# Control of gradient-driven instabilities through nonlinear interaction with shear Alfvén waves

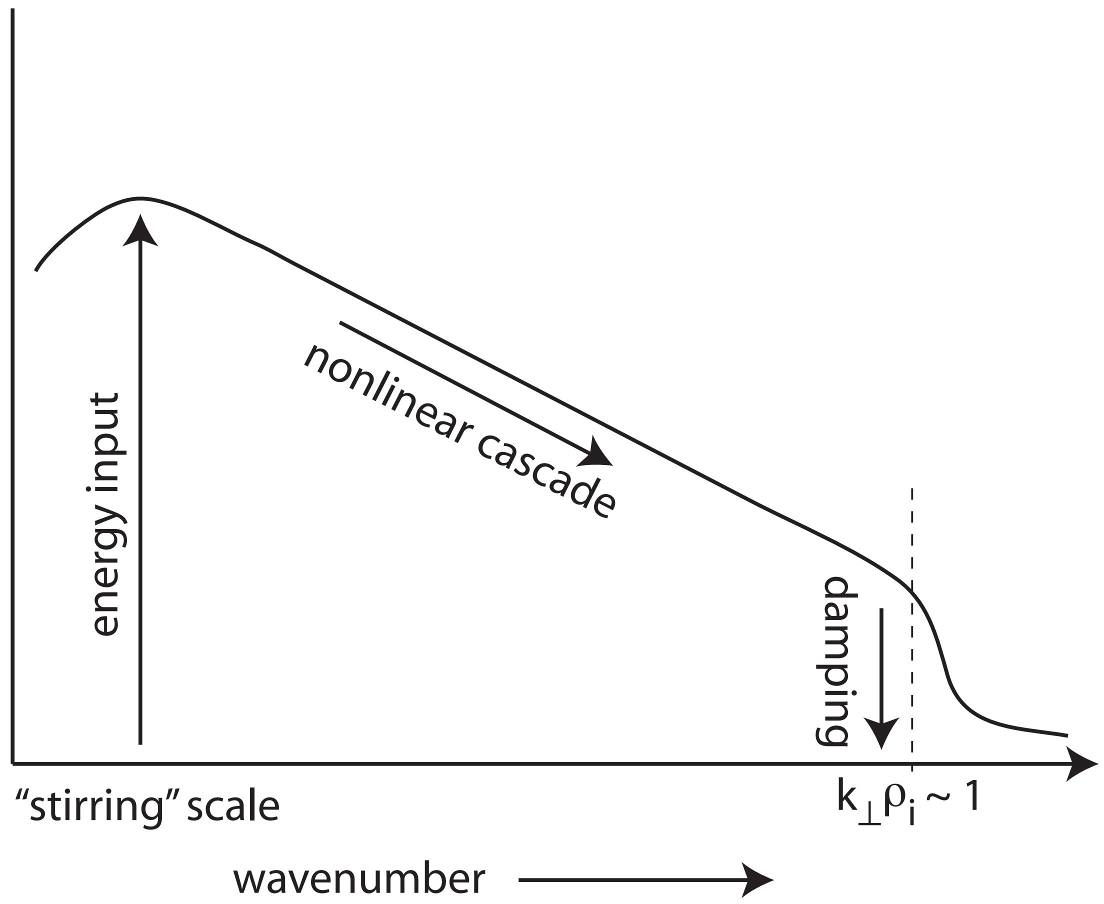
T.A. Carter, D. Auerbach, B. Brugman, S. Vincena,
P. Popovich, P. Pribyl

Dept. of Physics and Astronomy, UCLA

# Summary/Outline

- Study of the nonlinear properties of fundamental waves in a laboratory plasma (Large Plasma Device at UCLA)
- Wave-wave interactions among kinetic shear Alfvén waves in uniform plasma
  - Quasimode driven nonlinearly by beating of co-propagating Alfvén waves [T.A. Carter, B. Brugman, P. Pribyl, W. Lybarger, PRL (2006)]
- In nonuniform plasma, SAW beat wave interacts with gradient-driven instability [D.W. Auerbach, T.A. Carter, S. Vincena, P. Popovich, arXiv: 1004.0647, PRL accepted]
  - Unstable mode suppressed (synchronized?) in favor of driven second mode, overall fluctuation amplitude reduced

# Why do we care about Alfvén wave interactions?




- Low frequency turbulence in magnetized plasma (e.g. solar wind, accretion disk)
- Energy is input at "stirring" scale (e.g. MRI in accretion disk, tearing mode or Alfvén Eigenmode in tokamak or RFP) and cascades nonlinearly to dissipation scale

- From a weak turbulence point of view, cascade is due to interactions between linear modes: Alfvén waves
- Laboratory study of wave-wave interactions among antenna-launched Alfvén waves

# Understanding of drift turbulence and transport critical for magnetic confinement fusion

- Gradient-driven instabilities responsible for rapid cross-field transport of heat, particles and momentum in magnetic confinement devices

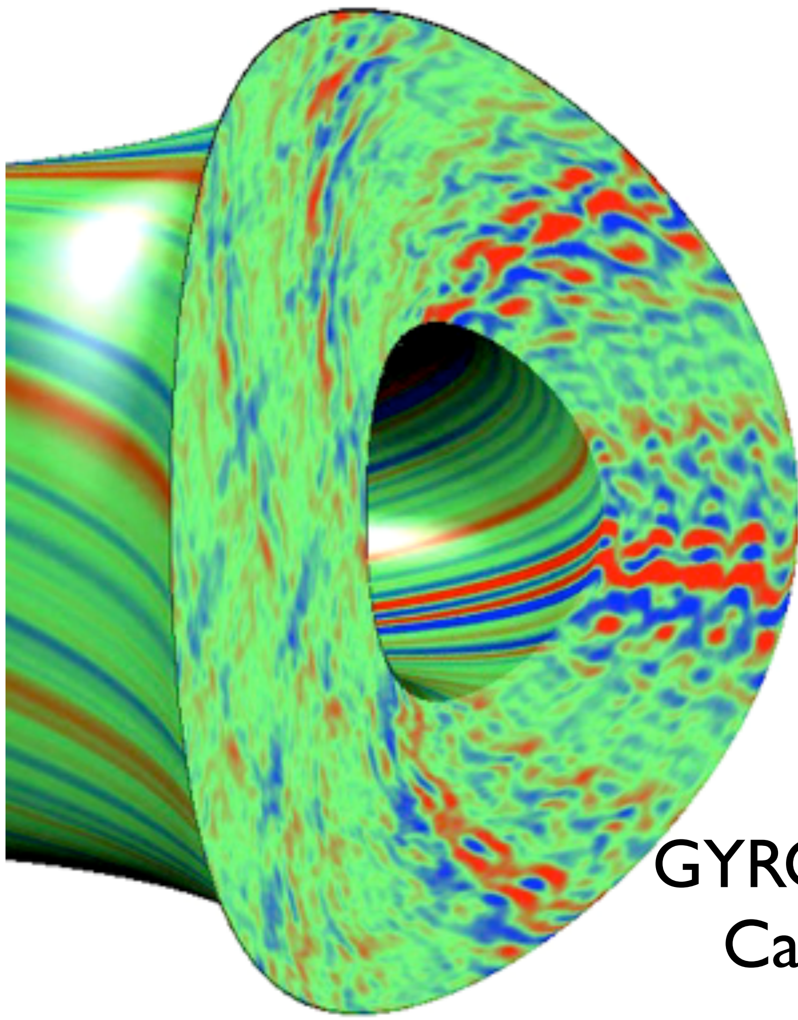
- Size of ITER set largely by transport considerations

GYRO Simulation
Candy, Waltz

- Turbulence and transport modified by flow/flow shear (H-mode, externally driven flow, e.g. biasing on LAPD [Carter & Maggs, PoP 16, 012304 (2009)])

- Can we find other ways to control turbulence and transport? Active control of drift instabilities, using externally launched waves?

# Understanding of drift turbulence and transport critical for magnetic confinement fusion

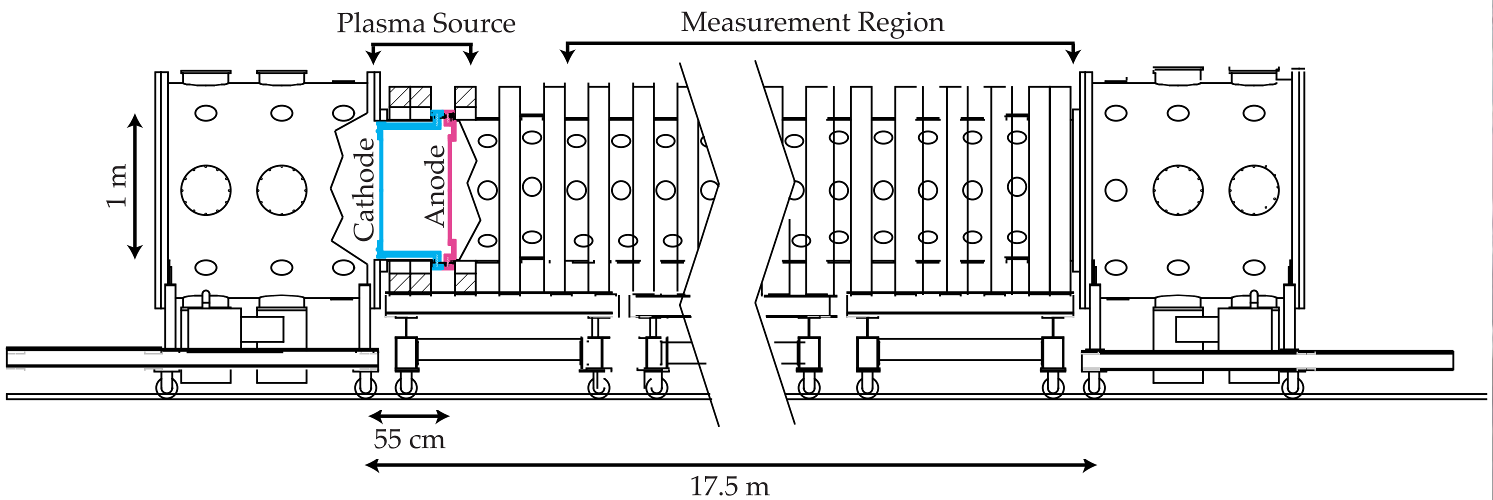


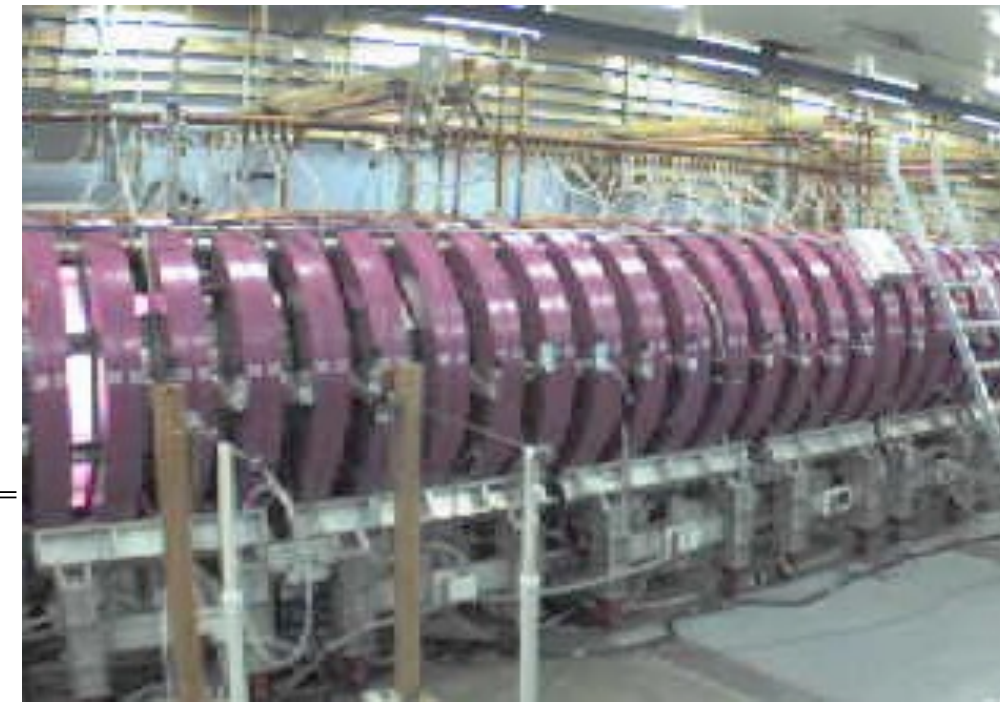
GYRO Simulation
Candy, Waltz

- Gradient-driven instabilities responsible for rapid cross-field transport of heat, particles and momentum in magnetic confinement devices
- Size of ITER set largely by transport considerations

- Turbulence and transport modified by flow/flow shear (H-mode, externally driven flow, e.g. biasing on LAPD [Carter & Maggs, PoP 16, 012304 (2009)])
- Can we find other ways to control turbulence and transport? Active control of drift instabilities, using externally launched waves?

# The LArge Plasma Device (LAPD) at UCLA

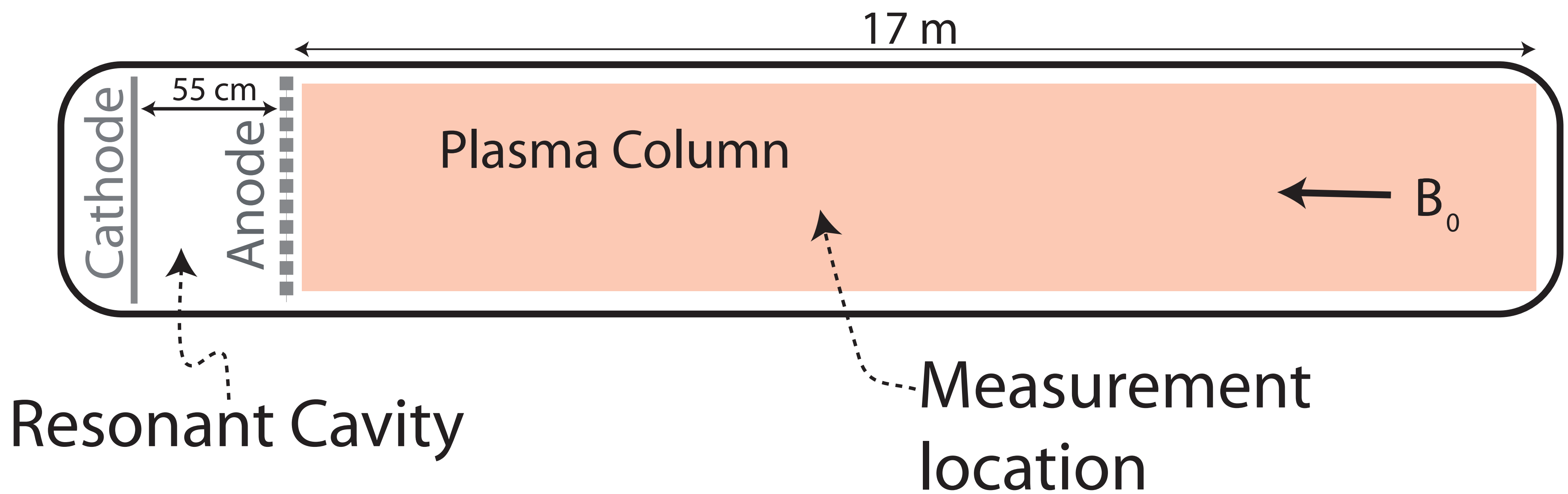


- US DOE/NSF sponsored user facility
- Solenoidal magnetic field, cathode discharge plasma
- $0.5 < B < 2\ \mathrm{kG}, n_e \sim 10^{12}\ \mathrm{cm}^{-3}, T_e \sim 5\ \mathrm{eV}, T_i \sim 1\ \mathrm{eV}$
- Large plasma size, D~60cm (1kG: ~300 $\rho_i$, ~100 $\rho_s$)
- High repetition rate: 1 Hz
- Similar parameters to tokamak far edge plasmas: can study basic processes relevant to fusion plasmas (drift turbulence, transport, intermittency, …)

# Wave source: cylindrical Alfvén eigenmodes in LAPD (Alfvén wave maser)

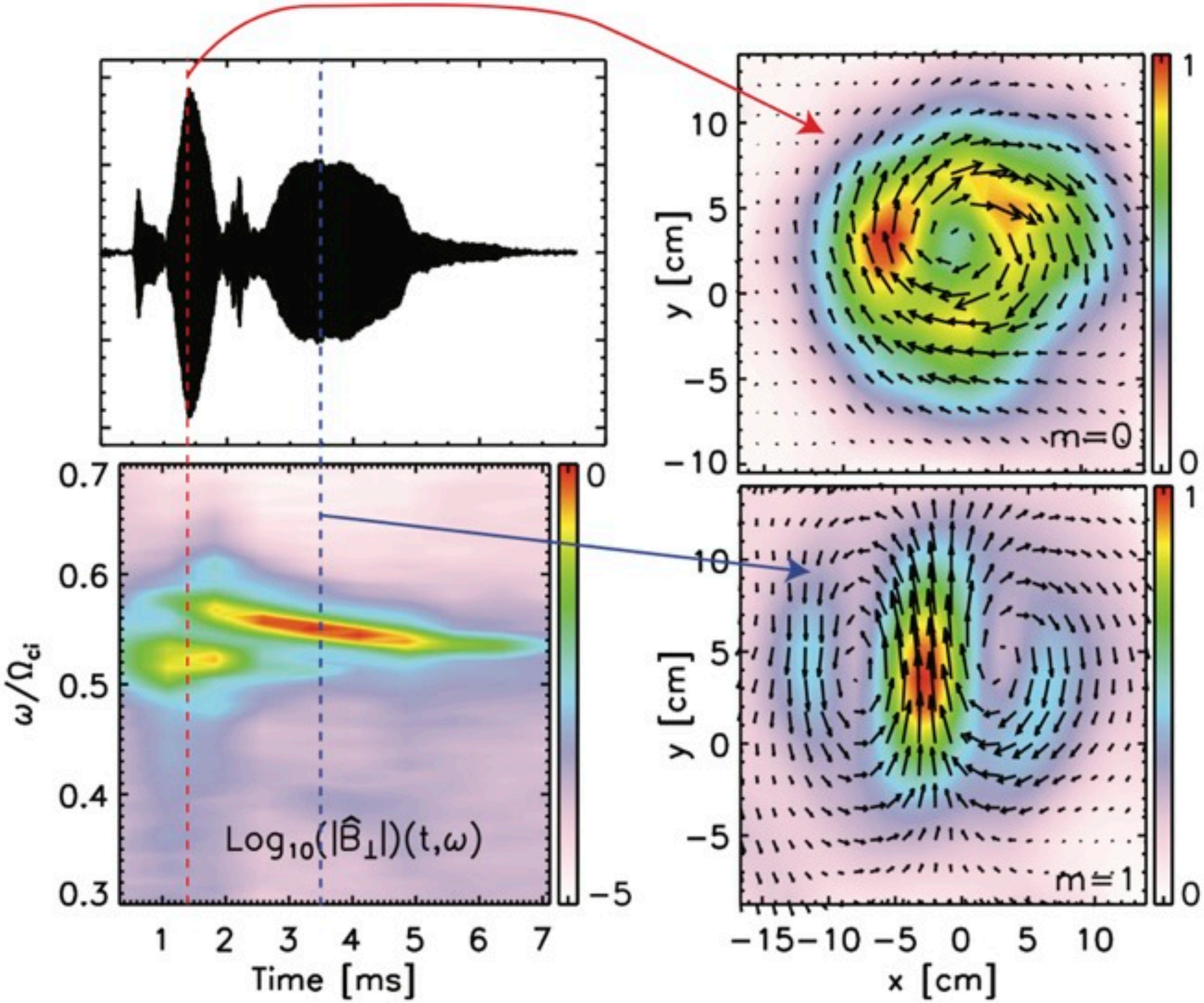
- Source region (cathode/anode) acts as cavity for shear Alfvén waves



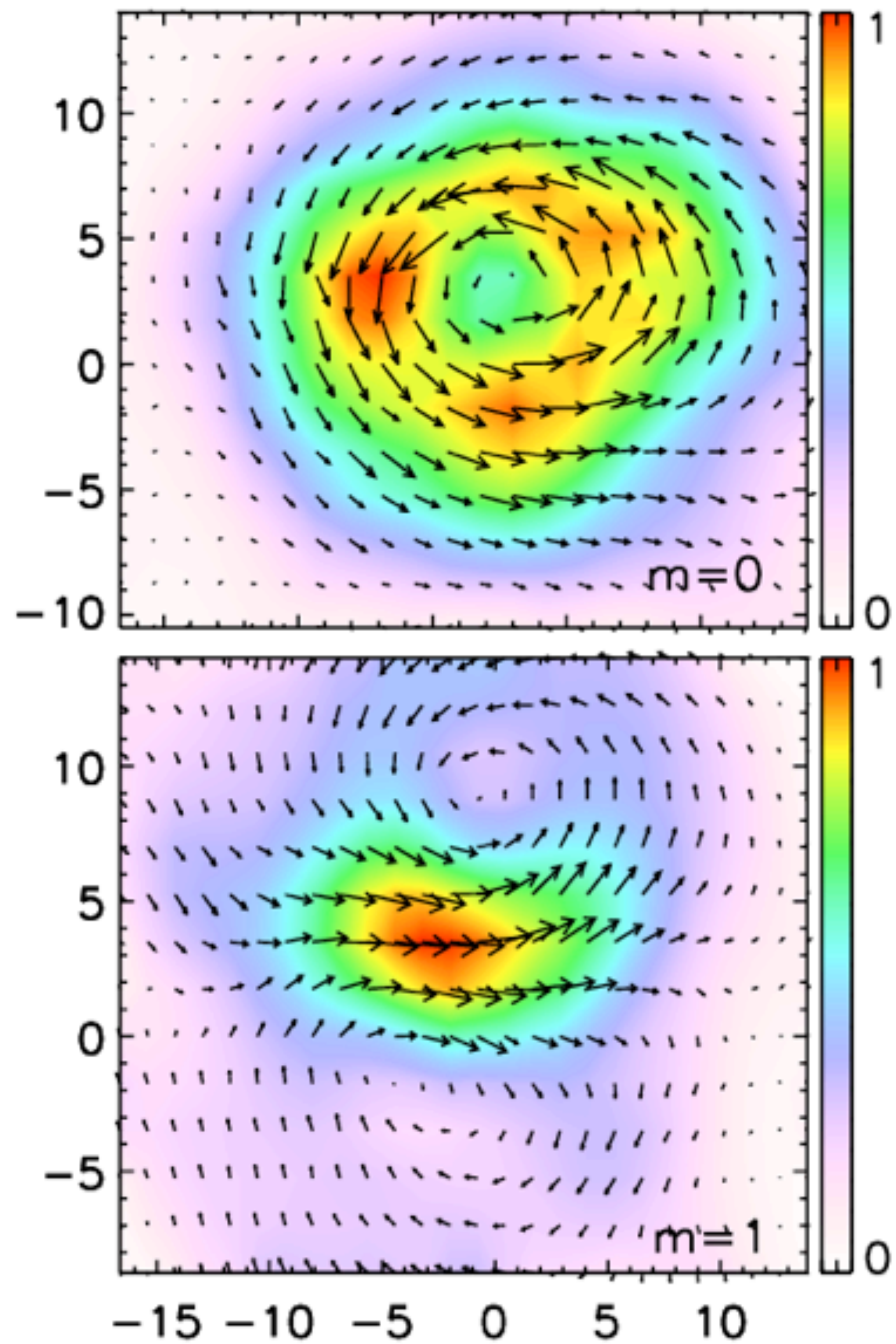

Maggs, Morales, PRL 91, 035004 (2003)

Maggs, Morales, Carter, PoP 12, 013103 (2005)

# Cylindrical Alfvén eigenmodes in LAPD (Alfvén wave maser)

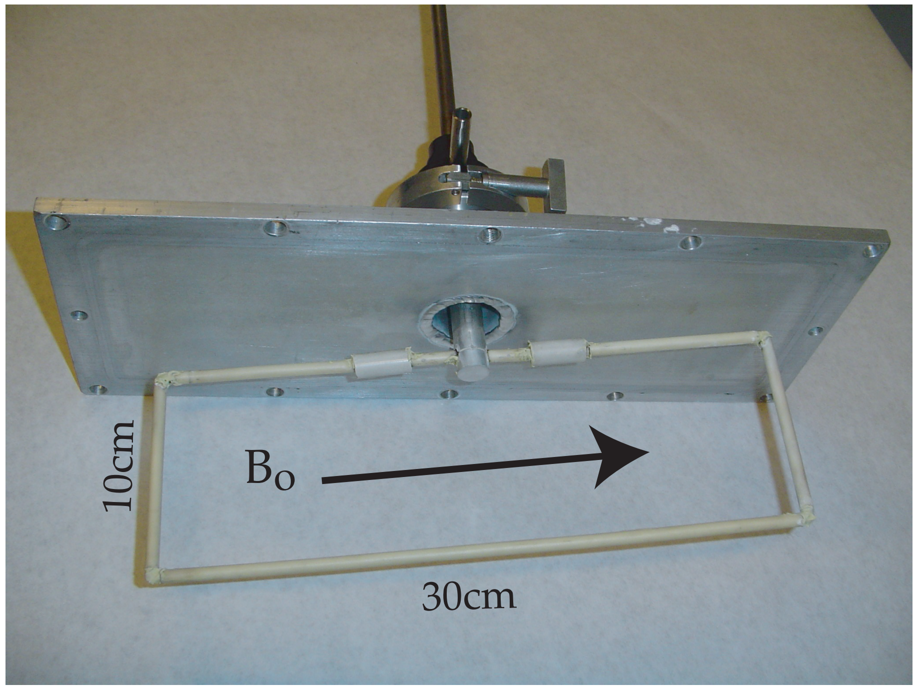


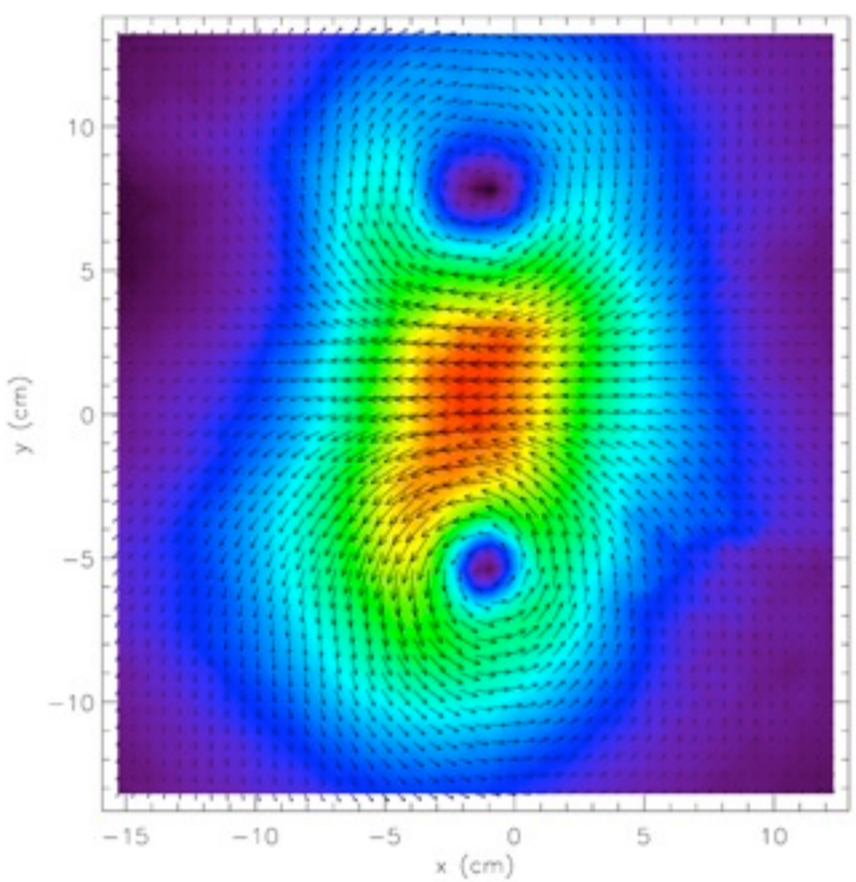

- Source region (cathode/anode) acts as cavity for shear Alfvén waves
- Get spontaneous emission of AWs when discharge current exceeds threshold
- See m=0, m=1 cylindrical eigenmodes

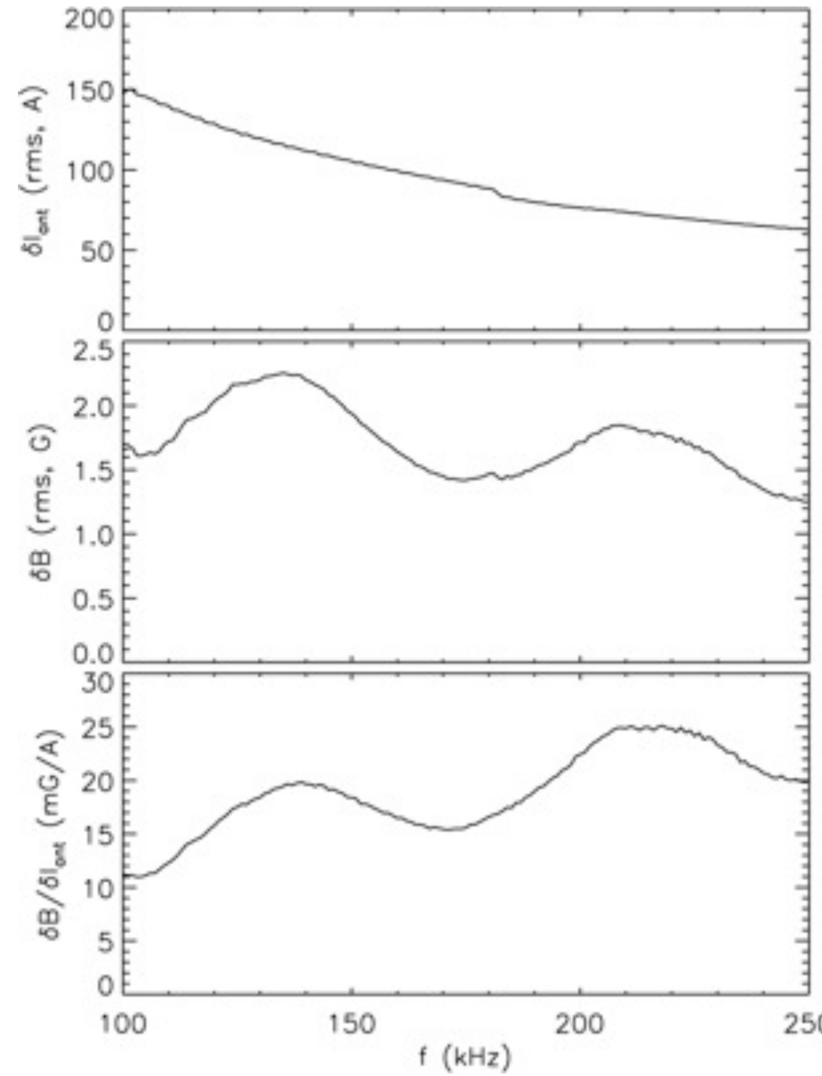


m=0
m=1
10
5
0
−5
−10
1
0
−15 −10 −5 0 5 10

# Antennas for generation of large amplitude Alfvén waves in LAPD



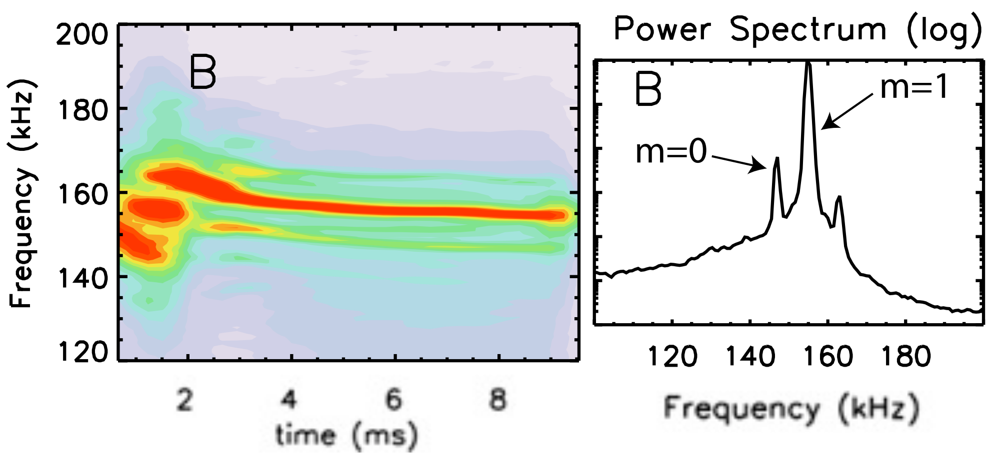




- Broadband excitation of large amplitude waves (up to 10G) using novel drivers (up to 1kA @ 1kV pulsed)
- More flexible than maser in generating wide range of frequencies

# Observation of co-propagating wave-wave interaction in LAPD

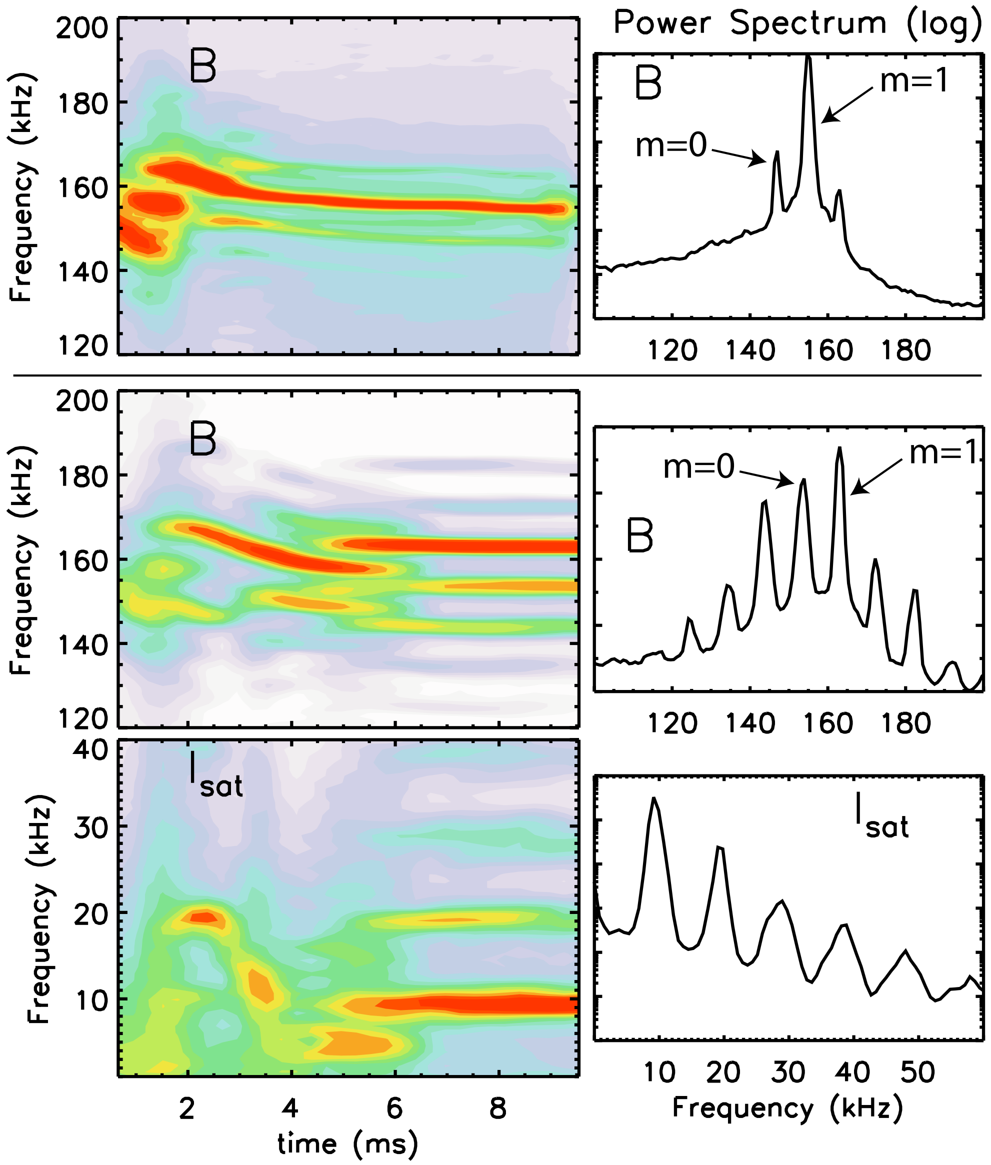
- Spontaneous multimode emission by the cavity is often observed, e.g. m=0 and m=1




T.A. Carter, B. Brugman, et al., PRL 96, 155001 (2006)

# Observation of co-propagating wave-wave interaction in LAPD

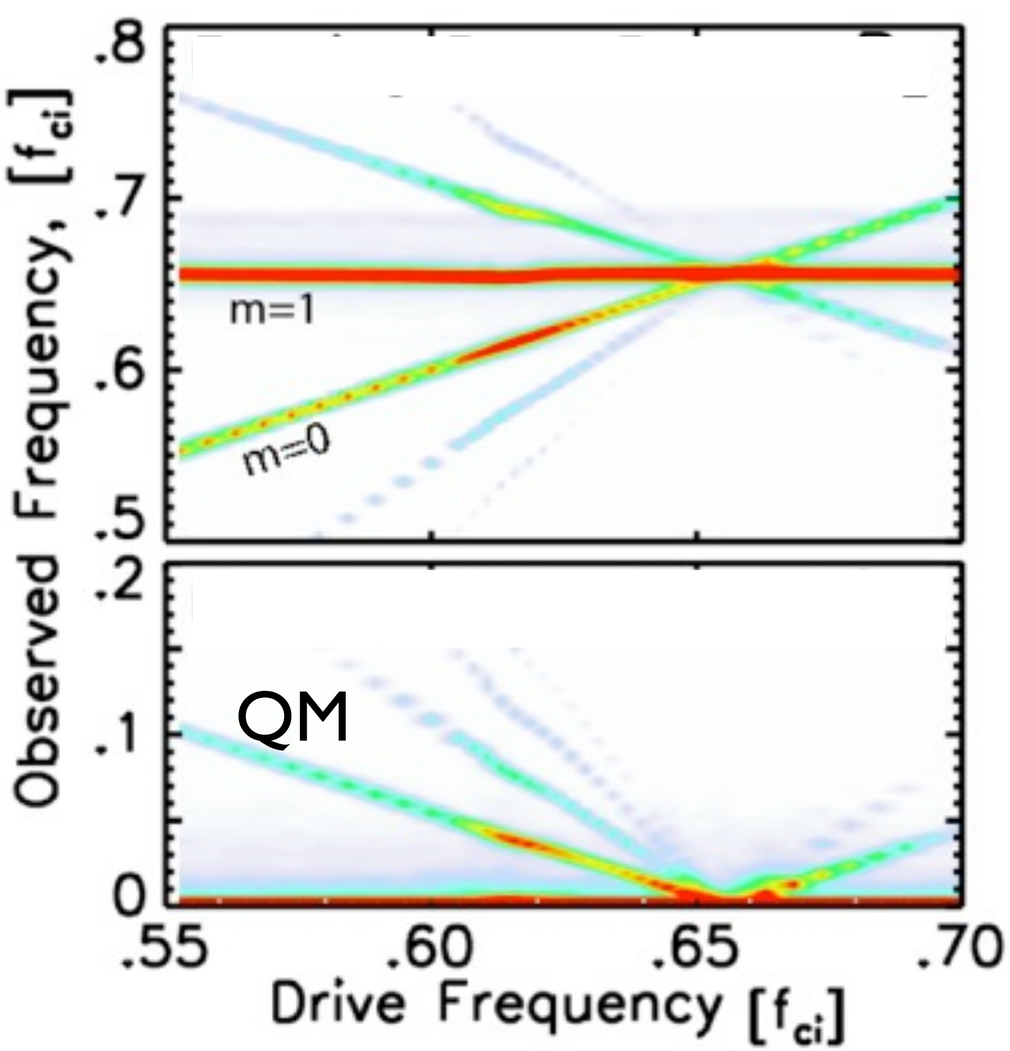
- Spontaneous multimode emission by the cavity is often observed, e.g. m=0 and m=1




- Can control multimode emission (e.g. current, shortening the plasma column)
- With two strong primary waves, observe beat driven quasimode which scatters pump waves, generating sidebands
- Strong interaction: "pump" $\delta B/B \sim 1\%$, QM $\delta n/n \sim 10\%$

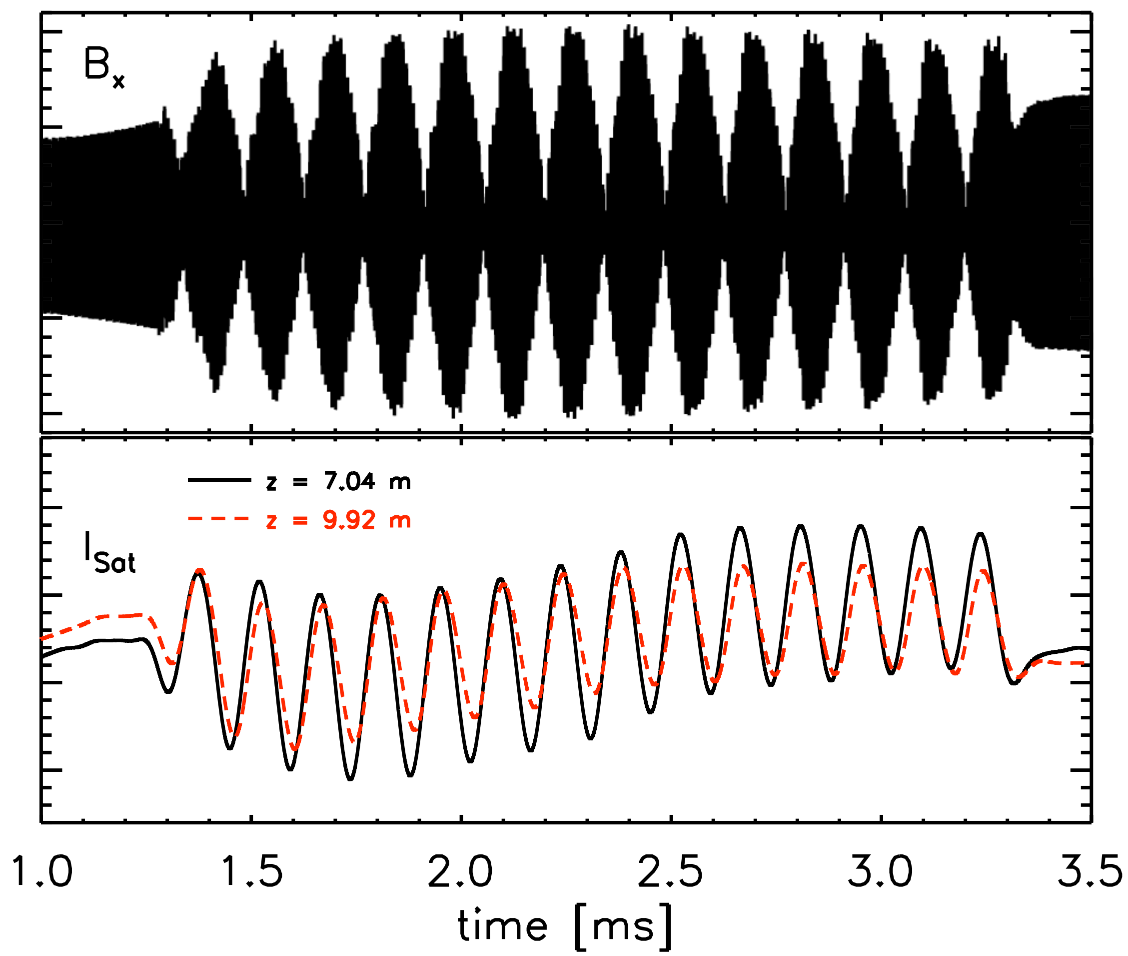
T.A. Carter, B. Brugman, et al., PRL 96, 155001 (2006)

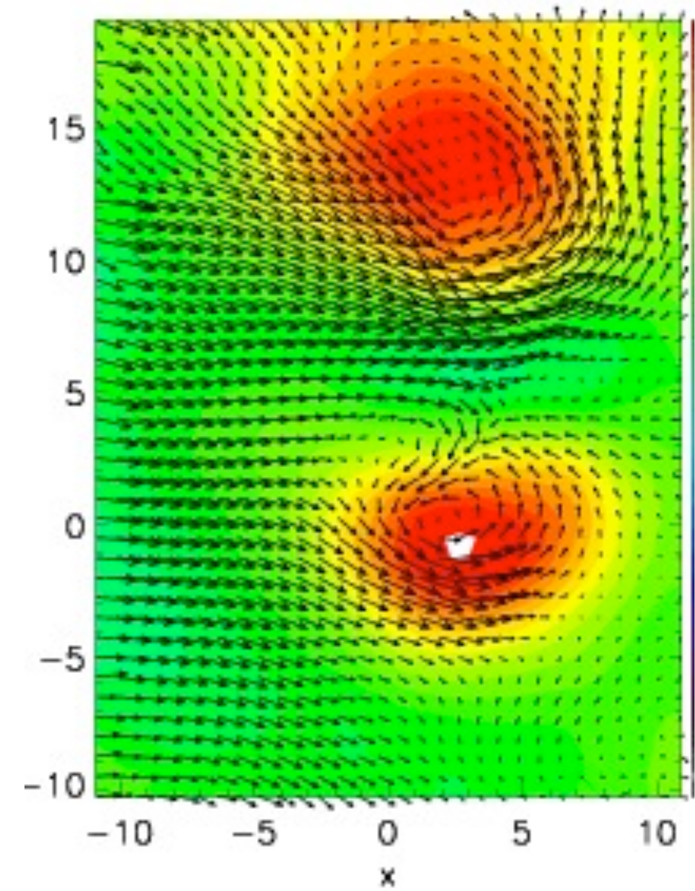
# Driven cavity, antenna launched waves used to study properties of interaction




Driven cavity: can produce QMs with range of beat frequencies (limited by width of cavity resonance for driven m=0)

# Antenna generated quasimodes

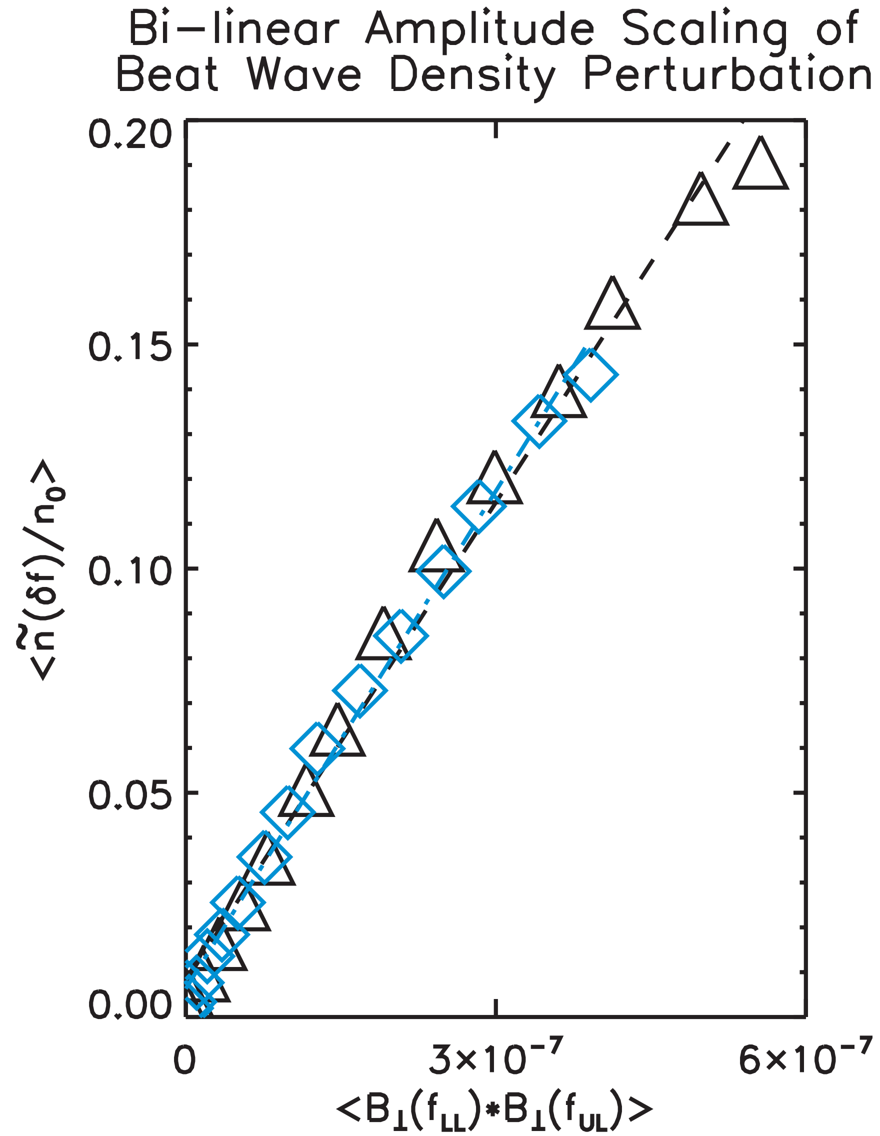


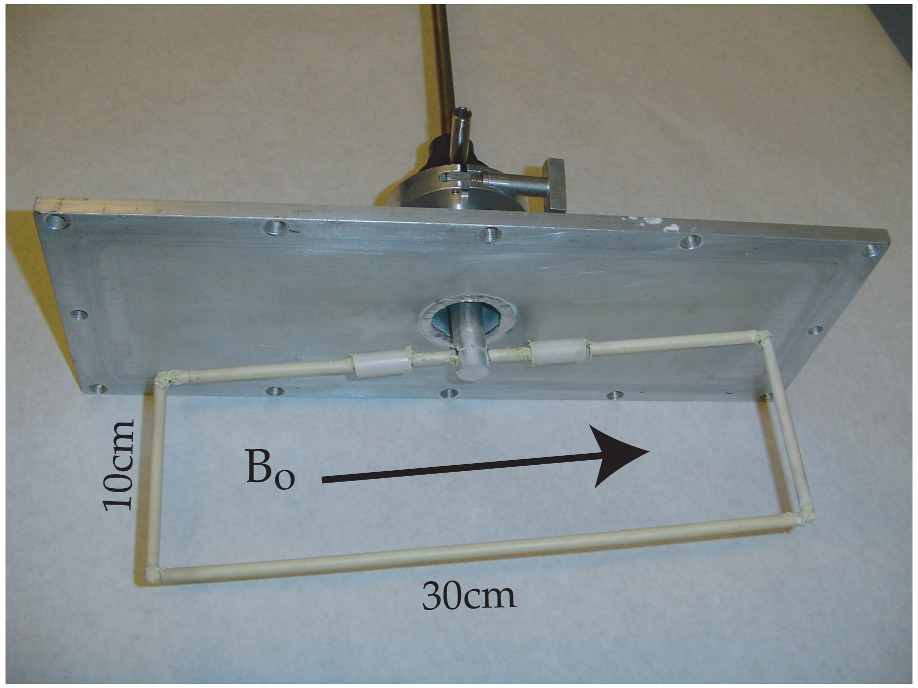




- Two antennas launch co-propagating AWs, which beat to generate quasimode
- QM localized to AW current channels in uniform plasma

# Driven cavity, antenna launched waves used to study properties of interaction

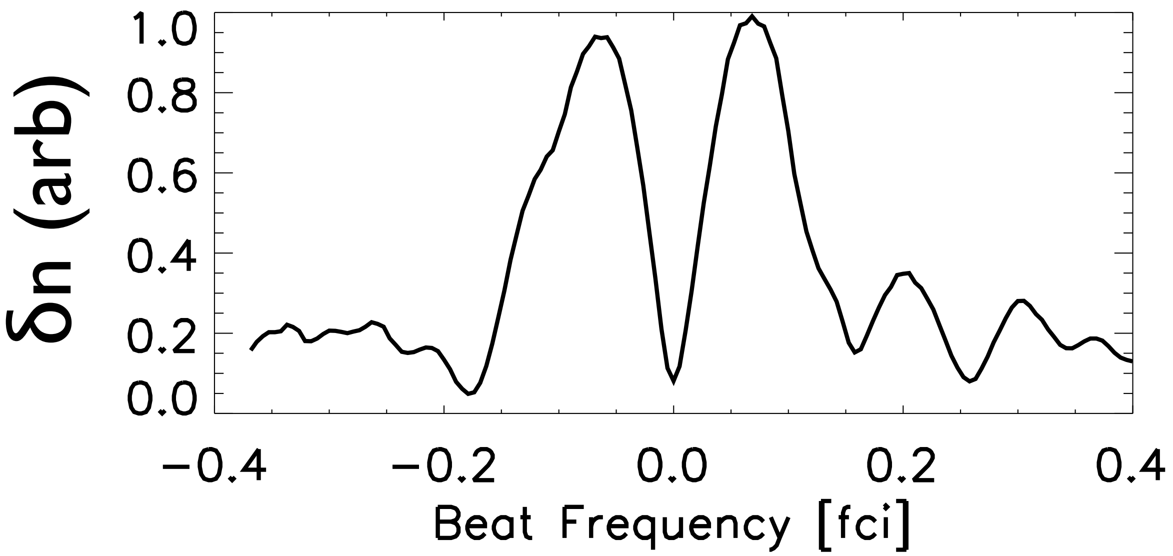
Interaction reproduced using antenna-launched waves (not restricted by cavity resonance), see bilinear amplitude scaling

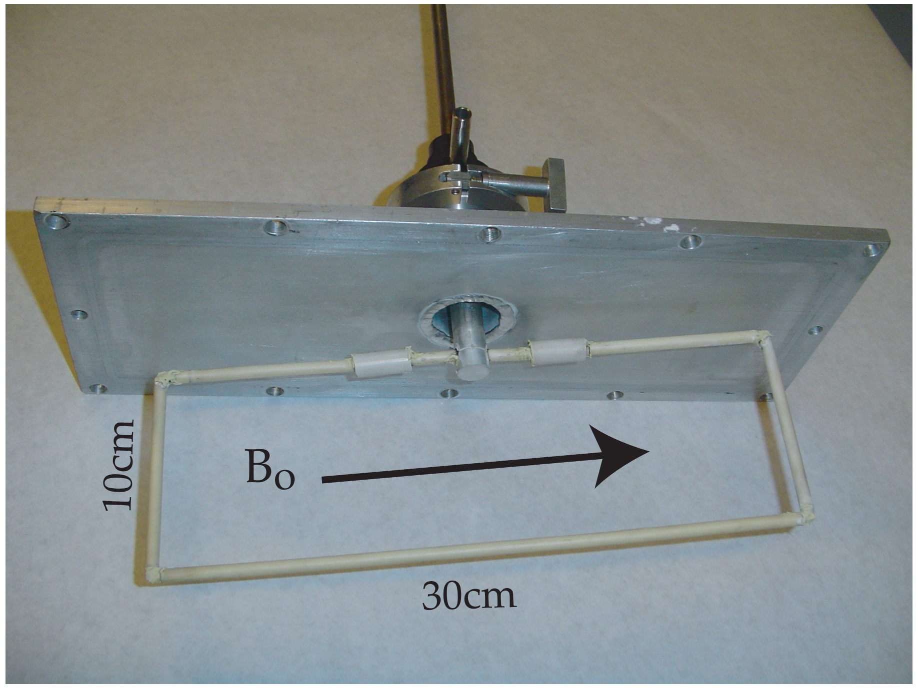


# Driven cavity, antenna launched waves used to study properties of interaction

Antenna-driven interaction: see resonant-like behavior versus driven beat-wave frequency



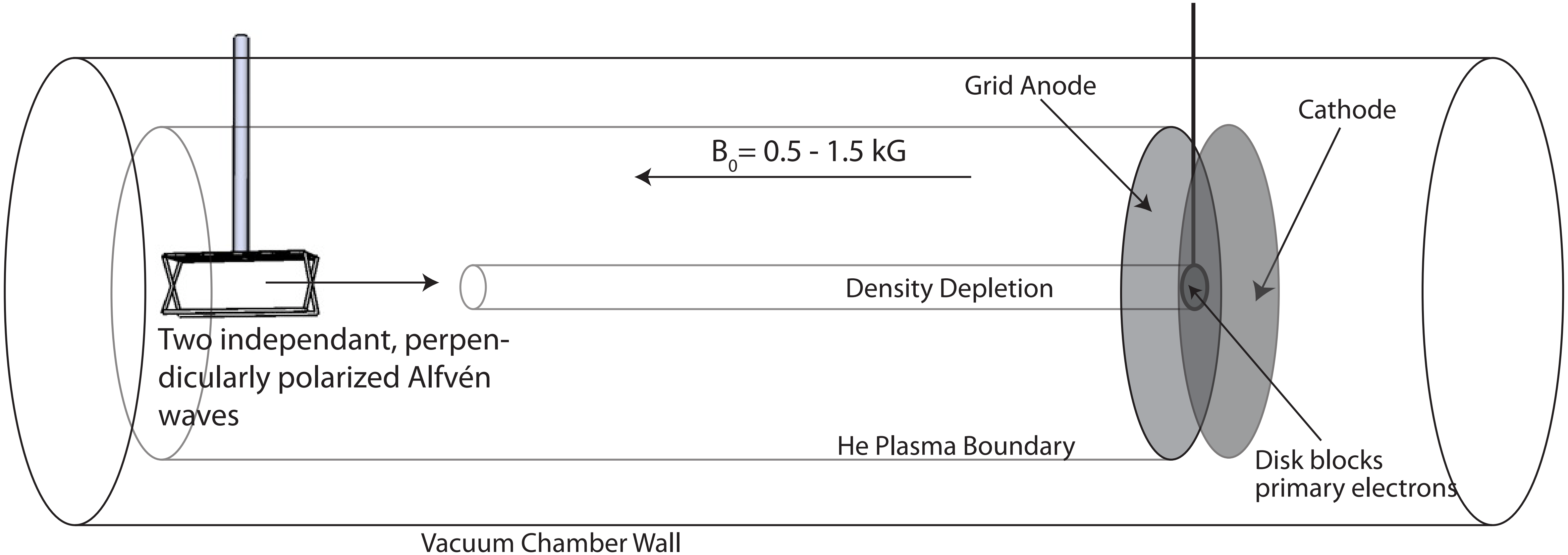
# Beat driven wave is off-resonance Alfvén wave; theory consistent with observed amplitude, resonant behavior

- Nonlinear Braginskii fluid theory, $k_\perp >> k_{||}$, $\omega/\Omega_{ci} \sim 1$

$$\frac{\delta n}{n_o} = \frac{\delta k_\perp v_A}{\Omega_{ci}} \frac{k_{\|,1} v_A}{\Omega_{ci}} \frac{k_{\|,2} v_A}{\Omega_{ci}} \frac{\left( \frac{(\delta k_\perp + 2k_{\perp,1}) v_A}{\Omega_{ci}} \left( 1 + 2\frac{\Omega_{ci}}{\delta\omega} \right) - \frac{\delta k_\perp v_A}{\Omega_{ci}} \right)}{\left( 1 - \left( \frac{\delta\omega}{\delta k_\| v_A} \right)^2 \right)} \left[ \frac{B_1^* B_2}{B_o^2} \right]$$

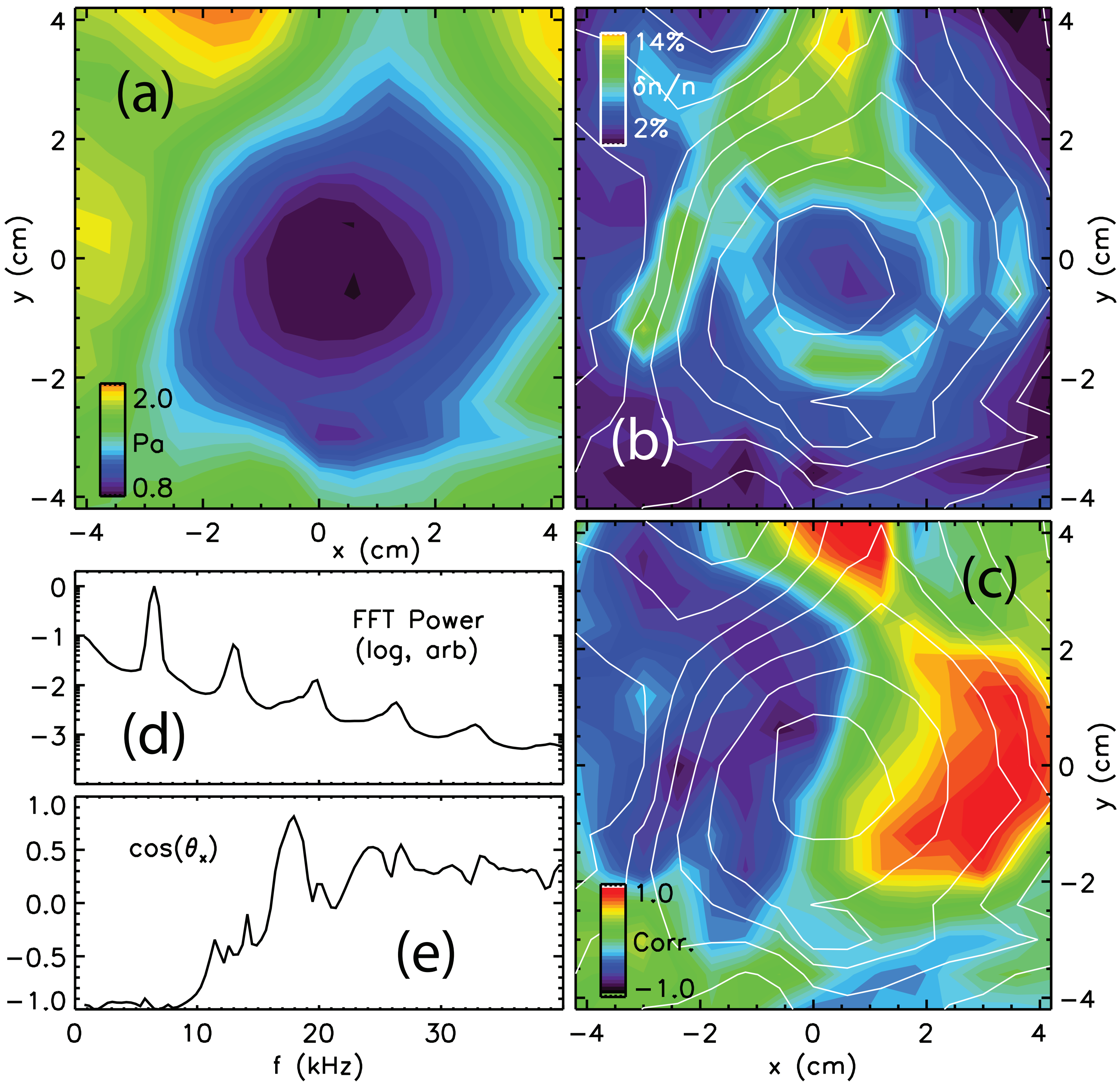
- Exhibits resonant behavior (for Alfvénic beat wave) - reasonable agreement with experiments
- Ignoring resonant demoninator, $\delta n/n \sim$ 1-2% for LAPD parameters
- Dominant nonlinear forcing is perpendicular (NL polarization drift): easier to move ions across the field to generate density response due to $k_\perp >> k_{||}$

# KAW beat-wave/instability interaction experiment




- Density depletion formed by inserting blocking disk into anode-cathode region, blocking primary electrons therefore limiting plasma production in its shadow
- Instability grows on periphery of striation/depletion (drift-Alfvén waves studied in depth [Burke, Peñano, Maggs, Morales, Pace, Shi… ])
- Launch KAWs into depletion, look for interaction

# Unstable fluctuations observed on depletion

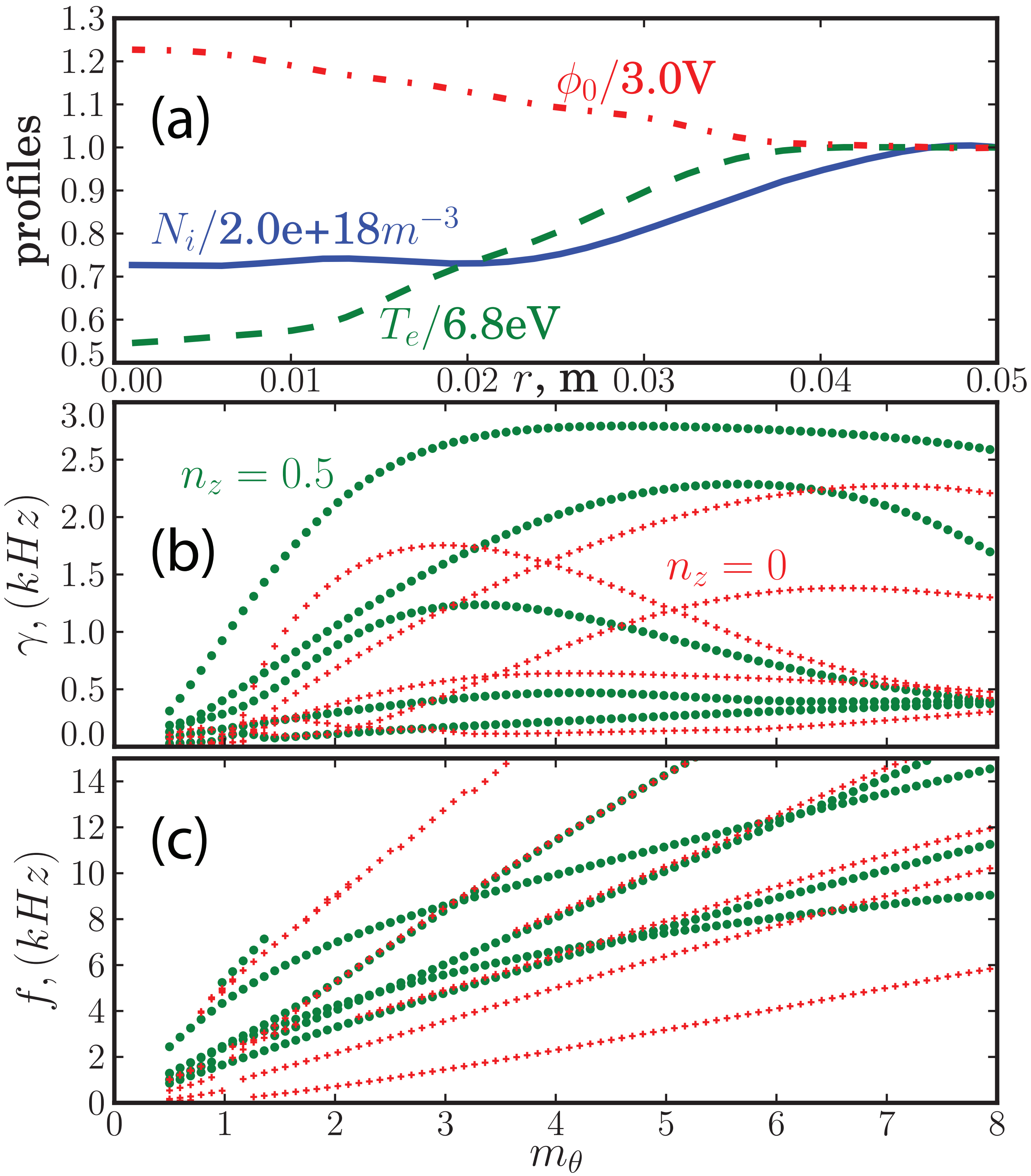



- m=1 coherent fluctuation observed localized to pressure gradient
- Drift-Alfvén wave?

$$\frac{\delta n}{n} \sim \frac{e\delta\phi}{k_B T_e}$$

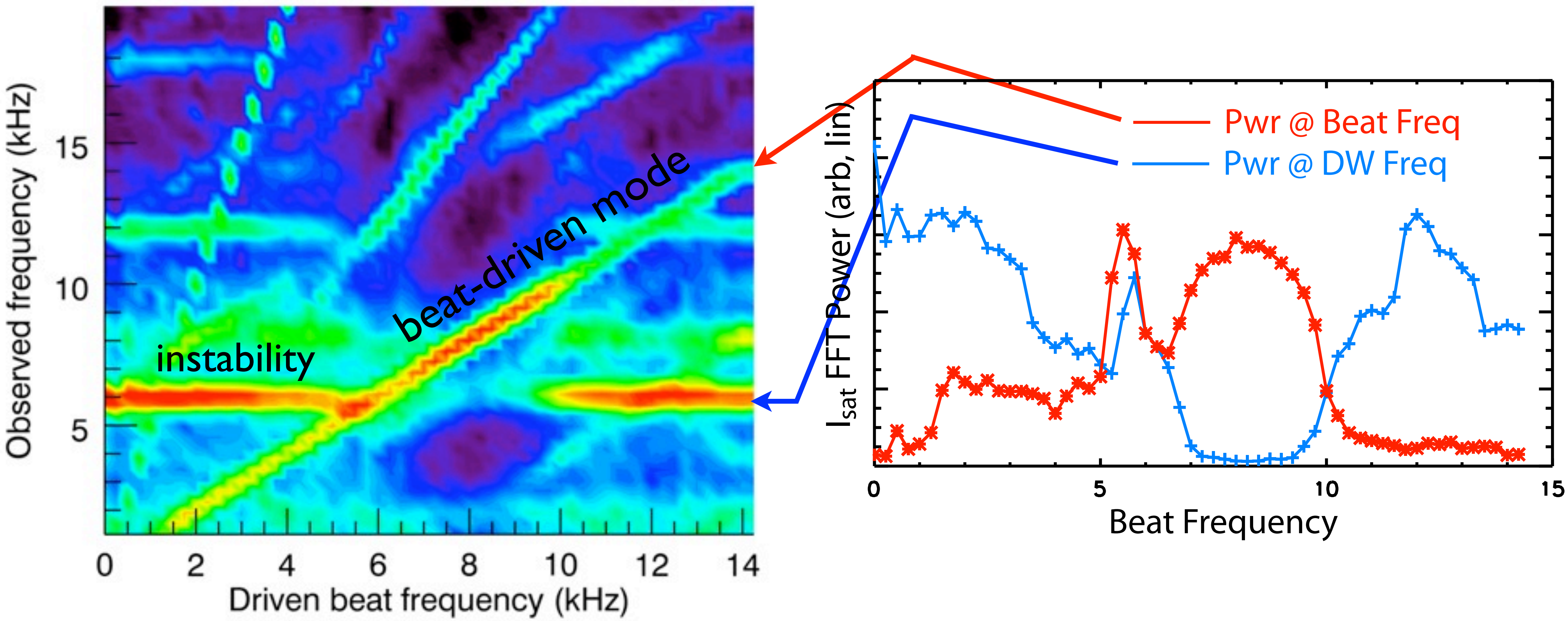
- However, Density-potential cross-phase (~180) inconsistent

# Both pressure gradient and shear flow driven modes unstable



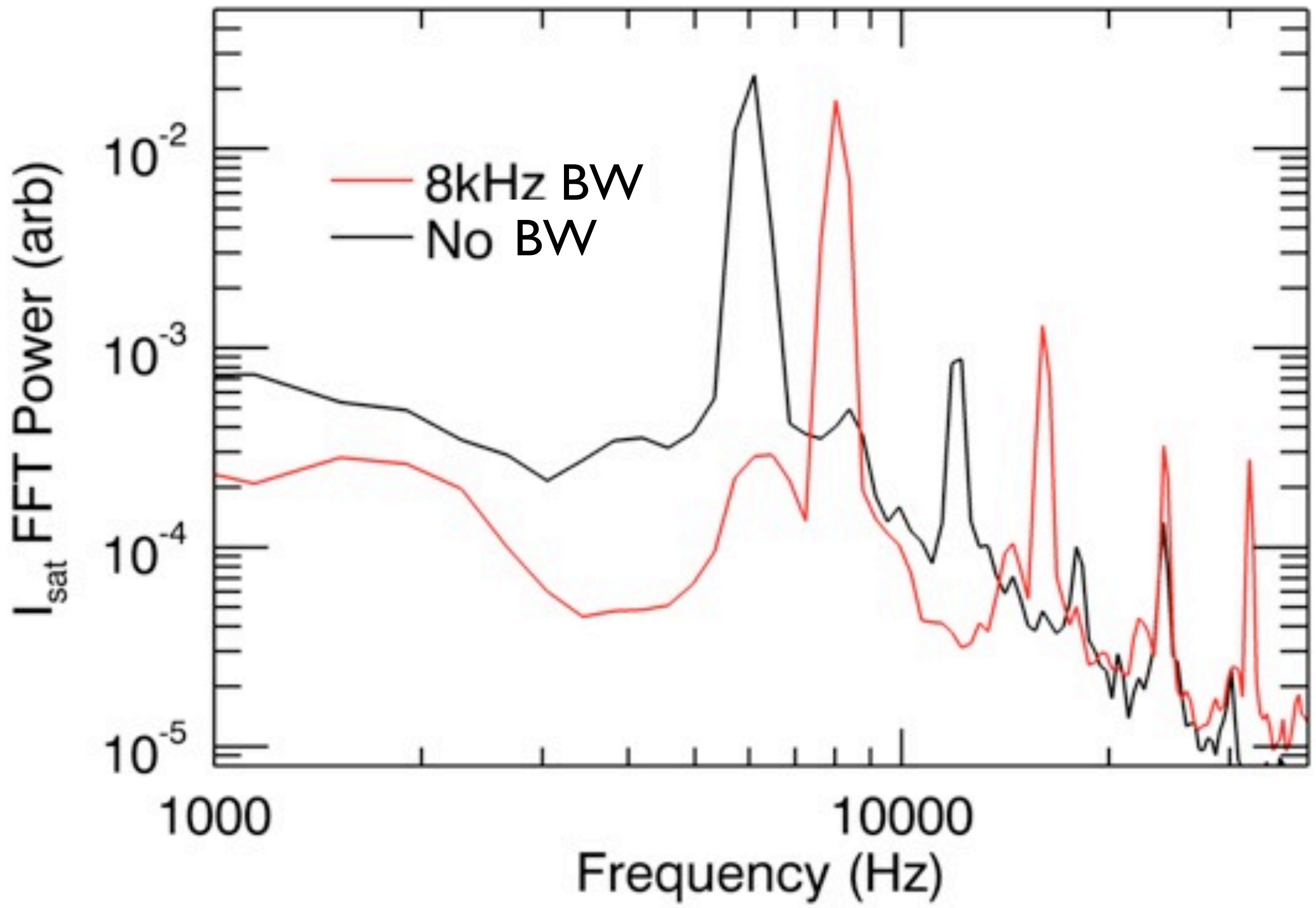

- Flows/potential gradient also present in density depletion
- Drift-wave and flute-like (Kelvin-Helmholtz) unstable on measured profiles (linear Braginskii fluid calculation)
- Nonlinear calculations (BOUT) in progress

# Resonant drive and mode-selection/suppression of instability



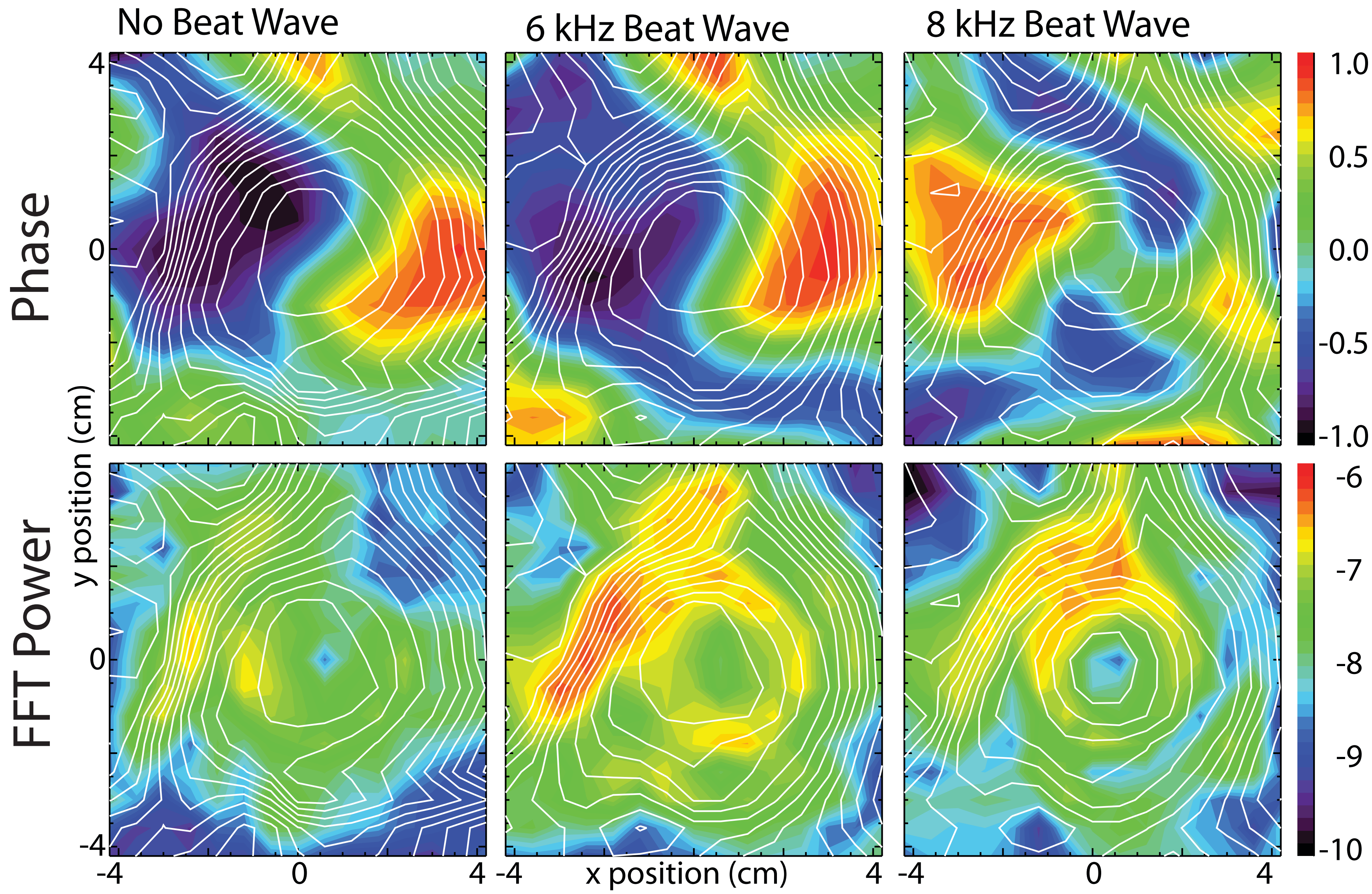

- Beat response significantly stronger than uniform plasma case
- Resonance at (downshifted) instability frequency observed, suppression of the unstable mode observed above (and slightly below)
- Instability returns at higher beat frequency

# BW controls unstable mode and reduces broadband noise



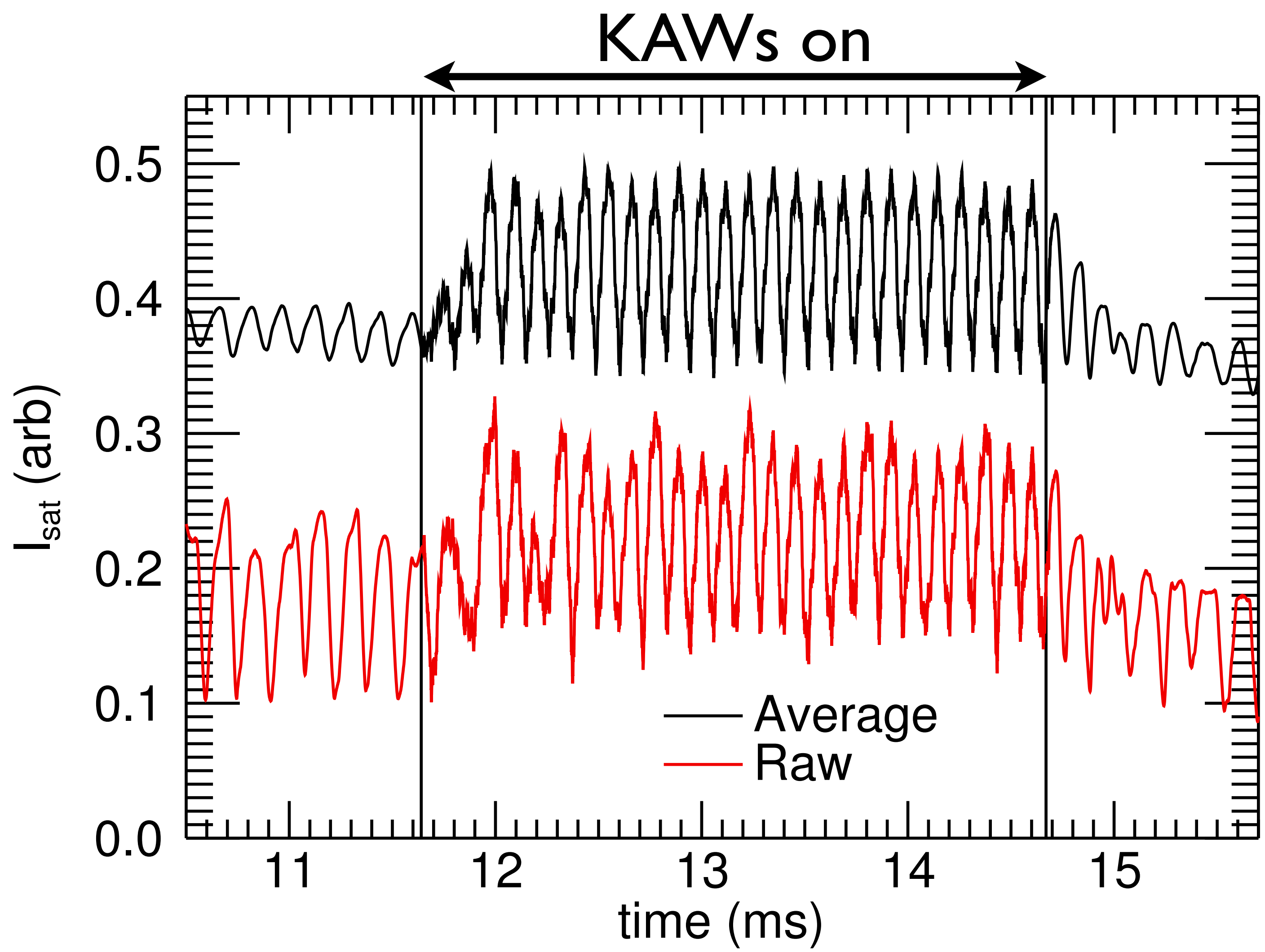

- Threshold for control: beat-driven mode has comparable (but less) amplitude than original unstable mode
- With beat wave, quieter at wide range of frequencies (previously generated nonlinearly by unstable mode?)

# Structure of beat-driven modes suggest coupling to linear modes



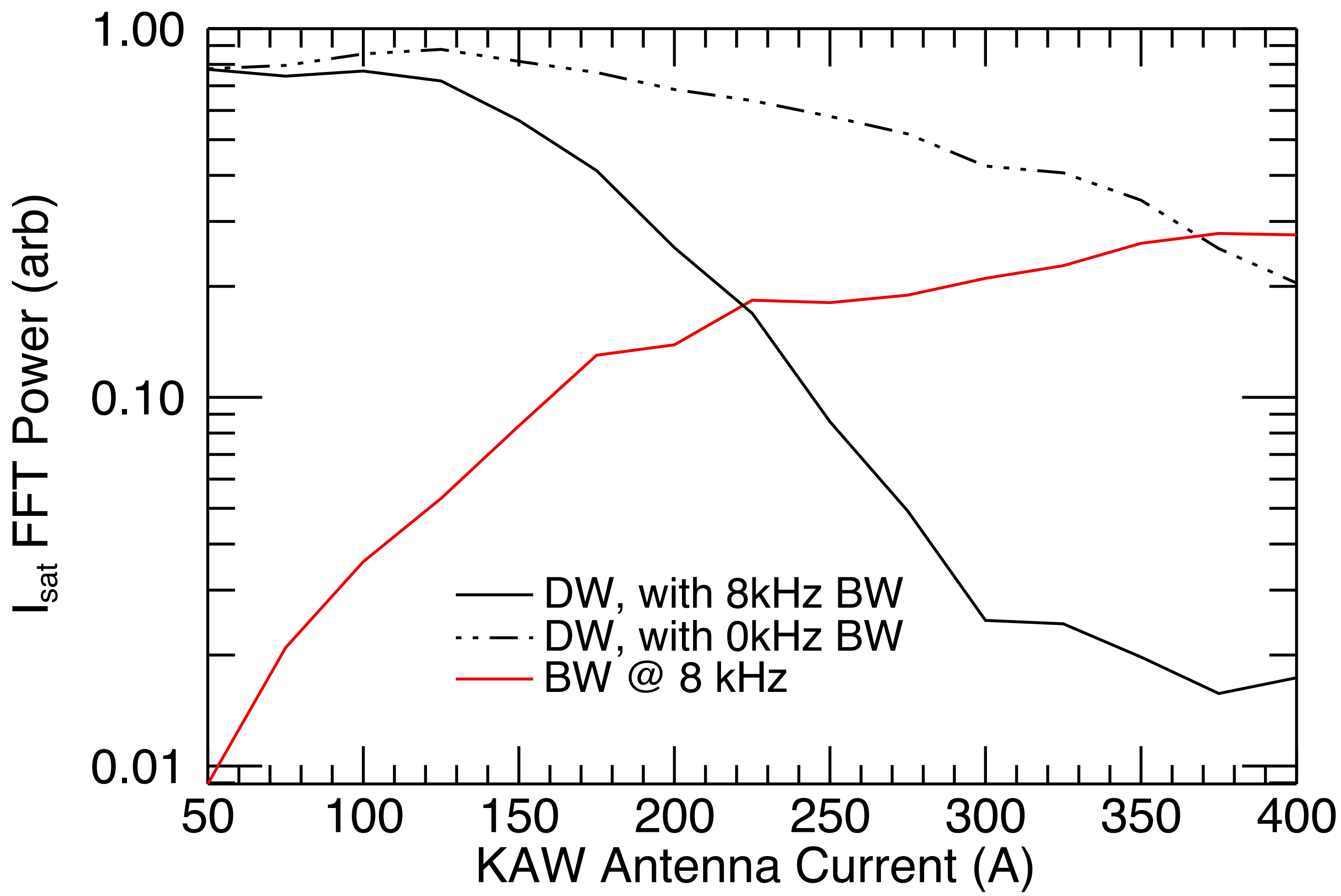

- Beat wave has m=1 (6 kHz peak), m=2 (8 kHz peak)
- Rotation in electron diamagnetic direction (same as instability)

# More evidence for coupling to linear waves: Ring-up/Ring-down observed



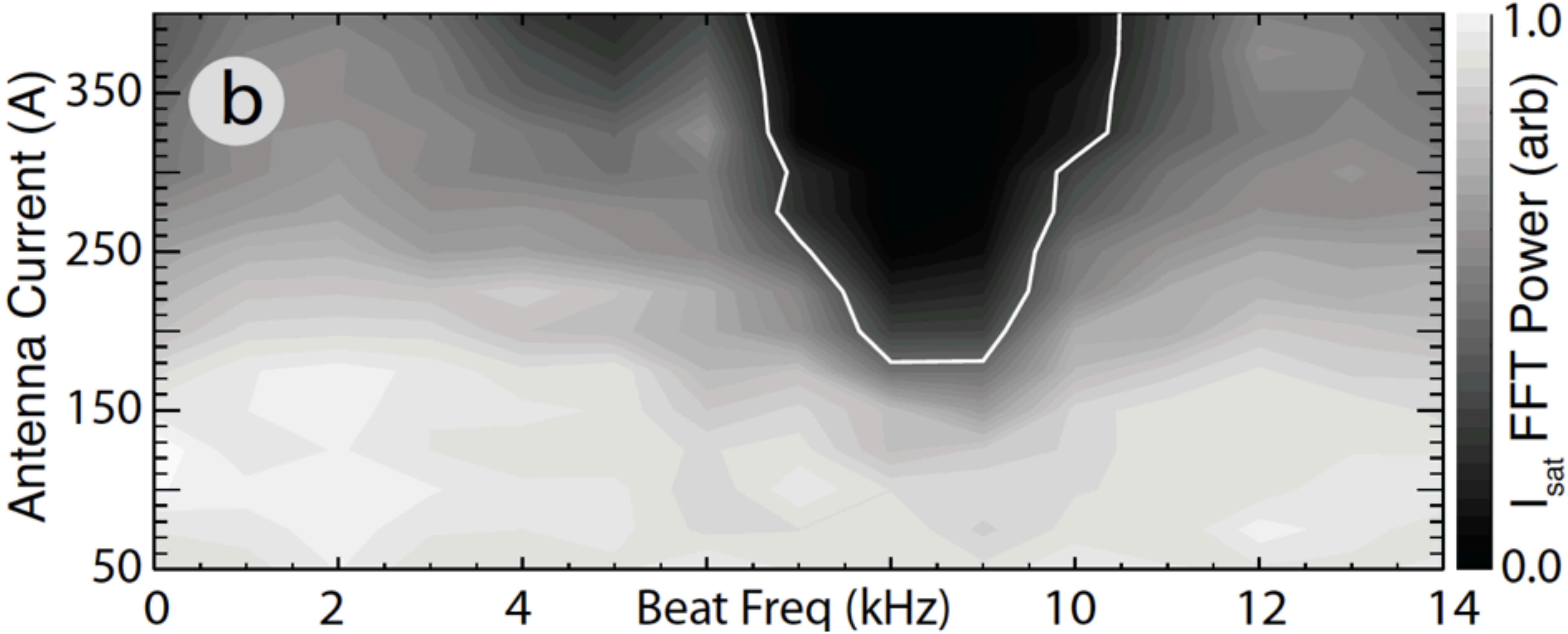

- 8kHz wave persists (rings down) after drive is shut-off; ring-up also observed
- Provides further support for coupling of BW to linear mode (DW/KH)

# Threshold for control, saturation of BW observed



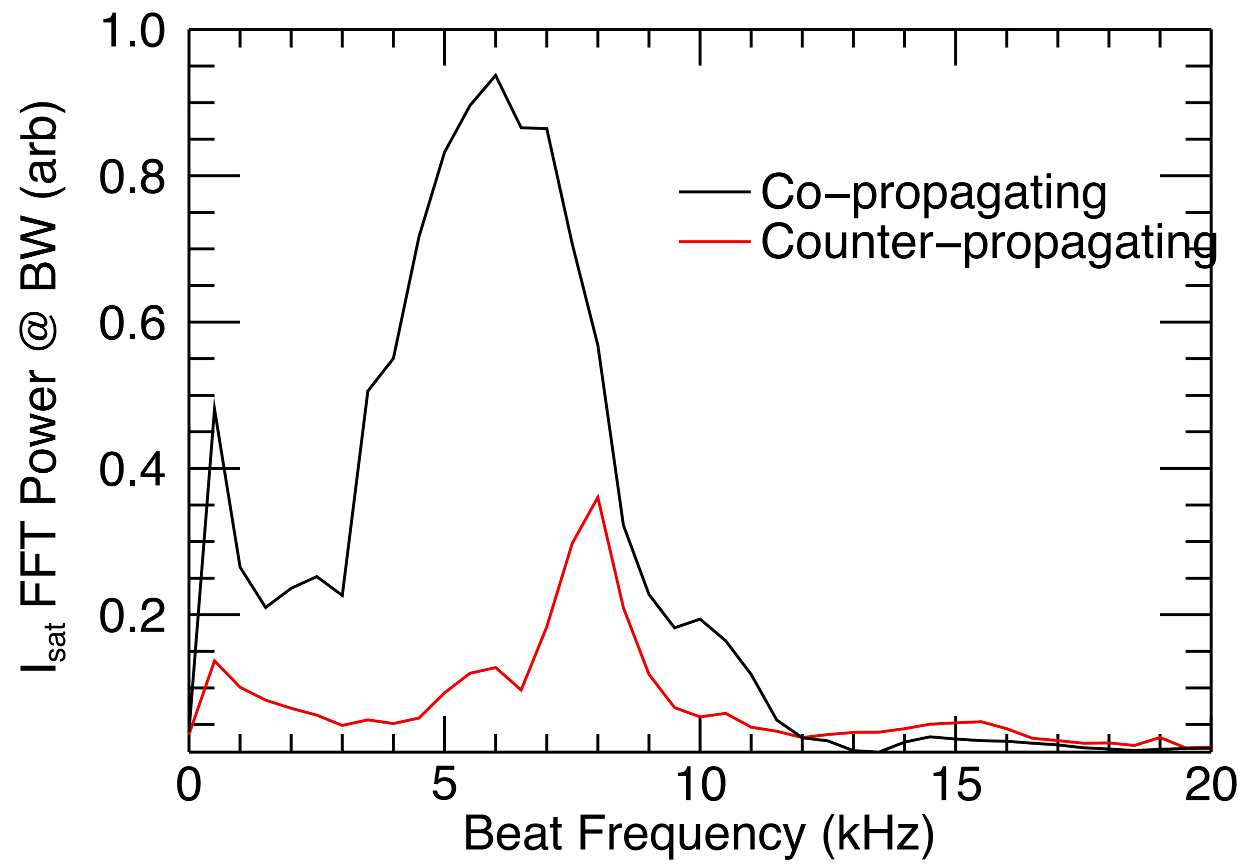

- Modification of DW seen starting at PBW/PDW ~ 10%; maximum suppression for comparable BW power
- Two effects: electron heating from KAWs modifies profiles, causing some reduction in amplitude without BW
- BW response seems to saturate as DW power bottoms out

# Frequency width of control depends on amplitude



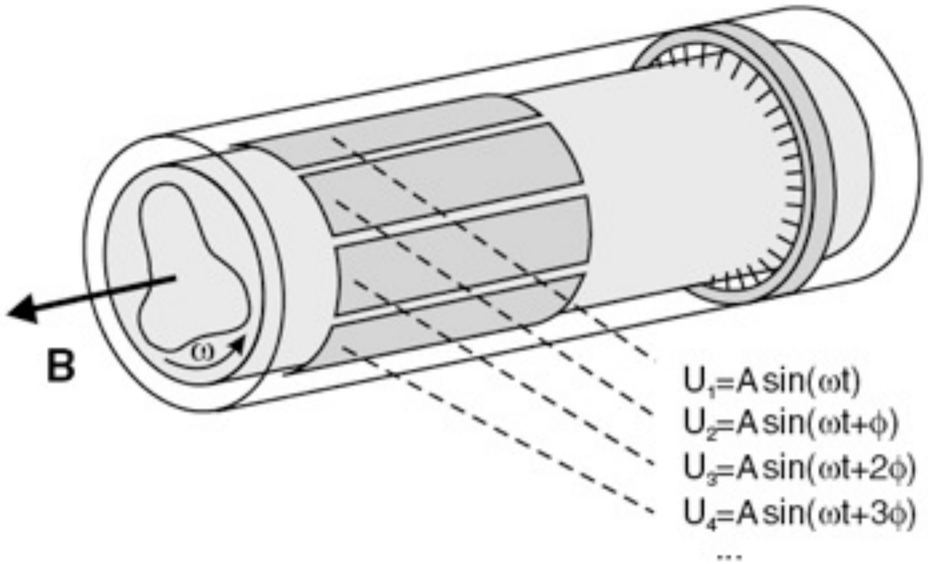

- Window of mode stabilization/control increases with increasing BW drive

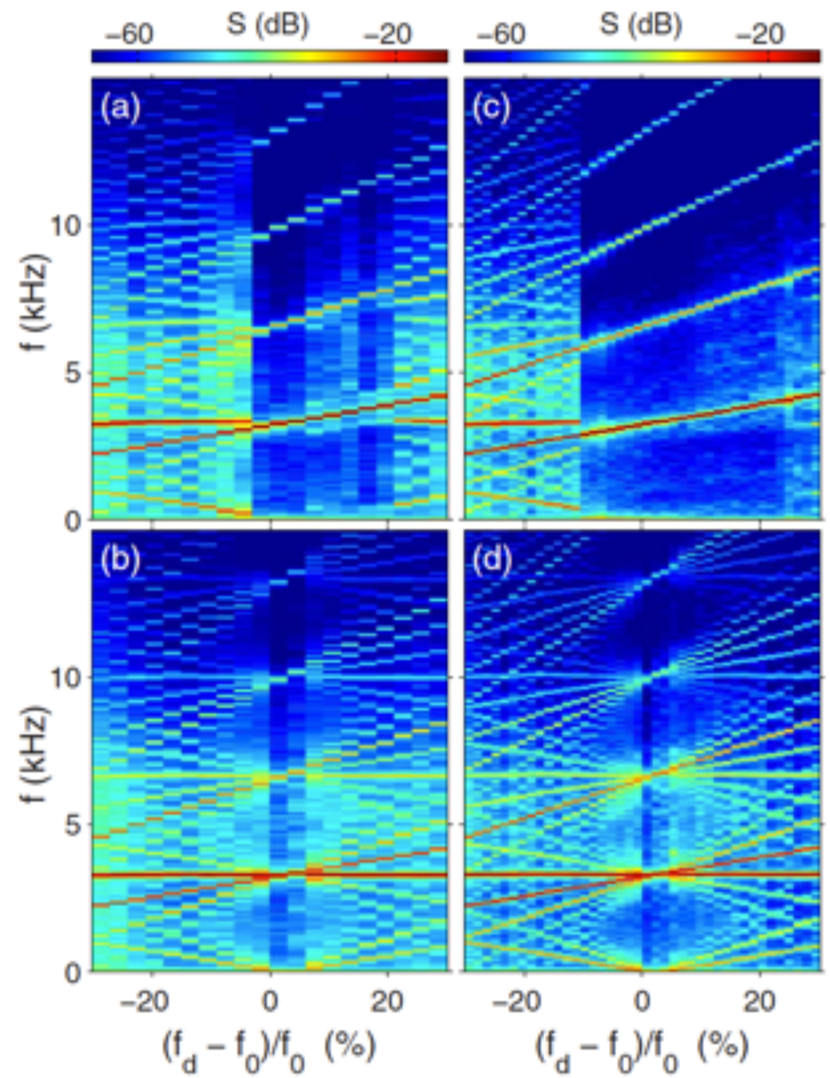
# Parallel BW wavelength matters: weak resonant drive/suppression for counter-propagation

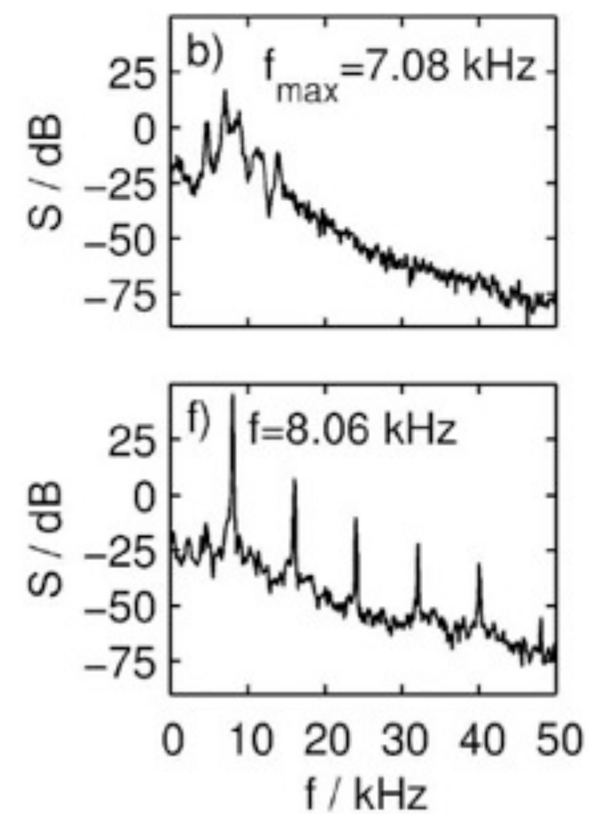



- Co-propagating BW has small $k_{||}$, similar to drift-wave
- Counter-propagating mode has short wavelength, expect inefficient coupling to DW/KH (but could couple to IAW…)

# Similar behavior seen using external antenna to excite drift-waves



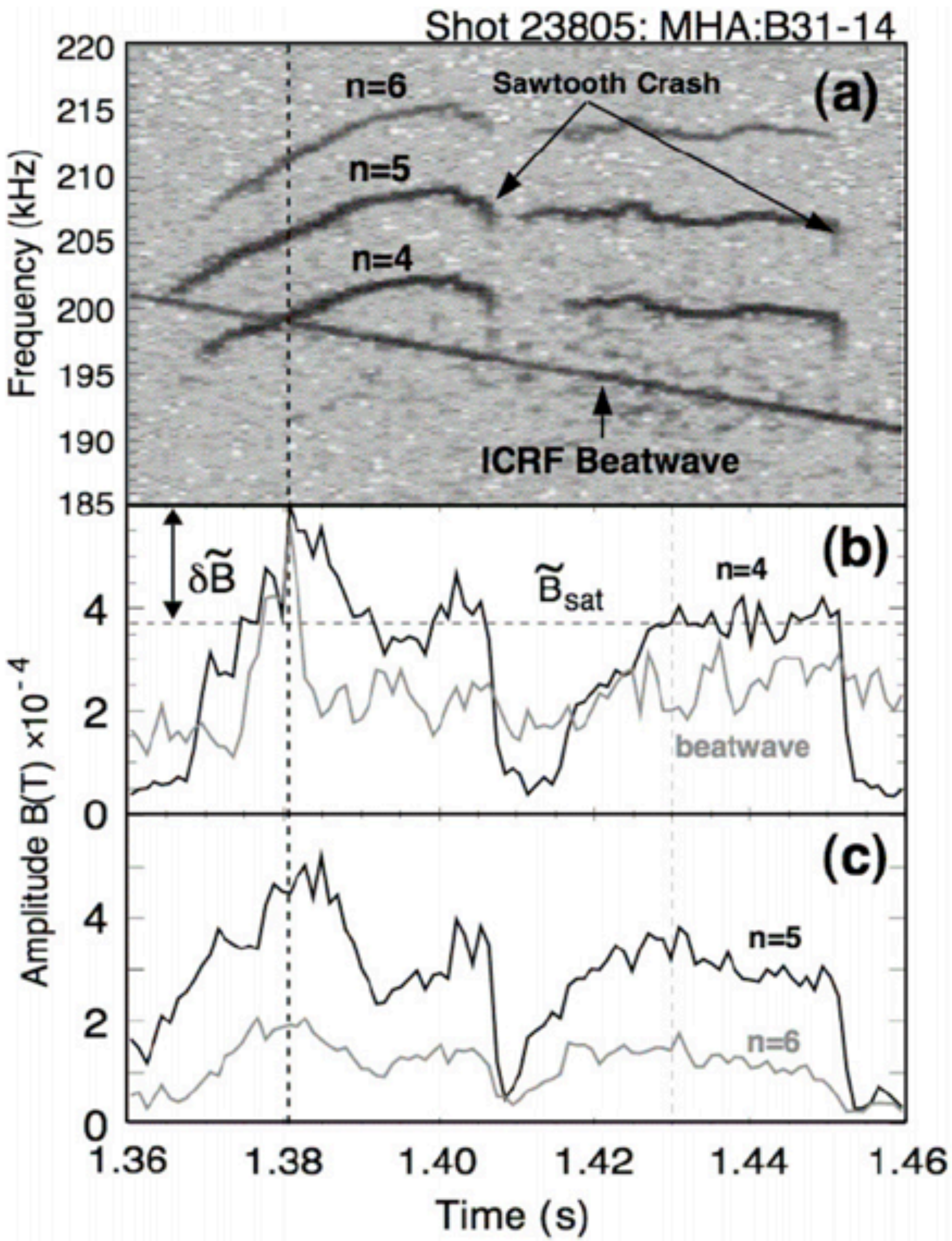




Schroeder, et al PRL 2001
Brandt, et al, PoP 2010

- Used external antenna structure on small basic plasma device to try to directly excite drift-waves
- Saw collapse of spectrum onto coherent drift-wave at the driven frequency (+ harmonics), transport modified

# ICRF beat waves used to drive AEs




Sassenberg, et al., NF 50, 052003 (2010)

- ICRF BWs used to excited TAEs in JET [Fasoli, et al.] and ASDEX [Sassenberg, et al.]

# HHFW Beat Waves in NSTX?

- Modulate HHFW power or simultaneously launch two frequencies at once, look to interact with low frequency modes
  - Attempt to excite/control ITG/TEM/etc?
  - Excite *AEs; study linear properties, do MHD spectroscopy, perhaps control fast ion/bulk transport (GAE control?)
  - Interact with edge modes (EHO: R. Goldston)

# Summary/Outline

- Study of the nonlinear properties of fundamental waves in a laboratory plasma (Large Plasma Device at UCLA)
- Wave-wave interactions among kinetic shear Alfvén waves in uniform plasma
  - Quasimode driven nonlinearly by beating of co-propagating Alfvén waves [T.A. Carter, B. Brugman, P. Pribyl, W. Lybarger, PRL (2006)]
- In nonuniform plasma, SAW beat wave interacts with gradient-driven instability [D.W. Auerbach, T.A. Carter, S. Vincena, P. Popovich, arXiv: 1004.0647, PRL accepted]
  - Unstable mode suppressed (synchronized?) in favor of driven second mode, overall fluctuation amplitude reduced