Energetic Particle Driven Modes
Relevant to Advanced Tokamak Regimes

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

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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

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

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

- 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 $q_{\text{min}}$ in the Current Rise of Alcator C-MOD

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

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

- What role do Cascades play in ITB triggering?
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Prediction: Mode Transitions from Core Localized to Global Structure: \textit{TFTR-DT}

- Is there any evidence for such a transition?
Internal Measurements on JT-60U show Transition from Core Localized to Global TAE with Decreasing $q_{\text{min}}$
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 $n=3$
- Fast ion loss not observed

S.E. Sharapov et al., PRL 93 (2004) 165001
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A “Sea of Alfvén Eigenmodes” Observed in DIII-D Plasmas Driven by 80 keV Neutral Beams

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

BES cross power: \( r/a = 0.3 \)

- \( k_\theta = 0.53 \) cm\(^{-1} \)
- \( 0.45 \)
- \( 0.40 \)
- \( 0.30 \)
- \( 0.18 \)

Simulation: \( n = 4 \) to 15

- \( \delta n/n \approx 0.3 \% \) 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”?

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

Modeling requires 80% beam ion density reduction on axis

*Note: The graph shows a comparison between measured neutron emission rates and modeled rates, indicating the need for further investigation.*
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
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Internal mode structure resolved using Reflectometry on TFTR

Density eigenmode: $n=2$

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