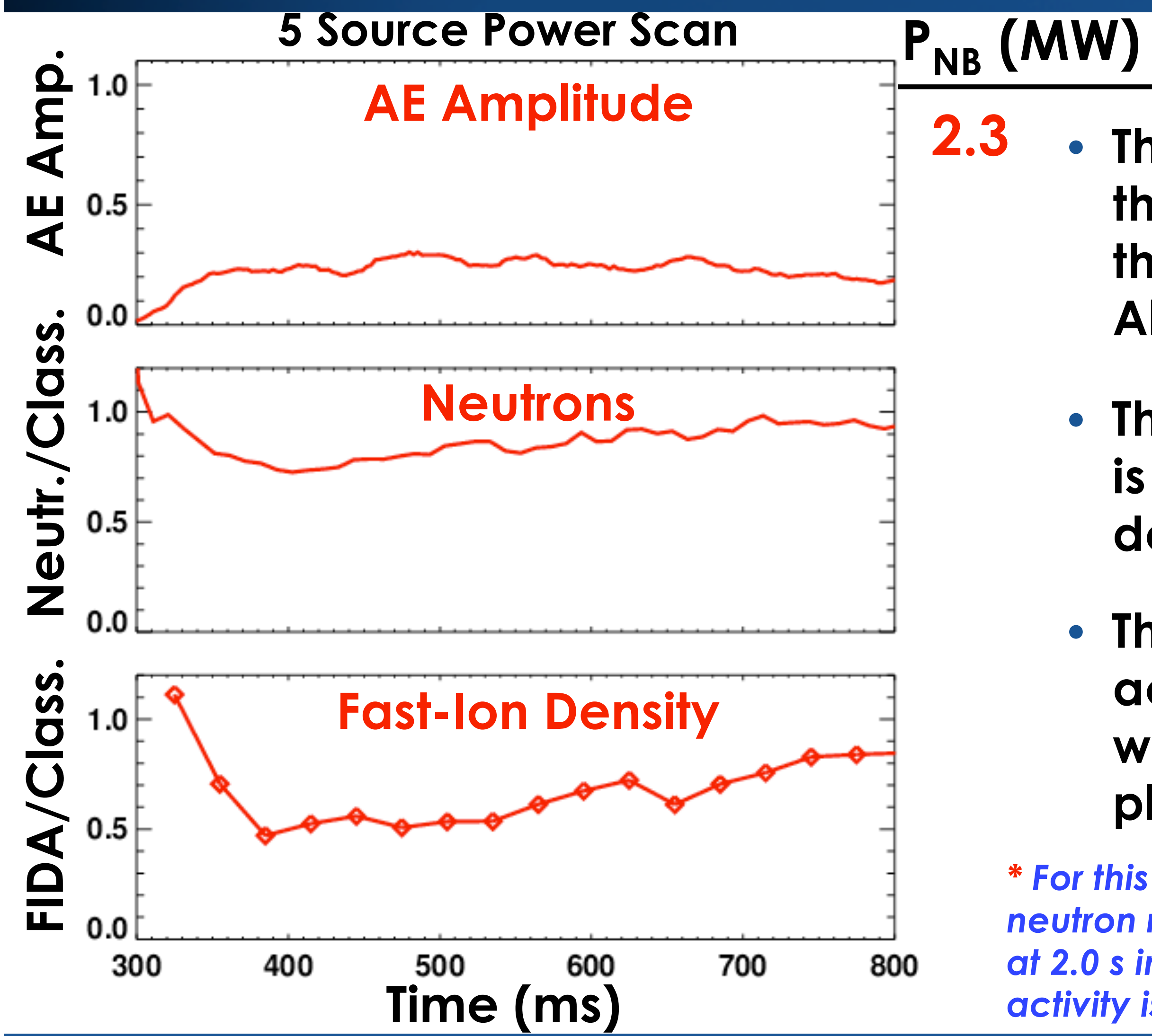
Alfvén Eigenmodes Degrade Fast-ion Confinement



- Volume-averaged neutron rate is below the classical TRANSP prediction during strong Alfvénic activity
- Fast-ion D_α (FIDA) diagnostic measures ions with vertical energy between 30-80 keV with 5 cm spatial resolution* along midplane
- Fast-ion density near ρ_{qmin} is reduced more than the neutrons

*Heidbrink, PPCF 46 (2004) 1855; Luo, RSI 77 (2006) submitted.

The Fast-ion Deficit Correlates With Alfvén Activity



- The discrepancy between the classical prediction and the data is largest when the Alfvén modes are strong
- The measured FIDA deficit is larger than the neutron deficit
- The strength of the Alfvén activity tends to increase with beam power in similar plasmas

** For this comparison, the FIDA density and neutron rate are normalized by their values at 2.0 s in the 1-source shot (when Alfven activity is undetectable)*

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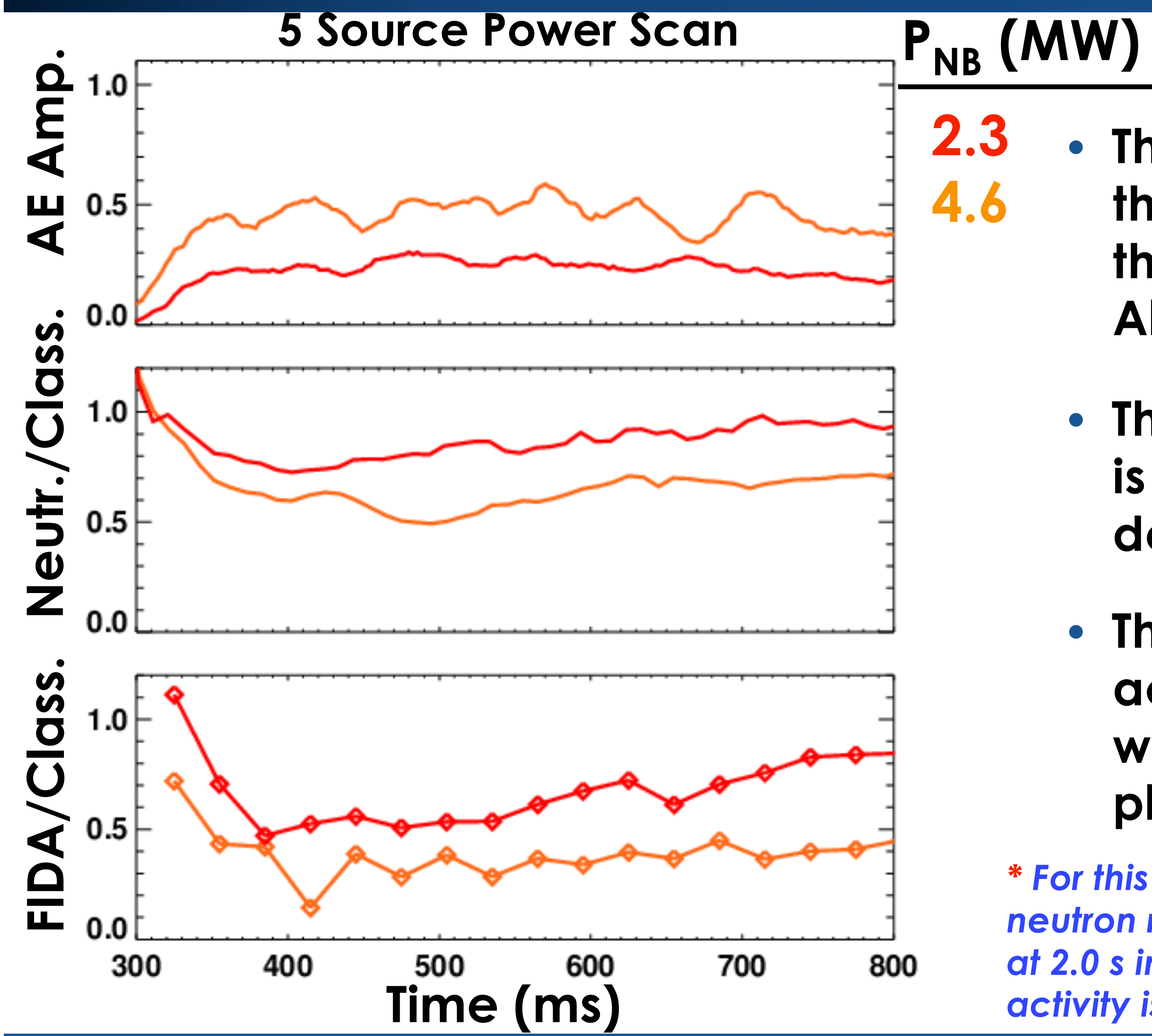

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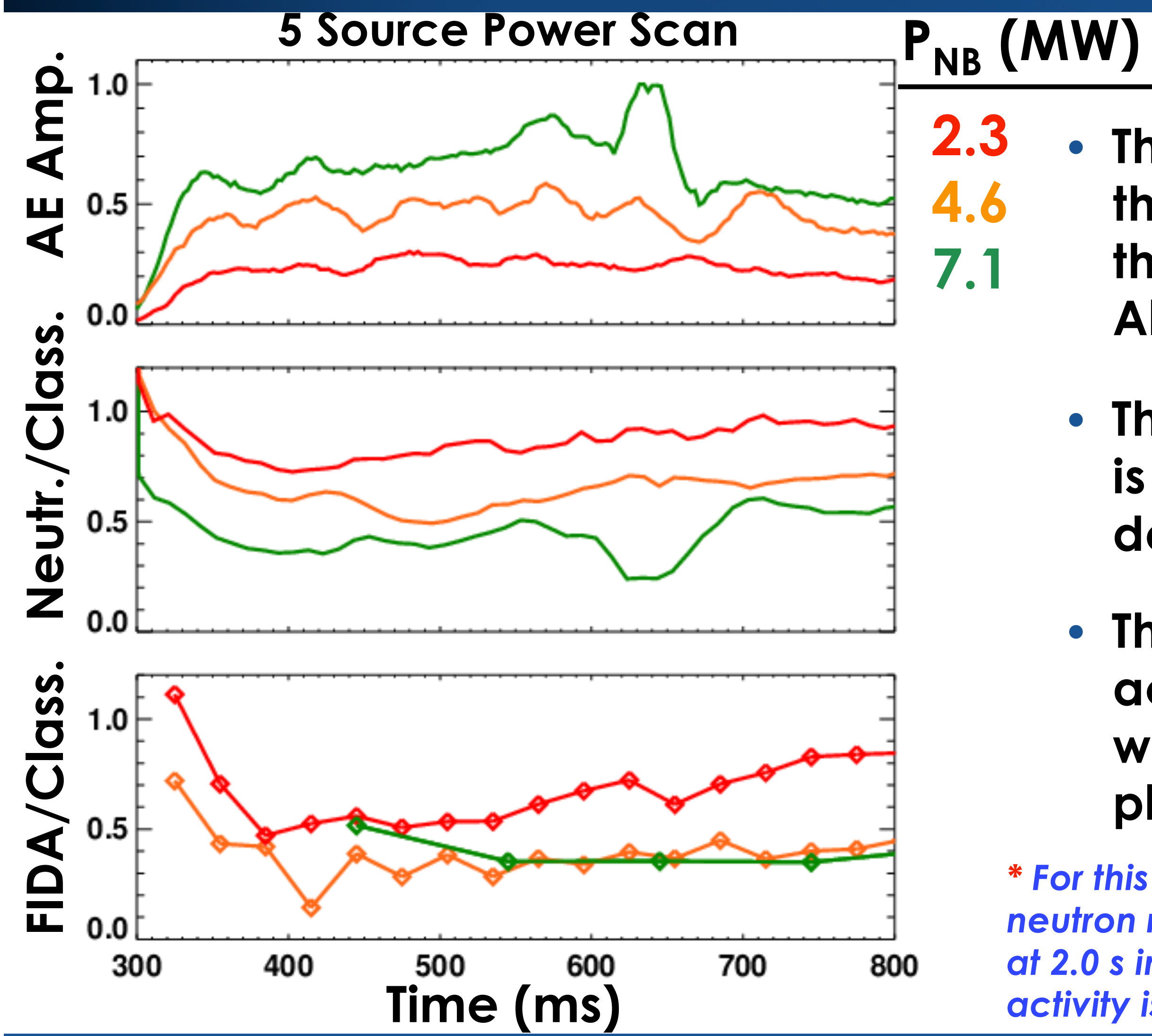

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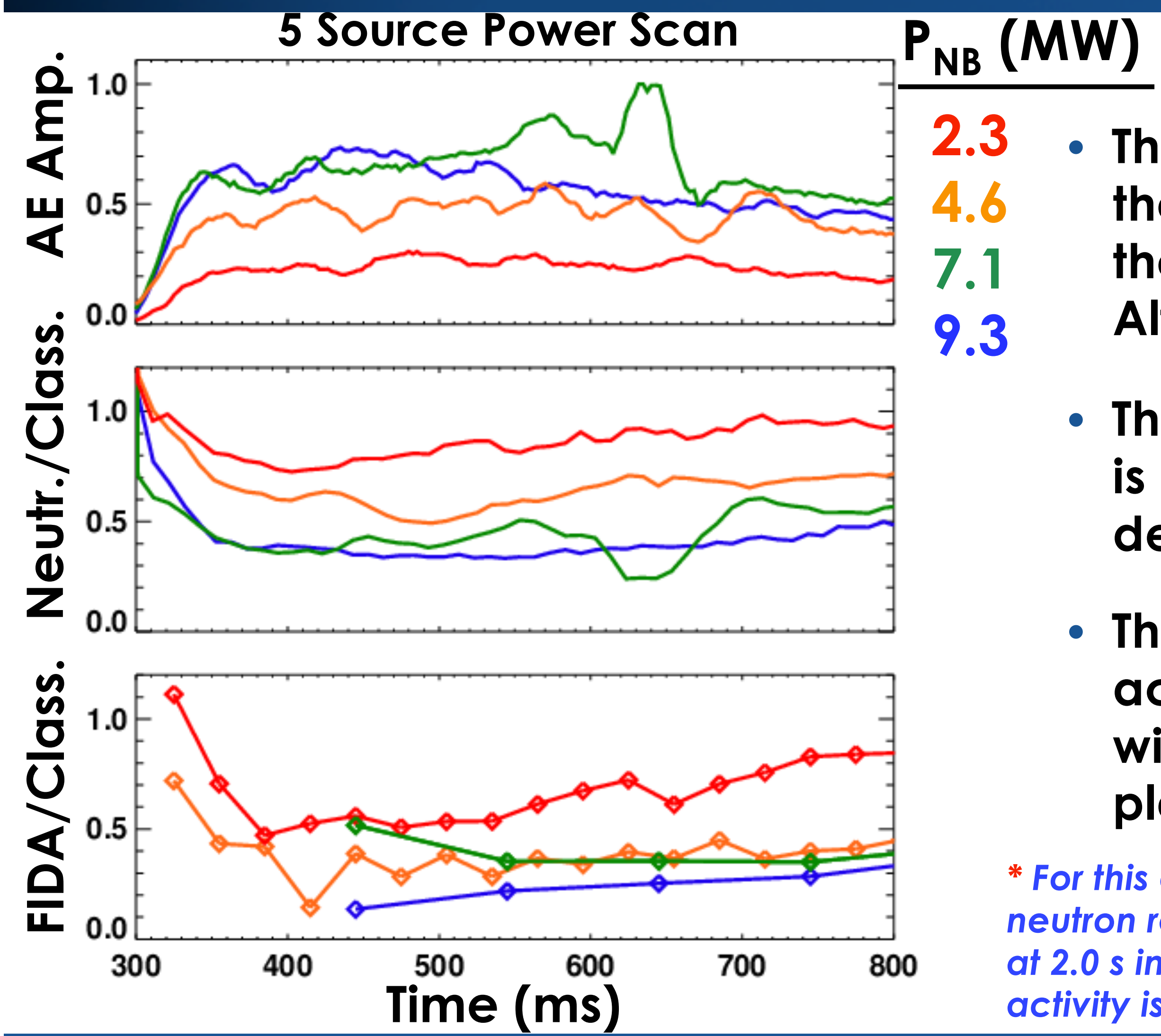

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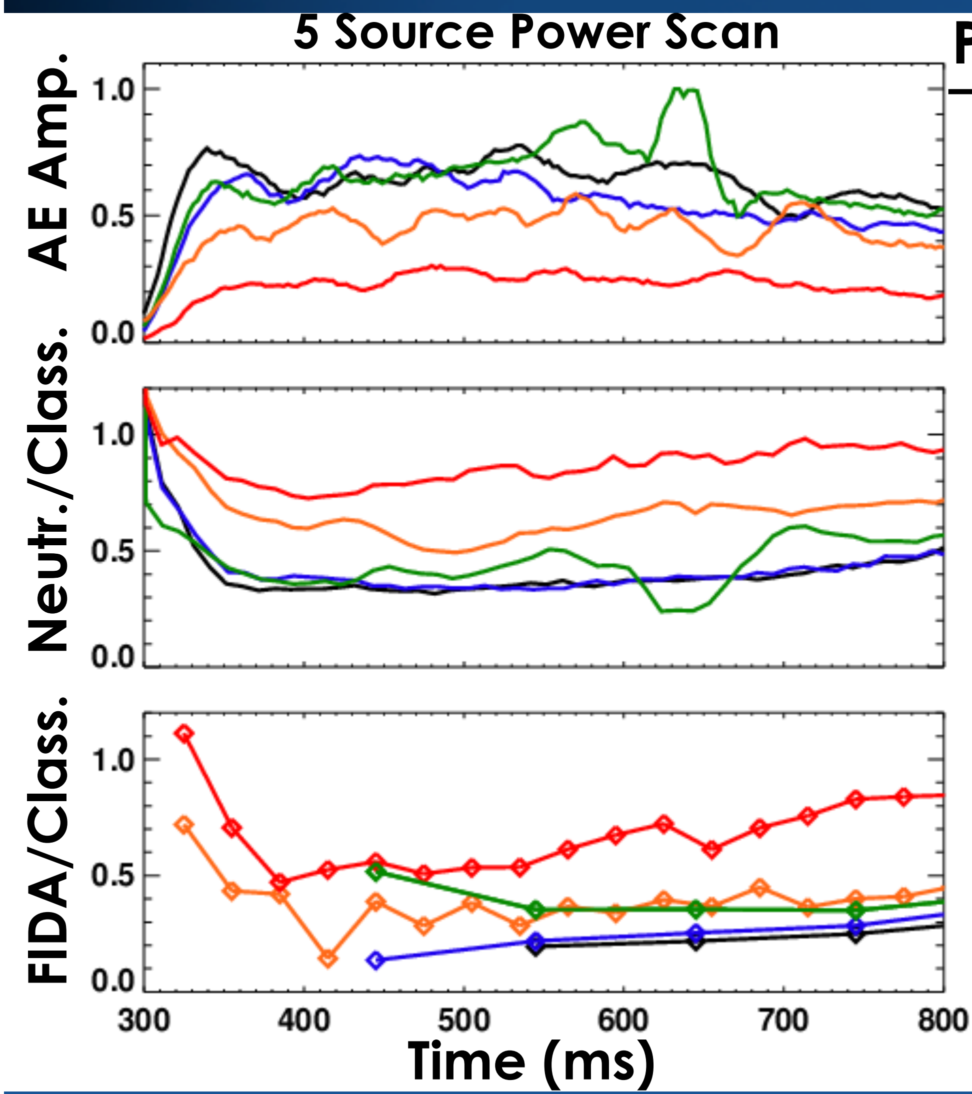

P_{NB} (MW)

2.3
4.6
7.1
9.3
11.4

- **The discrepancy between the classical prediction and the data is largest when the Alfvén modes are strong**
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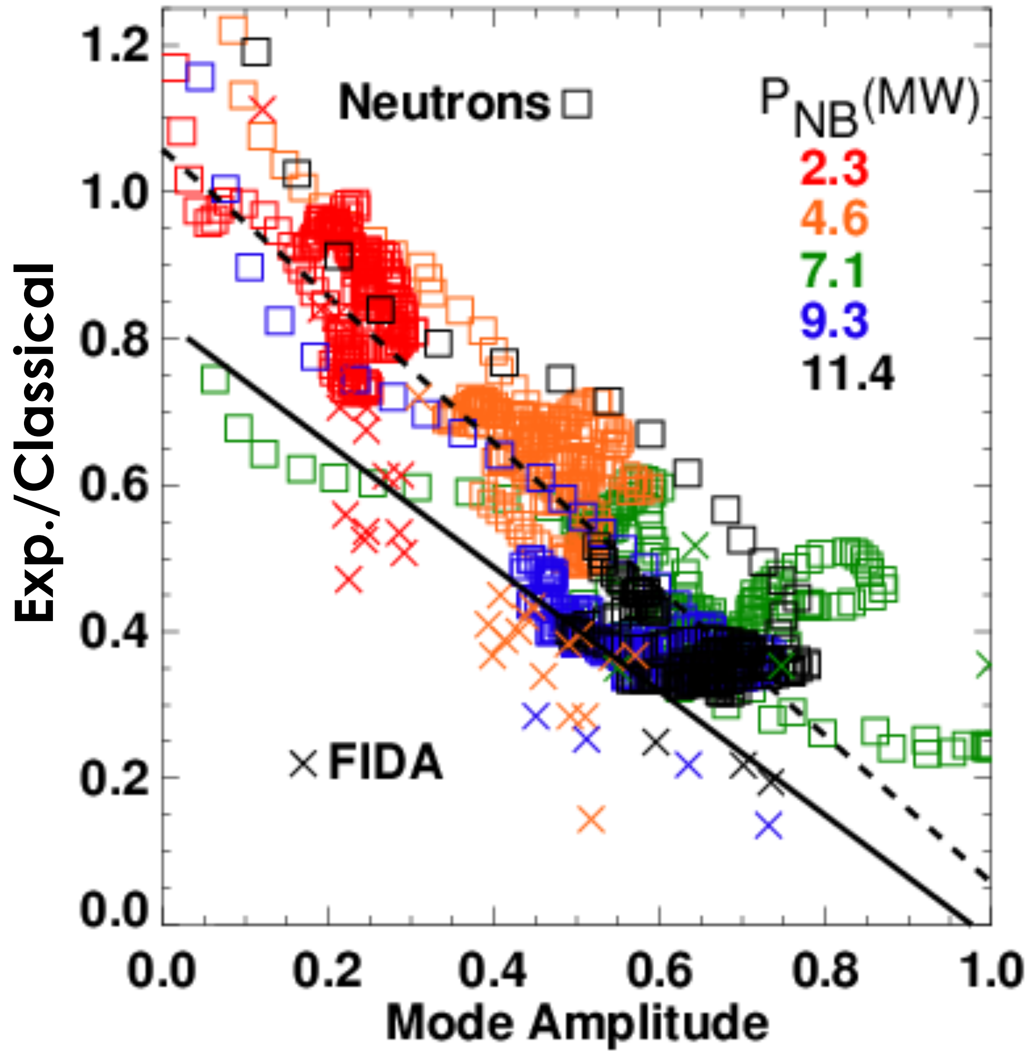

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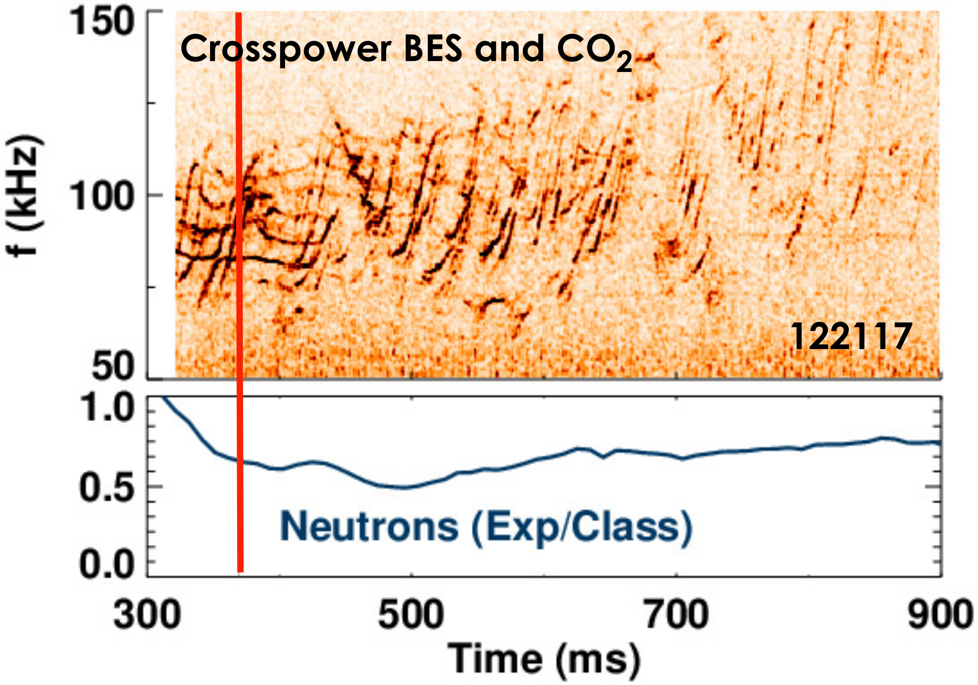
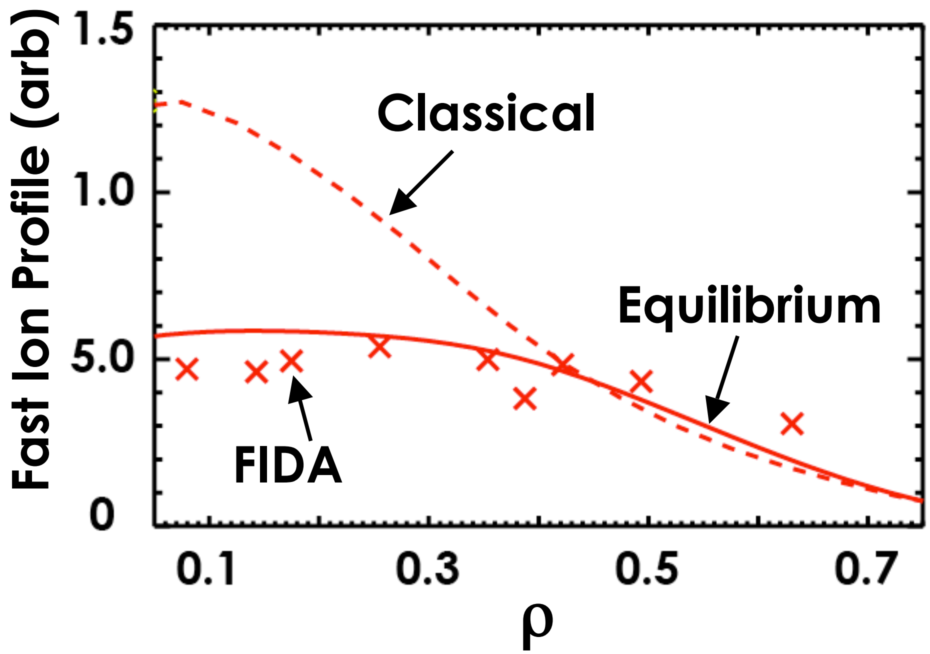
The Fast-ion Density Profile is Flattened





- During strong Alfvén activity, the fast-ion density profile from FIDA is nearly flat
- The fast-ion profile inferred from the equilibrium* is also very flat
- The classical profile computed by TRANSP peaks on axis

**The kinetic EFIT equilibrium uses MSE and magnetics data to compute the pressure profile. Subtraction of the thermal pressure yields the fast-ion pressure.*

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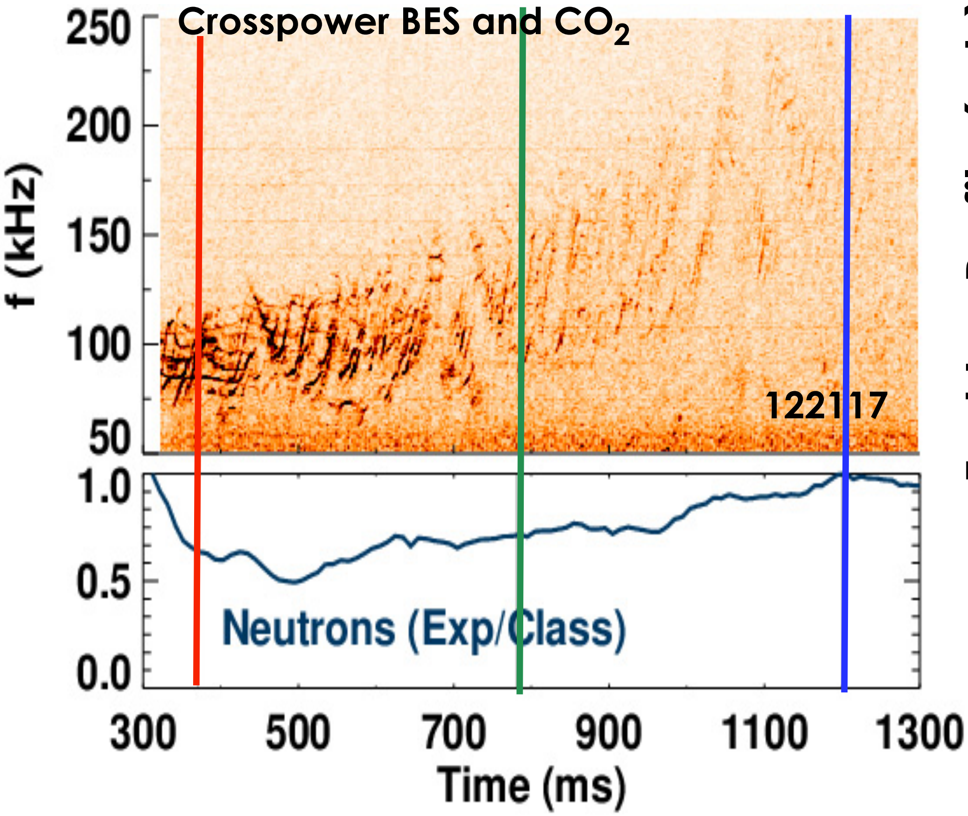
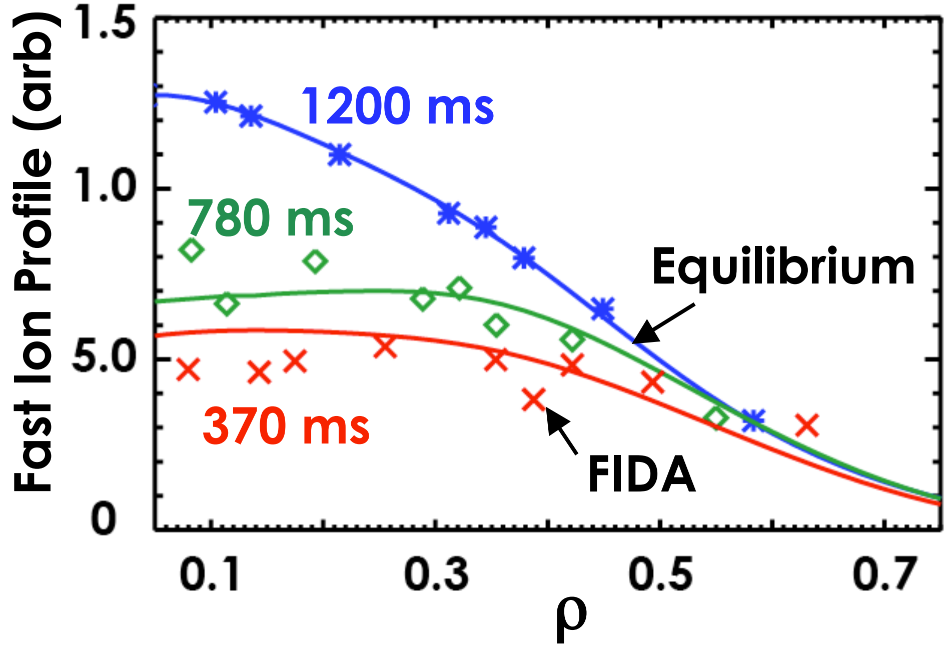
The Fast-ion Density Profile is Flattened but Recovers As Alfvén Activity Decreases





**For this comparison, the FIDA density profile is normalized to the equilibrium profile at 1.20 s*

- **The FI profile remains flat during the strongest Alfvén activity**
- **As the AE activity weakens the profile peaks but is still broader than classically predicted**

Heidbrink, UP1.00014, Thursday 9:30 AM

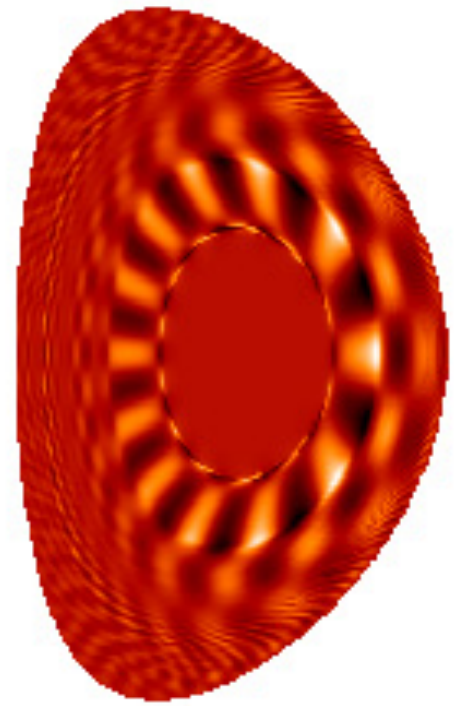
Conclusions

- Ideal MHD calculations are in agreement with ECE measured temperature perturbation structure for both TAEs and RSAEs

- Mode-coupling has been observed between an RSAE and TAE

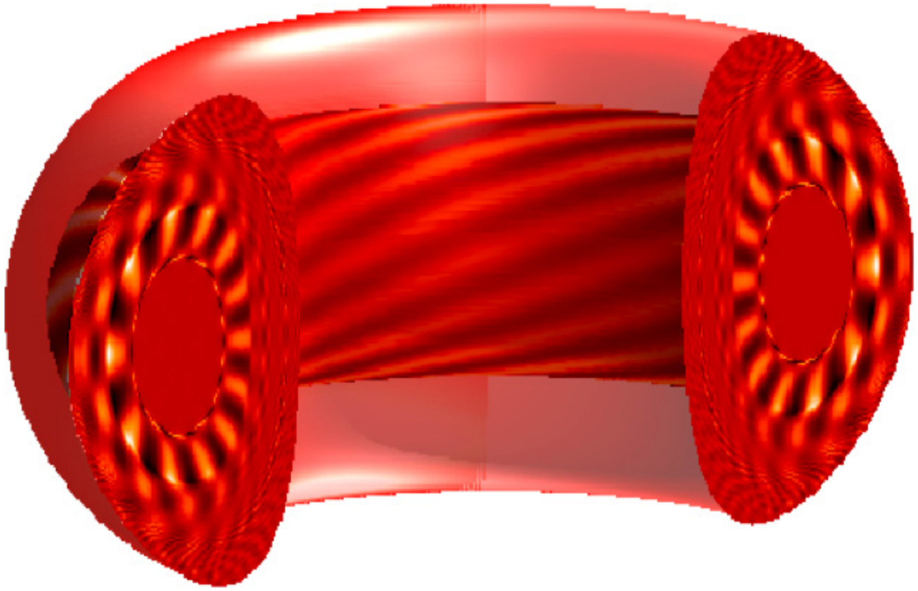
- Fast ion density diagnostic shows flattening of radial profile during periods of increased AE activity

- Reductions in neutron production are also correlated with AE amplitude



Future Work

- Validated eigenmodes will be used in conjunction with orbit following routines to asses physical mechanisms for beam ion redistribution and impact on plasma performance



- Self-consistent nonlinear simulations will also address these issues as well as offer information about the saturated mode amplitudes. Recent work by G.Y. Fu using the M3D code is very promising

In general, owing to many experimental and theoretical advances and an increased interaction between the two, this is an exciting time for Alfvén Eigenmode research

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Extra Slides

δT_e and δn_e From Displacement

$$\frac{\delta T_e}{T_e} = -(\gamma - 1)\nabla \cdot \xi - \xi \cdot \frac{\nabla T_e}{T_e}$$

Electron Temperature Perturbation

$$\frac{\delta n_e}{n_e} = -\nabla \cdot \xi - \xi \cdot \frac{\nabla n_e}{n_e}$$

Electron Density Perturbation

ξ = Field Line Displacement

γ = 5/3 = Ratio of Specific Heats

How Do the Alfvén Eigenmodes Cause FI Transport?

Conjecture at this point but several possibilites:

Previous experiments on DIII-D documenting large losses due to AEs were probably a result of resonant particles EXB drifting out of the plasma.

- **Predicts losses scale as dB/B**

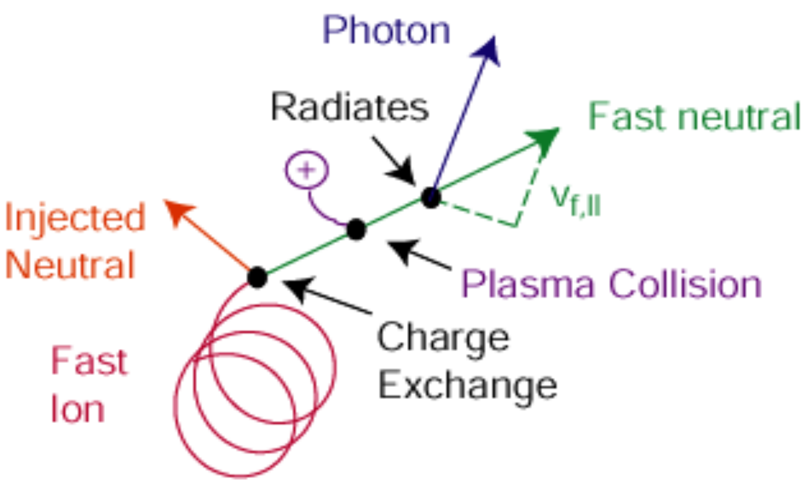
Orbit stochasticity caused by overlapping islands in fast ion phase space.

- **dB/B ~ 5 x 10^{-4} close to where this is predicted to start for a single mode (10^{-3}/m)* but we have multiple modes - increases the effect.**
- **Losses should scale as $(dB/B)^2$ and exhibit a threshold**

Other…

***** H.L. Berk, et al. *Phys. Fluids B* **5** (1993)

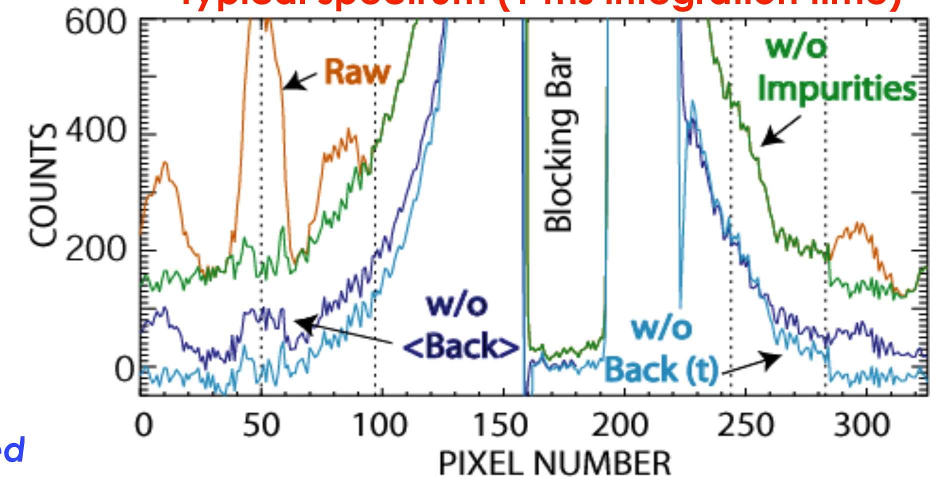
Fast-ion D_α (FIDA) Diagnostic



- A type of Charge Exchange Recombination Spectroscopy
- Use vertical view to avoid bright interferences
- Exploit large Doppler shift (measure wings of line)

- FIDA Signal $\propto n_{FI}\, n_o$
- Background subtraction usually dominates uncertainty
- Achieved resolution: ~5 cm, ~10 keV, 1 ms

Typical spectrum (1 ms integration time)



Heidbrink, PPCF 46 (2004) 1855; Luo, RSI (2006) submitted

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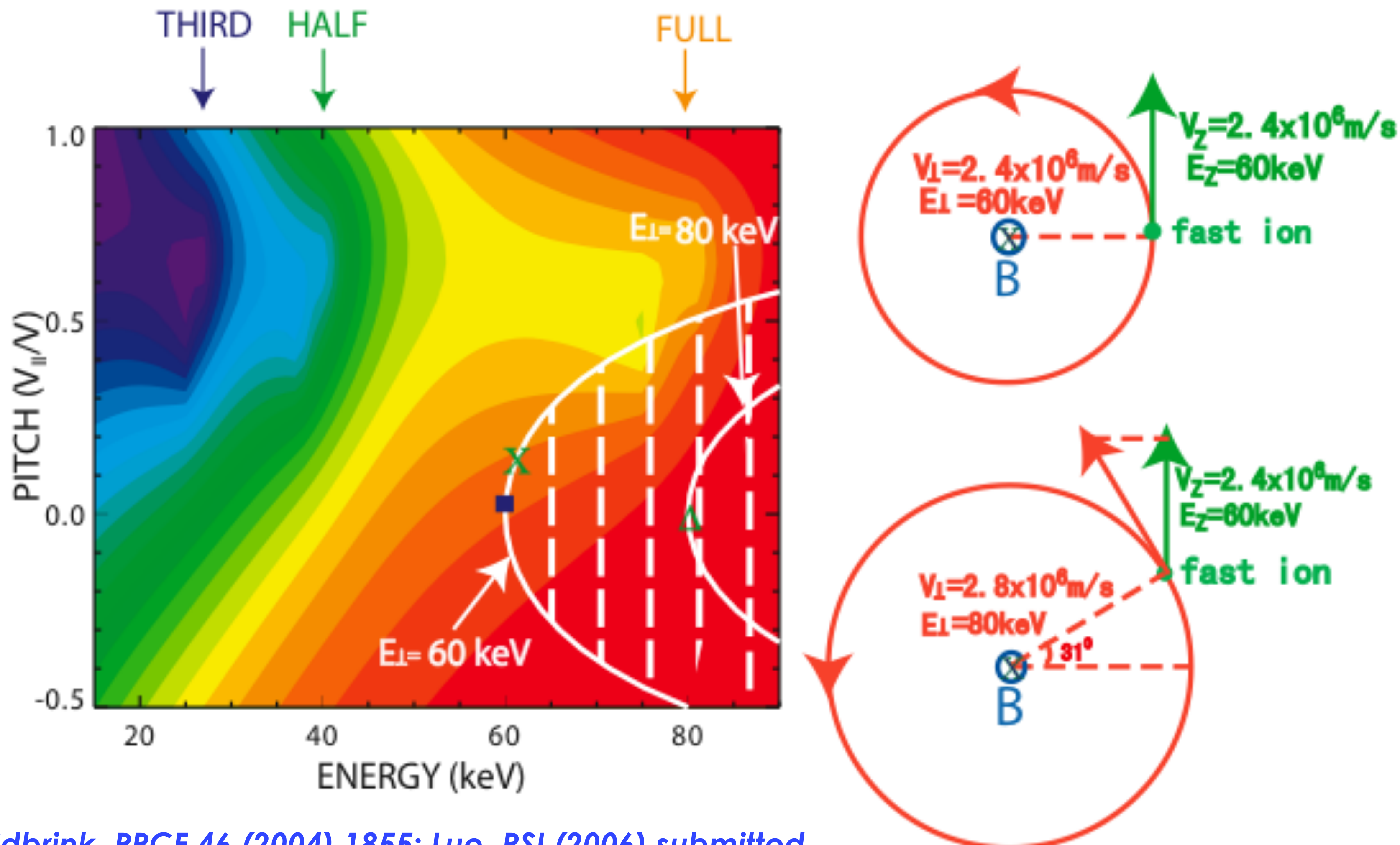
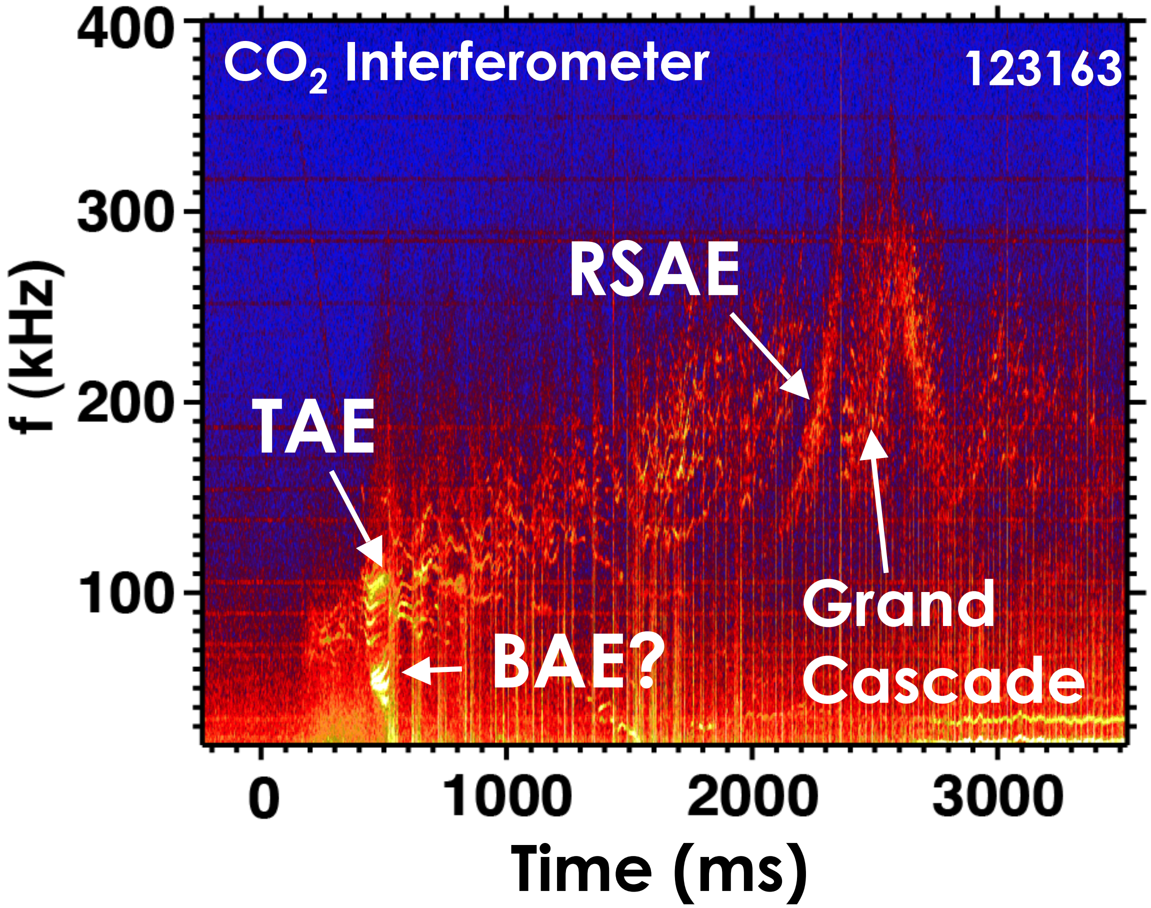
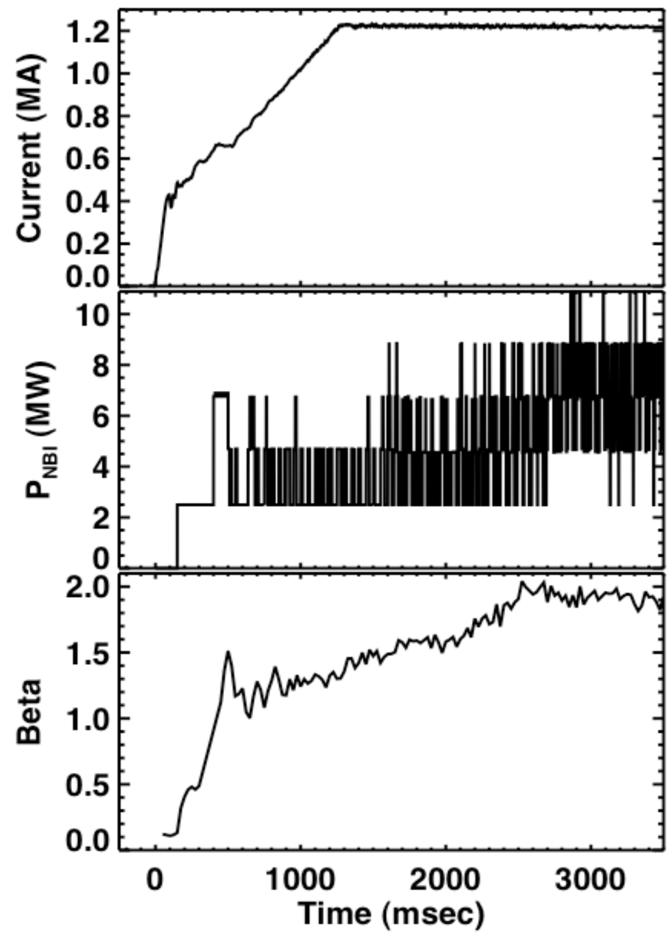
Fast-ion D_α (FIDA) Diagnostic cont.



Heidbrink, PPCF 46 (2004) 1855; Luo, RSI (2006) submitted.

A Variety of Alfvén Eigenmodes Are Routinely Observed in DIII-D AT Plasmas





- Neutral beam heated AT plasma with reverse central shear

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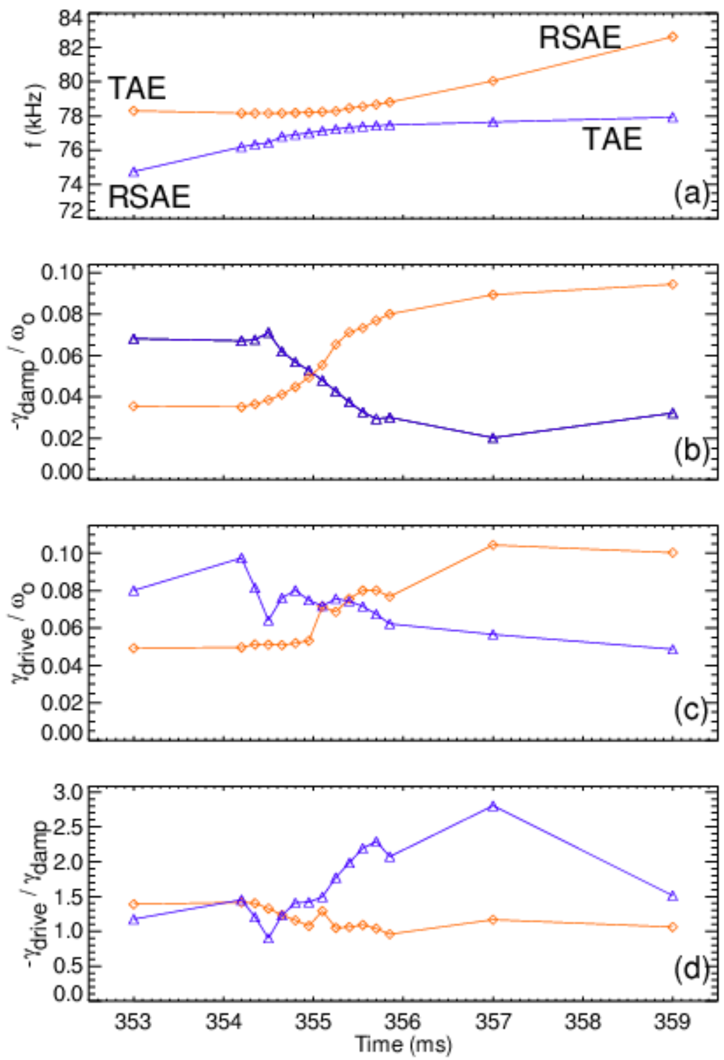
Drive and Damping Change Throughout Coupling Process



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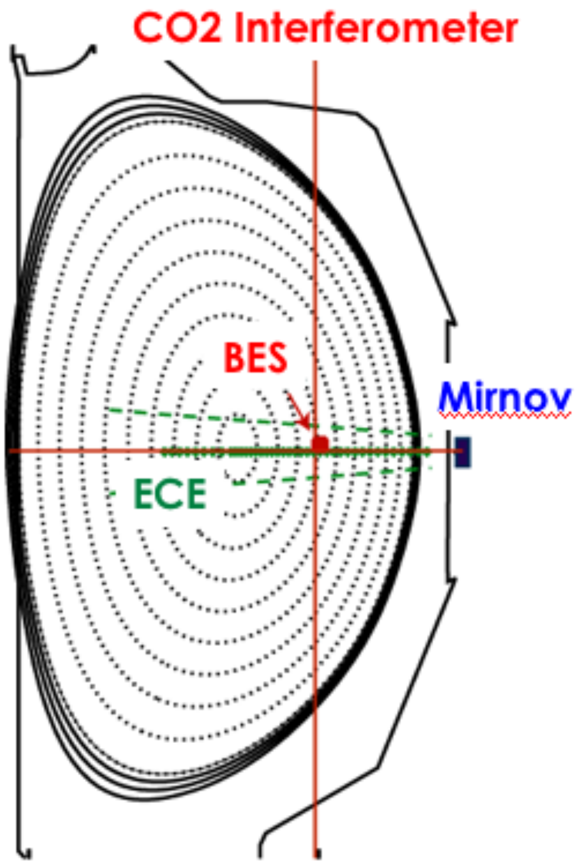
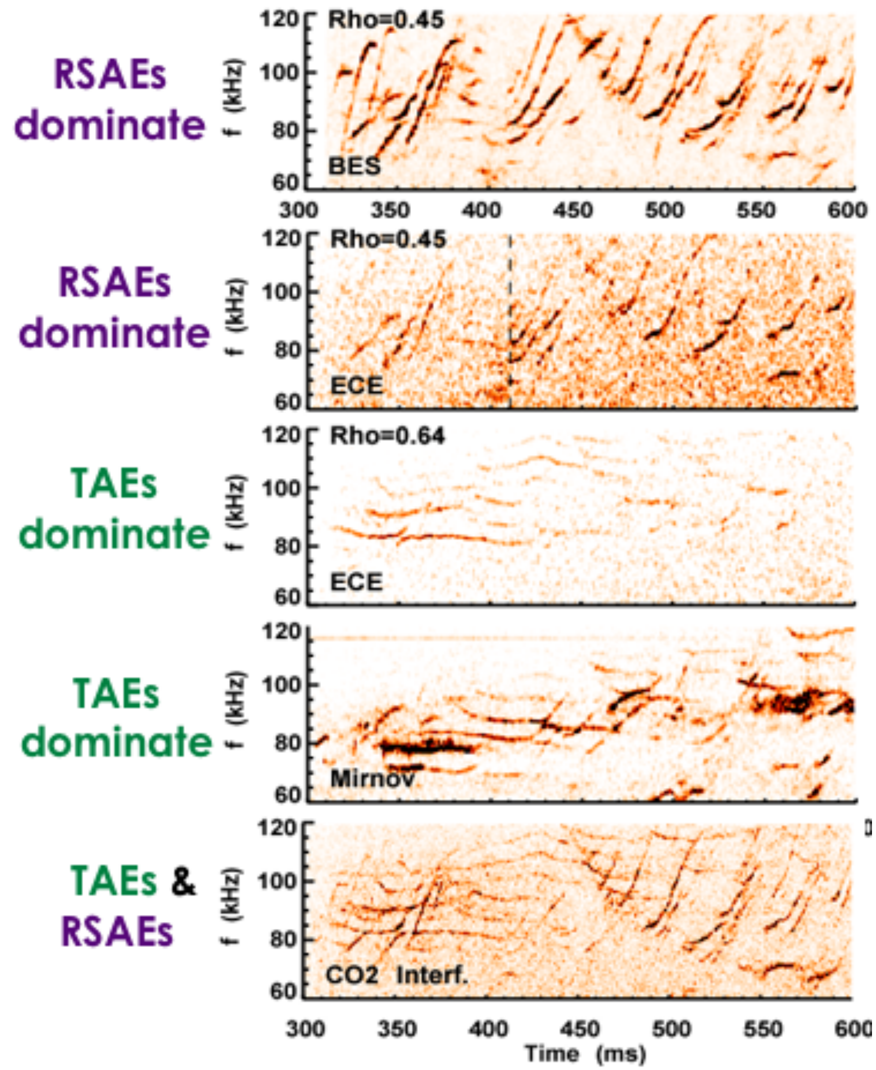
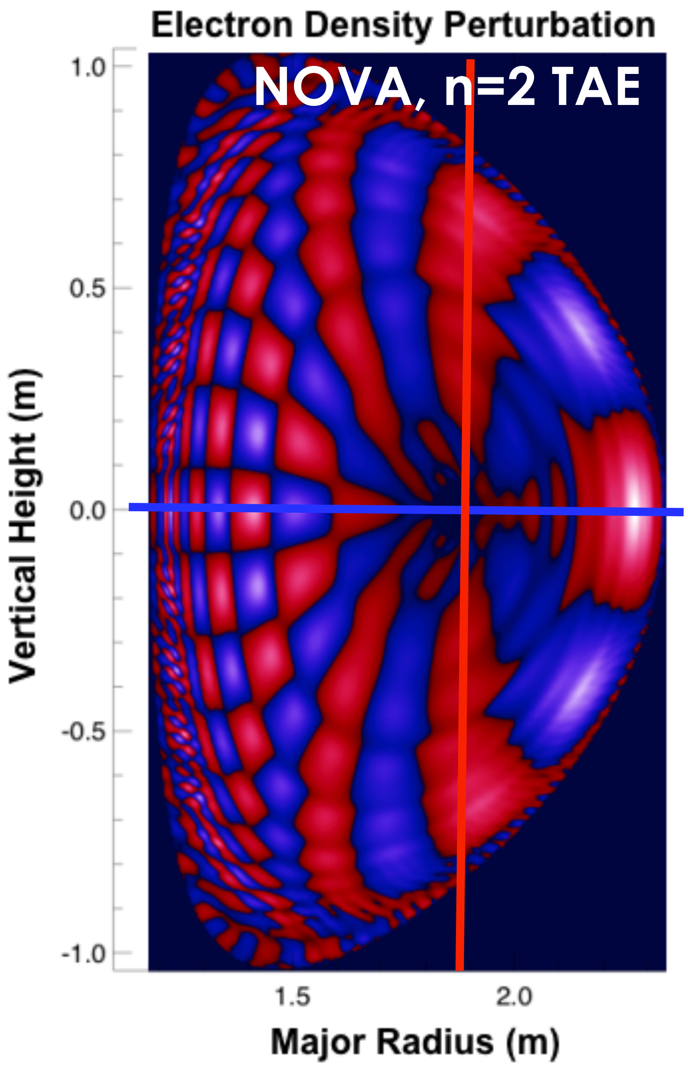
Signals Depend on the Mode Structure

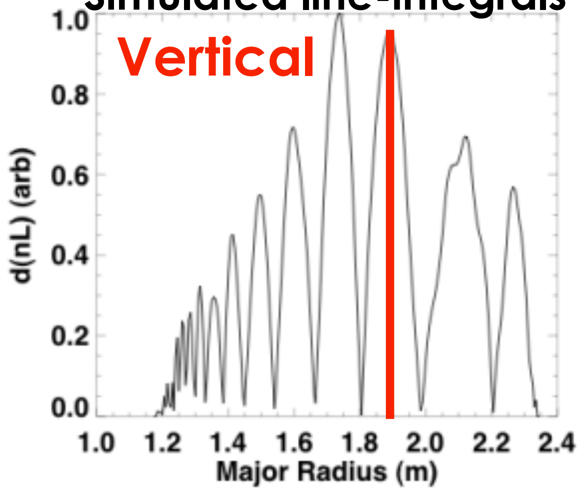


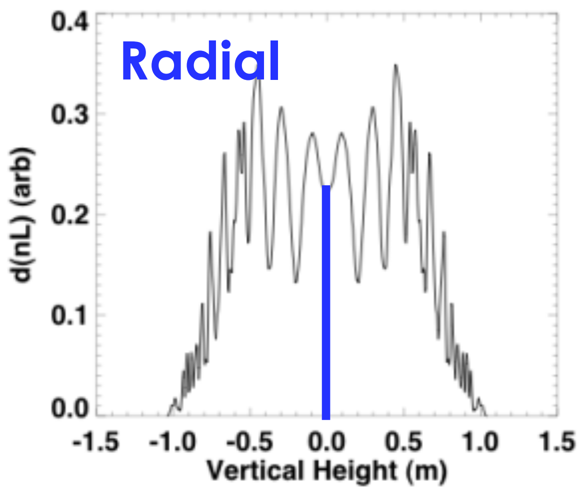


The Difference Between Vertical and Radial Line-integrated Views Can Be Understood Using NOVA Modeling



Simulated line-integrals





By taking simulated line-integrals through the density perturbation obtained using NOVA, the asymmetry between radial and vertical views is accurately reproduced.

$\Delta n_e L / \Delta n_e L \sim 5$

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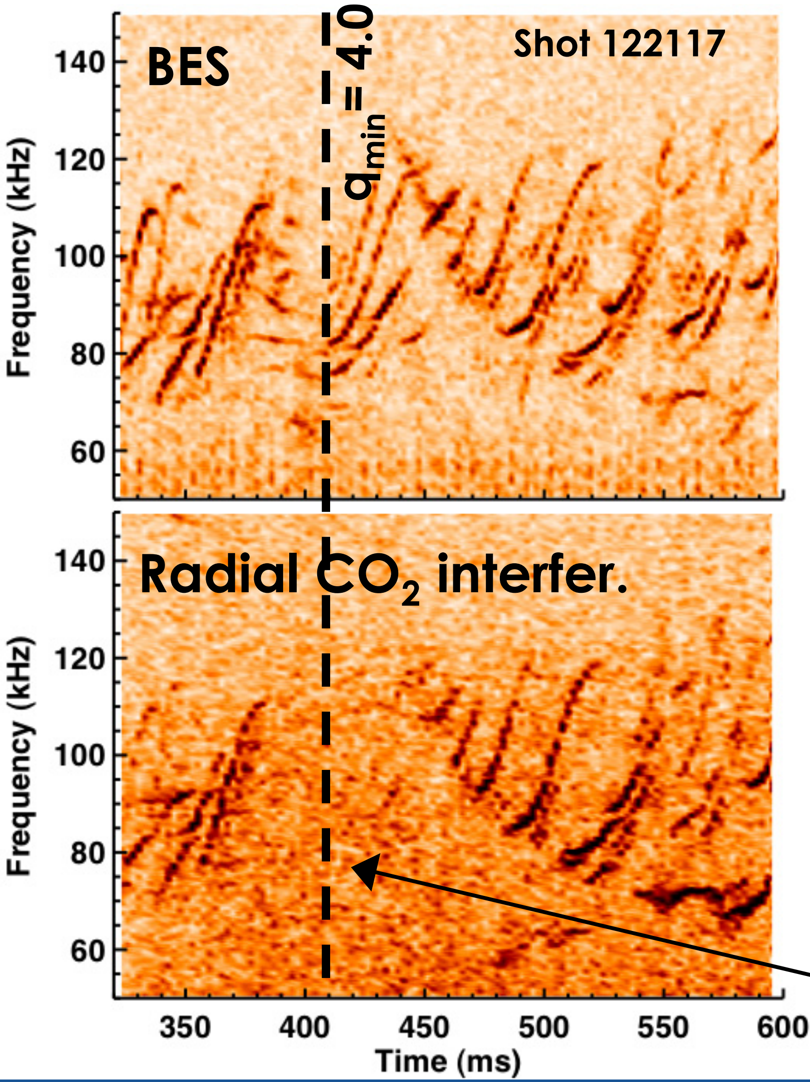
Line-Integrated Effects Are Made Apparent by Comparison With BES



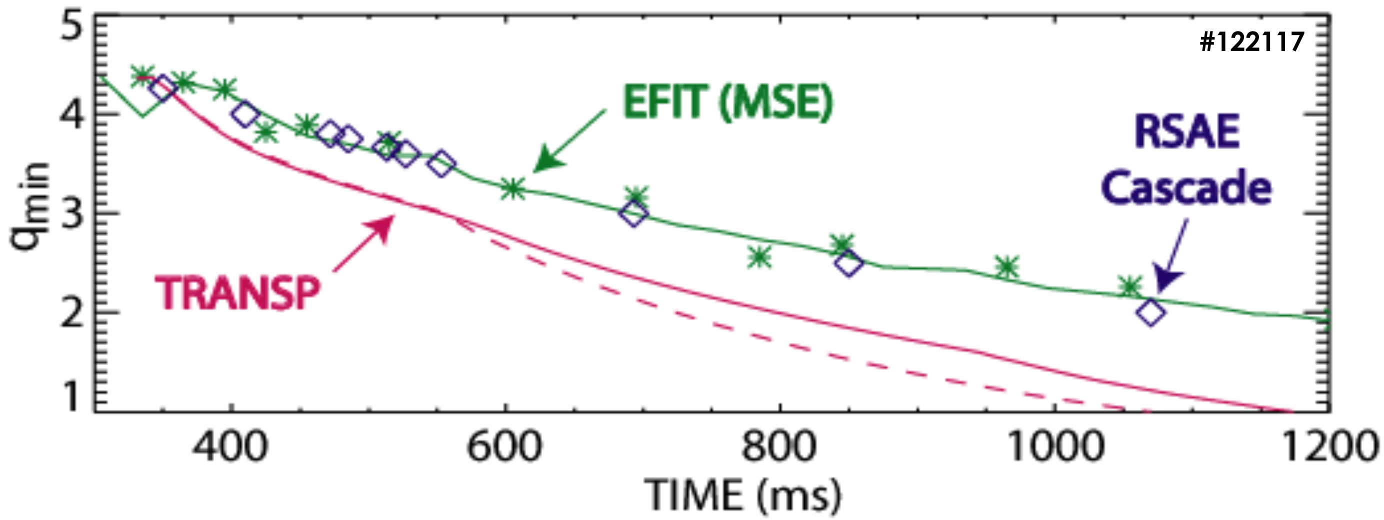
Grand Cascade is missing!

BES (local measurement) shows modes at q_{min}= 4 crossing whereas with line-integrated measurement, modes are not clearly discernable.

At q_{min}= 4, only even m i.e. m/n = 4/1, 8/2, 12/3 …

Potentially contrary to what one may expect.

Fast-ion Transport Broadens the Profile of Neutral-Beam Driven Current



- **The current diffuses more slowly than classically predicted**
- **Independent determinations of q_{min} from MSE-based equilibrium reconstructions and from the RSAE integer q crossings agree**
- **Apparently co-circulating fast ions that move to $\rho \sim 0.5$ broaden the NBCD profile.***

**Ferron, this conference; Wong, PRL 93 (2004) 085002; Wong, NF 45 (2005) 30.*