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)]
- Interaction between Alfvén waves and drift-Alfvén waves
  - Large amplitude Alfvén waves modify background plasma: e.g. strong electron heating localized to wave current channels
  - Heated filaments drive unstable drift-Alfvén waves which interact with incident Alfvén wave, generating sidebands and turbulent broadening

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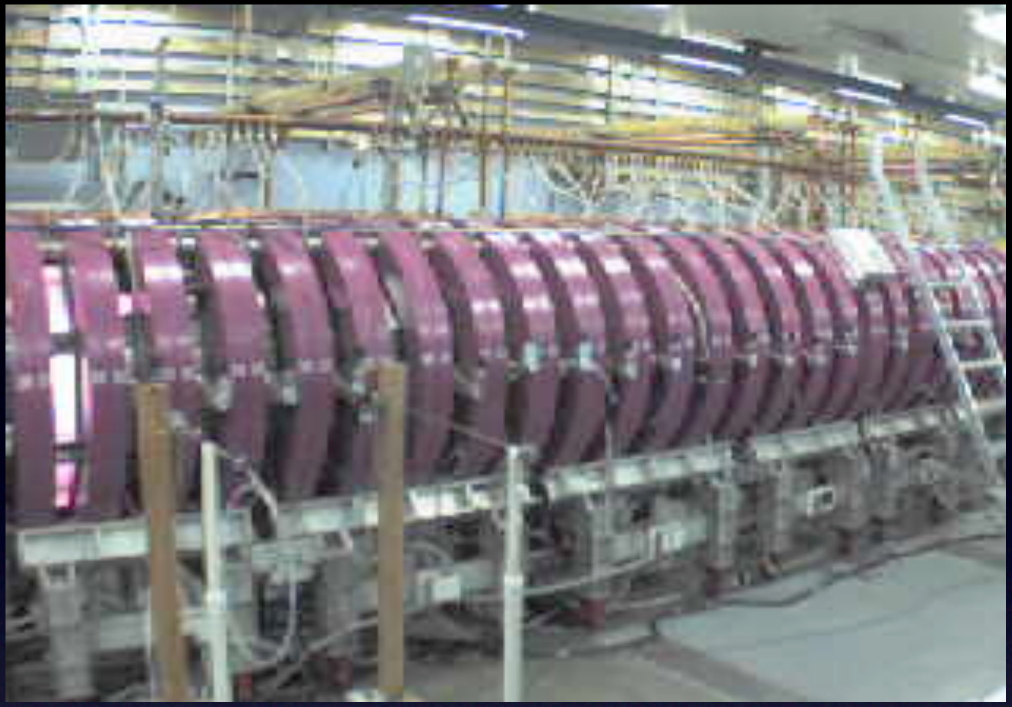
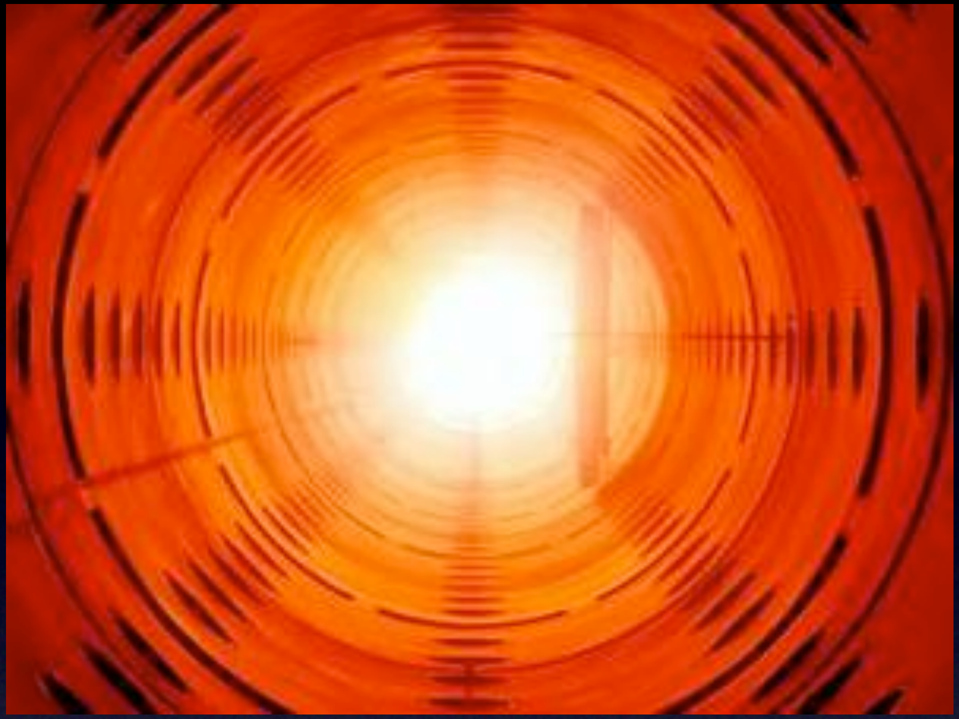
The Large Plasma Device at UCLA

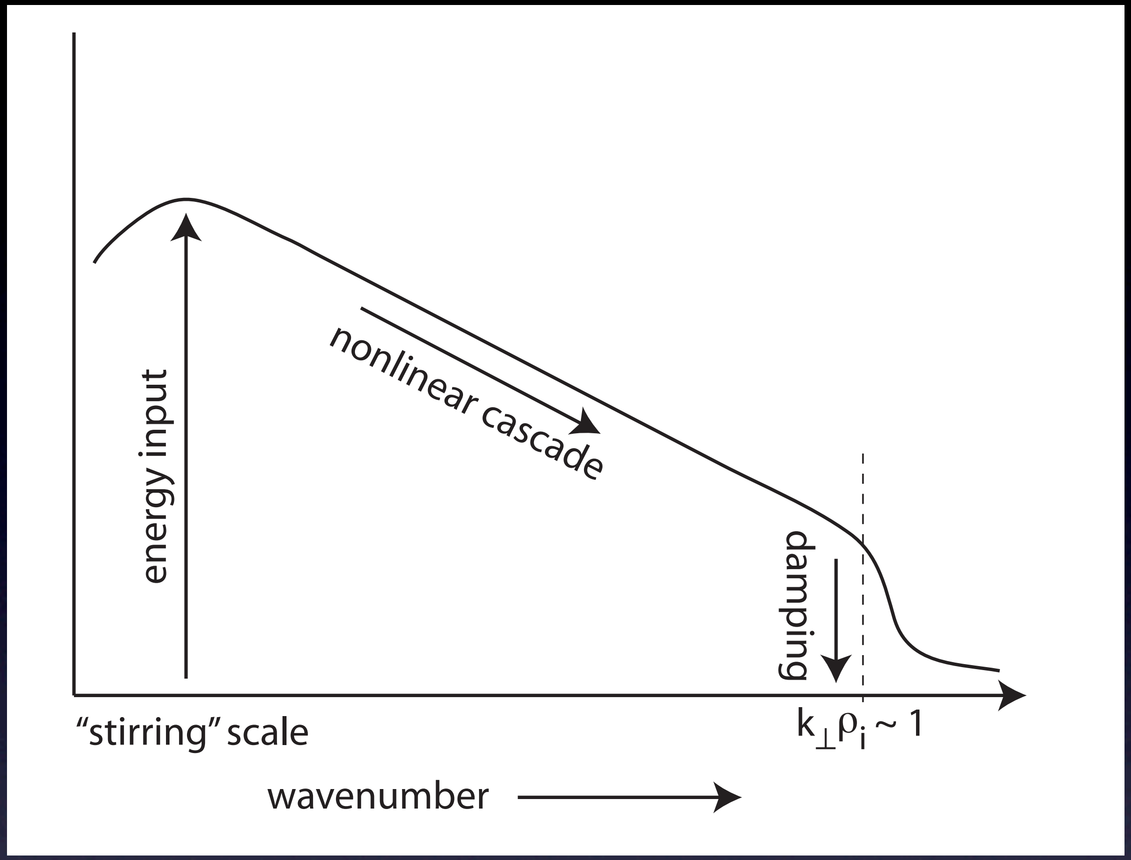




- Barium Oxide cathode source (50V, 10kA)
- $0.5 < B < 2\,\mathrm{kG}$, $n_e \sim 10^{12}\,\mathrm{cm}^{-3}$, $T_e \sim 5\,\mathrm{eV}$, $T_i \sim 1 eV$
- 1m diameter, 20m long chamber
- He, Ne, Ar, H plasmas
- 1Hz rep rate, 10ms pulse length
- International user facility (http://plasma.physics.ucla.edu/bapsf)

Alfvén waves and interactions in LAPD

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



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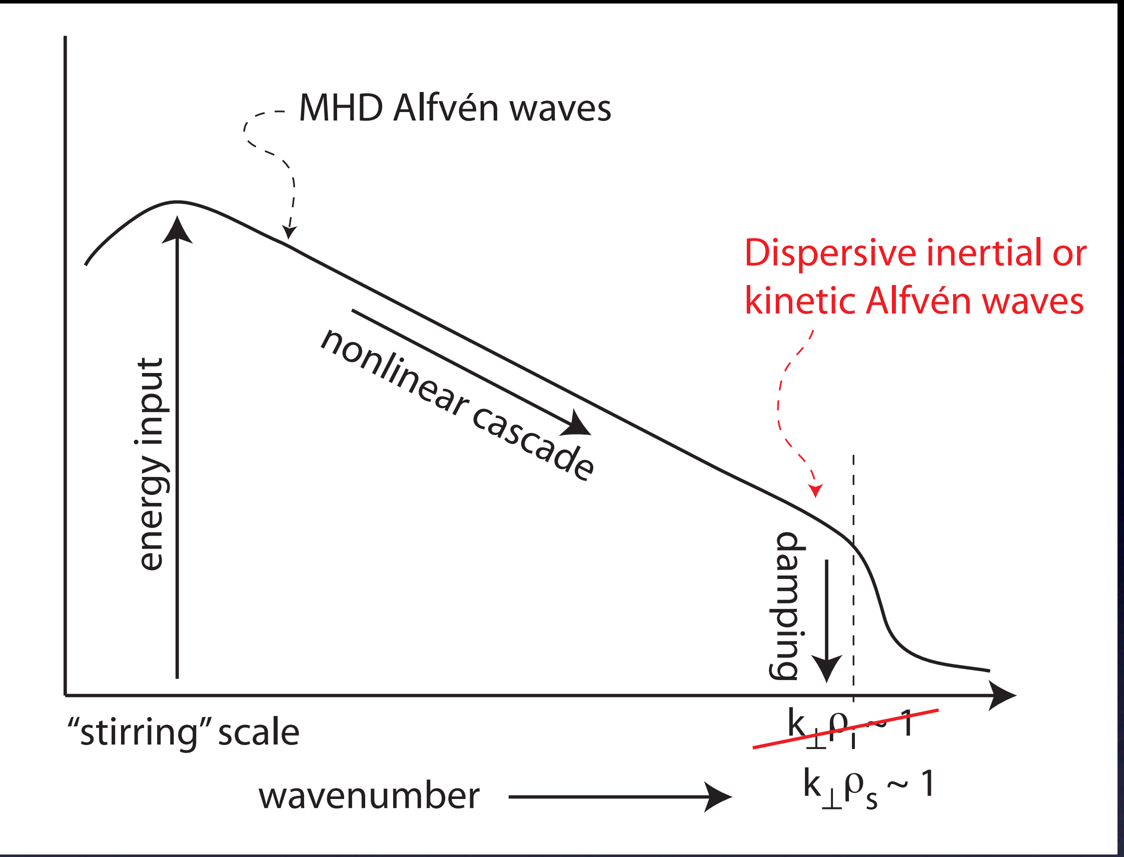
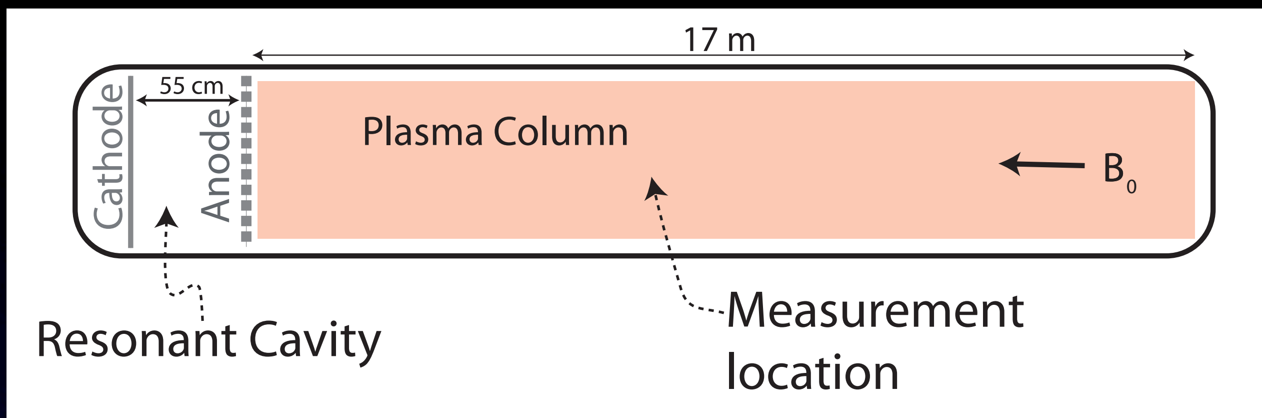


- Incompressible MHD theory of interactions (e.g. Goldreich-Sridhar): Only counter-propagating waves interact
- In LAPD experiments, waves have $k_\perp \rho_s \sim 1$, $\omega/\Omega_i \sim 1$
  - dispersive kinetic or inertial Alfvén waves
  - Co-propagating interaction allowed (waves can pass through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

Large amplitude wave sources: the Alfvén wave maser, loop antenna



- 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: $\delta B/B > k_{||}/k_{\perp}$
- Frequency: $f/f_{ci} \sim 0.6$

y (cm)

x (cm)

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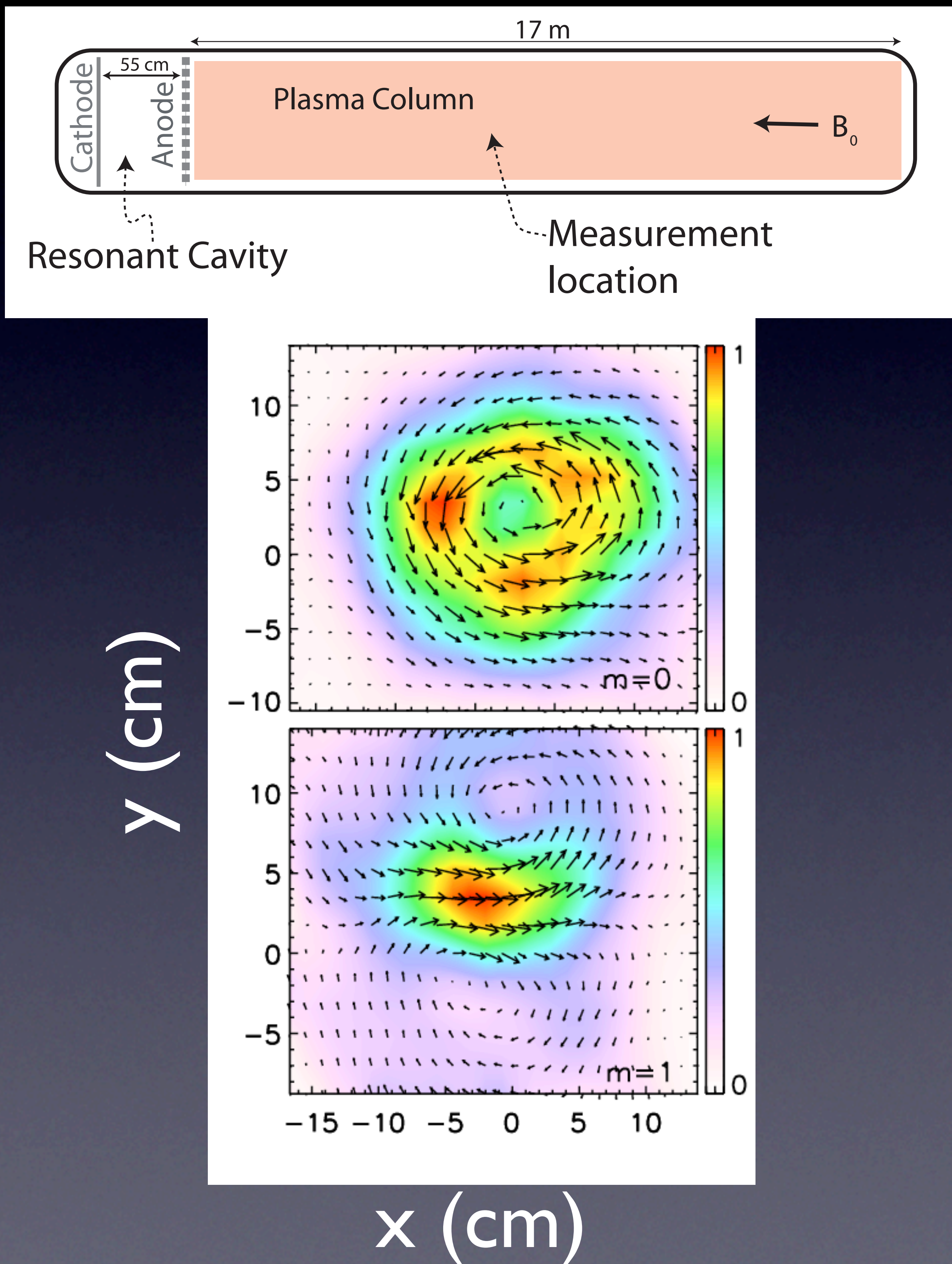

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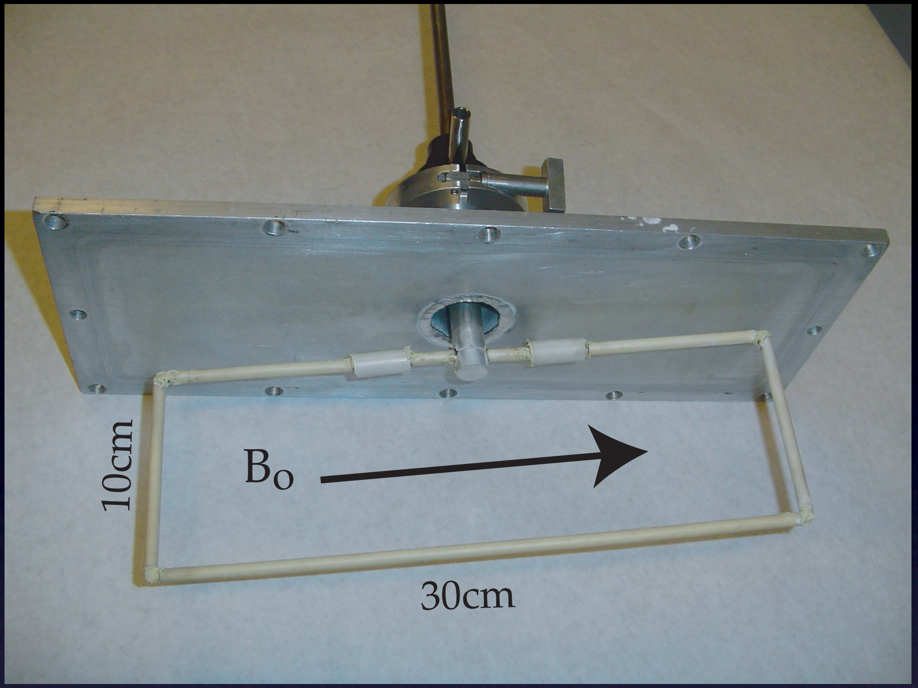
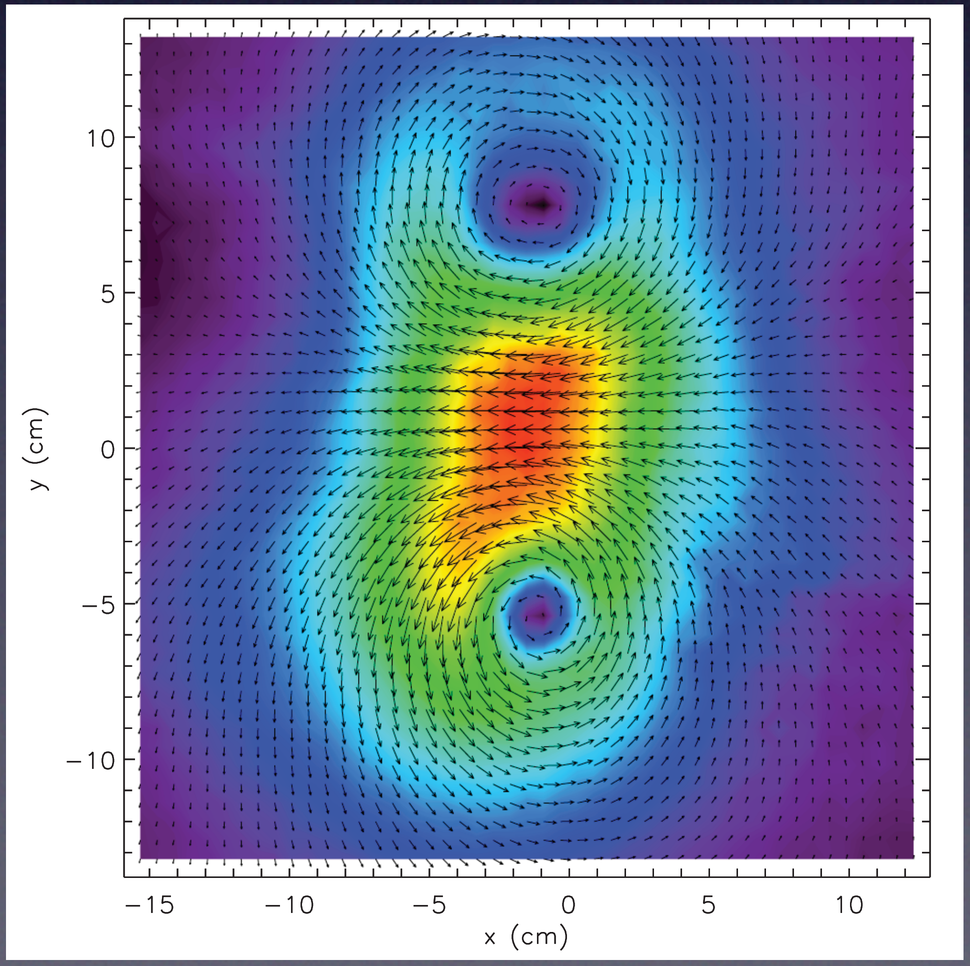
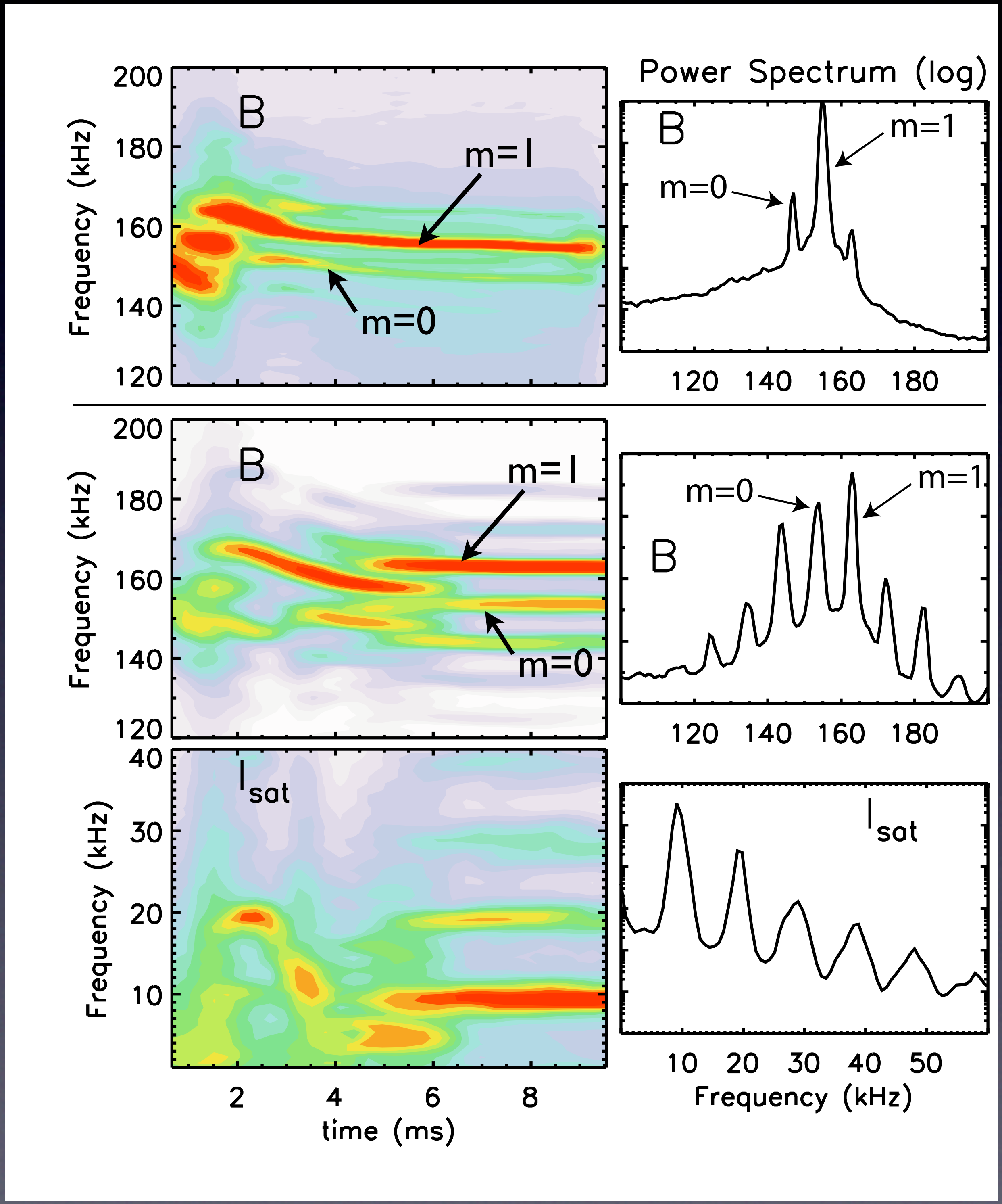
Large amplitude wave sources: the Alfvén wave maser, loop antenna

- Broadband excitation of large amplitude waves (up to 10G) using novel drivers (up to 1kA pulsed, ~15kW wave power)
- Two wave current channels (corresponding to top and bottom strap of antenna)





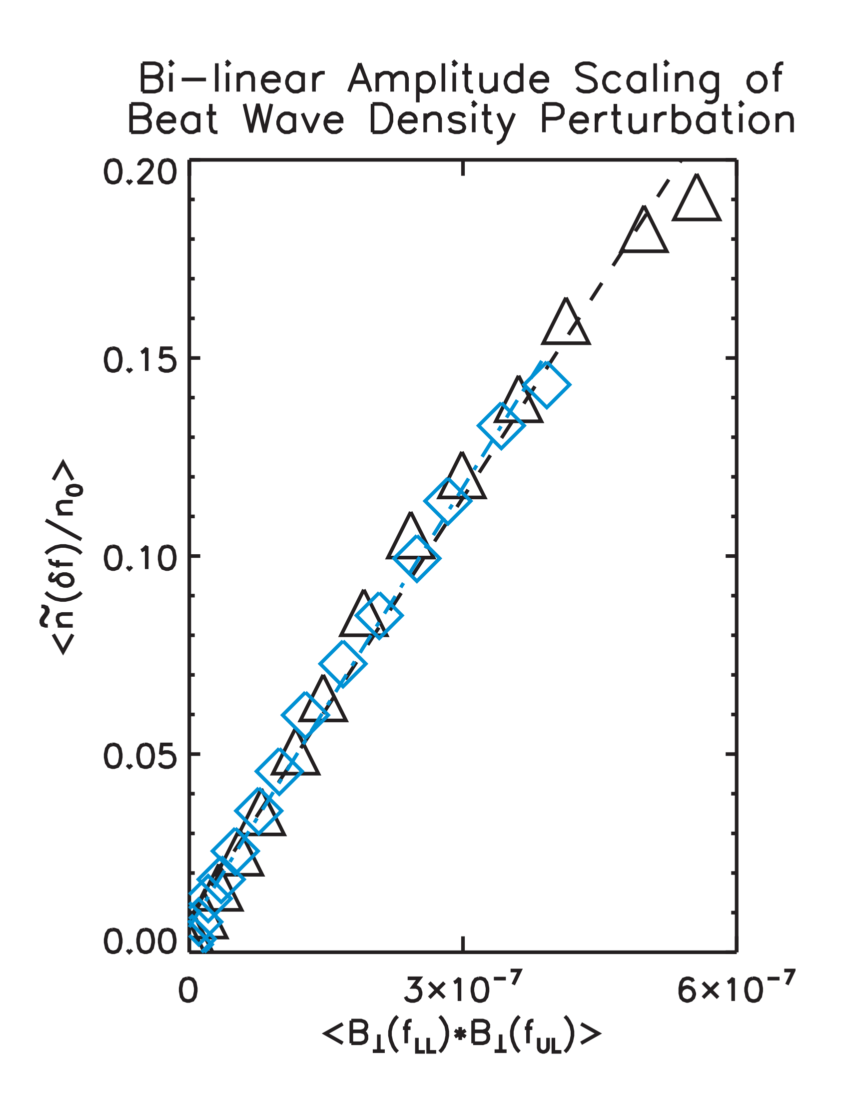
Nonlinear interaction observed during simultaneous emission of two waves

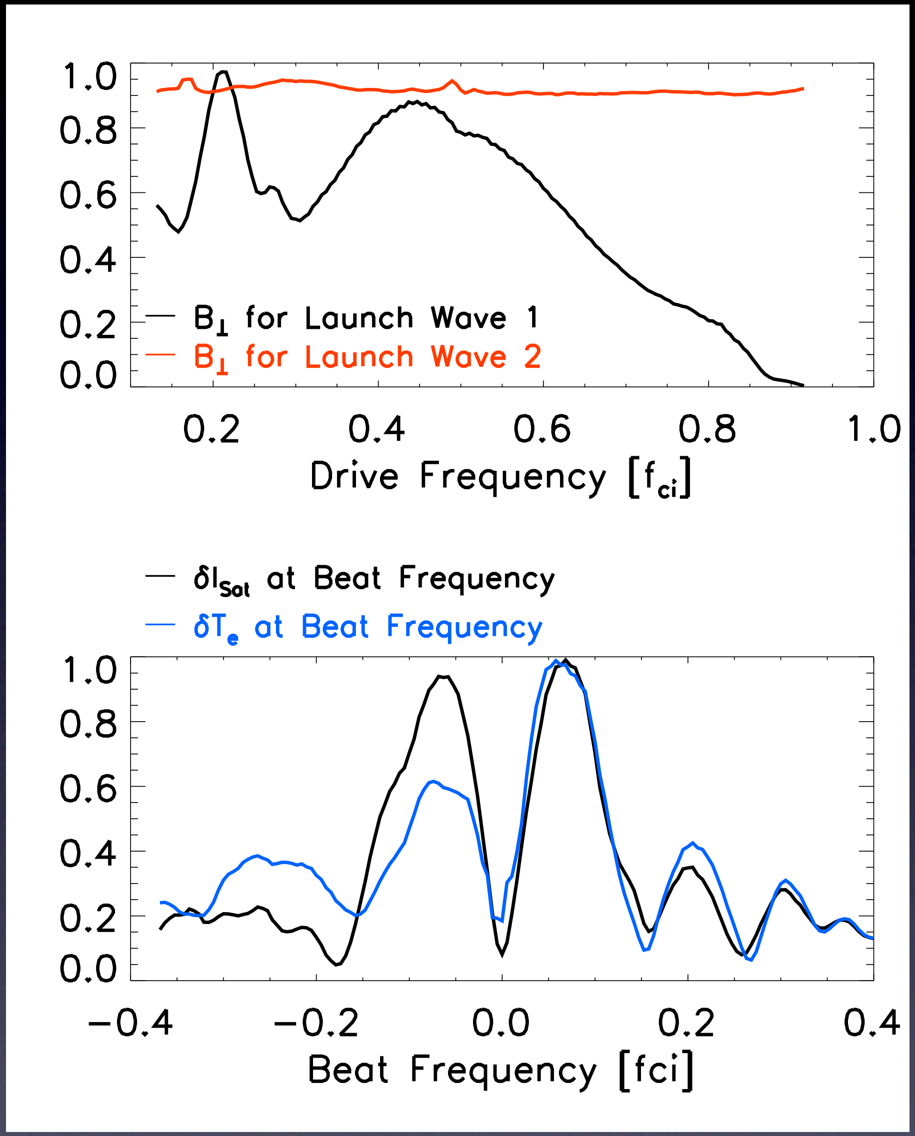


- Simultaneous emission of large amplitude m=0 and m=1 cavity modes
- Copropagating waves beat together, generate strong nonlinear quasimode at beat frequency ($\delta n/n \sim 10\%$)
- Pump Alfvén waves scatter off of low-frequency quasimode, generating a series of sidebands
- Consistent with nonlinear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

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

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

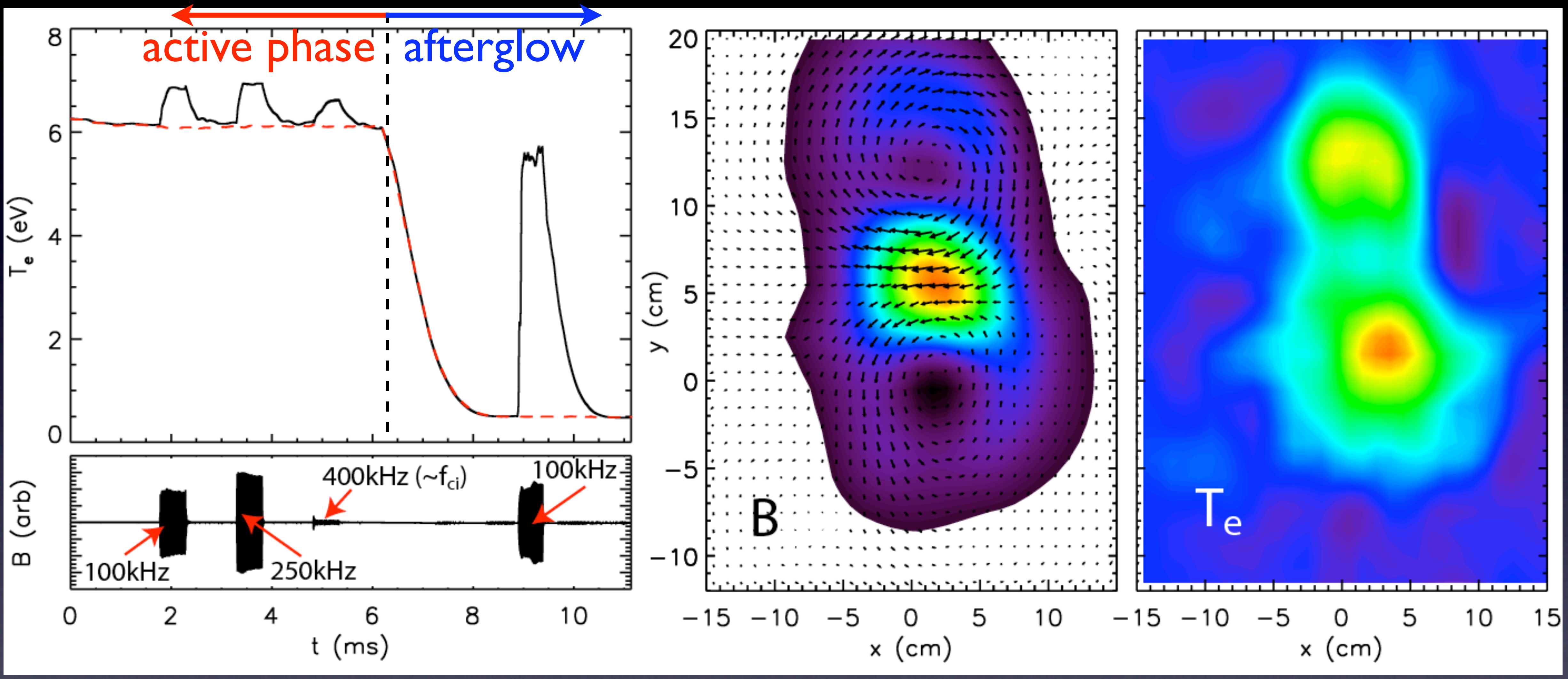
Beat driven wave is off-resonance Alfvén wave; theory consistent with observed amplitude, resonant behavior

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

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

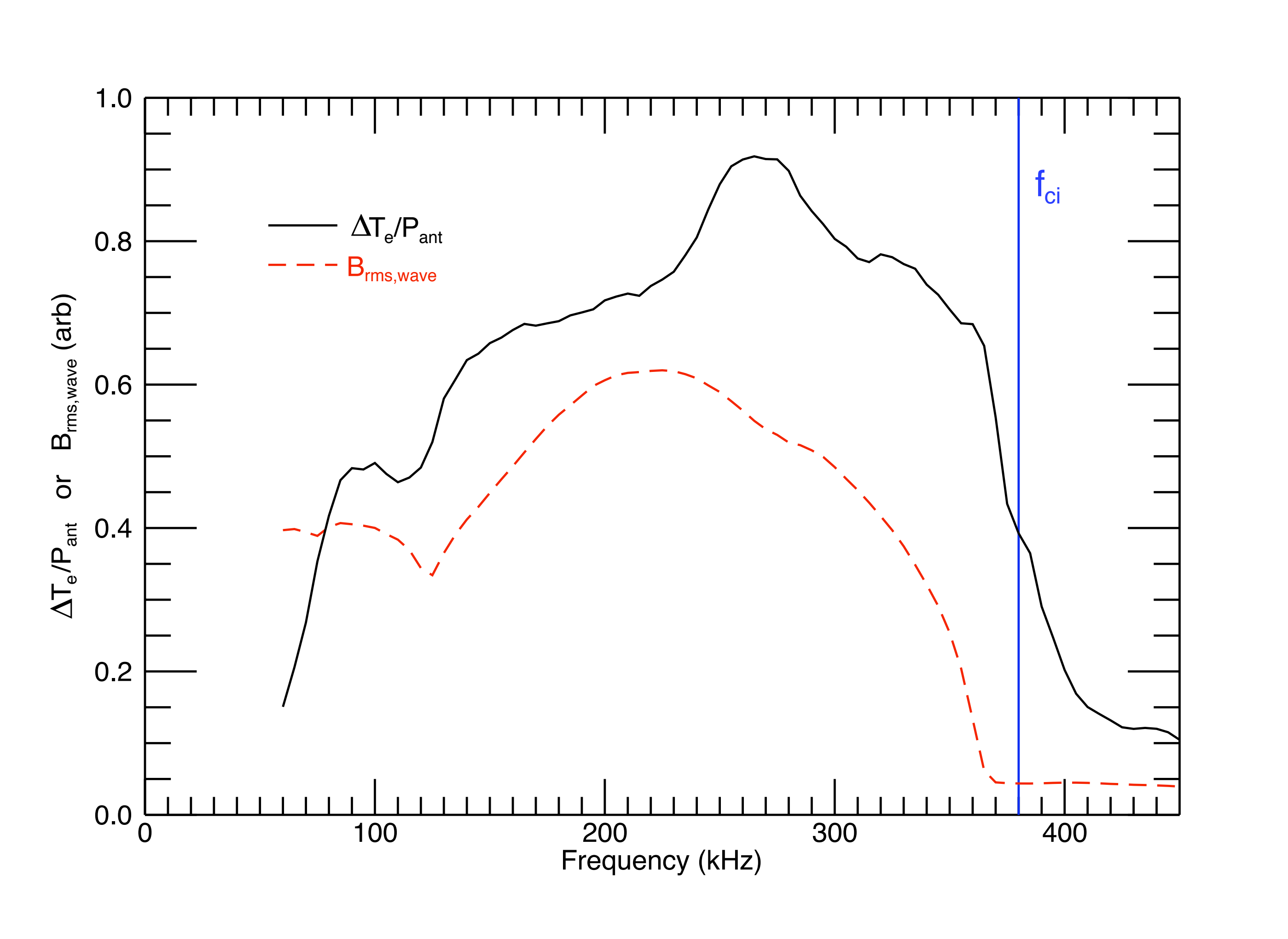
- Exhibits resonant behavior (for Alfvénic beat wave) - reasonable agreement with experiments (except "harmonics")
- Ignoring resonant demoninator, $\delta n/n \sim$ 1-2% for LAPD parameters
- Dominant nonlinear forcing is perpendicular (NL polarization drift): easier to move ions across the field to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

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

Movie of heating during afterglow: interaction of wave with self-heated filaments

RMS wave current   Electron Temperature

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

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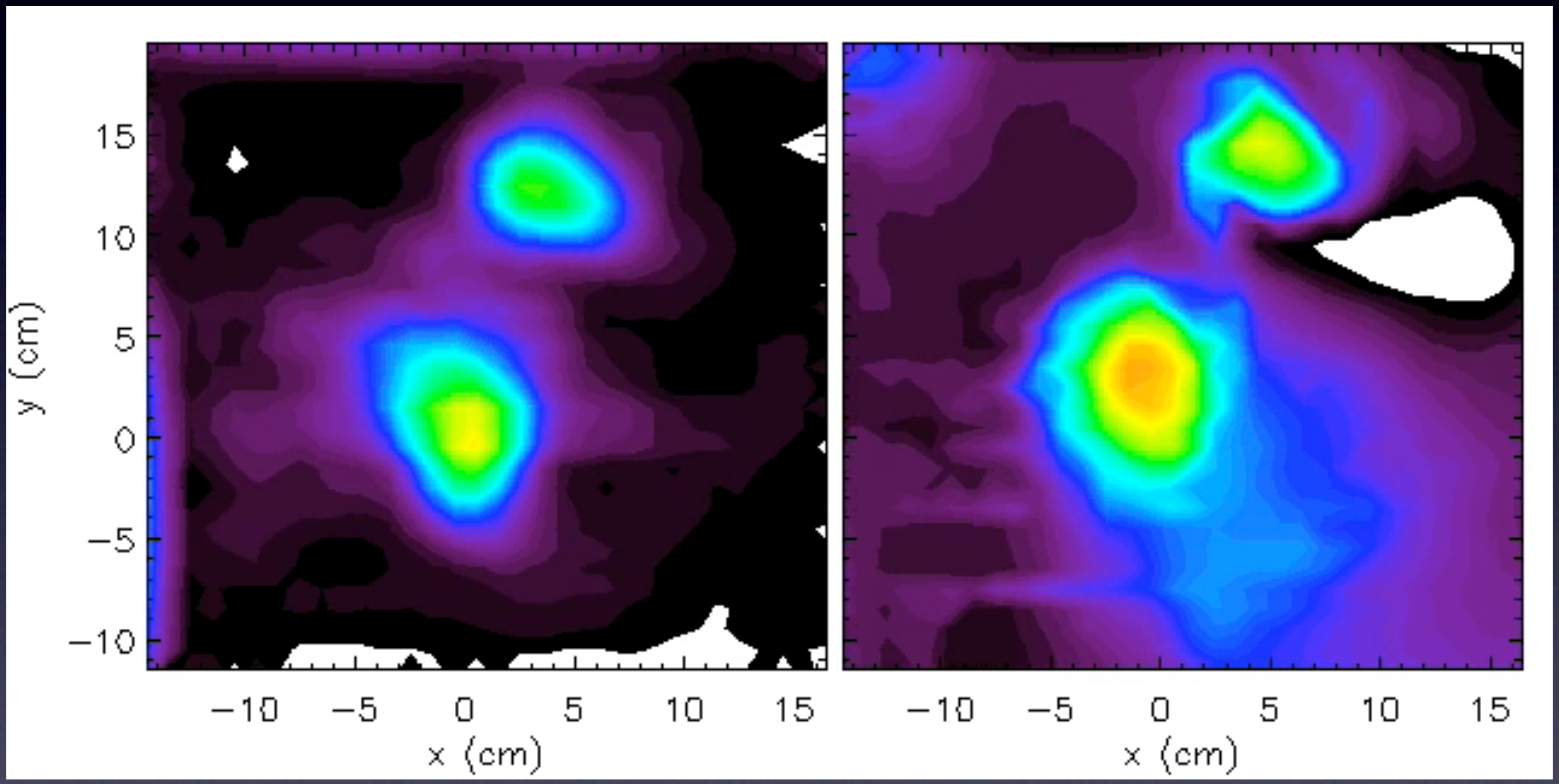

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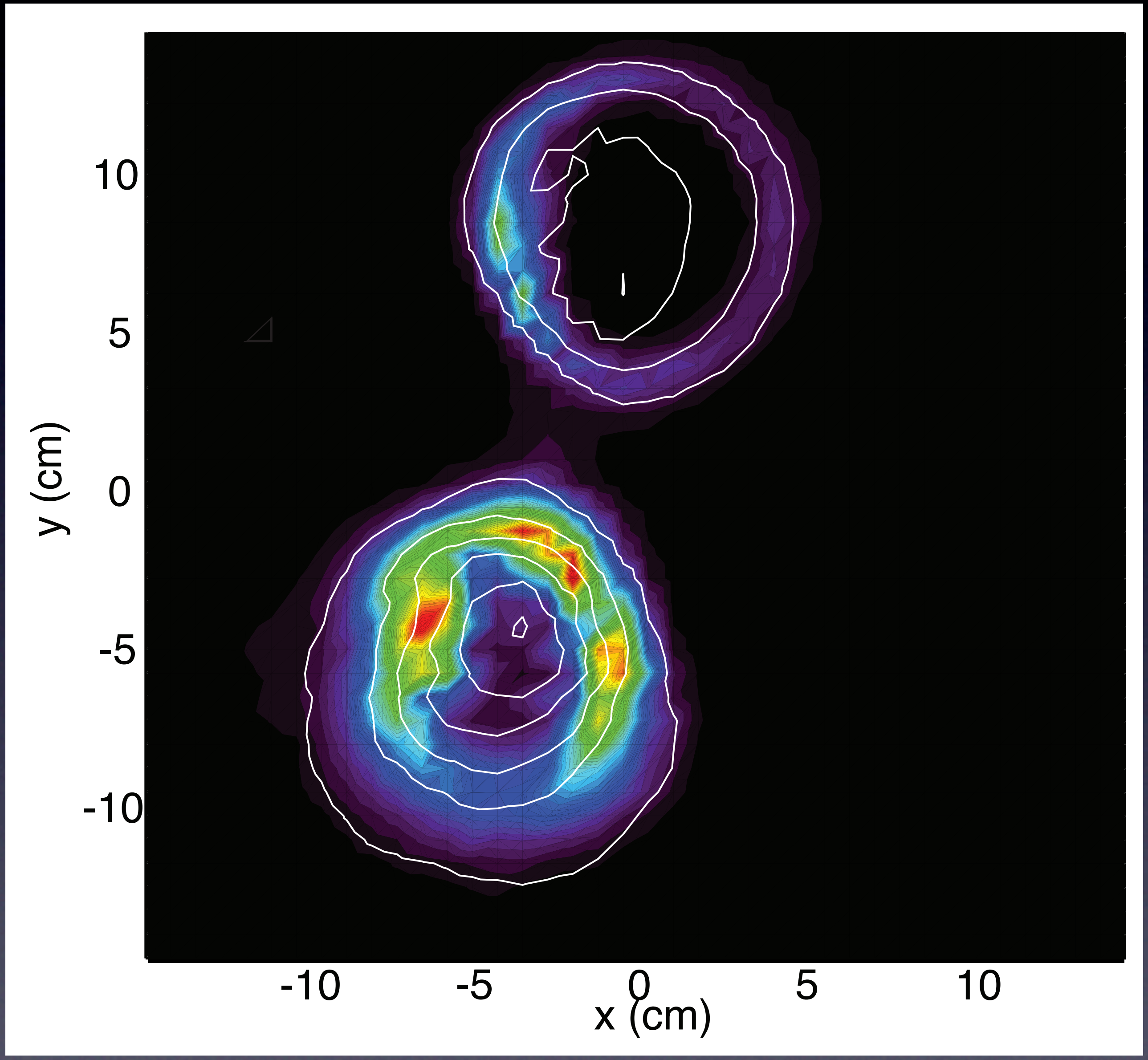
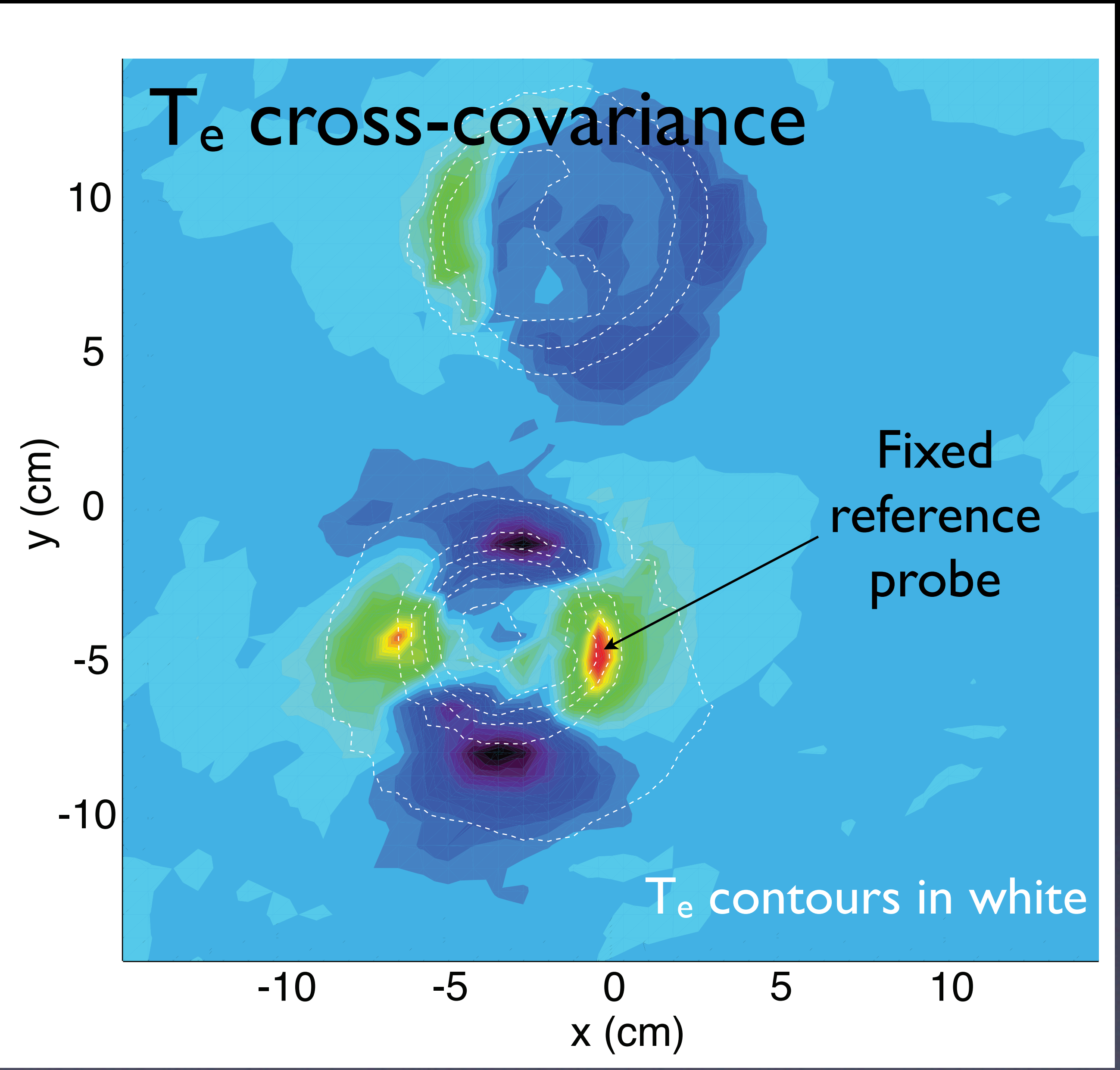
Low frequency fluctuations observed on heating-produced temperature gradients



- 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 (Maggs, Morales)

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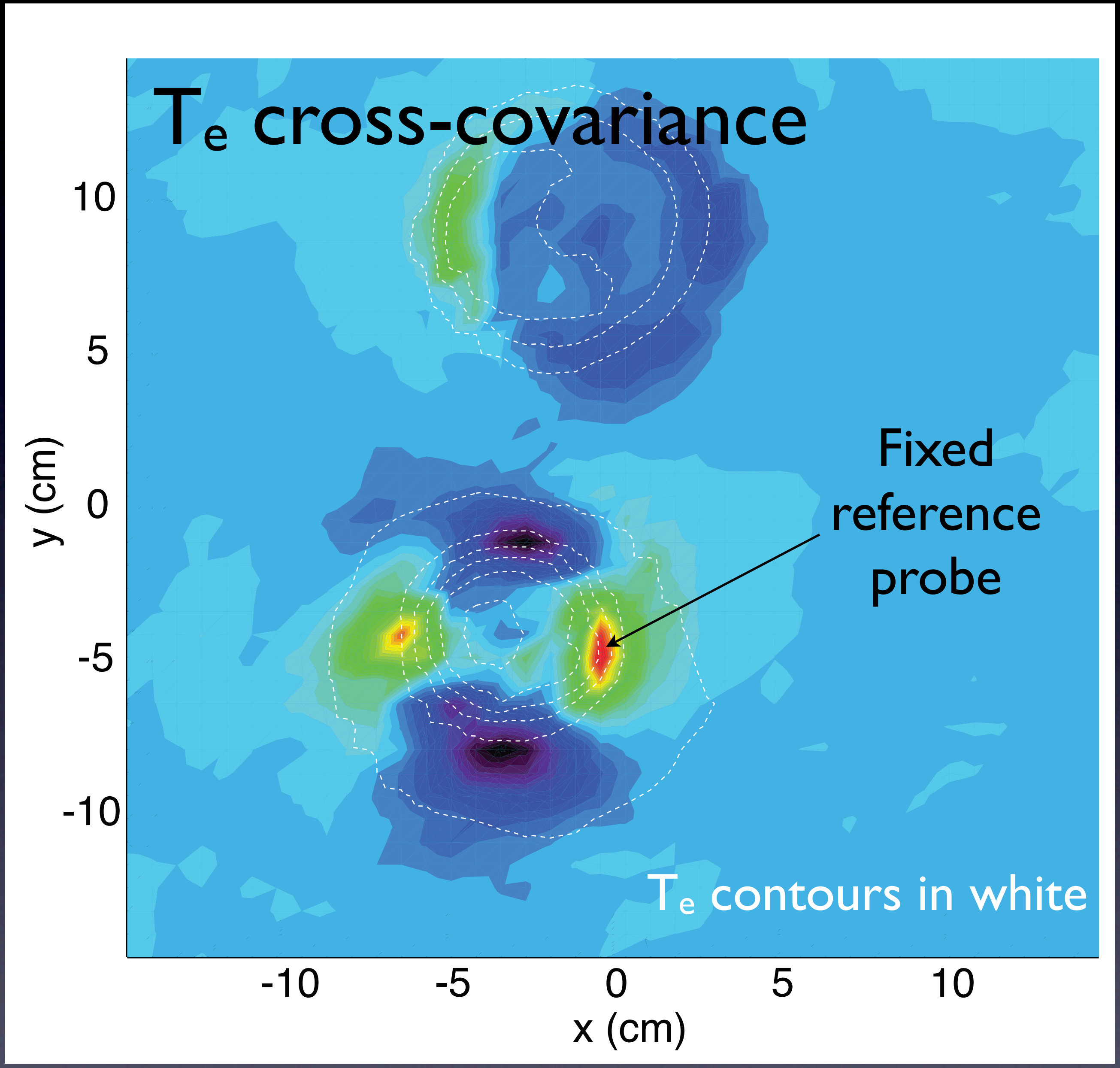

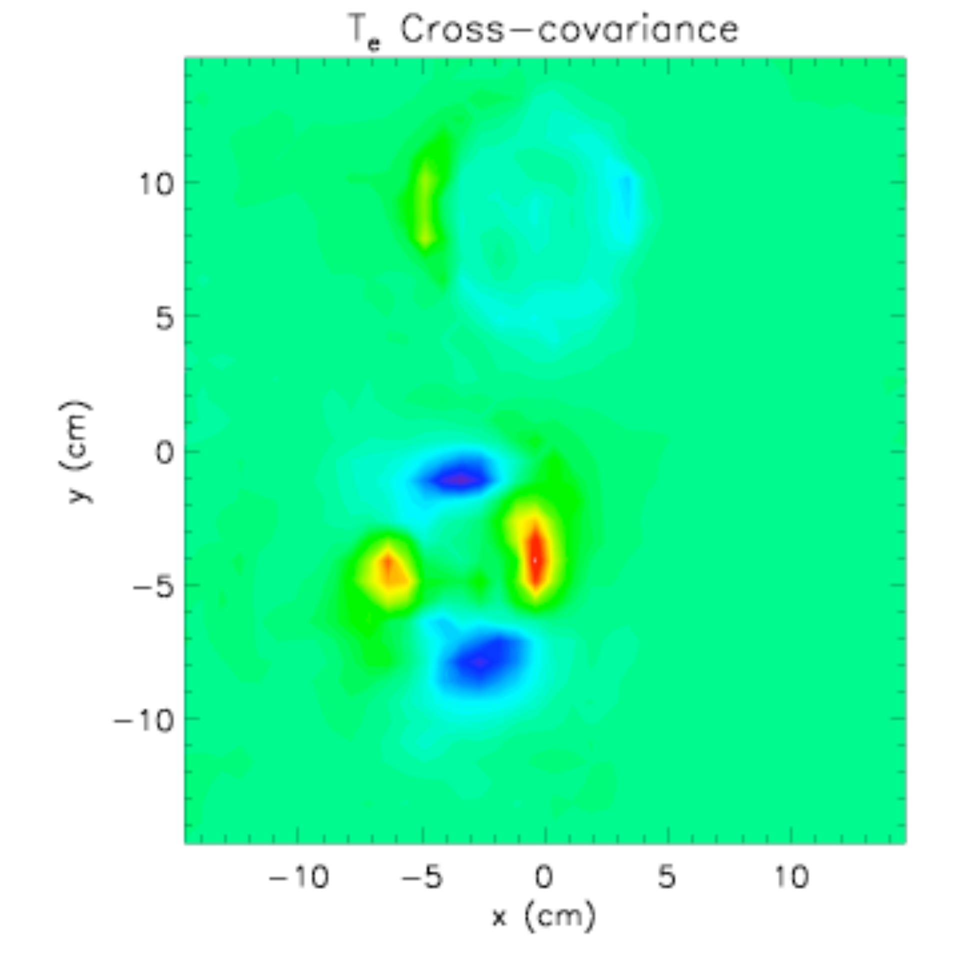

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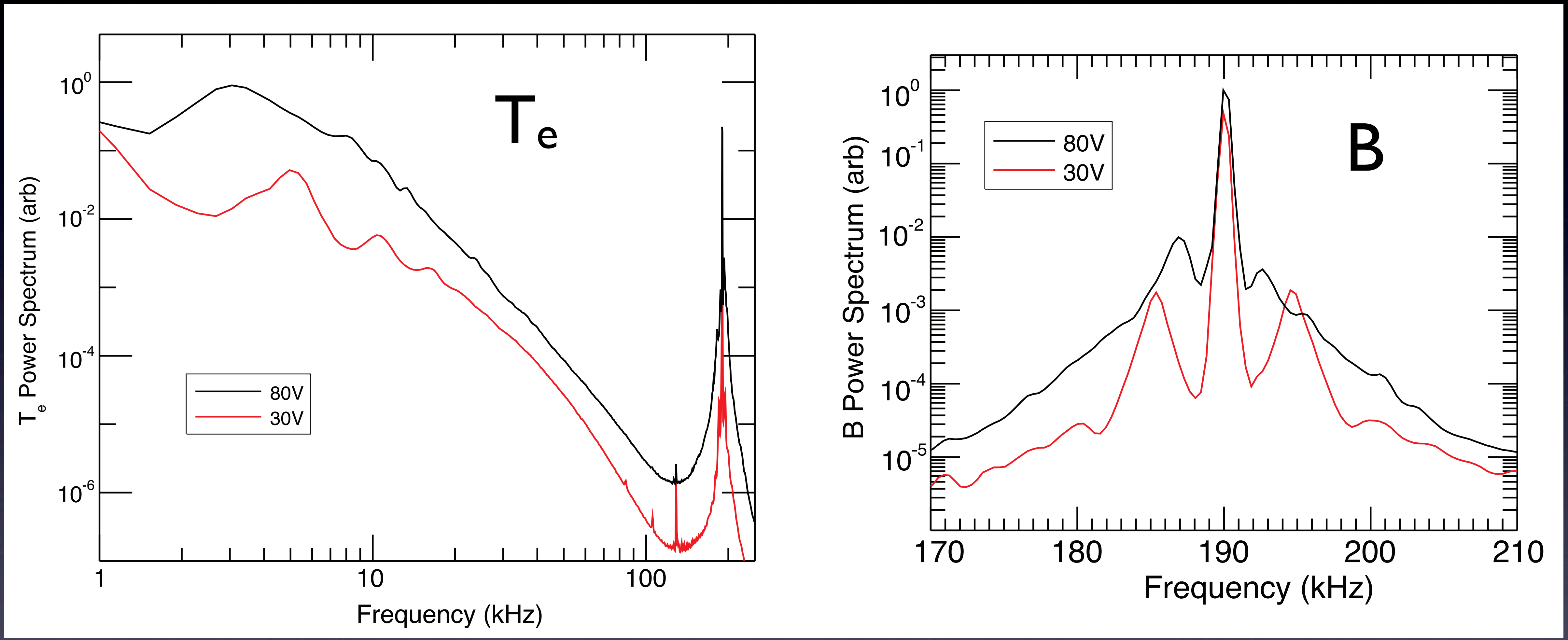
Sideband generation and turbulent broadening from interaction with drift-Alfvén fluctuation



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

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