The Basic Plasma Science Facility at UCLA: studies of the fundamental physics of plasma waves

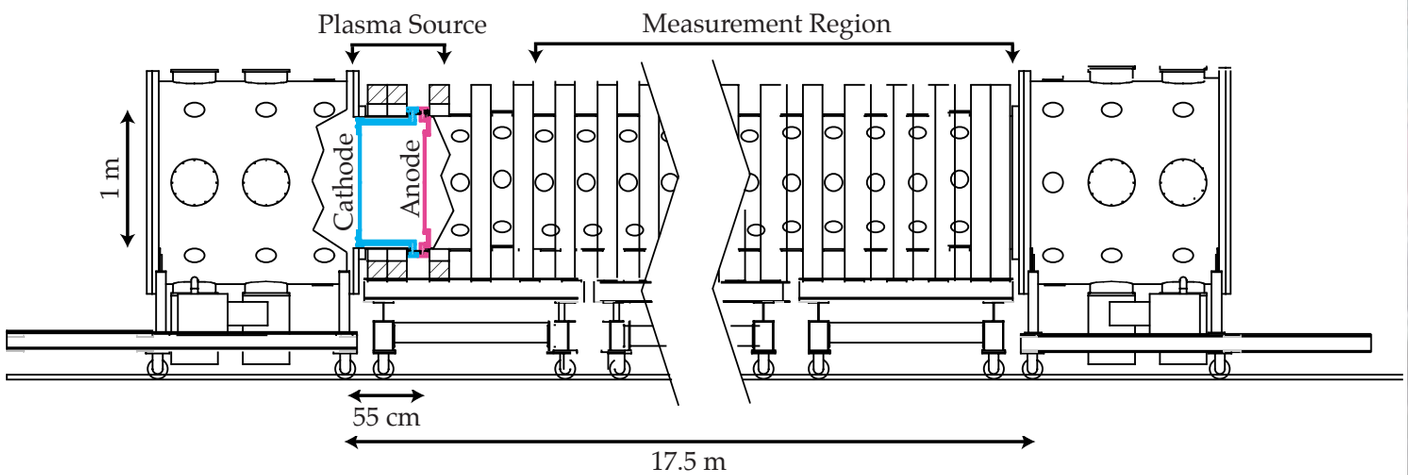
Troy Carter
Department of Physics and Astronomy, UCLA
(+ many others)

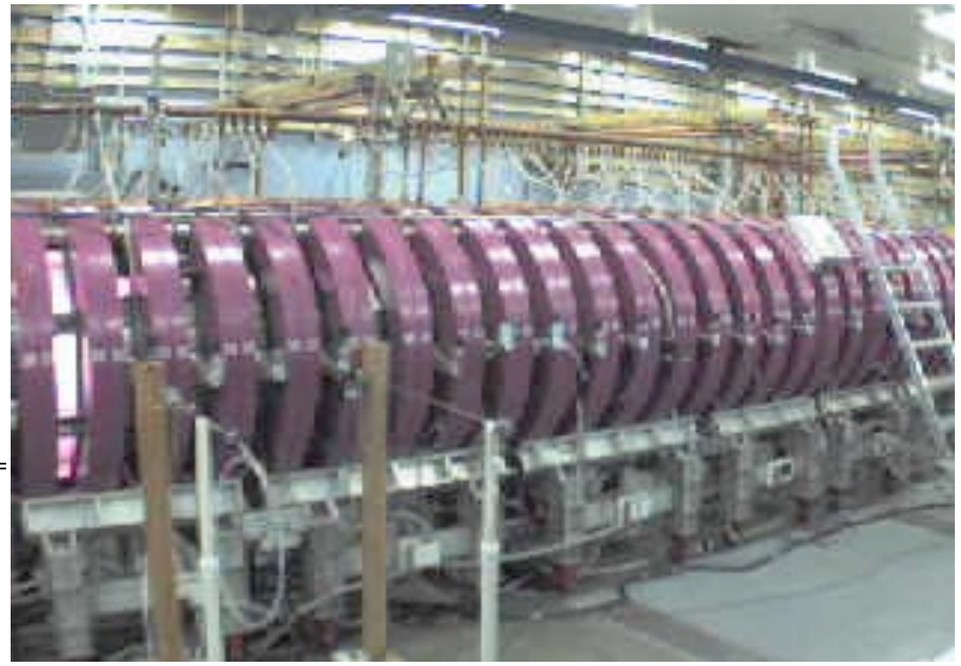
UCLA

Summary/Outline

- Large Plasma Device (LAPD): Flexible, well-diagnosed experiment for studying basic plasma processes (motivations from space, astro, fusion), target for code validation.
  - Kinetic/inertial Alfvén waves: dispersion and damping, characteristics in multi-ion species plasmas
- Nonlinear interactions among shear Alfvén waves
  - Uniform plasma: Quasimode driven nonlinearly by beating of co-propagating Alfvén waves
  - In nonuniform plasma, SAW beat wave interacts with gradient-driven instability: unstable mode suppressed in favor of driven second mode, overall fluctuation amplitude reduced
- Plans and initial results for ICRF-related studies using LAPD

The LArge Plasma Device (LAPD) at UCLA

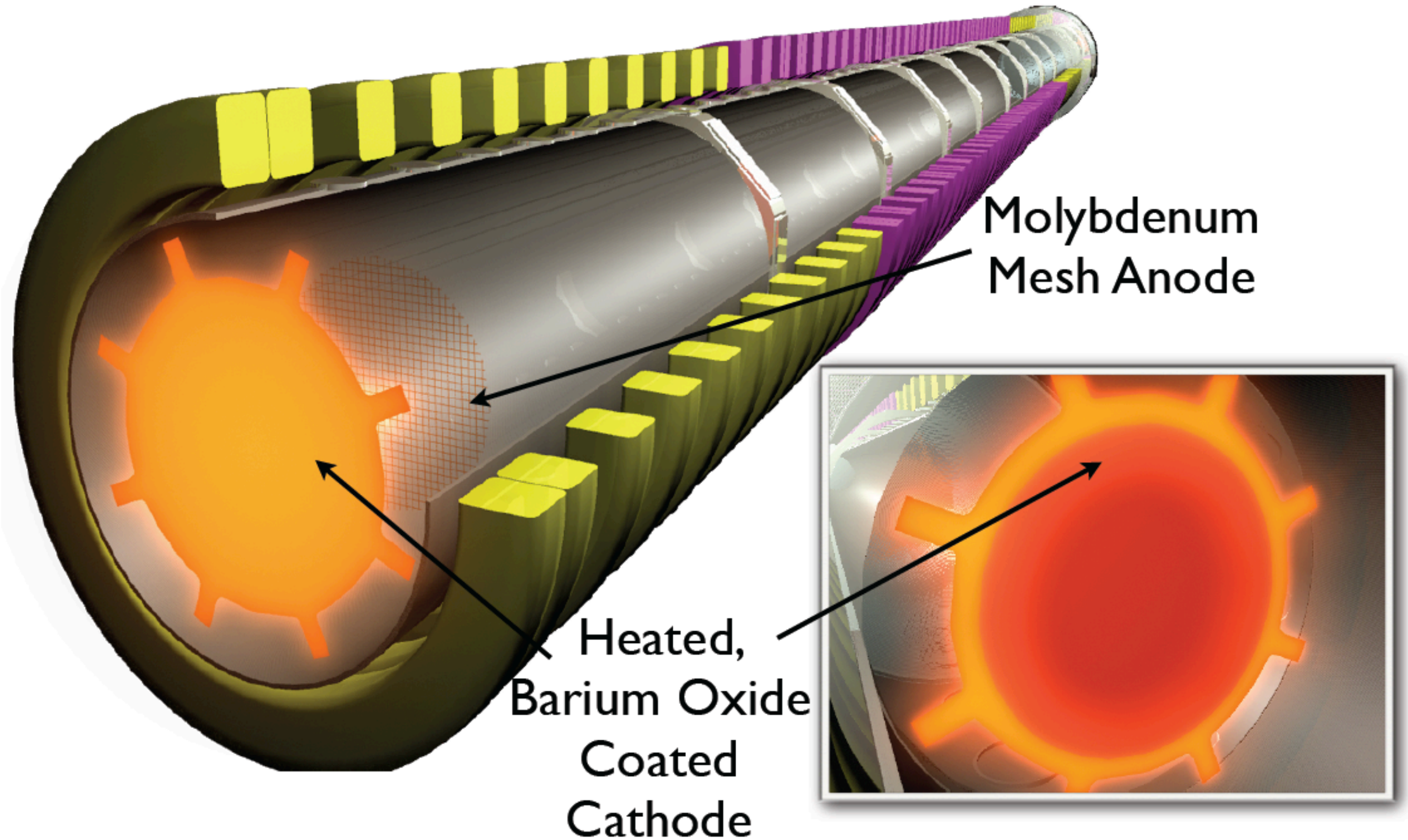




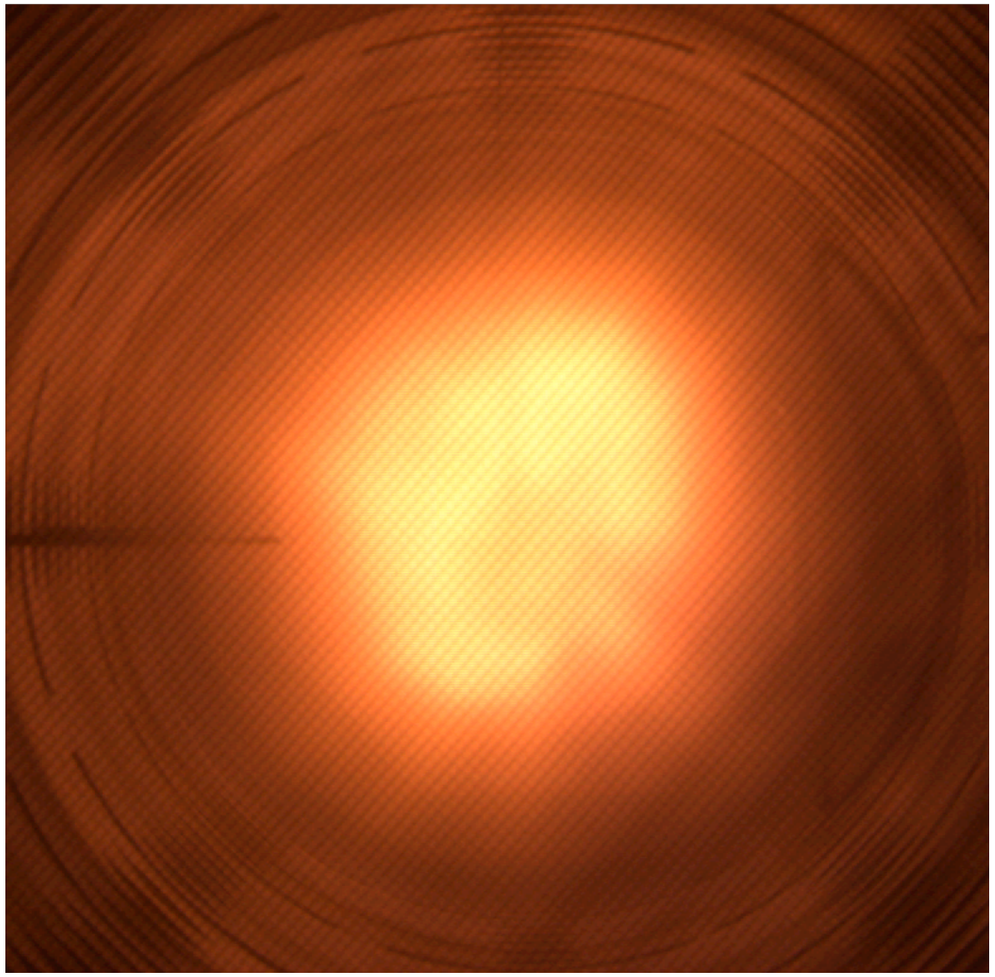
- US DOE/NSF sponsored user facility
- Solenoidal magnetic field, hot cathode discharge plasma
- $0.5 < B < 2\,\mathrm{kG}, n_e \sim 10^{12}\,\mathrm{cm}^{-3}, T_e \sim 5\,\mathrm{eV}, T_i \sim 1\,\mathrm{eV}$
- Large plasma size, 17m long, D~60cm (1kG: ~300 ρ_i, ~100 ρ_s)
- High repetition rate (1 Hz), pulse length ~10-20ms

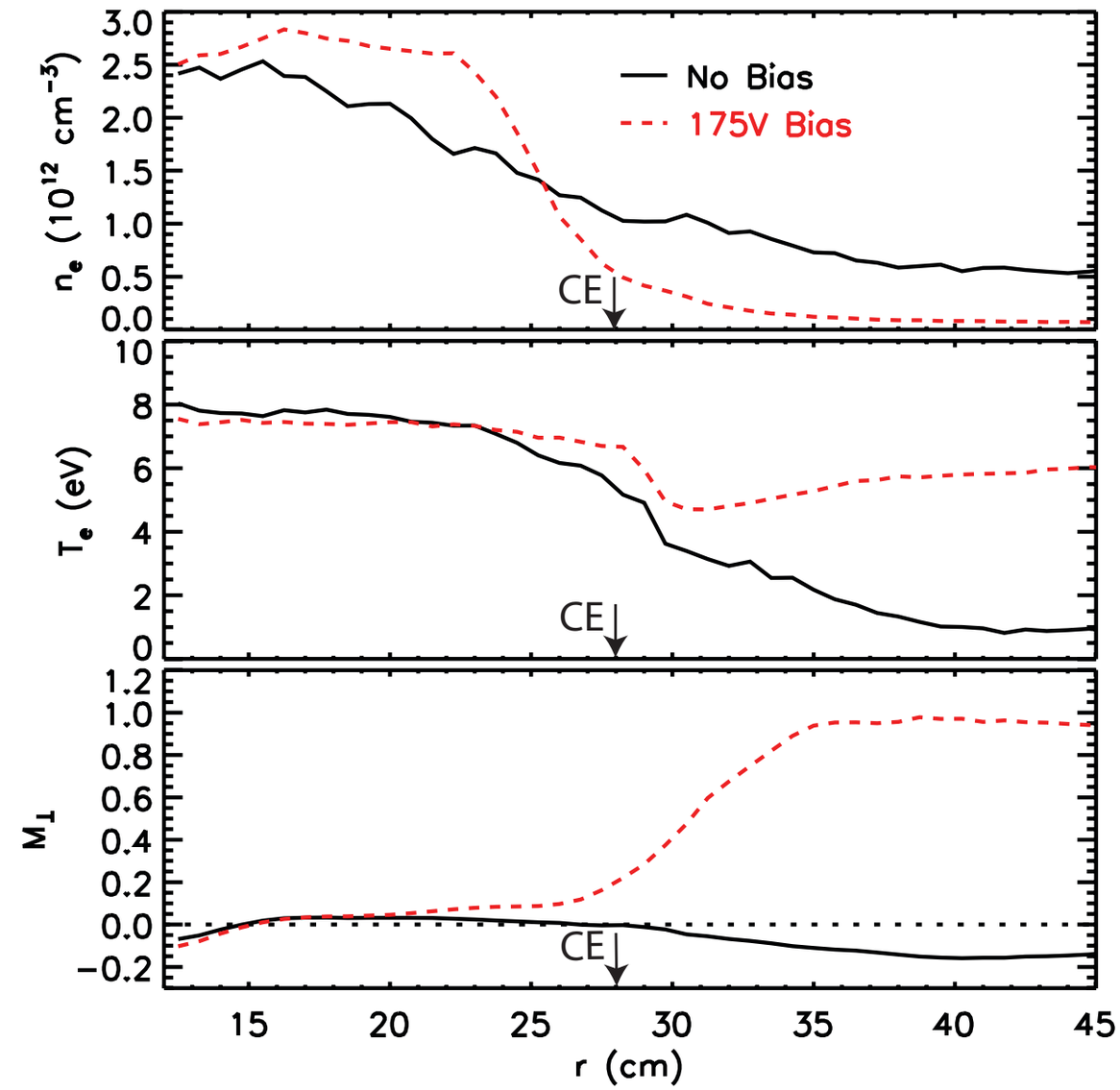
http://plasma.physics.ucla.edu

LAPD Plasma source



Example Plasma Profiles



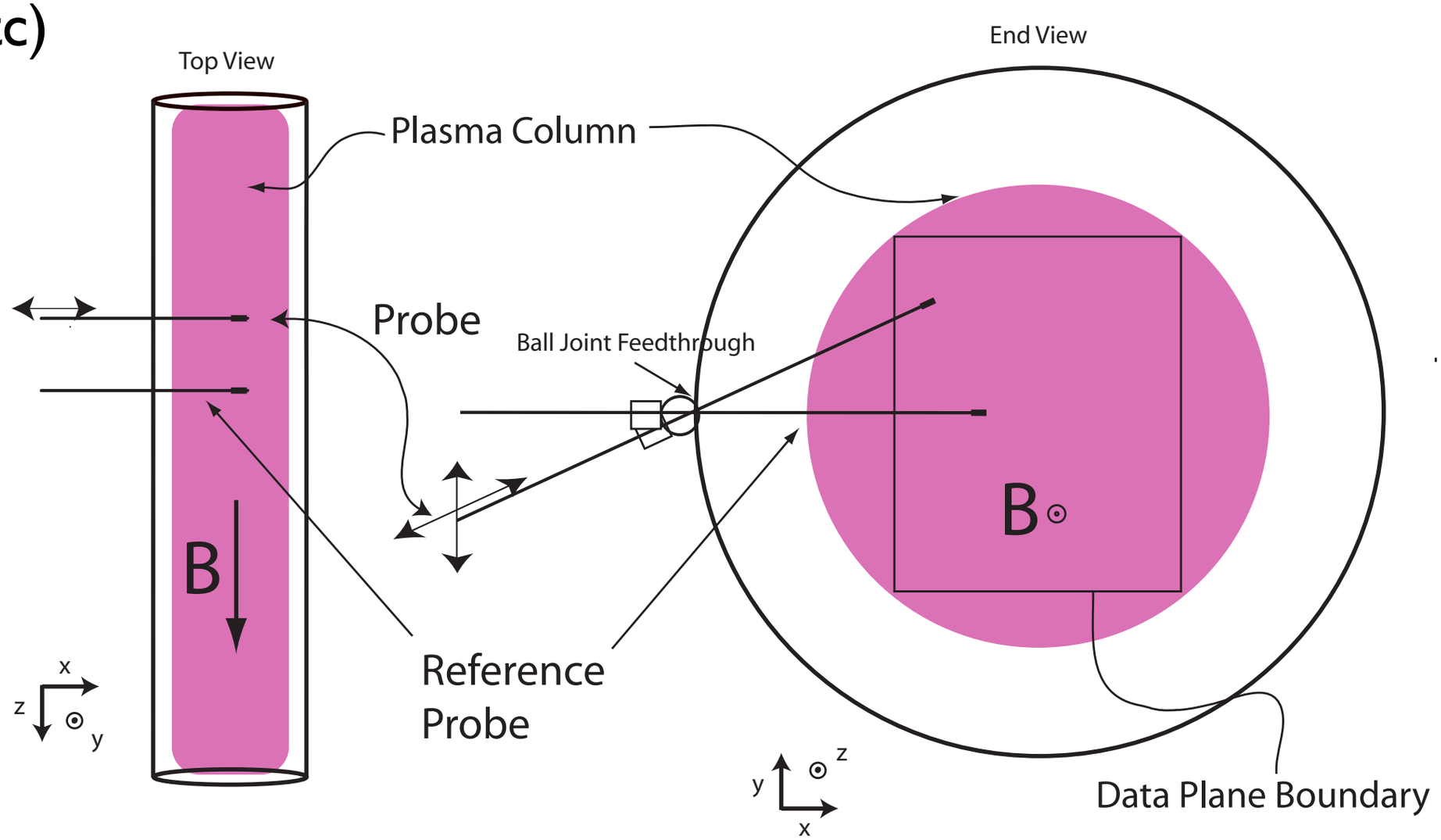


- Low field case (400G) (also shown: with particle transport barrier via biasing*); generally get flat core region with D=30-50cm
- Quiescent core region, broadband turbulence generally observed in the edge region

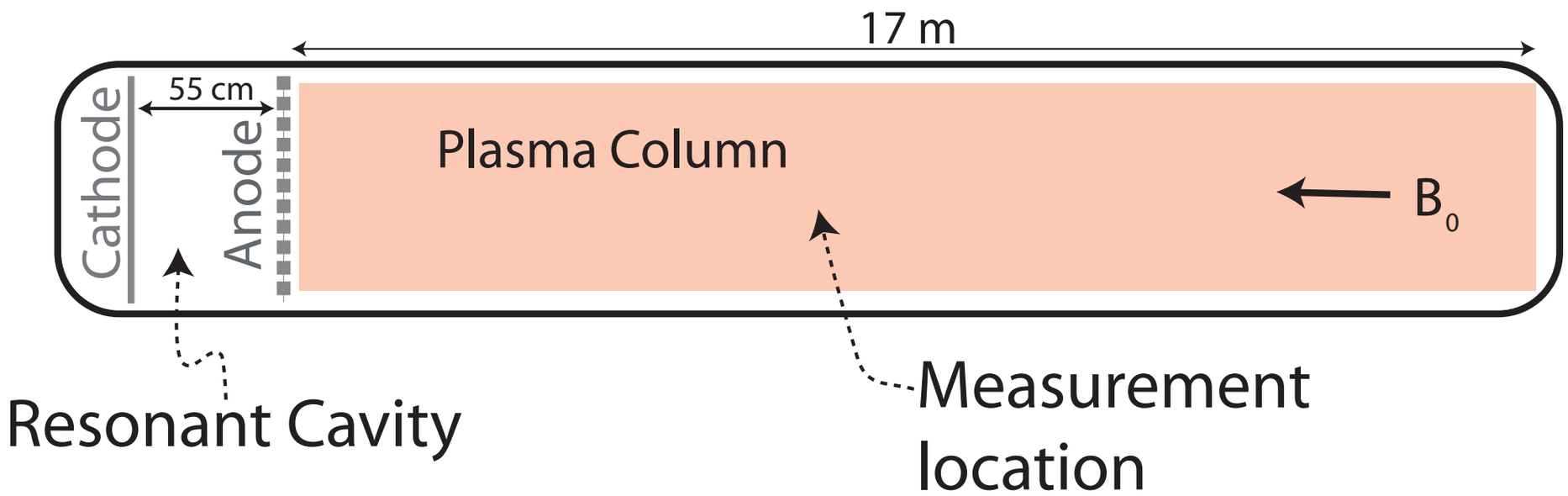
* Carter, et al, PoP 16, 012304 (2009)

Measurement methodology in LAPD

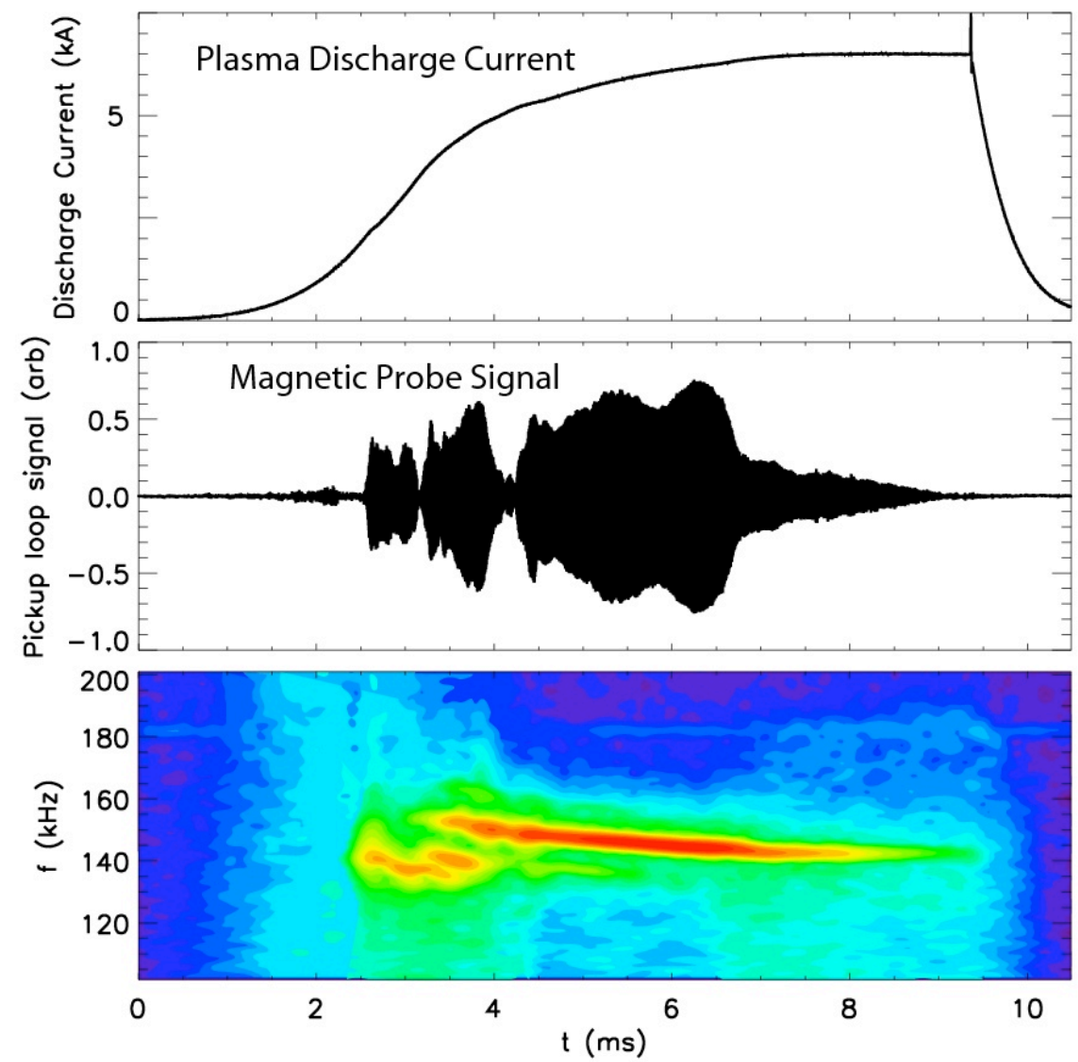
- Use single probes to measure local density, temperature, potential, magnetic field, flow: move single probe shot-to-shot to construct average profiles
- Add a second (reference) probe to use correlation techniques to make detailed statistical measurements of turbulence (structure, etc)



Example data: cylindrical Alfvén eigenmodes in LAPD

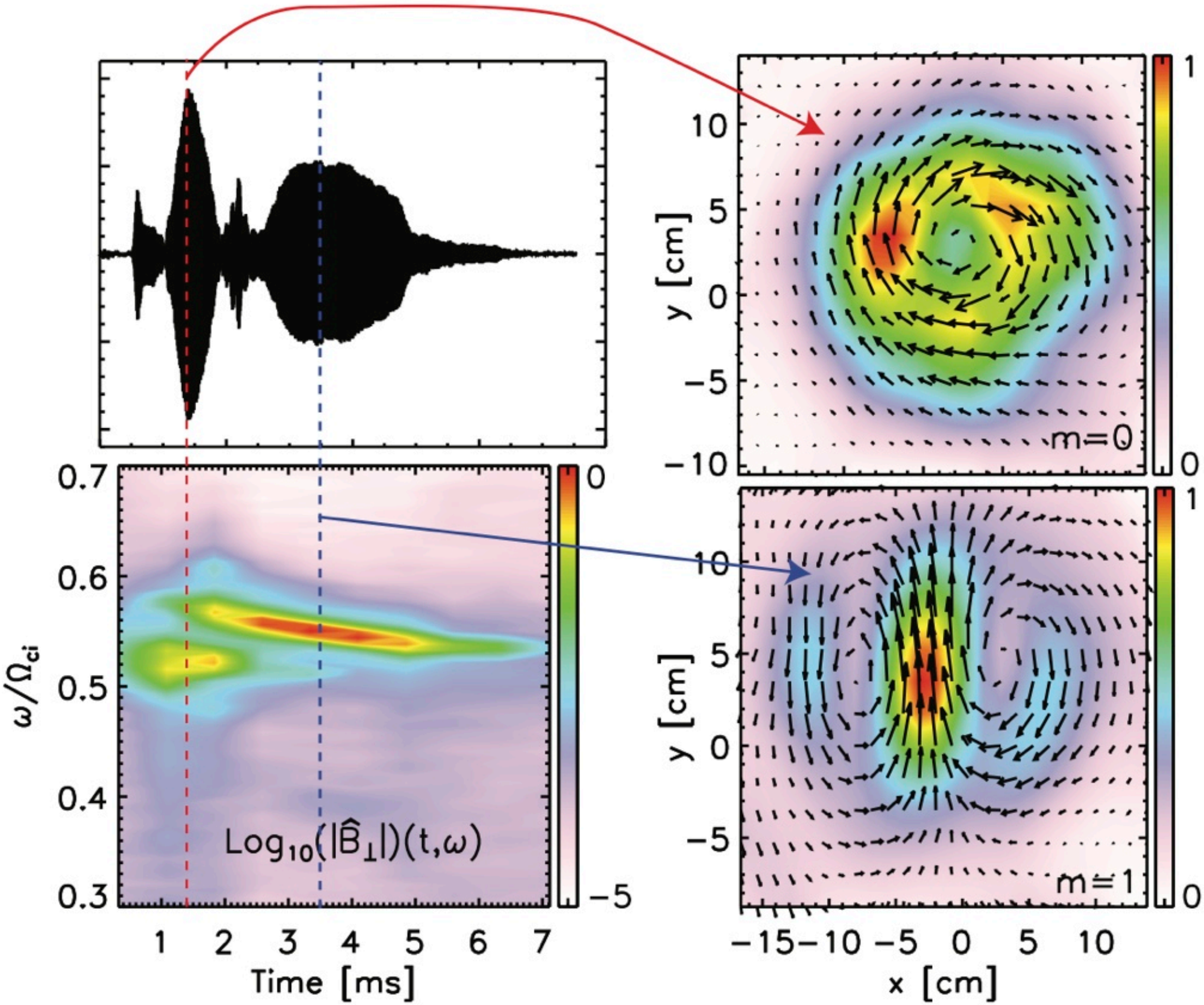


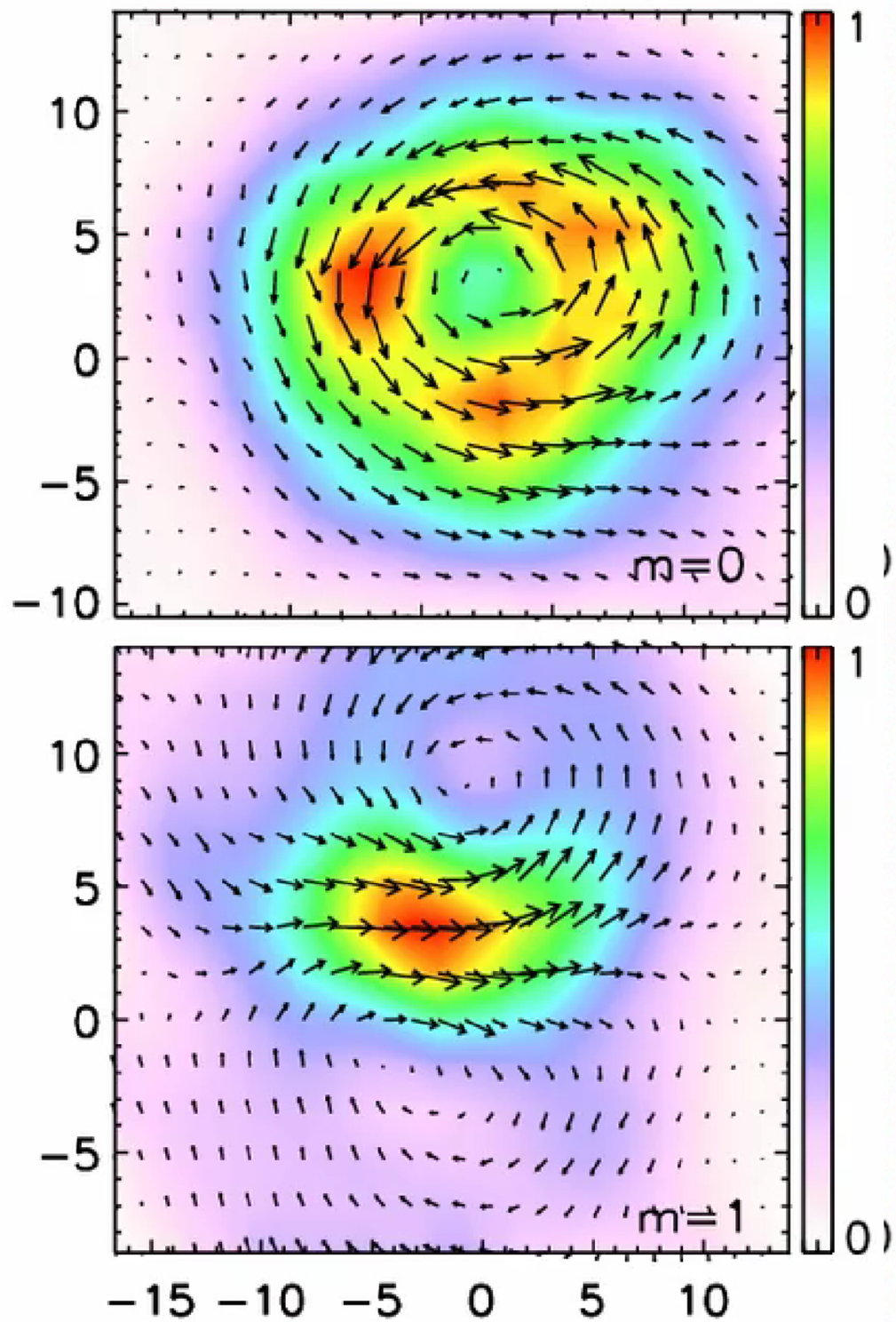
- Plasma source acts as resonant cavity for shear Alfvén waves
- Driven spontaneously by discharge current (thought to be inverse Landau damping on return current electrons)
- Alfvén wave "MASER"



Maggs, Morales, PRL 91, 035004 (2003)
Maggs, Morales, Carter, PoP 12, 013103 (2005)

Measured structure of Alfvén eigenmodes in LAPD




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

Example LAPD Users and Research Areas

- Basic Physics of Plasma Waves, e.g. linear properties of inertial and kinetic Alfvén waves, Whister, Lower Hybrid waves [Gekelman, Morales, Maggs, Vincena…, Kletzing, Skiff, Howes; Colestock]
- Drift-wave turbulence and transport, validation of edge turbulence simulation (BOUT++) [Schaffner, Friedman, Popovich, Carter, Umansky, Pace, Maggs, Morales, Horton]
- Nonlinear interactions between Alfvén waves [Brugman, Auerbach, Carter, Vincena, Boldyrev, Howes]
- Physics of fast ion interaction with Alfvén waves and turbulence [Zhou, Zhang, Heidbrink, Carter, Vincena, Breizman, …]
- Reconnection [Lawrence, Gekelman, Carter, Van Compernolle]
- Alfvén waves and collisionless shocks driven by laser blow-off [Niemann, Gekelman, Vincena]
- Fast Waves/Physics of ICRF [D'Ippolito, Myra, Wright, Van Compernolle, Carter, Gekelman …]

Kinetic and Inertial Alfvén waves: introduce dispersion and damping at finite $k_\perp$

- At finite $k_\perp$, wave obtains parallel electric field
- In low β plasma (LAPD), key additional physics is parallel electron response

$$\frac{v_{\rm A}^2}{v_{\rm th,i}^2} = \frac{B^2 m_{\rm i}}{\mu_o \rho T_{\rm i}} = \frac{1}{\beta_{\rm i}} \qquad \frac{v_{\rm A}^2}{v_{\rm th,e}^2} = \frac{1}{\beta_e}\frac{m_e}{m_i} = \frac{1}{\bar{\beta}_e}$$

- Use kinetic electron response in parallel direction (ignore ion response)

$$\epsilon_{zz} \approx 1 + \frac{1}{k_\parallel^2 \lambda_D^2}\left(1 + \zeta_e Z(\zeta_e)\right) \quad ; \quad \zeta_e = \frac{\omega}{\sqrt{2} k_\parallel v_{\rm th,e}}$$

- For simplicity, assume cold ions, $k_\perp \rho_e << 1$; use cold perpendicular response

Kinetic and Inertial Alfvén waves

- Inertial Alfvén wave: cold electron response, $v_A >> v_{th,e}$

$$(\zeta_e \gg 1) \qquad \epsilon_{zz} \approx 1 - \frac{\omega^2}{\omega_{\rm pe}^2} + \frac{i\sqrt{\pi}\zeta_e}{k_\parallel^2 \lambda_D^2} \exp\left(-\zeta_e^2\right)$$

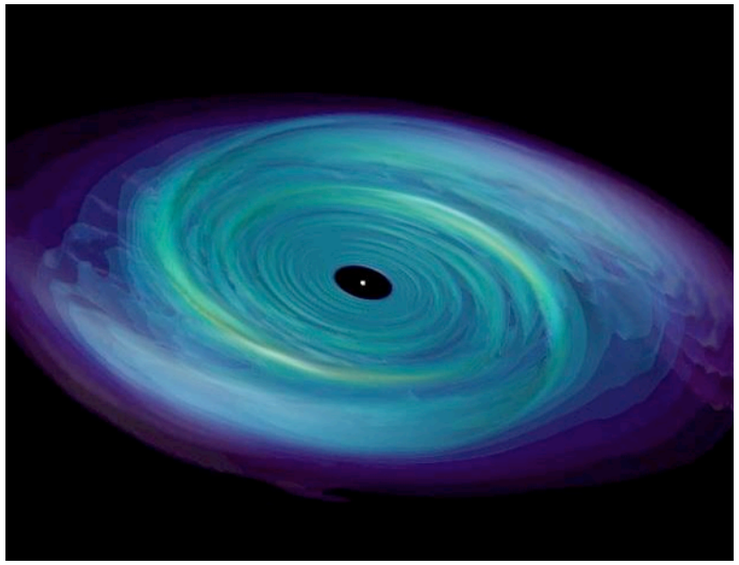
$$\omega_r^2 = \frac{k_\parallel^2 v_A^2}{(1 + k_\perp^2 \delta_e^2)} \quad , \quad \delta_e = \frac{c}{\omega_{\rm pe}}$$ (backward perp. wave)

- Kinetic Alfvén wave: hot electron response, $v_A << v_{th,e}$

$$(\zeta_e \ll 1) \qquad \epsilon_{zz} \approx 1 + \frac{1}{k_\parallel^2 \lambda_D^2} + \frac{i\sqrt{\pi}\zeta_e}{k_\parallel^2 \lambda_D^2} \exp\left(-\zeta_e^2\right)$$

$$\omega_r^2 = k_\parallel^2 v_A^2 \left(1 + k_\perp^2 \rho_s^2\right) \quad , \quad \rho_s = \frac{C_s}{\Omega_i}$$ (forward perp. wave)

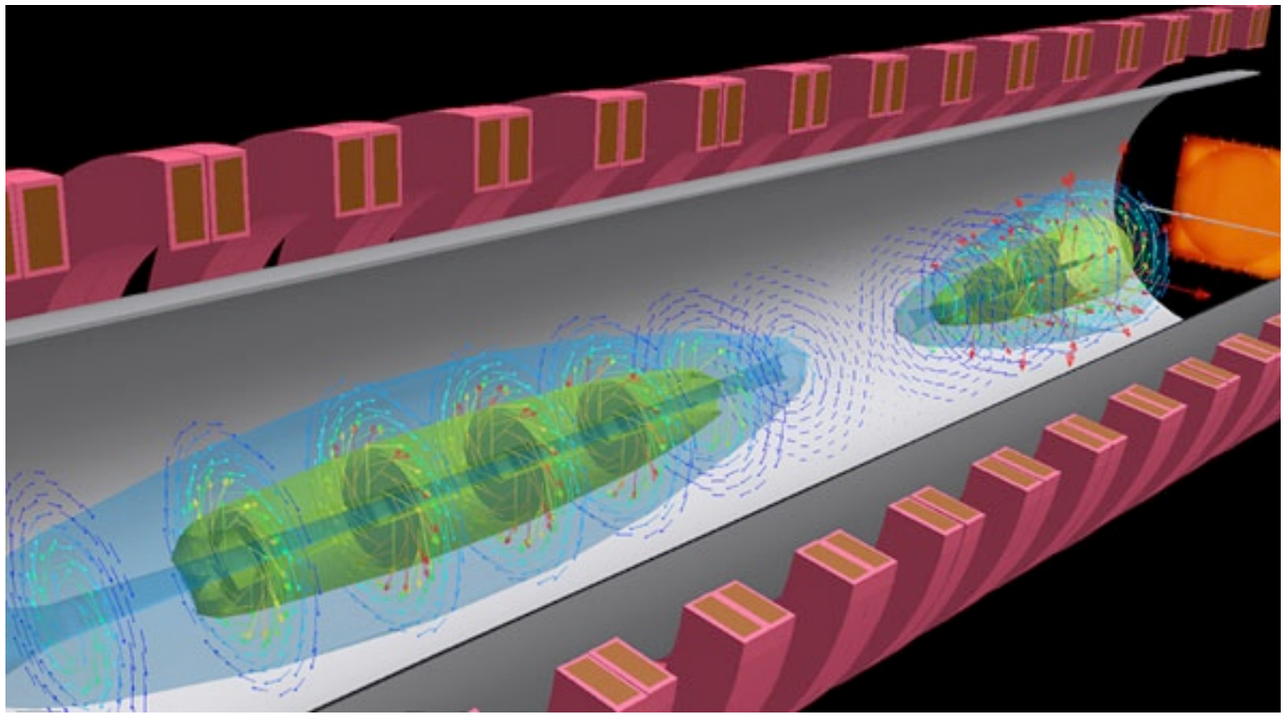
Importance of KAW and IAW

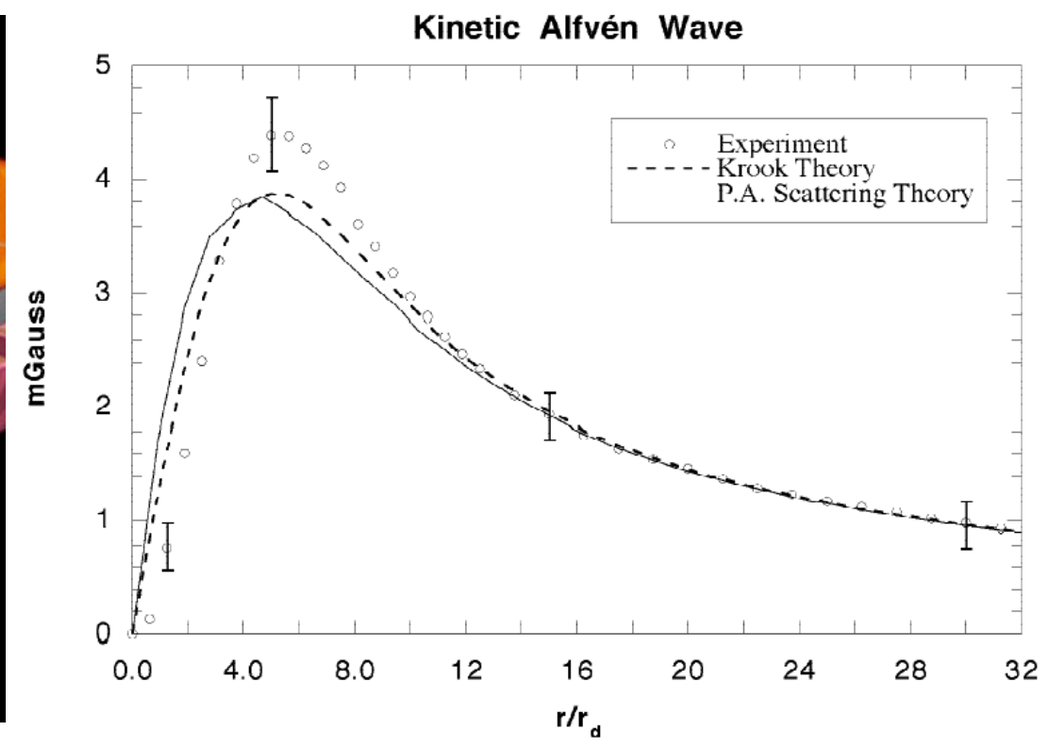


- Space plasmas: IAW/KAW observed in auroral zones, possible mechanism for auroral electron acceleration [Louarn, et al., GRL 21, 1847 (1994); Chaston, et al GRL 26, 647 (1999)]
- Fusion devices: mode conversion to KAWs source of damping for Alfvén eigenmodes [Hasegawa and Chen, PRL 35, 370 (1975)]
- Space/Astro plasmas: KAWs terminate cascade in MHD/ Alfvénic turbulence [Bale, et al. PRL 94, 215002 (2005); Sahraoui, et al. PRL 102, 231102 (2009)].

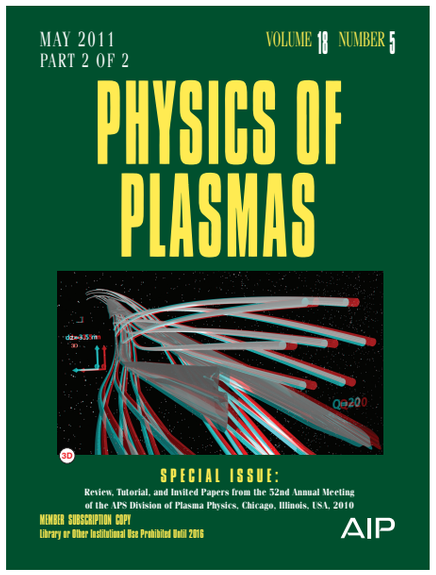
IAW/KAW wave studies in LAPD

- Below: 3D AW pattern from a small antenna (comparable to skin depth, sound gyroradius)





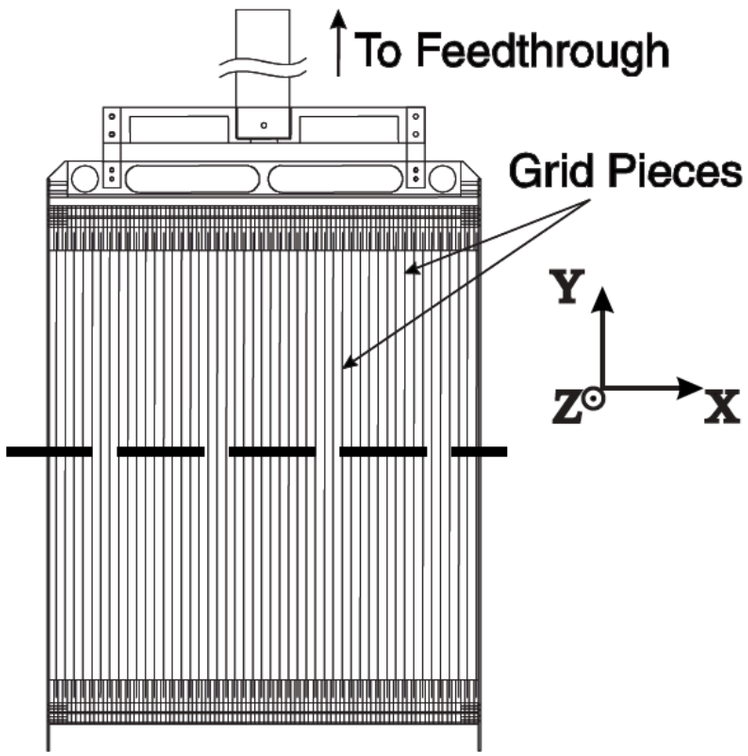
- A number of issues studied by UCLA group: radiation from small source, resonance cones, field line resonances, wave reflection, conversion from KAW to IAW on density gradient… [Gekelman, Maggs, Morales, Vincena, Leneman, et al]

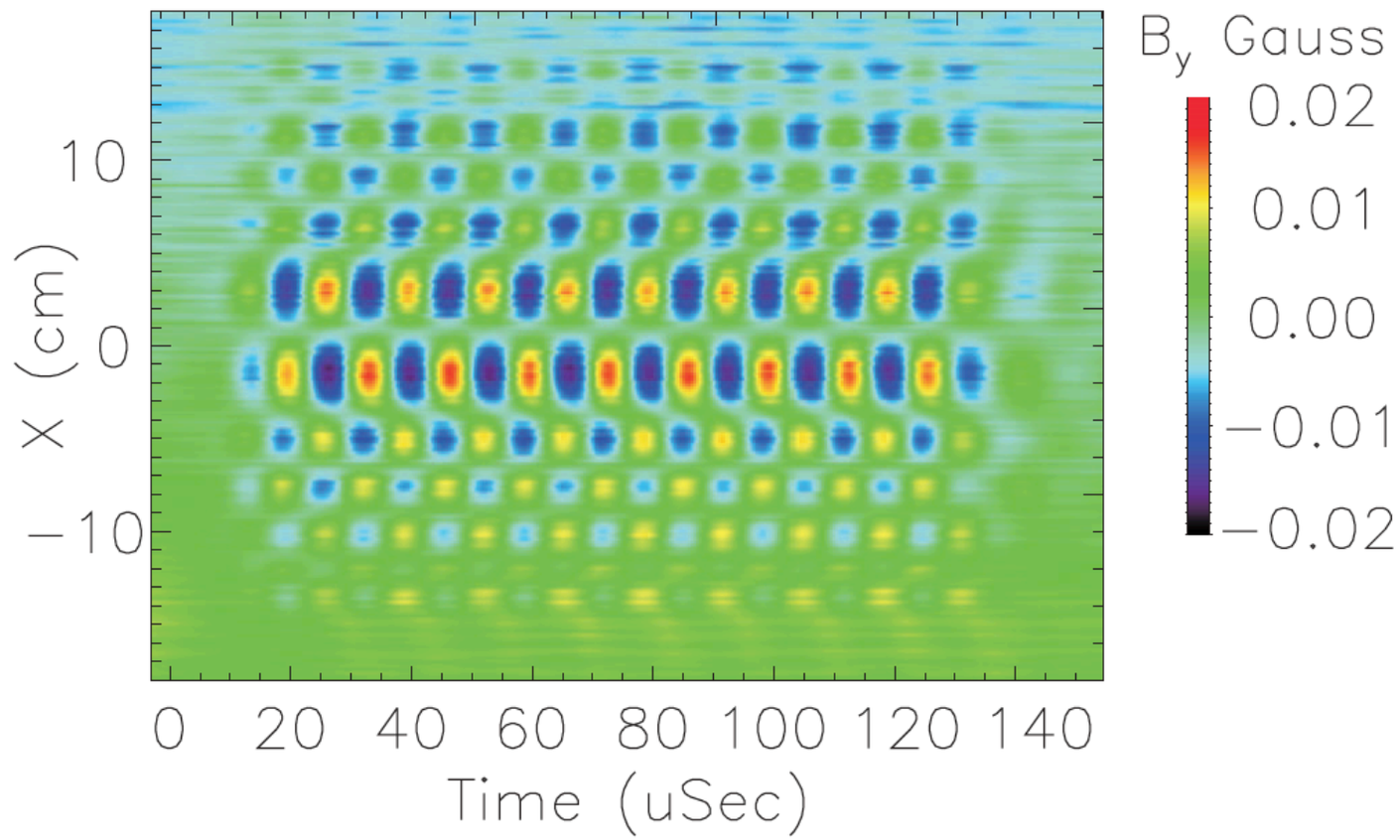


Details, publication list at http://plasma.physics.ucla.edu

W. Gekelman, et al., Phys. Plasmas 18, 055501 (2011)

Study of IAW/KAW dispersion & damping



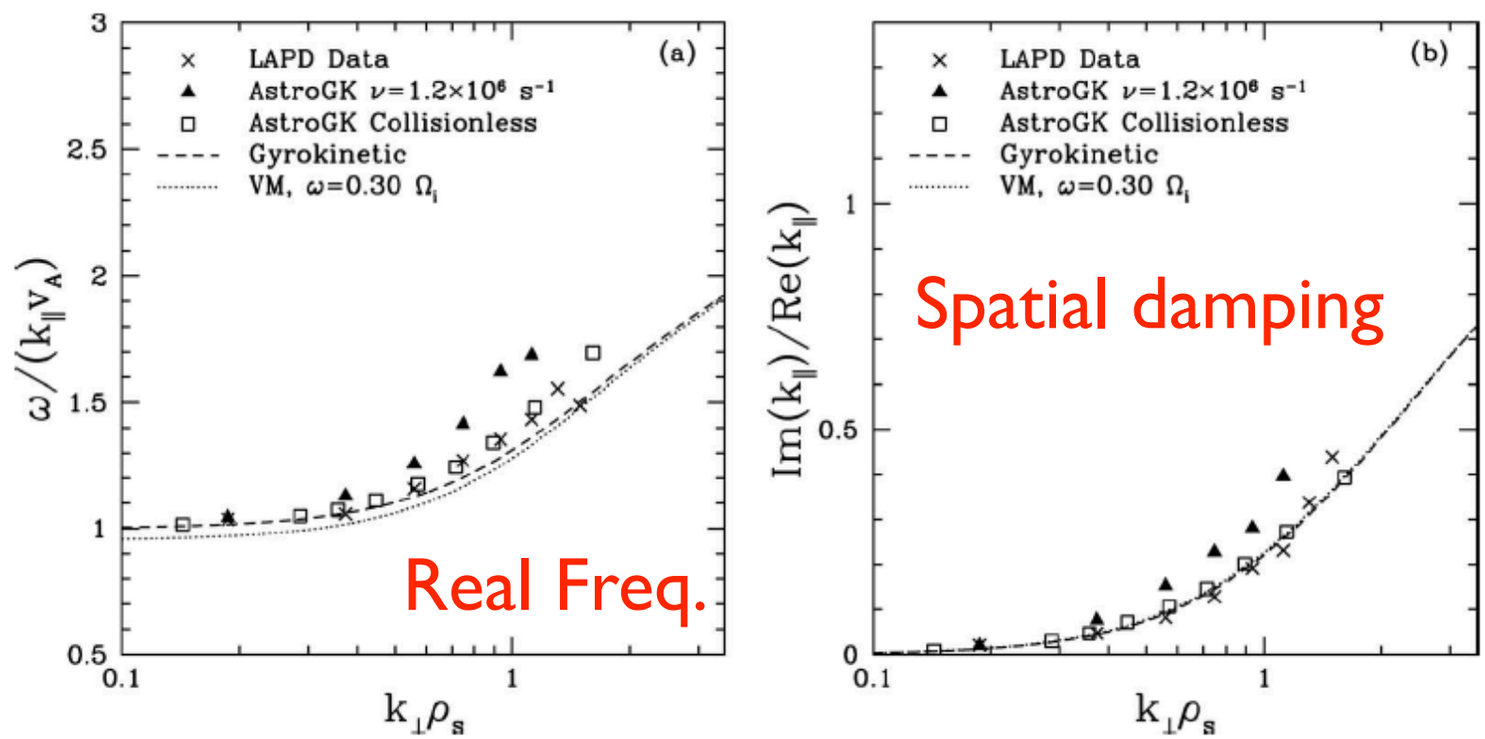


- Special antenna built to create plane-wave-like AWs with control over wavenumber for detailed dispersion/ damping measurements [U. Iowa group, Kletzing, Skiff + students]

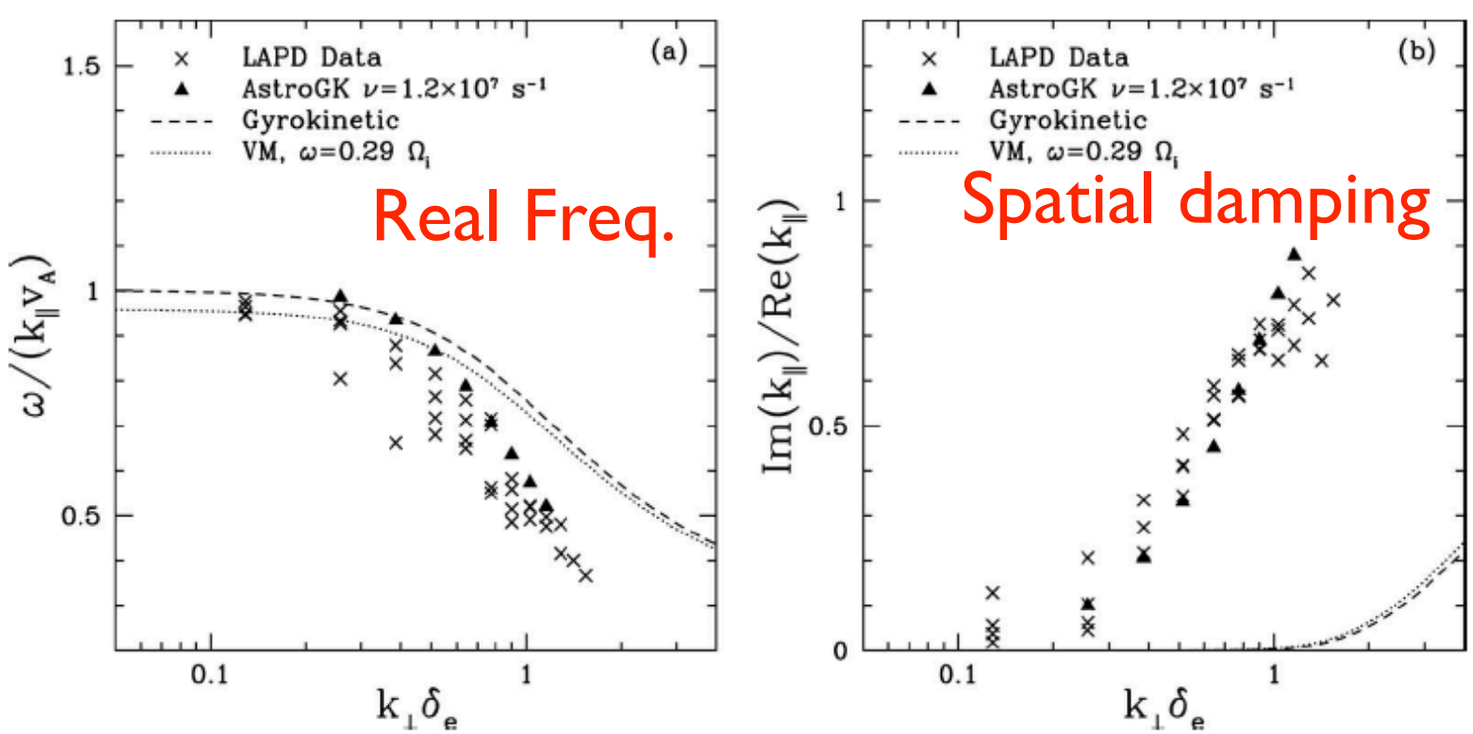
Kletzing, et al, PRL 104, 095001 (2010)

Measured dispersion and damping, GK modeling

- Measurements compare well to AstroGK simulations, including collisions (crucial to get inertial AW dispersion/damping right)



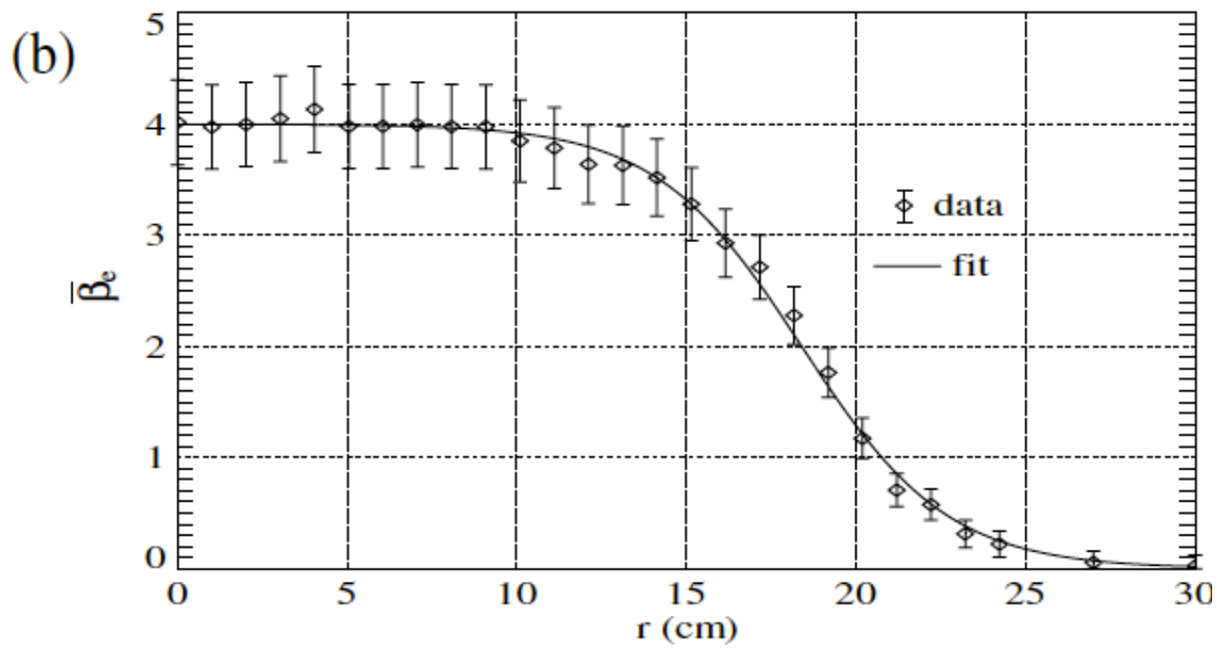
kinetic AW

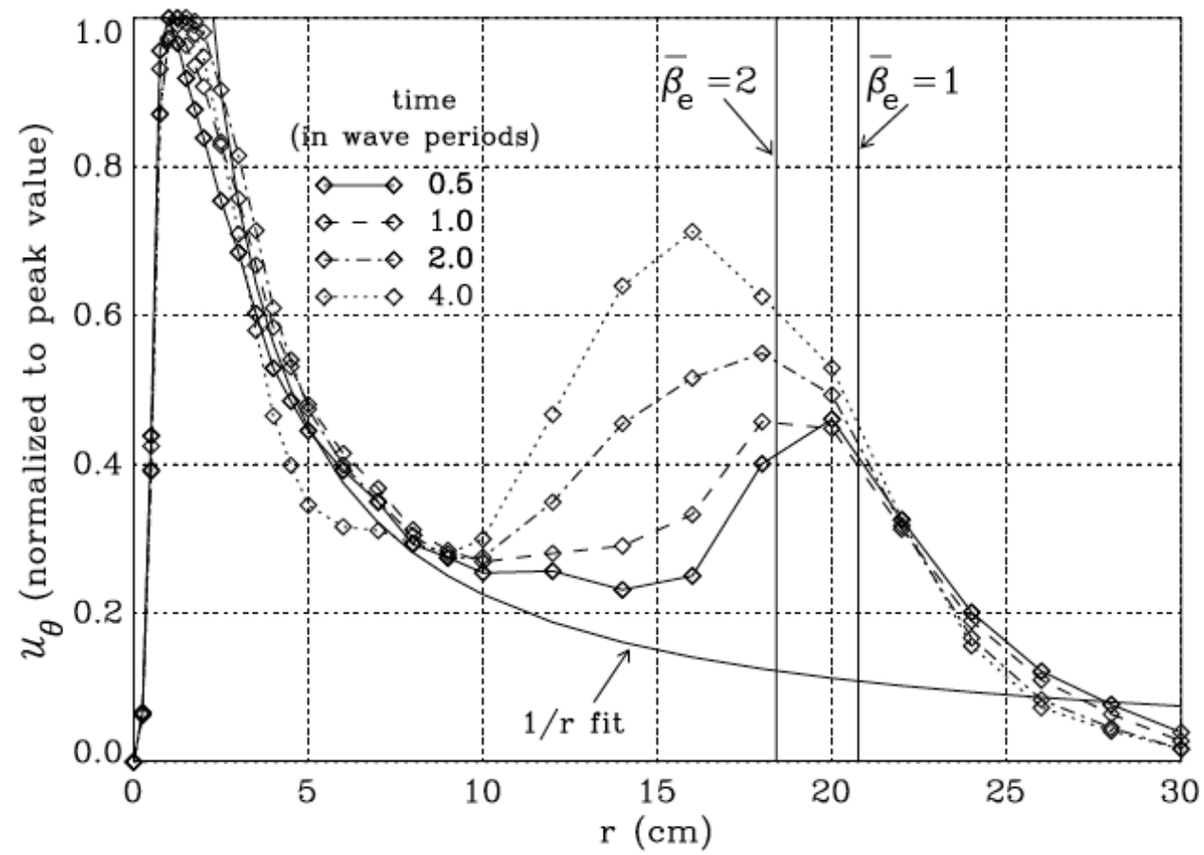


inertial AW

Nielson, Howes, et al, PoP **17**, 022105 (2010)

Conversion of KAW to IAW on pressure gradient



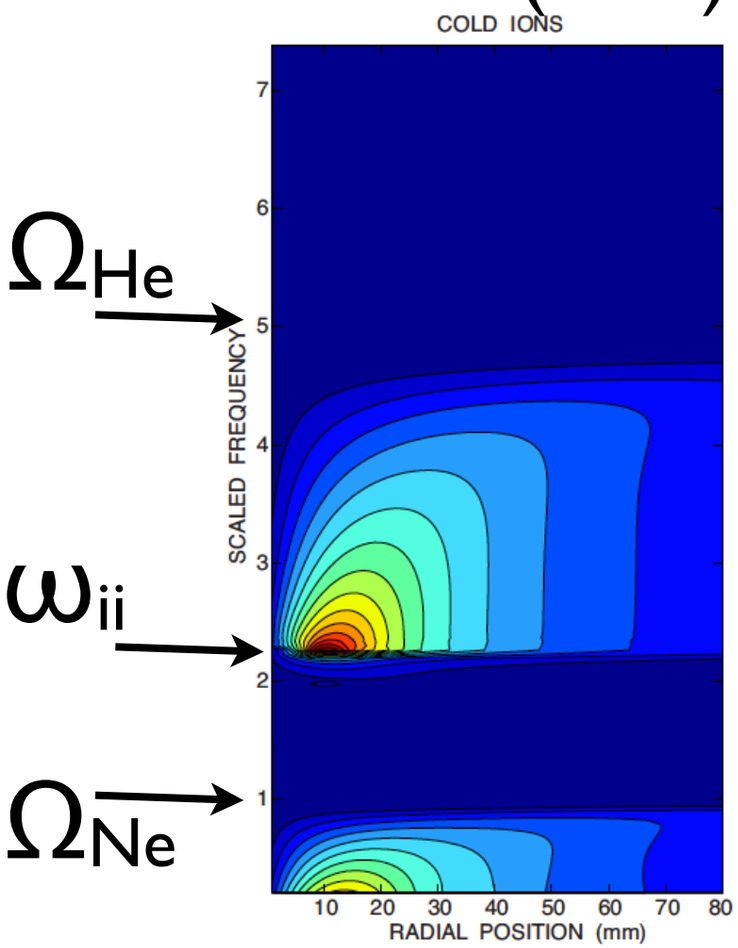


- In presence of pressure (beta) gradient, conversion of KAW to IAW possible: needed to explain field line resonances in magnetosphere
- See accumulation of wave energy in plasma edge, consistent with conversion from KAW (forward wave) to IAW (backward wave)

Vincena, Gekelman, Maggs, PRL 93, 105003 (2004)

Shear waves in multi-ion plasmas

model (cold)



- He/Ne and H/He gas mixtures; Ion-ion hybrid is cutoff for shear wave, get two propagation bands

Vincena, Morales, Maggs, PHYSICS OF PLASMAS 17, 052106 (2010)

Shear waves in multi-ion plasmas

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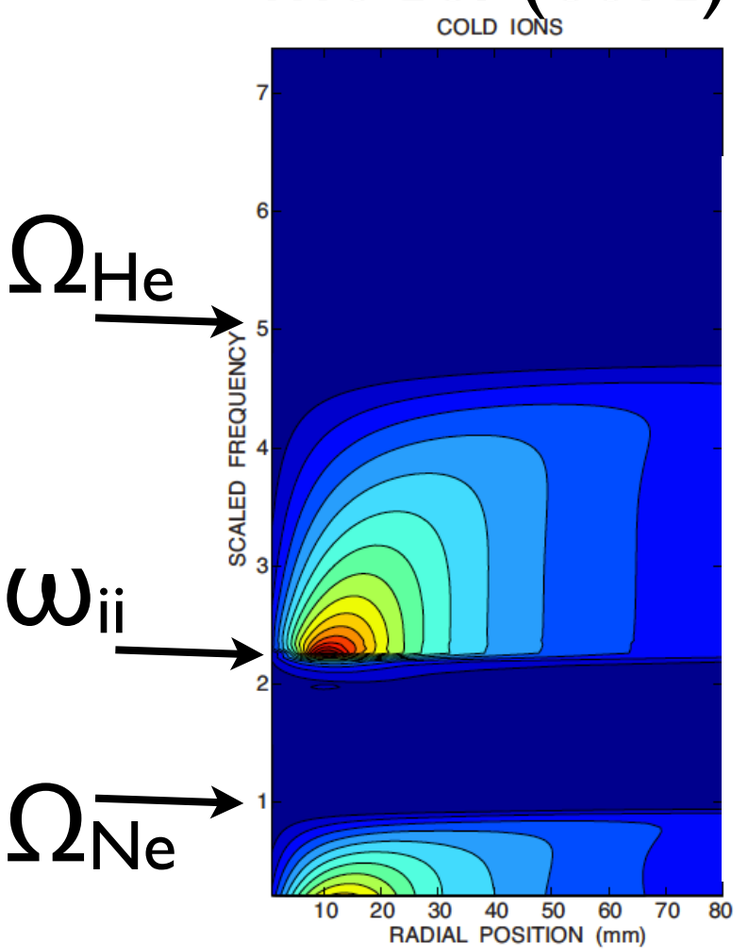
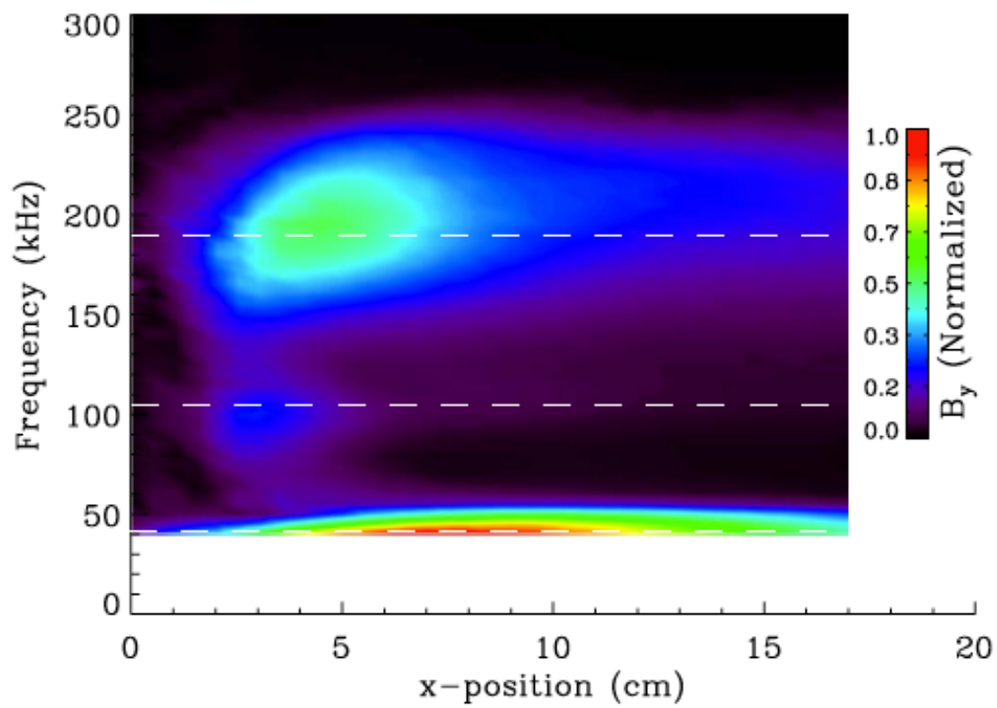


experiment

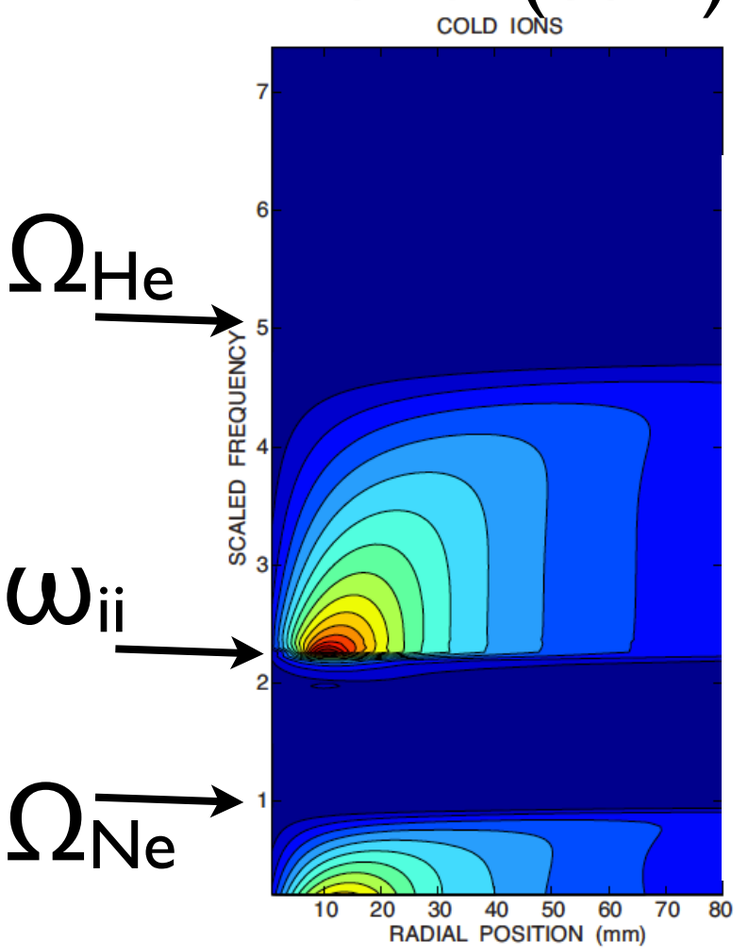


- He/Ne and H/He gas mixtures; Ion-ion hybrid is cutoff for shear wave, get two propagation bands
- Two propagation bands observed in expt, gap moves with concentration: mode in gap is IBW

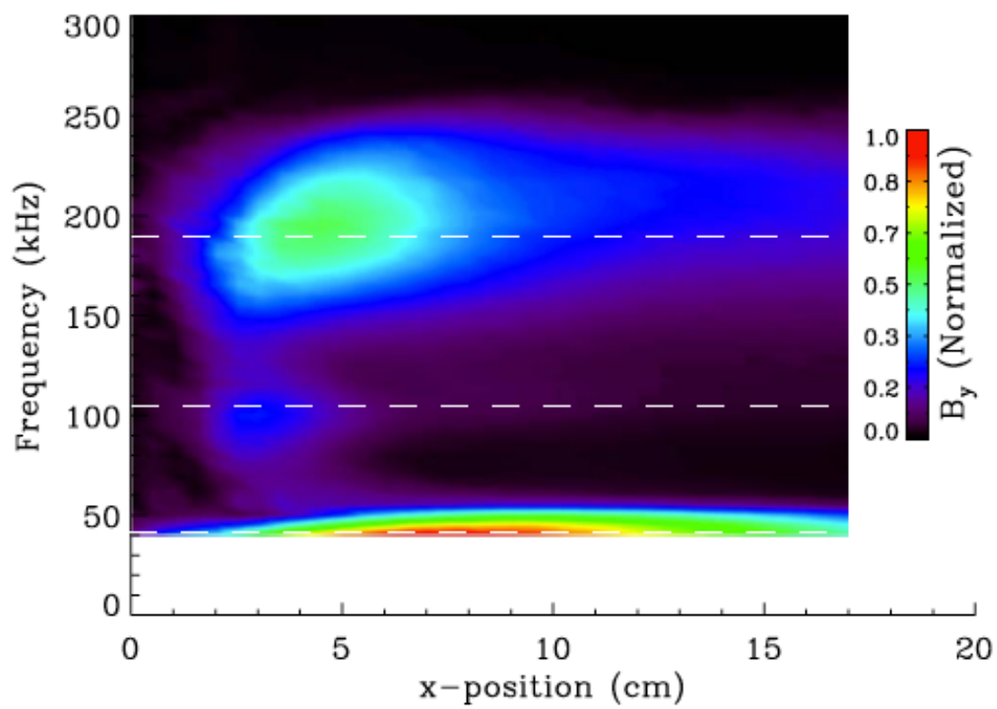
Vincena, Morales, Maggs, PHYSICS OF PLASMAS 17, 052106 (2010)

Shear waves in multi-ion plasmas

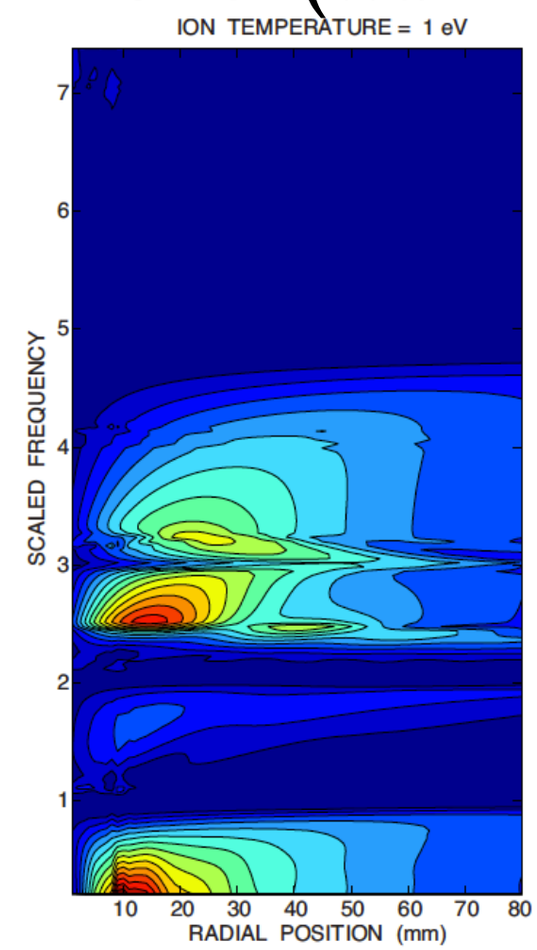
model (cold)



experiment



model (warm)



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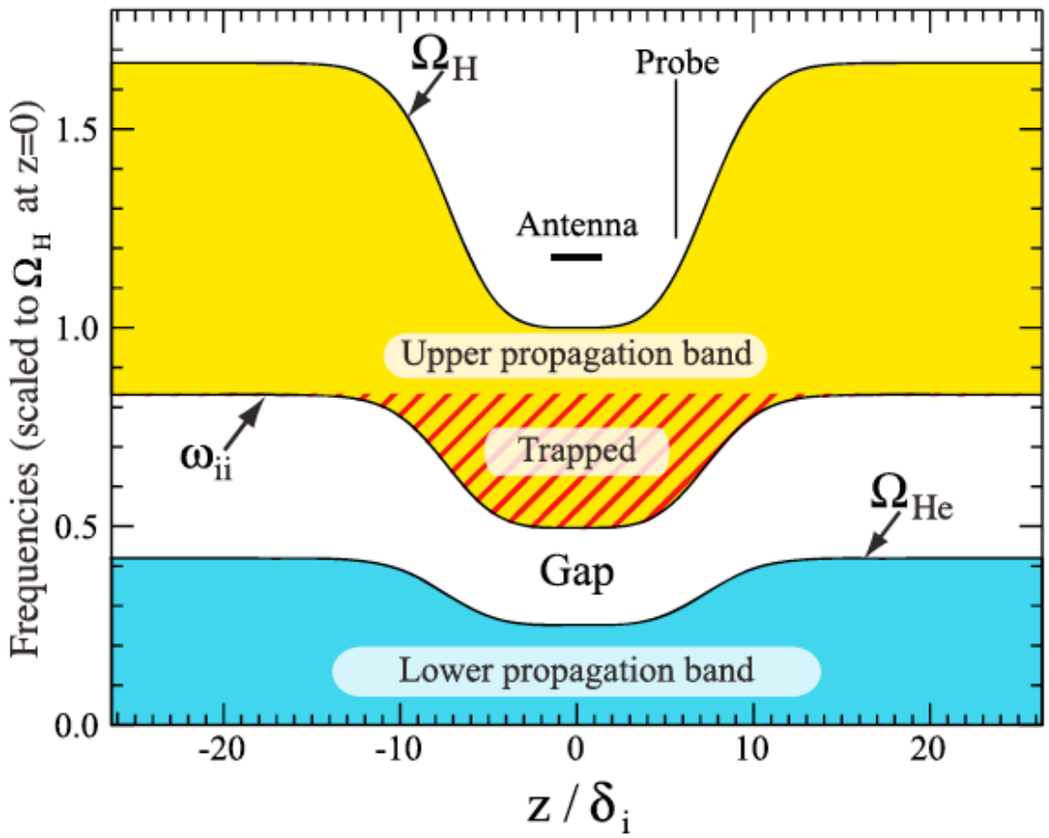
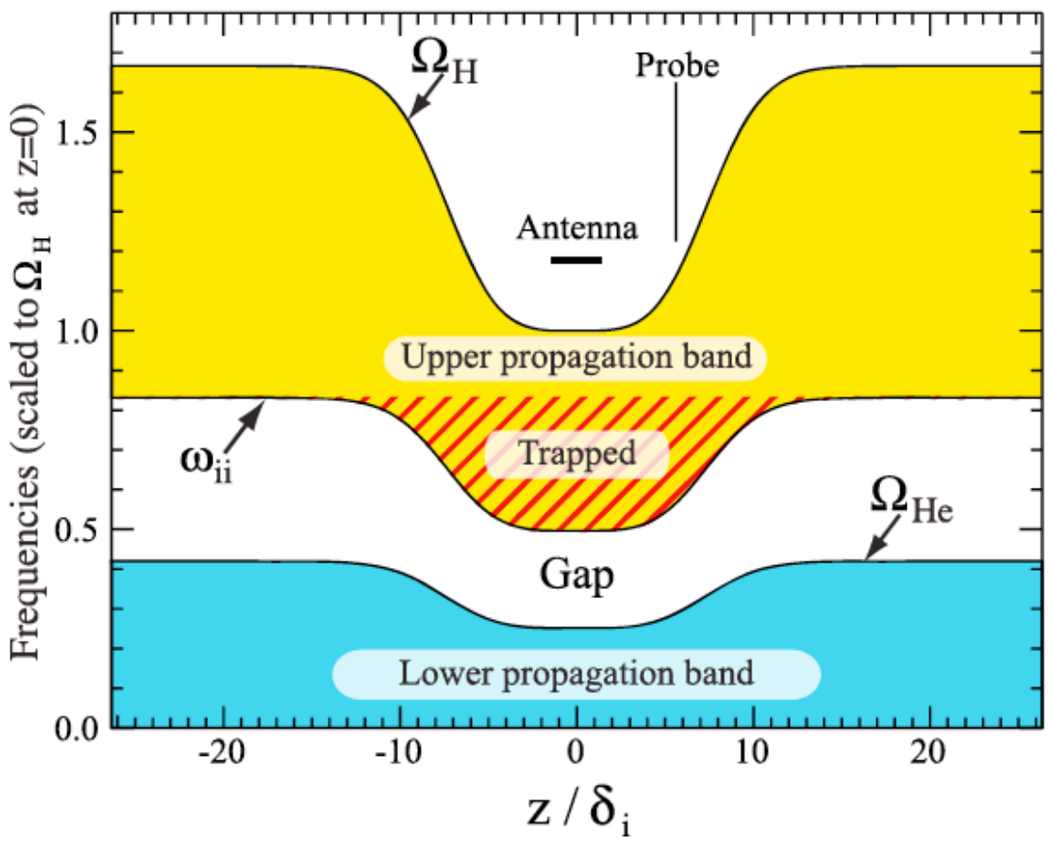
Vincena, Morales, Maggs, PHYSICS OF PLASMAS 17, 052106 (2010)

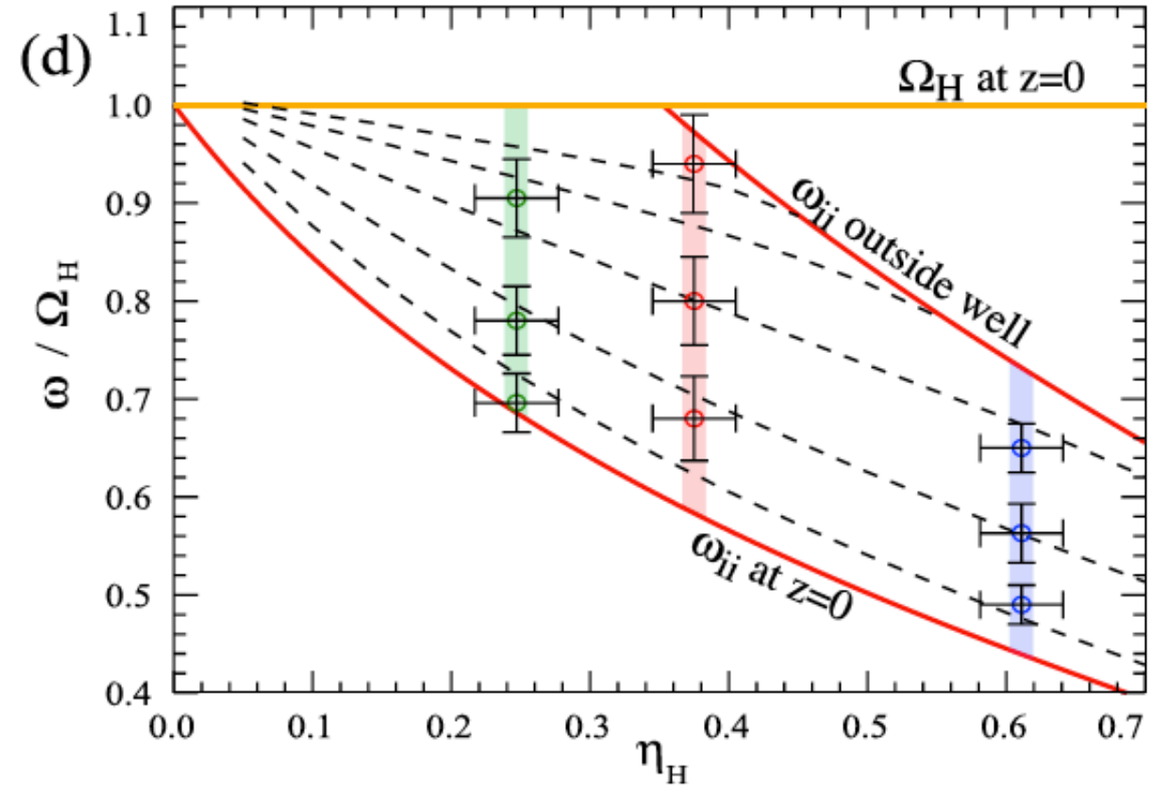
Multi-ion Shear Wave Resonator



- Shear wave resonator based on ion-ion hybrid cutoff proposed to explain magnetospheric observations [Russell et al]

Multi-ion Shear Wave Resonator

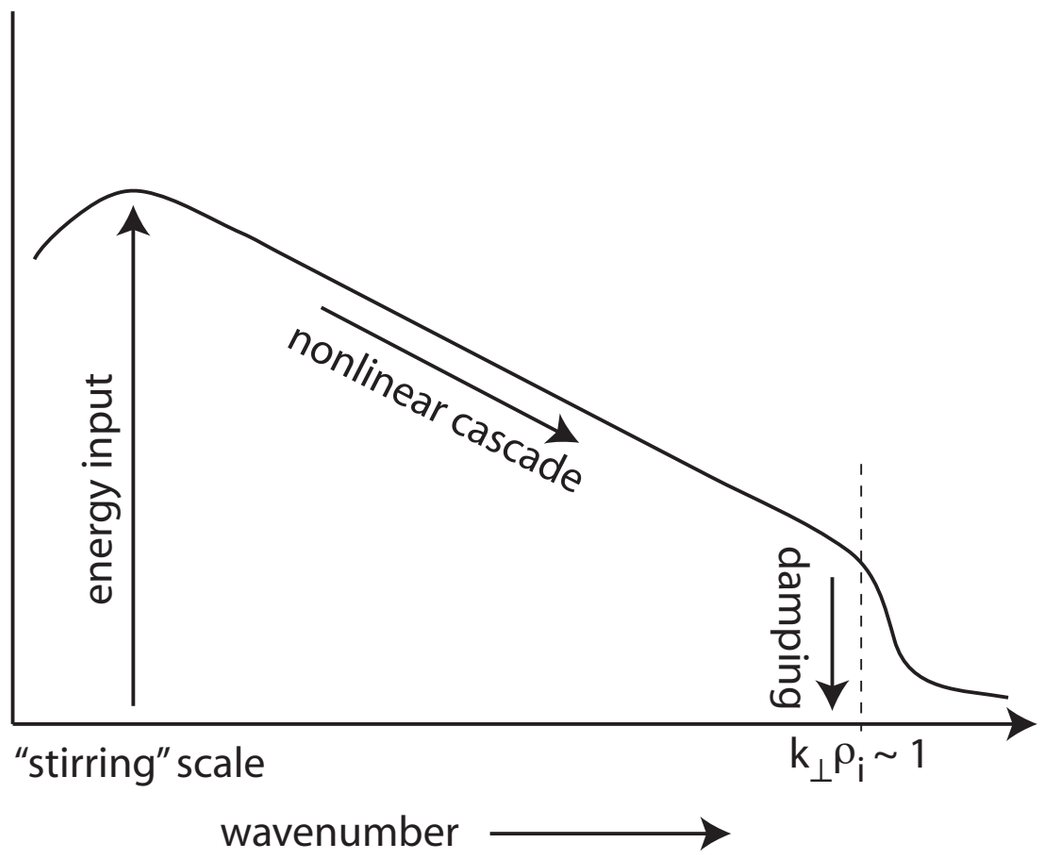




- Shear wave resonator based on ion-ion hybrid cutoff proposed to explain magnetospheric observations [Russell et al]
- Realized in LAPD using mirror field, observed resonances agree with theory

Vincena, Farmer, Maggs, Morales, GRL 38, L11101 (2011)

Nonlinear Alfvén waves: motivation from MHD turbulence

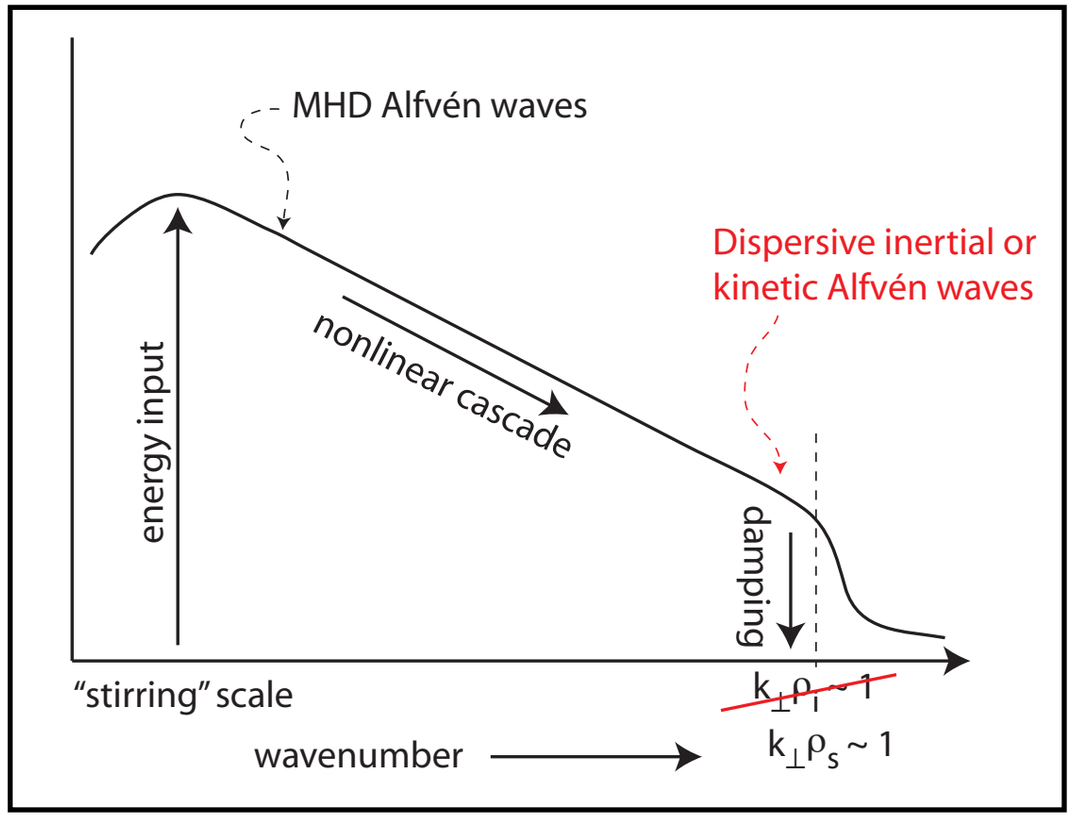


- Low frequency turbulence in magnetized plasma (e.g. solar wind, accretion disk)
- Energy is input at "stirring" scale (e.g. MRI in accretion disk, tearing mode or Alfvén Eigenmode in tokamak or RFP) and cascades nonlinearly to dissipation scale

- From a weak turbulence point of view, cascade is due to interactions between linear modes: shear Alfvén waves
- Motivates laboratory study of wave-wave interactions among Alfvén waves

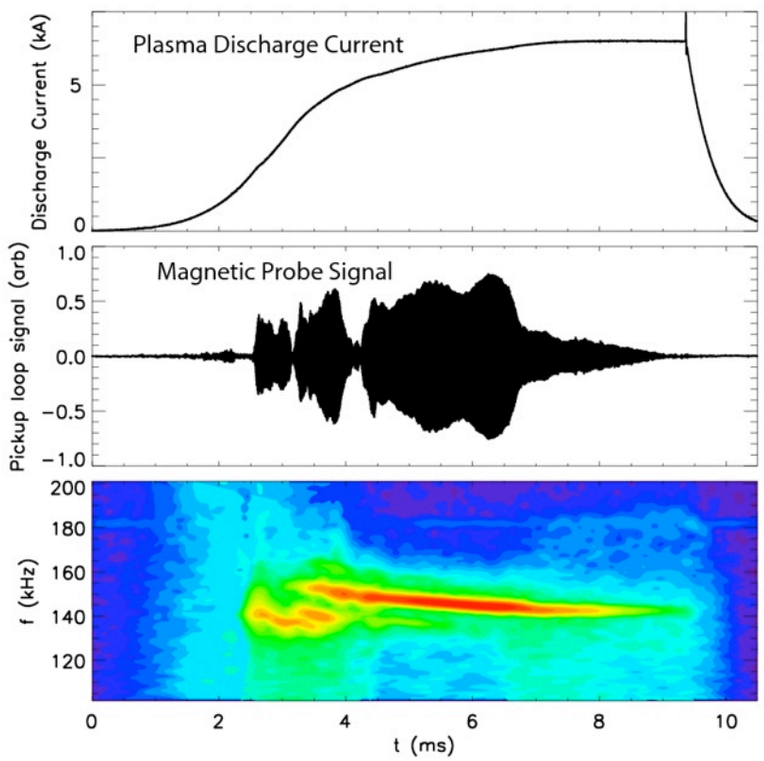
Alfvén wave interactions in LAPD

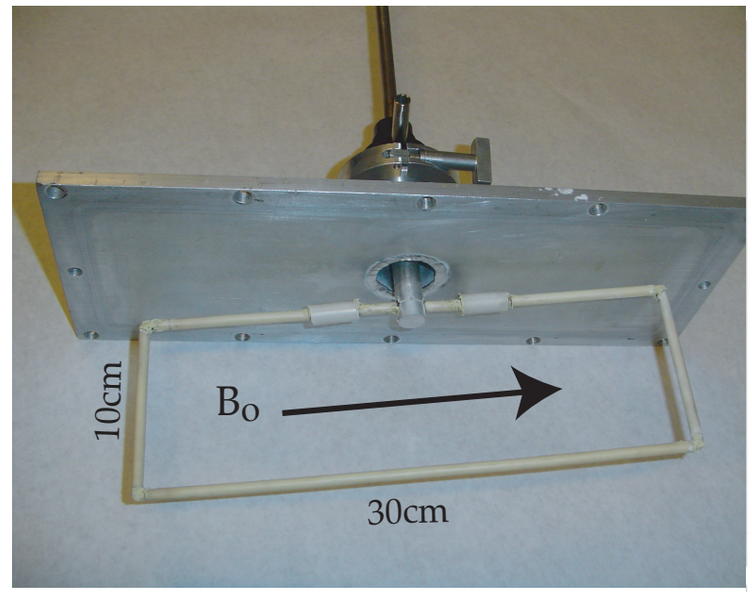
Experiment: generate large amplitude Alfvén waves in LAPD and study wave-wave interactions



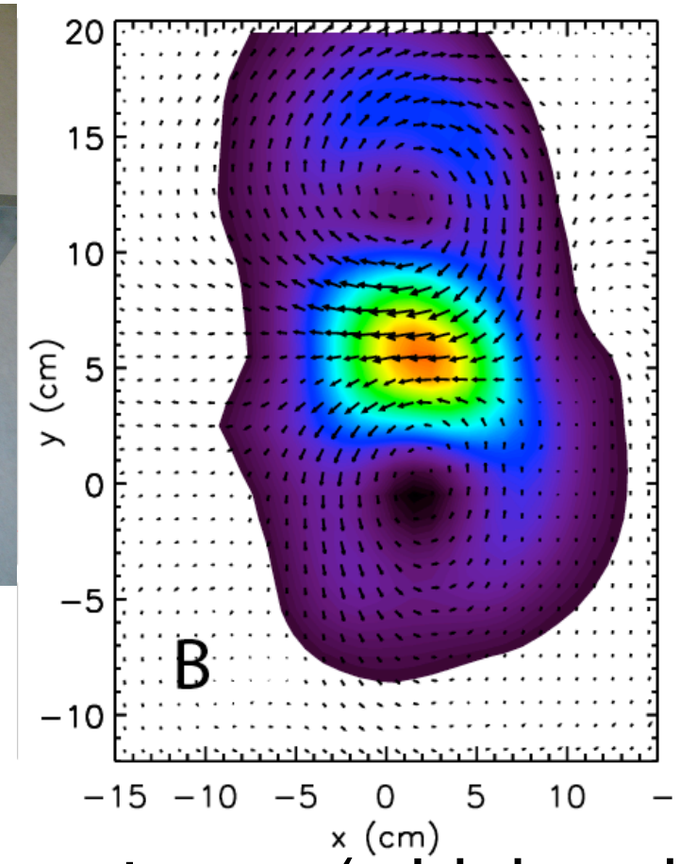
- Incompressible MHD theory of interactions (e.g. Goldreich-Sridhar): Only counter-propagating waves interact
- In LAPD experiments, waves have $k_\perp \rho_s \sim 1$, $\omega/\Omega_i \sim 1$
  - dispersive kinetic or inertial Alfvén waves
  - Co-propagating interaction allowed (waves can pass through one another)
  - Decay instabilities possible (parametric, modulational)

Large amplitude wave sources: MASER and Antenna



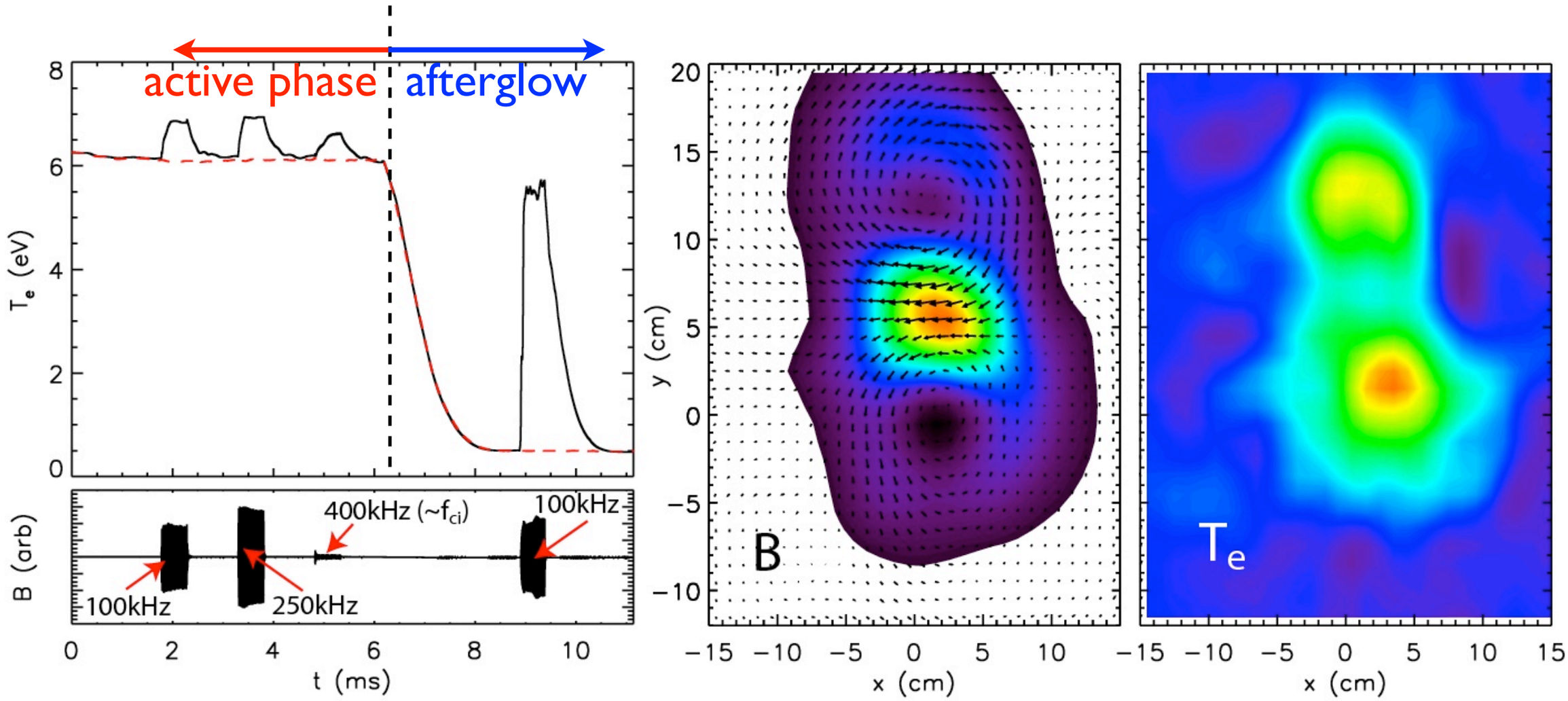


I ~ 1kA,V ~ 1kV



- Resonant cavity (MASER, narrowband), loop antenna (wideband)
- Both can generate AWs with δB/B ~ 1% (~10G or 1mT); large amplitude from several points of view:
  - Wave beta is of order unity $$\beta_w = \frac{2\mu_o p}{\langle \delta B^2 \rangle} \approx 1$$
  - Wave Poynting flux ~ 200 kW/m2, same as discharge heating power density
  - From GS theory: stronger nonlinearity for anisotropic waves; here $k_{||}/k_{\perp} \sim \delta B/B$

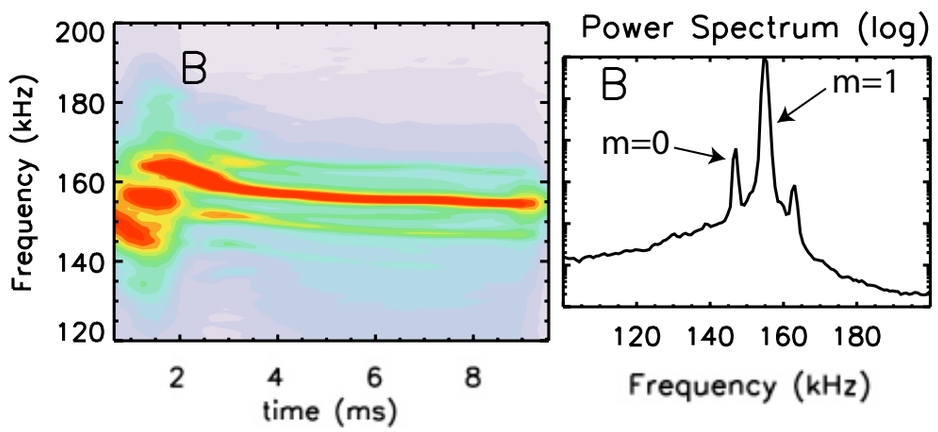
Strong electron heating by large amplitude shear Alfvén waves



- Localized heating observed, on wave current channel
- Heating in afterglow consistent with Poynting flux ~ discharge heating power density

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



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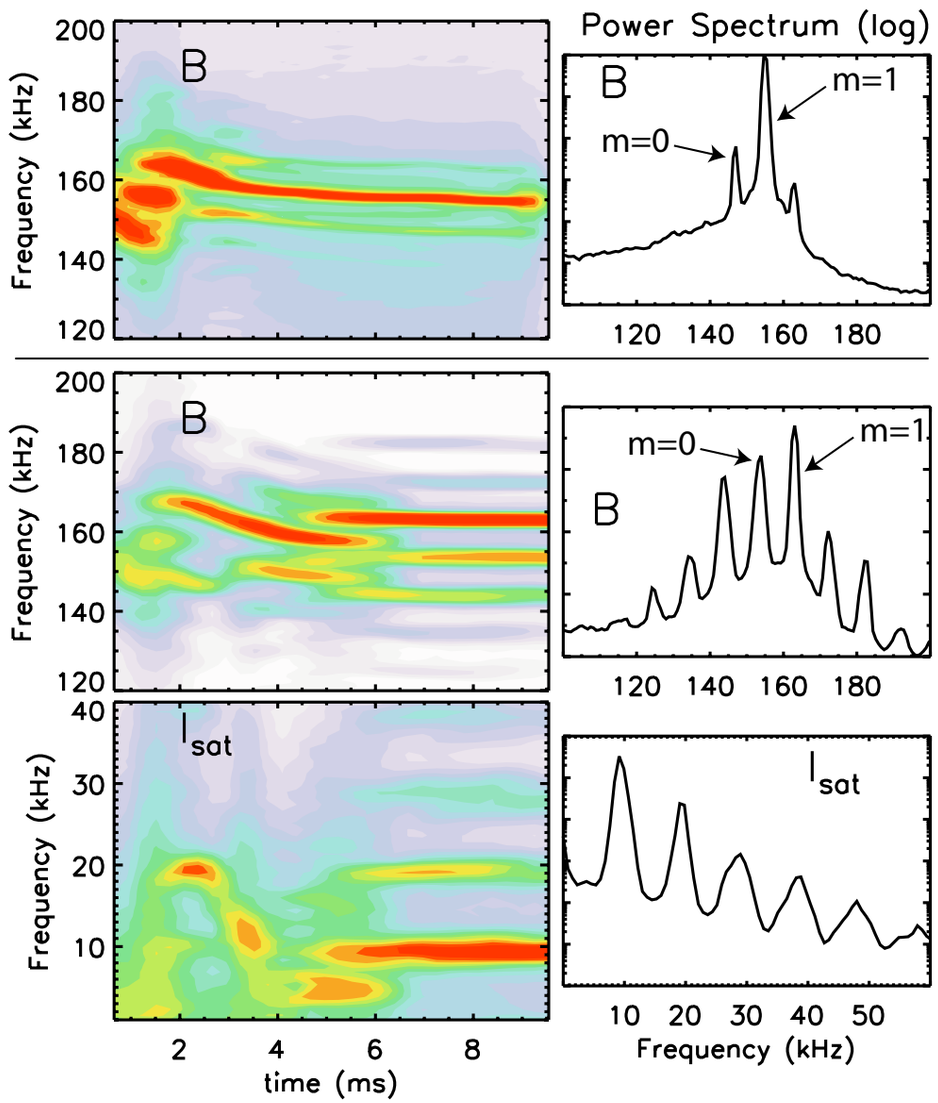
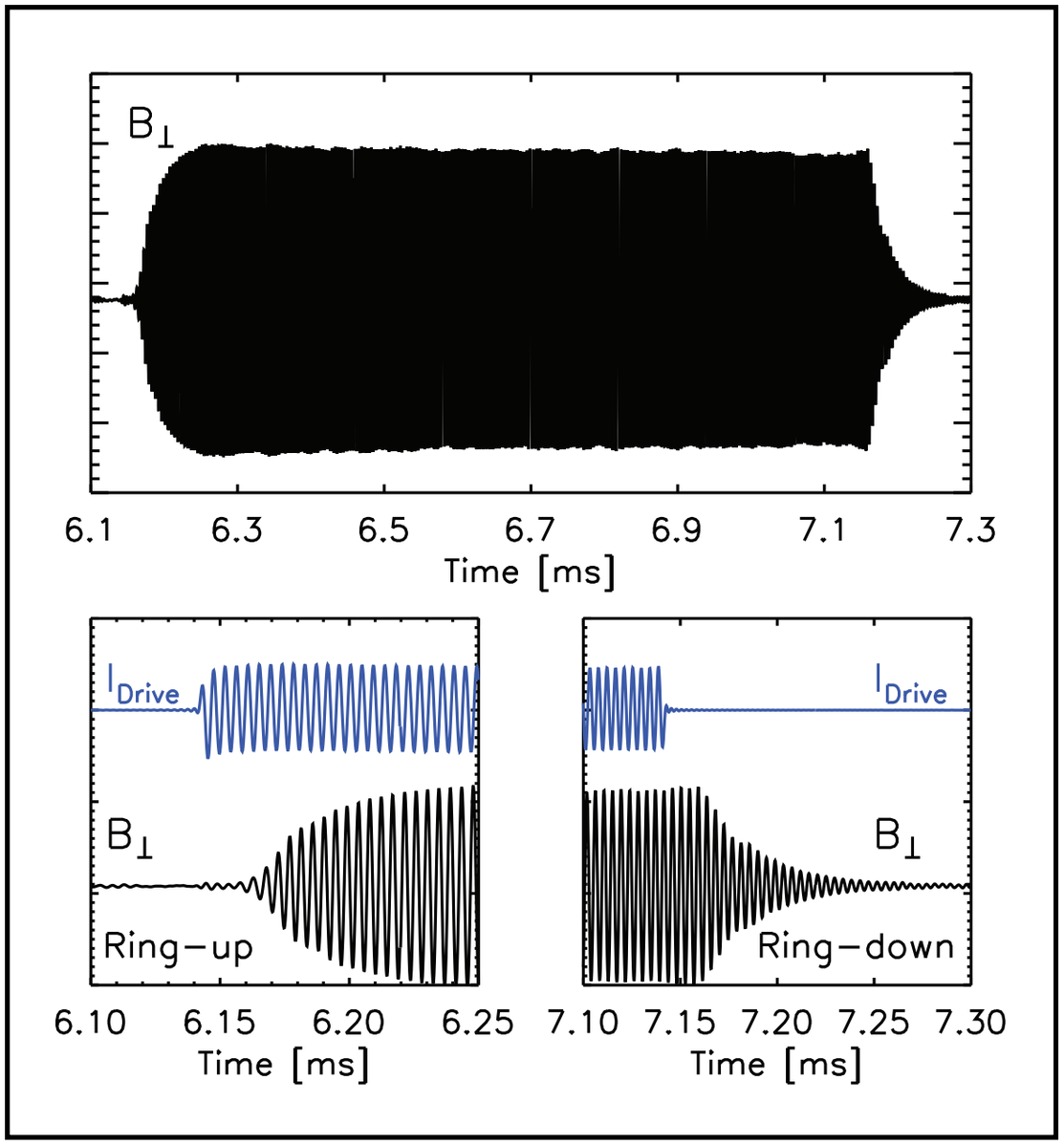
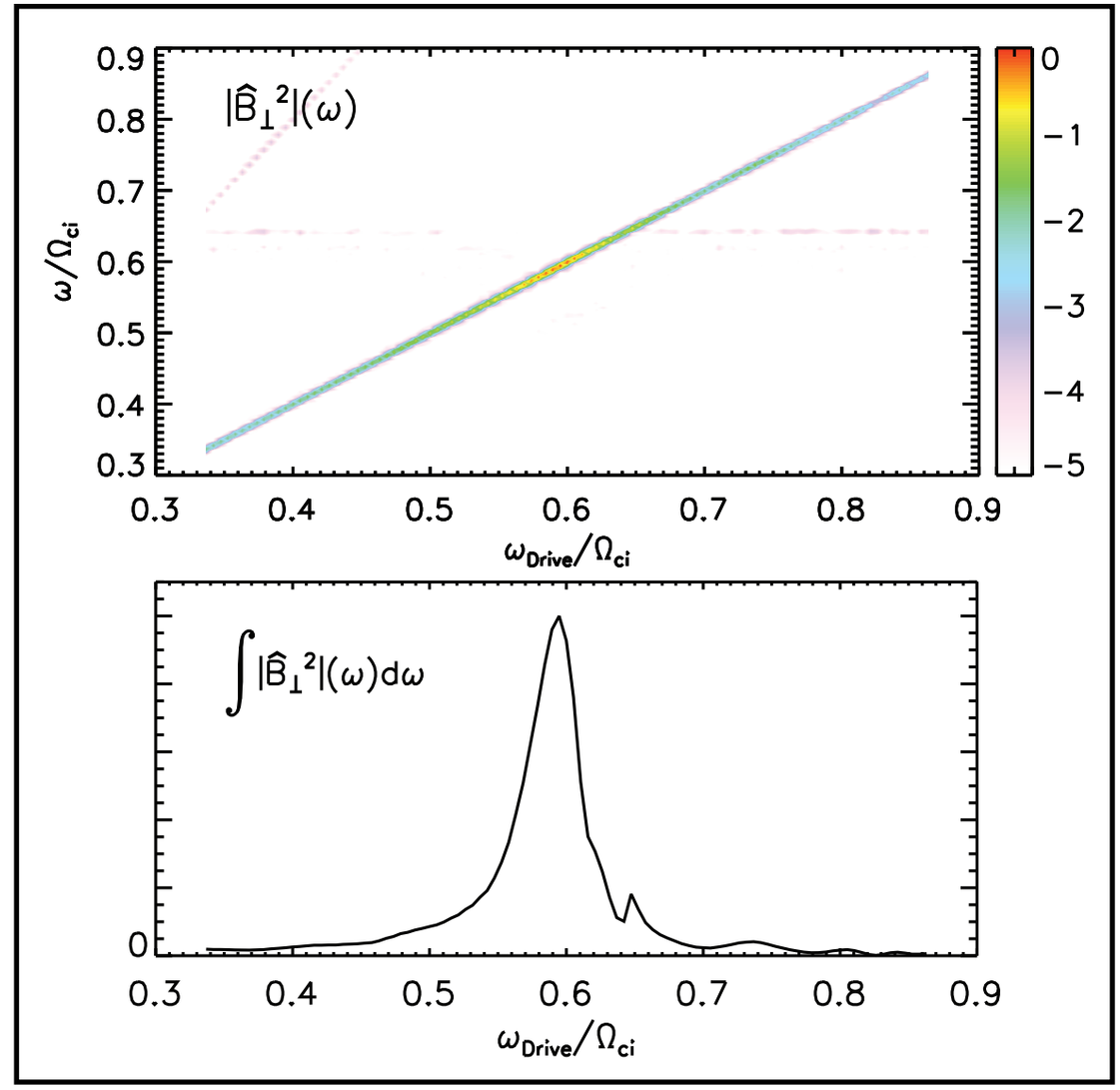


- Can control strength of multimode emission (e.g. change current, shorten plasma column)
- With two strong primary waves, observe low frequency mode, at beat frequency, sidebands
- Nonresonant process: Low f mode is quasimode, $C_s \ll v_\phi < v_A$
- Strong interaction: "pump" δB/B~1%, QM δn/n~10%

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

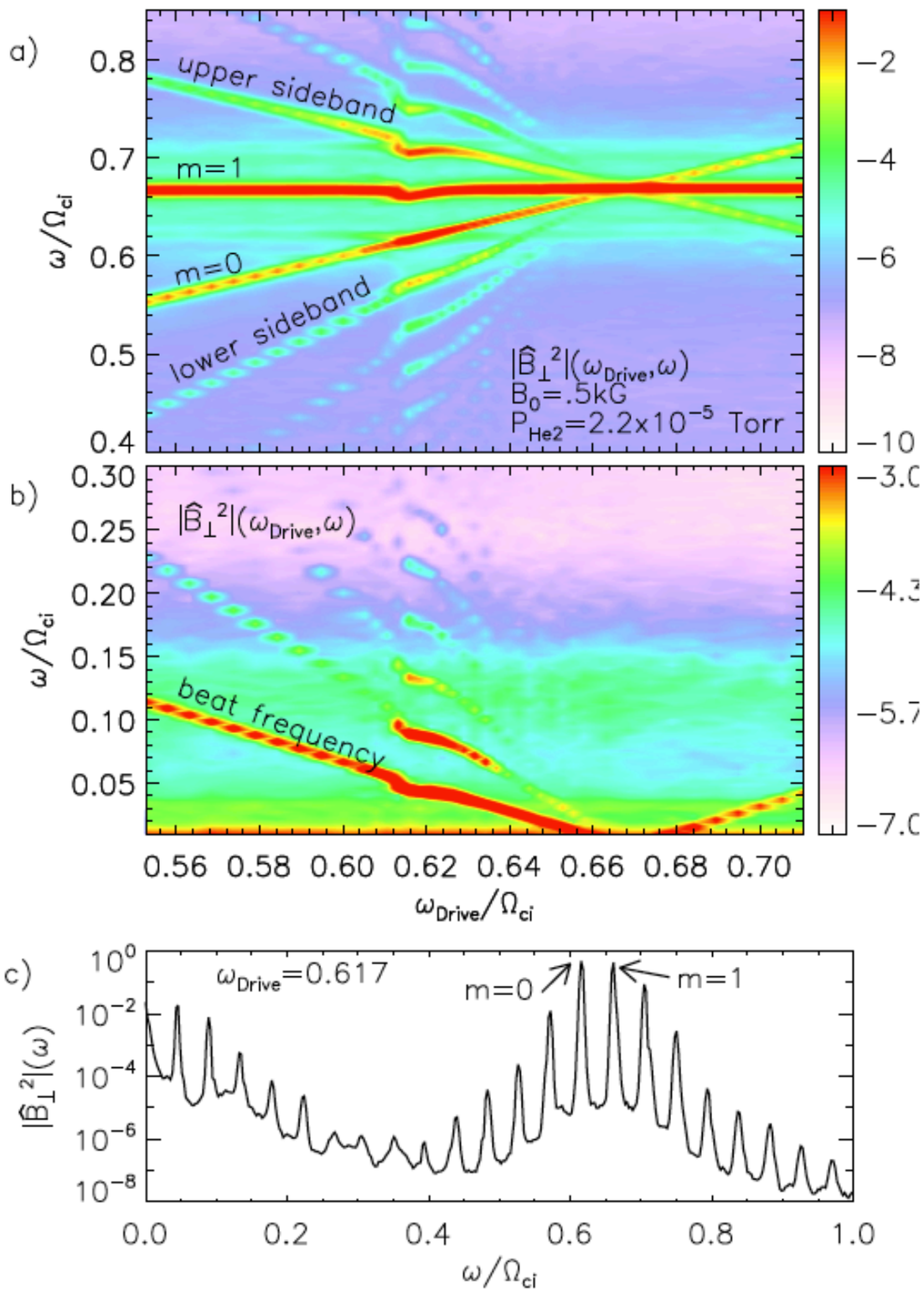
Driven cavity allows controlled interaction studies





- External voltage oscillation applied to anode-cathode to excite cavity
- Primarily excite m=0 mode (symmetry of drive?)

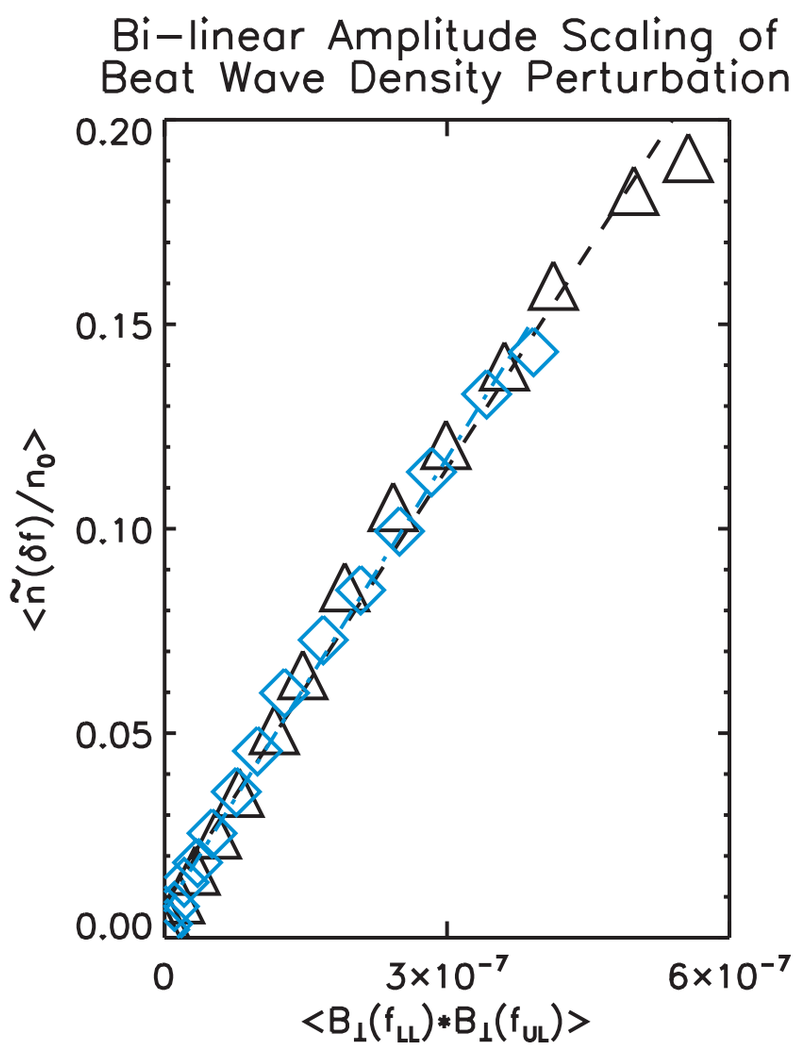
Driven cavity, antenna launched waves used to study properties of interaction

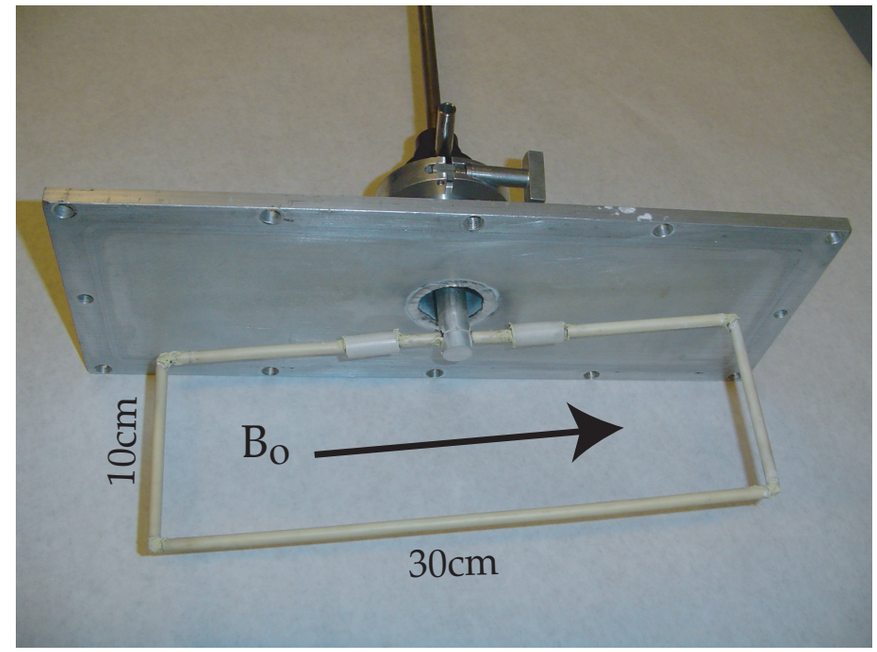


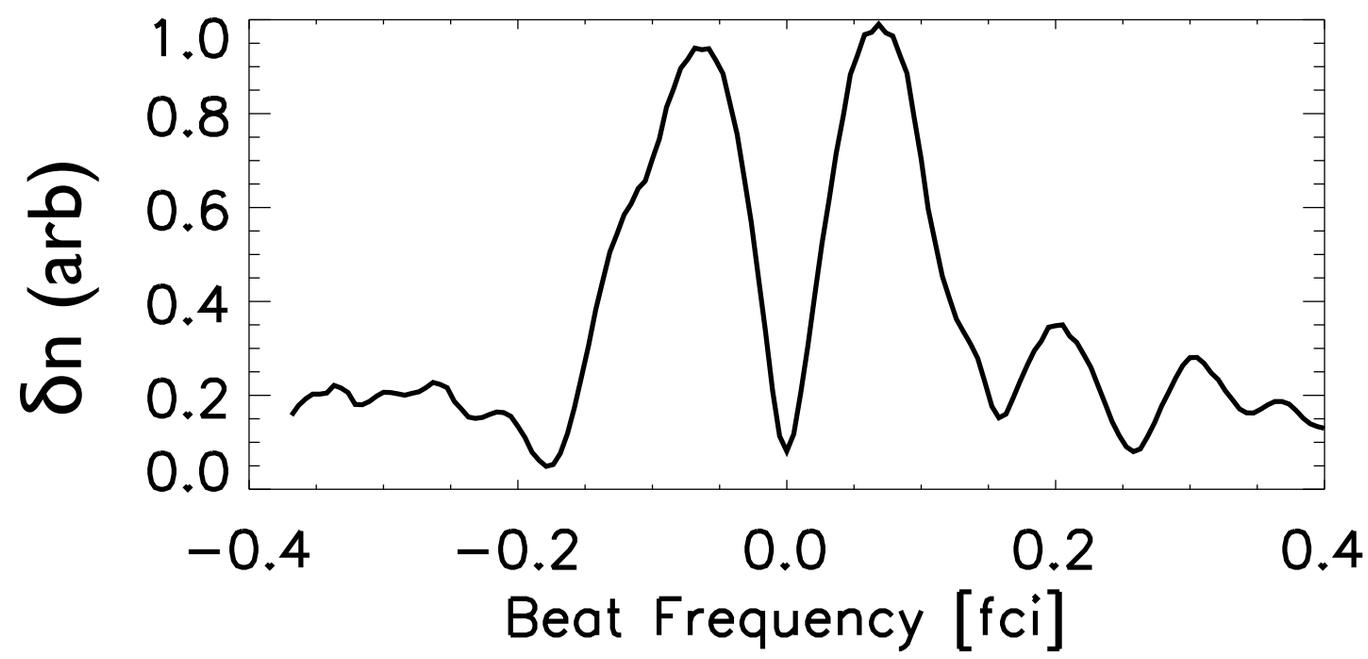
Driven cavity: can produce QMs with range of beat frequencies (limited by width of cavity resonance for driven m=0)

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

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







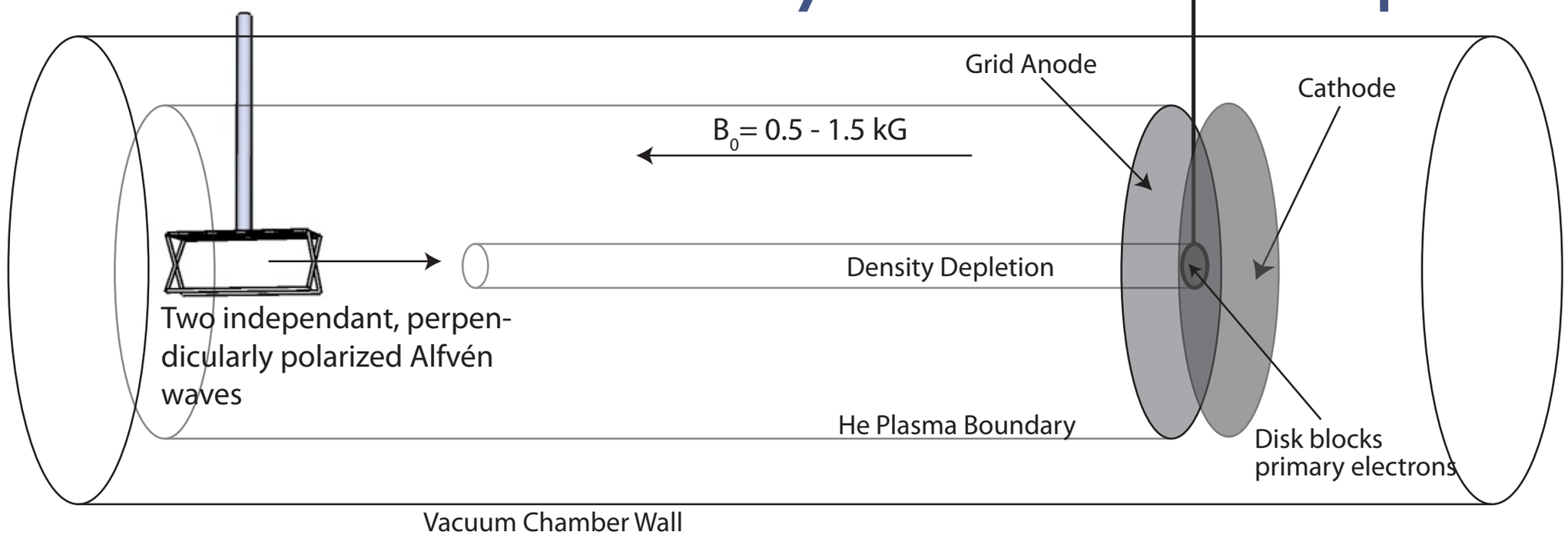
Beat driven wave is off-resonance Alfvén wave; theory consistent with observed amplitude, resonant behavior

- 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 $k_\perp >> k_{||}$

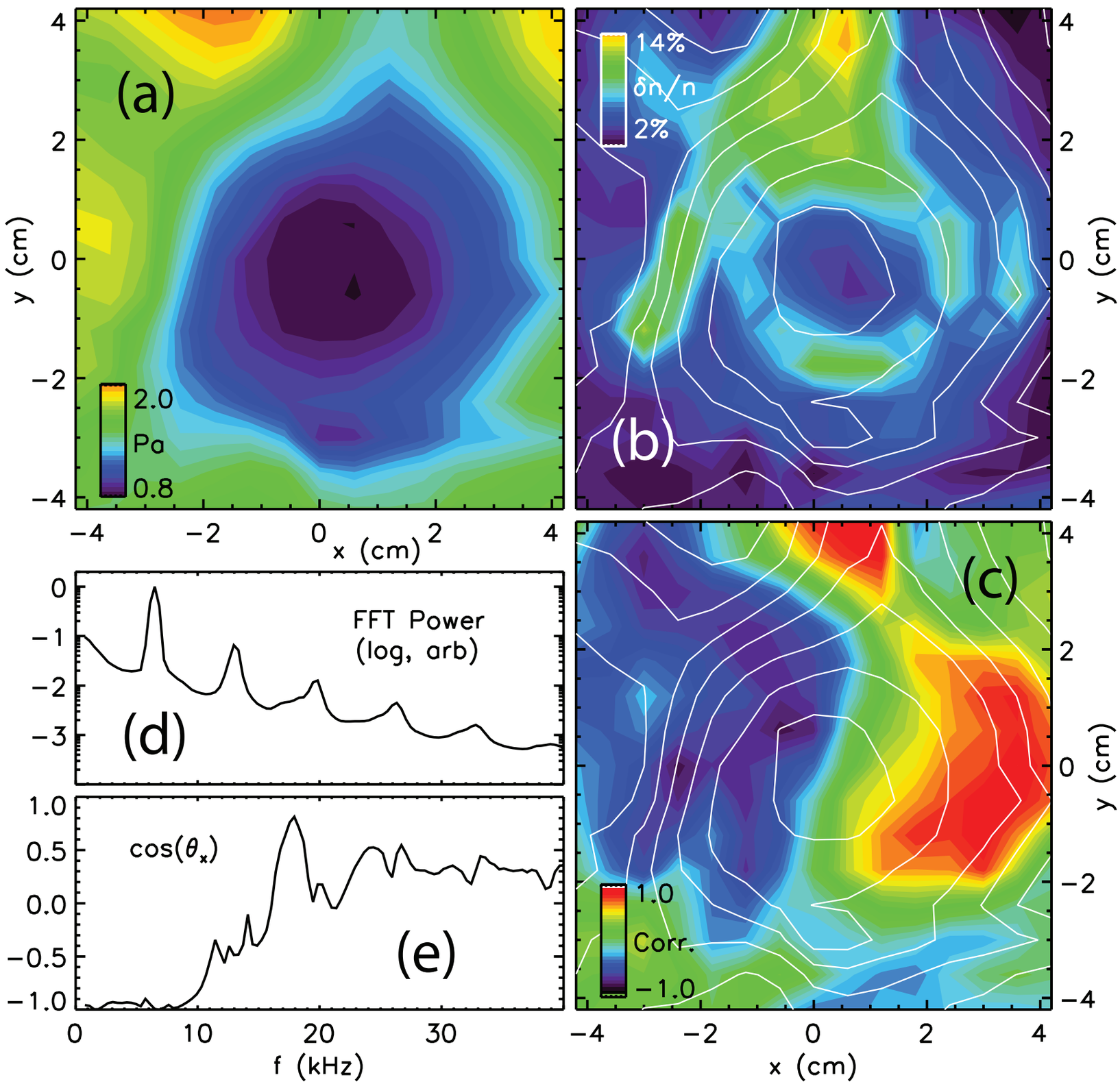
KAW beat-wave/instability interaction experiment



- Alfvén beat waves easily driven at ~10kHz, near drift-wave frequency in LAPD edge: can we nonlinearly drive DWs?
- Use simple target: narrow density depletion with coherent gradient driven instability (rather than broadband turbulence in edge)
- Launch KAWs into depletion, see resonant drive of instability, suppression of instability with off-resonant drive

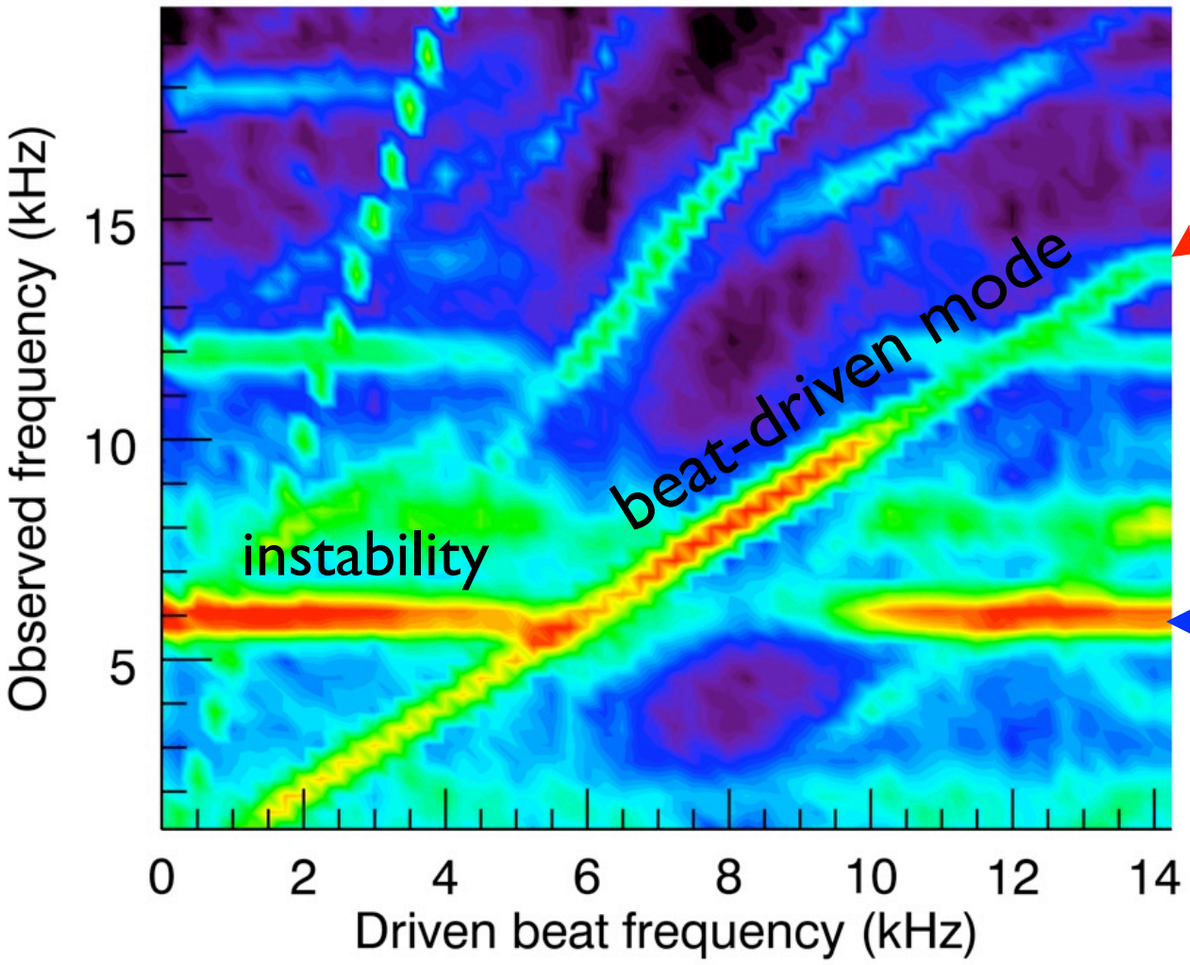
D.W. Auerbach, et al., PRL 105, 135005 (2010)
D.W. Auerbach, et al., PoP 18, 055708 (2011)

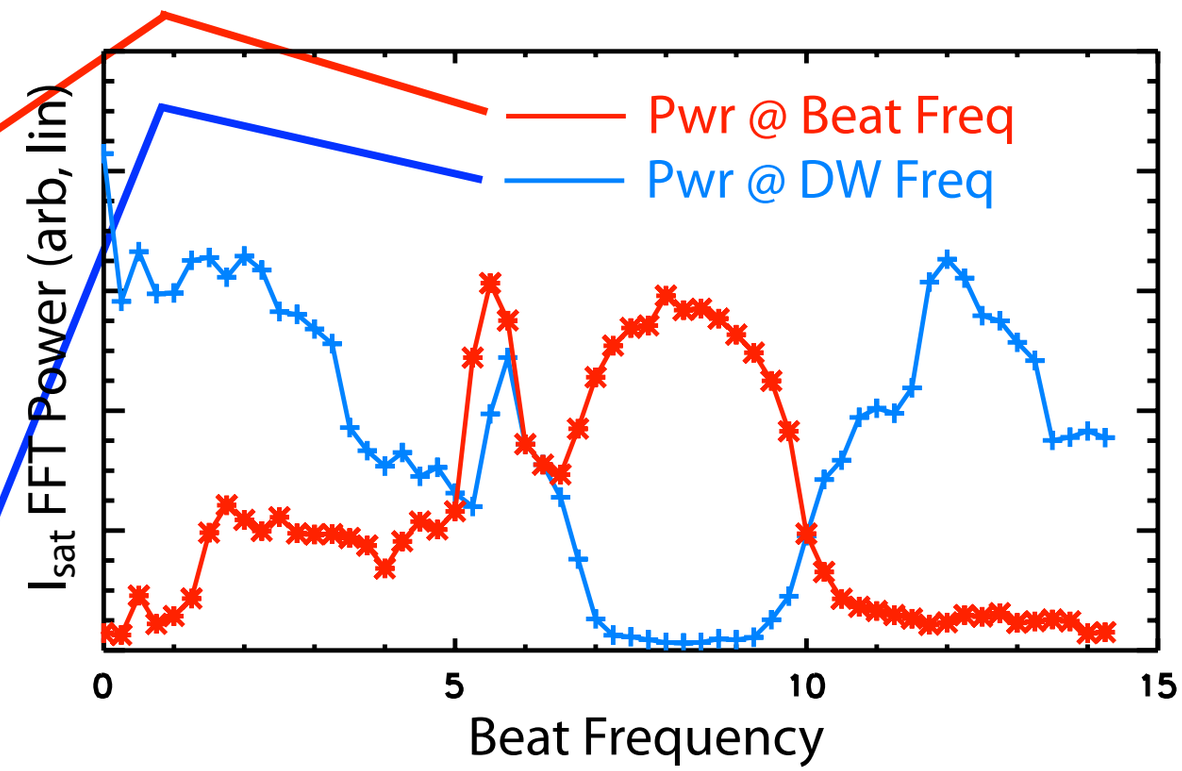
Unstable fluctuations observed on depletion



- m=1 coherent fluctuation observed localized to pressure gradient
- Drift-wave and flute-like (Kelvin-Helmholtz) unstable on measured profiles (linear Braginskii fluid calculation)
- Mode has characteristics of both

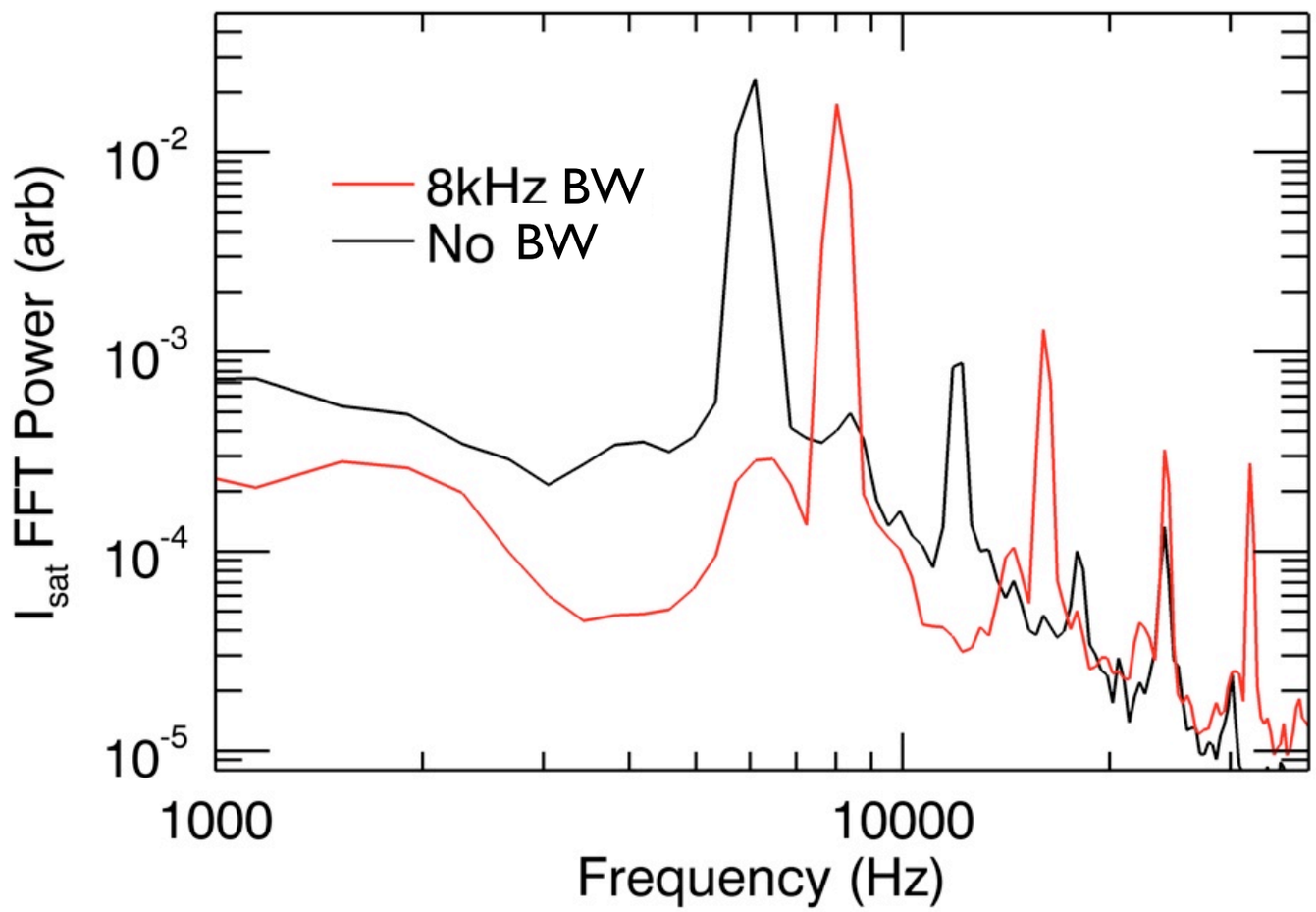
Resonant drive and mode-selection/suppression of instability





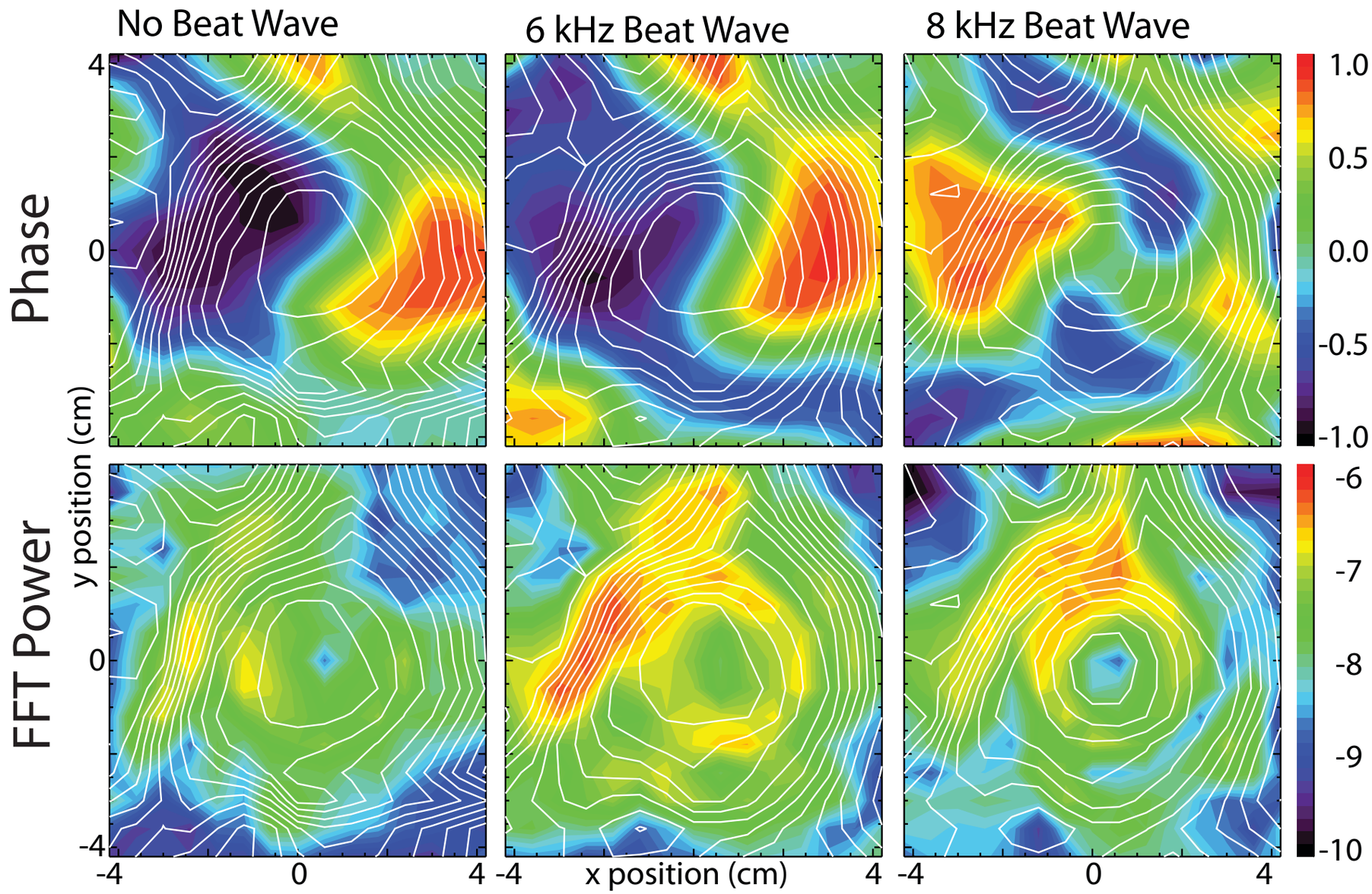
- Beat response significantly stronger than uniform plasma case
- Resonance at (downshifted) instability frequency observed, suppression of the unstable mode observed above (and slightly below)
- Instability returns at higher beat frequency

BW controls unstable mode and reduces broadband noise



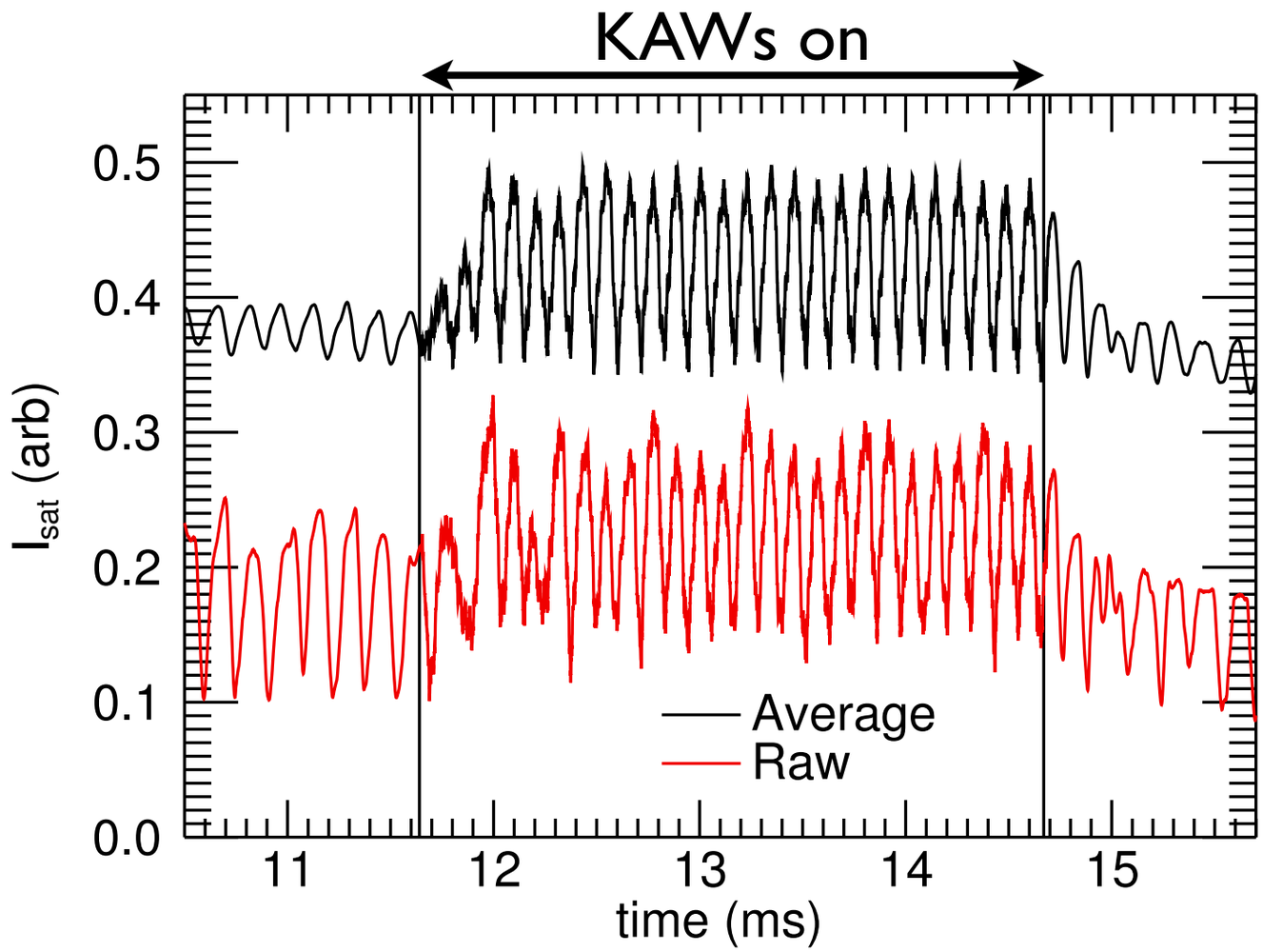
- Threshold for control: beat-driven mode has comparable (but less) amplitude than original unstable mode
- With beat wave, quieter at wide range of frequencies (previously generated nonlinearly by unstable mode?)

Structure of beat-driven modes suggest coupling to linear modes



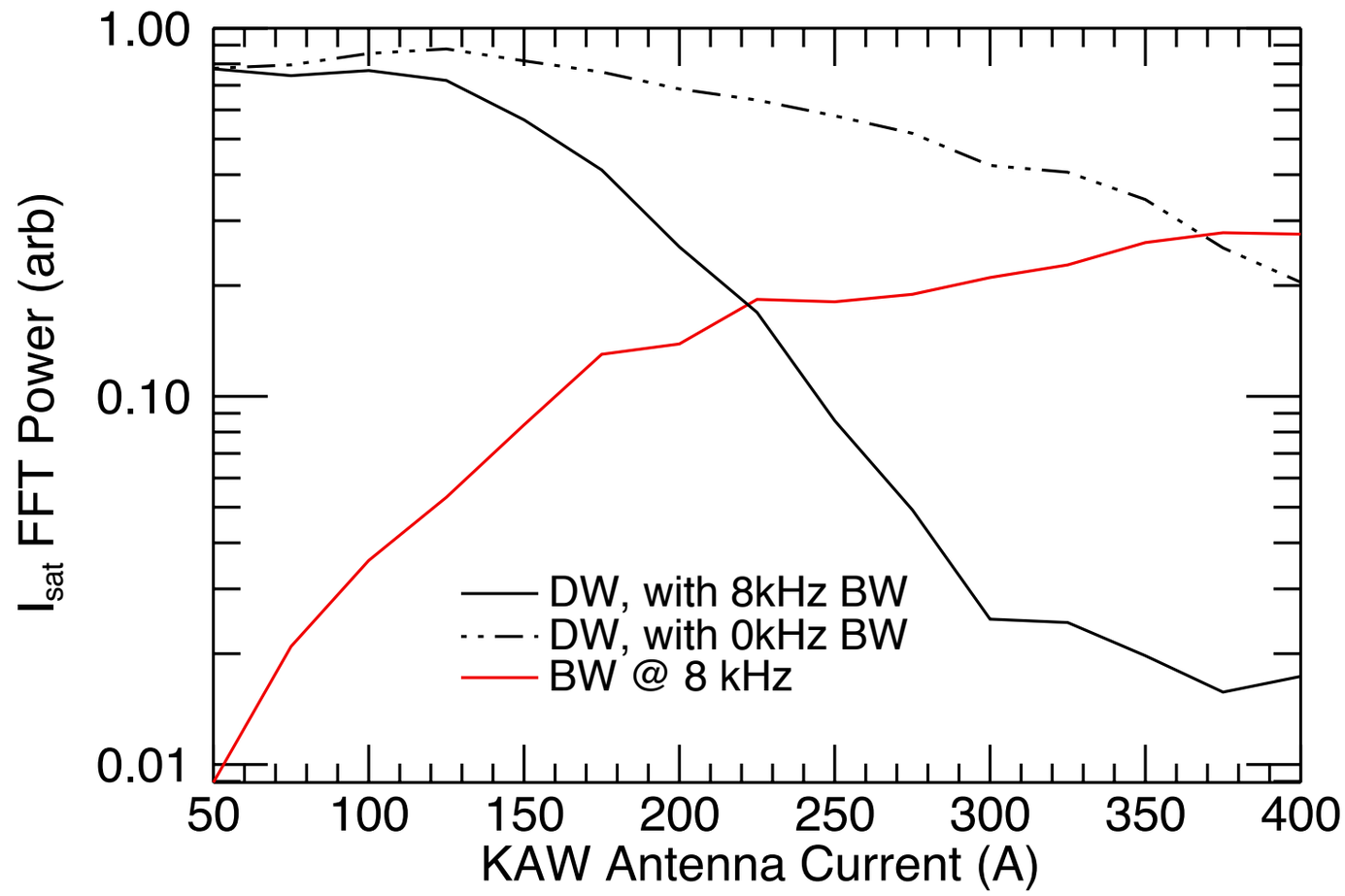
- Beat wave has m=1 (6 kHz peak), m=2 (8 kHz peak)
- Rotation in electron diamagnetic direction (same as instability)

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



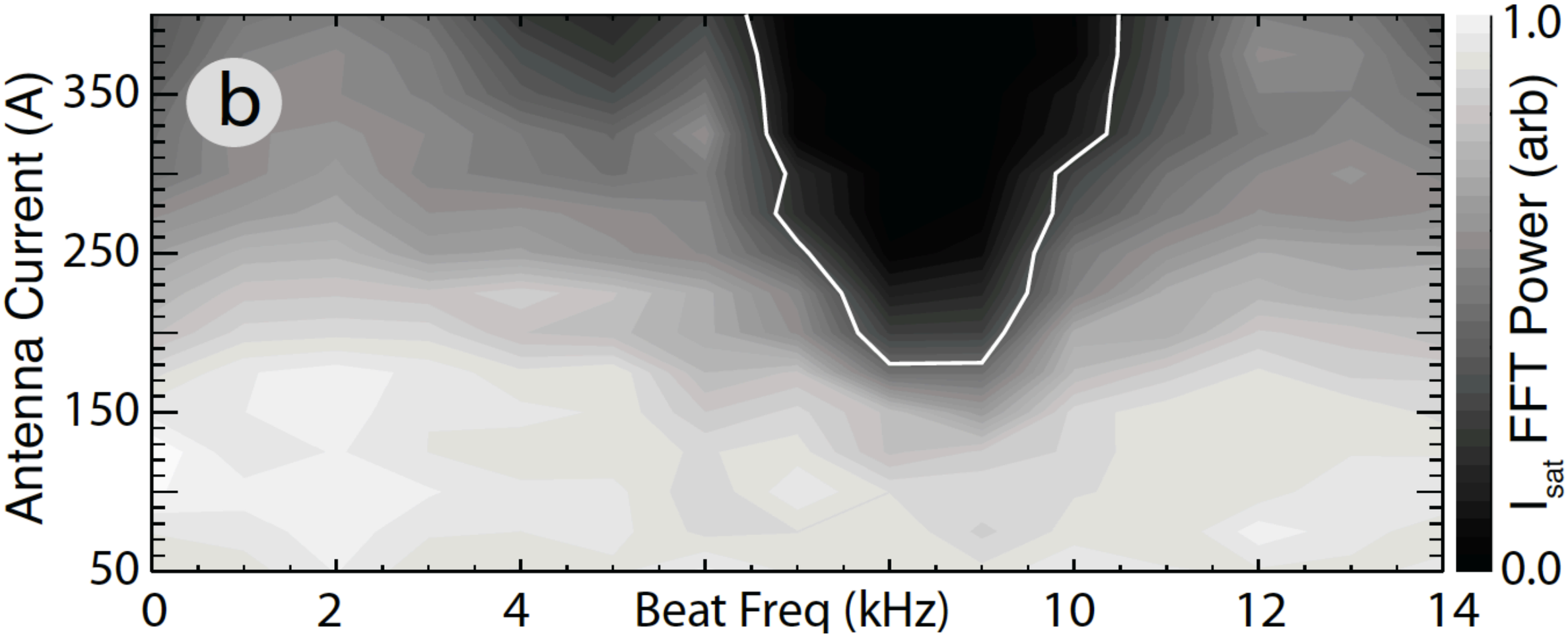
- 8kHz wave persists (rings down) after drive is shut-off; ring-up also observed
- Provides further support for coupling of BW to linear mode (DW/KH)

Threshold for control, saturation of BW observed



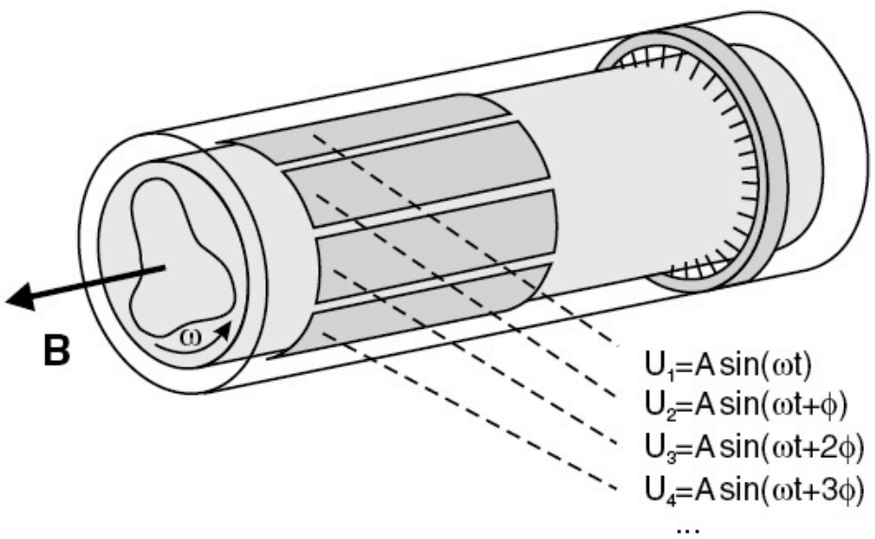
- Modification of DW seen starting at PBW/PDW ~ 10%; maximum suppression for comparable BW power
- Two effects: electron heating from KAWs modifies profiles, causing some reduction in amplitude without BW
- BW response seems to saturate as DW power bottoms out

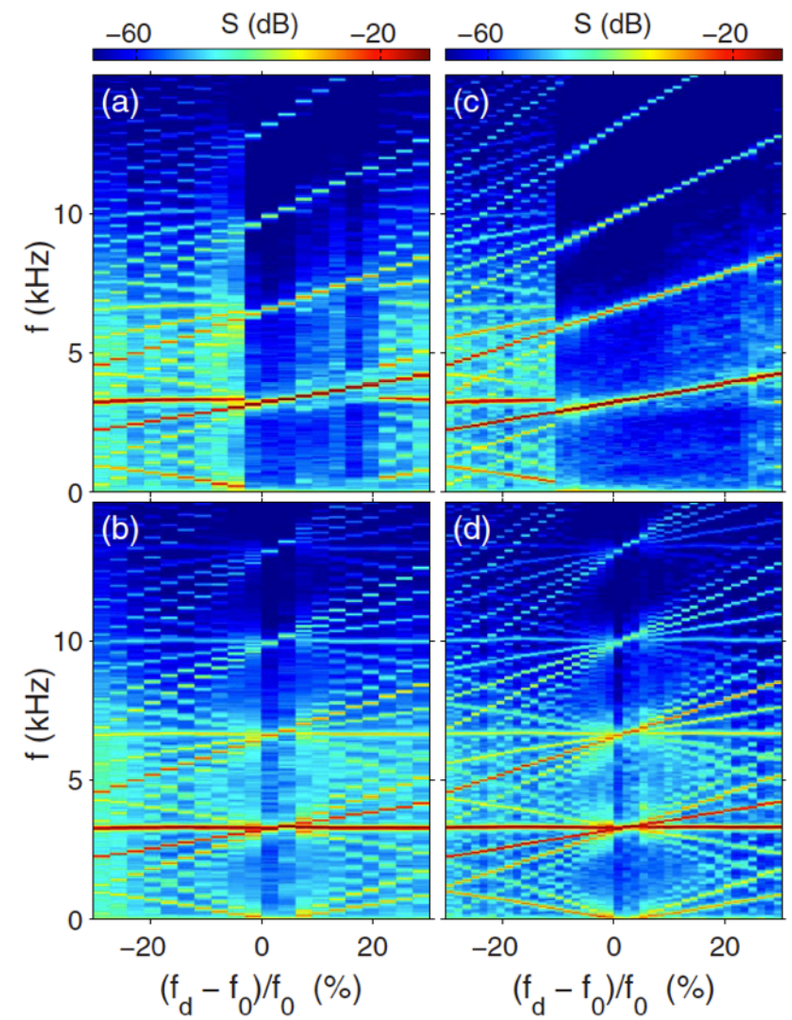
Frequency width of control depends on amplitude

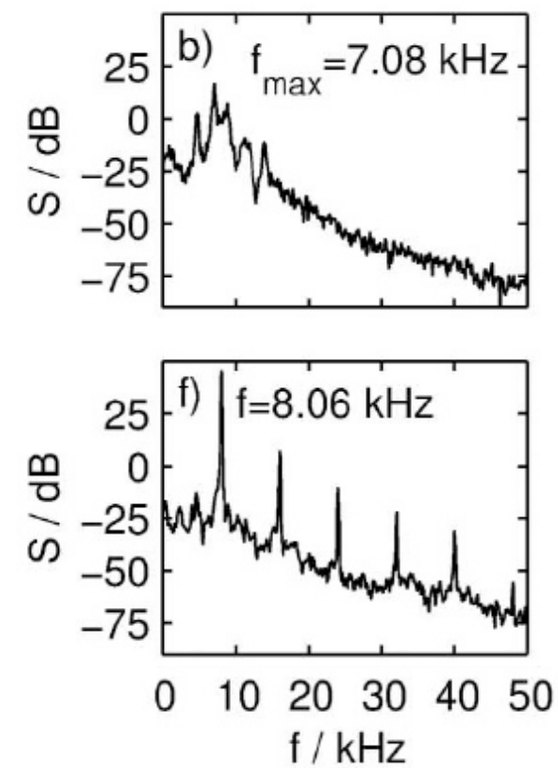


- Window of mode stabilization/control increases with increasing BW drive

Similar behavior seen using external antenna to excite drift-waves



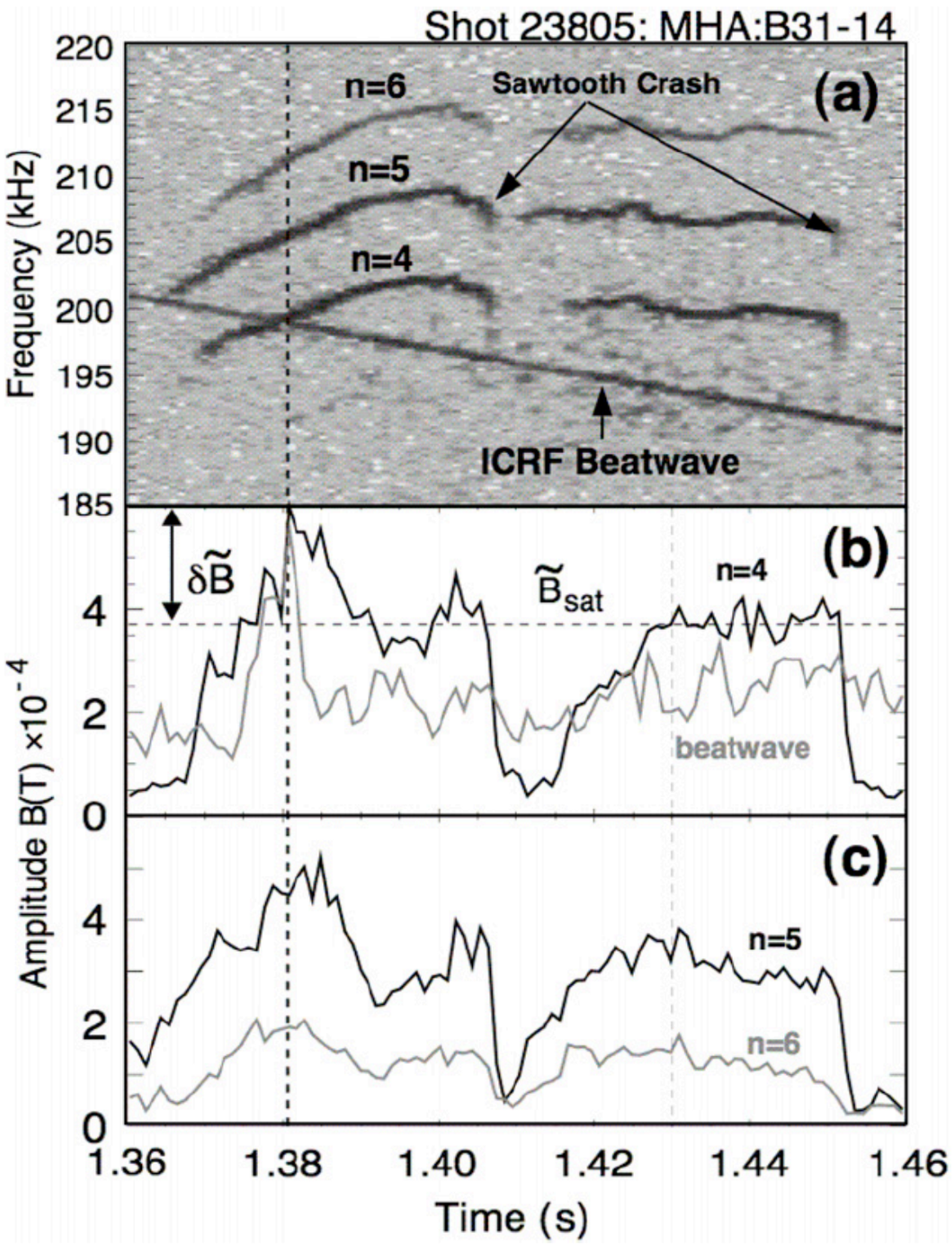




Schroeder, et al PRL 2001
Brandt, et al, PoP 2010

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

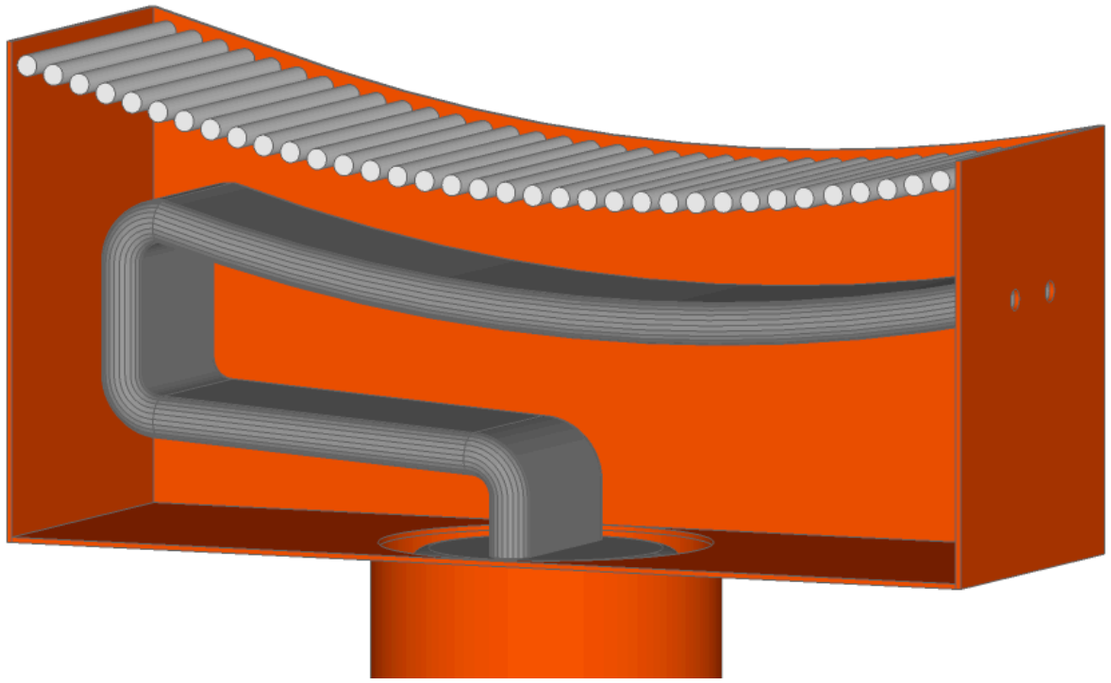
ICRF beat waves to excite low-frequency modes?

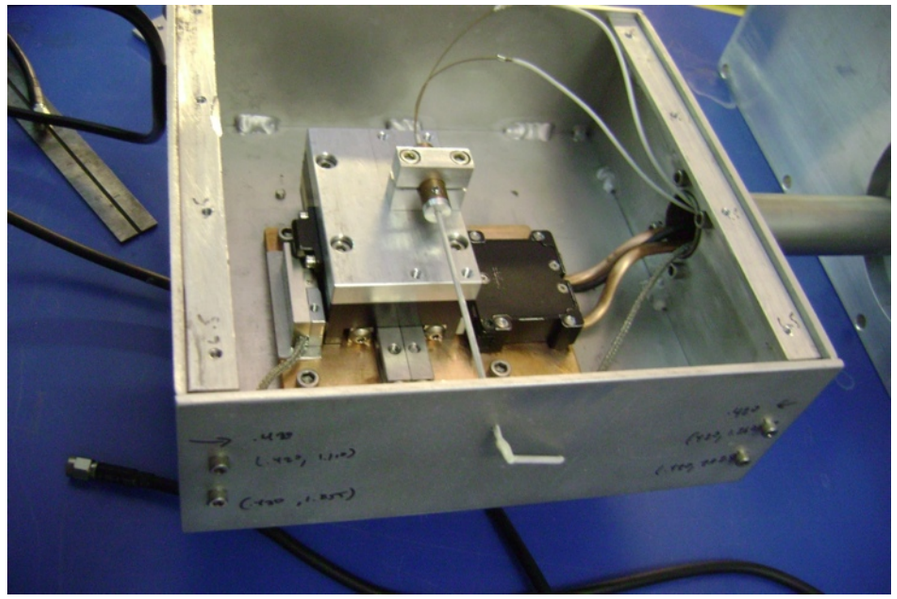


Sassenberg, et al., NF 50, 052003 (2010)

- ICRF BWs used to excited TAEs in JET [Fasoli, et al.] and ASDEX [Sassenberg, et al.]
- Could use ICRF to interact with control lower frequency modes (drift-waves, GAMs, EHO, QCM, etc)?

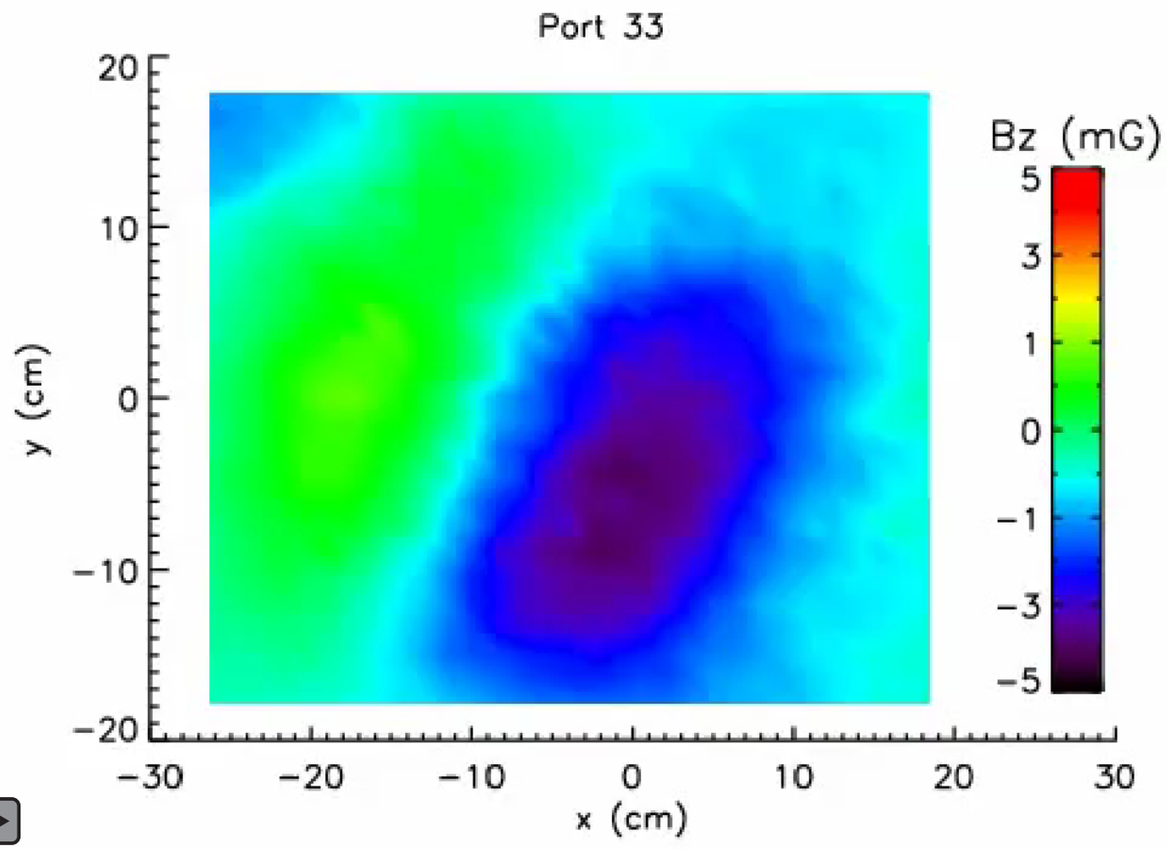
RF Campaign on LAPD

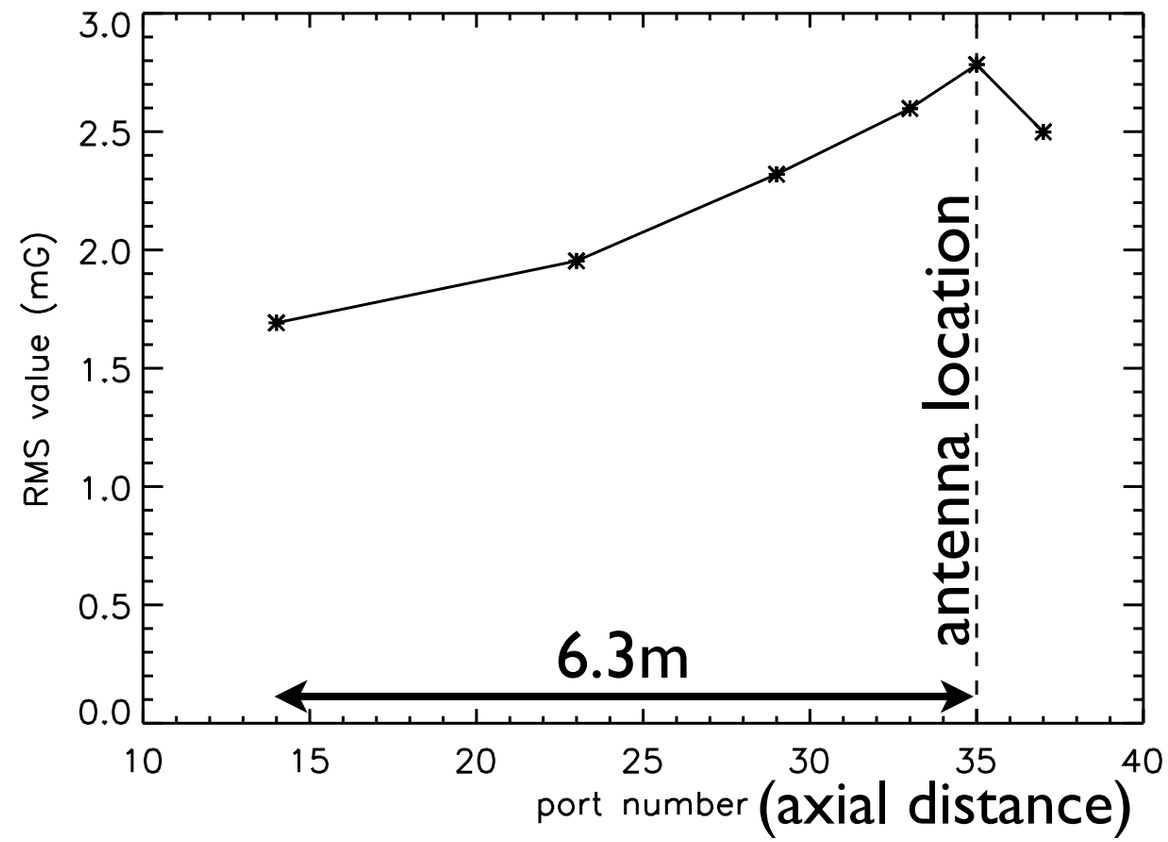




- Study fast waves in LAPD: Basic properties (dispersion, damping), Slow wave production/RF Sheaths, ...
- Campaign led by D. D'Ippolito, involvement from Lodestar, MIT, UCLA, Torino (TOPCYL), others?
- Antenna fabricated, successful launch of fast waves at low power; plate/probe apparatus for RF sheath study built

Initial data on HHFWs in LAPD





- High harmonic launch required to have propagating modes. Fixed frequency source, 3 MHz; ~8th harmonic at 1kG
- See propagating modes, both perpendicular and parallel (multiple bounces); damping observed

Summary/Outline

- Large Plasma Device (LAPD): Flexible, well-diagnosed experiment for studying basic plasma processes (motivations from space, astro, fusion), target for code validation.
  - Kinetic/inertial Alfvén waves: dispersion and damping, characteristics in multi-ion species plasmas
- Nonlinear interactions among shear Alfvén waves
  - Uniform plasma: Quasimode driven nonlinearly by beating of co-propagating Alfvén waves
  - In nonuniform plasma, SAW beat wave interacts with gradient-driven instability: unstable mode suppressed in favor of driven second mode, overall fluctuation amplitude reduced
- Plans and initial results for ICRF-related studies using LAPD