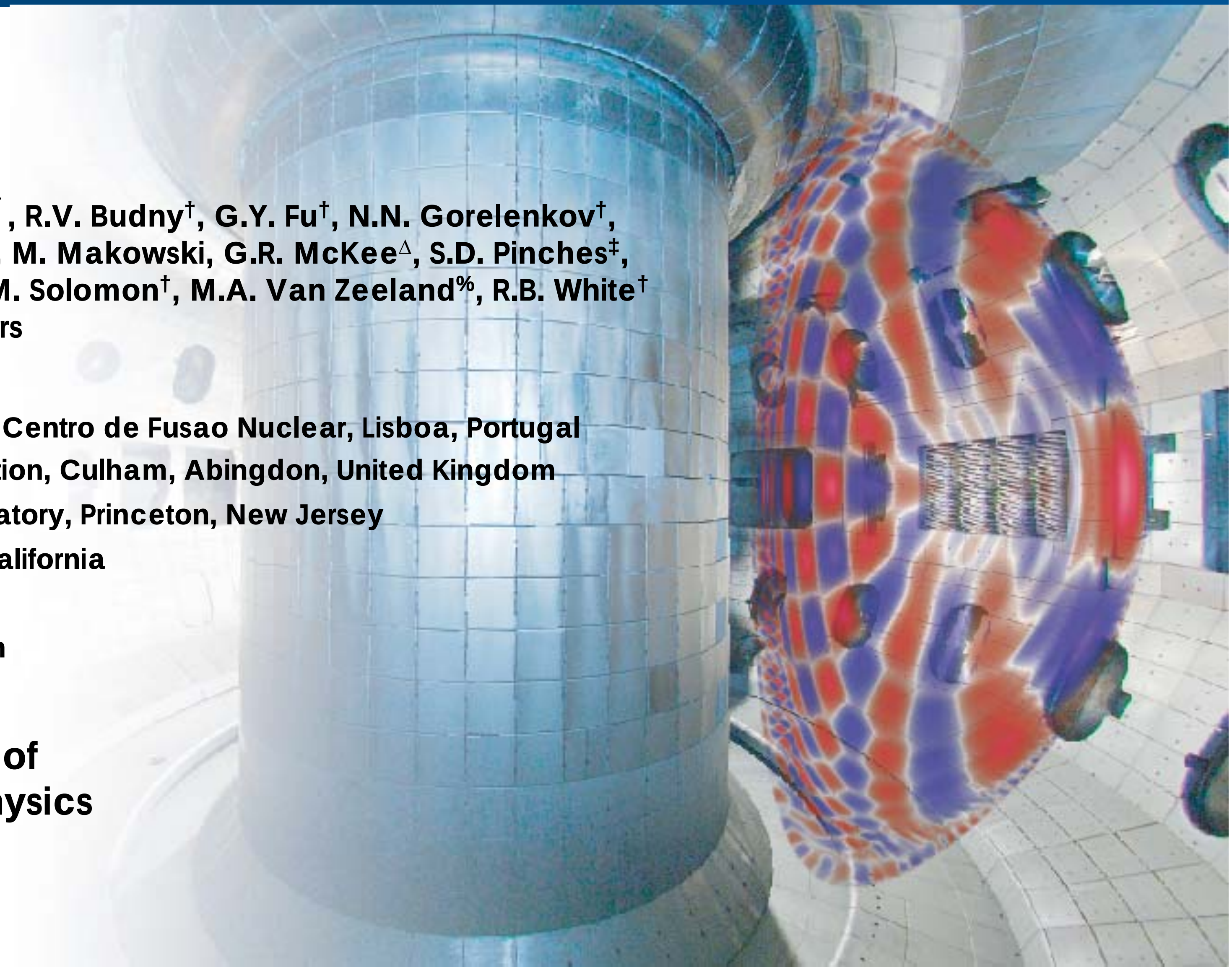
Excitation of Alfvén Waves By Low Velocity Supra Thermal Ions in the DIII-D and JET Tokamaks



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Presented at
Forty-Ninth APS Meeting of
the Division of Plasma Physics
Orlando, Florida
November 12–16, 2007

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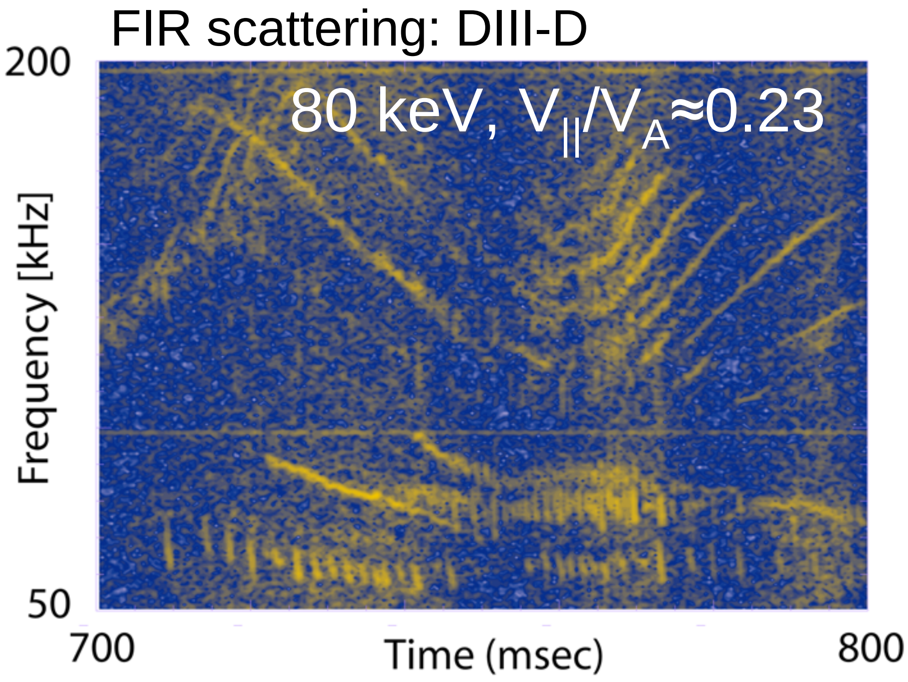
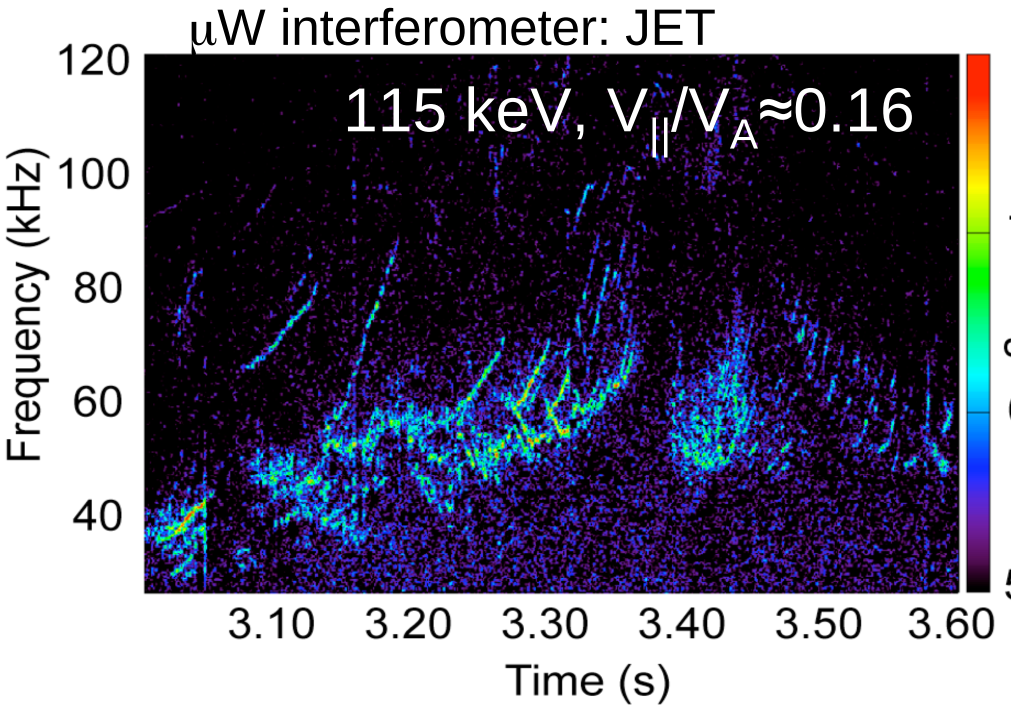
PPPL PRINCETON PLASMA PHYSICS LABORATORY

Recent Surprise : Rich Spectrum of Alfvén Waves Excited by Low Velocity Supra Thermal Ions in Fusion Plasmas





- **Excitation of Alfvén waves previously explored for $V_{||} \sim V_A$**
  - Requires high ion energies (> 1 MeV) or low V_A (low - B)
- **However, many Alfvén waves now seen for $V_{||}$ well below V_A**
- **Rapid progress made in mode identification**
  - **the challenge is to understand the excitation mechanism**

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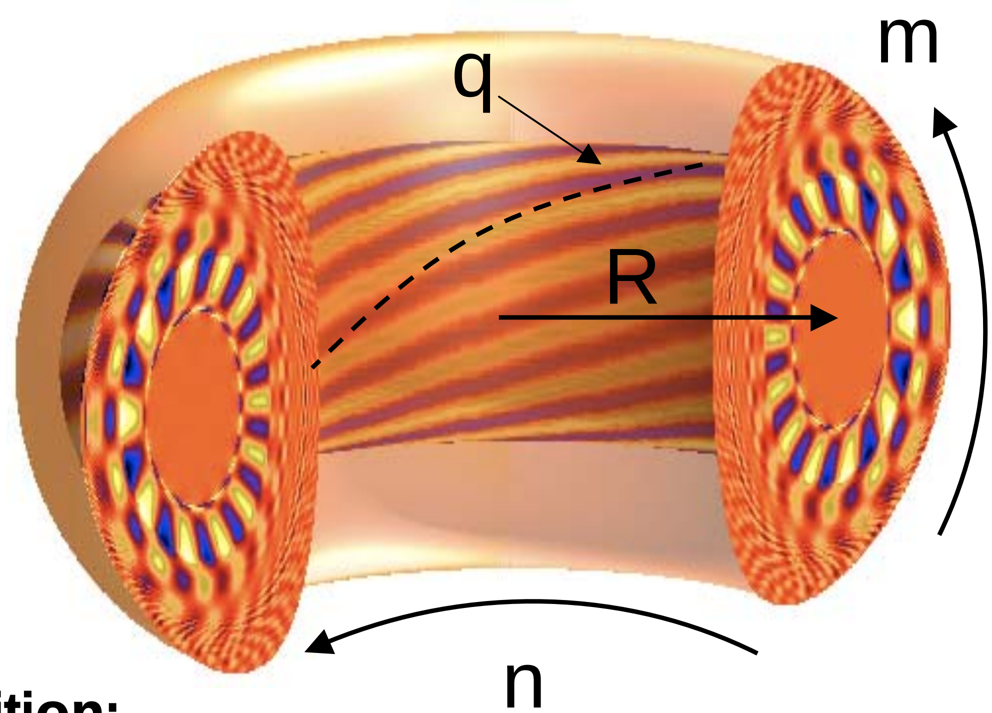
Fundamental Resonance Condition Cannot Explain Many Alfvén Waves Driven by Low Energy Ions

- **Shear Alfven wave**

$\omega \approx k_{||} \; V_A$

- **common varieties**

RSAE : single m
TAE : couples m, m+1
EAE : couples m, m+2



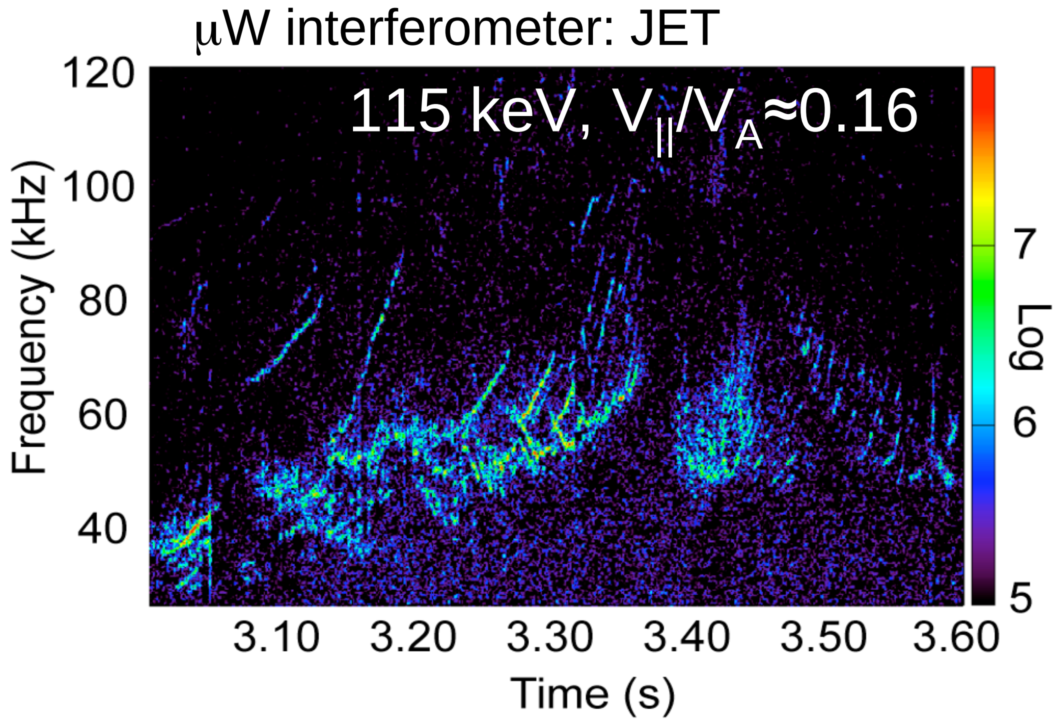
- **Fundamental resonance condition:**

$\omega_{MHD} \approx (k_{||} \pm 1/qR)\, V_{||}$; $V_{||}=0.23\, V_A$ in DIII-D and $0.16\, V_A$ in JET

RSAE : $V_{||} \approx 1/5\, V_A$ or $-1/3\, V_A$
TAE : $V_{||} = \pm 1/3\, V_A$ or $\pm V_A$
EAE : $V_{||} = \pm 1/2\, V_A$

Excitation can be Explained by Invoking Higher Order Resonances, relevant for Advanced Tokamak Regimes

- **Advanced tokamak regimes have high central q**
  - High $k_\perp$ ($\approx$ q n / r)
  - High Δ_b ($\approx$ q ρ_b)



Higher order resonances:

$$\omega_{MHD} \approx (k_{||} \pm p/qR)\, V_{||}$$

p= 2,3,4…

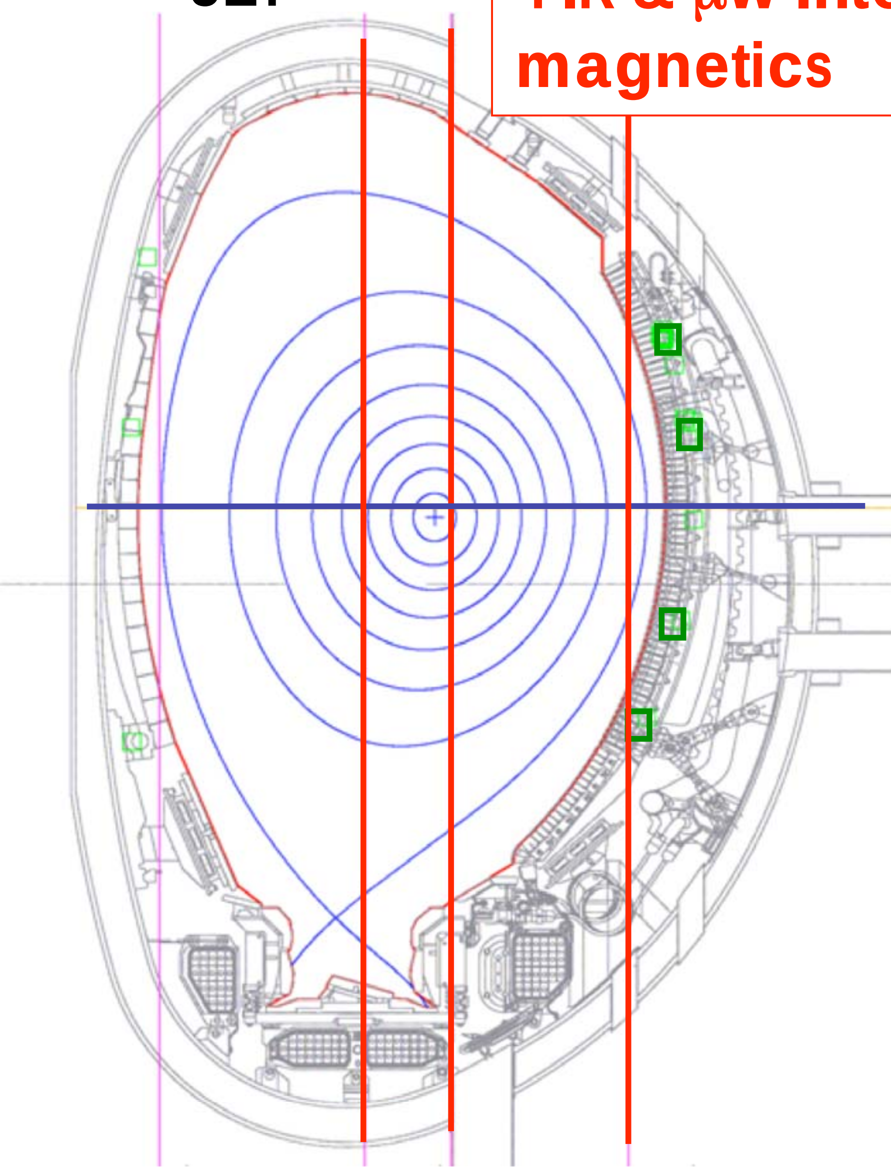
- **Resonant velocity strongly decreases for large p**
  - $V_{||} \propto V_A / p$

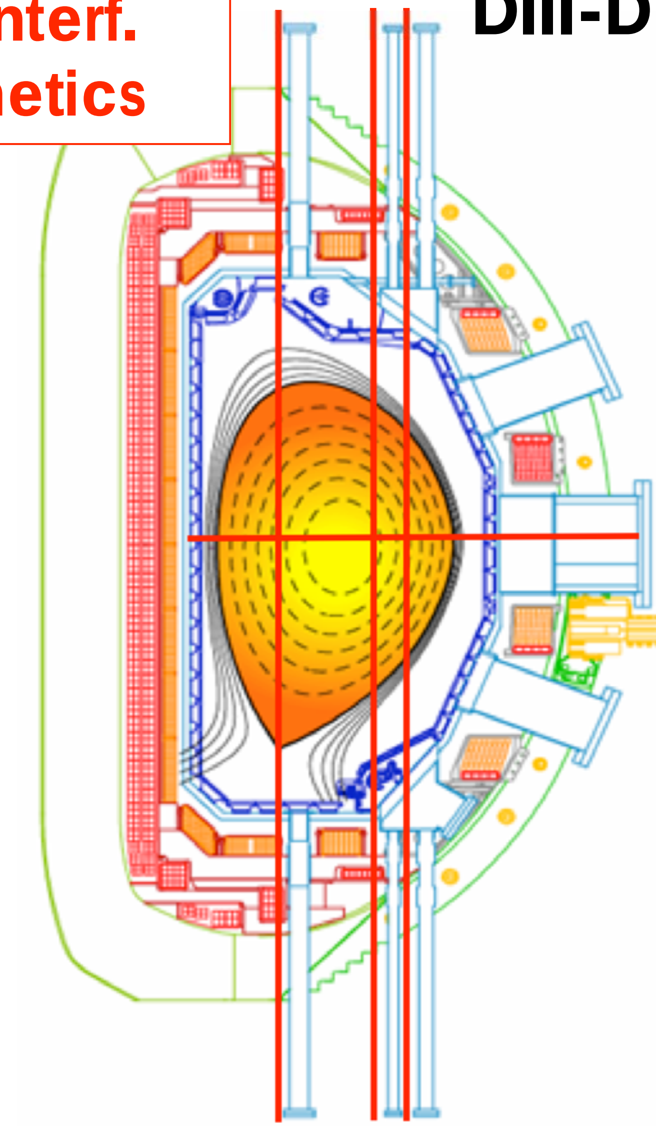
- **Importance: In high-q, steady state regimes, multiple high order resonances can greatly enhance instability drive and affect fast ion transport**

Outline

- **Observation of Alfvén wave excitation below the fundamental resonance condition in DIII-D and JET**
- **Ideal MHD analysis of radial mode structure, location**
- **Stability analysis and coupling to high order resonances**
- **Implications**

JET and DIII-D Have Comparable Diagnostics and Complementary Parameters for Alfvén Wave Studies





for same n,q

$\rho^{JET} = 0.7\ \rho^{DIII\text{-}D}$

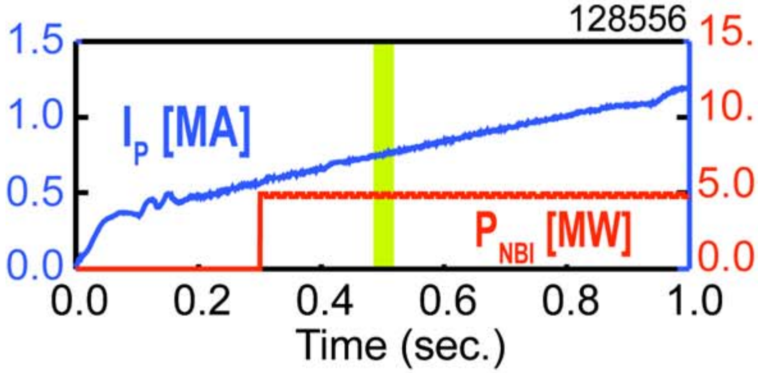
$k_\perp^{JET} = 0.5\ k_\perp^{DIII\text{-}D}$

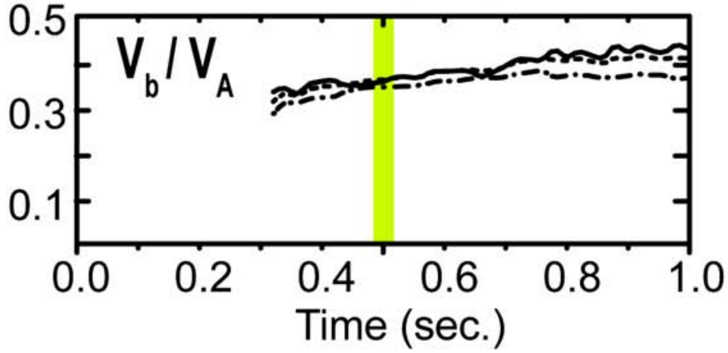
$V_A^{JET} \approx 2 \mathrm{x} V_A^{DIII\text{-}D}$

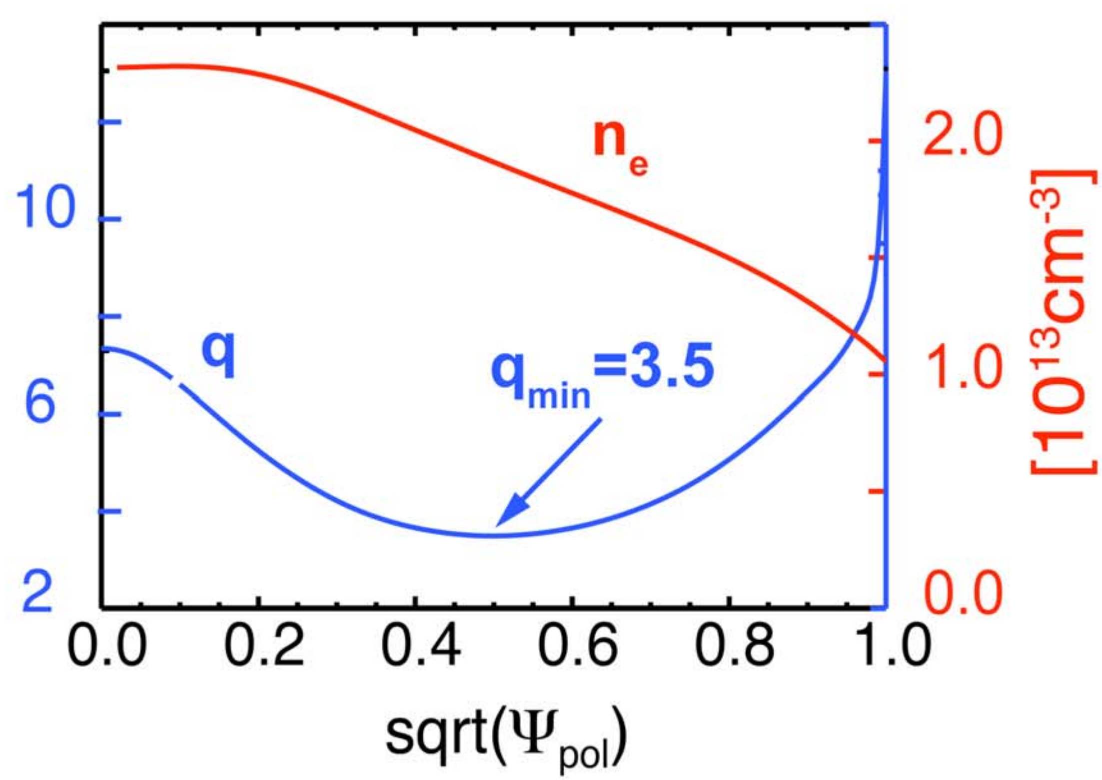
$E_b \leq 120$ keV $B_T = 3.45$ T, R=3.0 m

$E_b \leq 80$ keV $B_T = 2.10$ T, R=1.7 m

Experimental Scenario on DIII-D for Alfvén Eigenmode Study in Reverse Magnetic Shear Plasmas







- **Early beam heating is used to delay current penetration and create reverse magnetic shear**

DIII-D Measurements in Reverse Magnetic Shear Plasmas Indicate Many Unstable Alfven Eigenmodes

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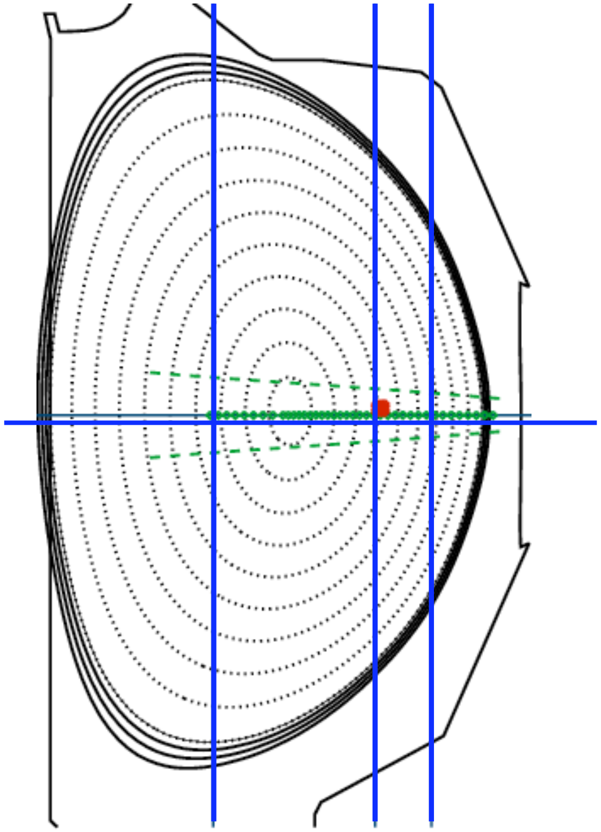
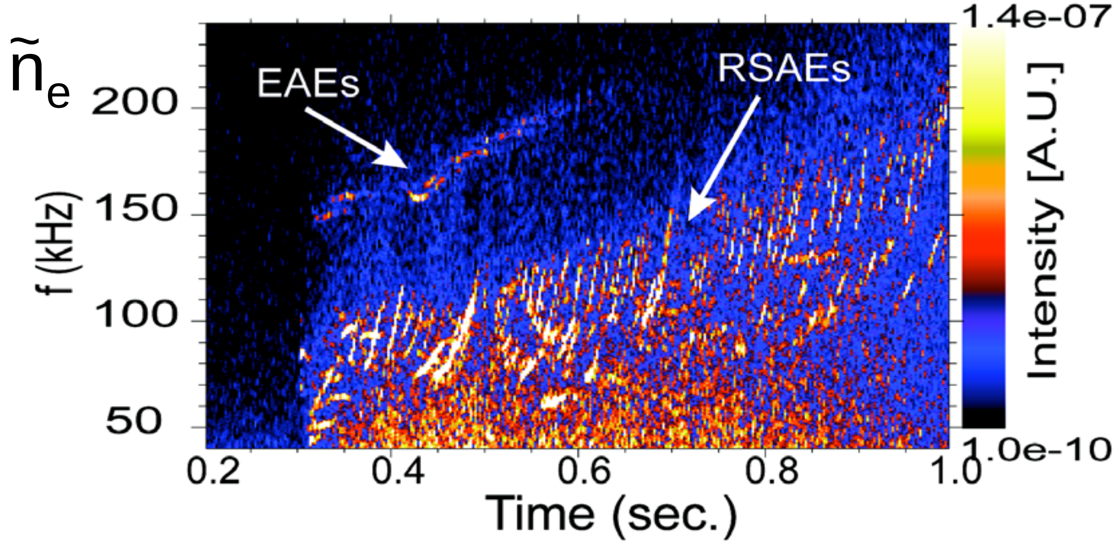
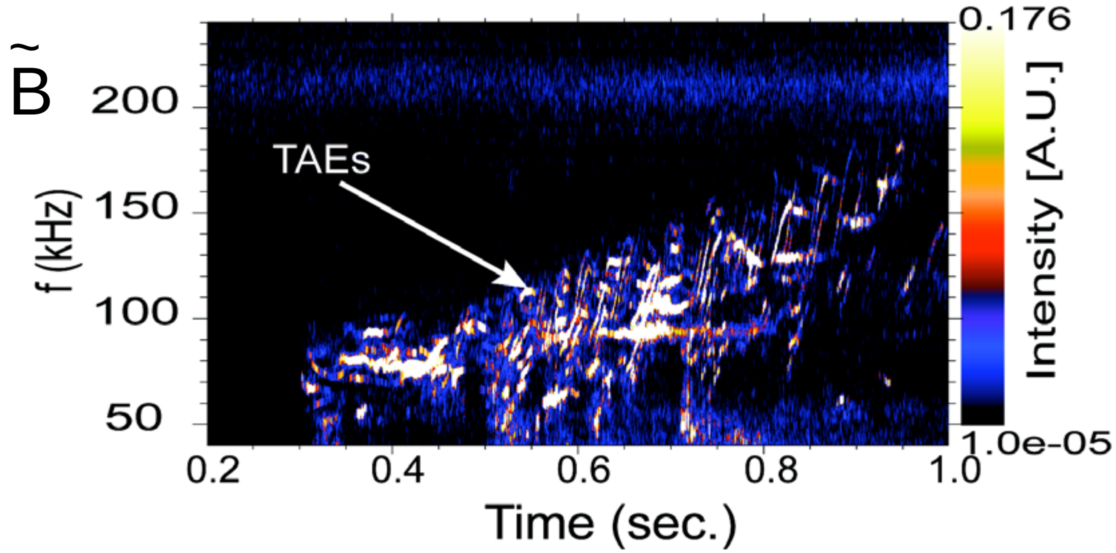
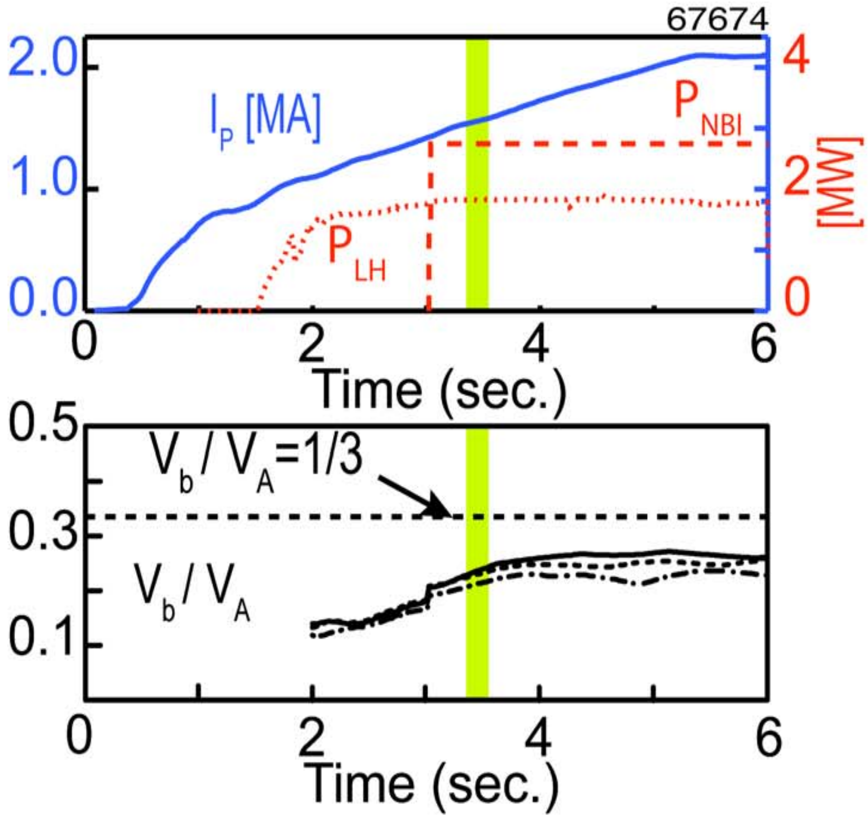


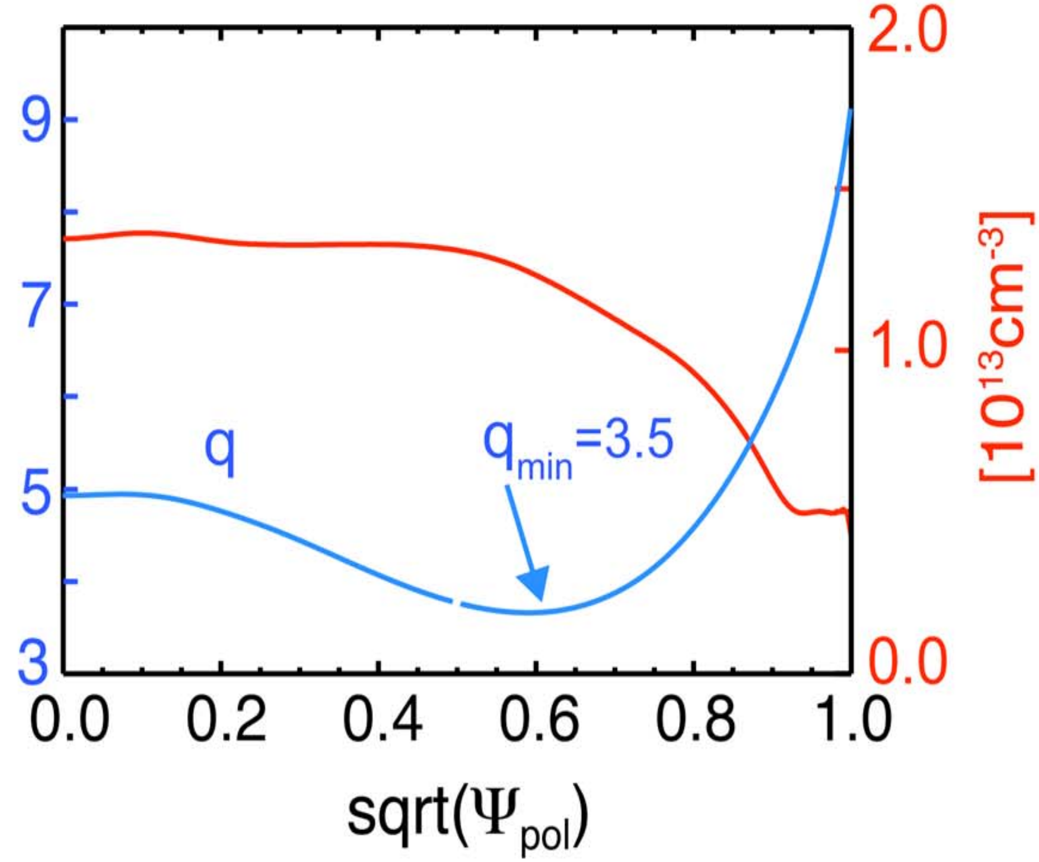




- **Difficult to go below $V_{\|} = 0.25$ V in DIII-D**

Experimental Scenario on JET Alfvén Eigenmode Study in Reverse Magnetic Shear plasmas





- Lower Hybrid Current drive is used to obtain reversed shear (P_{LHCD}=2MW)

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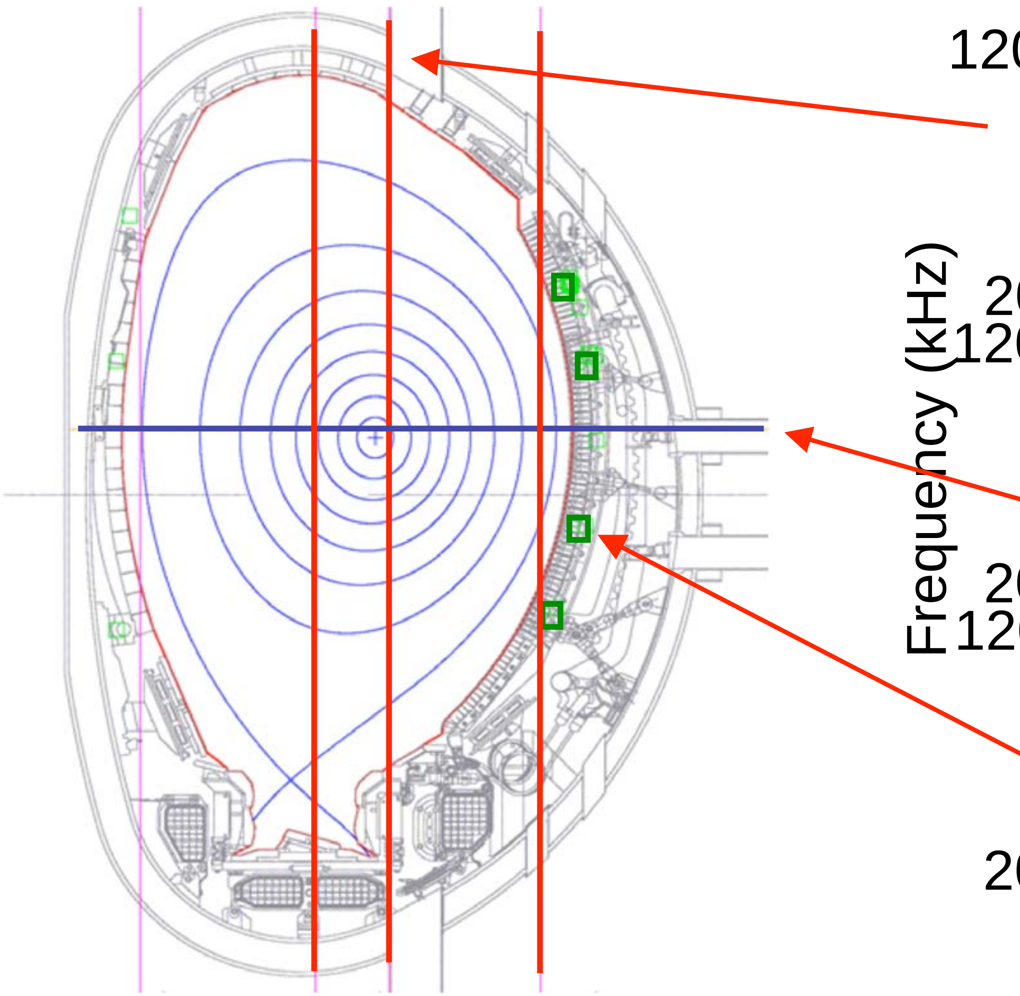
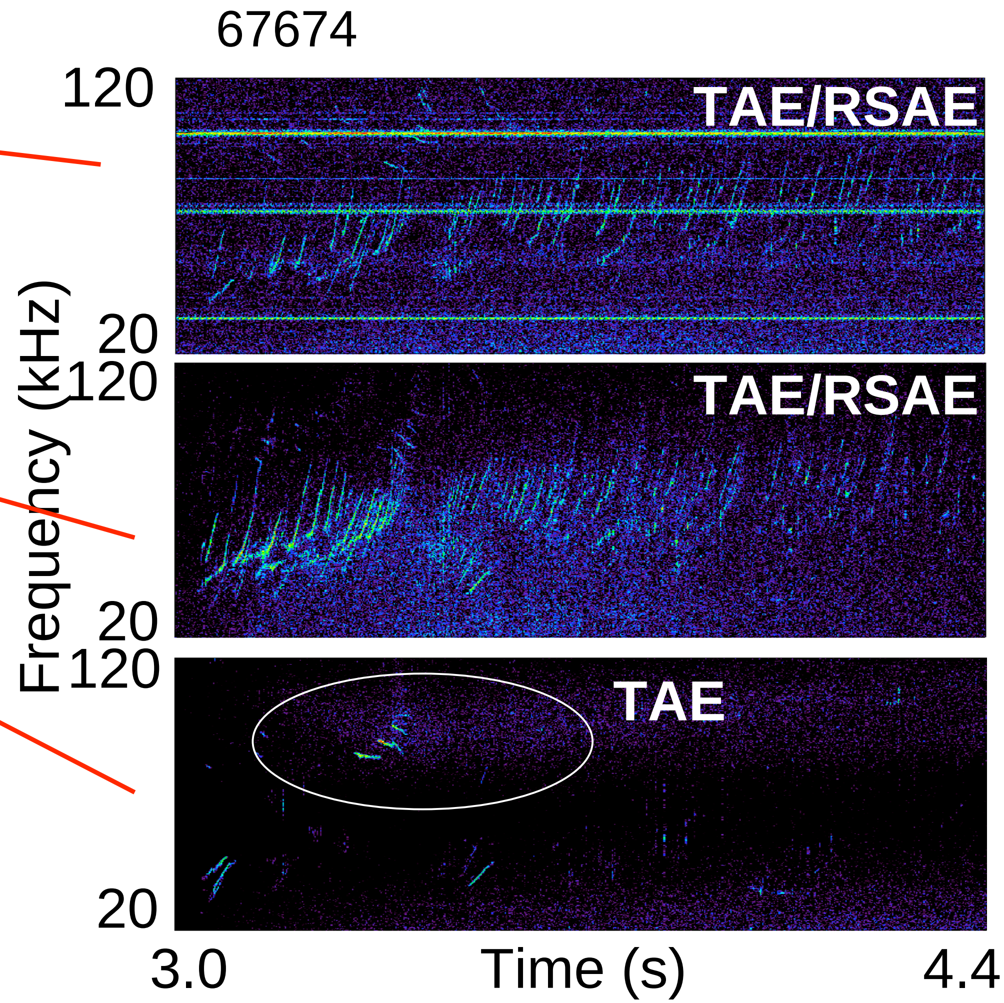
JET in Reverse Magnetic Shear Plasmas Indicate Many : Unstable Alfvén waves even for $V_{||} \approx 0.16\ V_A$





- RSAEs have been observed in JET down to $V_{||} \approx 0.11\ V_A$ in JET

Modes Observed Below the Fundamental Resonance Condition in DIII-D and JET

	Fundamental resonance	JET $V_{\|\|} \approx 0.16\ V_A$	DIII-D $V_{\|\|} \approx 0.23\ V_A$
RSAE	$V_{RES} \geq 0.2\ V_A$	✓	✓
TAE	$V_{RES} \geq 0.33\ V_A$	✓ ✓	✓ ✓
EAE	$V_{RES} \geq 0.5\ V_A$		✓ ✓

✓ =mode observed

✓ ✓ =mode observed below fundamental resonance

Modes Observed Below the Fundamental Resonance Condition in DIII-D and JET

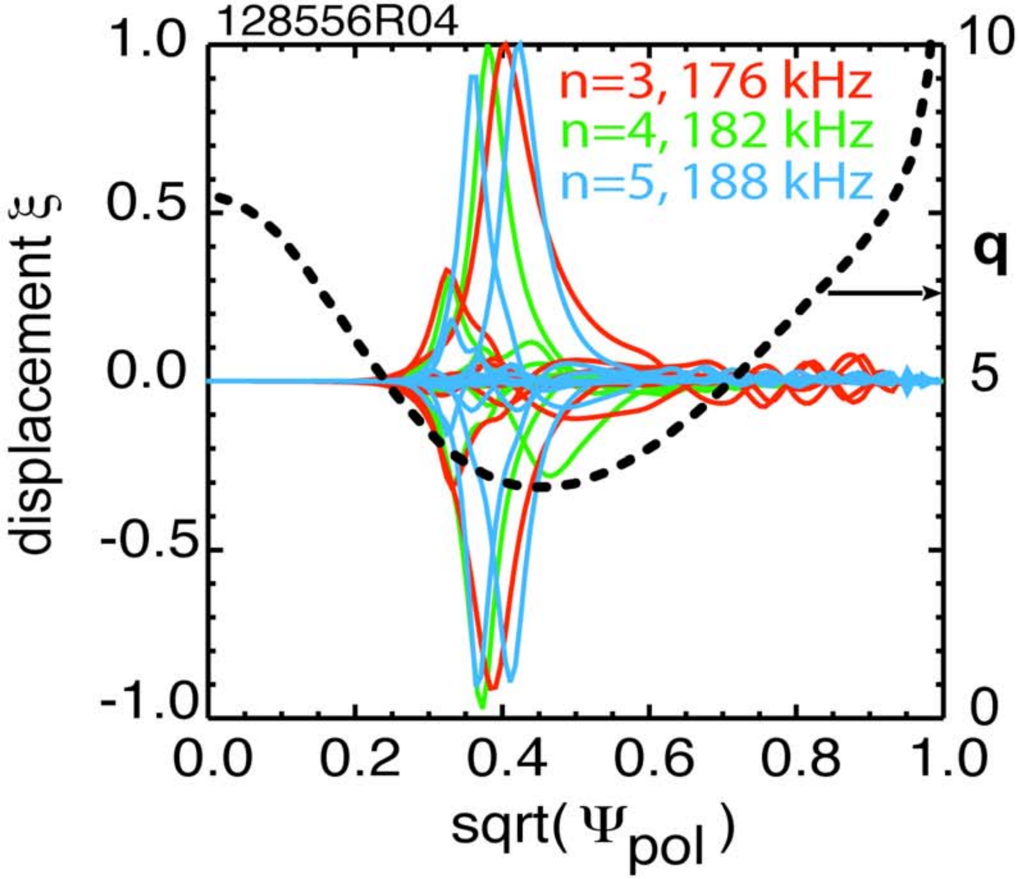
	Fundamental resonance	JET $V_{\|\|} \approx 0.16\ V_A$	DIII-D $V_{\|\|} \approx 0.23\ V_A$
RSAE	$V_{RES} \geq 0.2\ V_A$	✓	✓
TAE	$V_{RES} \geq 0.33\ V_A$	✓ ✓	✓ ✓
EAE	$V_{RES} \geq 0.5\ V_A$		✓ ✓

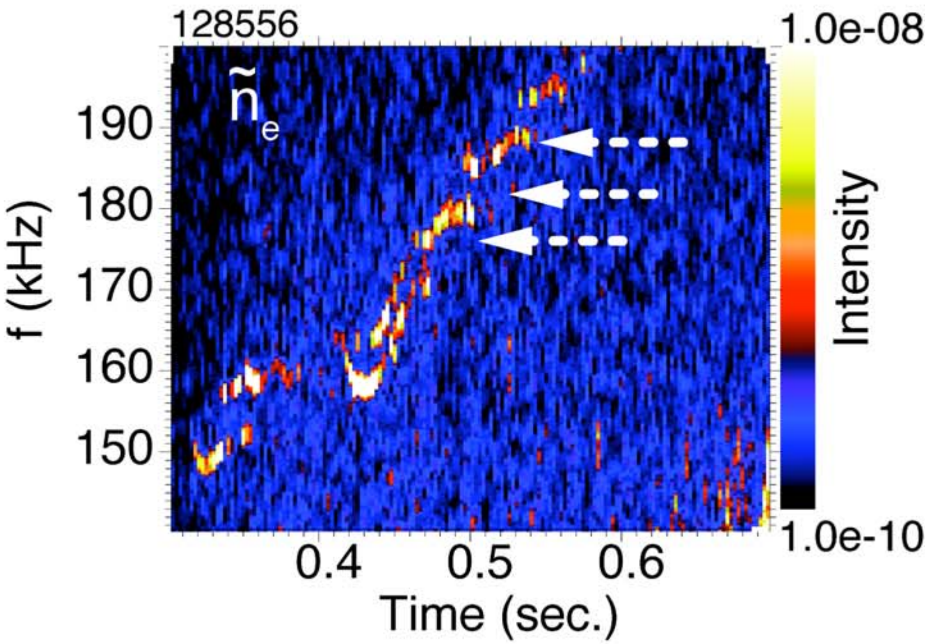
- TAE in JET and EAE in DIII-D are well matched: $V_{||}/V_{RES} \approx 0.5$

Outline

- **Observation of Alfvén wave excitation below the fundamental resonance condition in DIII-D and JET**
- **Ideal MHD analysis of radial mode structure, location**
- **Stability analysis and coupling to high order resonances**
- **Implications**

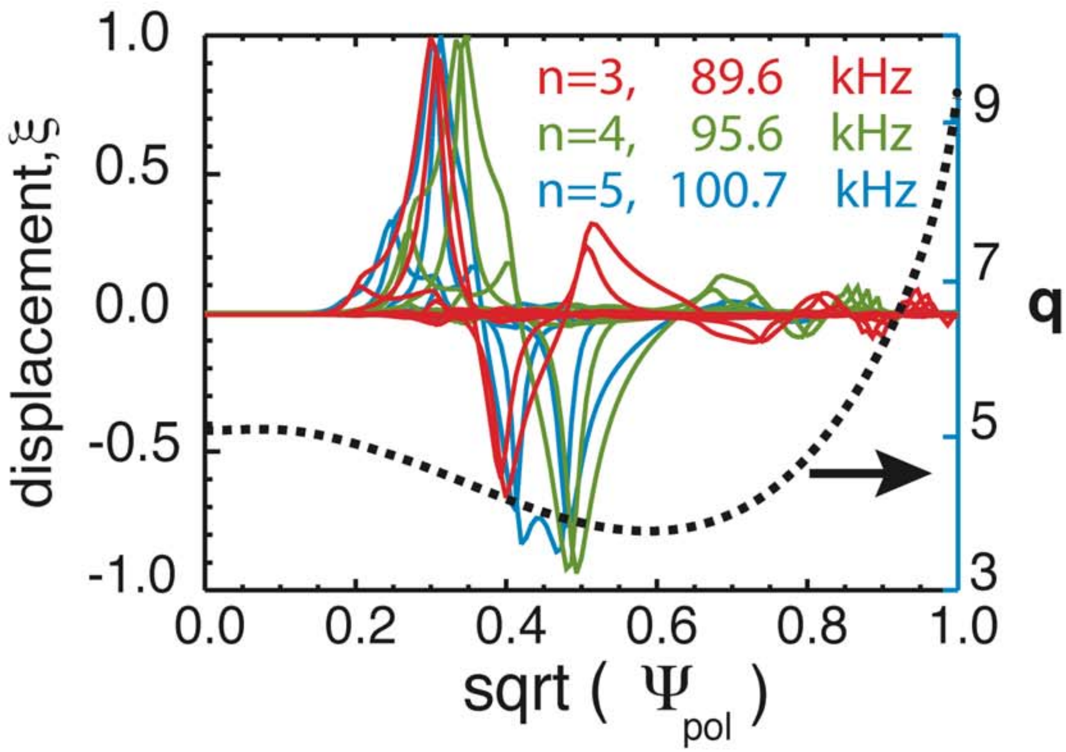
Eigenmode Analysis Confirms Localization of EAEs to the Reverse Magnetic Shear Region of DIII-D

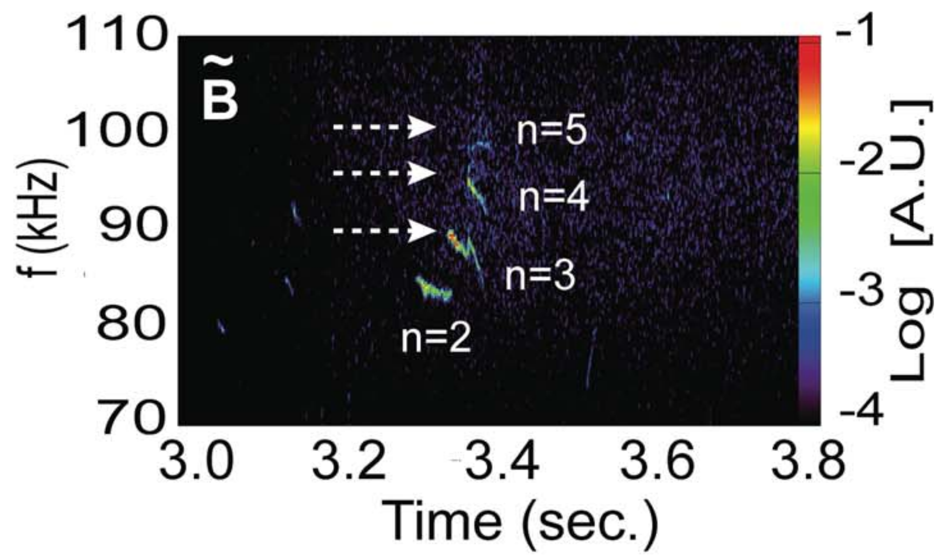




- **Mode frequencies agree with experiment**
- **Core localization agrees with EC emission measurements**

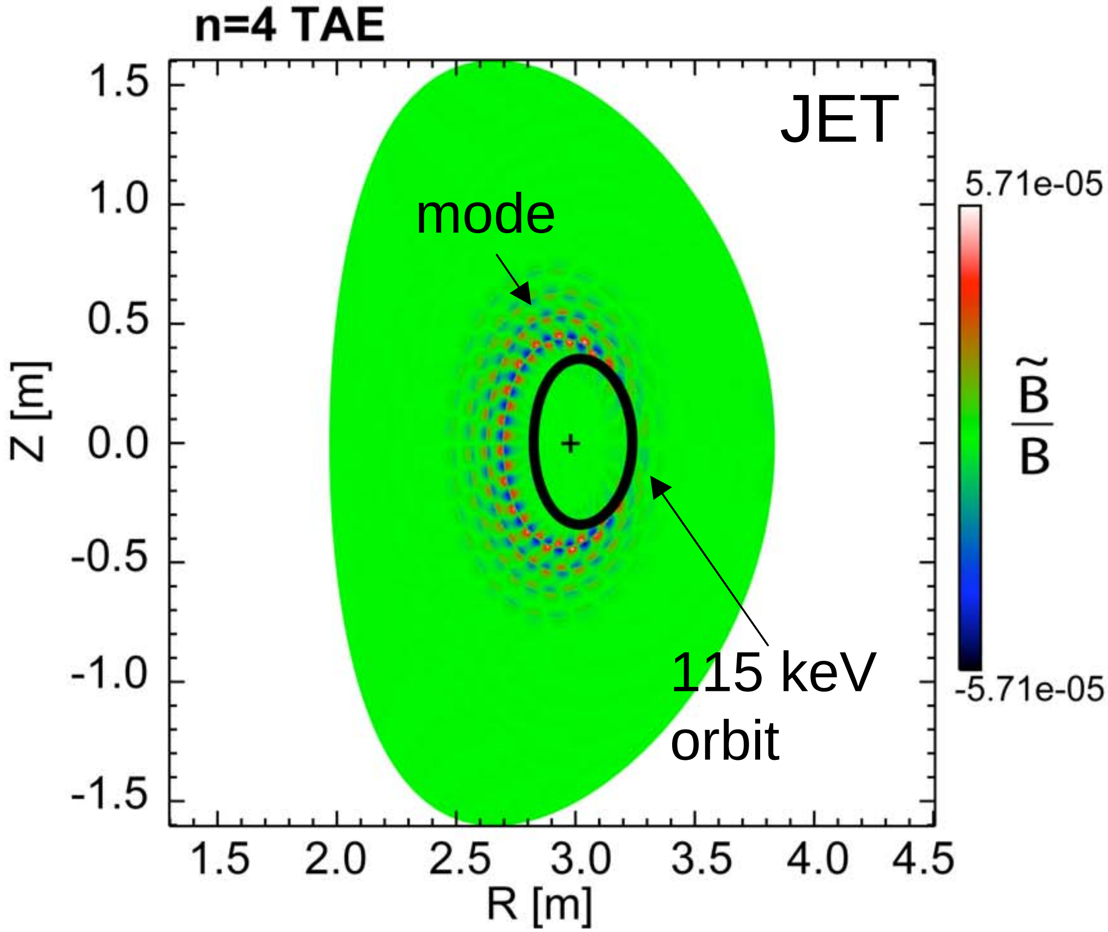
Eigenmode Analysis Confirms Localization of TAEs to the Reverse Magnetic Shear Region of JET

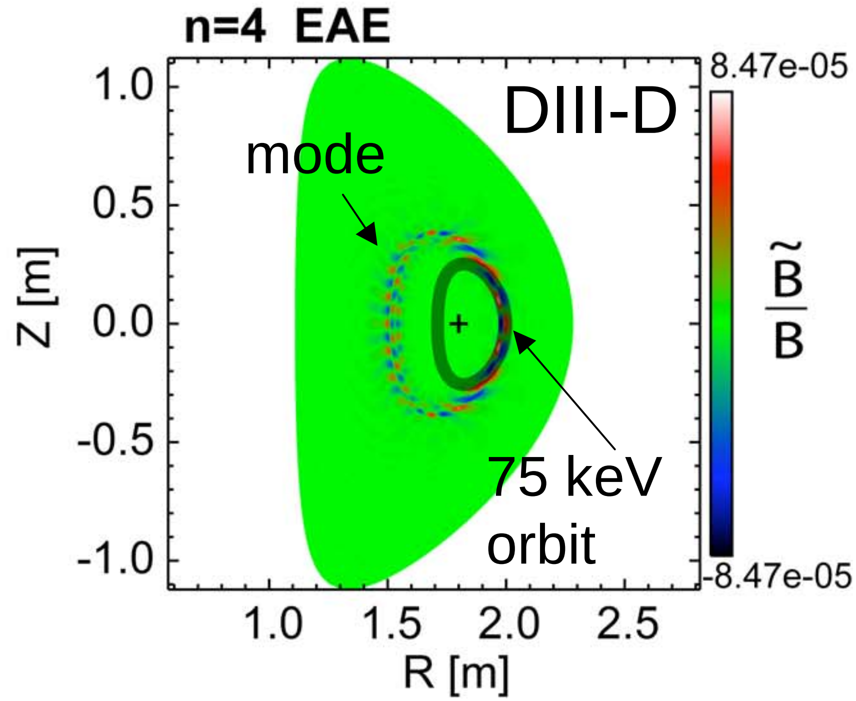




- **Calculations agree with magnetic measurements for mode frequency and toroidal mode number (n=3, 4, 5)**
- **Core localization confirmed from central interferometer measurements**

Short Poloidal Wavelength and Large Beam Ion Drift Orbits in JET and DIII-D Reverse Shear Plasmas





- **$k_\theta\rho \approx 1$ in JET and ≈ 2 in DIII-D, expect high order resonances**

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Outline

- **Observation of Alfvén wave excitation below the fundamental resonance condition in DIII-D and JET**

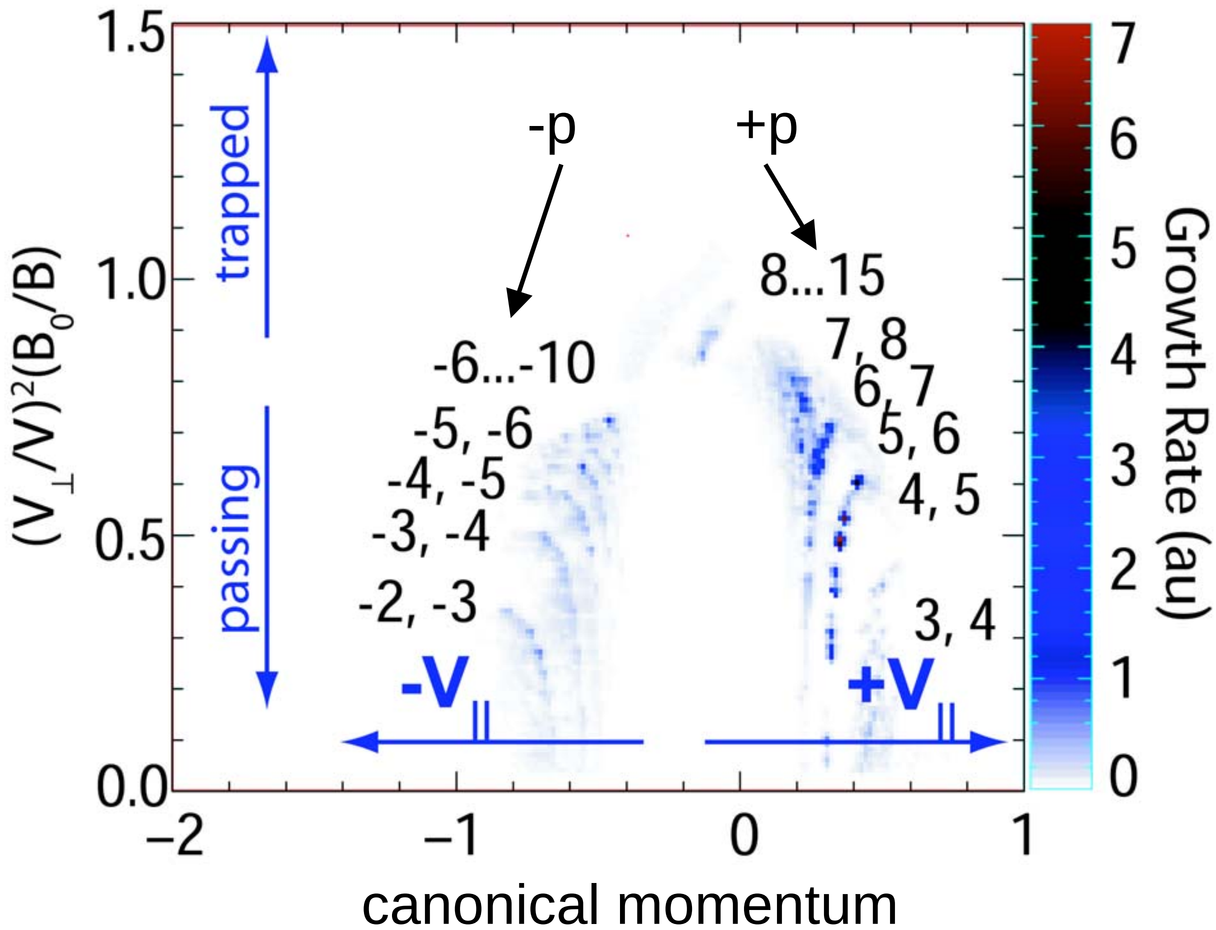
- **Ideal MHD analysis of radial mode structure, location**

- **Stability analysis and growth rate from high order resonances**

- **Implications**

NOVA-K Analysis Reveals Many High Order Resonances Contribute to Mode Drive for EAEs in DIII-D

- $V_{||} \propto \omega/p$ at high p
- p=const.→ $V_{||}$≈const.
- 75 keV ions injected into region of strong high order resonances



- Scattering of co-injected 75 keV ions into counter going orbits calculated using the TRANSP code

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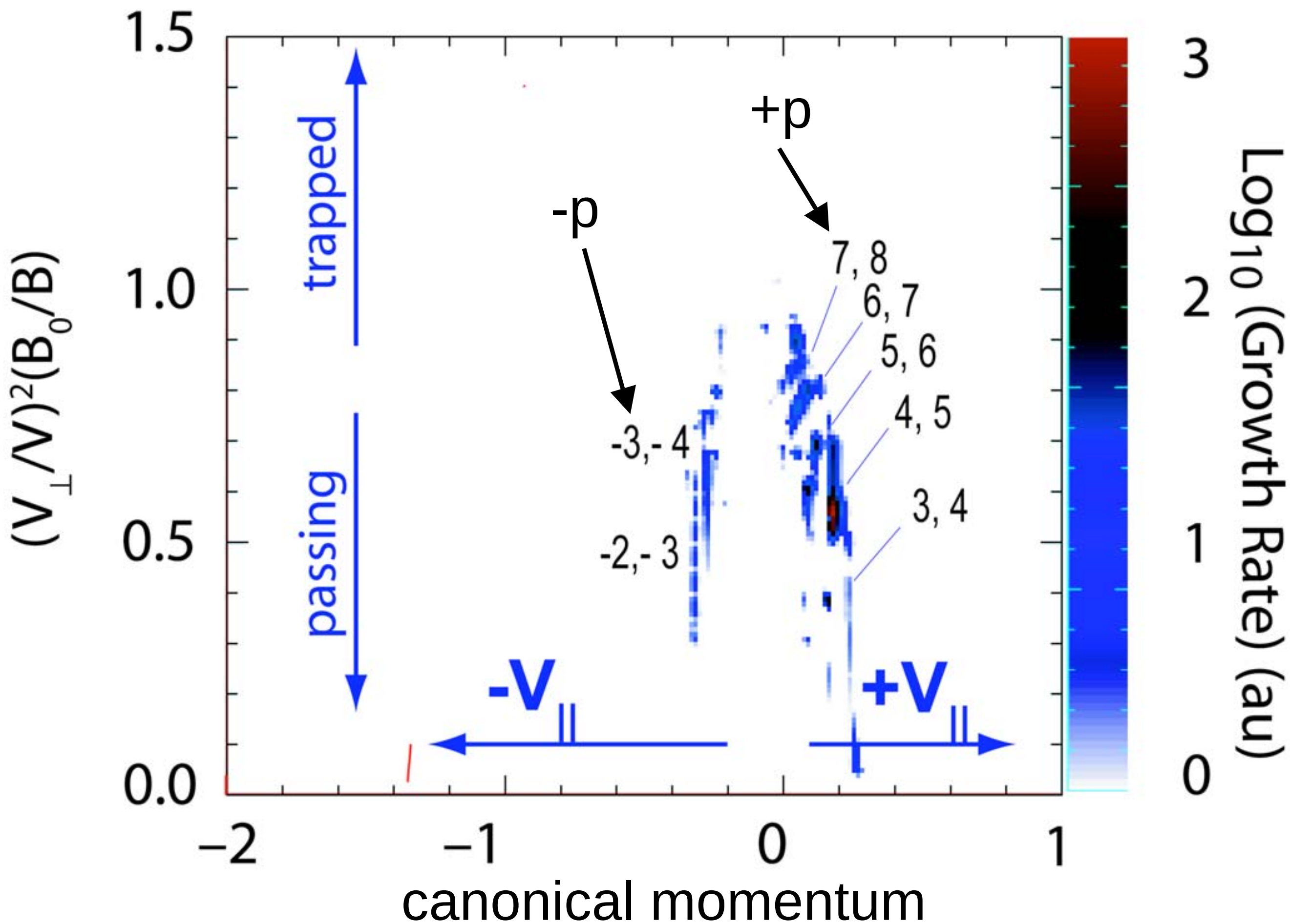
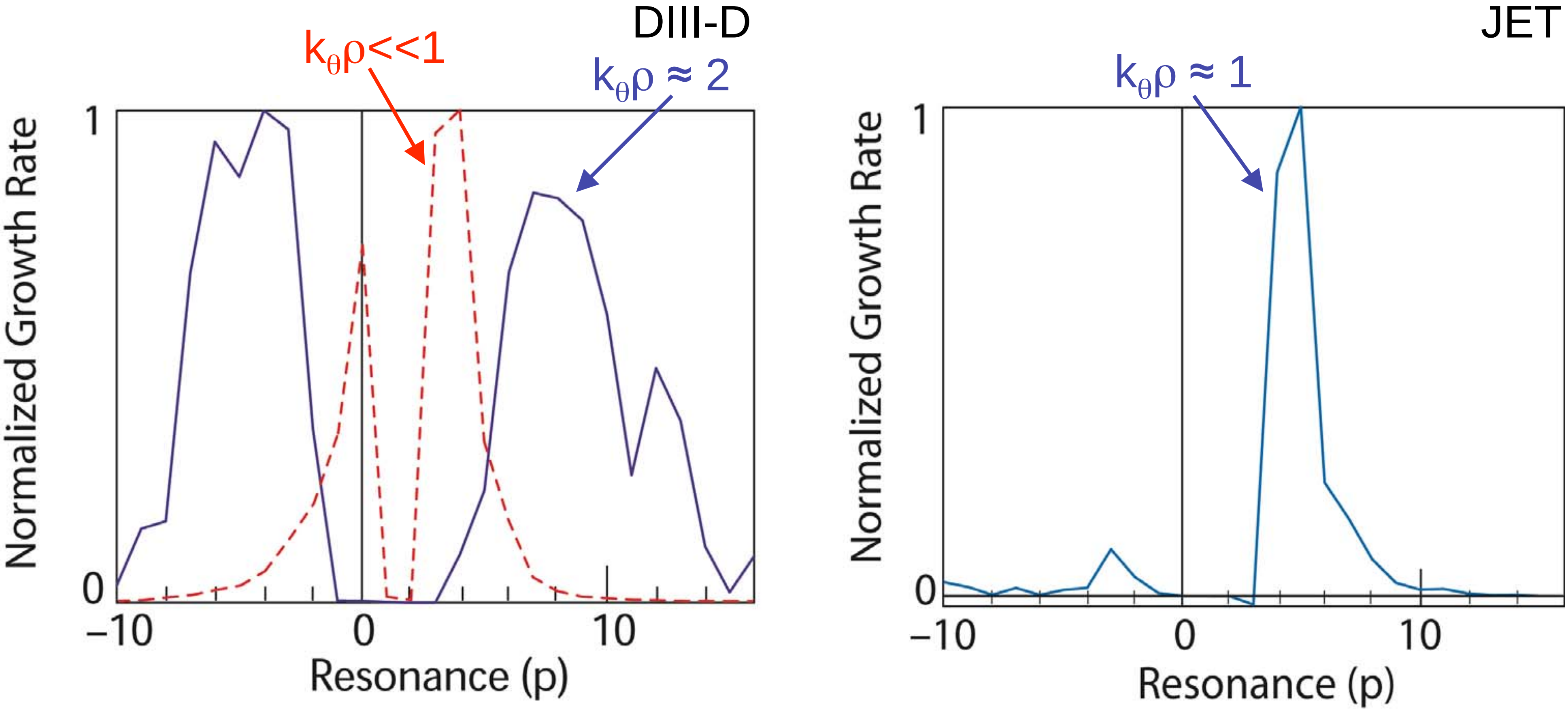
NOVA-K Analysis Reveals Dominant High Order Resonances Contribute to Mode Drive for TAEs in JET

- **115 keV ions injected into region of strong p=4,5 resonances**
- **All resonances are for passing ions**



- **Scattering of co-injected 115 keV ions into counter going orbits calculated using the TRANSP code**

Contribution to Mode Drive from co-going Beam Ions Comes Mostly From p=6-10 in DIII-D and p=4-5 in JET



- **Forcing $k_\theta\rho$<<1 in DIII-D shifts the spectrum down to the lowest accessible resonance; dramatically weakens drive**

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Simple Estimate of High Order Resonance Condition Consistent with NOVA-K Stability Analysis

	High order resonance	JET $V_{||} \approx 0.16\ V_A$	DIII-D $V_{||} \approx 0.23\ V_A$
RSAE	$V_{RES} \geq V_A/4p$	$p \geq 2$	$p \geq 1$
TAE	$V_{RES} \geq V_A/2p$	$p \geq 3$	$p \geq 2$
EAE	$V_{RES} \geq V_A/p$	$p \geq 6$	$p \geq 4$

- No clear velocity threshold for mode excitation, consistent with experiment
- EAE not seen in JET plasma, consistent with higher threshold

High Order Resonance Excitation of Alfvén Waves Confirmed in High-q Regimes on JET and DIII-D

- **Large drift orbits and high k_θ at high-q are key to excitation**
- **Implications**
  - No sharp velocity threshold
  - Resonance can extend over a large region of phase space
  - Fast ion transport induced by these multiple resonances needs to be assessed

- **In ITER, growth rate peaks For $k_\theta \rho_\alpha \approx 1$ (n=8-20)**
  - High order resonances will contribute to mode drive in steady state regimes
- **Future work: Identify losses associated with these resonances**