# Energetic Particle Driven Modes Relevant to Advanced Tokamak Regimes

## Contributions from JET, DIII-D, Alcator C-MOD, JT-60U and TFTR-DT

Presented by R. Nazikian
Princeton Plasma Physics Lab.

20th IAEA Fusion Energy Conference
Thursday, November 4th, 2004
Vilamoura, Portugal

# Collective Oscillations of Energetic Particles in Fusion Plasmas

- Energetic particles are generally well behaved
  - *collective effects remain an uncertain area*

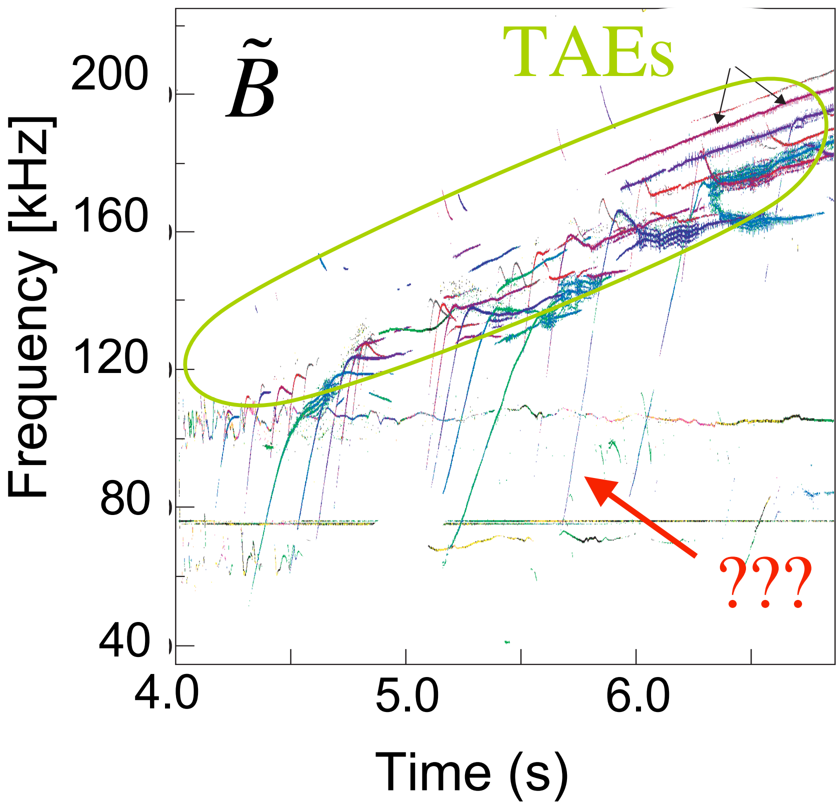
- Loss of energetic ions can have significant impact on device
  - *e.g. Jacquinot OV/2-2*

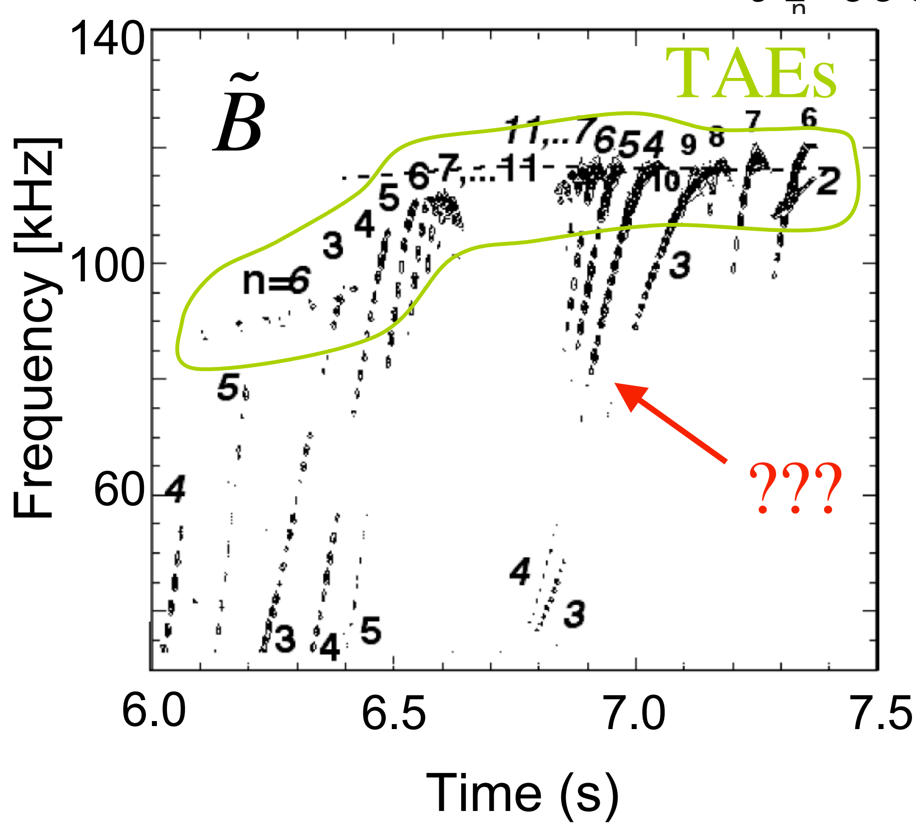
- Good news: TFTR and JET DT in positive magnetic shear
  - *classical behavior of 3.5 MeV alpha particles*

- Steady State confinement regimes less well characterized
  - *frequency sweeping modes seen in many experiments*
  - *outstanding issues in neutron emission in TFTR and DIII-D*

# Early Observation of Frequency Sweeping seen in Reverse Shear Plasmas: Edge Magnetic Data

JET S. Sharapov et al., Phys. Lett. **A289** (2001) 127 H. Kimura et al., Nucl. Fusion **38** (1998) 1303 JT-60U




- Toroidal Alfvén eigenmodes (TAEs) predicted in 1989, observed in 1991 - well understood.
- Frequency sweeping was a puzzle since mid 90s:
  - Resolution involved Japan - EU - US collaboration

# New Understanding Developed Through Close Collaboration with US, Japan and EU researchers

- Frequency sweeping modes are resonant shear Alfvén waves
  - *consistent observations across multiple facilities*

- Recent breakthrough in the use of core fluctuation diagnostics
  - *many core localized modes observed*

- Observation of a "Sea of Alfvén Eigenmodes" in plasma core in DIII-D with short poloidal scale : $n<40,\ k_\theta < 2cm^{-1}$

- Future directions, implications for ITER diagnostics

# New Understanding Developed Through Close Collaboration with US, Japan and EU researchers

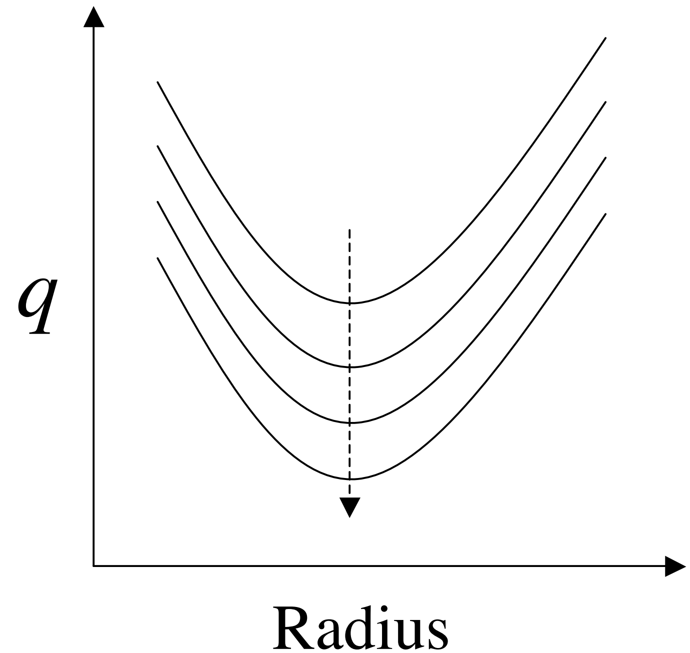
- Frequency sweeping modes are resonant shear Alfvén waves
  - *consistent observations across multiple facilities*

- Recent breakthrough in the use of core fluctuation diagnostics
  - *many core localized modes observed*

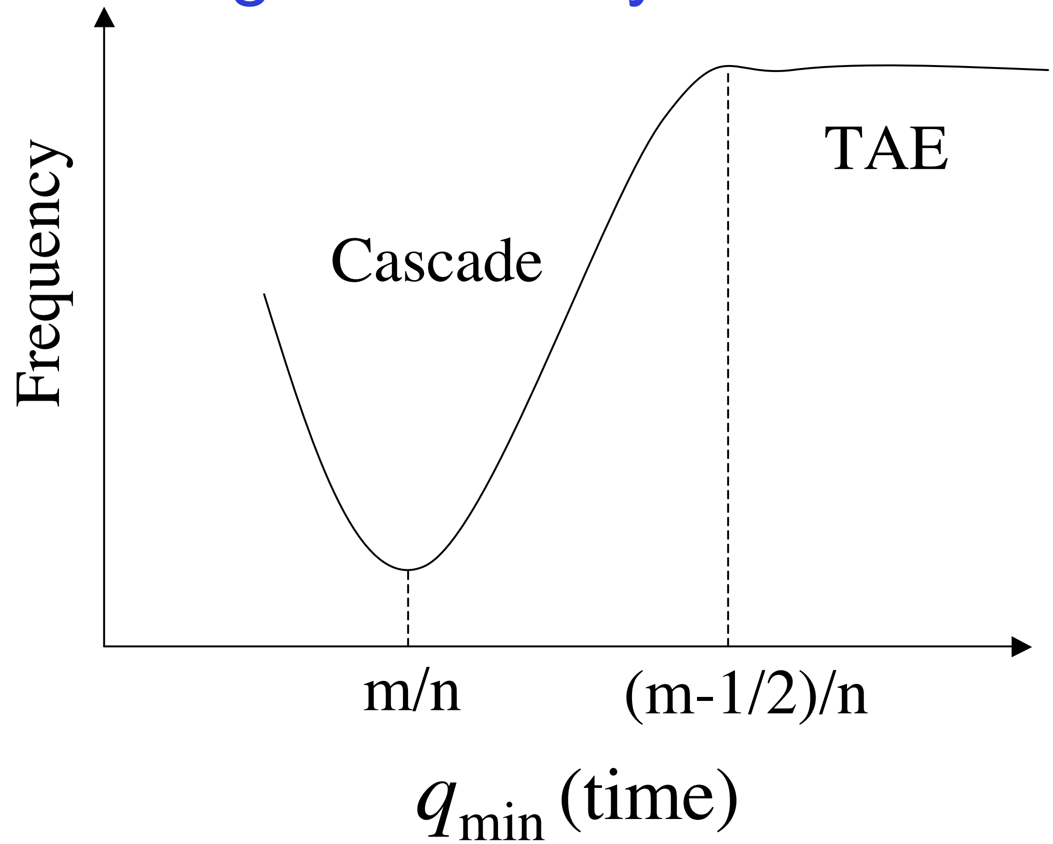
- Observation of a "Sea of Alfvén Eigenmodes" in plasma core in DIII-D with short poloidal scale : $n<40$, $k_\theta < 2cm^{-1}$

- Future directions, implications for ITER diagnostics

# Prediction: Frequency Sweeping *Very Sensitive* to the Evolution of Minimum Magnetic Safety Factor




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

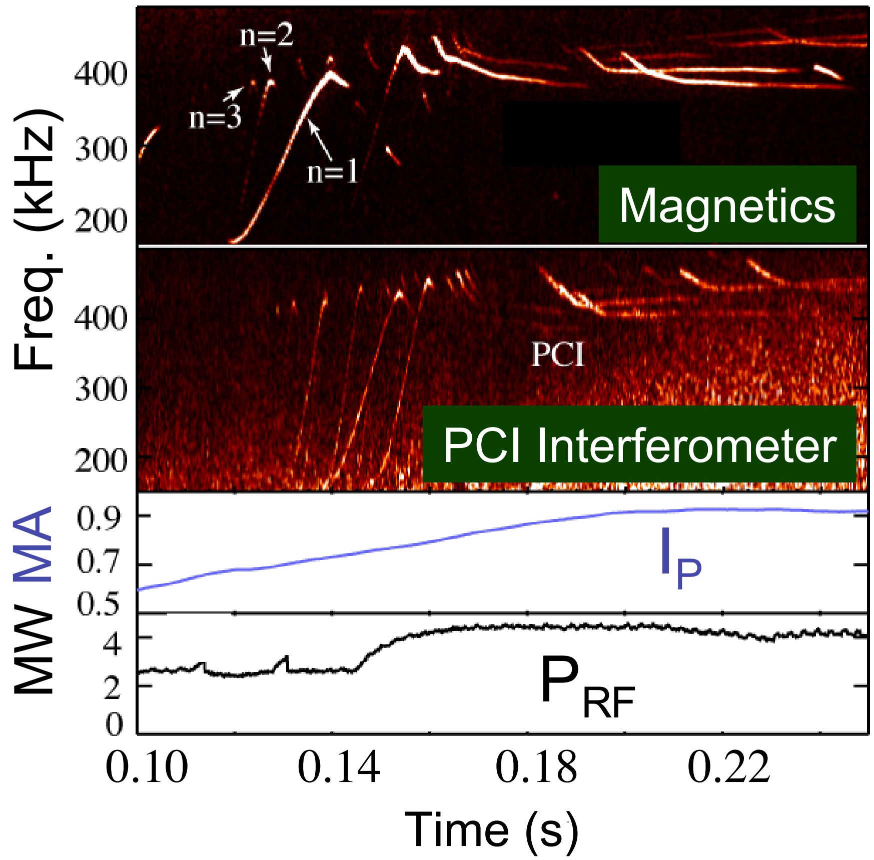


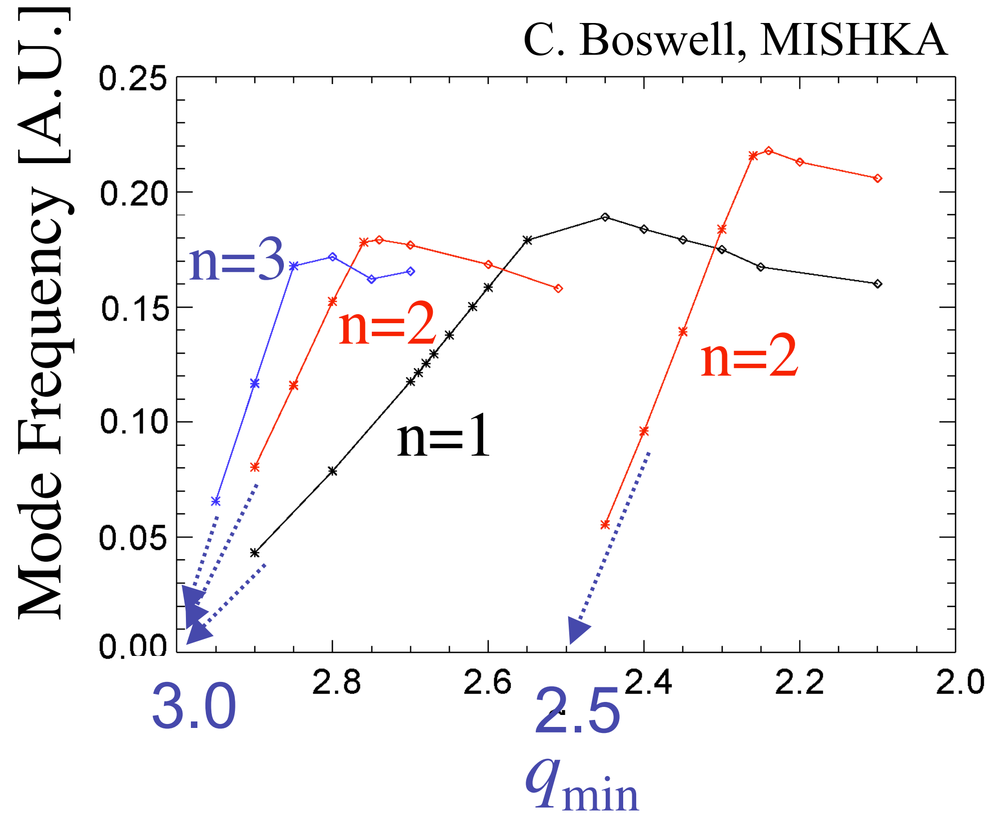

- Prediction: Modes can identify rational $q_{min}$ crossings
  - sensitivity increases with mode number

H.L. Berk et al., PRL **87** (2001) 185002

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

# MHD Spectroscopy and the Evolution of $q_{min}$ in the Current Rise of Alcator C-MOD

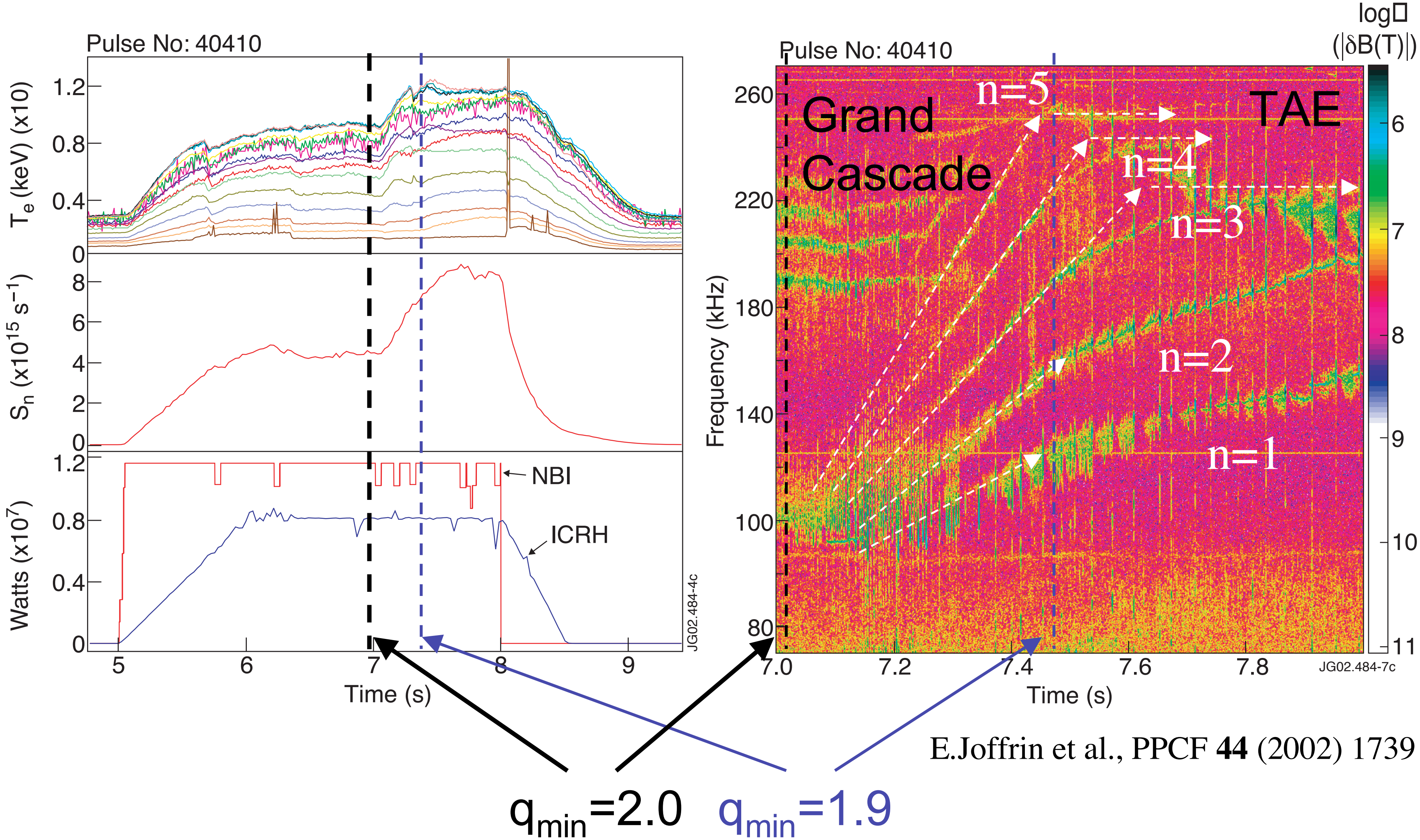



J. A. Snipes et al., Proc. 31st EPS (2004)

- MHD spectroscopy useful when MSE is challenging
- Higher-n gives higher $q_{min}$ resolution
- Core fluctuations measurements access higher-n

# Application of MHD Spectroscopy: Onset of ITB Triggered by Integer $q_{min}$ Crossing on JET




E.Joffrin et al., PPCF **44** (2002) 1739

- What role do Cascades play in ITB triggering ?

# New Understanding Developed Through Close Collaboration with US, Japan and EU researchers

- Frequency sweeping modes are resonant shear Alfvén waves
  - *consistent observations across multiple facilities*

- Recent breakthrough in the use of core fluctuation diagnostics
  - *core localization determined*
  - *many core localized modes observed*

- Observation of a "Sea of Alfvén Eigenmodes" in plasma core in DIII-D with short poloidal scale : $n<40$, $k_\theta < 2cm^{-1}$

- Future directions, implications for ITER diagnostics

# New Understanding Developed Through Close Collaboration with US, Japan and EU researchers

• Frequency sweeping modes are resonant shear Alfvén waves

  *- consistent observations across multiple facilities*

• Recent breakthrough in the use of core fluctuation diagnostics

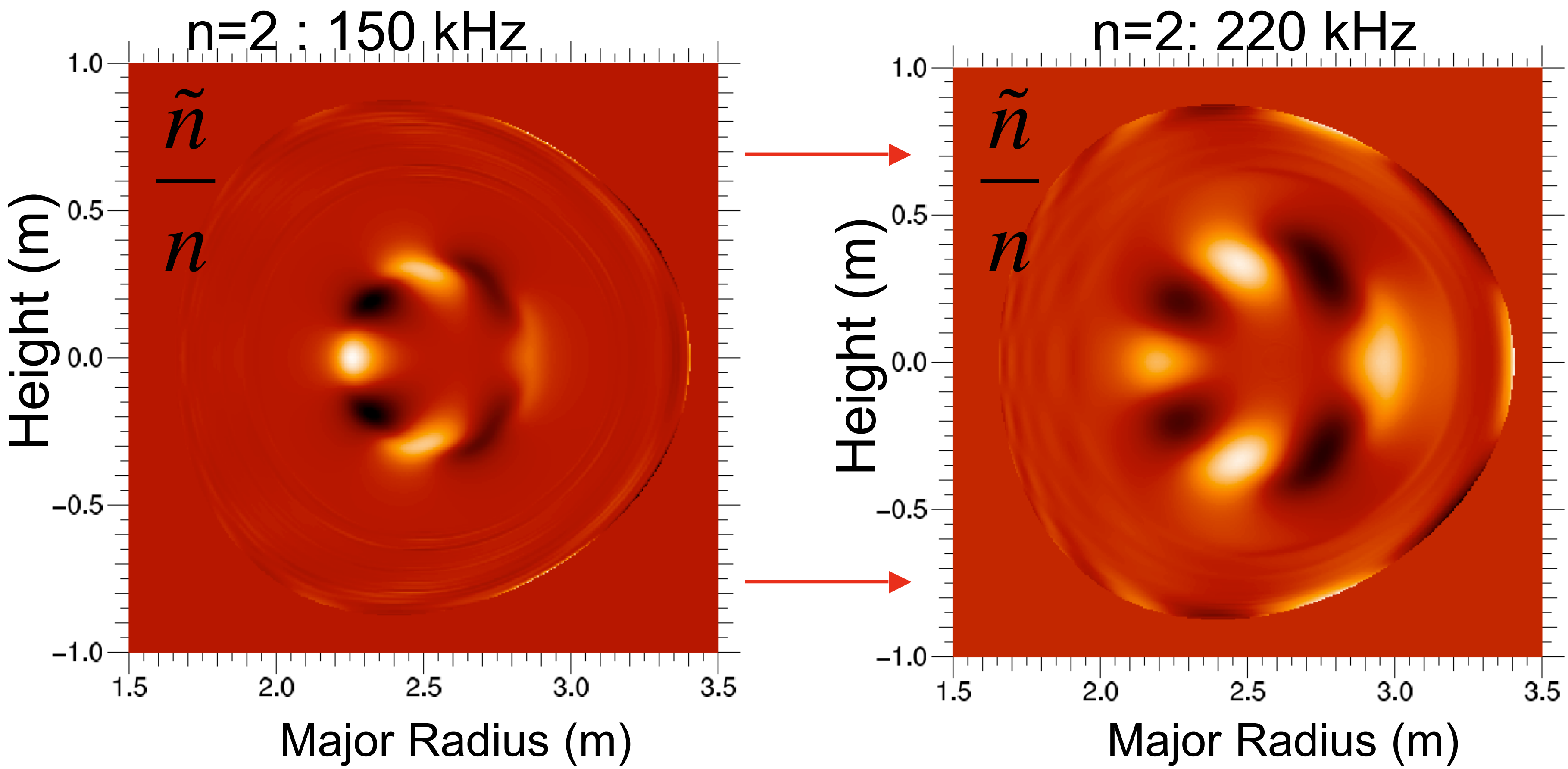
  *- core localization determined*

  *- many core localized modes observed*

• Observation of a "Sea of Alfvén Eigenmodes" in plasma core in DIII-D with short poloidal scale : $n<40$, $k_\theta < 2cm^{-1}$

• Future directions, implications for ITER diagnostics

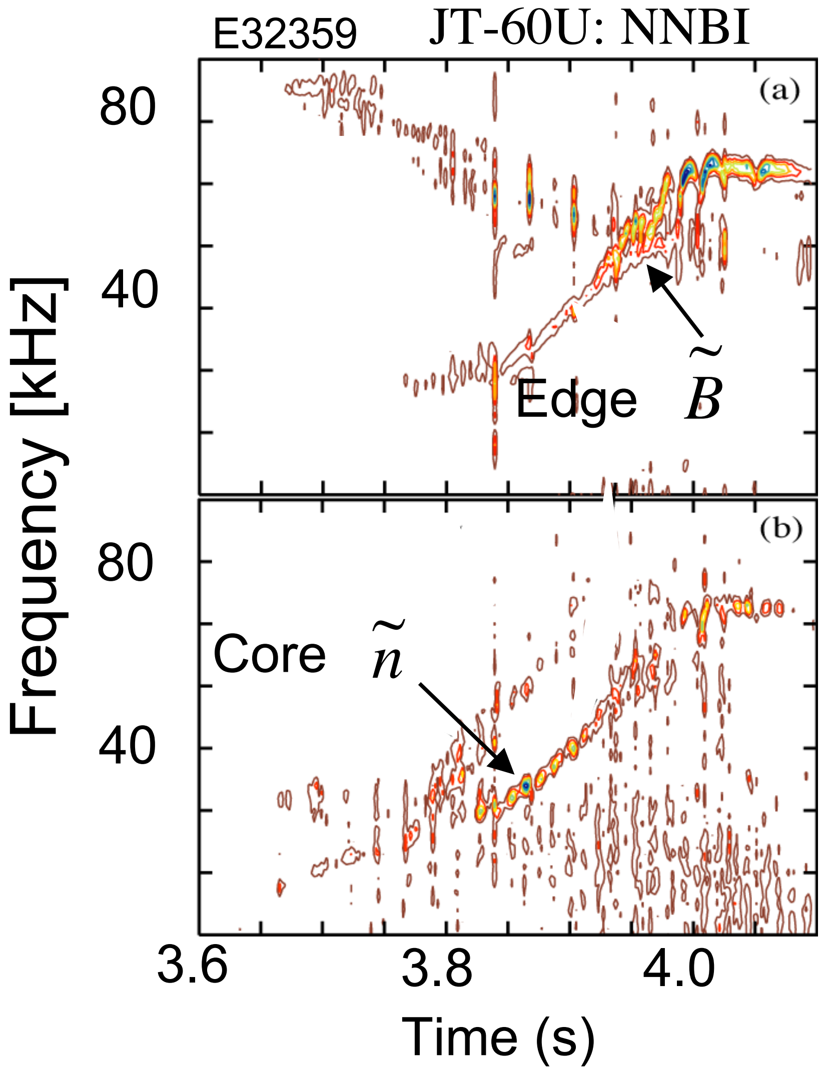
# Prediction: Mode Transitions from Core Localized to Global Structure: *TFTR-DT*




*Core localized* *Global Structure*

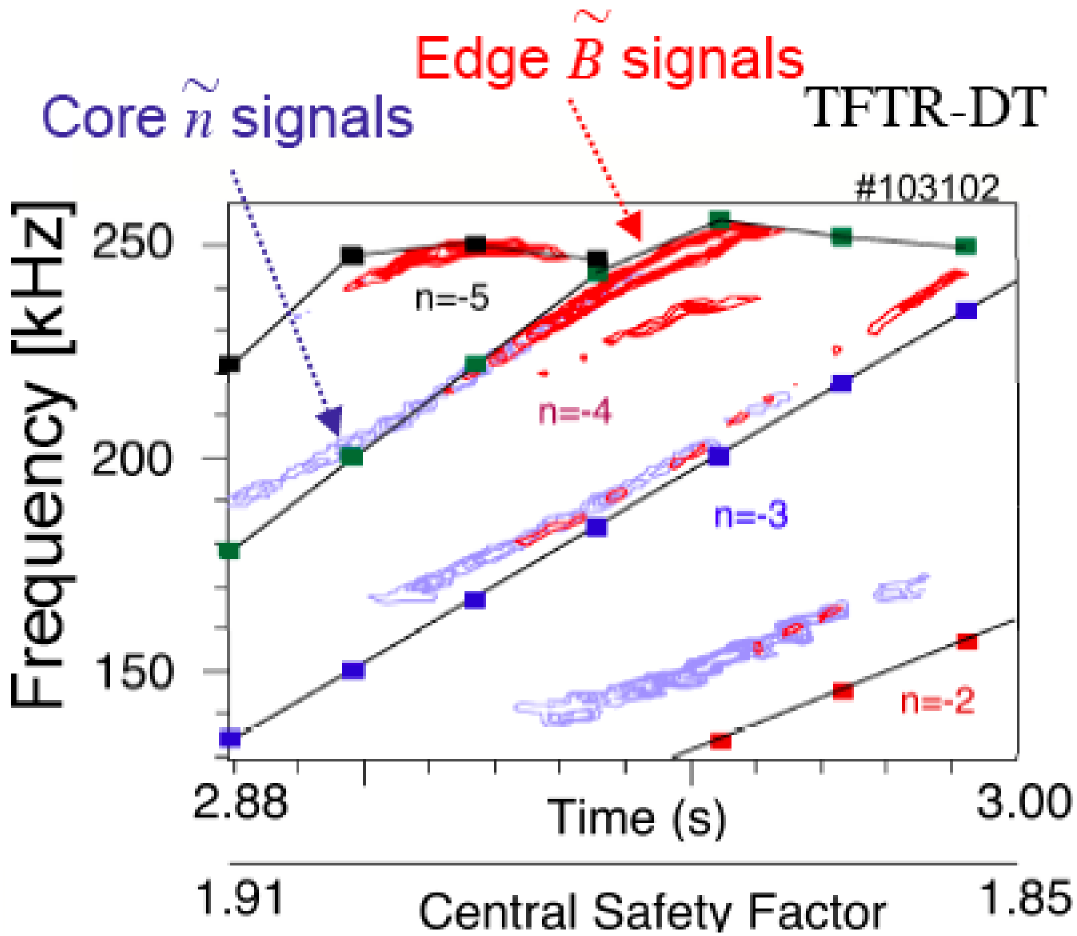
- Is there any evidence for such a transition?

# Internal Measurements on JT-60U show Transition from Core Localized to Global TAE with Decreasing $q_{min}$



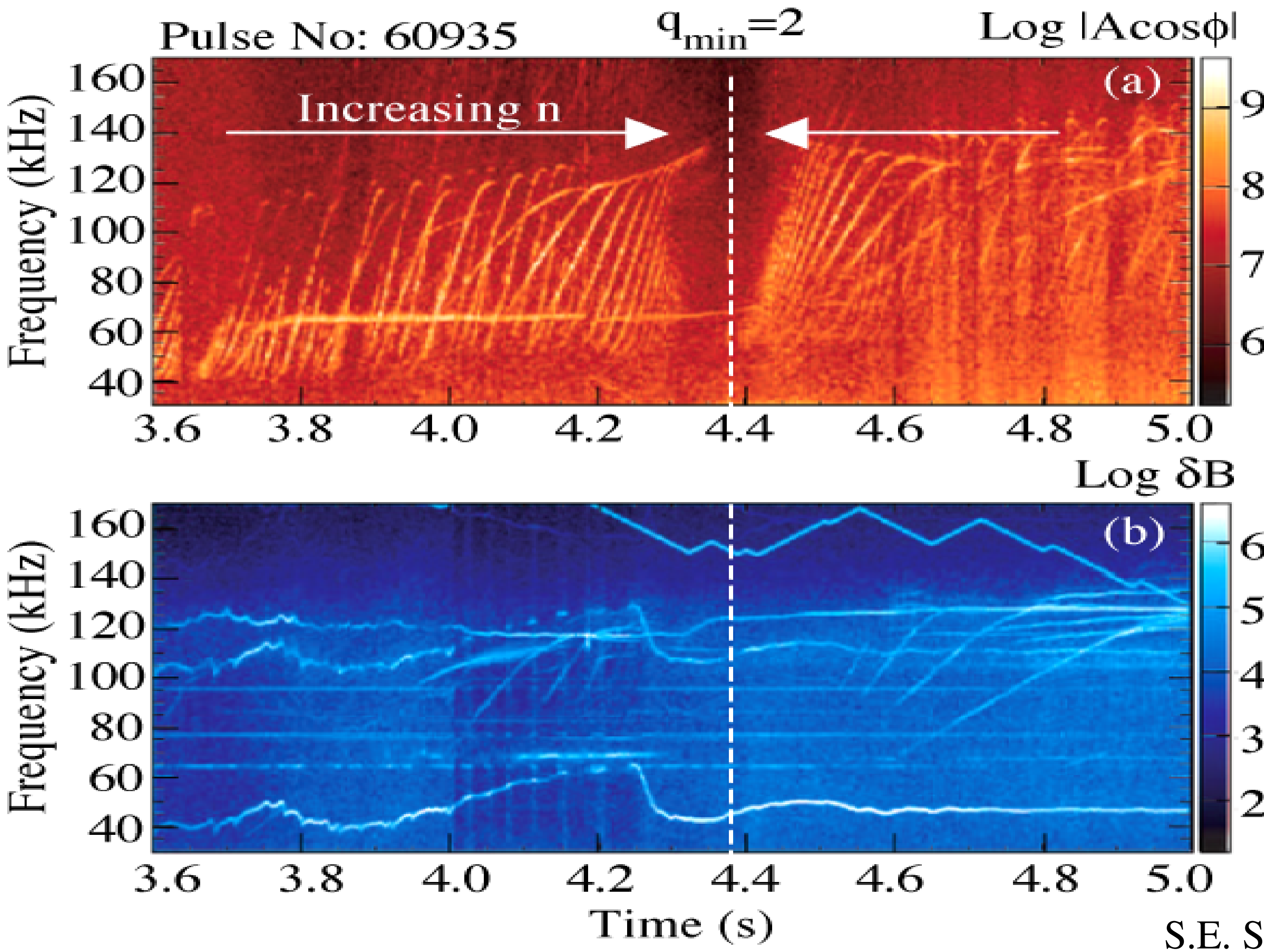

K. Shinohara et al., Nucl. Fusion **41** (2001) 603

# Internal Measurements in TFTR-DT Appear before Edge Magnetic Signals




- Reflectometer measures density fluctuations in the plasma core
  - $\tilde{B}/B \sim 2 \times 10^{-6}$ No alpha particle loss is observed

# Breakthrough: Interferometer Measurements Reveal Many Hidden Modes in Reverse Shear Plasmas on JET




- Interferometer $n > 16$
- Reflectometer

$\tilde{B}/B \approx 1.5 \times 10^{-4}$ for n=3

- Magnetics $n < 5$

- Fast ion loss not observed

S.E. Sharapov et al., PRL **93** (2004) 165001

# New Understanding Developed Through Close Collaboration with US, Japan and EU researchers

- Frequency sweeping modes are resonant shear Alfvén waves
  - *consistent observations across multiple facilities*

- Recent breakthrough in the use of core fluctuation diagnostics
  - *core localization determined*
  - *many core localized modes observed*

- Observation of a "Sea of Alfvén Eigenmodes" in plasma core in DIII-D with short poloidal scale : $n<40$, $k_\theta < 2cm^{-1}$
  - *excitation with low voltage beams, small $\rho/a$*

- Future directions, implications for ITER diagnostics

# New Understanding Developed Through Close Collaboration with US, Japan and EU researchers

• Frequency sweeping modes are resonant shear Alfvén waves

*- consistent observations across multiple facilities*

• Recent breakthrough in the use of core fluctuation diagnostics

*- core localization determined*

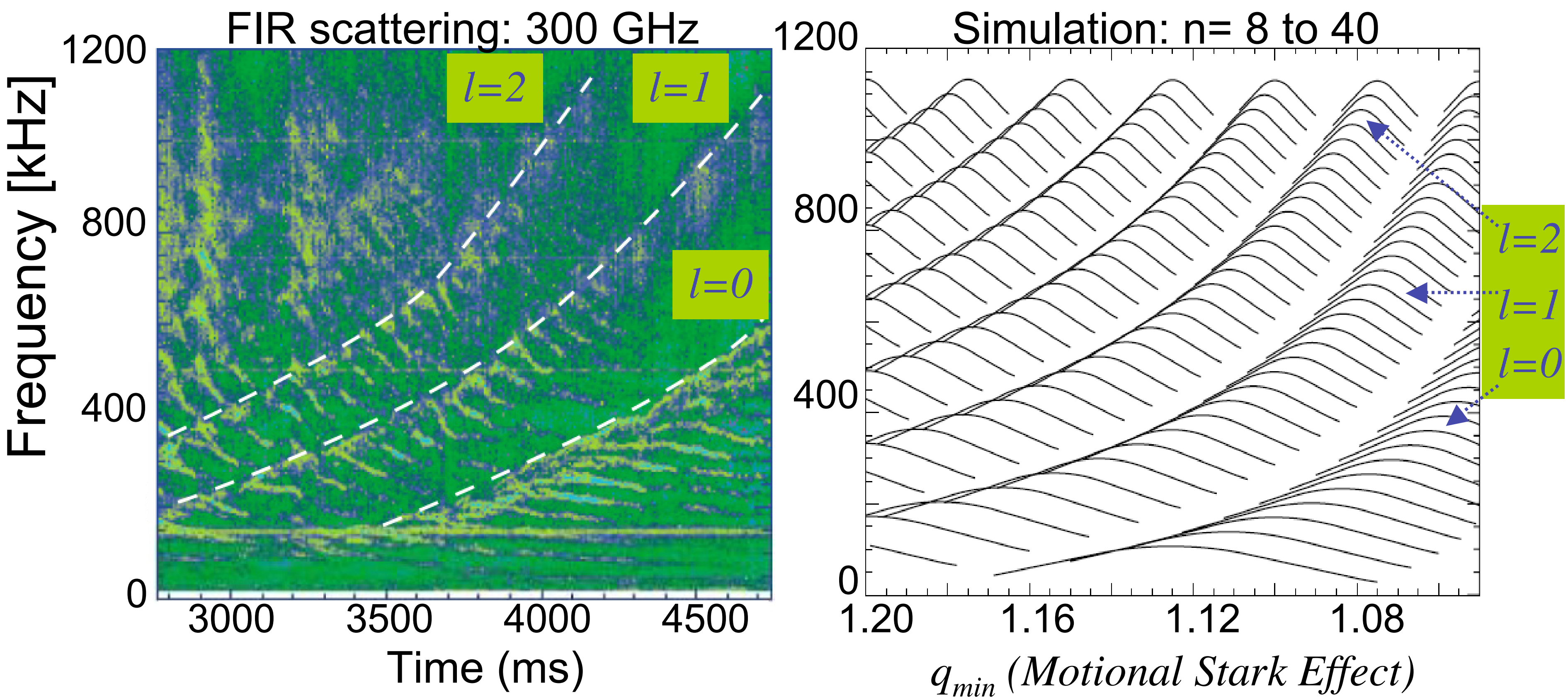
*- many core localized modes observed*

• Observation of a “Sea of Alfvén Eigenmodes” in plasma core in DIII-D with short poloidal scale : $n<40$, $k_\theta < 2cm^{-1}$

*- excitation with low voltage beams, small $\rho/a$*

• Future directions, implications for ITER diagnostics

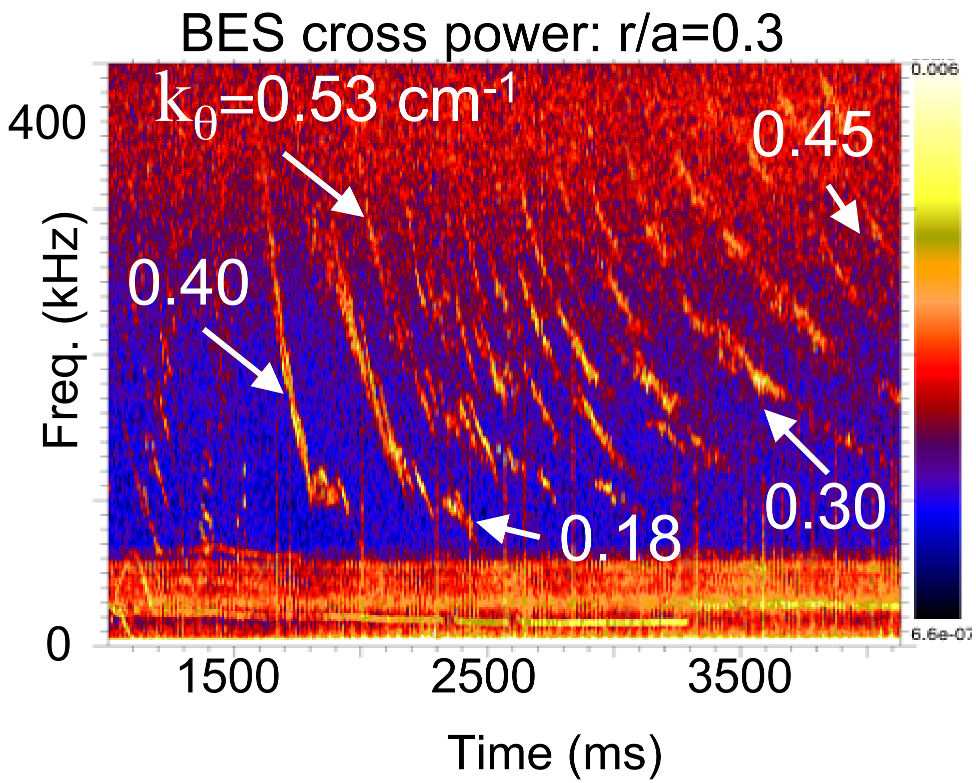
# A "Sea of Alfvén Eigenmodes" Observed in DIII-D Plasmas Driven by 80 keV Neutral Beams

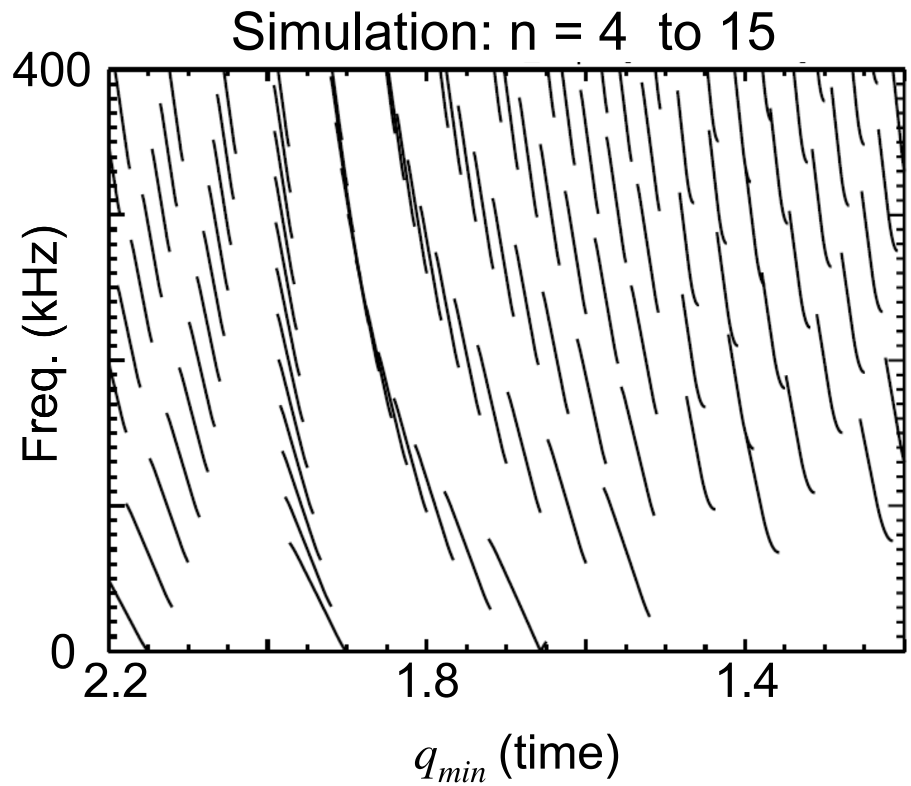



- Bands of modes $m=n+l$, $l=0, 1, 2, \ldots$ : $\omega_{n+1}-\omega_n \approx \omega_{rot}$ (CER)
- Neutral beam injection opposite to plasma current: $V_{||} \approx 0.3 V_A$
- 8 <n< 40, $k_\theta$ up to 2.0 $cm^{-1}$ (Turbulent scale length !!)

# Beam Emission Spectroscopy Resolves Local Poloidal Wavenumber and Amplitude on DIII-D

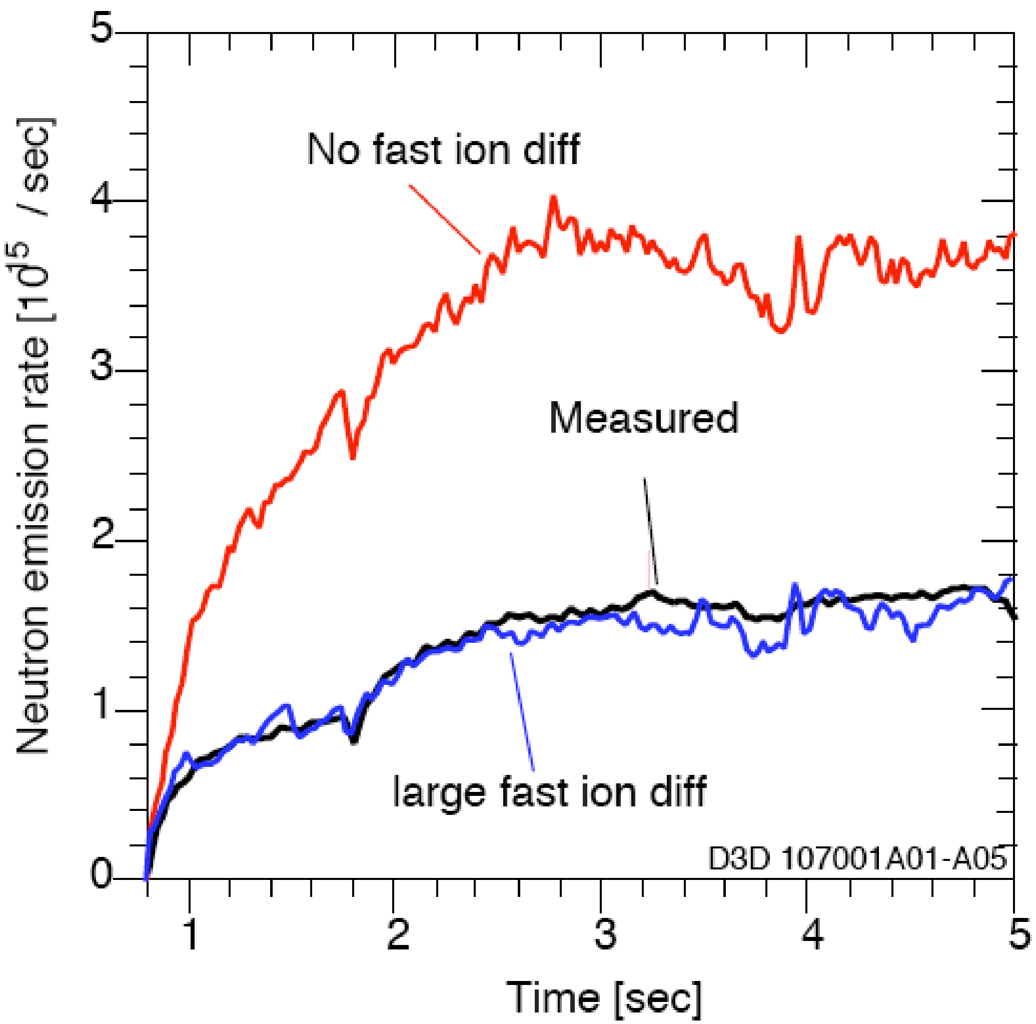
*G. McKee (U. Wisc.)*




- $\delta n/n \approx 0.3$ % from 100-300 kHz ($\delta B/B \approx 0.02\%$)
- Higher frequencies have higher $k_\theta$
  - comparison with eigenmodes structure underway
- Modes propagate in plasma current direction in $E_r=0$ frame

# Future work: Can the neutron deficit in DIII-D be attributed to a "Sea of Alfvén Eigenmodes"?




TRANSP

Modeling requires 80% beam ion density reduction on axis

- Need confined fast ion measurements to corroborate analysis!
  -> see Sharapov, next speaker.

# Core Fluctuation and Confined Fast Ion Measurements are Essential for Understanding Fast Ion Transport

- Rapid progress in theory of reverse shear plasmas

- New internal observations reveal many unstable high-n modes
  - e.g. “Sea of Alfvén Eigenmodes” in DIII-D

*Future work*

- Correlate mode activity with fast ion redistribution
  - need a direct measurement of confined fast ions

*Note*

- Internal mode and confined fast ion detection essential in a burning plasma experiment
  - At present no plans exist for such measurements on ITER

# Core Fluctuation and Confined Fast Ion Measurements are Essential for Understanding Fast Ion Transport

• Rapid progress in theory of reverse shear plasmas

• New internal observations reveal many unstable high-n modes

- e.g. “Sea of Alfvén Eigenmodes” in DIII-D

*Future work*

• Correlate mode activity with fast ion redistribution

- need a direct measurement of confined fast ions

*Note*

• Internal mode and confined fast ion detection essential in a burning plasma experiment

- At present no plans exist for such measurements on ITER

# Core Fluctuation and Confined Fast Ion Measurements are Essential for Understanding Fast Ion Transport

• Rapid progress in theory of reverse shear plasmas

• New internal observations reveal many unstable high-n modes

- e.g. "Sea of Alfvén Eigenmodes" in DIII-D

*Future work*

• Correlate mode activity with fast ion redistribution

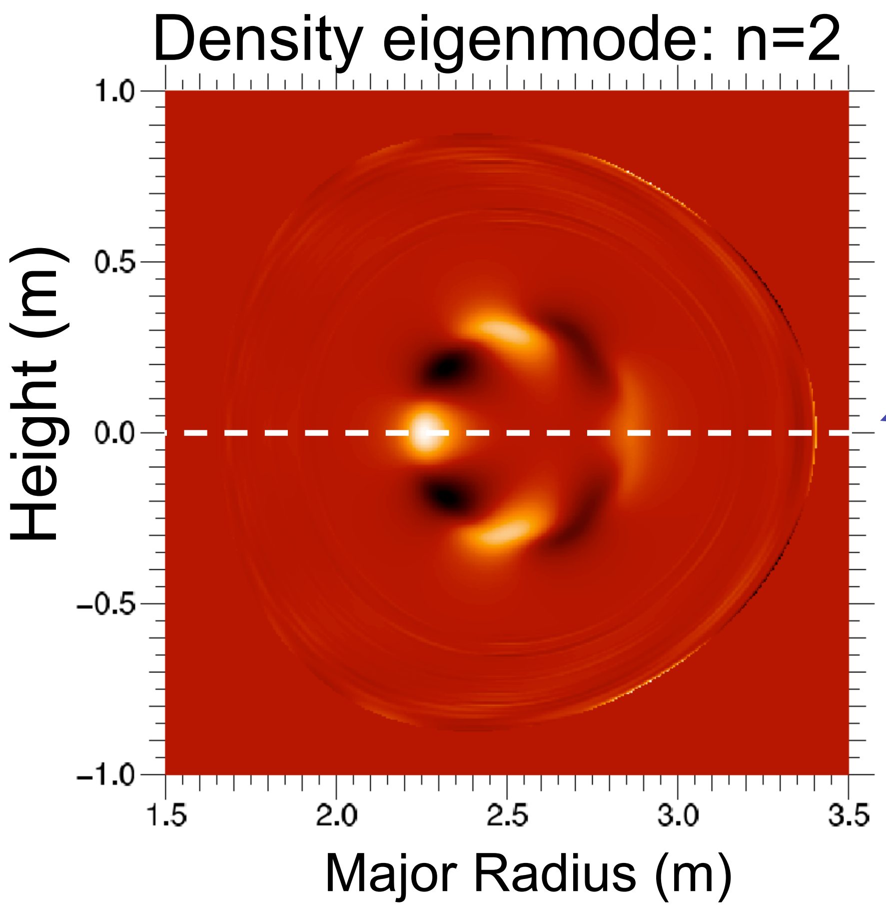
- need a direct measurement of confined fast ions

*Note*

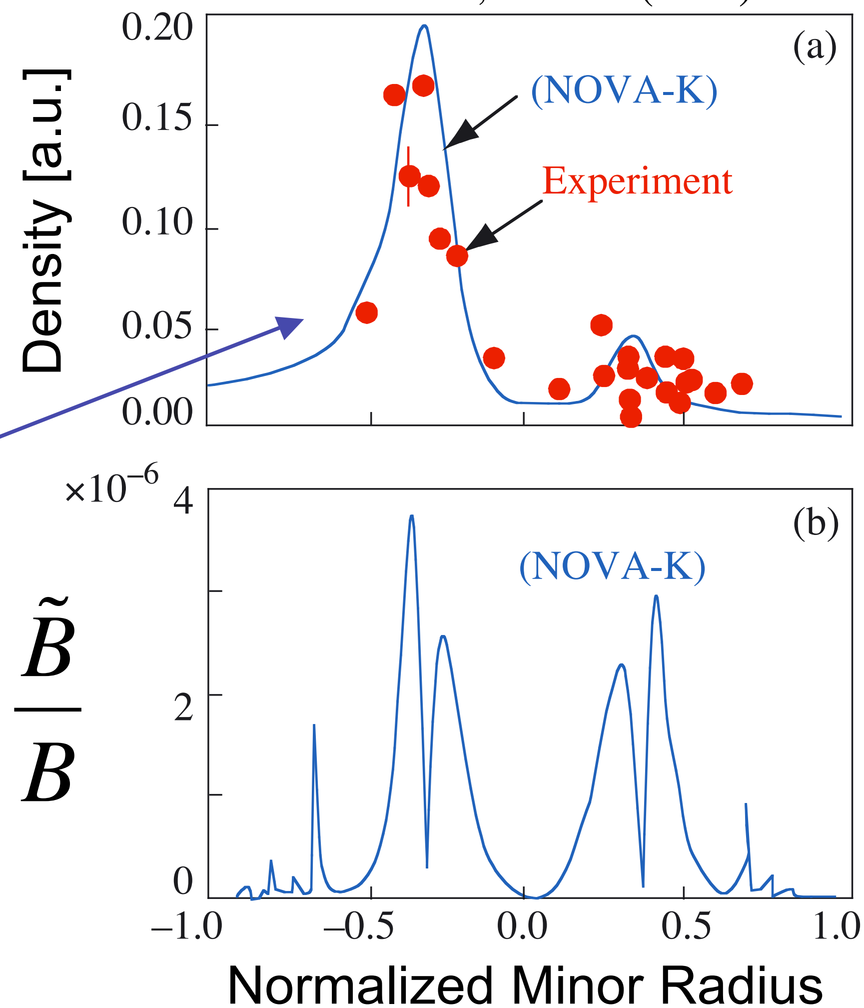
• Internal mode and confined fast ion detection essential in a burning plasma experiment

- At present no plans exist for such measurements on ITER

# Internal mode structure resolved using Reflectometry on TFTR




R. Nazikian et al., PRL **91** (2003) 125003




- $\tilde{B}/B \sim 2\times 10^{-6}$ No alpha particle loss is observed