Excitation of Alfvenic Modes: Highlights and Future Directions in Theory-Experiment Comparison

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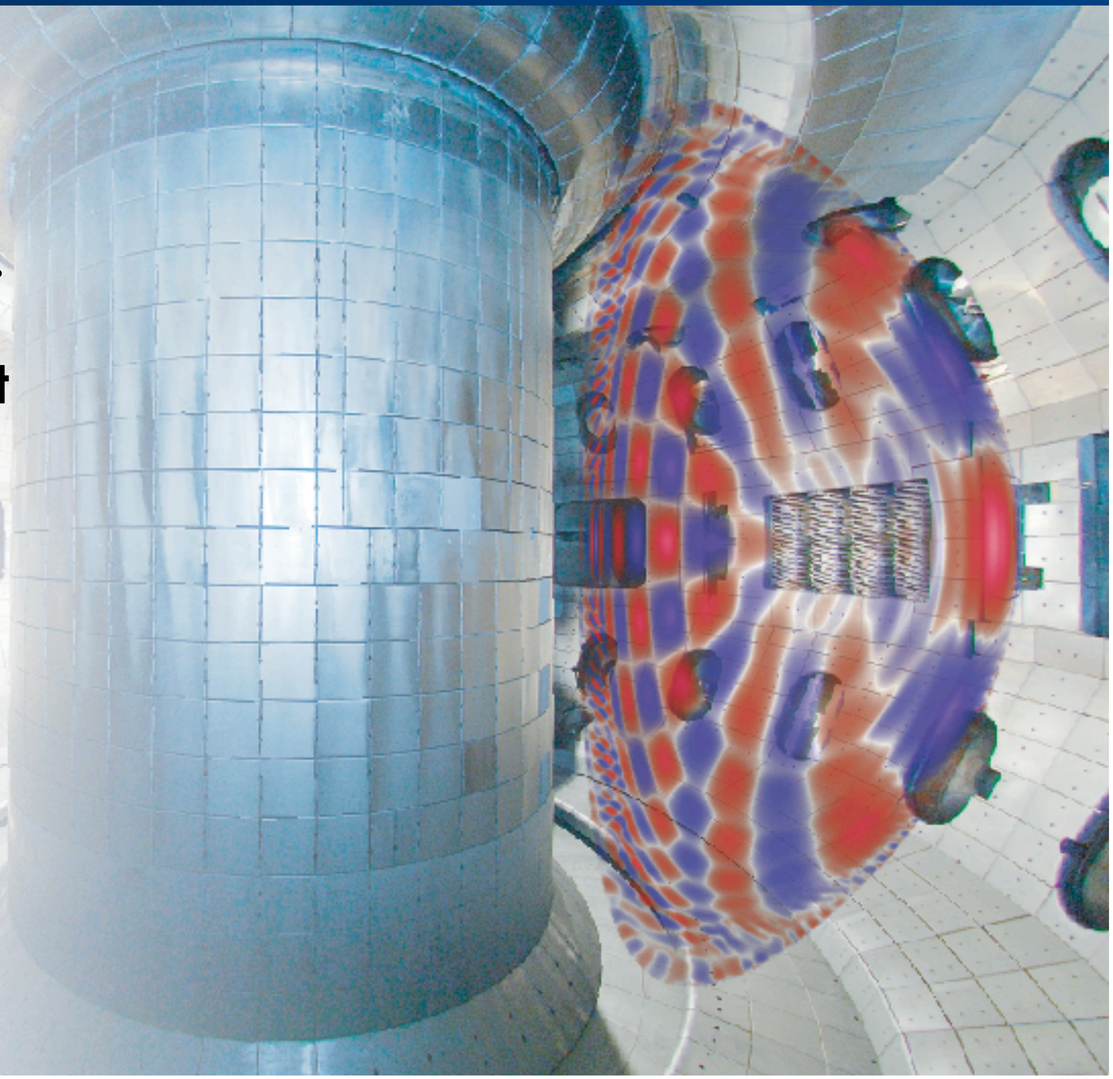


Thanks to many colleagues at JET, DIII-D, AUG, NSTX, MAST, JT60-U, LHD, C-MOD, PPPL, UC Irvine, UT Austin and other institutes for valuable input

ITER SUMMER SCHOOL

Aix en Provence, France
June 21st, 2011

Background: ITER is expected to Produce 500 MW of Fusion Power for up to 400s in its First Phase of Operation (≈2024)

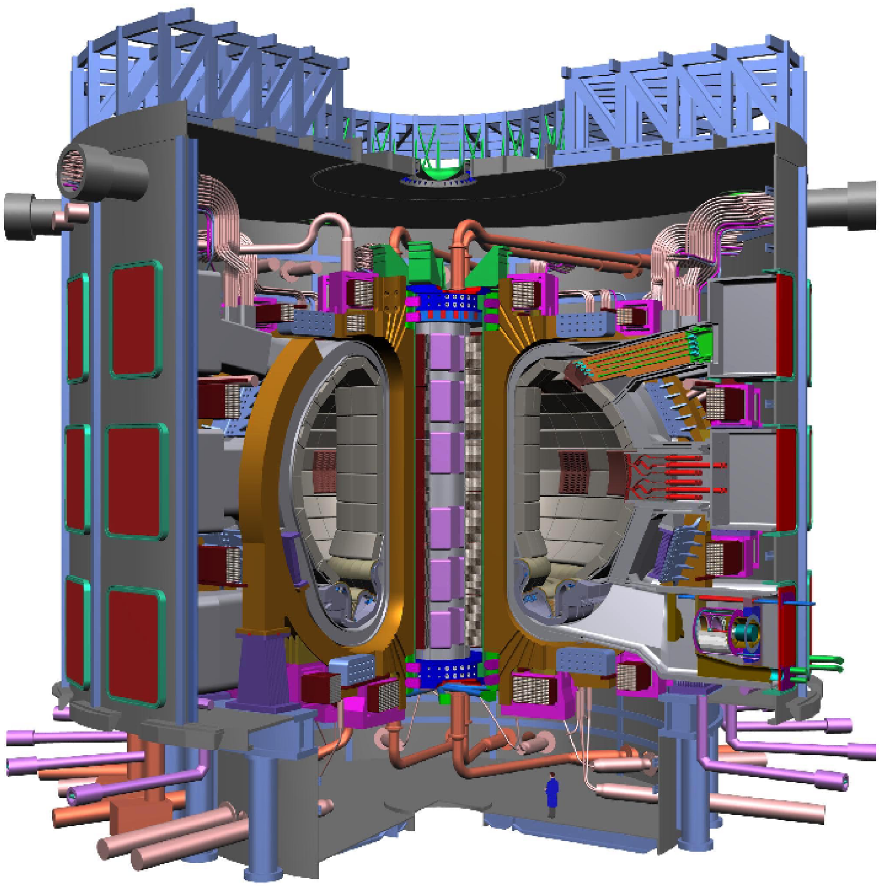
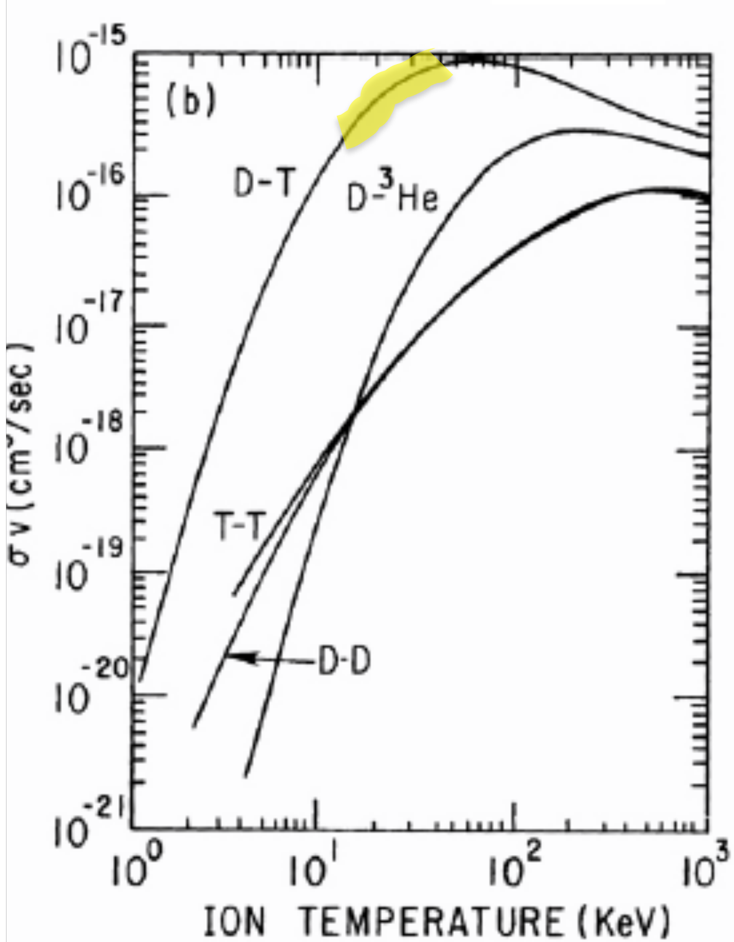


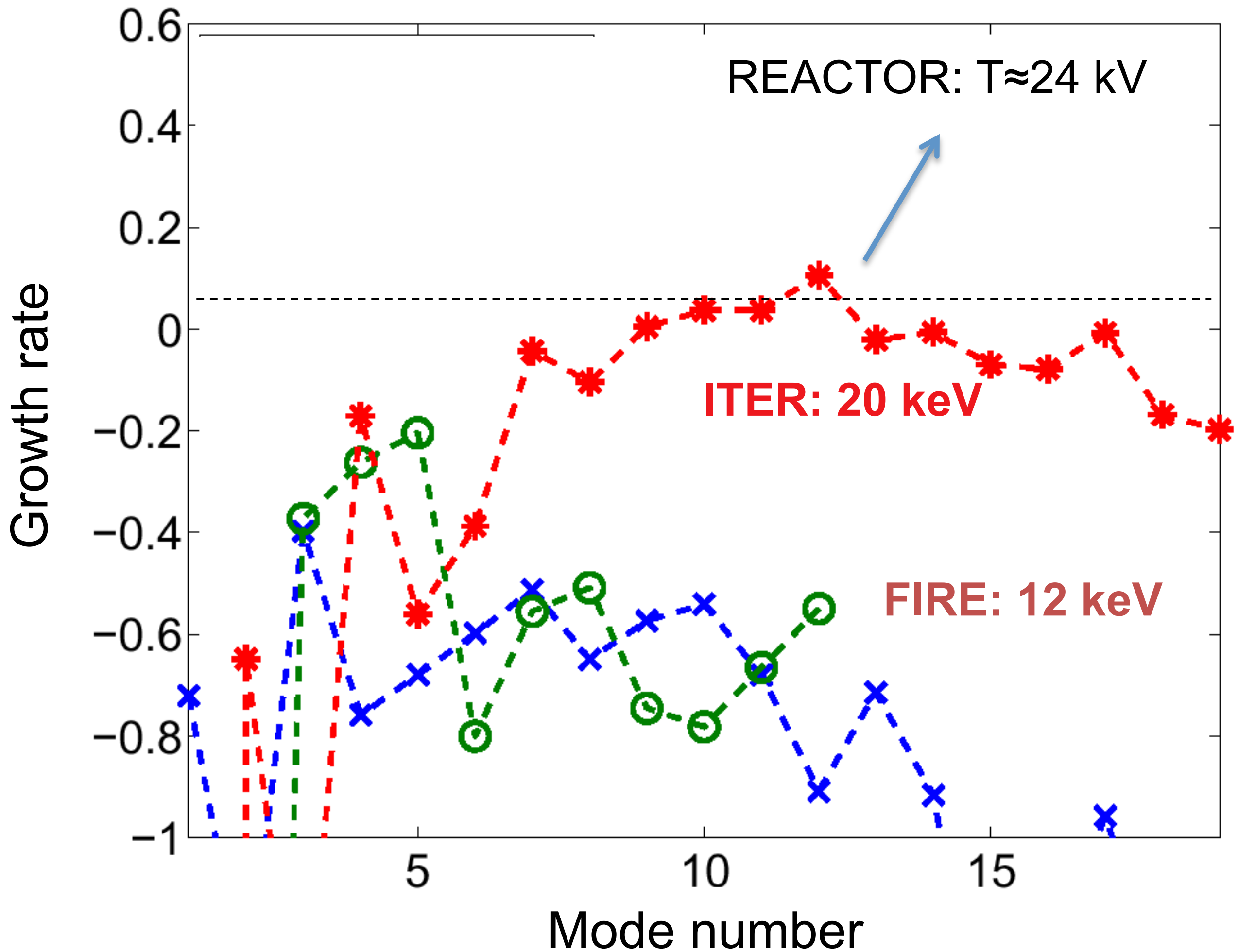
Figure 2.1-2 ITER Tokamak Cutaway



D+T -> n(14.1 MeV) + α(3.5 MeV)

The alpha particles should remain well confined for a slowing down time ≈ 1 sec.

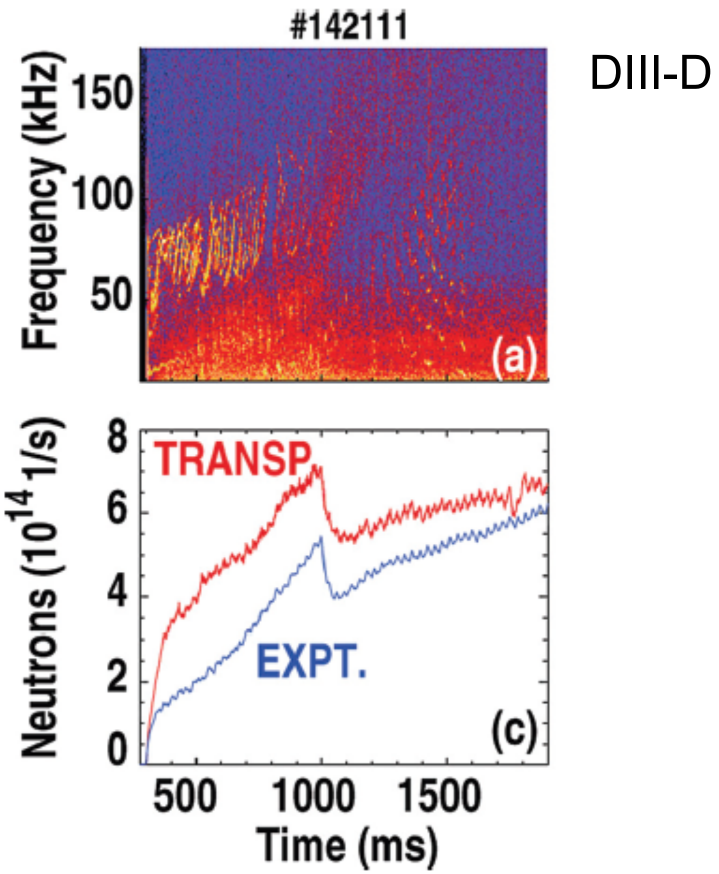
Jump Forward: Sea of Alfven Waves Calculated to be Near Marginal Stability in ITER (and DEMO and REACTOR)

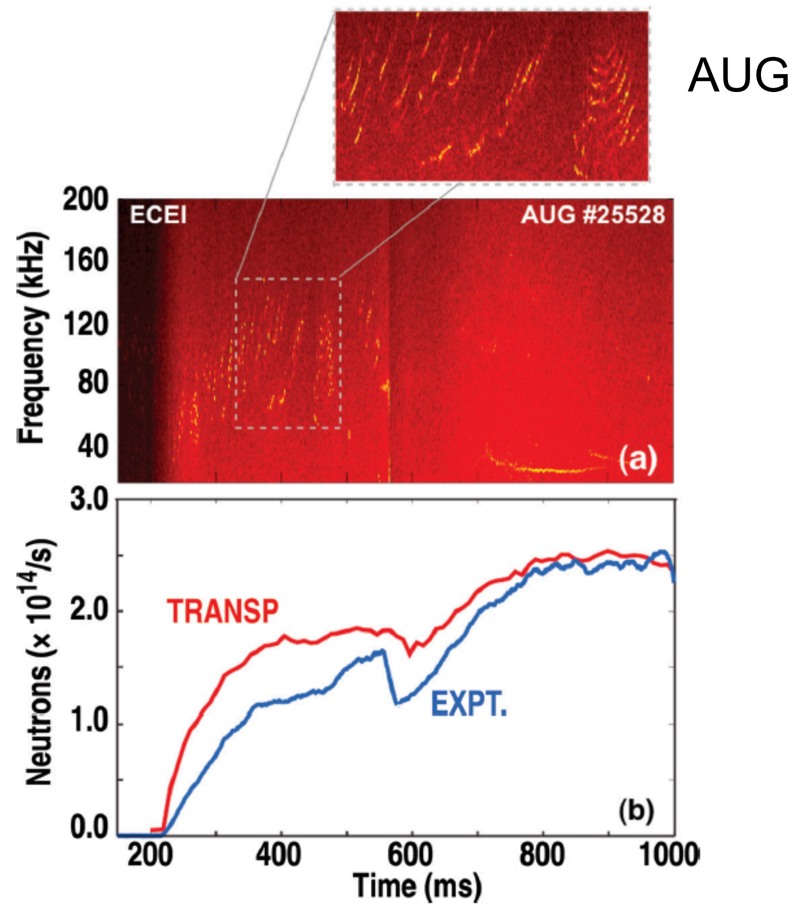


Nova-K
Gorelenkov

Do we have the right modes? Do we understand stability? Can these modes lead to significant transport and/or loss of alphas? Can we control these instabilities?

Depletion and loss of core energetic ions observed during central Alfven eigenmode activity on multiple devices





Classical over predicts the core fast ion population when modes are present. What will happen in ITER?
10% loss of alphas in ITER → +3 MW/m^2 peak heat load !!

ITER construction site: the project is very real and so are the challenges

Excavation site

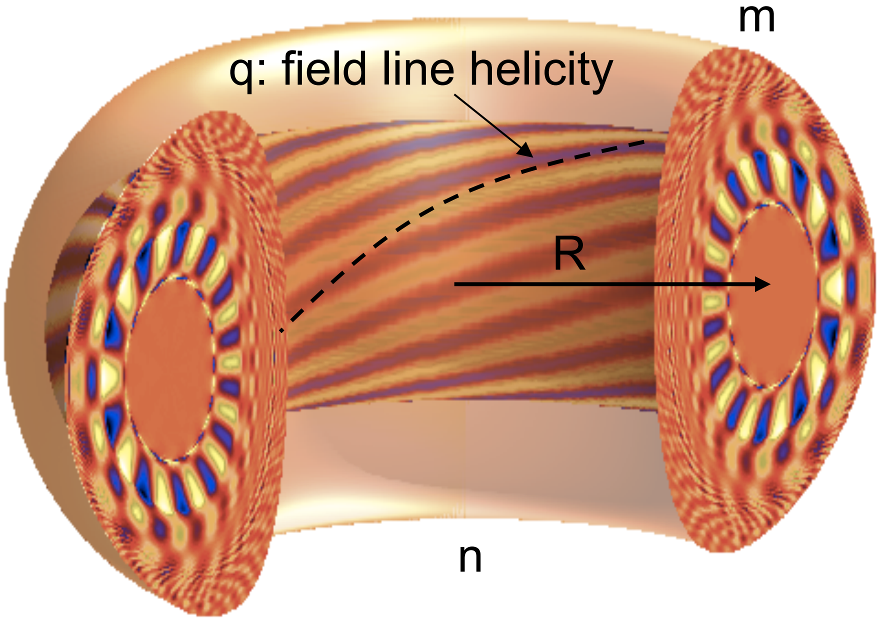
Do we understand the landscape of modes?

Do we understand drive and damping?

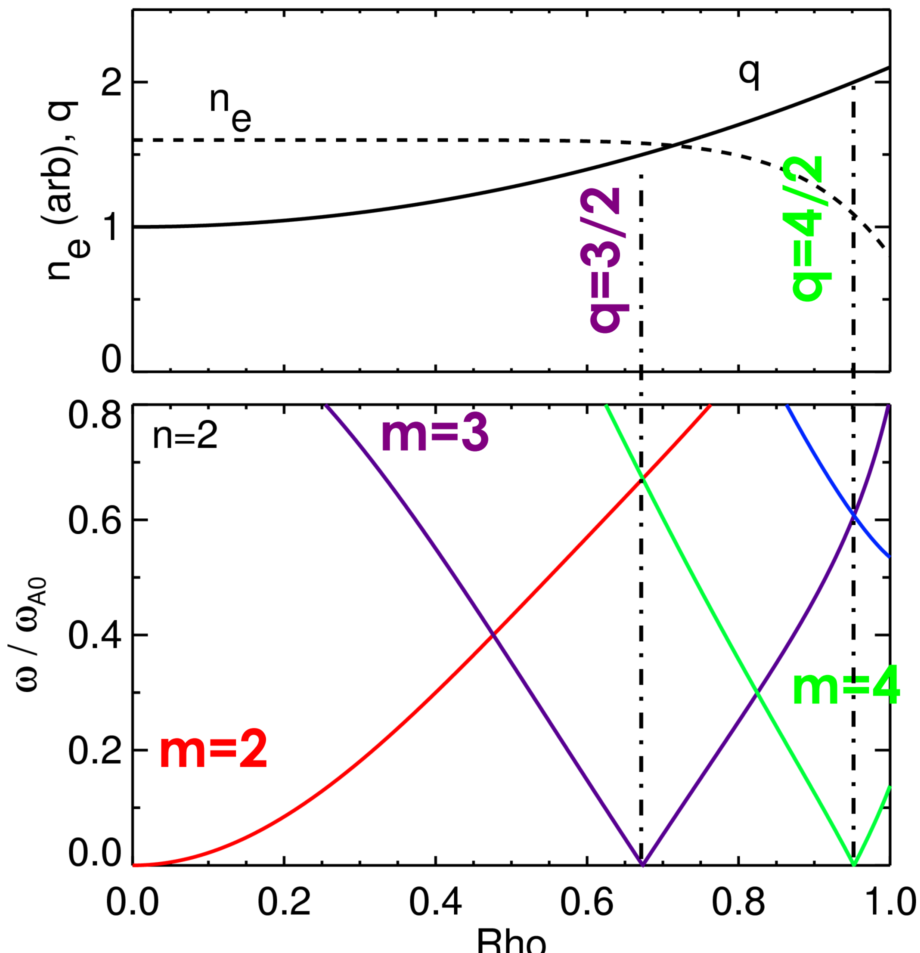
Can these modes lead to significant transport and/or loss of alphas?

Can we control these instabilities?

A micro tutorial: Shear Alfvén Waves Prescribe a Continuum of Modes in Magnetic Confinement Systems



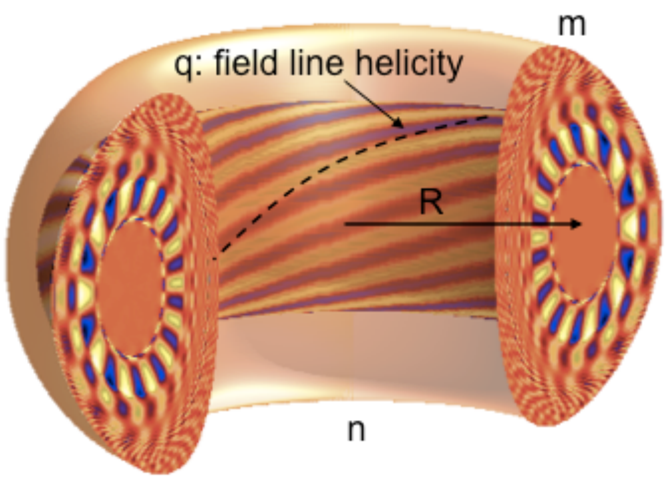
$$\omega_A = k_{\parallel} V_A = \frac{(m - nq)}{qR} V_A$$

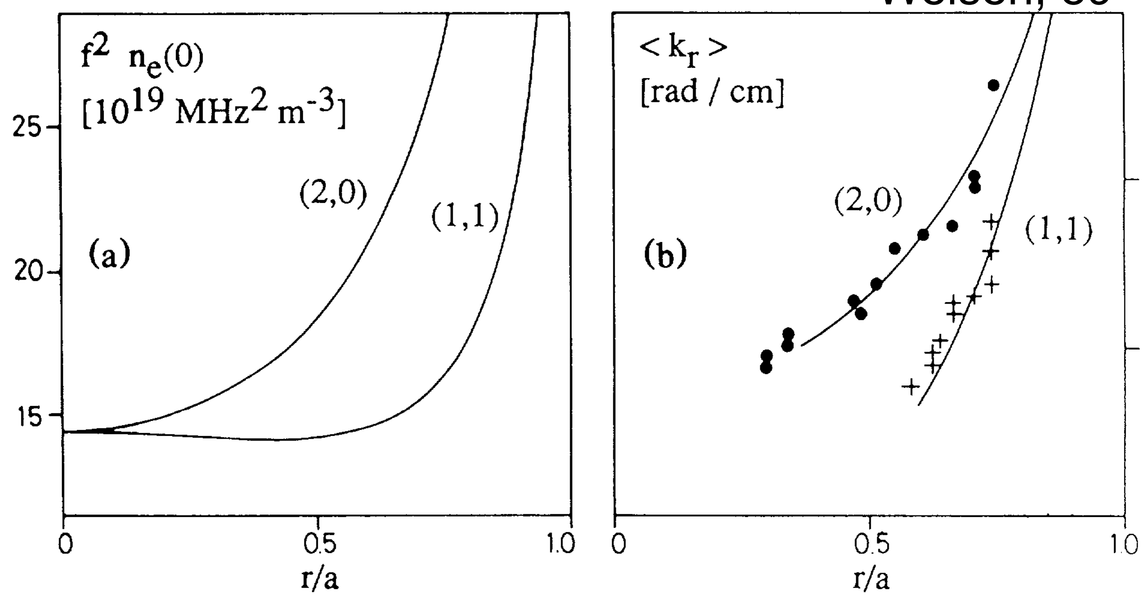


- Extension to KAW and idea for plasma heating (Chen, Hasegawa: 74, 75)
  - identified on TCA (Weisen 1982)
- KAWs can be driven by energetic particles, but unlikely
  - assumes positive magnetic shear (Rosenbluth & Rutherford: 1975)

Interferometer measurements on TCA consistent with KAW excitation using external antennas

Weisen, 89





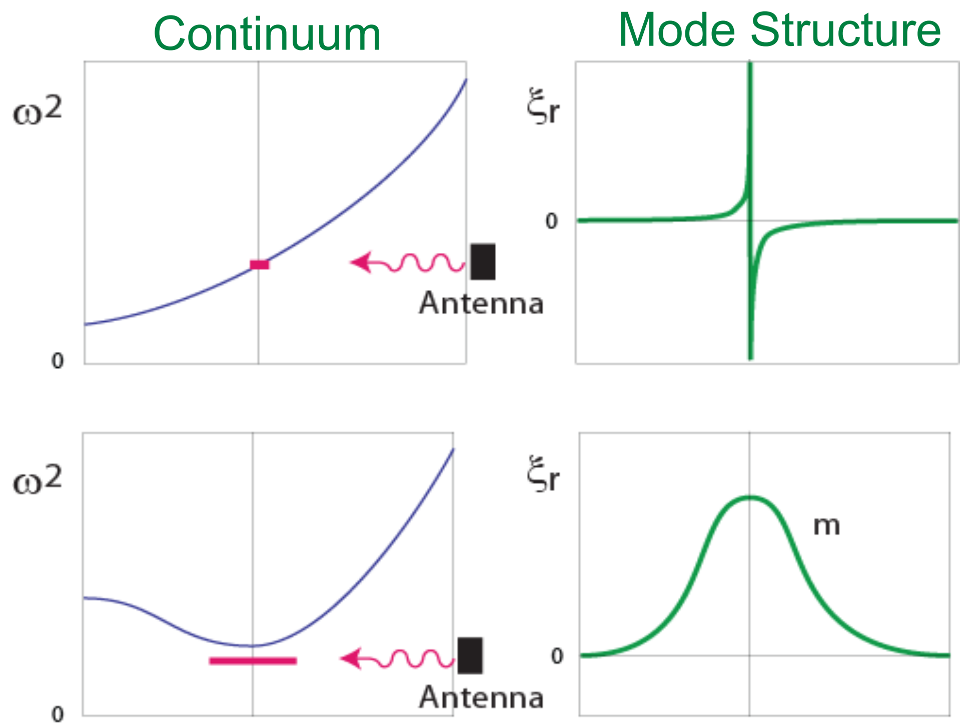
$$\omega_{KAW} \approx k_{\parallel} V_A \sqrt{1 + 2\left(k_r \rho_i\right)^2} \quad : \quad T_e \approx T_i$$

$$\omega_{antenna} \rightarrow \omega_{KAW}$$

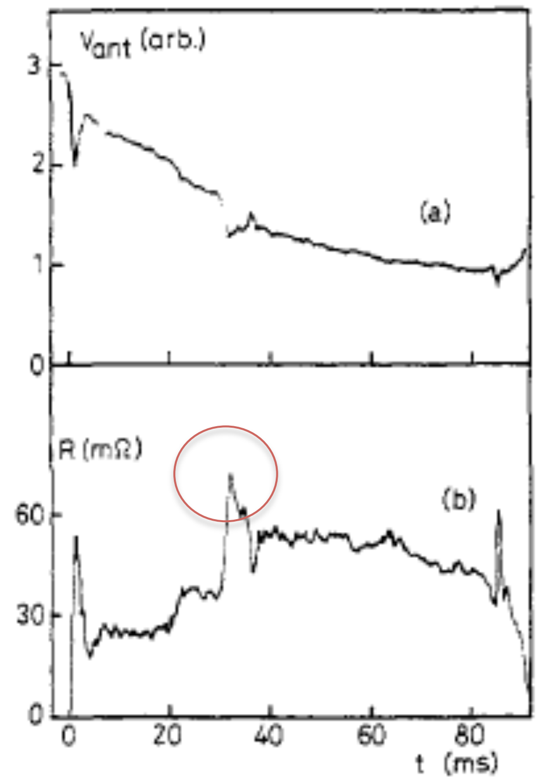
$$(m,n)_{antenna} \rightarrow k_{\parallel}$$

- Imaging interferometer used to identify location of peak density fluctuation
  - corresponds to location of mode conversion to KAW

Sharp Resonances Observed on TCA Antennas Helped Usher in the Era of the Alfvén Eigenmode



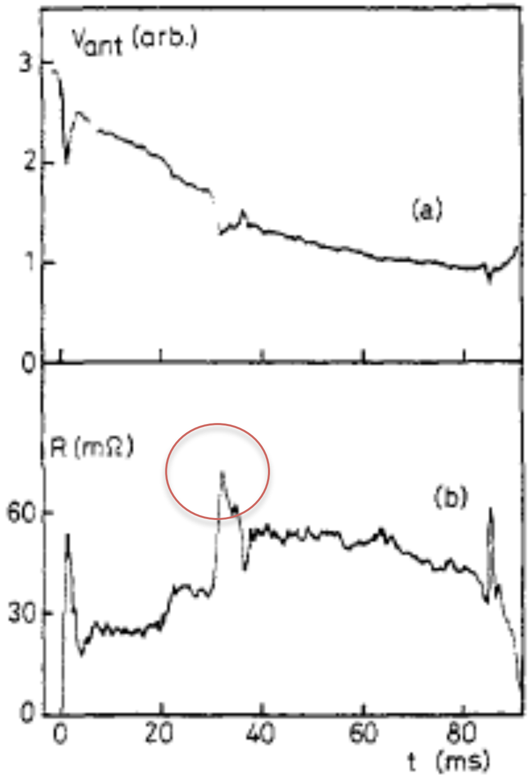
A. De Chambrier, PPCF 1982



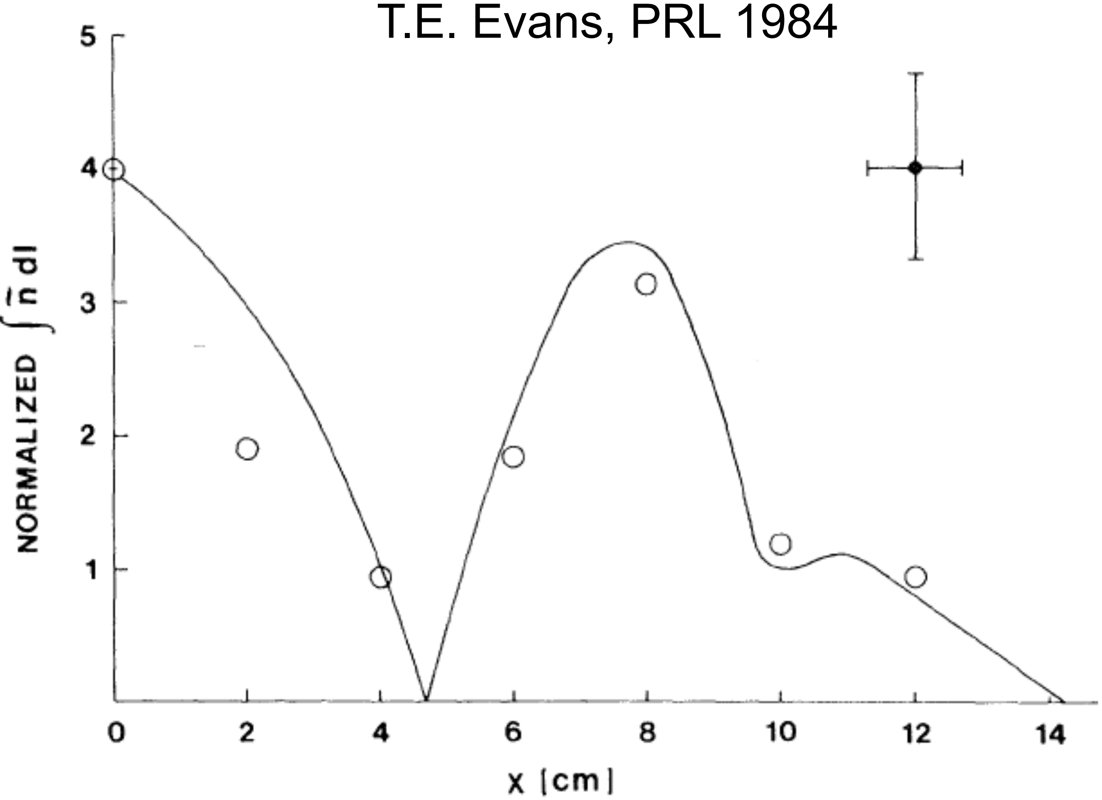
- Global Alfven Eigenmode (GAE) is a cylindrical mode (m,n) that lies just below a minimum in the Alfven continuum
- Shows up as spikes in antenna loading.

T.E. Evans produced one of the first detailed mapping of the internal structure of Alfven eigenmode

A. De Chambrier, PPCF 1982

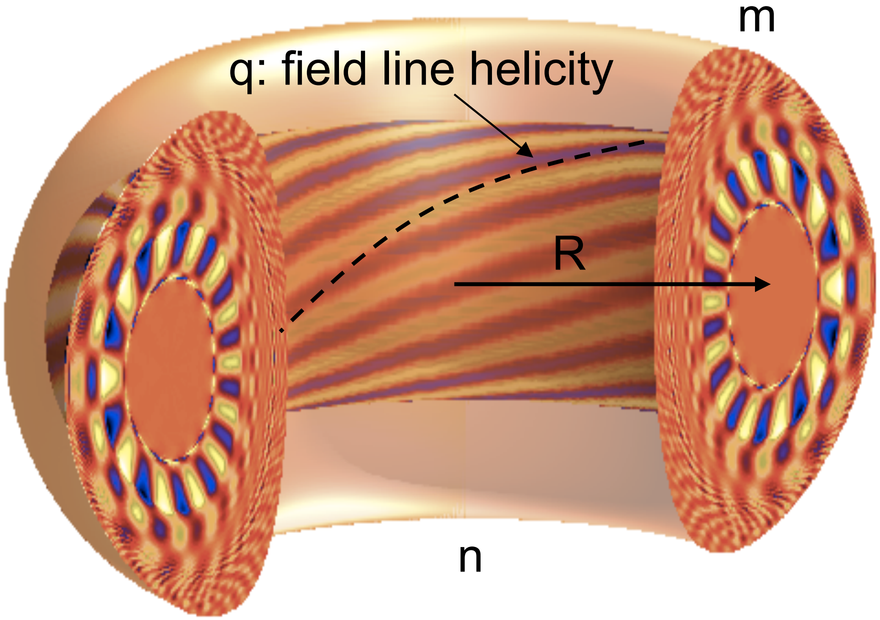


T.E. Evans, PRL 1984

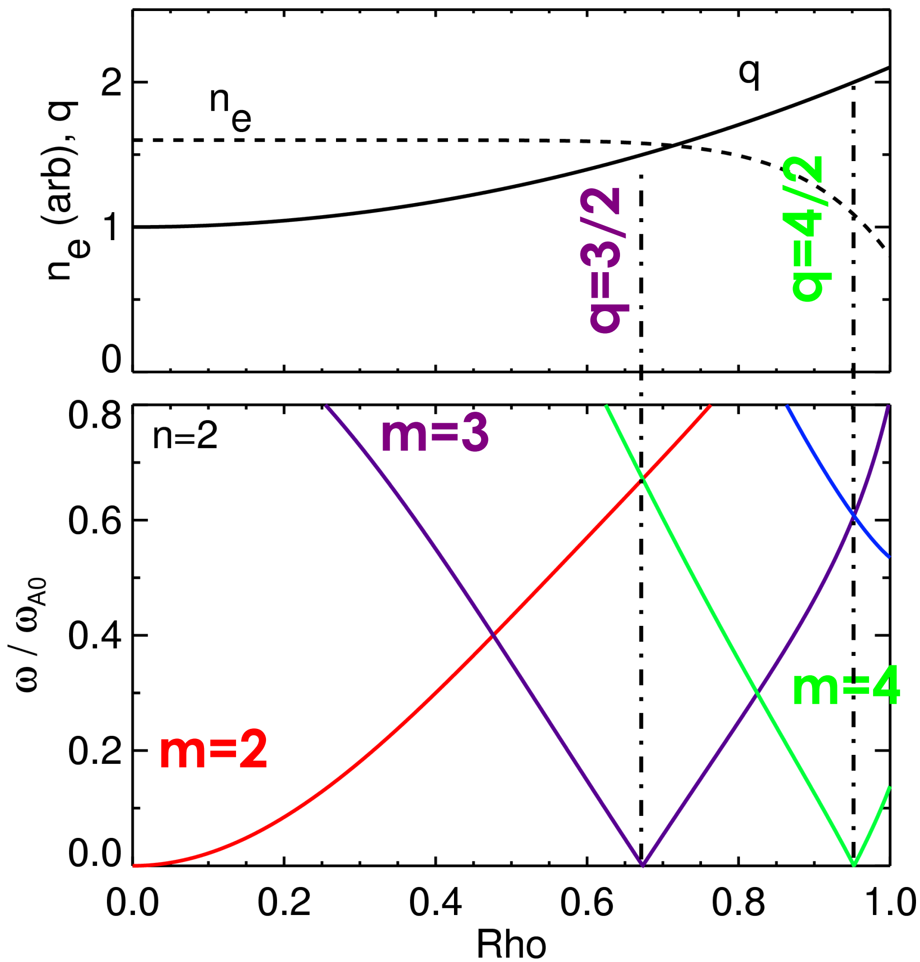


- Imaging interferometer (open circles) agrees closely with theory for GAE (solid line)
- Internal measurement helps resolve ambiguity of loading measurement
  - multiplicity of modes possible in tokamak

A micro tutorial: Shear Alfvén Waves Prescribe a Continuum of Modes in Magnetic Confinement Systems

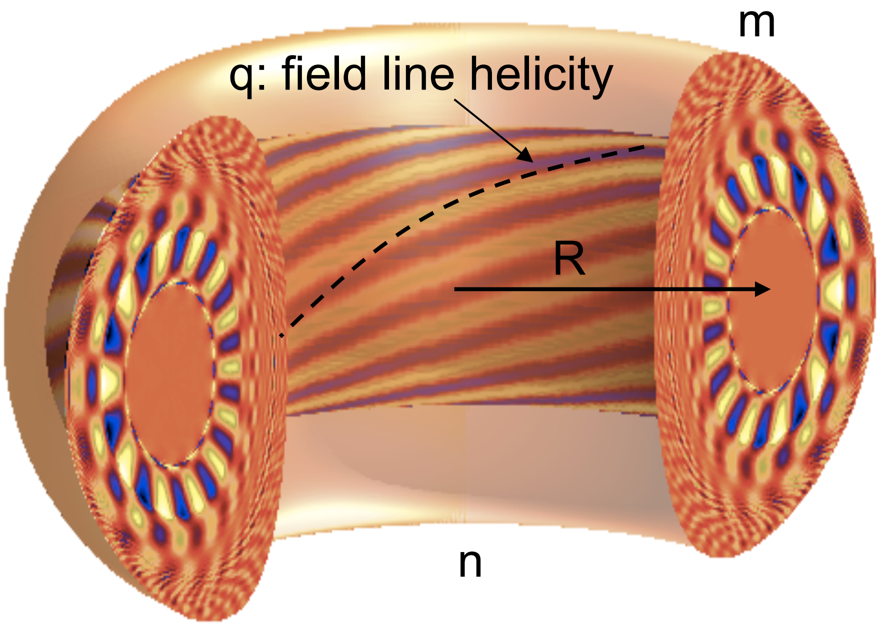


$$\omega_A = k_{\|} V_A = \frac{(m - nq)}{qR} V_A$$



• Toroidicity breaks degeneracy at frequency crossings between m, m+1 continuum

A micro tutorial: continuum gaps and global gap modes develop due to plasma inhomogeneity along field lines



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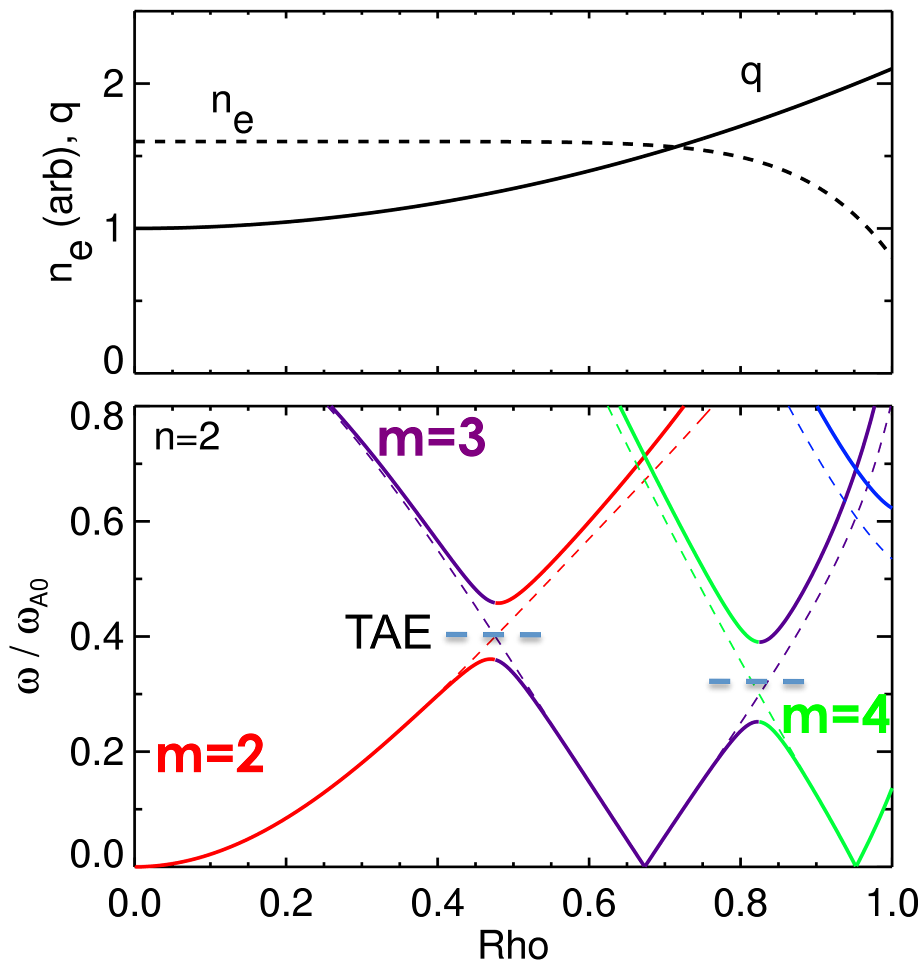
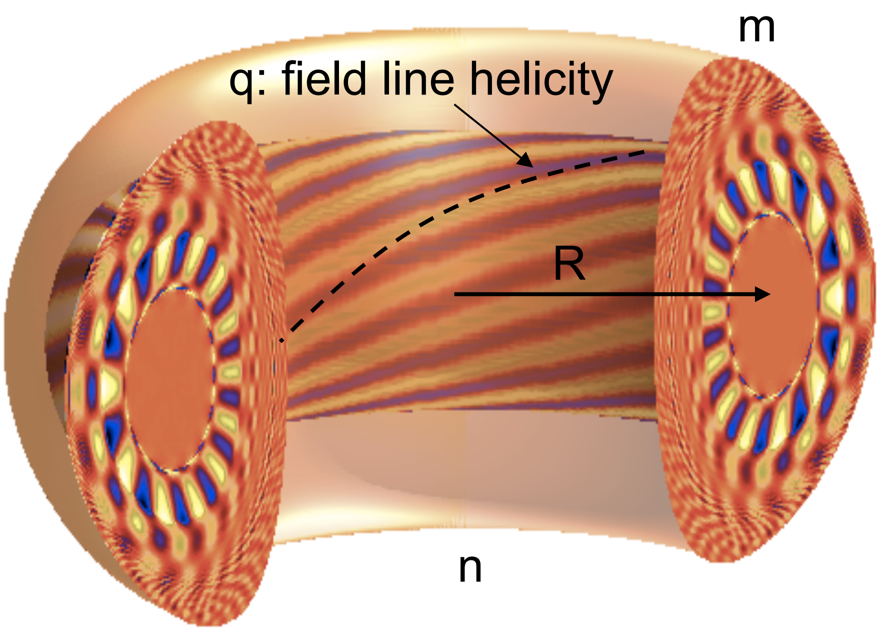


- Gaps in the continuum: m,m+1: (Kieras 82), m,m+2, (Dewar, 74)
- Global low-n toroidal gap modes discovered (Cheng & Chen, 85)
- Potential for strong interaction with Alfven velocity ions (Fu & VanDam, 89)

A micro tutorial: A zoo of gap modes discovered that can interact with particles near the Alfvén velocity



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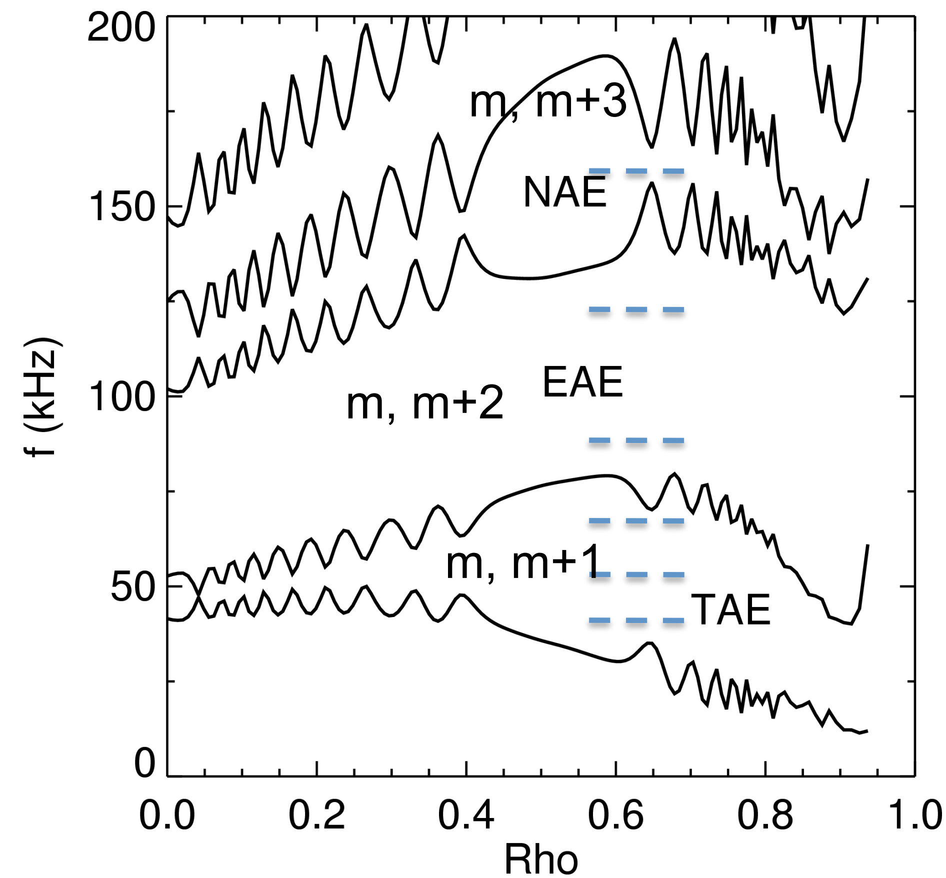


- **A zoo of modes discovered**

$k_{\|}=$ 1/2qR, (TAE) Cheng&Chen,85

1/qR, (EAE) 3/2qR, … (NAE) Betti& Friedberg, 91,92

- **Resonance for deeply passing ions: back to this later**

$V_{\|} \sim V_A$ (Heidbrink, Wong, 91)

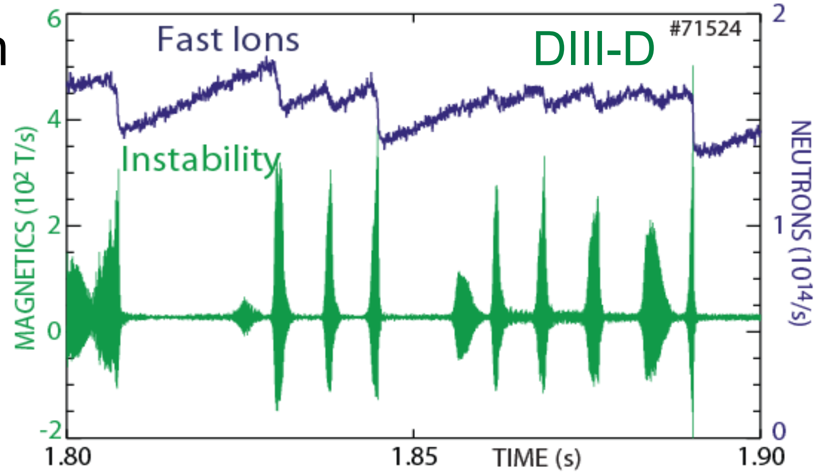
TAE Bursts and Rapid Fast Ion Loss Observed on DIII-D and TFTR

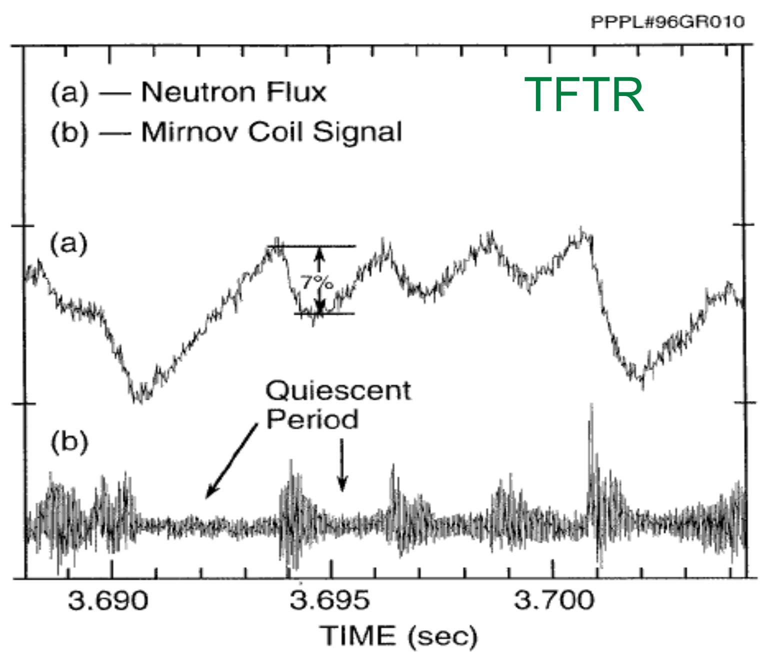
- Mode frequency and scaling consistent with TAE theory
  - mode structure not confirmed, only frequency

- Modes found to be more stable than theoretically expected
  – needed more beam power to excite modes

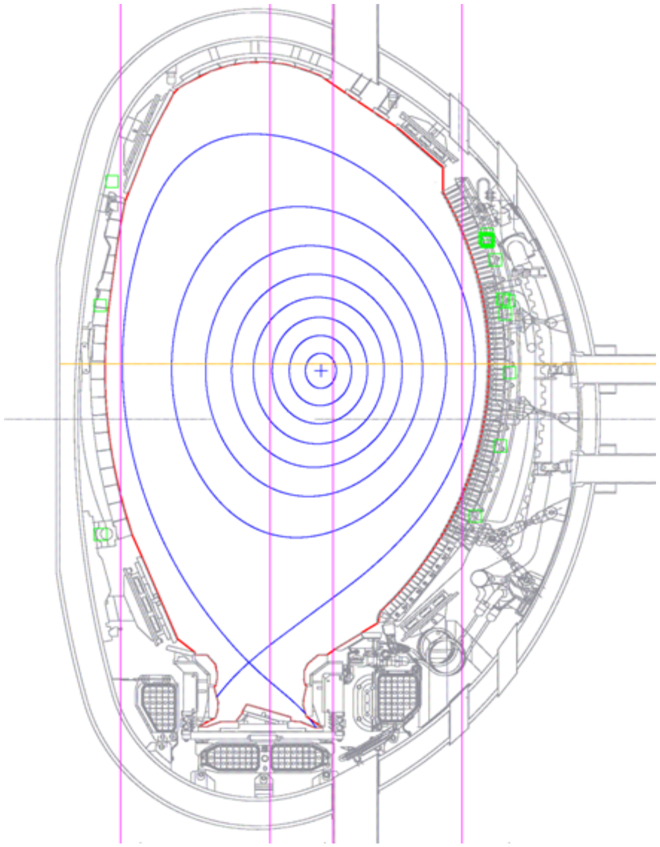
- Mode amplitude inadequate to account for strong losses of beam ions
  - amplitude based on external measurements
  - machine damage resulted on TFTR due to losses

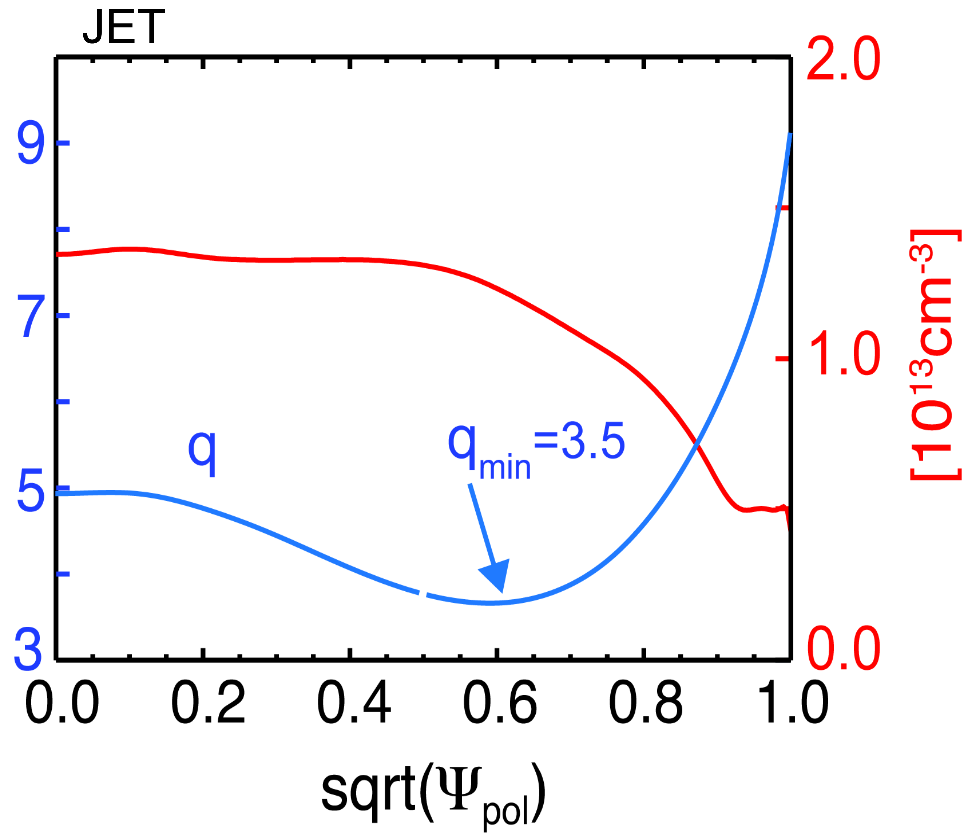
- Note: GAE not usually seen in tokamaks, seen more on stellarator, weak shear needed





Reverse magnetic shear operation relevant to steady state reactor regimes leads to new Alfvénic modes





- Lower Hybrid Current drive is used to obtain reversed shear
- New modes appear near q-min called Cascades or Reverse Shear Alfven Eigenmodes

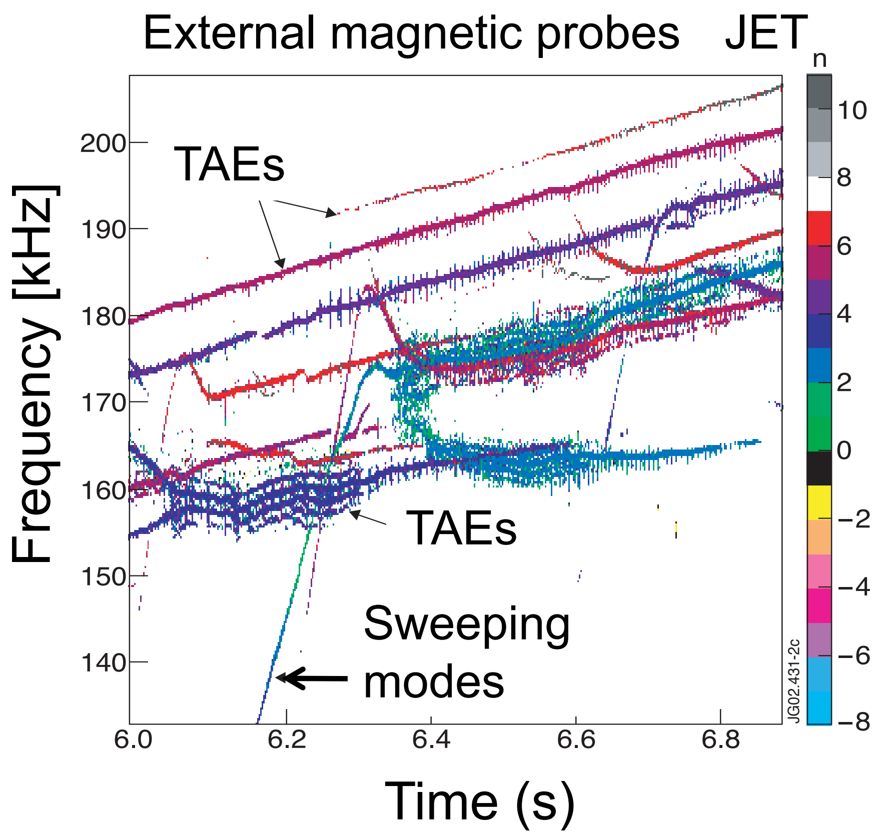
Early Observation of Frequency Sweeping Modes merging with TAE on JET and JT60-U went unexplained by gap mode theory

- External magnetic probe measurements reveal dominant TAEs

- but strong frequency sweeping activity observed

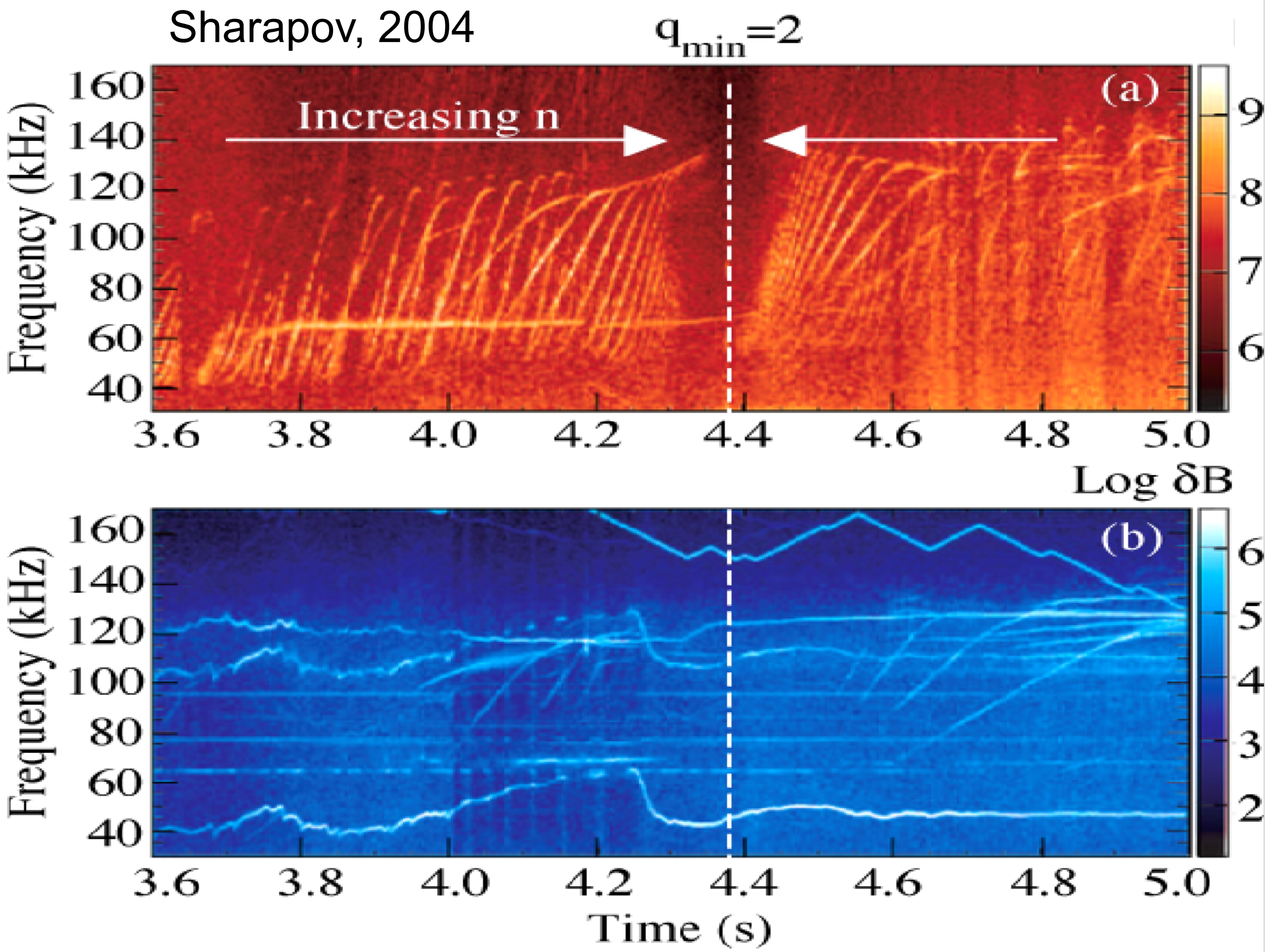
- Clear transition seen from the frequency sweeping to the frequency stable TAE regime

- Frequency sweeping modes do not "look" very important, but looks can be deceiving



Frequency sweeping modes can be the dominant instability in the core of reverse shear plasmas: Internal measurement needed

Sharapov, 2004

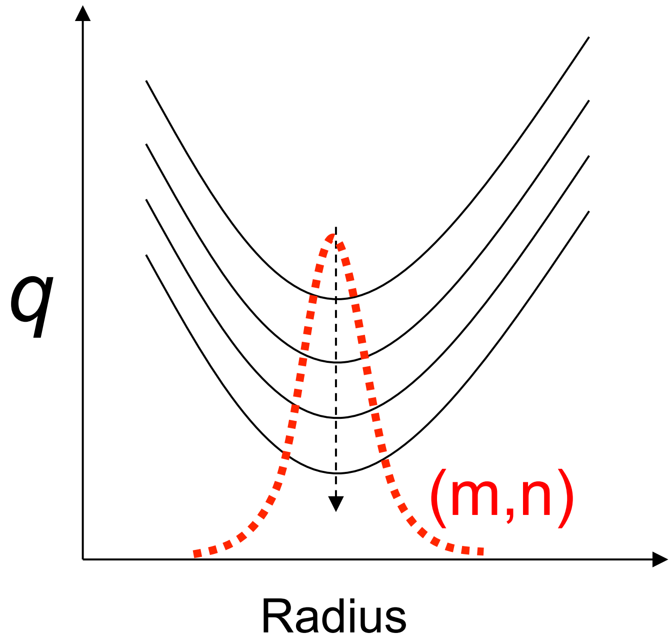


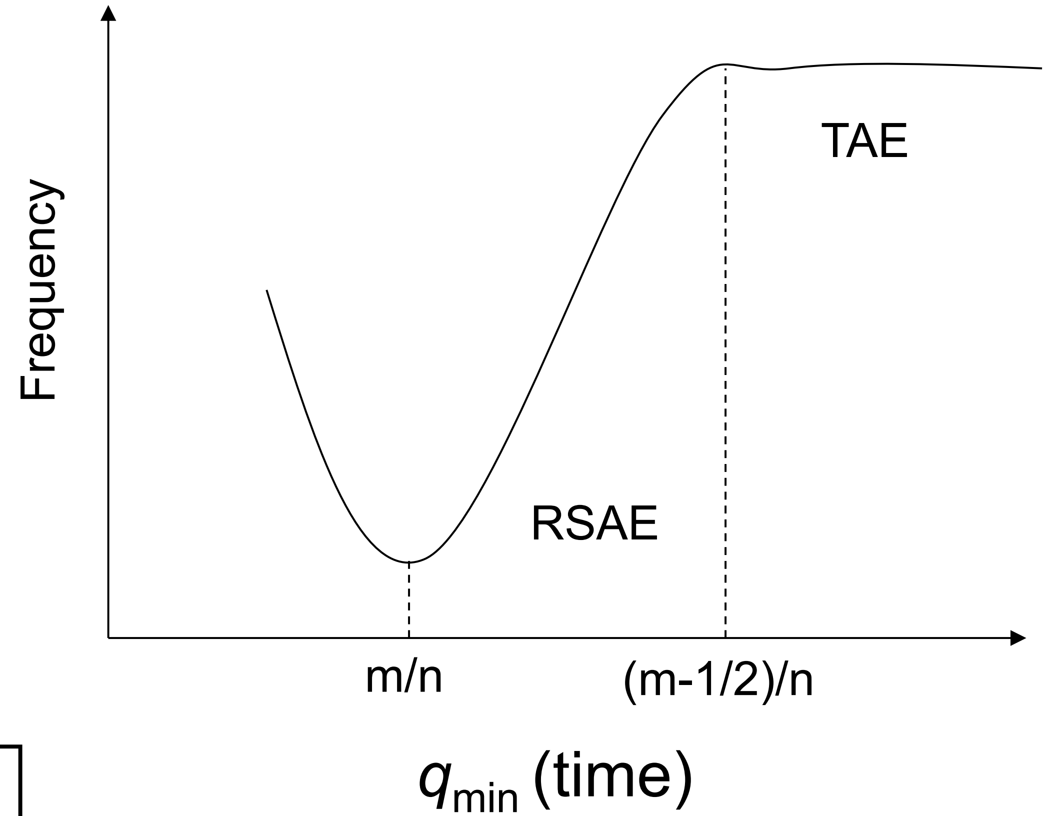
JET

- Interferometer
- Magnetic probe

- ”Sea” of modes up to N=16 observed on interferometer in JET
- International collaboration led to theory of RSAE: Berk, Briezman, Sharapov, 2001

Reverse Shear Alfvén Eigenmodes are cylindrical-like modes localized to the region near q_{min}



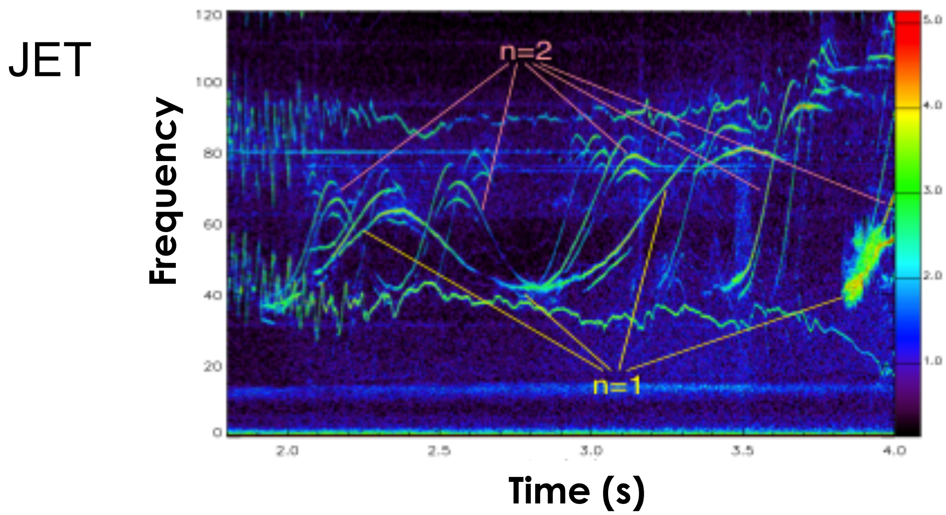


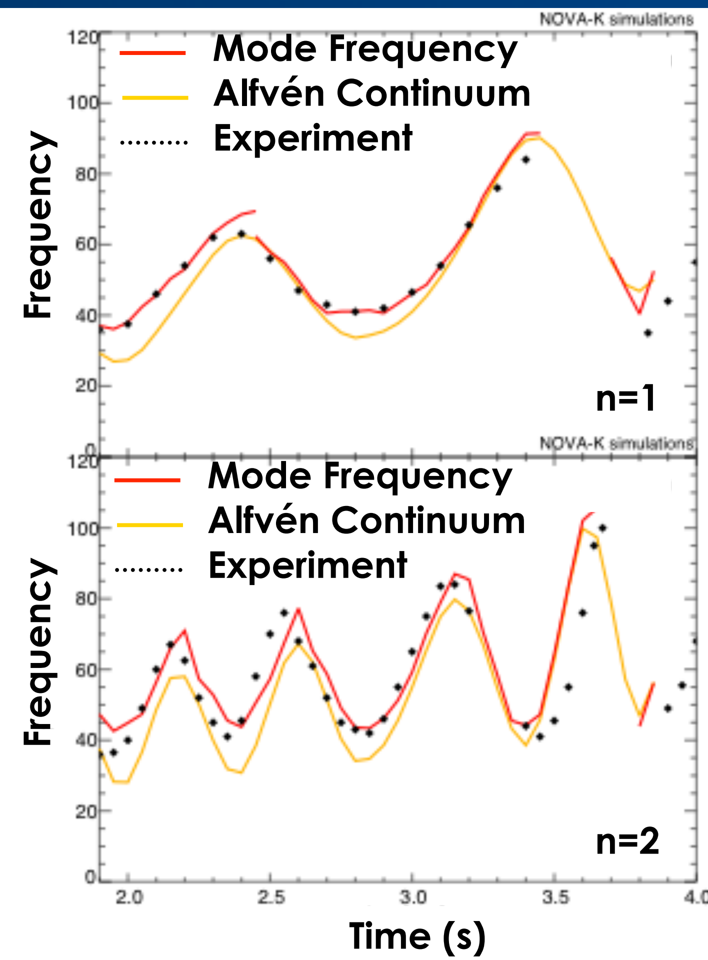
$$\boxed{\omega_{RSAE} = k_{\parallel} V_A = \frac{(m - nq_{\min})}{q_{\min} R} V_A}$$

• MHD Spectroscopy: Modes can be an accurate diagnostic of integer q_{min} crossing

Berk, Briezman, Sharapov, 2001

Excellent quantitative agreement on mode frequency observed on multiple devices

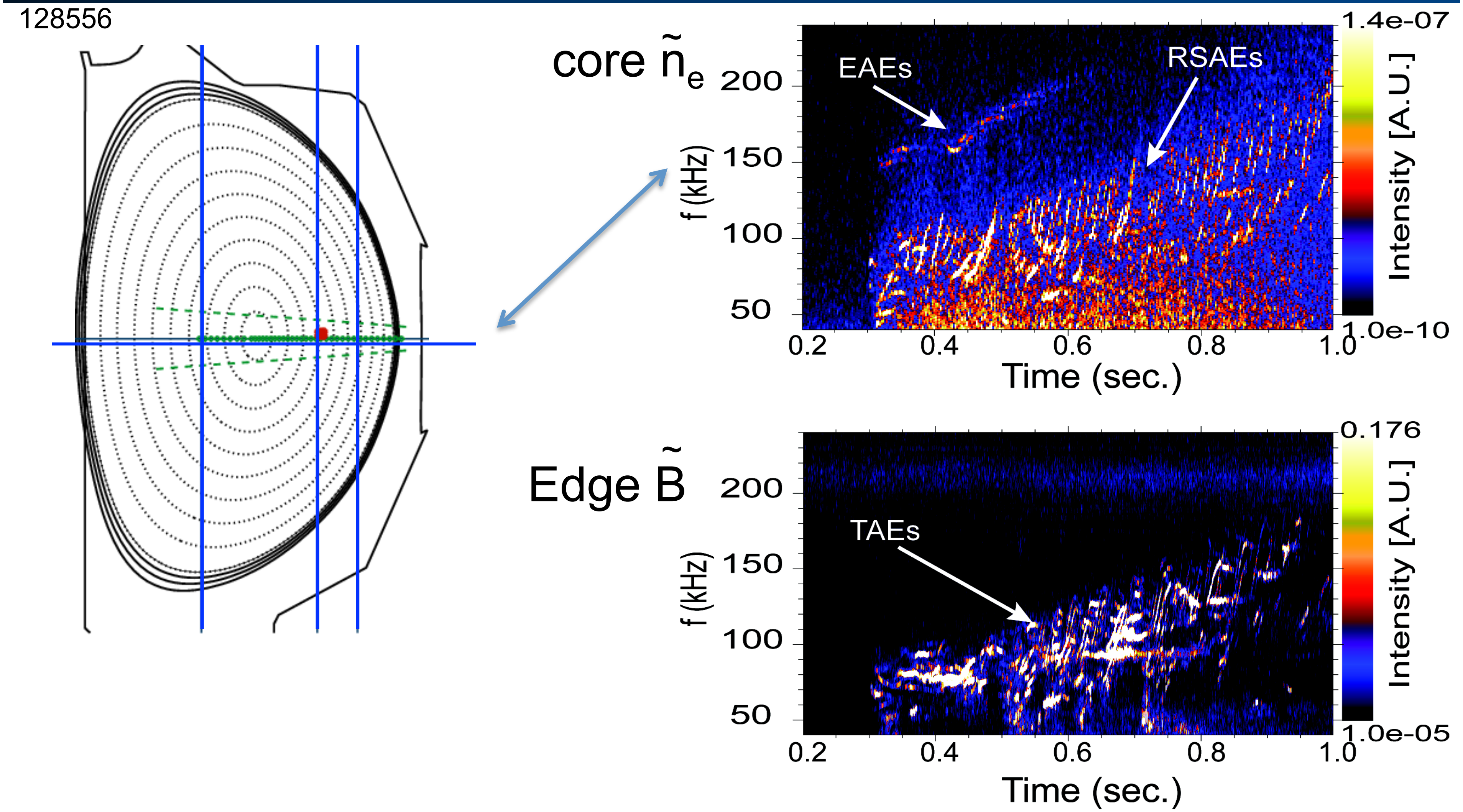




- The NOVA (ideal MHD) calculation agrees very well with the measured RSAE frequencies in JET
- The mode frequency follows the Alfvén continuum at q_{min}
- Similar observations on wide range of devices

G.J. Kramer , *2005*

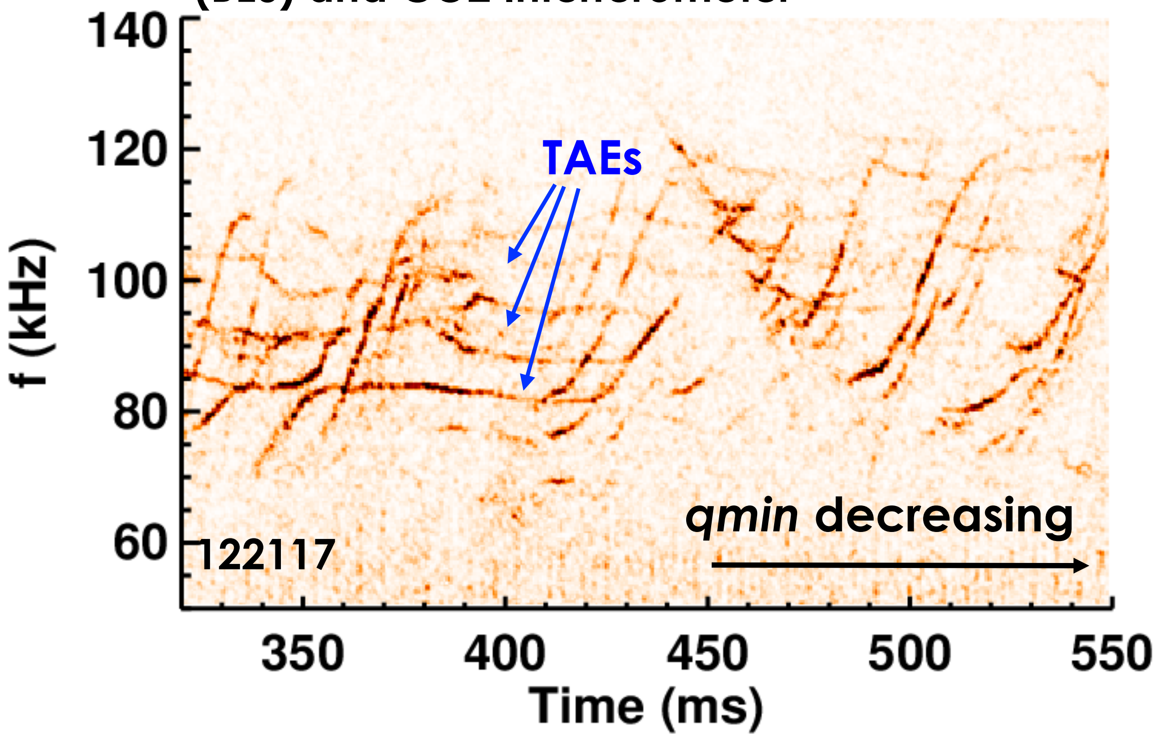
A rich landscape of Alfvén eigenmodes can be seen in reverse shear DIII-D plasmas



They are driven by 80 keV deuterium beams ($V_{NB}/V_A \sim 0.4$)

TAEs and RSAEs are Most Common AEs Observed and are Easily Identified Through Their Spectral Behavior

Crosspower Beam Emission Spectroscopy (BES) and CO2 Interferometer

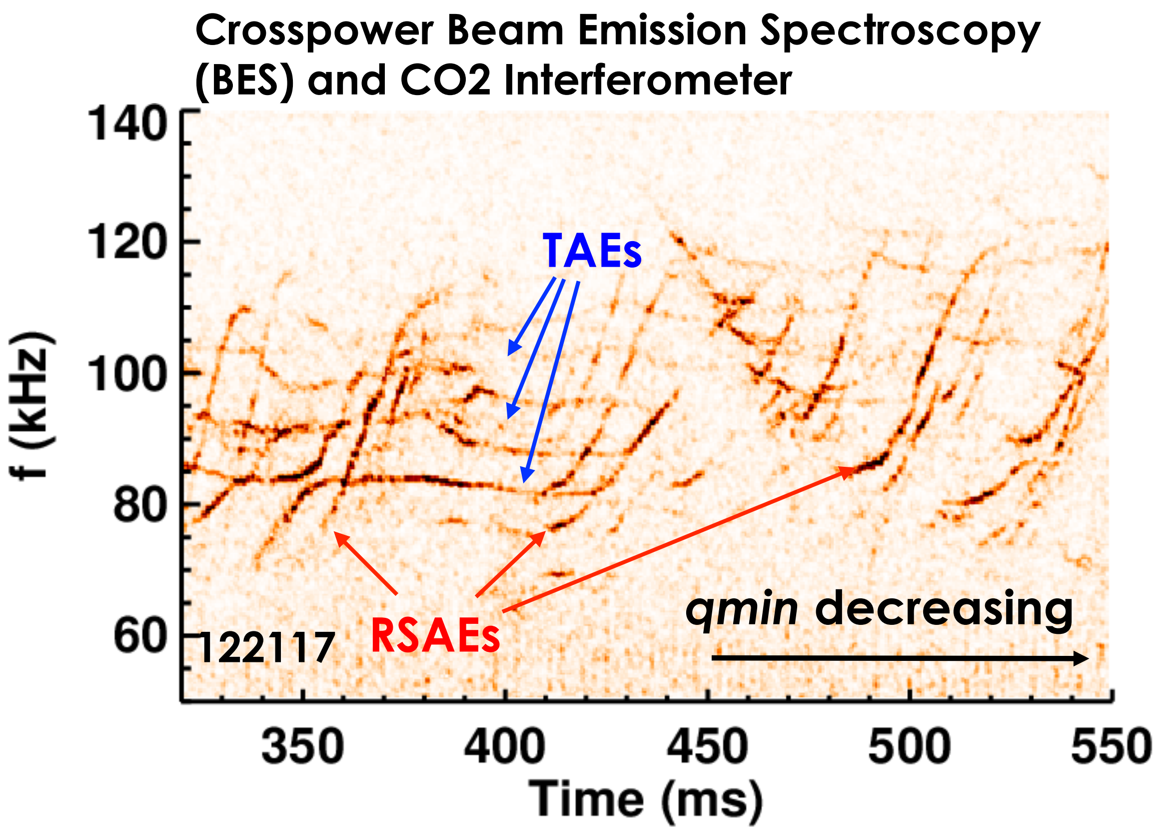


Toroidicity-induced Alfvén Eigenmodes (TAEs)

- Global modes
- Frequency changes gradually

$$\omega_{TAE} \approx \frac{V_A}{2R}\left(\frac{n}{m+1/2}\right)$$

TAEs and RSAEs are Most Common AEs Observed and are Easily Identified Through Their Spectral Behavior



Toroidicity-induced Alfvén Eigenmodes (TAEs)

- **Global modes**
- **Frequency changes gradually**

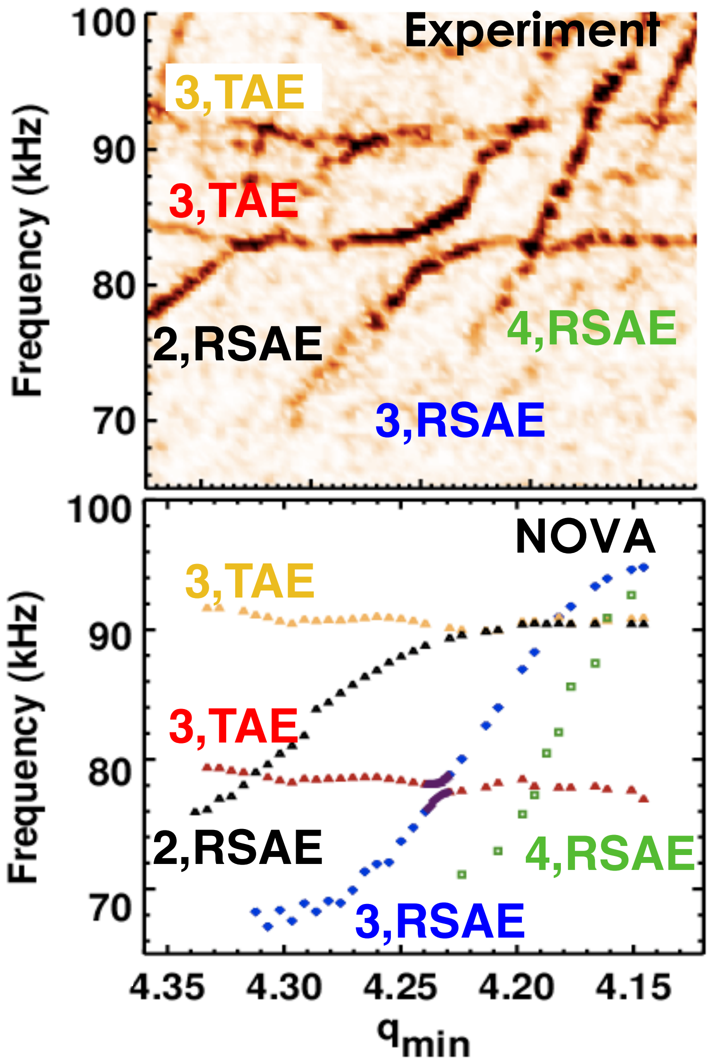
$$\omega_{TAE} \approx \frac{V_A}{2R}\left(\frac{n}{m+1/2}\right)$$

Reversed Shear Alfvén Eigenmodes (RSAE*)

- **Localized near *qmin***
- **Frequency sweeps upward as *qmin* decreases**

$$\omega_{RSAE} \approx \frac{(m - nq_{\min})V_A}{q_{\min}R}$$

Spectral Evolution of AE Activity is Reproduced Well by the Ideal MHD Code NOVA



- NOVA* solves for linear ideal MHD eigenmodes using experimentally measured profiles

- Modeling is extremely sensitive to range of q_{min} (shown range is only $\delta q/q$~5%)

*Cheng CZ, *Phys. Rep.* **211**, 1 (1992)

So, do we understand the landscape of modes?

- It is highly likely that the dominant energetic particle driven modes in ITER or in a reactor are already familiar to us

- The advent of internal fluctuation measurements has greatly enhanced our qualitative and quantitative understanding of the range of instabilities expected in a reactor

- The applicability of linear MHD theory to a wide range of observations facilitated early and close interaction between experiment and theory

Do we understand the landscape of modes?

Do we understand drive and damping?

Can these modes lead to significant transport and/or loss of alphas?

Can we control these instabilities?

Quantitative comparison on drive and damping is more challenging

• Multiple modes exist with similar frequency
  - need spatial structure measurements for positive ID
  - excellent example by T.E. Evans for GAE measurements on TCA

• Fast ion drive depends sensitively on particle distribution
  - need to measure fast ion profile/isotropy

• Additionally, theoretical tools are needed to self consistently evaluate the mode structure and damping
  - need to go beyond analytical estimates of non-ideal effects based on ideal mode structure
  - gyrokinetic codes

High Fusion Power Experiments on JET and TFTR did not Reveal Alfven Eigenmode Excitation: Why?

• 10.6 MW fusion power on TFTR, 94 (3 MW Pα)

• 16 MW fusion power on JET, 92

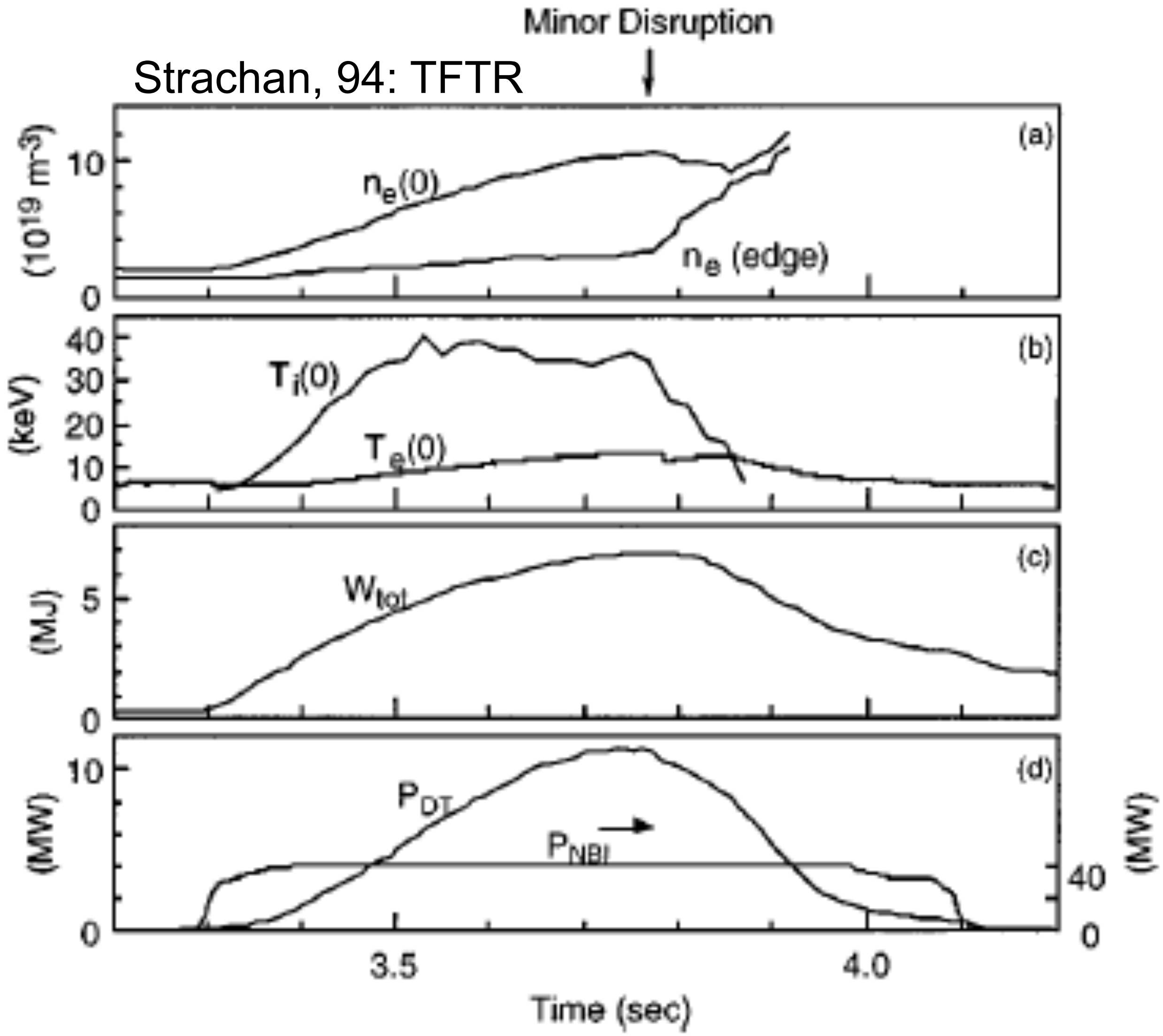
• Plenty of resonant alphas

• Why no modes?

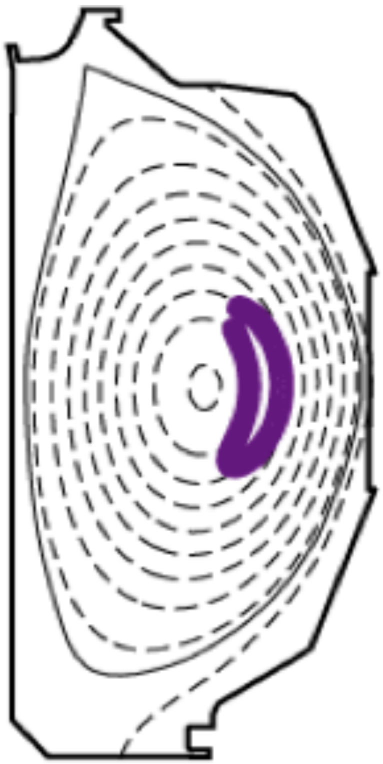
A. key role played by beam ion Landau damping

B. gap modes too far from core alpha drive in normal magnetic shear plasmas

Strachan, 94: TFTR



A micro-tutorial: Wave Particle Resonance Condition in Tokamaks

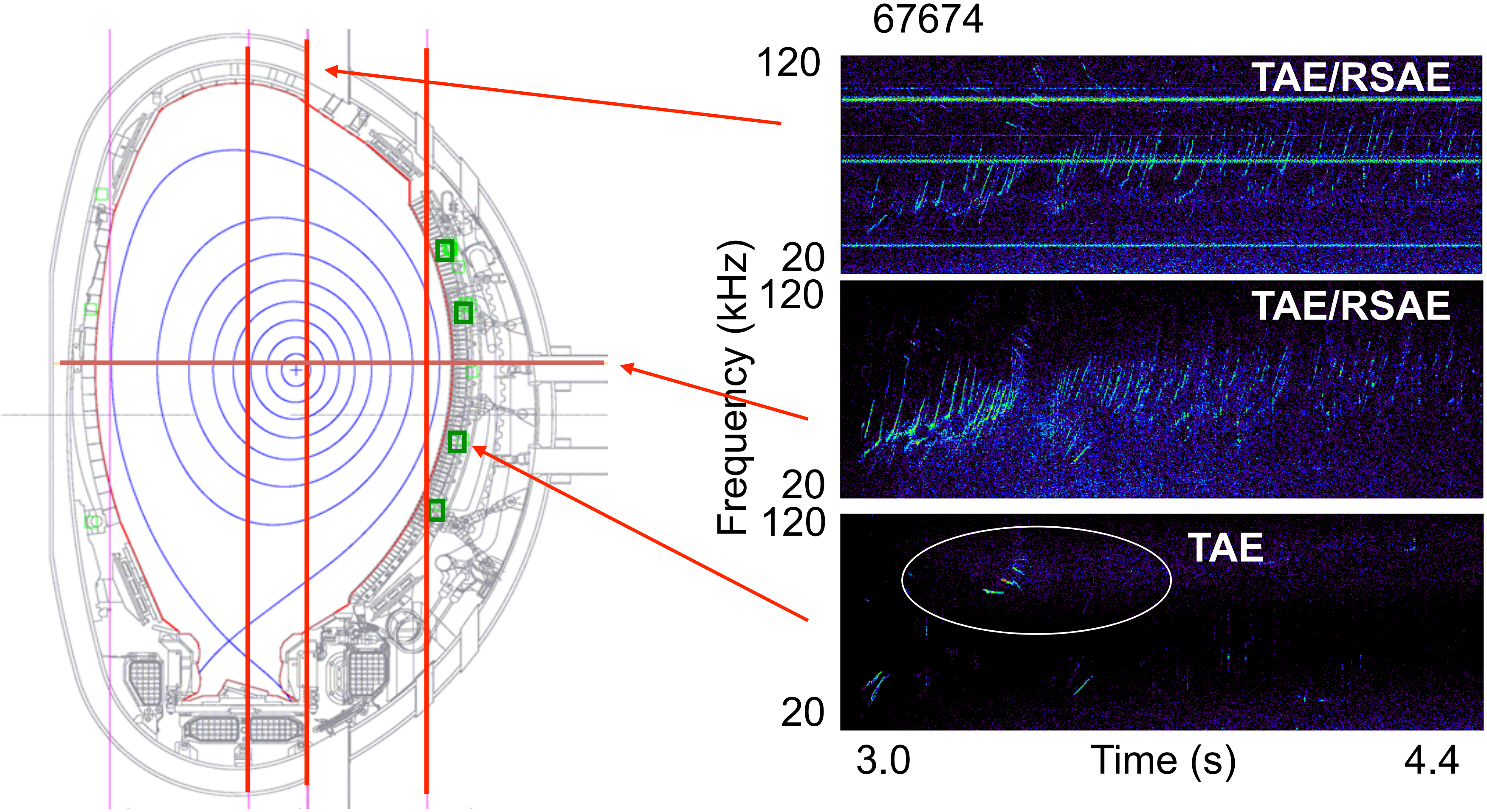


- Energy exchange requires $\oint V \cdot E \neq 0$
- For low frequency modes the electrons short out the parallel field, $E_{||}=0$; ideal MHD
- Gyromotion does not contribute for $\omega_{MHD} << \omega_c$
- Dominant energy exchange through drift (averaged) motion perpendicular to field lines,
- Product of drift velocity harmonics (l) and mode harmonics (m) leads to sideband resonance condition for passing particles m→ m+l, m-l ;

$$\omega = k_{||}V_A = (k_{||} \pm l/qR)V_\alpha \;:\; l = 1,\, 2,\, \ldots$$

- significance: resonances can occur for $V_\alpha < V_A$
- For TAE, $V_\alpha = V_A/3$ or V_A; thermal/beam ion interaction is now possible at high field
- For a slowing down distribution, Landau damping can be overcome with a sufficiently peaked pressure gradient.

TAEs observed in reverse magnetic shear JET plasmas for $V_{||} \approx 0.16\ V_A$! Validates role of high order resonances

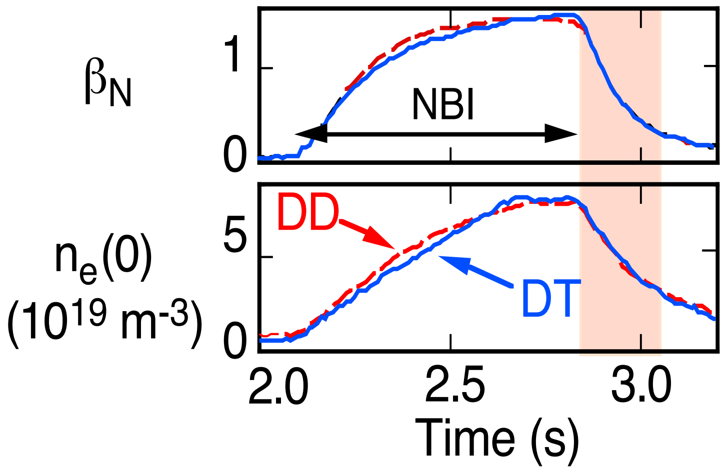


- **Note: resonance drives or damps mode according to competition between velocity gradient and pressure gradient**

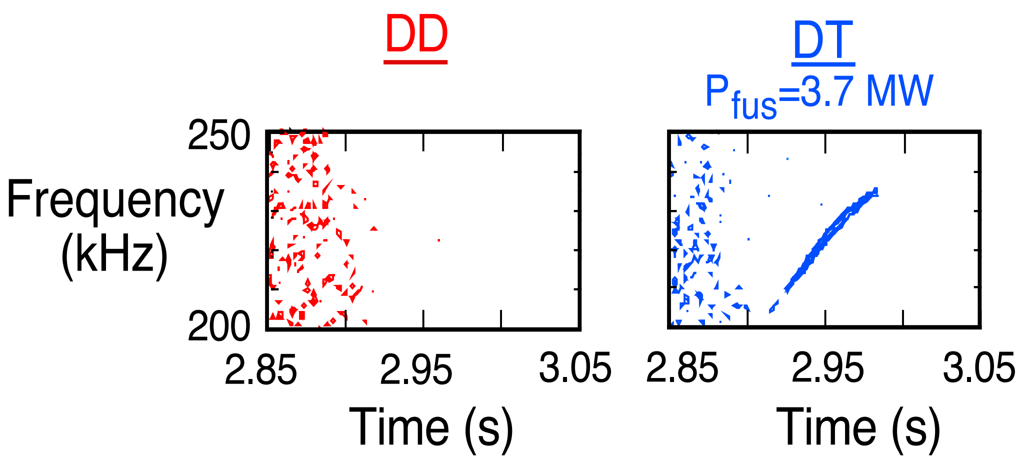
Rapid Discovery of Damping Mechanisms Brought Theory into Better Alignment with Experiment on TFTR, DIII-D

- Electron Landau damping, Fu & VanDam, 89
    - early damping estimates based mainly on this term
- Electron collisional damping, Gorelenkov & Sharapov, 91
- Thermal ion Landau damping, Betti & Friedberg, 92
- Continuum damping (mode frequency intersects the continuum)
    - Zonca & Chen, 92
- Radiative damping (mode frequency is just above the continuum) Mett & Mahajan, 92
- Beam ion Landau damping (basically ion Landau damping for a slowing down beam ion distribution) Fu, 96
    - led to proposal to investigate afterglow in DT experiments

Integrated understanding of drive and damping led to new Experiments in TFTR DT motivated by theoreticians



Magnetic Fluctuation Data



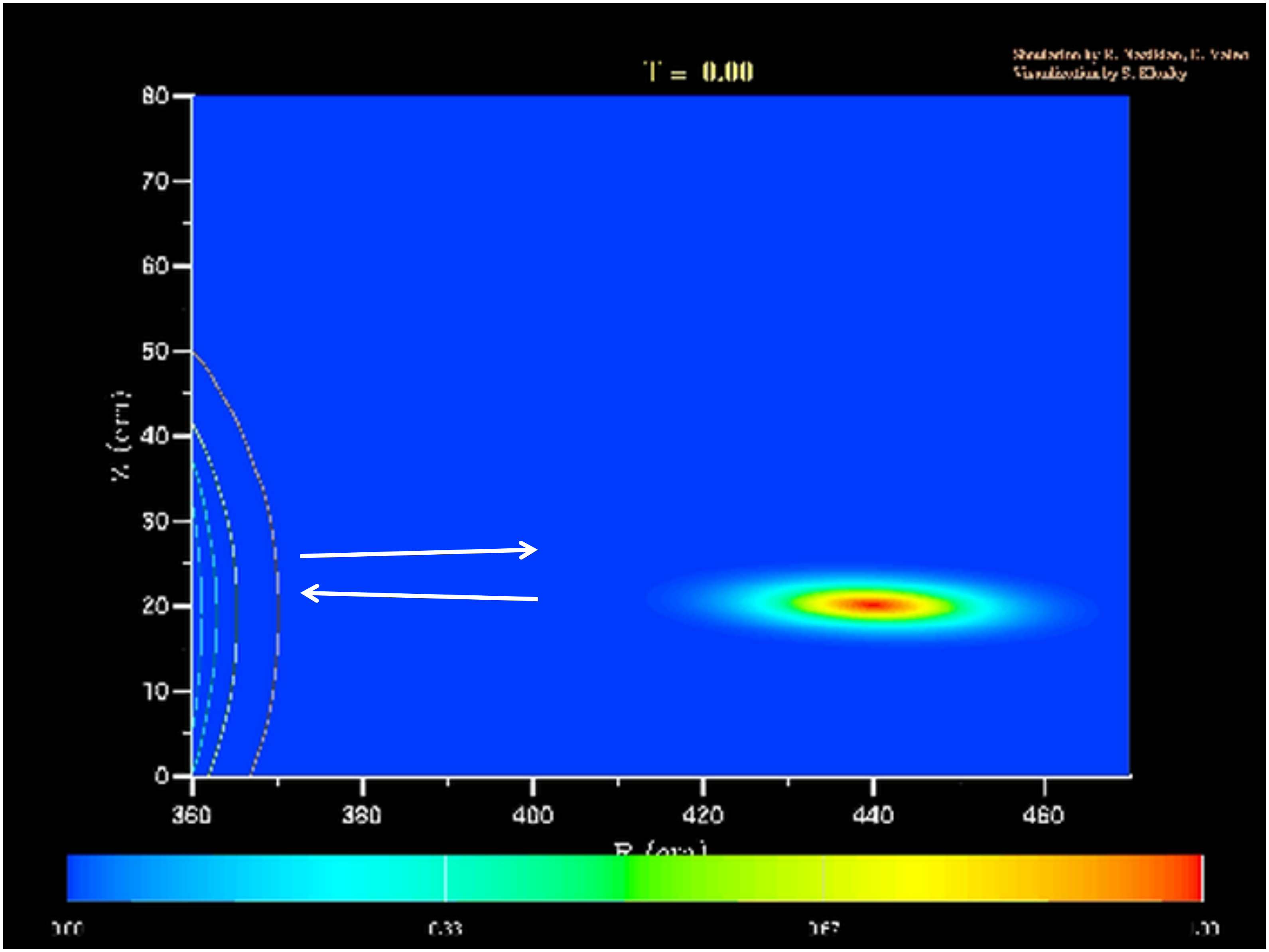
- Theorists recipe: (Fu, 96)

1. Reduce magnetic shear to produce more core localized modes
2. Look in the afterglow where beam ion damping is negligible
3. Alphas should not slow down as fast as beam ions, may excite the modes

- Modes observed:
  - Nazikian & Fu, 96

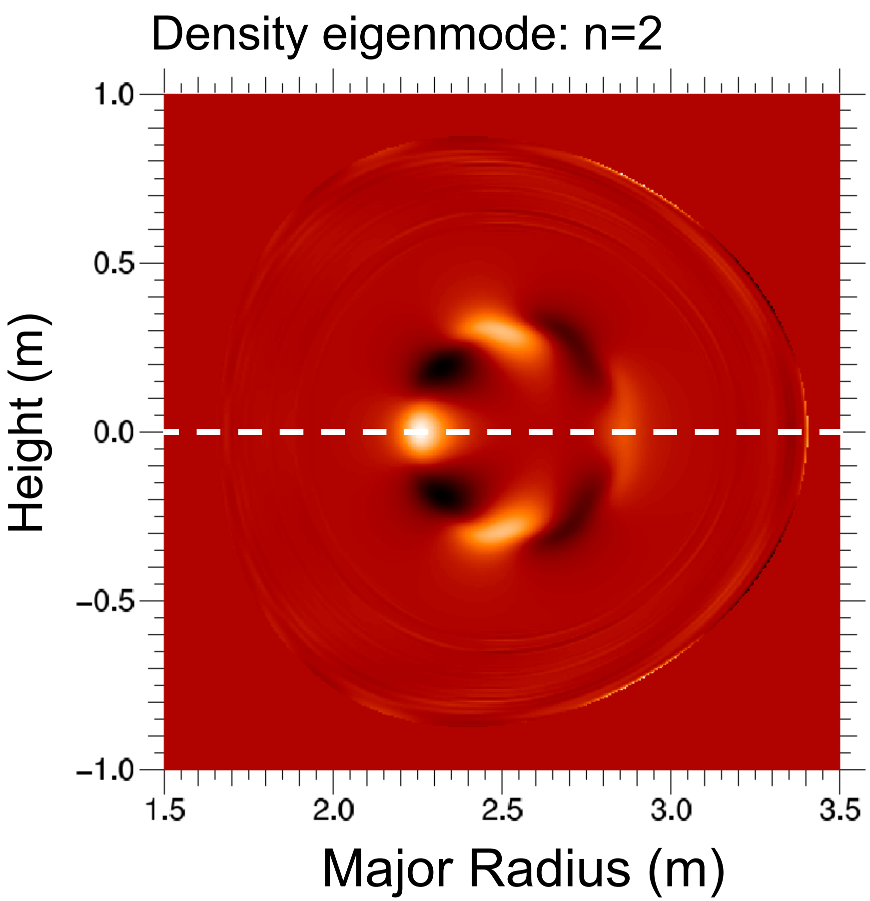
- Note: alpha pressure ~ 1/4 of peak value obtained in best DT shots

Reflectometry (microwave radar) used to verify the core localization of the alpha driven modes in TFTR DT Plasmas

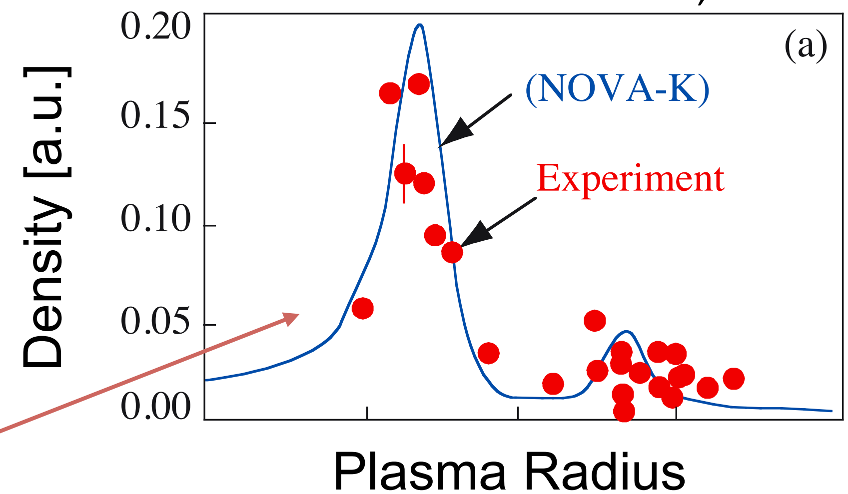


E. Valeo

Internal mode structure using reflectometry validates RSAE theory & NOVA simulation in TFTR DT experiments



Nazikian, 2003



- Mode localization to alpha source profile is key to mode drive
  - confirms theorists recipe
- Observe a mixture of predicted (TAE) and <u>unanticipated</u> (RSAE) modes
- Serious discrepancy with TAE theory only resolved after the understanding of RSAEs on JET several years later

So, do we understand Drive and Damping?

• High order resonances for mode drive validated using neutral beam injection in high field plasmas in DIII-D and JET

• Complex theoretician's recipe for the excitation of alpha driven TAEs in TFTR indicates integrated understanding of damping and drive mechanisms

• It is highly likely that the dominant damping mechanisms in ITER or in a reactor are already familiar to us

• We are likely in the right order of magnitude in our predictions for ITER

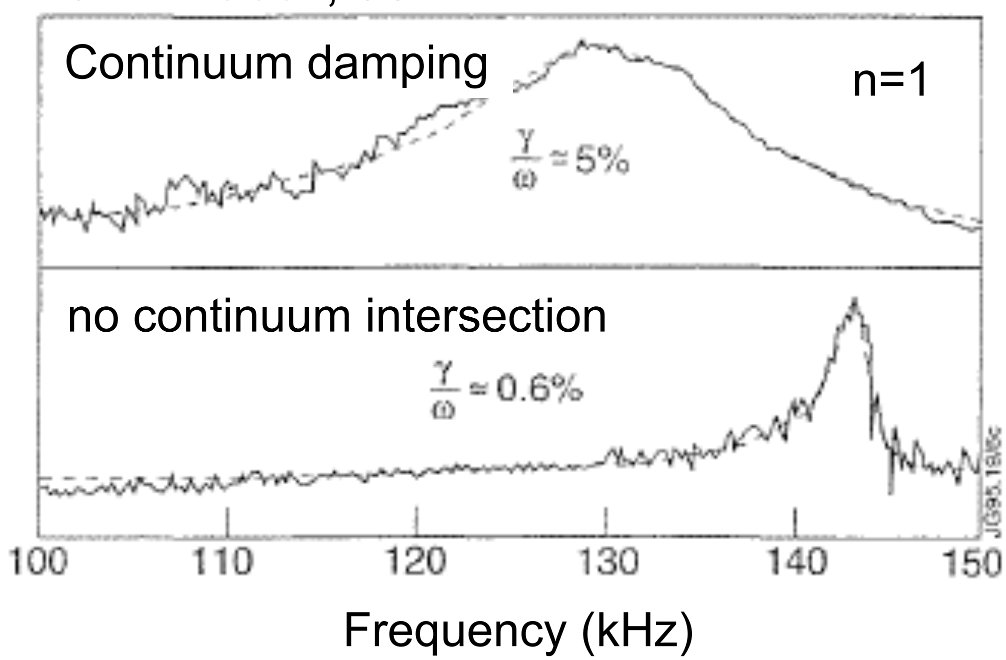
• However, it is difficult to validate separate components of the damping and drive

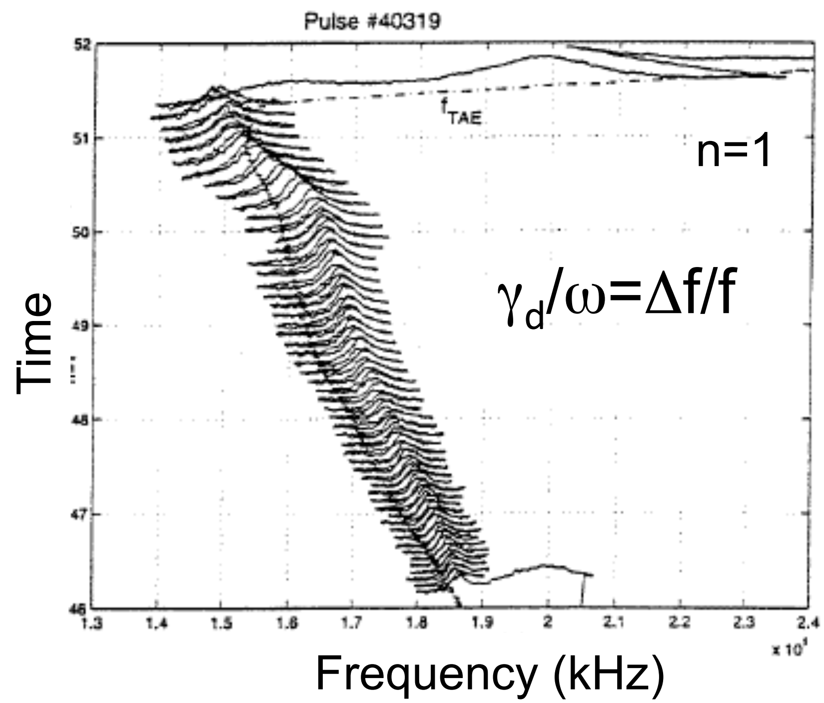
• Another approach is to measure the net damping of stable modes using antenna excitation (JET) and compare to calculated fast ion drive – Fasoli, 95

• Note: similar to antenna method used to drive stable KAWs and GAEs on TCA

Antenna Measurement of the Resonance Width Identifies Continuum Damping for low-n TAEs on JET

JET: Fasoli, 95





- High damping rate is consistent with edge continuum damping (Lauber, 2005)

- Issues of interpretation do arise; requires internal mode measurement and accurate equilibrium profiles to resolve

- Coupling to core localized modes is more challenging; requires mode overlap with the antenna pattern: high-n array developed on JET (Testa, Fasoli)

Do we understand the landscape of modes?

Do we understand drive and damping?

Can these modes lead to significant transport and/or loss of alphas?

Can we control these instabilities?

Can these modes lead to significant transport and/or loss of alphas?

• Nonlinear dynamics and fast ion transport is still at a qualitative level of comparison between theory and experiment

• Quantitative predictions of fast ion transport levels in unstable ITER regimes are premature

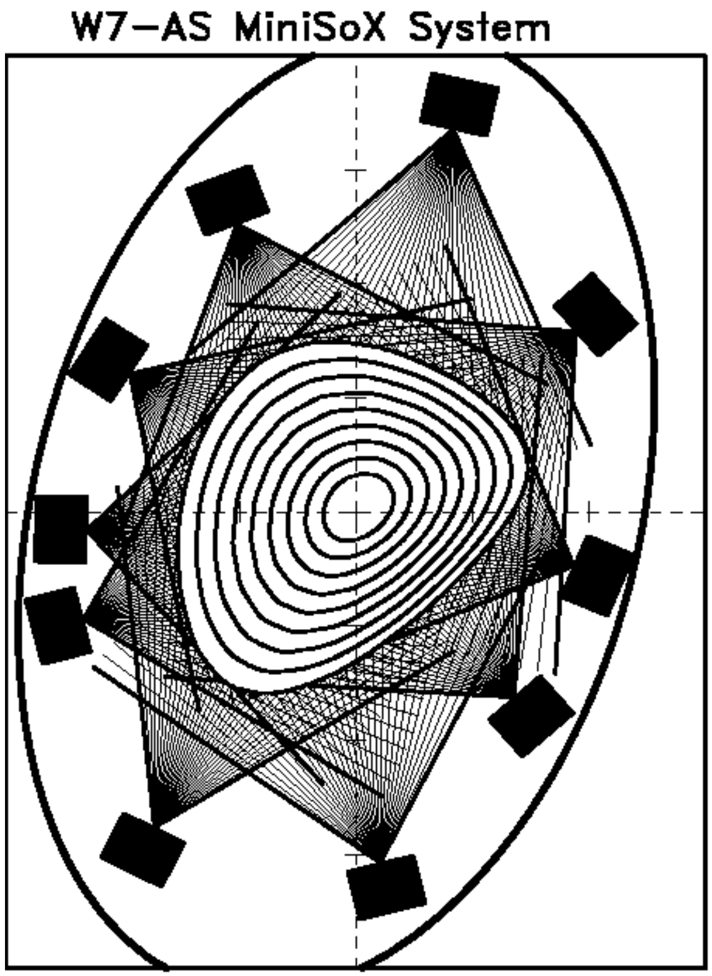
• As with mode damping, quantitative theory-experiment comparison requires

- internal mode amplitude and structure measurements
- fast ion distribution and loss measurements

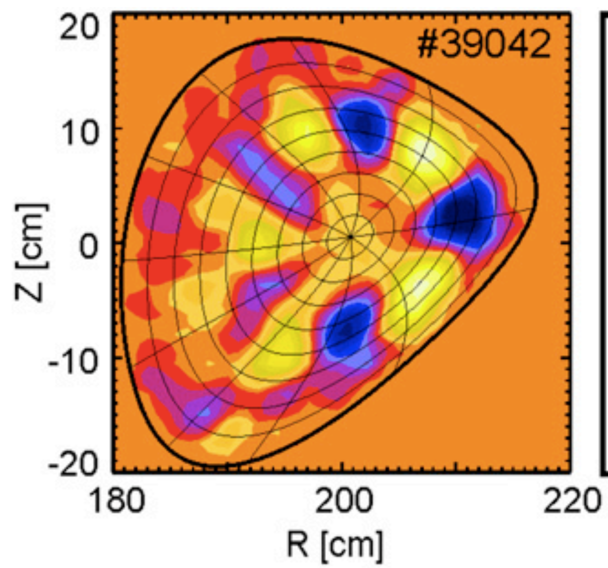
• Additionally, theoretical tools are needed to evolve the mode amplitude/ structure self consistently with the fast ion distribution

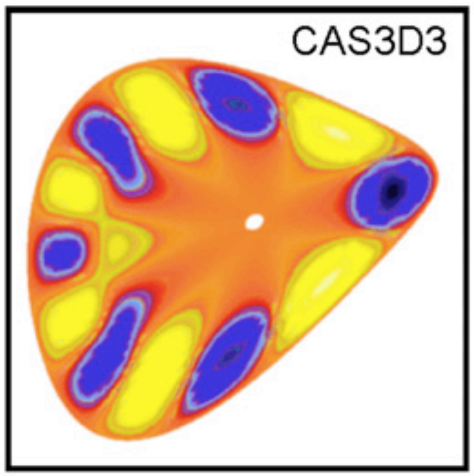
- first on the instability time scale for transient events
- more challenging; on the slowing down time scale for time average transport levels

Detailed TAE mode structure measurement using X-ray emission and comparison to theory on W7-AS



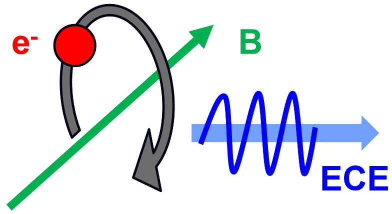
Weller, 94





- CAS3D3 calculation of TAE (right) qualitatively consistent with measurement (left)
  - GAE also seen
- Discrepancy may be due to accuracy of equilibrium reconstruction
- X-ray detection works best for large amplitude modes such as seen on W7-X

Radial Mode Structure Measured with ECE on DIII-D: Impressive agreement with ideal MHD theory



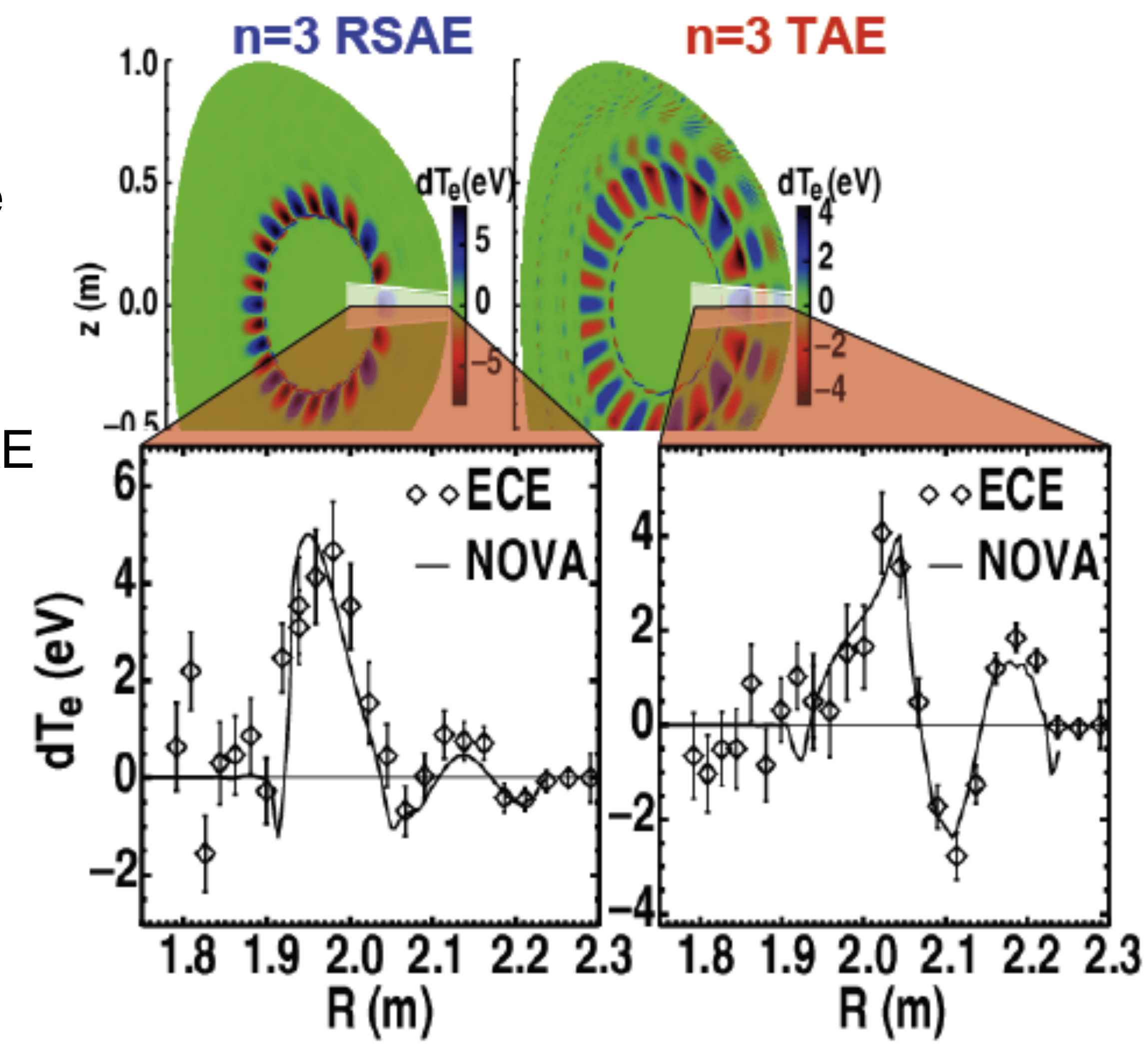
- NOVA code used to calculate TAE, RSAE radial structure, scaled to measurement

- Radial structure of RSAE, TAE resolved using electron cyclotron emission

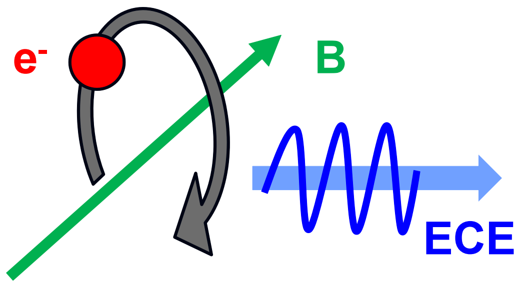
- RSAE is more core localized than TAE, as expected

- Detailed measurement of mode structure and amplitude can be used to compute transport

VanZeeland, 2006

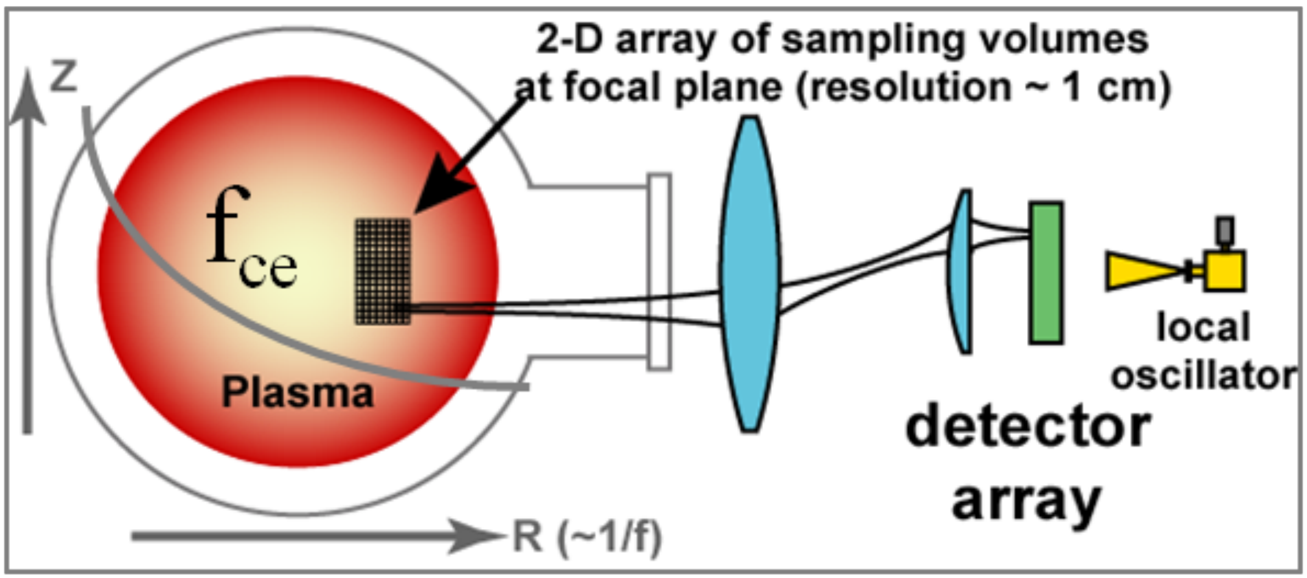


2-D Electron Temperature Imaging is a break through diagnostic



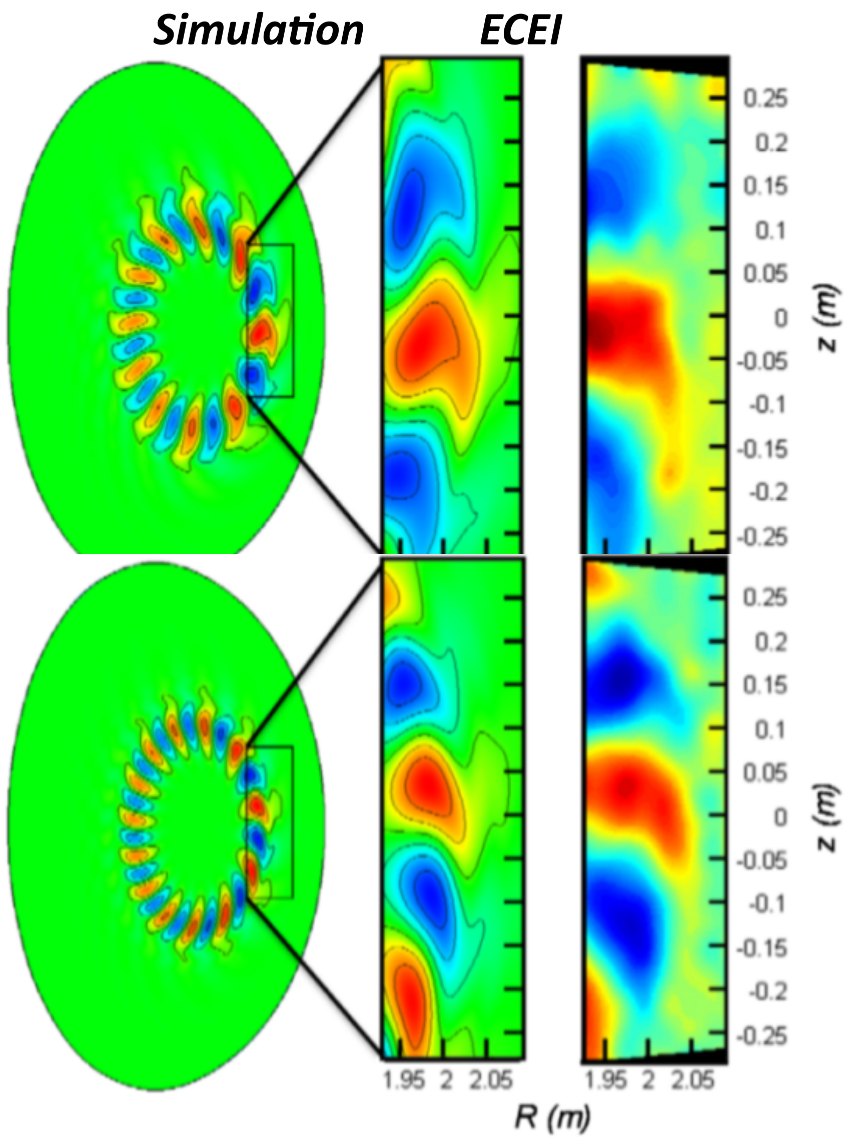
Radial localization is determined by cyclotron resonance
Vertical and horizontal localization are determined by view

- **Poloidal cross-section**
- **Up to 1 cm^2 spatial resolution**
- **Real-time T_e down to <1% with μ-sec time resolution**



UCI, PPPL, POSTEC,…

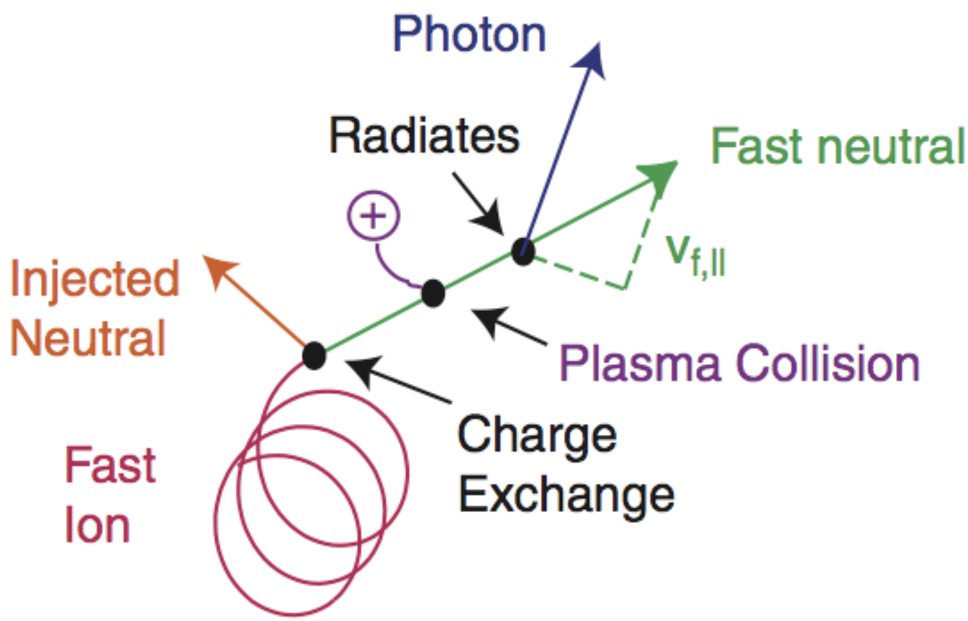
ECEI provides validation of 2-D Structure of RSAEs in DIII-D and AUG

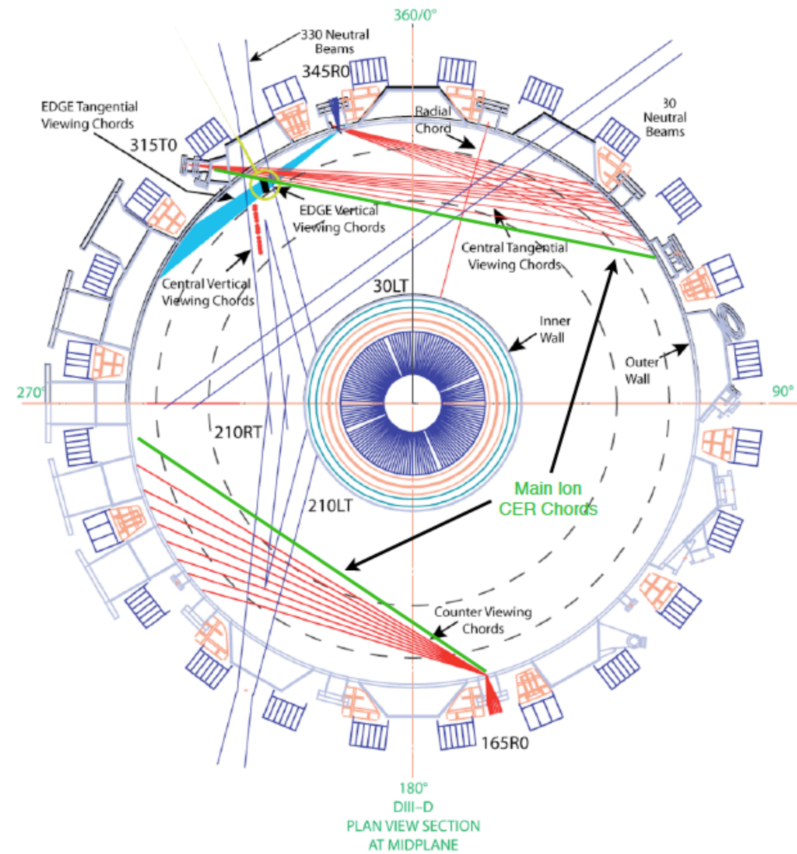


- Simulation using TAEFL code (D. Spong)
- Shearing of mode due to fast ion pressure, not consistent with ideal MHD theory
- Local mode amplitude measurement and validation of mode structure allows quantitative transport analysis

B. Tobias, et al., Phys. Rev. Lett. (submitted Aug., 2010)

Fast-Ion D_α (FIDA) Diagnostic provides breakthrough measurement of fast ion profile in DIII-D, AUG, NSTX

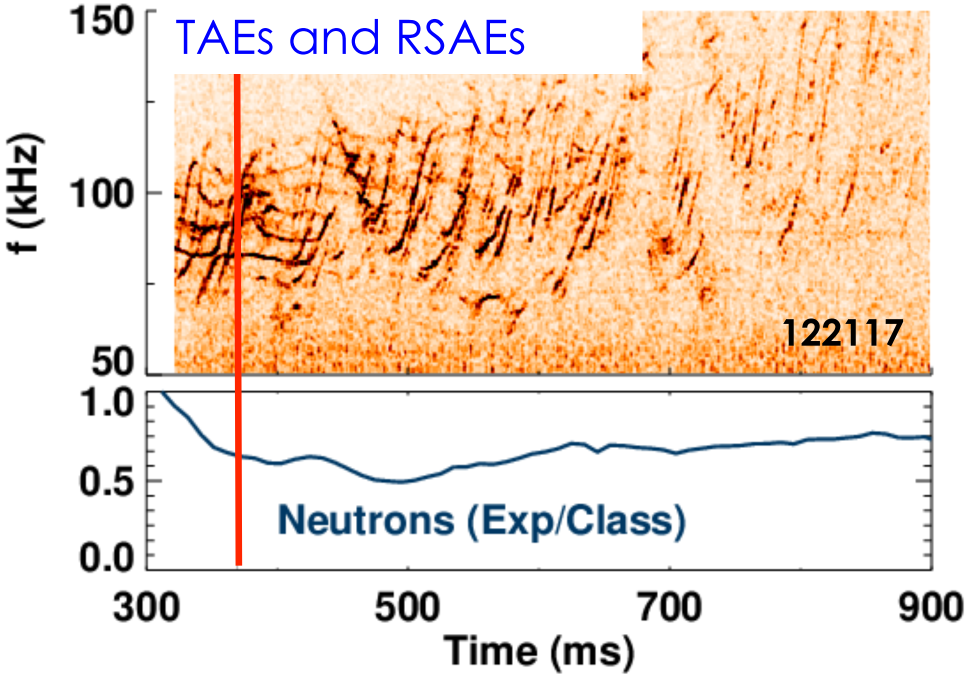


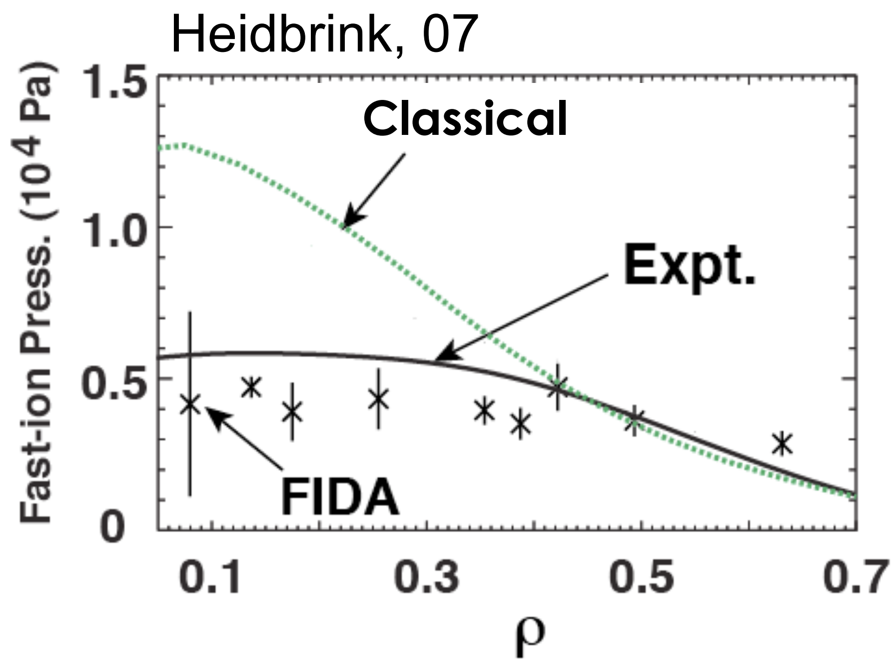


D-alpha spectrum includes:
(i) Beam emission spectrum
(ii) Thermal ion charge exchange emission with beam neutral
(iii) Beam ion charge exchange emission with beam neutral
(iv) Cold D-alpha line for D beyond plasma (very narrow)

Heidbrink, PPCF 46 (2004) 1855; Luo, RSI 78 (2007)

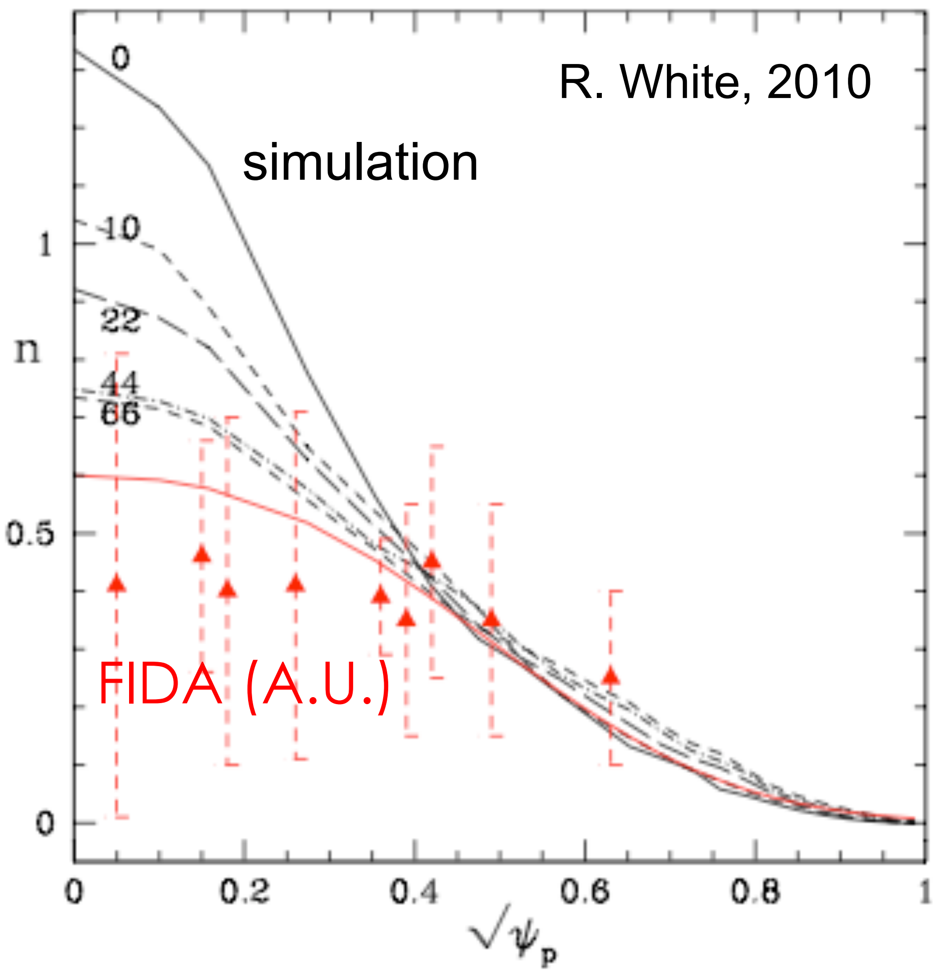
Flattening of the Central Fast Ion Density during AE activity is observed using active beam spectroscopy (FIDA)





- Neutral deuterium is injected into plasma and ionizes, drives modes
- Interferometer measurement of modes during beam injection (left)
- Spatial flattening of fast ion population is observed (right)

New guide center simulations using measured mode amplitudes on DIII-D show significant flattening, consistent with experiment



- 12 distinct modes, over 100 poloidal harmonics and their measured mode amplitudes were used in the ORBIT simulations

- Simulations ran with sources and sinks till a steady state solution was obtained

- 66 ms simulation, 10^4 mode periods

- strong fast ion flattening obtained

- Note: this is not a self consistent simulation, only fixed mode amplitudes

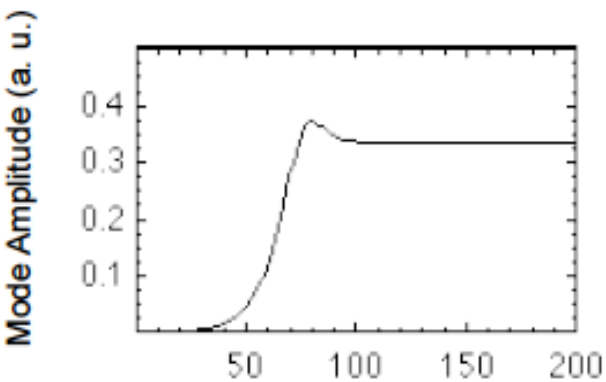
- These calculations represent the state of the art in the quantitative comparison of theory and experiment for fast ion transport
  – Similar calculations for NSTX

- THIS IS NOT A PREDICTIVE MODEL

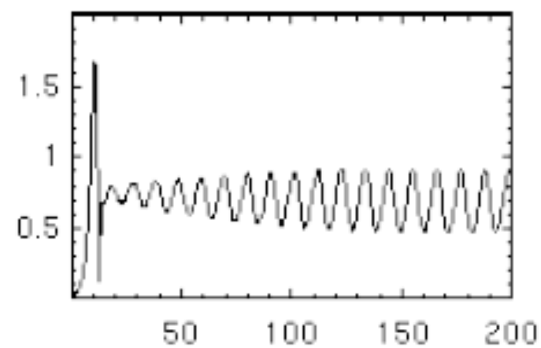
Progress towards predictive understanding: Analytical model for <u>single</u> unstable mode yield complex behaviors

Berk, Breizman, 92, 98

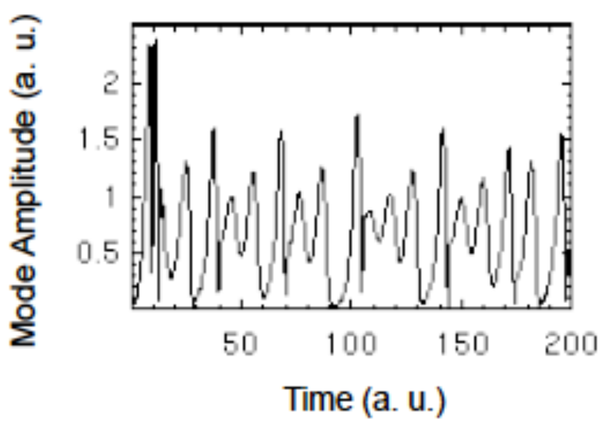
(1)-saturated mode



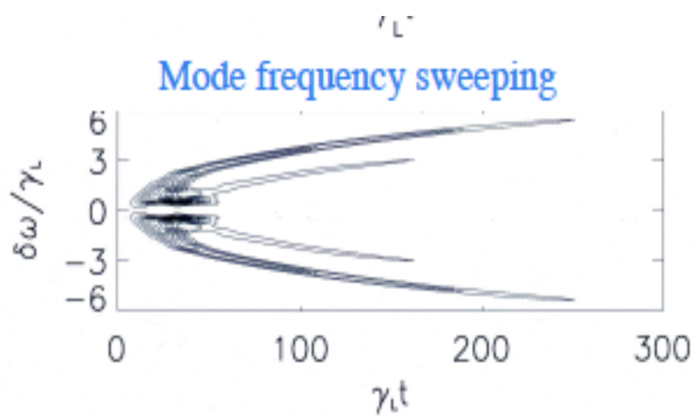
(2)-limit cycle



(3)-chaotic nonlinear state



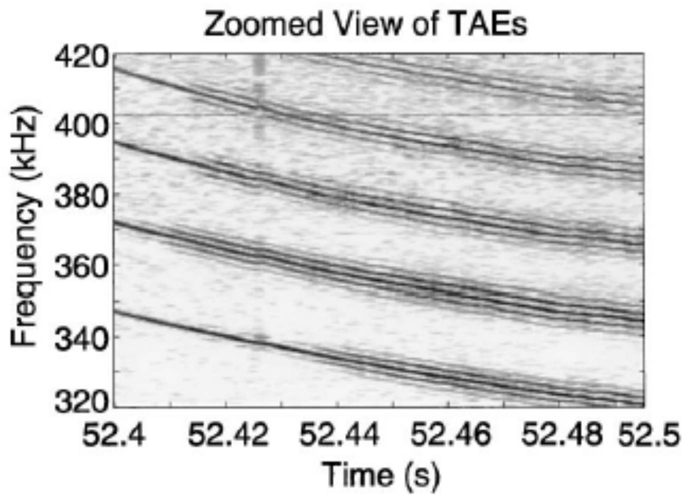
(4)-explosive growth

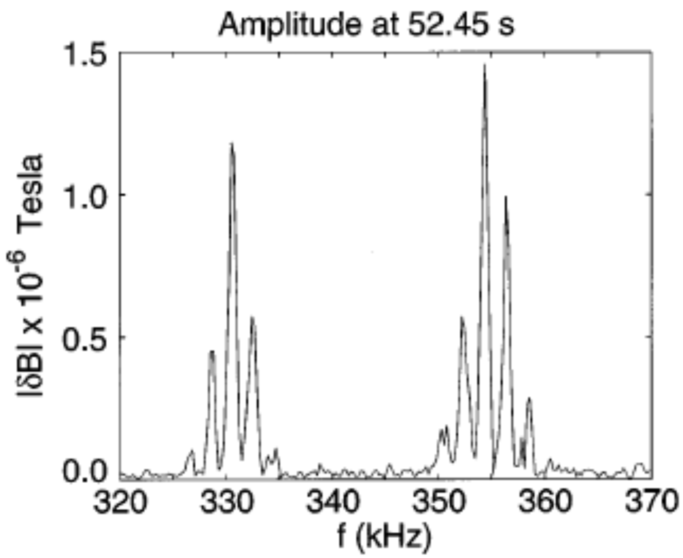


- Resonant part of phase space flattens as mode grows
- Mode would damp away if distribution flattens
- However, energetic particle drive is restored through collisional processes
- Interaction between growth, damping and collisons results in complex dynamics

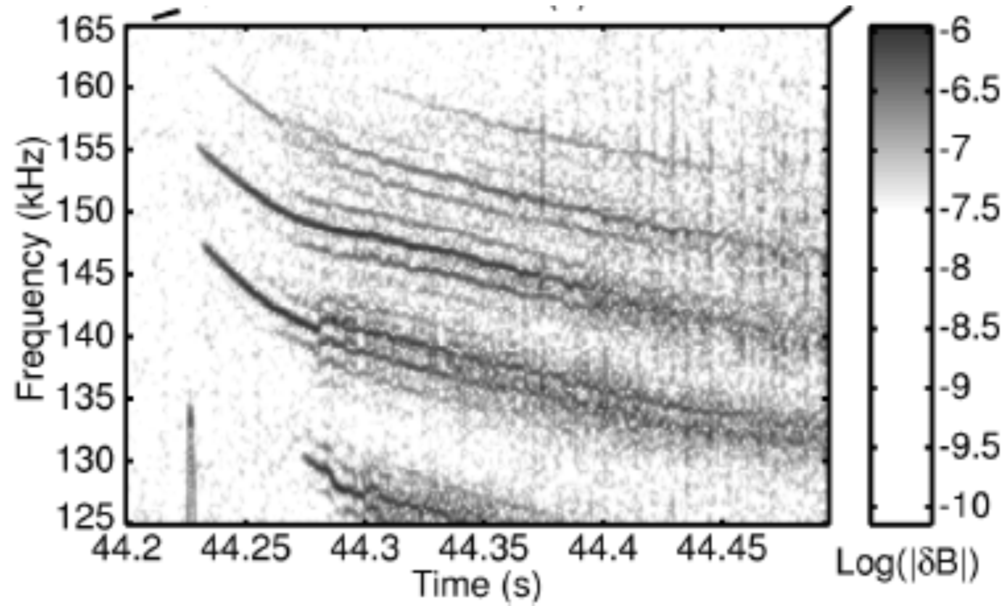
Observed behaviors of TAEs in JET and MAST qualitatively consistent with nonlinear single mode theory

1 & 2 seen on JET: Fasoli, 98

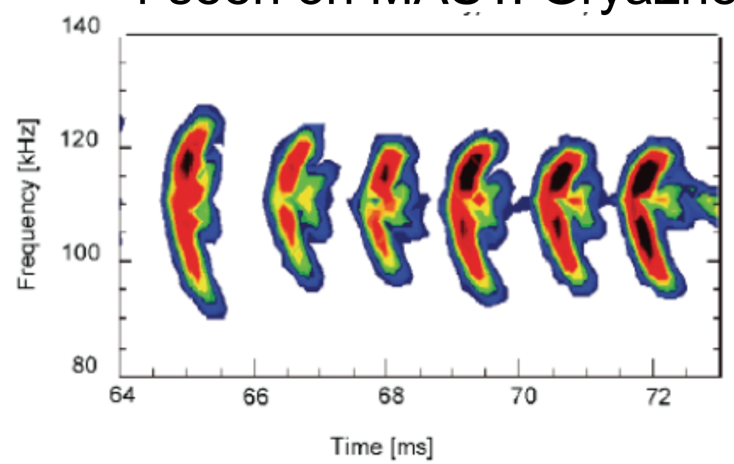




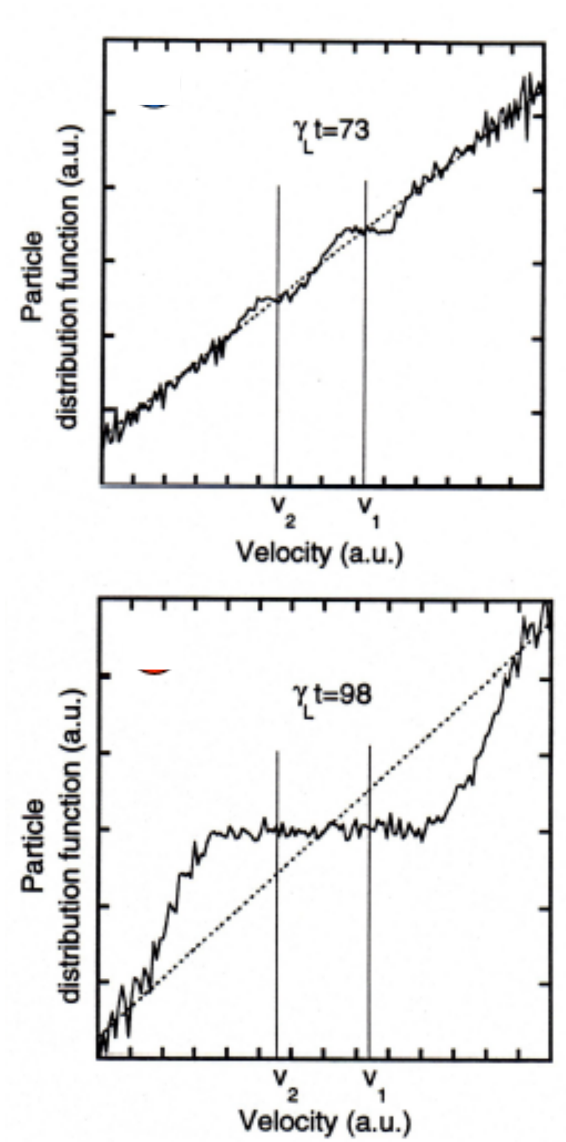
3 seen on JET: Heeter, 00



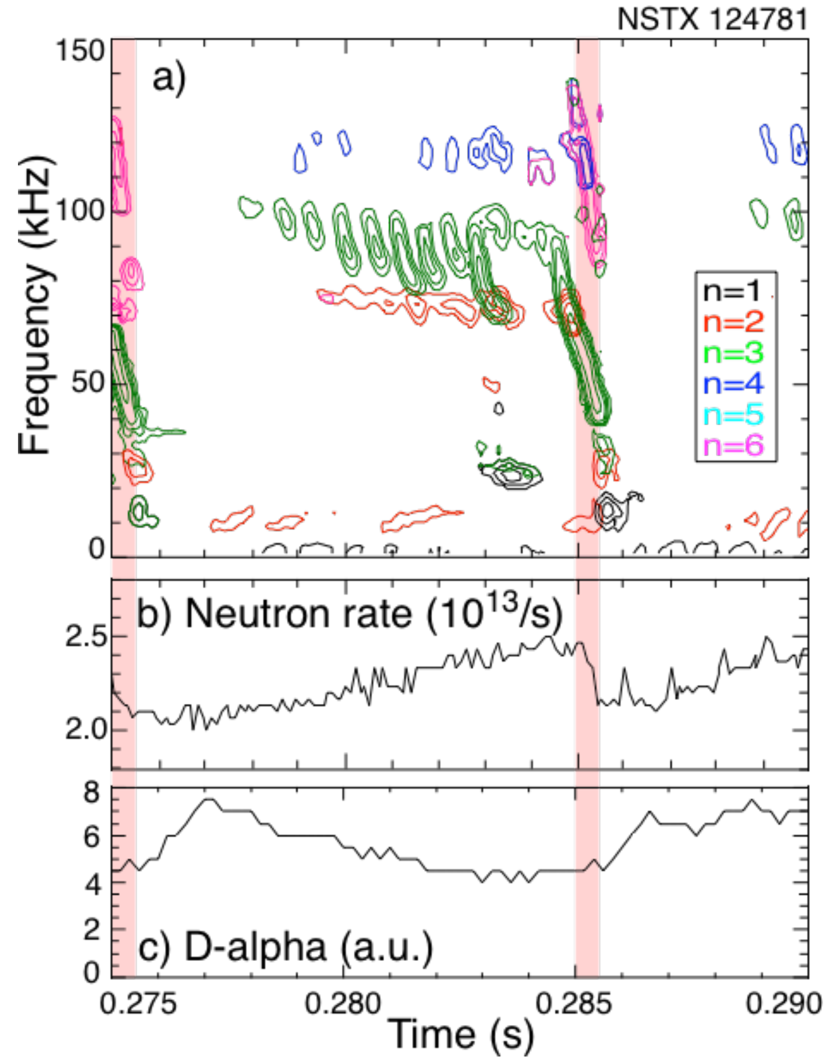
4 seen on MAST: Gryaznevich



Multimode dynamics less well understood: resonance overlap may produce intense mode bursts and loss of fast ions



NSTX: Fredrickson 04



ITER is a multimode dynamical system: Predictive understanding requires major theoretical and experimental advances

- Continued improvement in core fluctuation and fast ion measurements is essential for developing predictive understanding
  - need quantitative profile measurements
- Fixing the mode amplitudes to experimental averages yields significant beam ion transport in DIII-D
  - not a self consistent calculation
  - does not capture the dynamical behavior of the modes
- Analytic models reveal complex transient behaviors of Alfvénic modes qualitatively consistent with observations on JET, MAST and NSTX
- The near term challenge is to identify these complex single mode and multimode transient behaviors through self consistent simulation
- The longer term challenge is to self consistently evaluate the time average transport produced by these modes on a slowing down time scale

Do we understand the landscape of modes?

Do we understand drive and damping?

Can these modes lead to significant transport and/or loss of alphas?

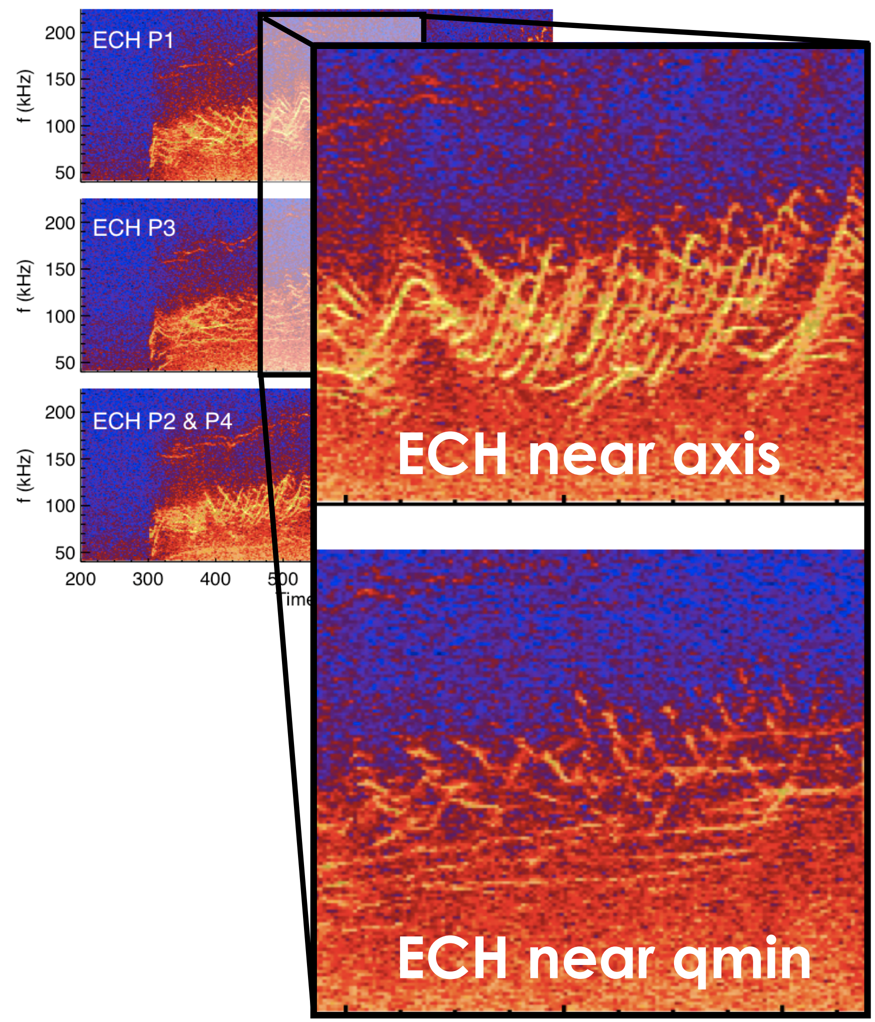
Can we control these instabilities?

ECH applied to Radius of q-min suppresses RSAE activity, leads to quiescent core on DIII-D

- For case with suppressed RSAEs, TAEs from the RSAE to TAE transition remain

- Global TAEs also appear in case with suppressed RSAEs

- Physics of suppression not understood yet



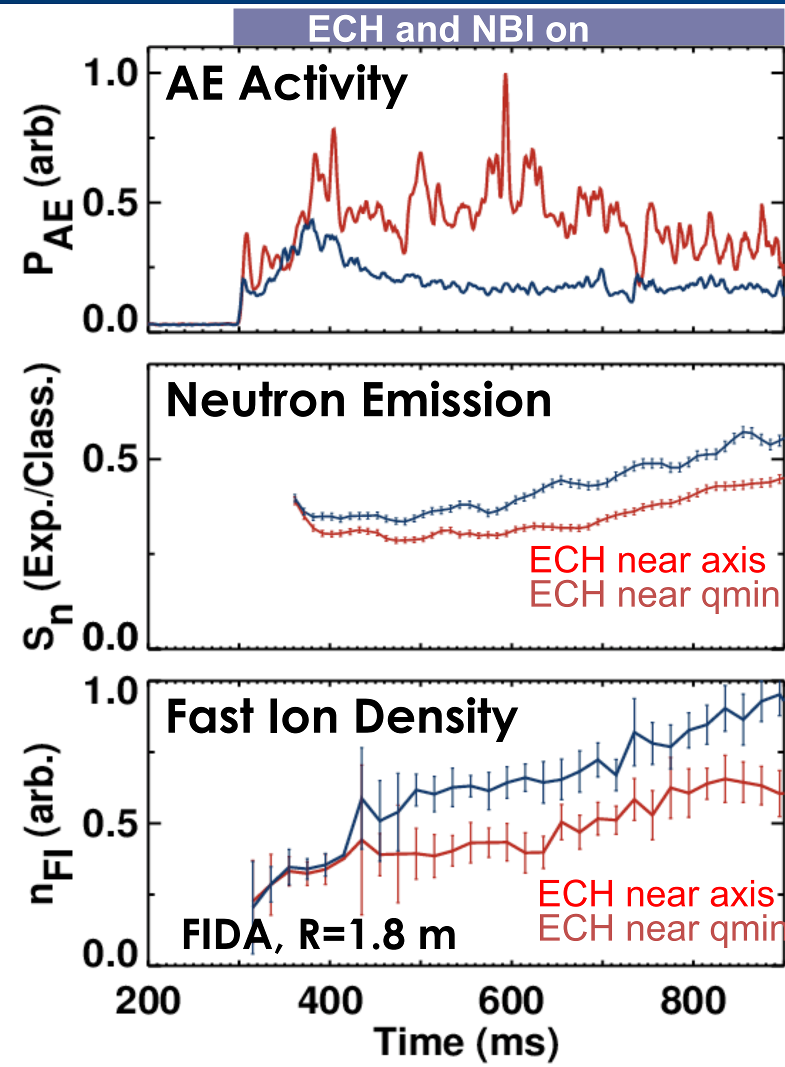
Discharges with Suppressed RSAE Activity Have Reduced Fast Ion Transport in DIII-D

- Neutron emission scaled to classical TRANSP predictions (S_n) shows large deficit in all cases
- S_n deficit is least in cases with reduced AE activity

FIDA* (Fast Ion D-alpha) ~ charge exchange measurement of fast ion density (nFI)

- Central n_{FI} is larger when AE activity is weaker

*W.W. Heidbrink, *et.al.*, *PPCF*, **46** (2004),



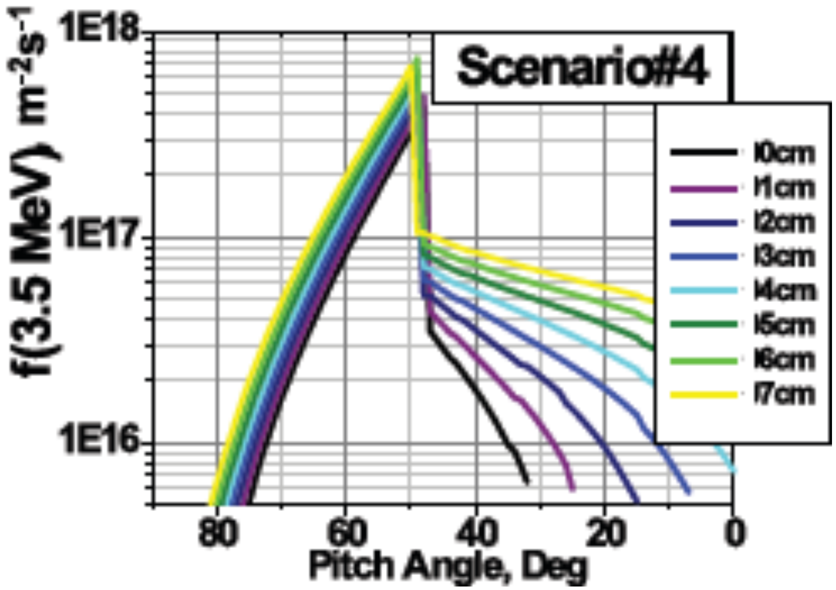
So what do we know?

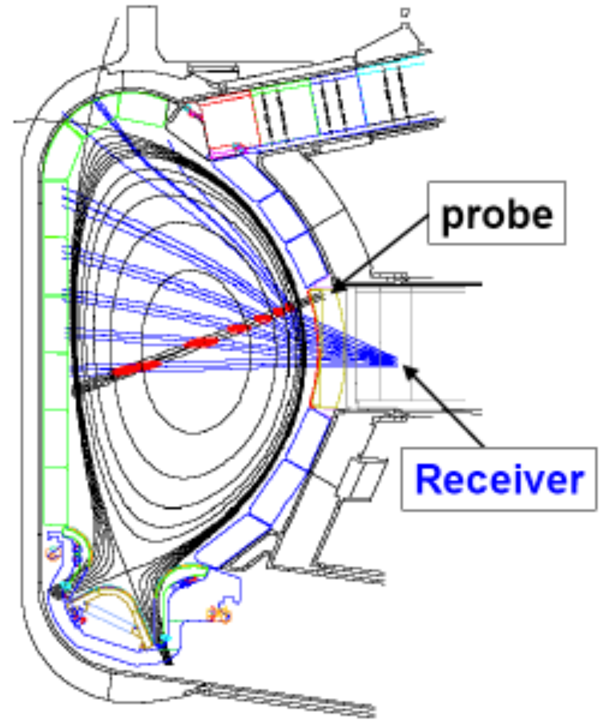
- Do we understand the landscape of modes?
  - No major surprises expected in ITER
- Do we understand drive and damping?
  - Within an order of magnitude, yes
  - Improvement is needed with (i) mode structure measurements, and (ii) kinetic theory of linear eigenmodes in realistic geometry
- Can these modes lead to significant transport and/or loss of alphas?
  - Yes, this is observed in present experiments
  - No reliable predictions for unstable ITER regimes
  - quantitative internal measurements of fast ion population, mode structure needed
  - Advances required in self consistent simulation
- Can we control these instabilities?

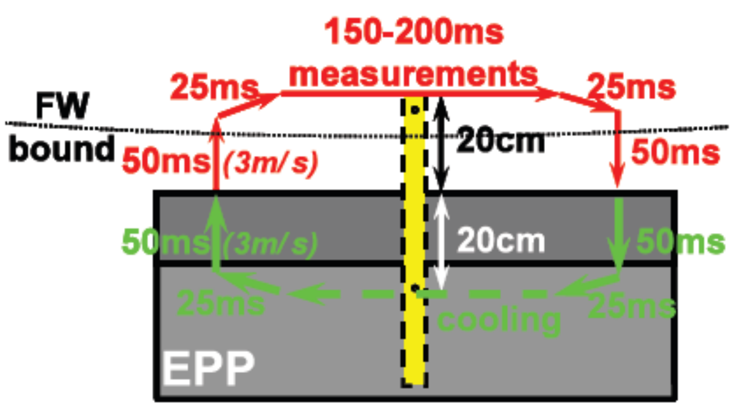
So what do we know?

- Do we understand the landscape of modes?
- Do we understand drive and damping?
- Can these modes lead to significant transport and/or loss of alphas?
- Can we control these instabilities? This research is still early stage.
  - Localized ECH has effect, not sure why
  - Modification of edge continuum can be effective for low-n modes
  - Enhanced ion Landau damping with low energy beam ions in plasma edge can suppress global modes

Last comment: ITER will require advanced diagnostics to contribute to fundamental understanding of AEs







Equatorial port plug

- Particle loss detectors
  - high heat load issues
- Confined alpha detectors
  - 60 GHz scattering system, below cyclotron resonance
- core AE detection
  - ECE, reflectometer, interferometer