Nonlinear processes associated with Alfvén waves in a laboratory plasma

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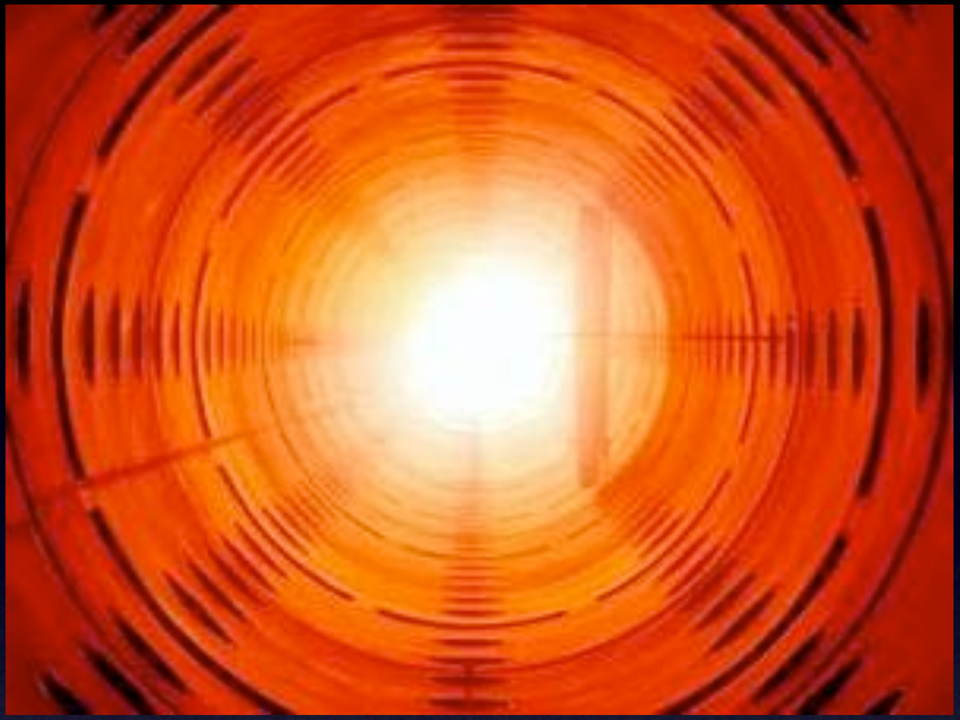
Summary

- Experimental study of large amplitude Alfvén waves and wave-wave interactions
- Strong nonlinear beat-wave interaction between co-propagating shear kinetic Alfvén waves observed [T.A. Carter, B. Brugman, et al., PRL 96, 155001 (2006)]
  - Strongly driven beat response, sideband generation
- Initial counter-propagating interaction experiments show some evidence for nonlinear cascade
  - Weak broadening perpendicularly; stronger parallel cascade?
- Strong electron heating by large amplitude Alfvén waves
  - Waves are strongly damped, leads to structuring of background plasma, secondary instabilities

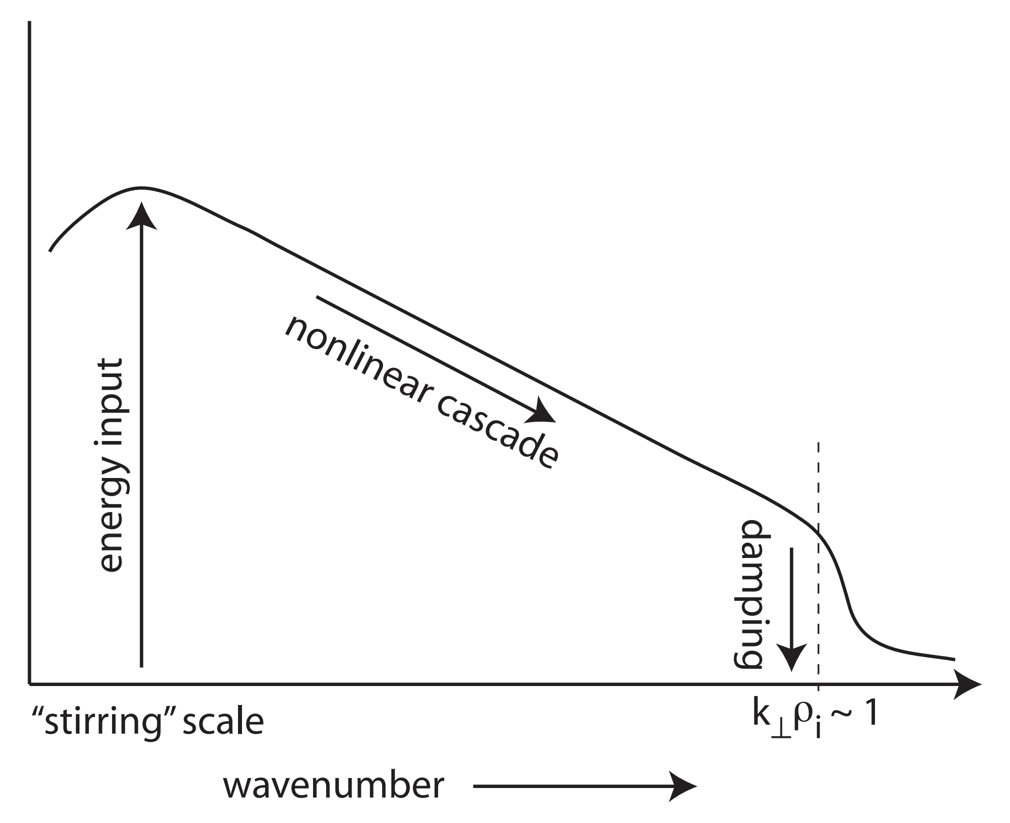
The Large Plasma Device at UCLA



- Barium Oxide cathode source (50V, 10kA)
- $0.5 < B < 2\,\mathrm{kG}\ ,\ n_e \sim 10^{12}\,\mathrm{cm}^{-3}\ ,\ T_e \sim 5\,\mathrm{eV}\ ,\ T_i \sim 1 eV$
- 1m diameter, 20m long chamber
- He, Ne, Ar, H plasmas
- 1Hz rep rate, 10ms pulse length
- International user facility (http://plasma.physics.ucla.edu/bapsf)

Alfvén waves and 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

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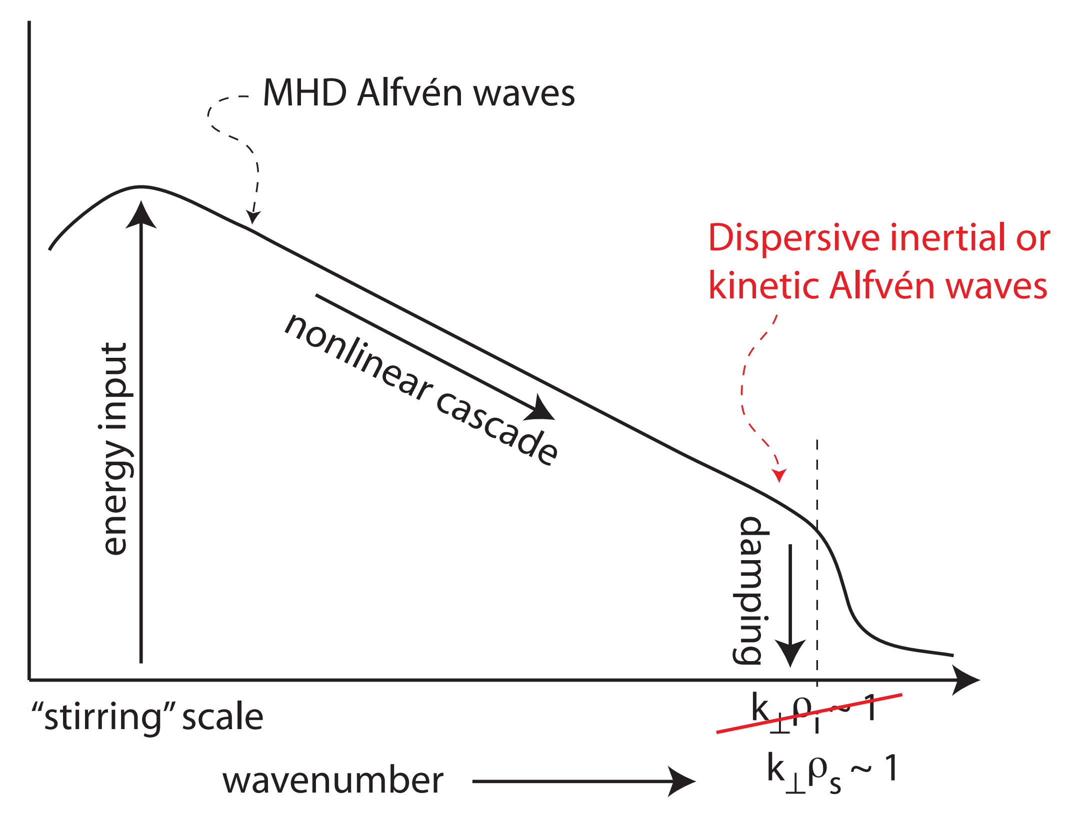


- Incompressible MHD theory of interactions (e.g. Goldreich-Sridhar): Only counter-propagating waves interact
- In LAPD experiments, waves have $k_\perp\rho_s \sim 1$, $\omega/\Omega_i \sim 1$
  - dispersive kinetic or inertial Alfvén waves
  - Co-propagating interaction allowed (waves can pass through one another)
  - Collisional (Coulomb) and Landau damping (finite $E_{||}$)

Kinetic and inertial Alfvén waves in low β plasmas

$$\frac{k_\perp^2 c^2}{\omega_{\mathrm{pe}}^2} - \left[\frac{v_{\mathrm{A}}^2}{v_{\mathrm{th,e}}^2}\frac{\left(1-\omega^2/\Omega_{\mathrm{c,i}}^2\right)\mu}{1-e^{-\mu}I_o(\mu)} - \zeta^2\right] Z'(\zeta) = 0$$

Cold ion, low β ($v_{\mathrm{A}} \gg v_{\mathrm{th,i}}$)

KAW $v_{\mathrm{A}} \ll v_{\mathrm{th,e}}$

$$\omega^2 = k_\parallel^2 v_{\mathrm{A}}^2 \left(1 + k_\perp^2 \rho_s^2 - \frac{\omega^2}{\Omega_{\mathrm{c,i}}^2}\right)$$

IAW $v_{\mathrm{A}} \gg v_{\mathrm{th,e}}$

$$\omega^2 = k_\parallel^2 v_{\mathrm{A}}^2 \frac{1-\omega^2/\Omega_{\mathrm{c,i}}^2}{1+k_\perp^2 c^2/\omega_{\mathrm{p,e}}^2}$$

- In LAPD, $\beta \approx m_e/M$, $v_A \approx v_{th,e}$
- KAW, IAW have parallel E-fields, can damp on electrons through Landau damping or collisional (Coulomb) damping

LAPD Parameters

LAPD Plasma Parameters with $B_0 = 1\text{kG}$

Ion species	He	c_S	11 [km/s]
Z	1	v_A	778 [km/s]
B_0	1 [kG]	$v_{th,e}$	1300 [km/s]
n_e	2×10^{12} [cm^{-3}]	$v_{th,i}$	2 [km/s]
T_e	6 [eV]	Ω_{ci}	382 [kHz]
T_i	1 [eV]	$\rho_S \equiv c_S/\Omega_{ci}$	5 [mm]
β_e	10^{-4}	$\delta_e \equiv c/\omega_{pe}$	5 [mm]

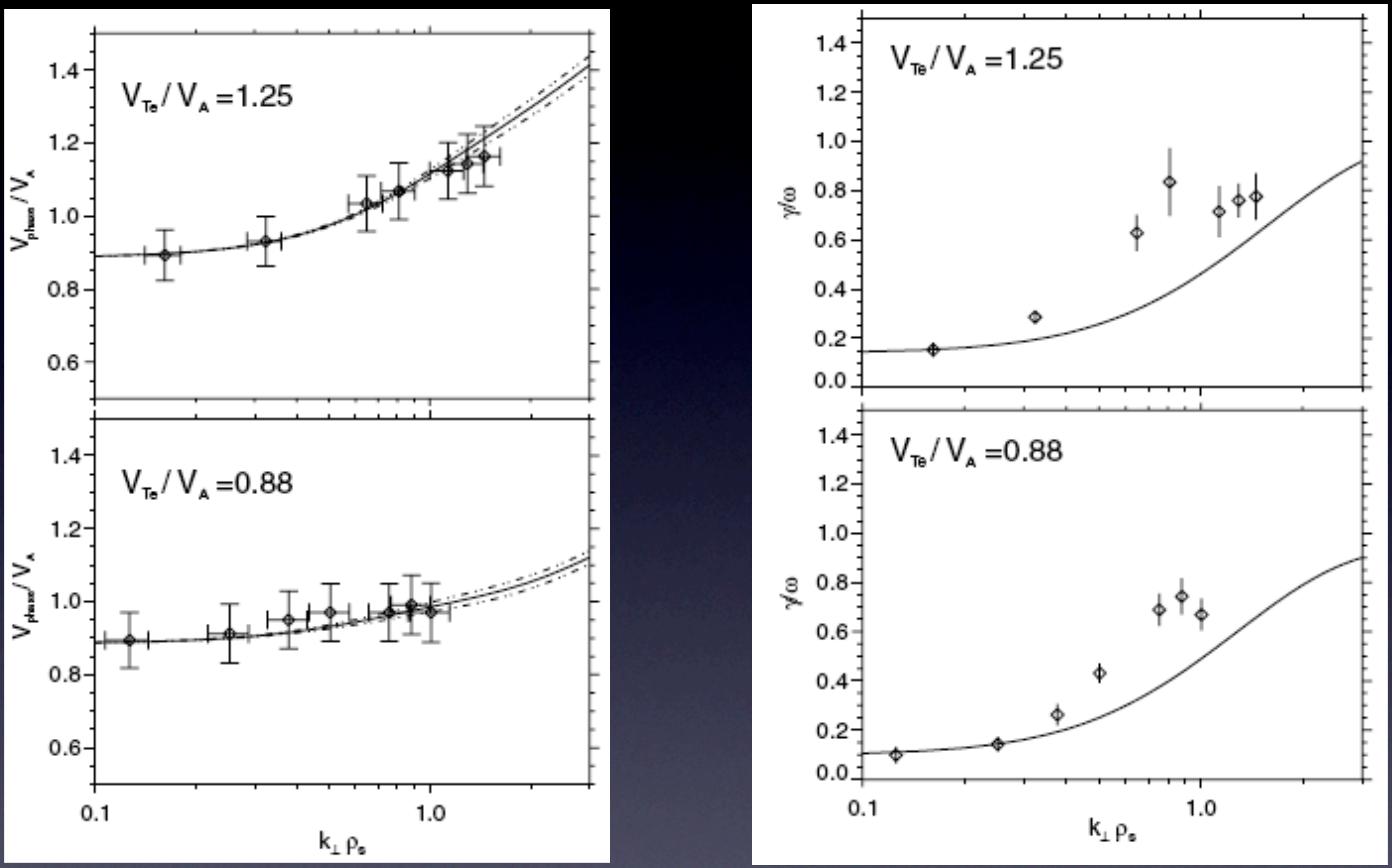
Typical Alfvén wave parameters $(f \sim 200\text{kHz})$

$$\lambda_\parallel \sim 2\text{ m} \qquad k_\parallel \lambda_{\text{mfp}} \sim 0.5$$

$$\lambda_\perp \sim 10\text{ cm} \qquad k_\perp \rho_s \sim k_\perp \delta_e \sim 0.3$$

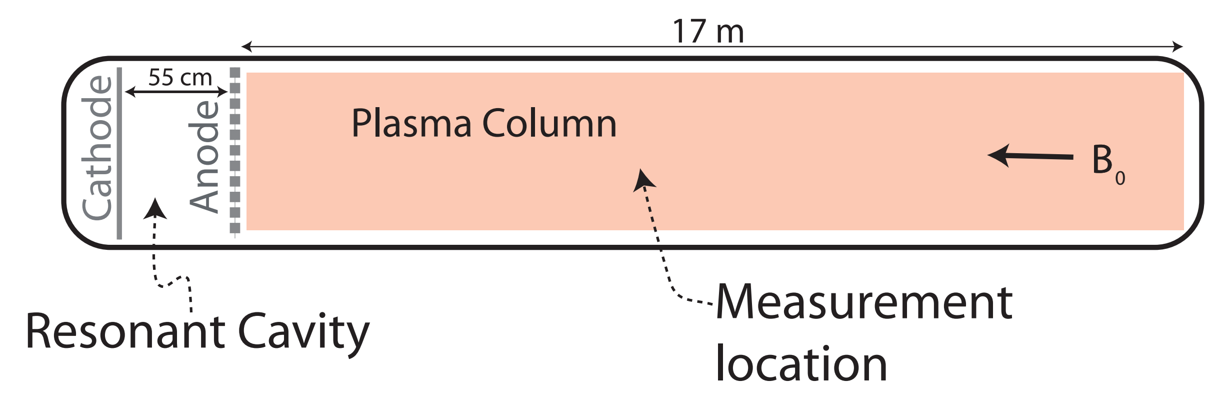
$$\frac{\omega}{\Omega_{ci}} \sim 0.5 \qquad \frac{\delta B}{B} \sim 0.01$$

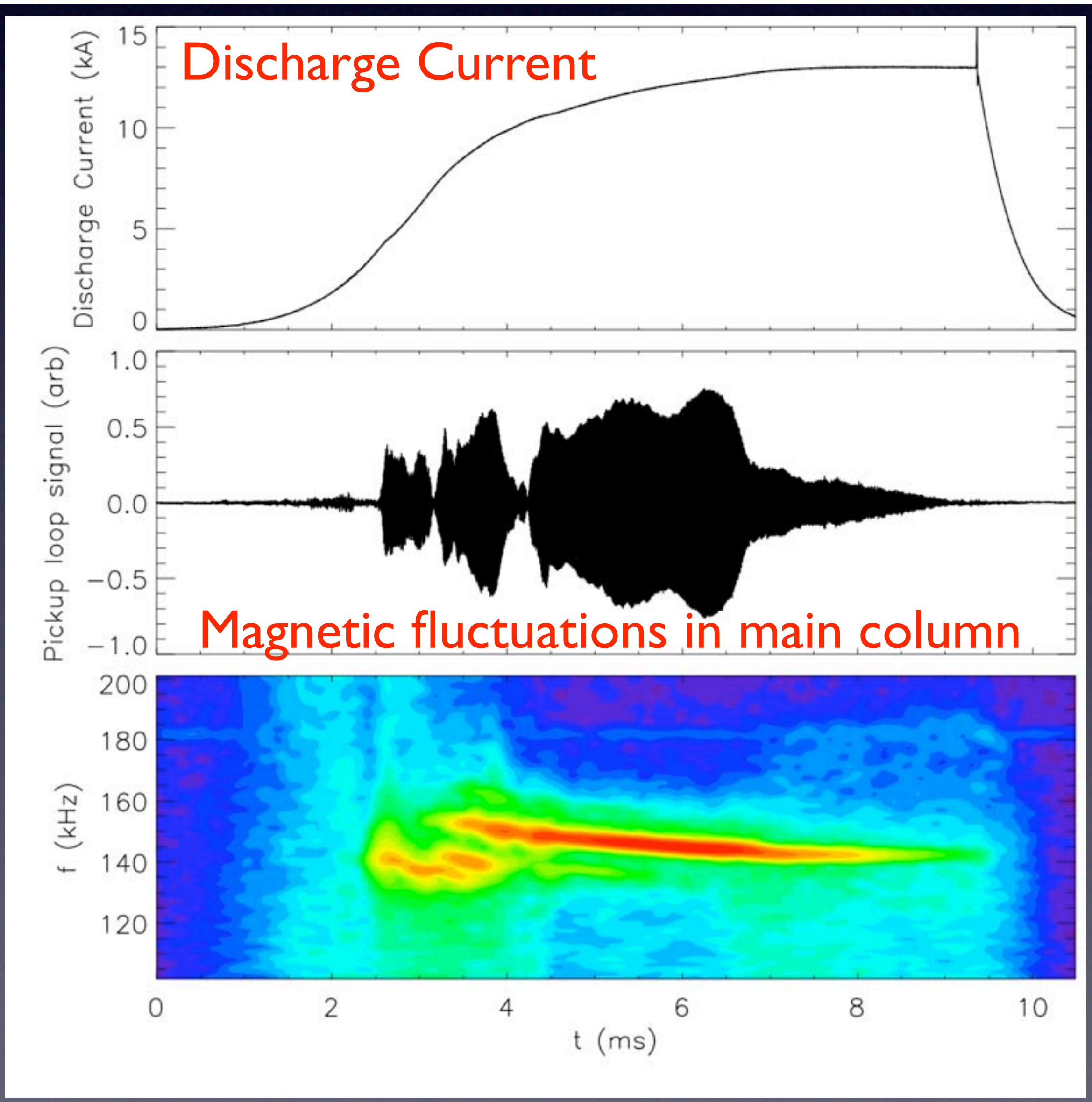
Linear properties of IAW and KAW in LAPD



- Kletzing, et al., PRL 90, 035004 (2003)
- See also Gekelman, Vincena, Leneman, etc...

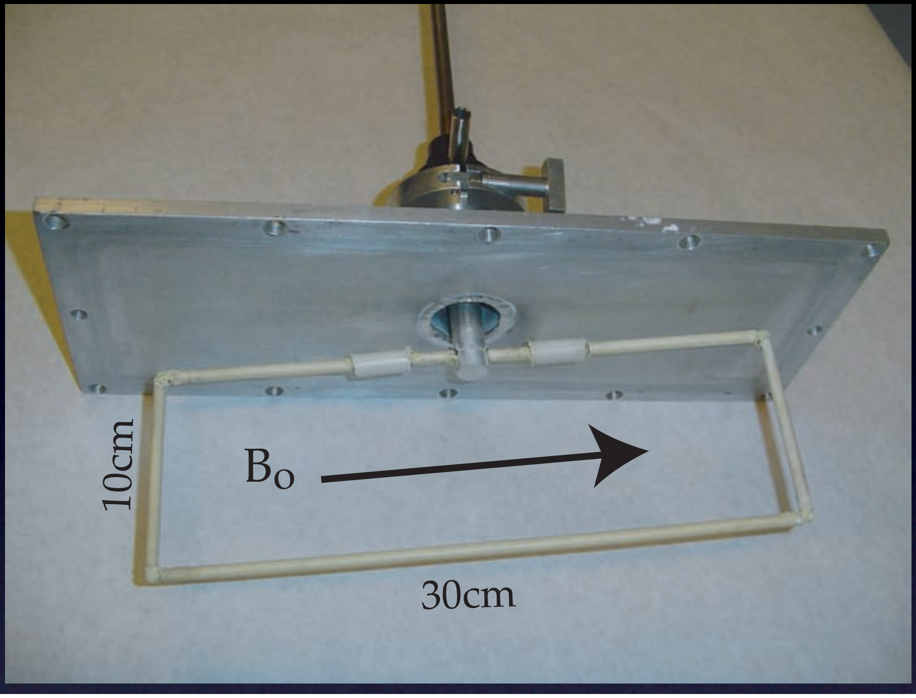
Large amplitude wave source: the Alfvén wave maser

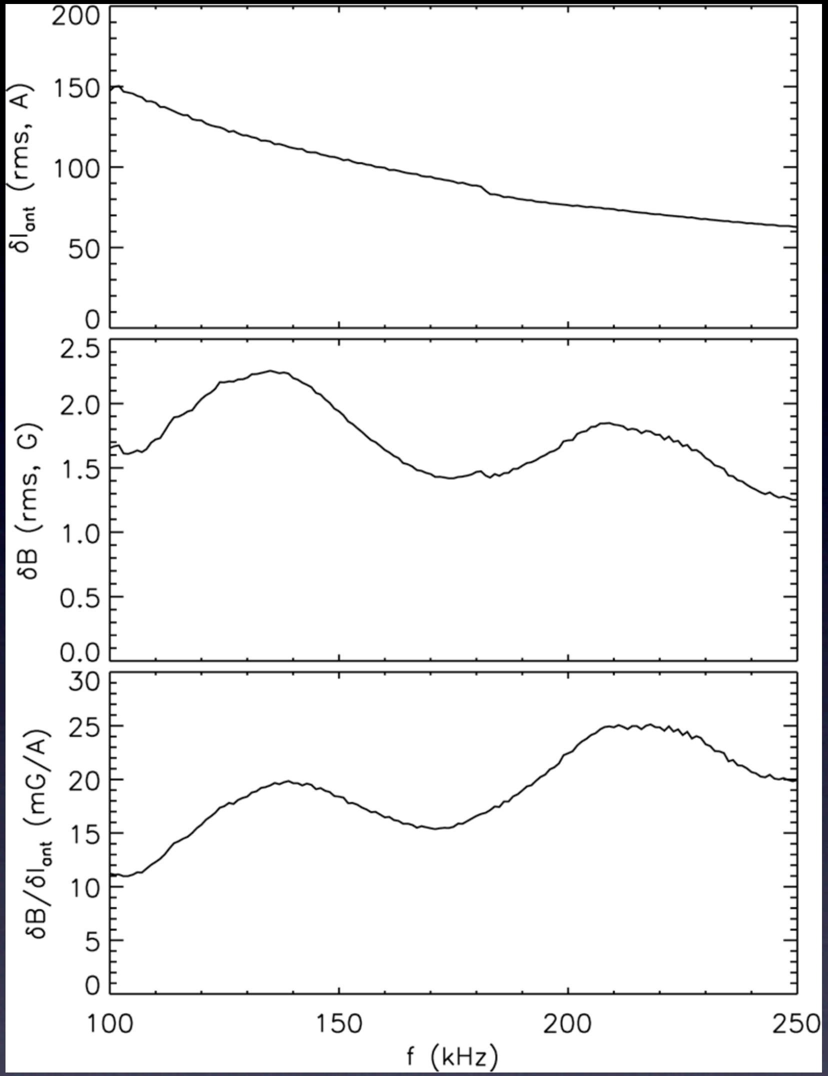


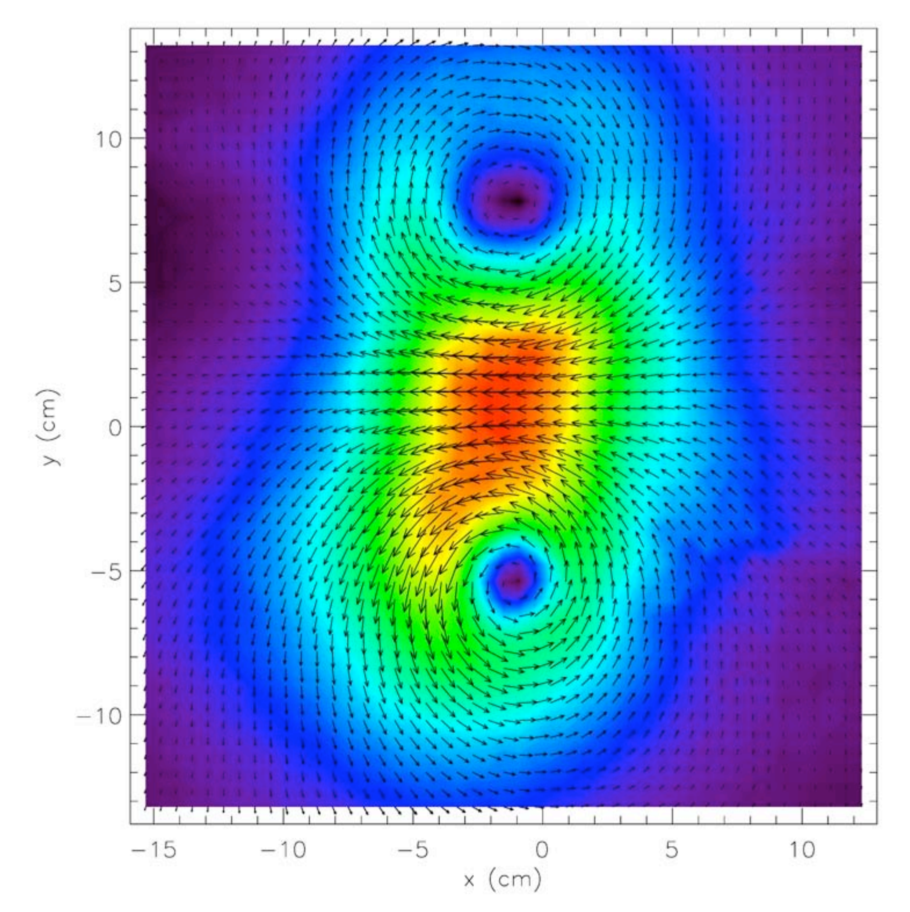


- Emission from resonant cavity driven by inverse Landau damping [Maggs, Morales PRL 03]
- Amplitude controllable by discharge current and B, up to $\delta B/B \sim$ few%
- Big enough to be nonlinearly relevant: $\delta B/B \sim k_{\|}/k_{\perp}$
- Frequency: $f/f_{ci} \sim 0.6$
- Mode hopping observed during current ramp up

Second tecnique: Alfvén wave loop antennas

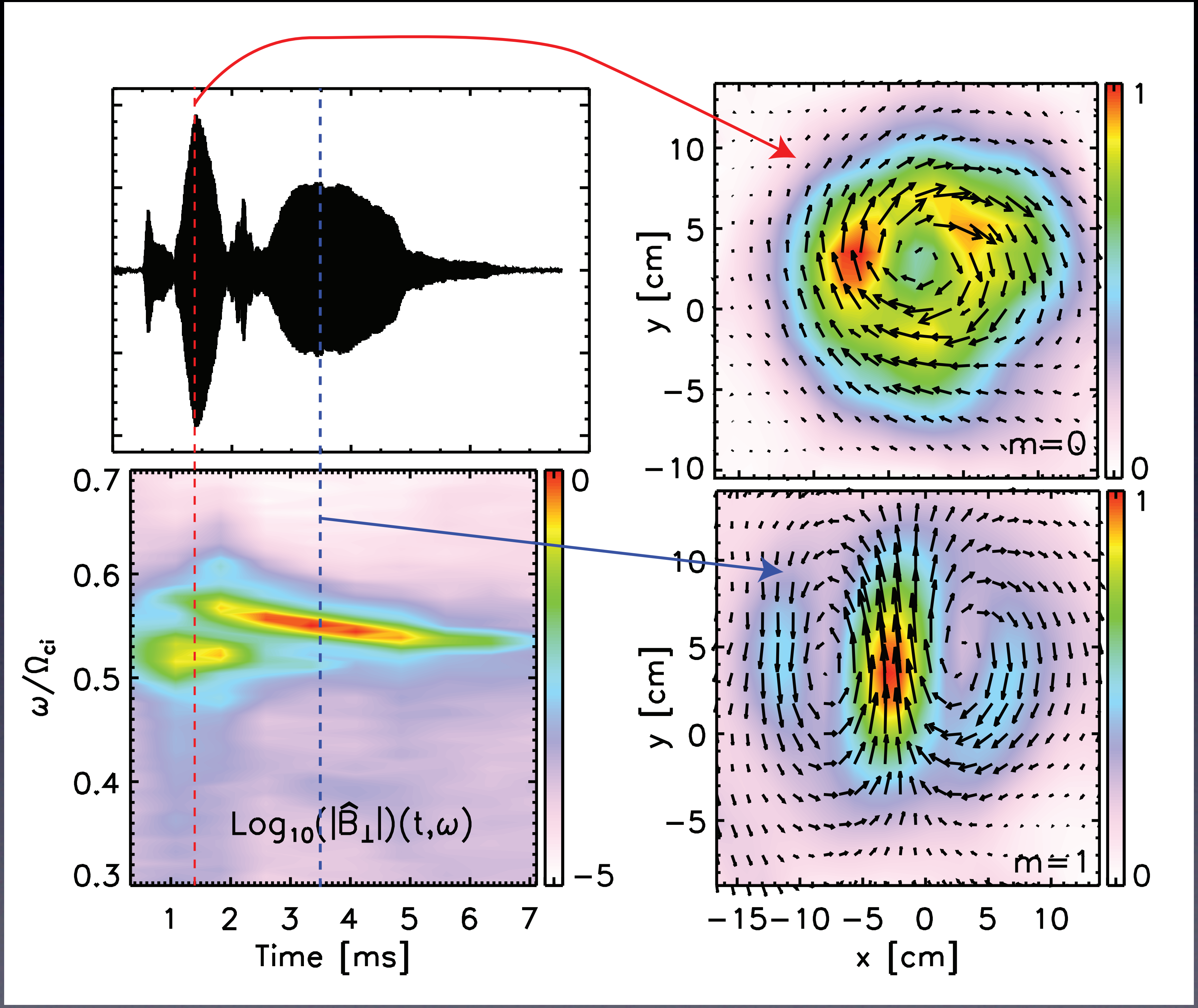


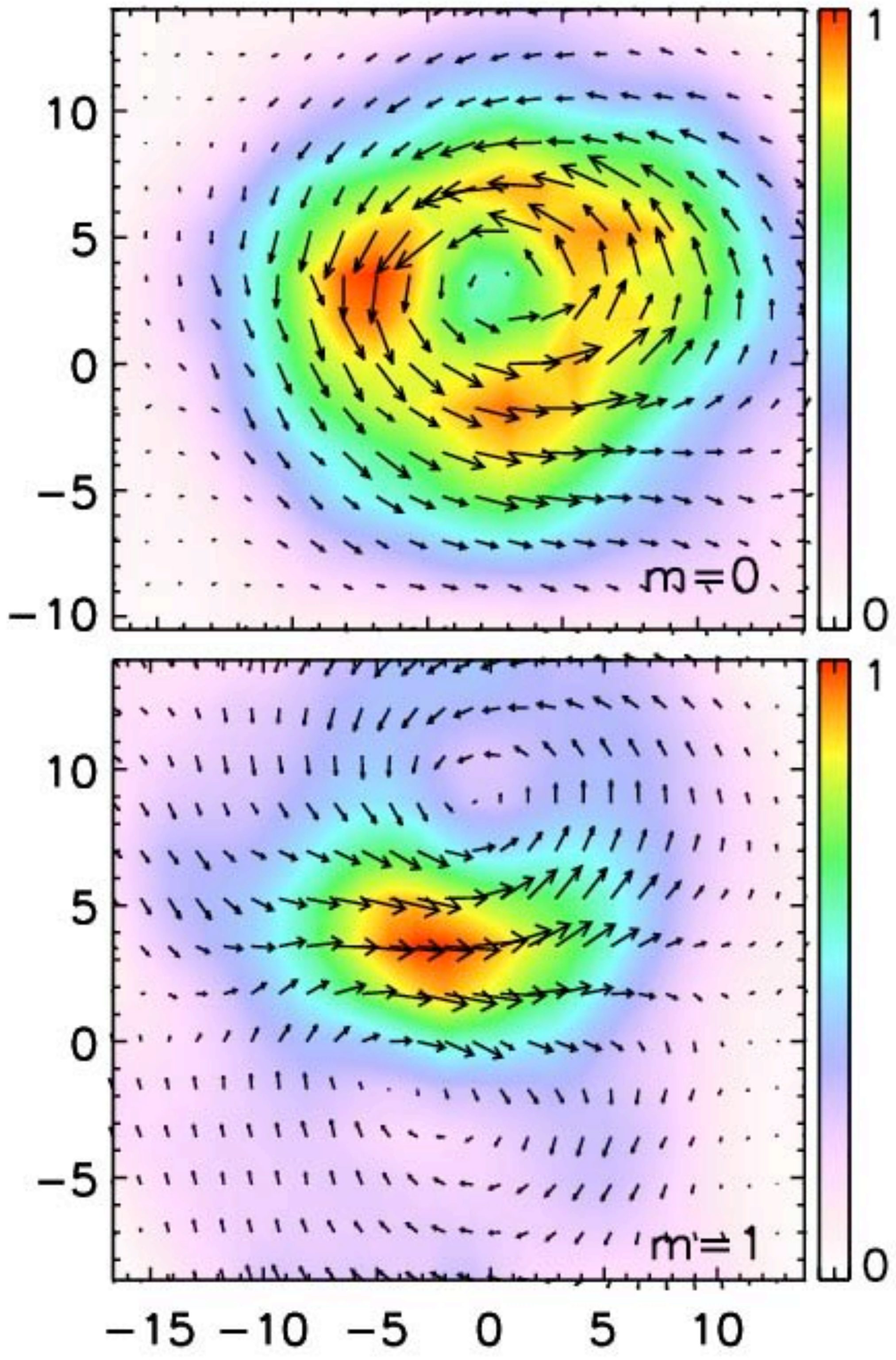




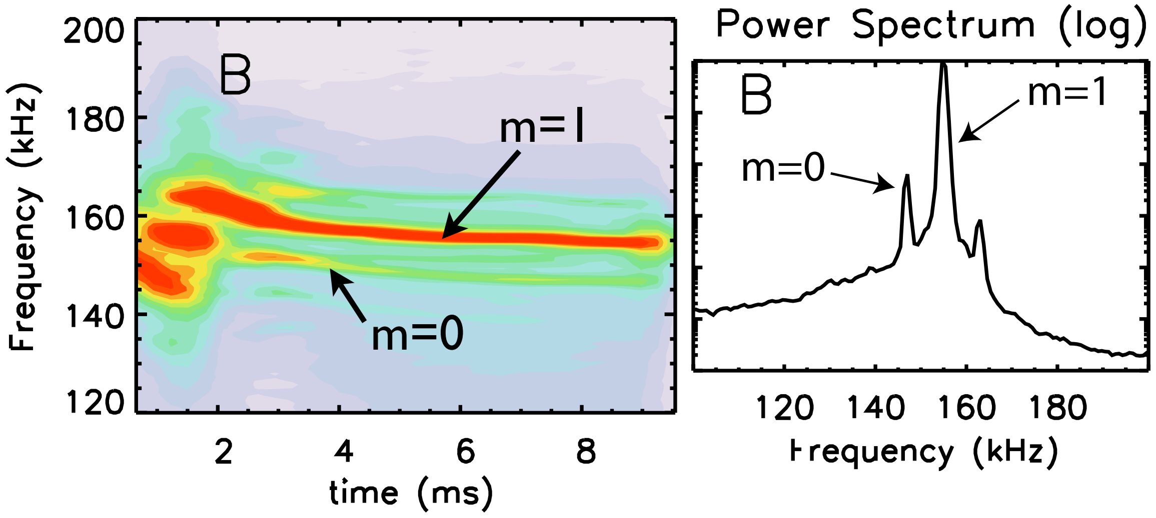
- Broadband excitation of large amplitude waves (up to 10G) using novel drivers (up to 1kA @ 1kV pulsed)
- More flexible than maser, easy counter-propagating arrangement

Structure of maser emission: m=0 and m=1 shear Alfvén eigenmodes




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

Nonlinear interaction observed during simultaneous emission of two waves (co-propagating)



- Simultaneous emission of large amplitude m=0 and m=1 cavity modes

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

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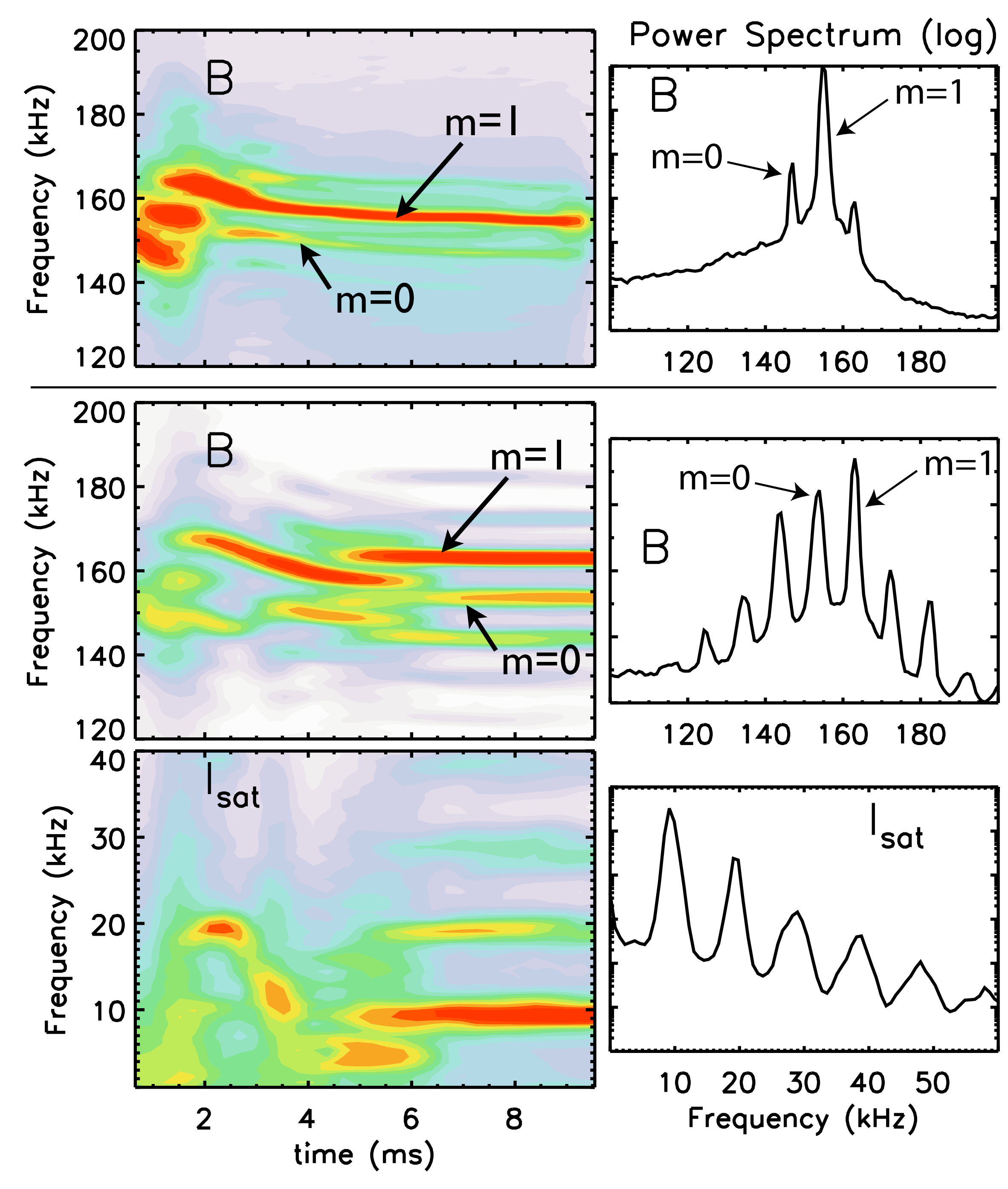
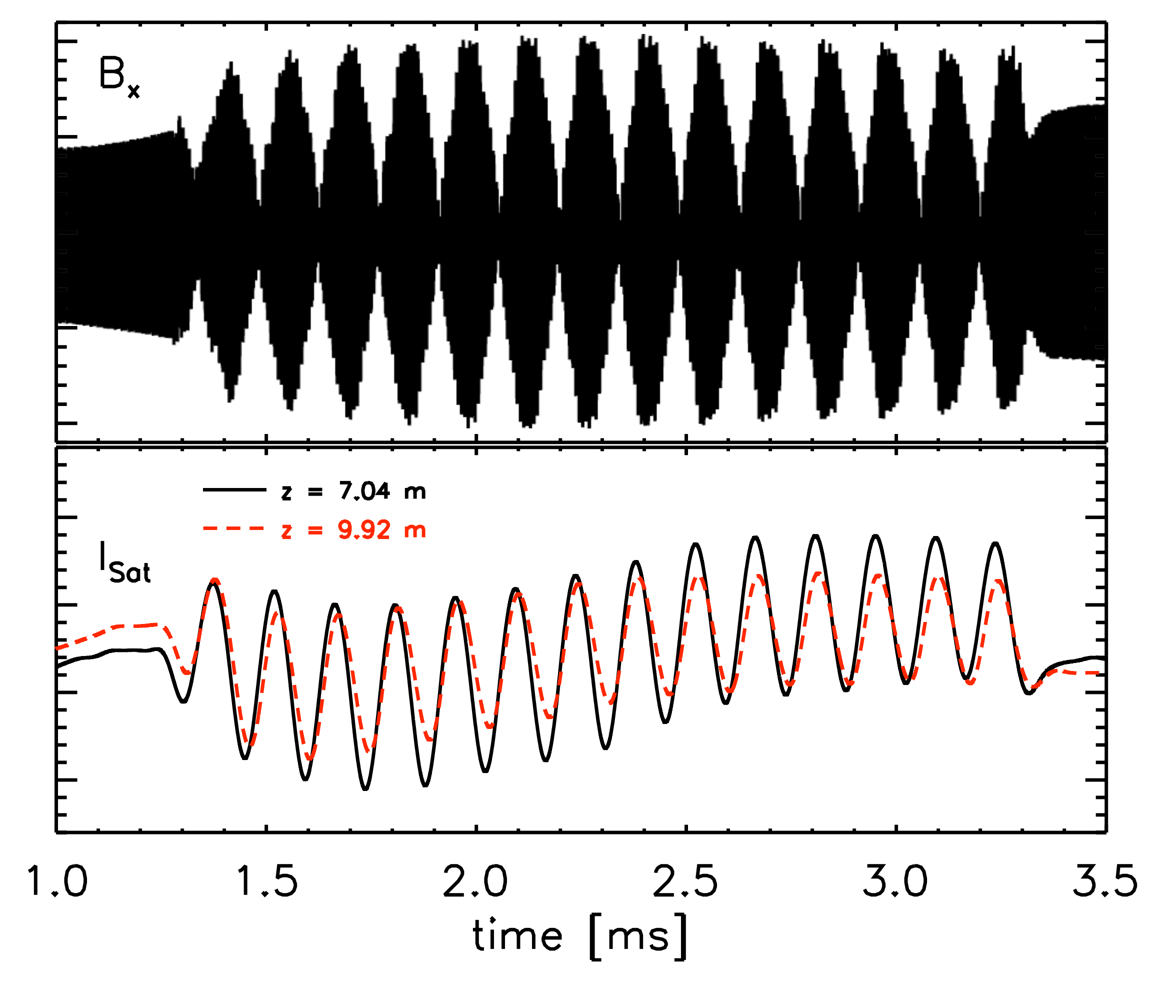


- Simultaneous emission of large amplitude m=0 and m=1 cavity modes
- Copropagating waves beat together, generate strong nonlinear quasimode at beat frequency ($\delta n/n \sim 10\%$)
- Pump Alfvén waves scatter off of low-frequency quasimode, generating a series of sidebands
- Consistent with nonlinear Braginskii two-fluid theory (drive is nonlinear ion polarization drift)

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

Phase velocity measurements: Low frequency mode is non-resonant quasimode, consistent with three-wave matching



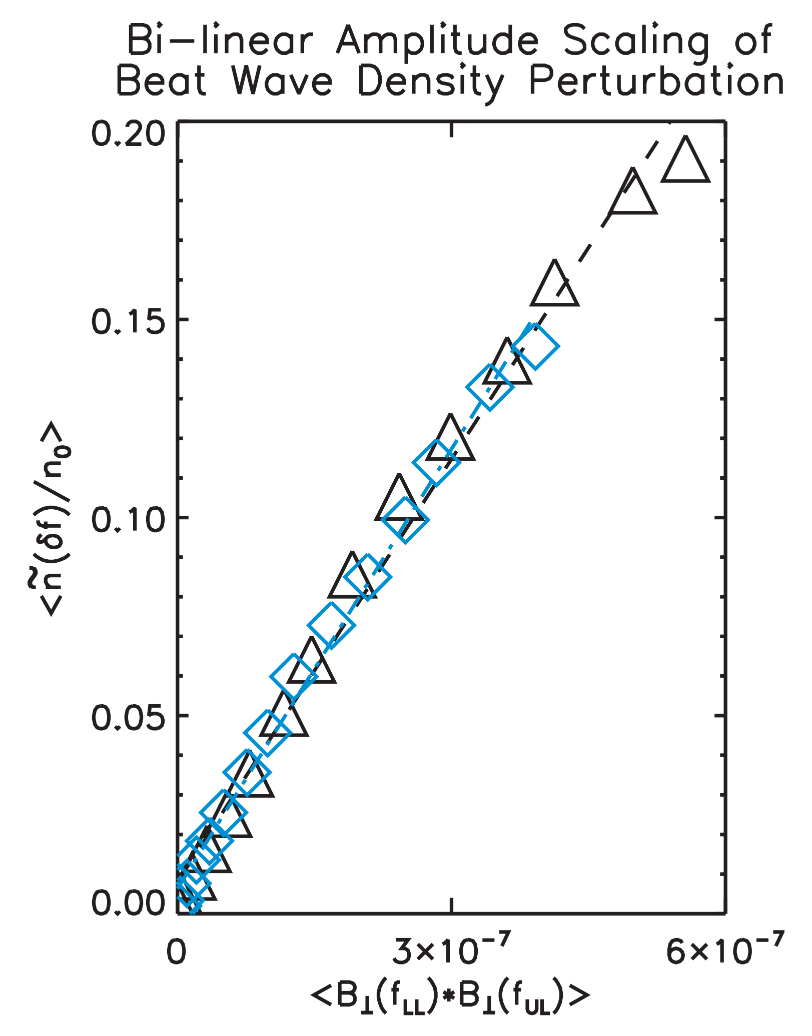
$$\omega^2 = k_\parallel^2 v_A^2 \left(1 + k_\perp^2 \rho_s^2 - \omega^2/\Omega_i^2\right)$$

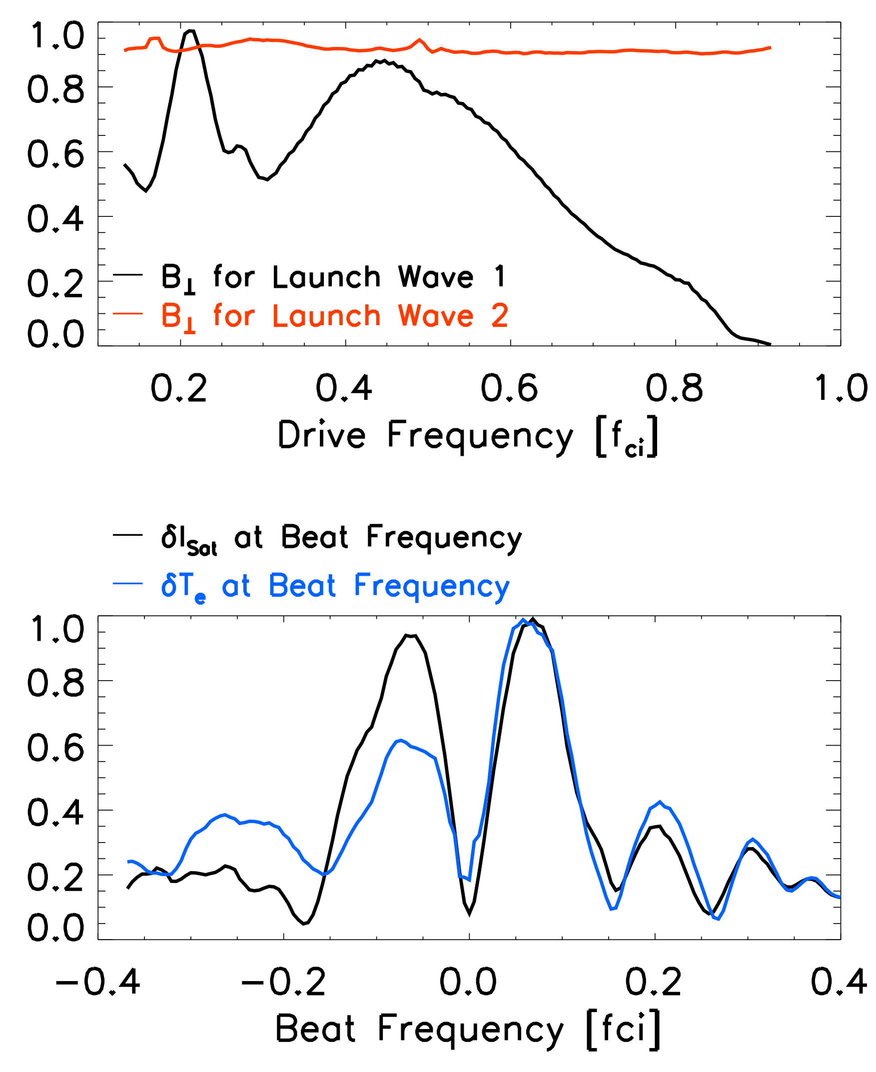
$$\omega_1 + \omega_2 = \omega_3$$

$$\vec{k}_1 + \vec{k}_2 = \vec{k}_3$$

- Measured phase velocity of density perturbation: 294±35 km/s
- Sound (slow wave) speed: ~10 km/s, Alfvén speed: ~550 km/s
- Computed phase velocity from three-wave matching: ~290 km/s

Amplitude and frequency scaling: interaction is strong and shows resonant behavior





- Bilinear scaling, as expected, but magnitude of $\delta n/n \geq \delta B/B$
- Resonant-like behavior of interaction with beat frequency (with significant harmonics)

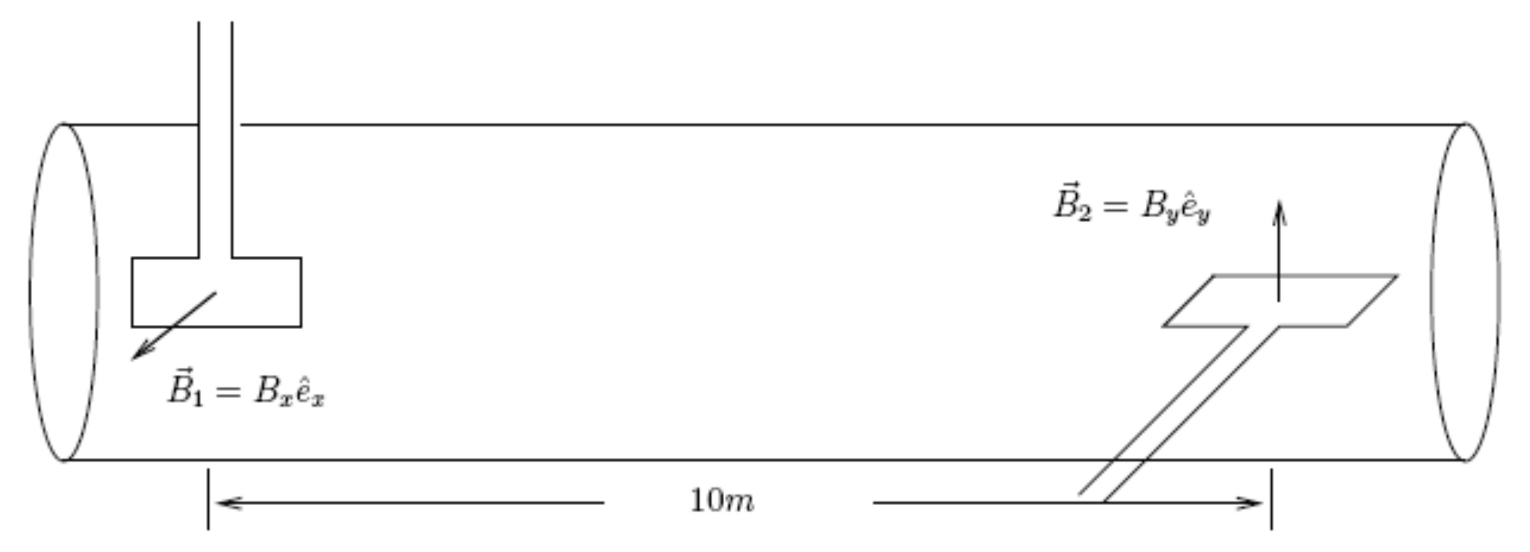
Beat driven wave is off-resonance Alfvén wave; theory consistent with observed amplitude, resonant behavior

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

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

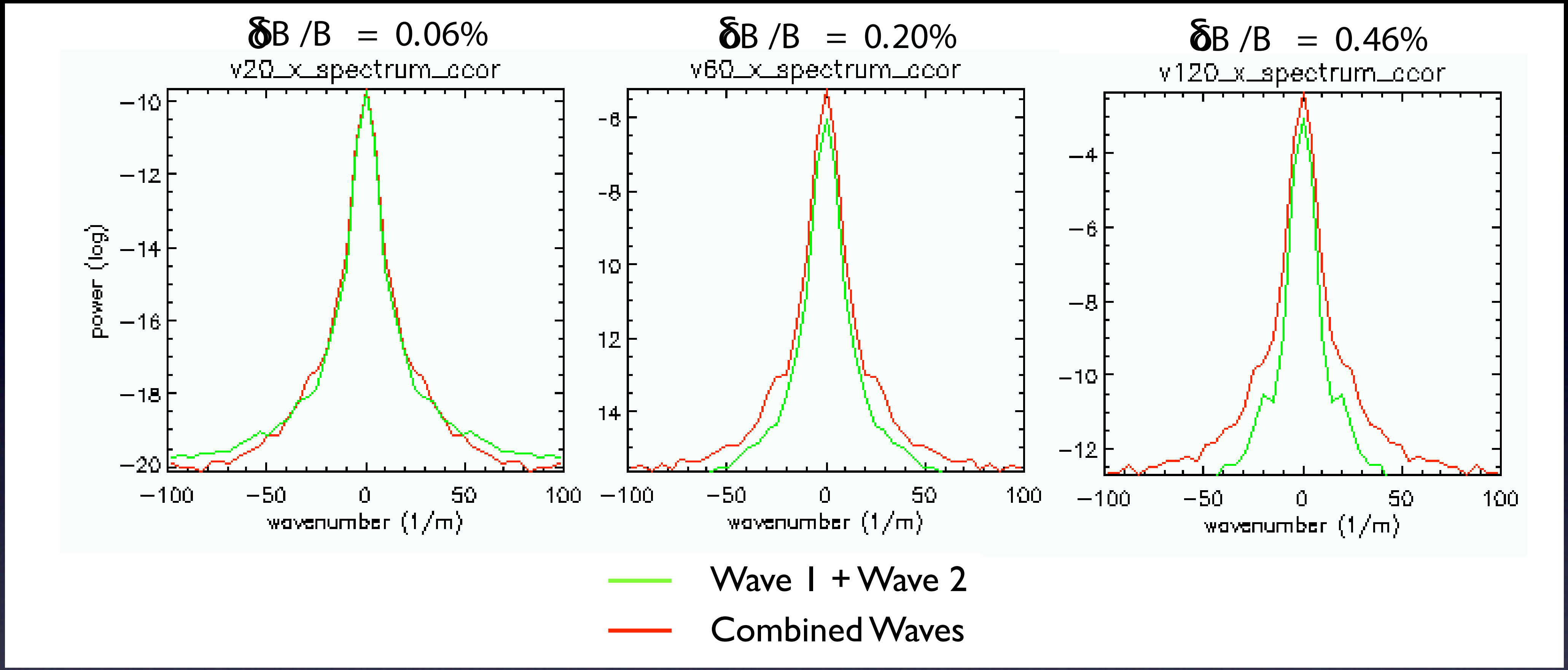
- Exhibits resonant behavior (for Alfvénic beat wave) - reasonable agreement with experiments (except "harmonics")
- Ignoring resonant demoninator, $\delta n/n \sim$ 1-2% for LAPD parameters
- Dominant nonlinear forcing is perpendicular (NL polarization drift): easier to move ions across the field to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

Counter-propagating interactions



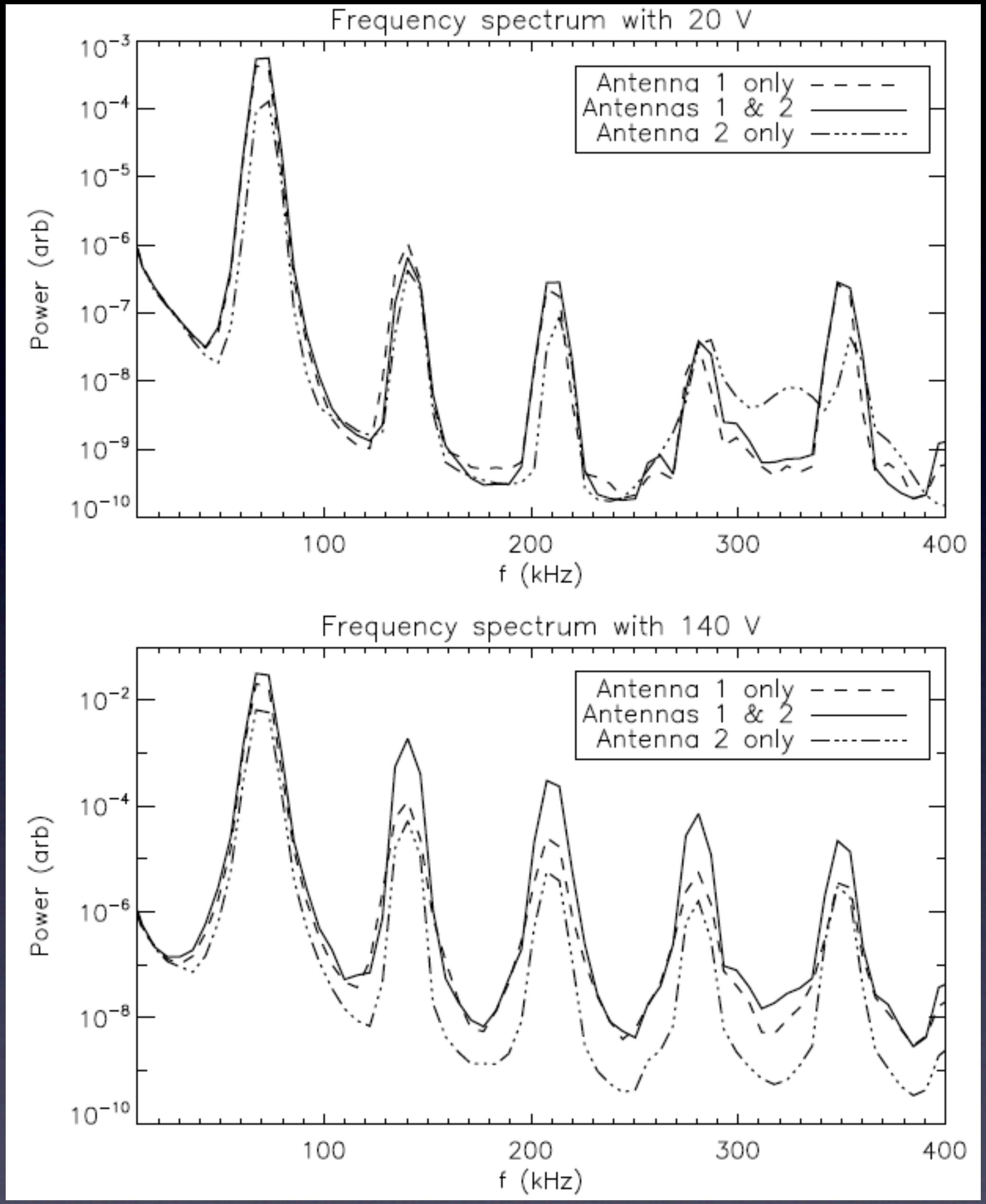
- Use two cross-polarized AW antennas to launch counter-propagating waves
- Single wave collision, absorbing boundary conditions (magnetic beach)
- $k_{\parallel}/k_{\perp} \sim 2.5\%$, strong interaction might be expected for $\delta B/B$ ~ few%?
- Measure magnetic field perturbations in between antennas

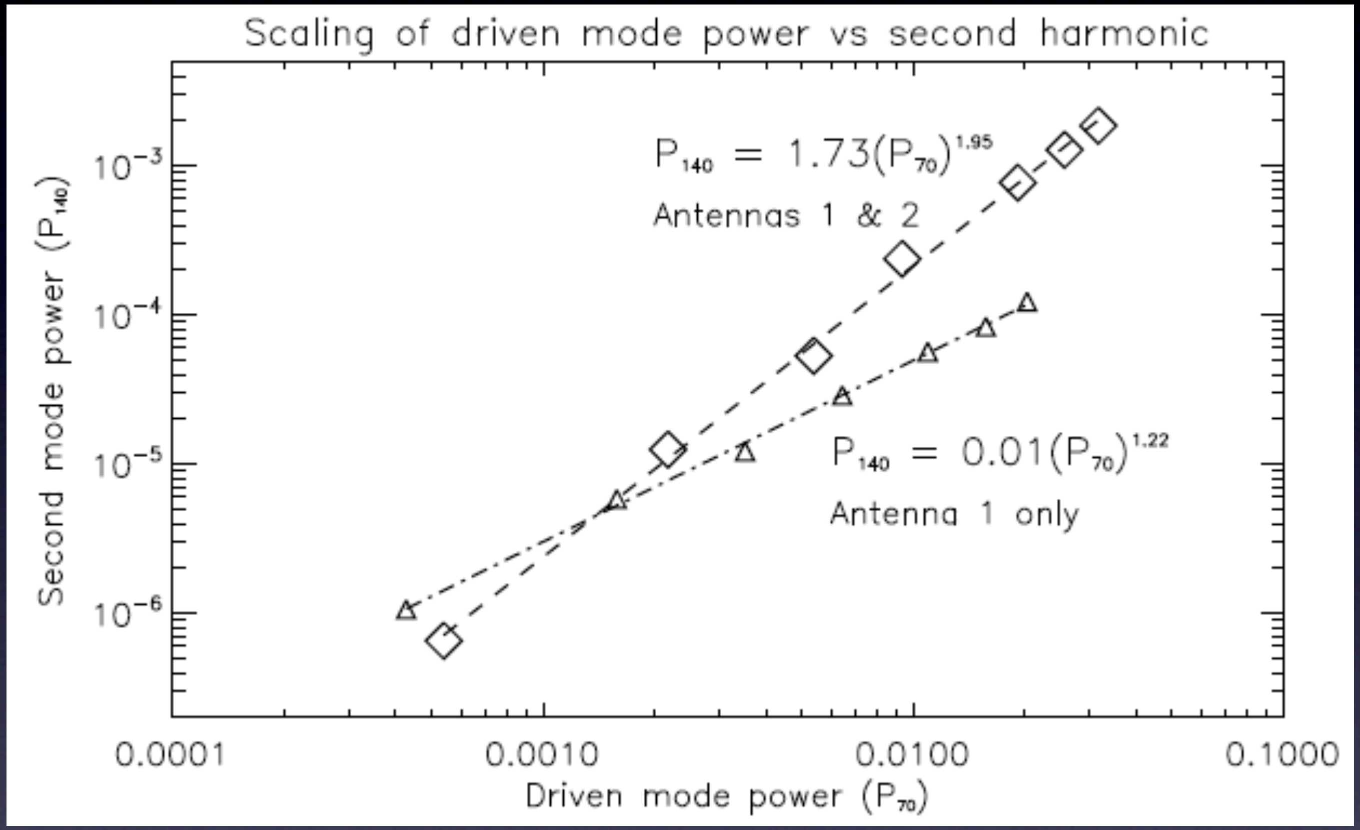
Broadening of perp. spectrum observed, but weak



- FFT of measured spatial correlation
- Broadening scales with increased wave amplitude, but is many orders of magnitude below pump amplitude
- Not yet in strong interaction regime (single collision not enough?)? Nonlinear transfer overwhelmed by damping?

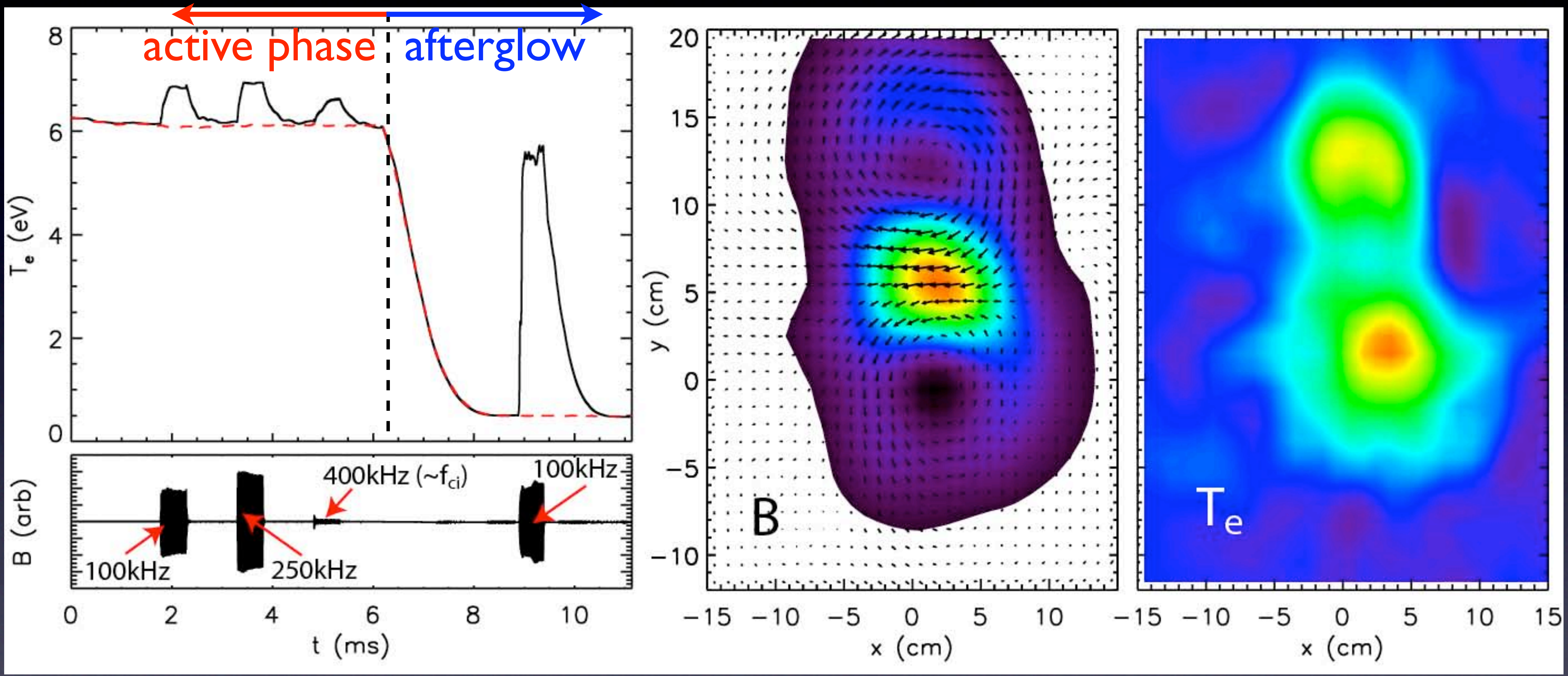
Evidence for parallel cascade?





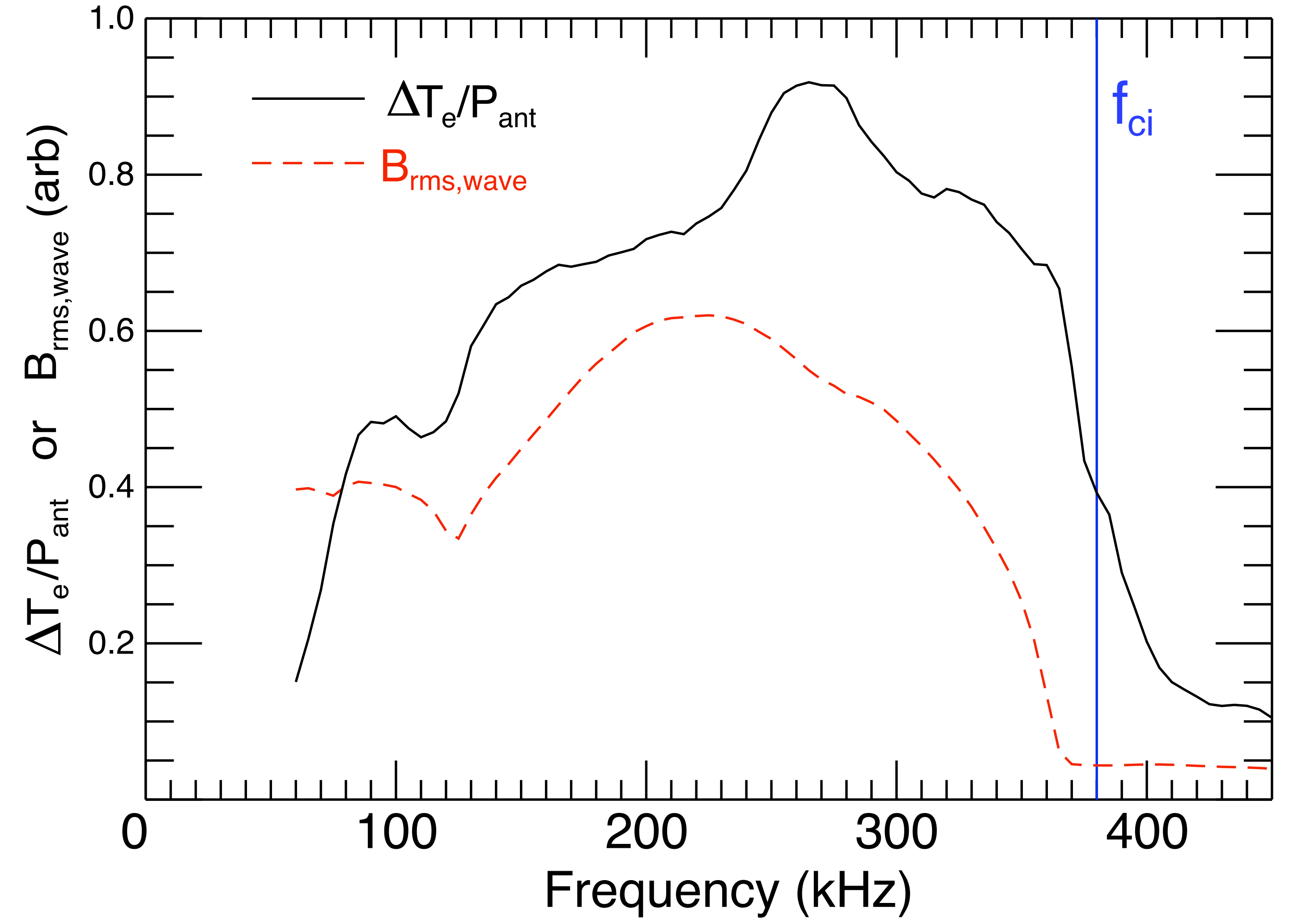
- Harmonics enhanced during interaction, parallel cascade?

Strong electron heating by antenna-launched Alfvén waves



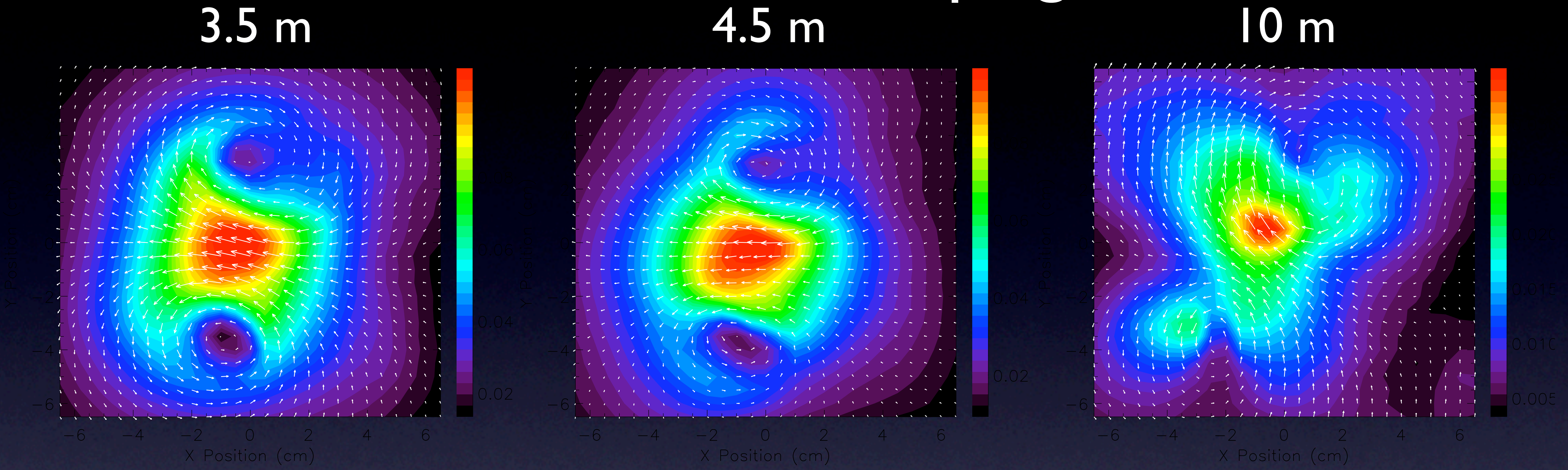
- Localized heating observed, on wave current channel
- Collisional or Landau damping? Near field heating?

Scaling of heating with frequency: consistent with Alfvén wave heating



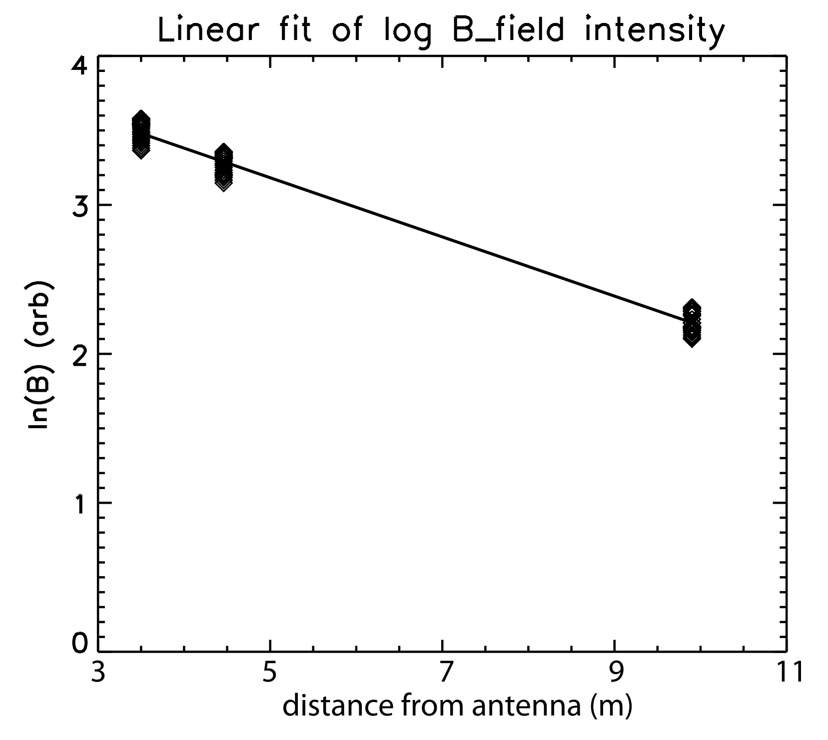
- Increasing heating efficiency with frequency, roll-off at cyclotron frequency consistent with collisional/Landau damping of Alfven waves
- Maximum Poynting flux of ~200kW/m^2, comparable to plasma source power density (50V, 3kA): wave damping can explain heating

Measured wave decay consistent with collisional damping


3.5 m

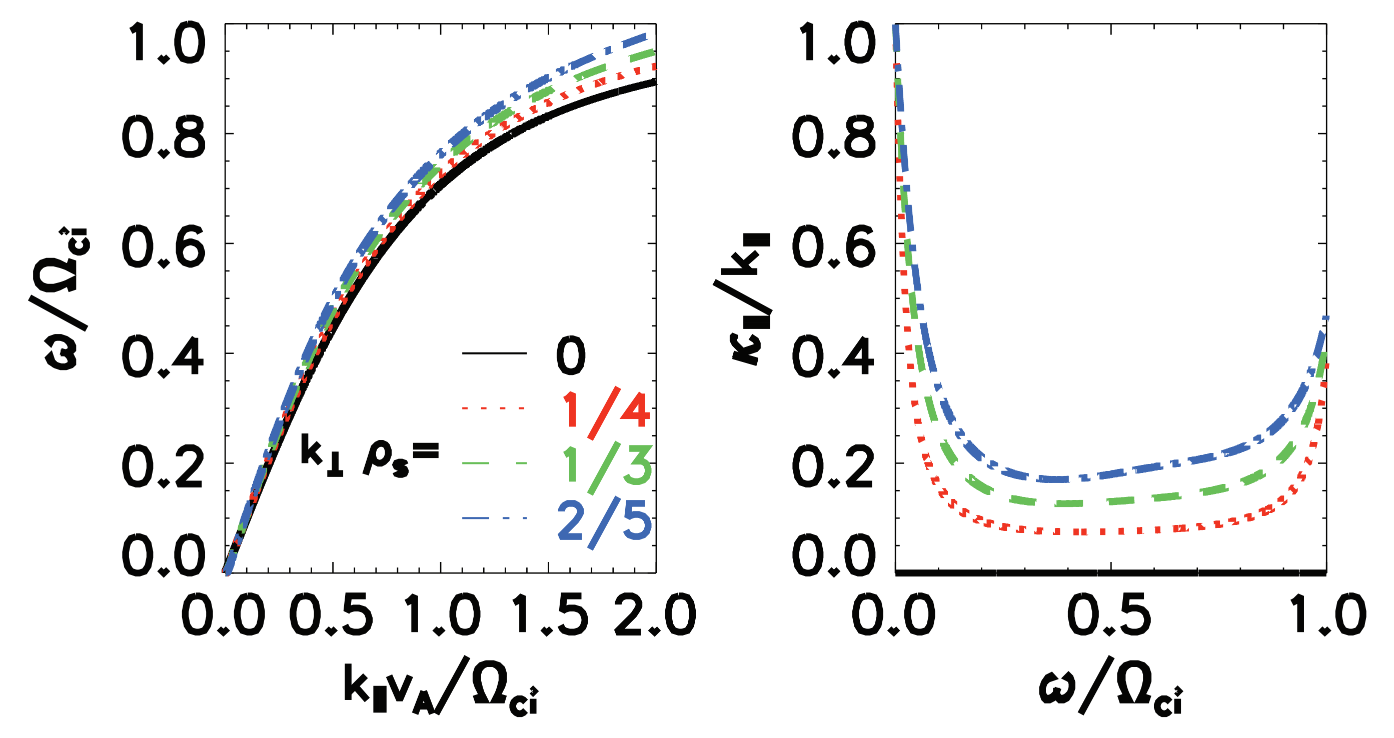
4.5 m

10 m



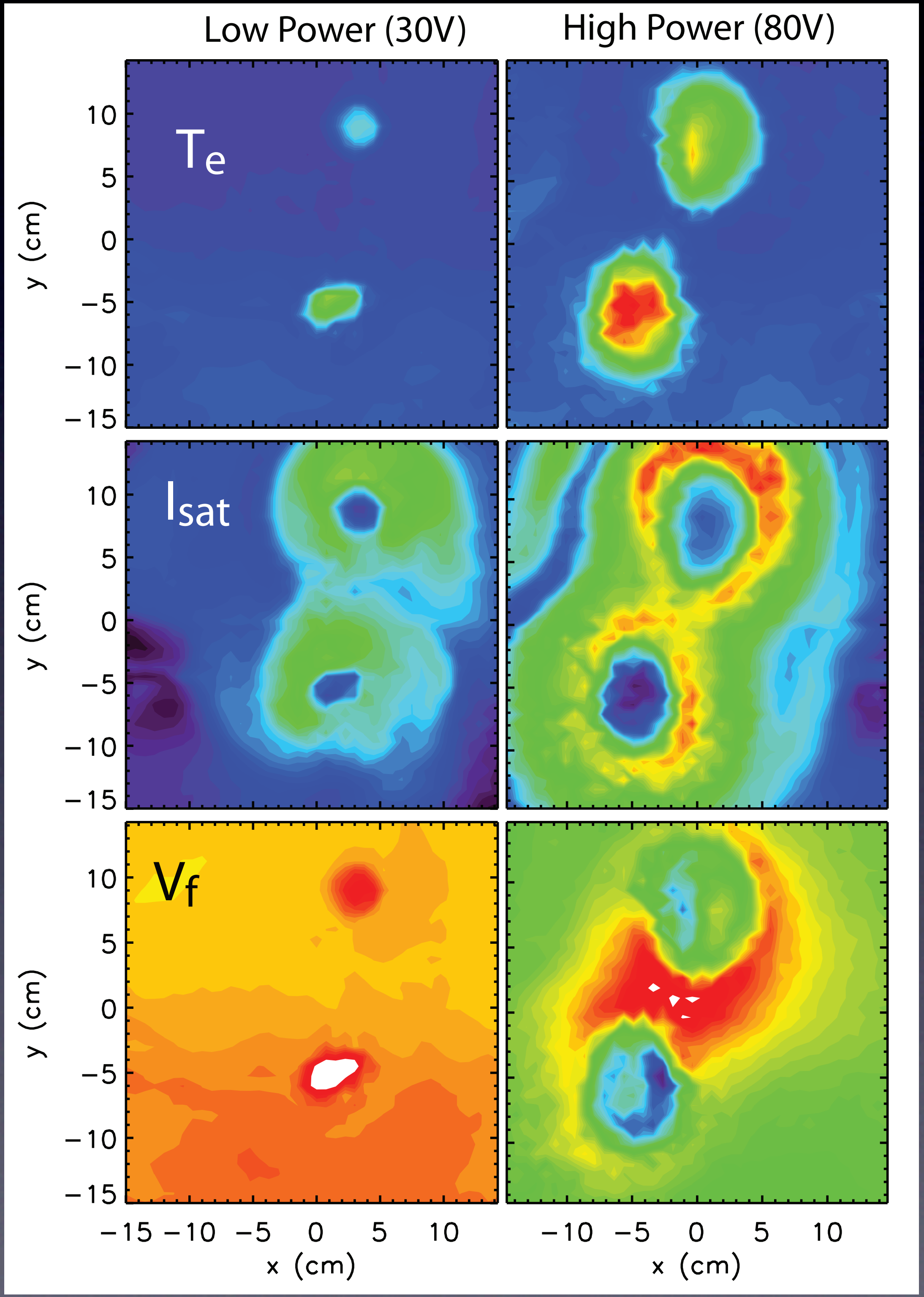
- Damping length measured ~5m, consistent with expected damping length due to electron-ion collisions
- Sufficient wave energy damped to explain large fraction (if not all?) of heating
- Wave structure significantly modified (rotated, distorted)

Braginskii calculated shear wave damping consistent with measurements



- Damping due to Coulomb collisions, yields $\lambda_d \sim 2\lambda_{alfven}$
- Role of Landau damping, nonlinear modifications to wave damping?

Temperature, density and potential modification in afterglow plasmas



- Strong heating on wave current channels
- Density depletion on current channel (density enhancement surrounding)
- Current channels tilt at high amplitude (due to potential, ExB flow? Consistent direction)
- Effect of structuring on wave propagation?

Movie of heating during afterglow: dynamics of wave current channels and heated region

RMS wave current   Electron Temperature

- Low frequency fluctuations observed, current channel wanders
- Drift-Alfvén waves driven by temperature gradients?

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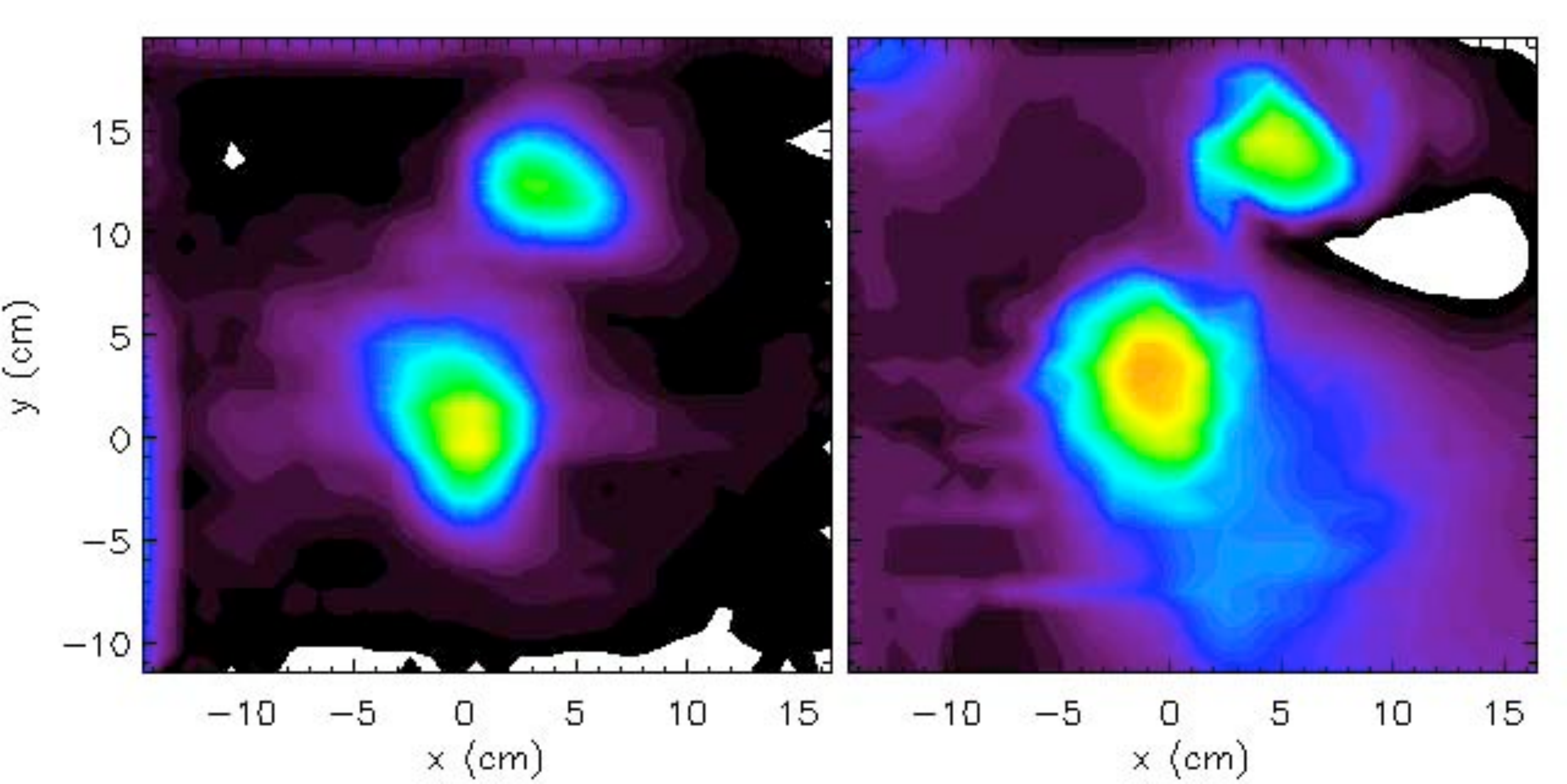

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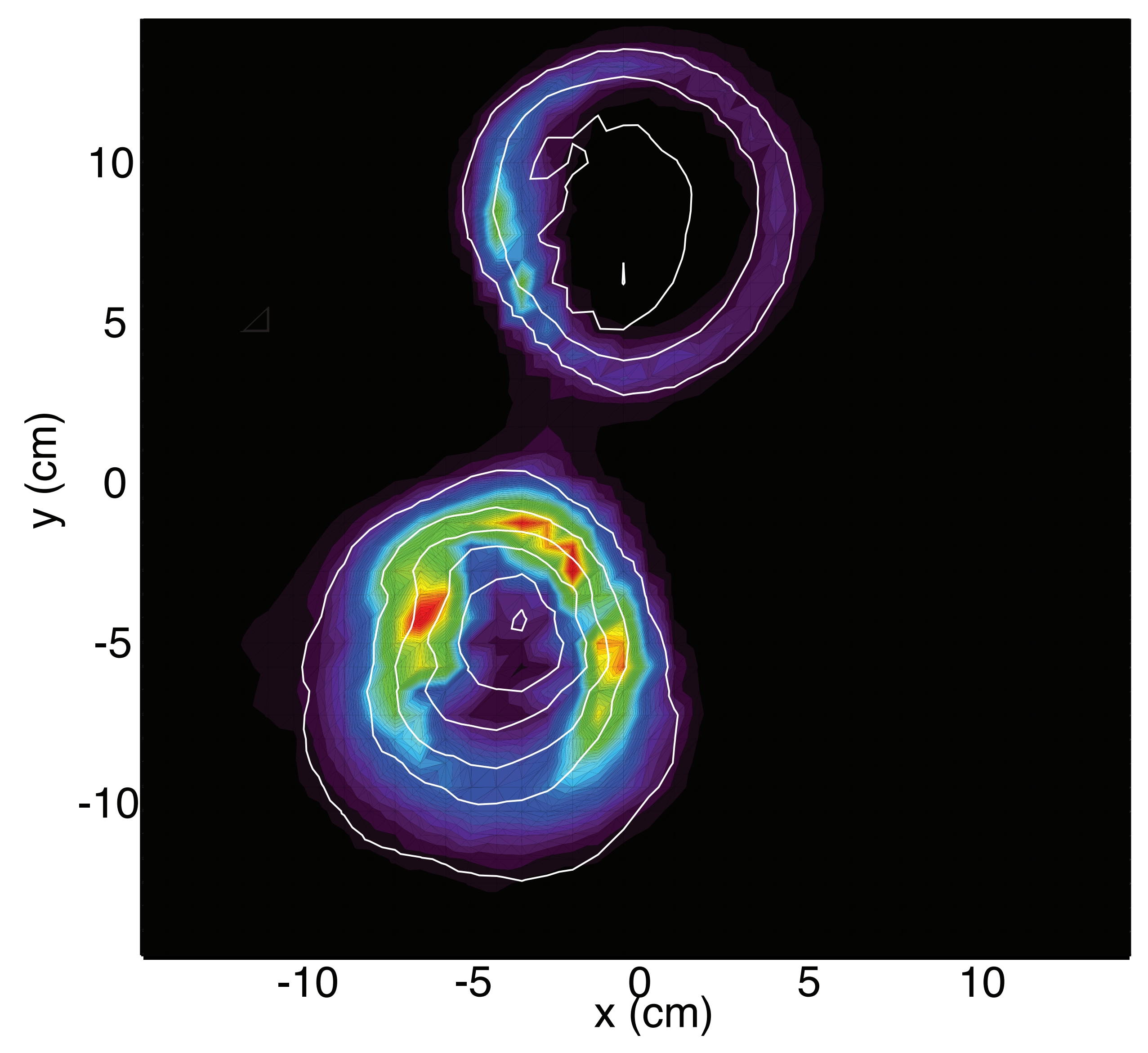
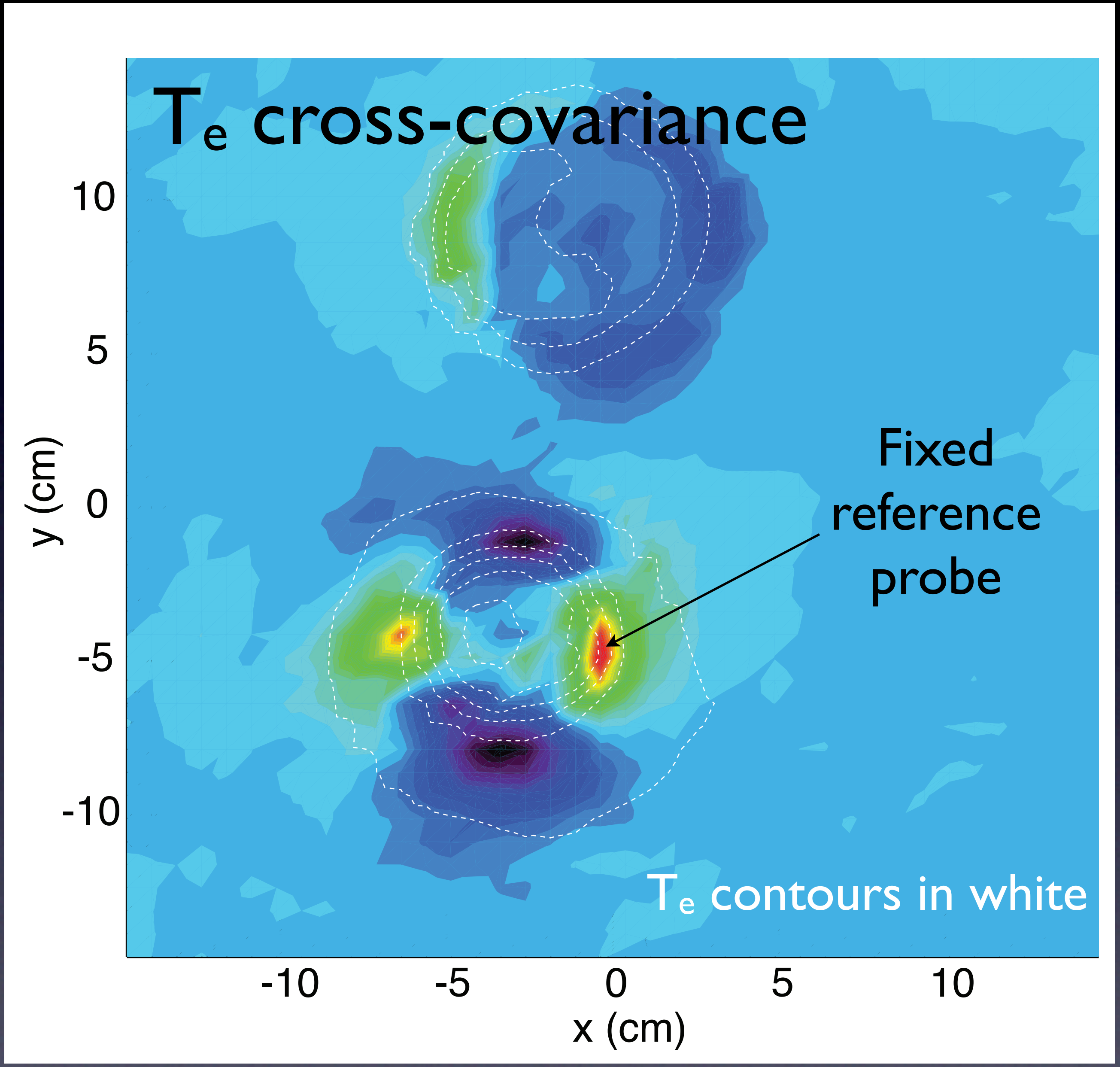
Low frequency fluctuations observed on heating-produced temperature gradients



- Contours: amplitude of fluctuations with 1 < f < 100 kHz

Mode structure of low frequency fluctuations: drift-Alfvén waves



- m=2 dominant mode observed
- similar to drift-Alfvén waves seen in electron beam heated filaments in LAPD (talk this meeting by G. Morales)

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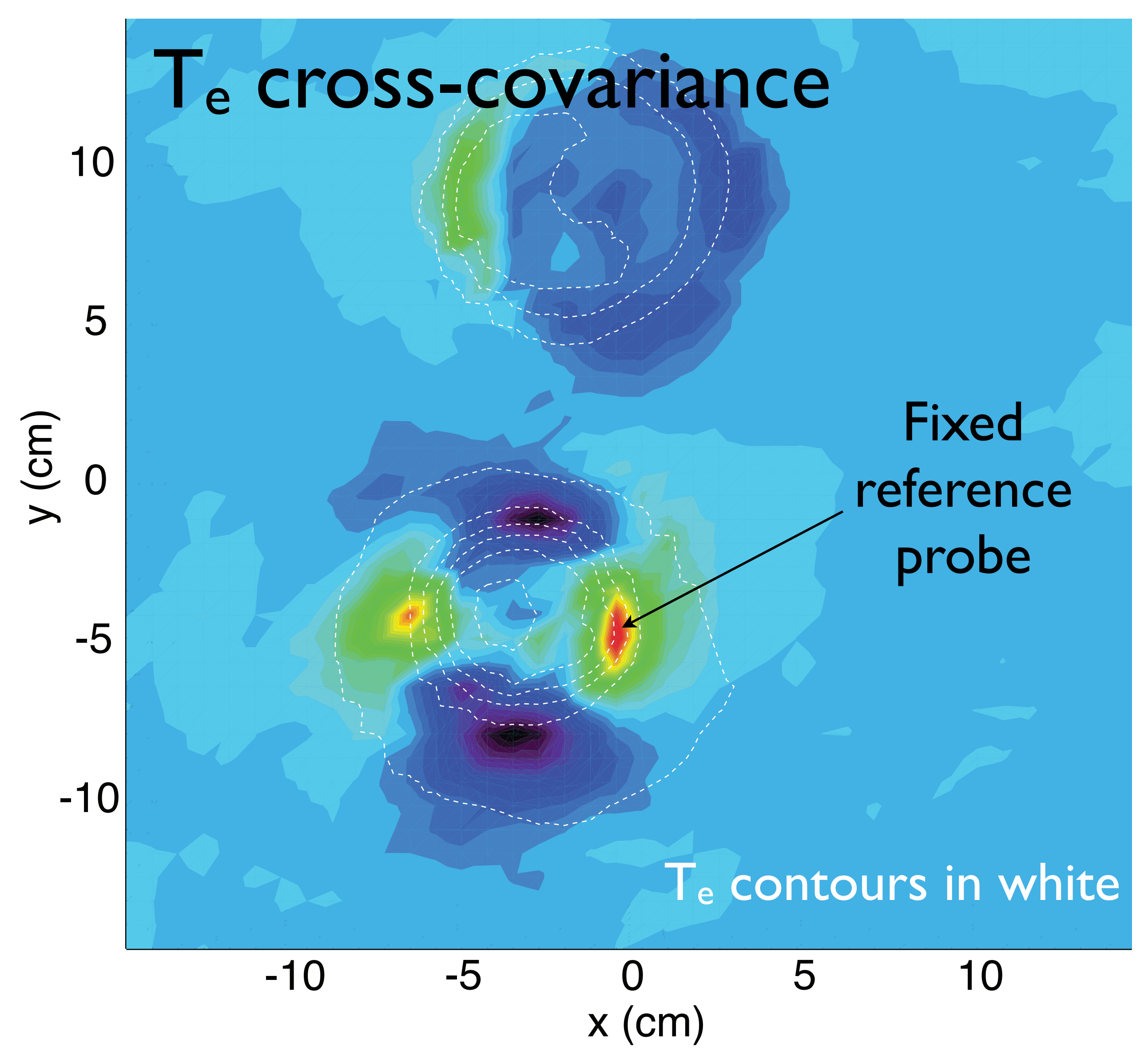

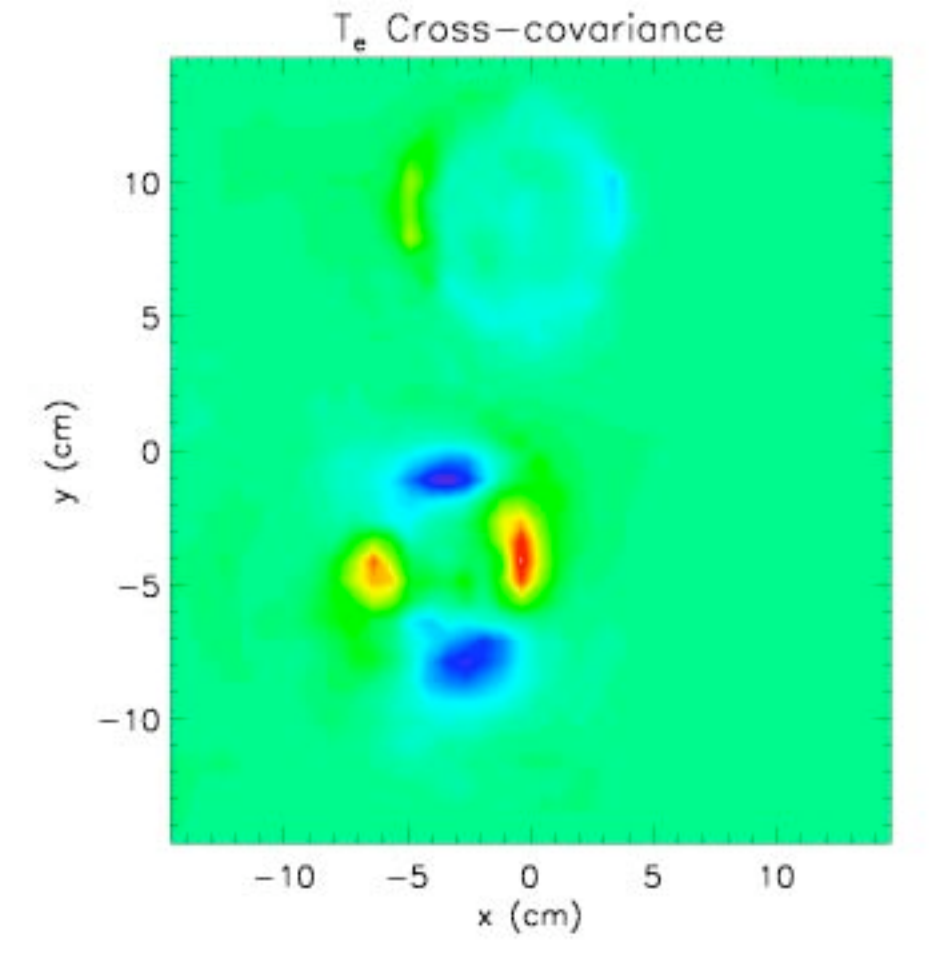

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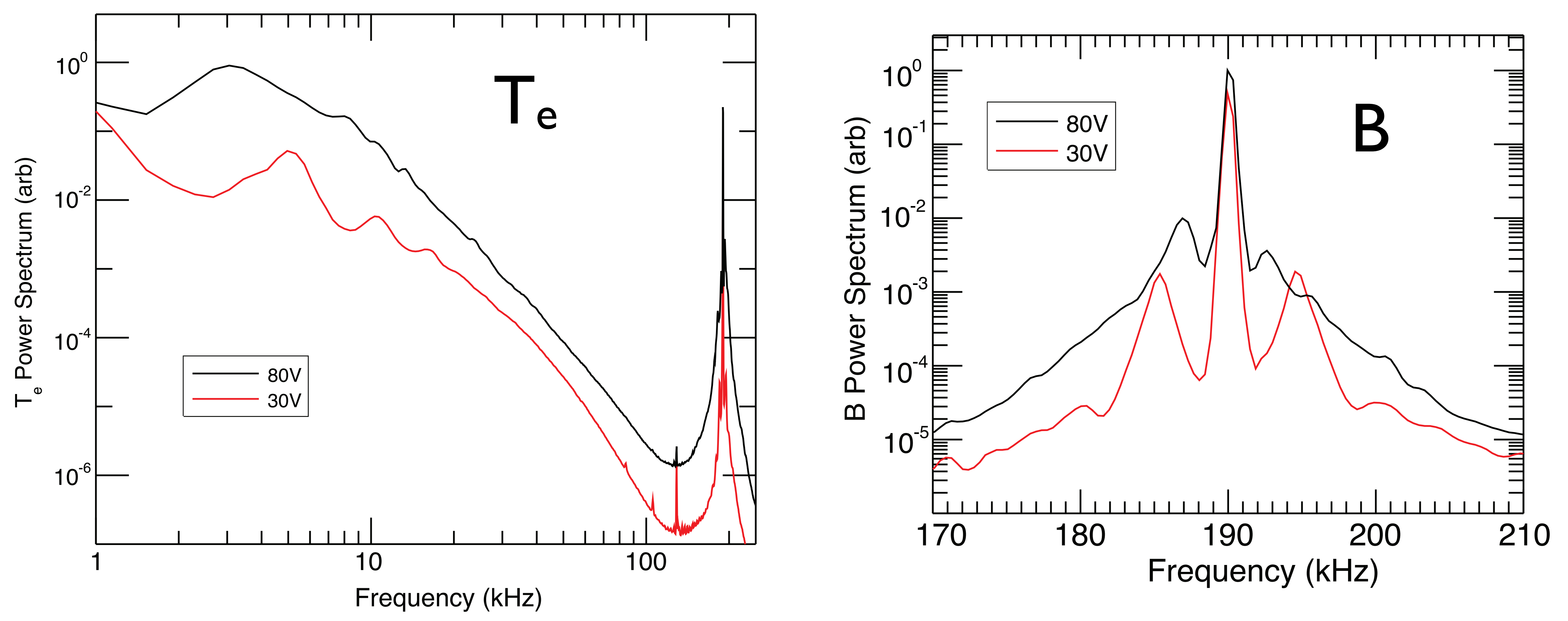
Sideband generation and turbulent broadening from interaction with drift-Alfvén fluctuation



- Sidebands separated by dominant drift-Alfvén wave frequency
- Larger drift wave frequency at lower power: smaller heated channel

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Future directions

- Continue counter-propagating studies
  - Higher amplitude, use reflecting boundary condition?
  - More quantitative studies of perpendicular and parallel cascade
  - Can we overcome damping? Heating needed on LAPD or new experiment may be needed at higher temperature, larger size
- Secondary instabilities associated with KAWs, interaction between KAW and drift-Alfvén waves
- Simulation: Braginskii fluid simulations underway (BOUT), plans for gyrokinetic simulation (AstroGK)