Observation of an Alfvén wave parametric instability in a laboratory plasma

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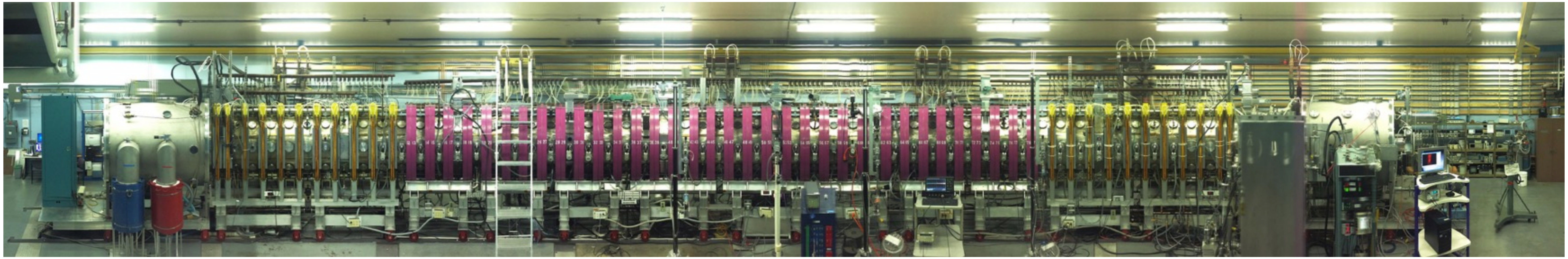
Summary/Outline

- Studies of large-amplitude shear Alfvén waves in the Large Plasma Device: three-wave interactions and decay instabilities
- Nonlinear excitation of ion acoustic waves [Dorfman & Carter, PRL, 110, 195001 (2013)]
  - Beating of two counter-propagating kinetic Alfvén waves (KAWs); resonant response observed consistent with ponderomotive excitation of ion acoustic wave
- Parametric instability of lone large-amplitude shear wave [Dorfman & Carter, PRL, 116, 195002 (2016)]
  - Finite frequency KAWs decay to co-propagating sideband KAWs and low frequency quasimode; qualitatively consistent with modulation decay instability.
- New LAPD capabilities (LaB6 plasma source + RF heating) enable high β, warm ion plasmas

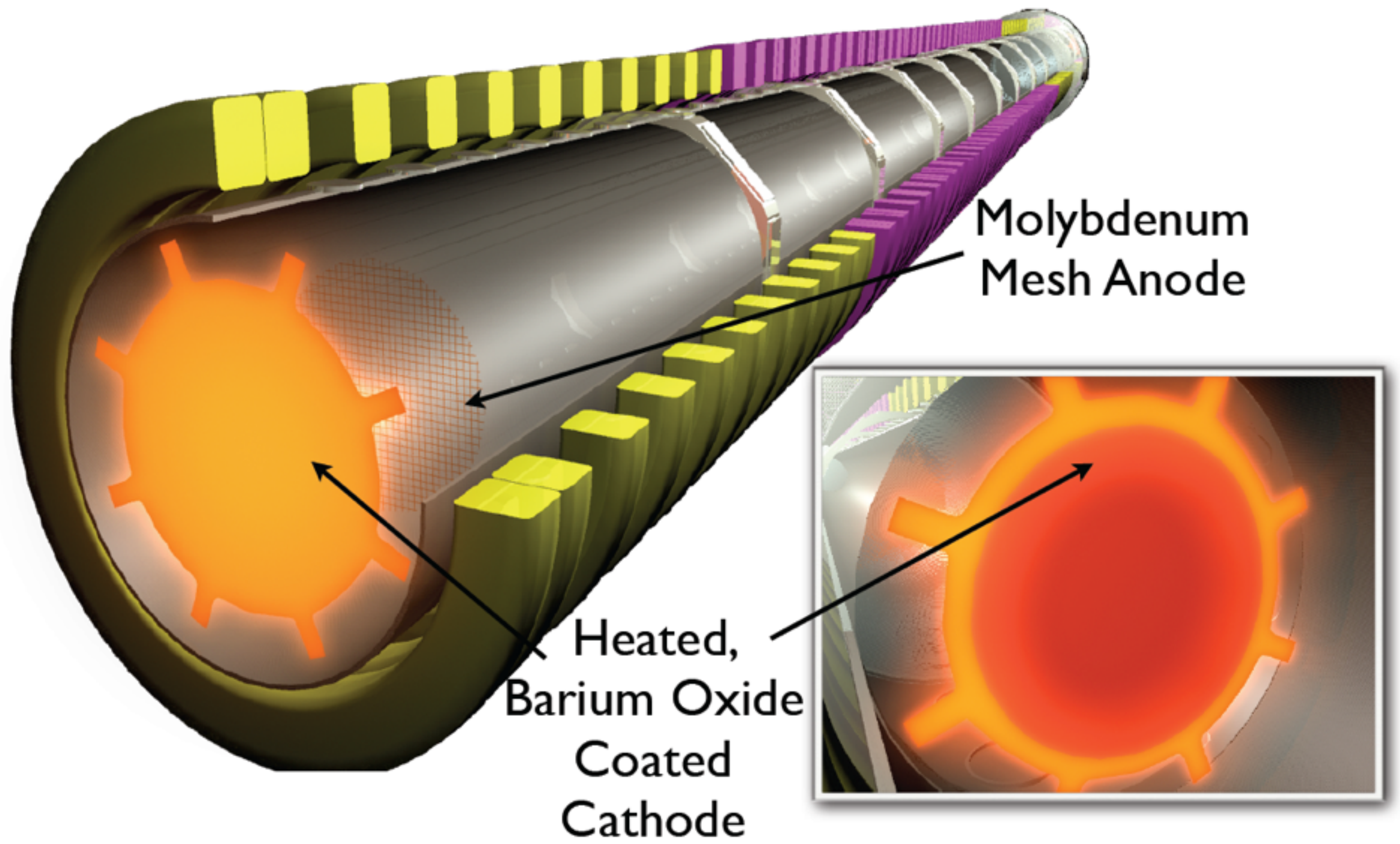
The LArge Plasma Device (LAPD)

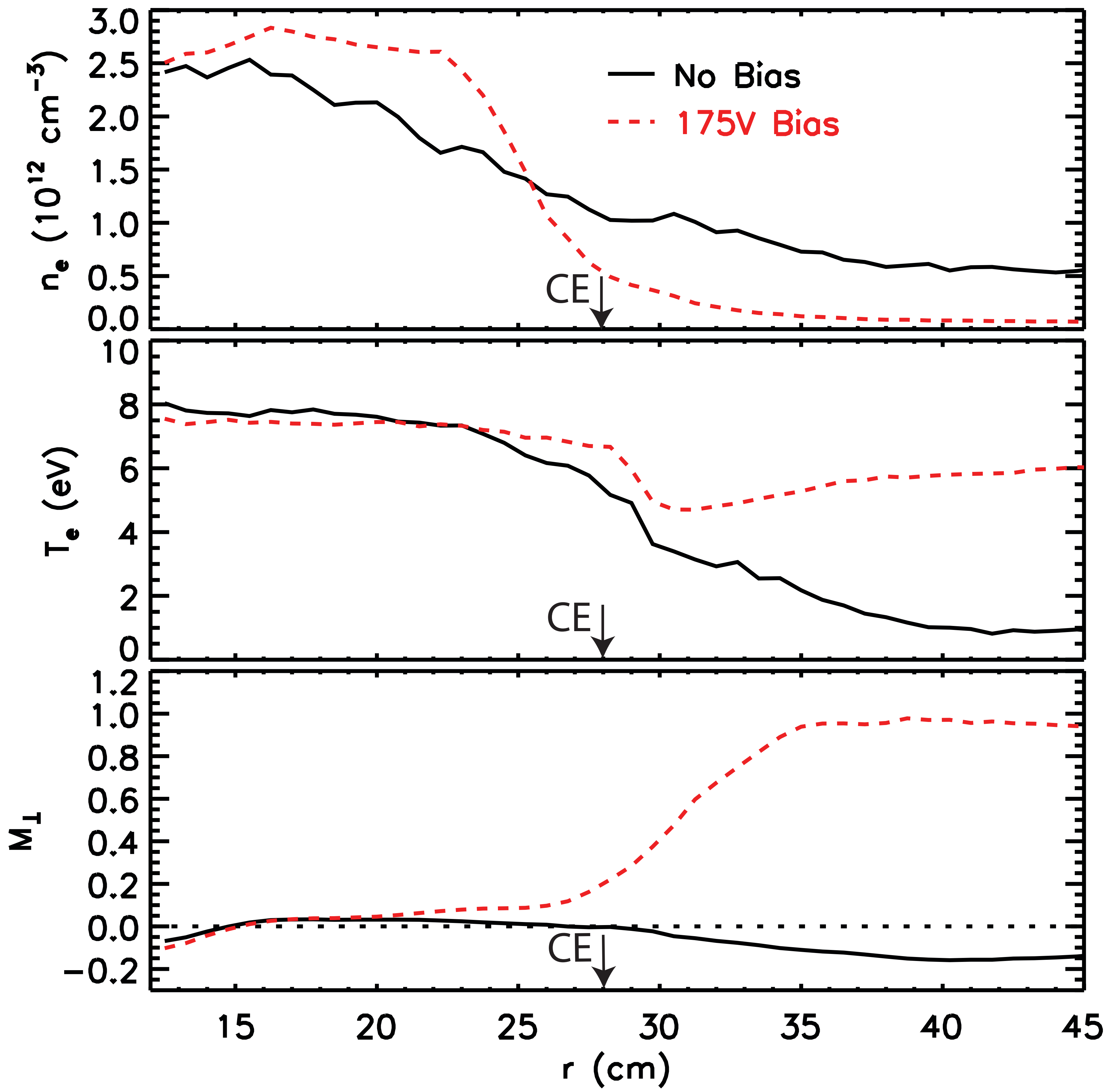


- Solenoidal magnetic field, cathode discharge plasma (BaO and LaB_6)
- BaO Cathode: $n \sim 10^{12}$ cm^{-3}, $T_e \sim$ 5-10 eV, $T_i \lesssim$ 1 eV
- LaB_6 Cathode: $n \sim 5\times10^{13}$ cm^{-3}, $T_e \sim$ 10-15 eV, $T_i \sim$ 6-10 eV
- B up to 2.5kG (with control of axial field profile)
- BaO: Large plasma size, 17m long, D~60cm (1kG: ~300 ρ_i, ~100 ρ_s)
- High repetition rate: 1 Hz
- US NSF/DOE Basic Plasma Physics User Facility

http://plasma.physics.ucla.edu

LAPD BaO Plasma source

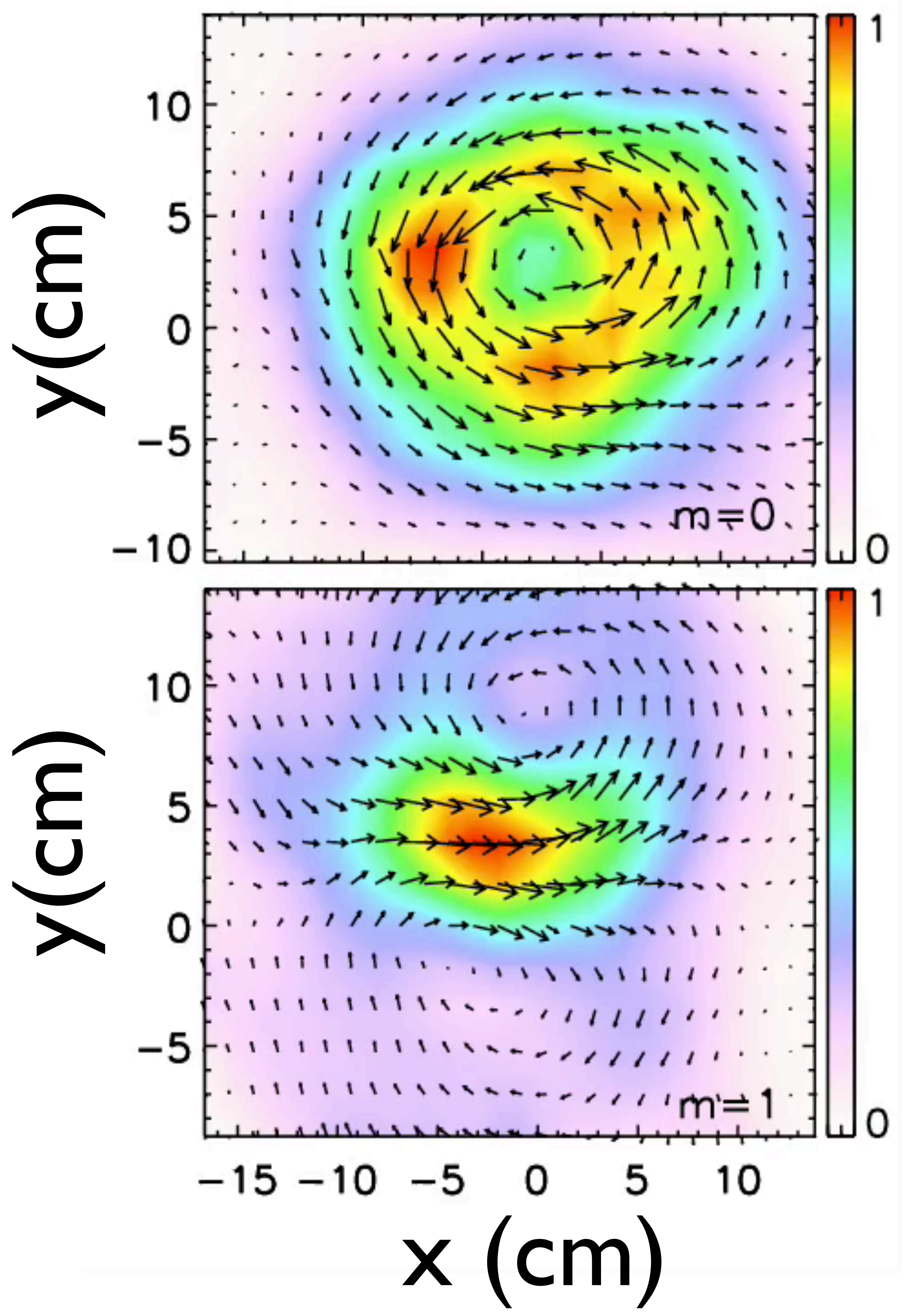




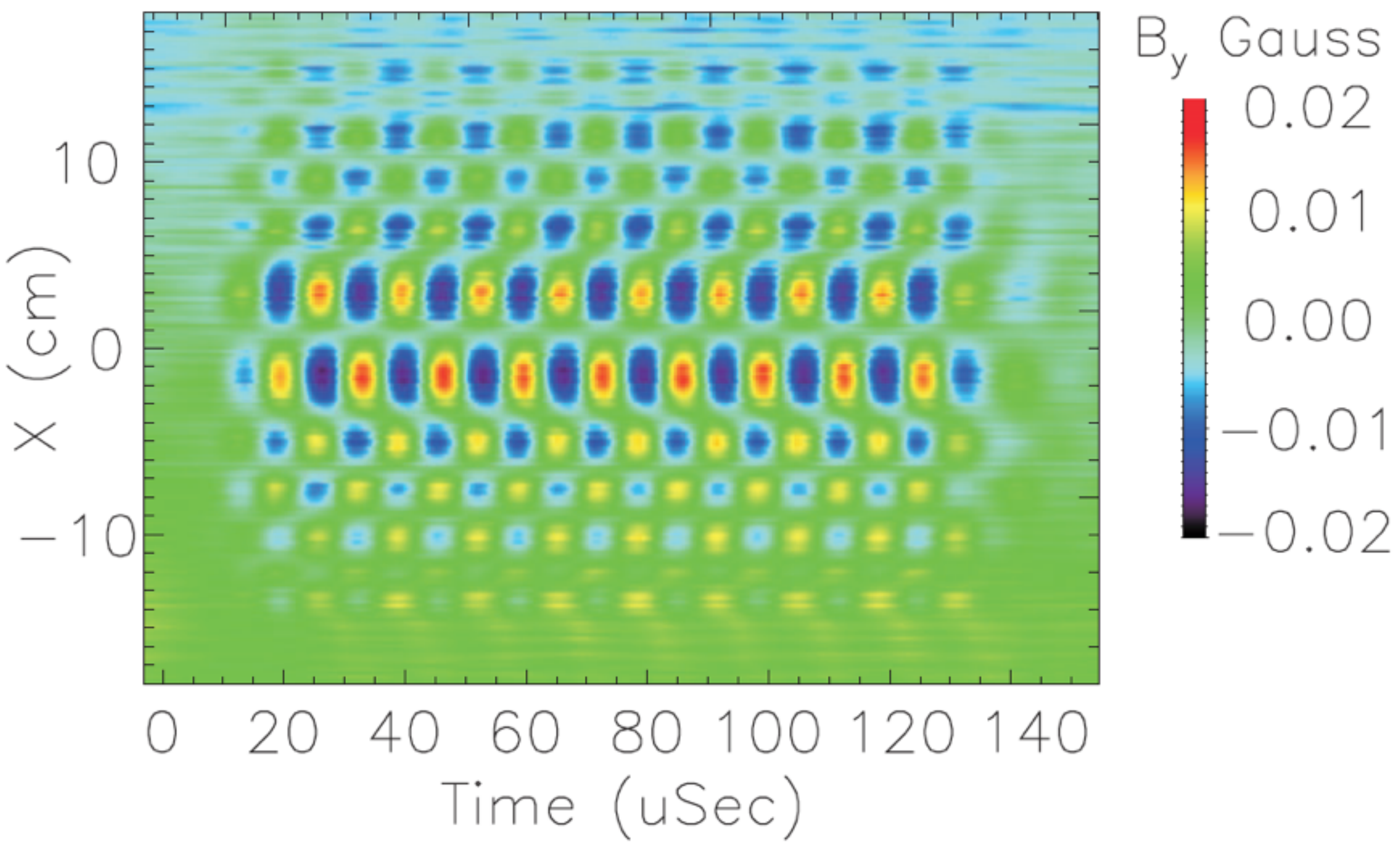
- Produces plasmas with 10-20 ms duration at 1 Hz rep rate
- Large quiescent core plasma (~60 cm diameter) for study of plasma waves, injection of ion/electron beams, etc.

Alfvén wave studies in LAPD

- LAPD's length set to enable AW research (to fit parallel wavelength (~few meters)). Examples:



Cylindrical AW eigenmodes, MASER produced
Maggs, et al., Phys. Plasmas 12, 013103 (2005)



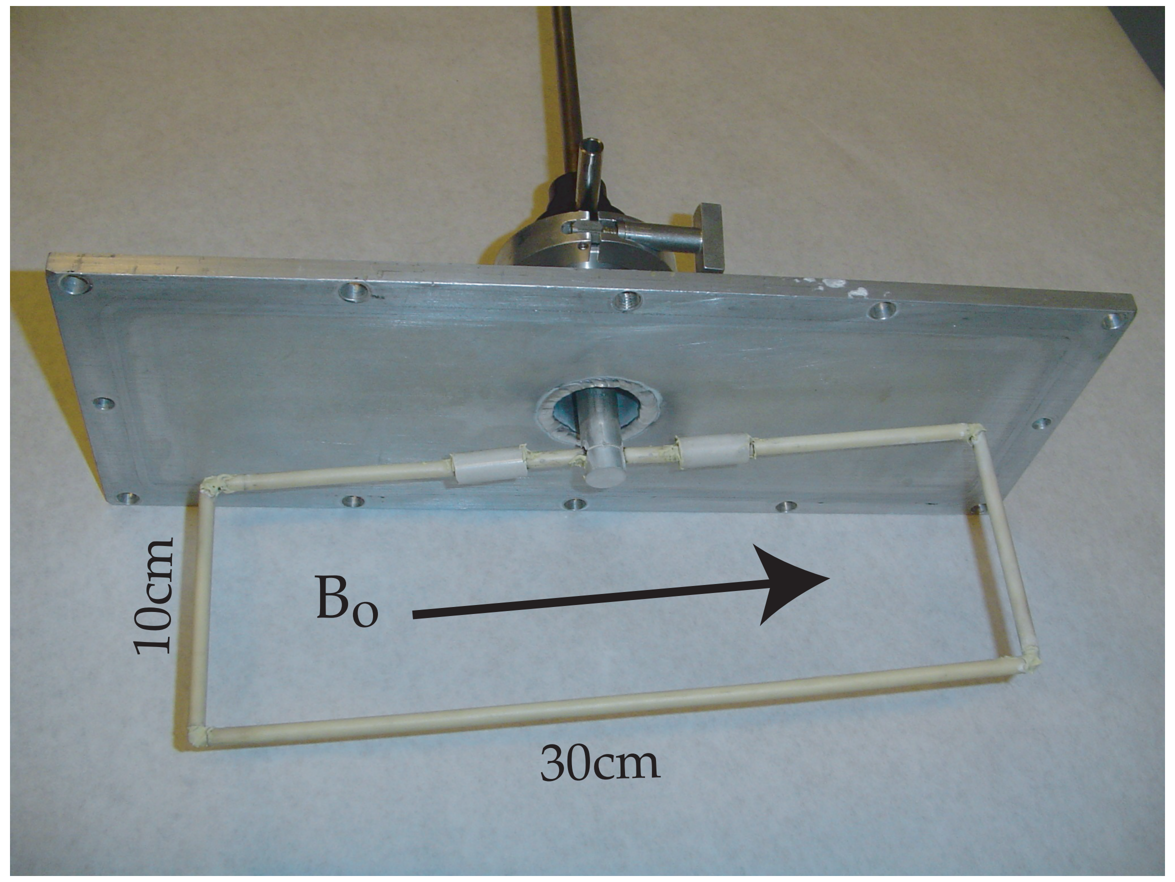
High $k_\perp$ kinetic Alfvén waves
Kletzing, et al, PRL 104, 095001 (2010)

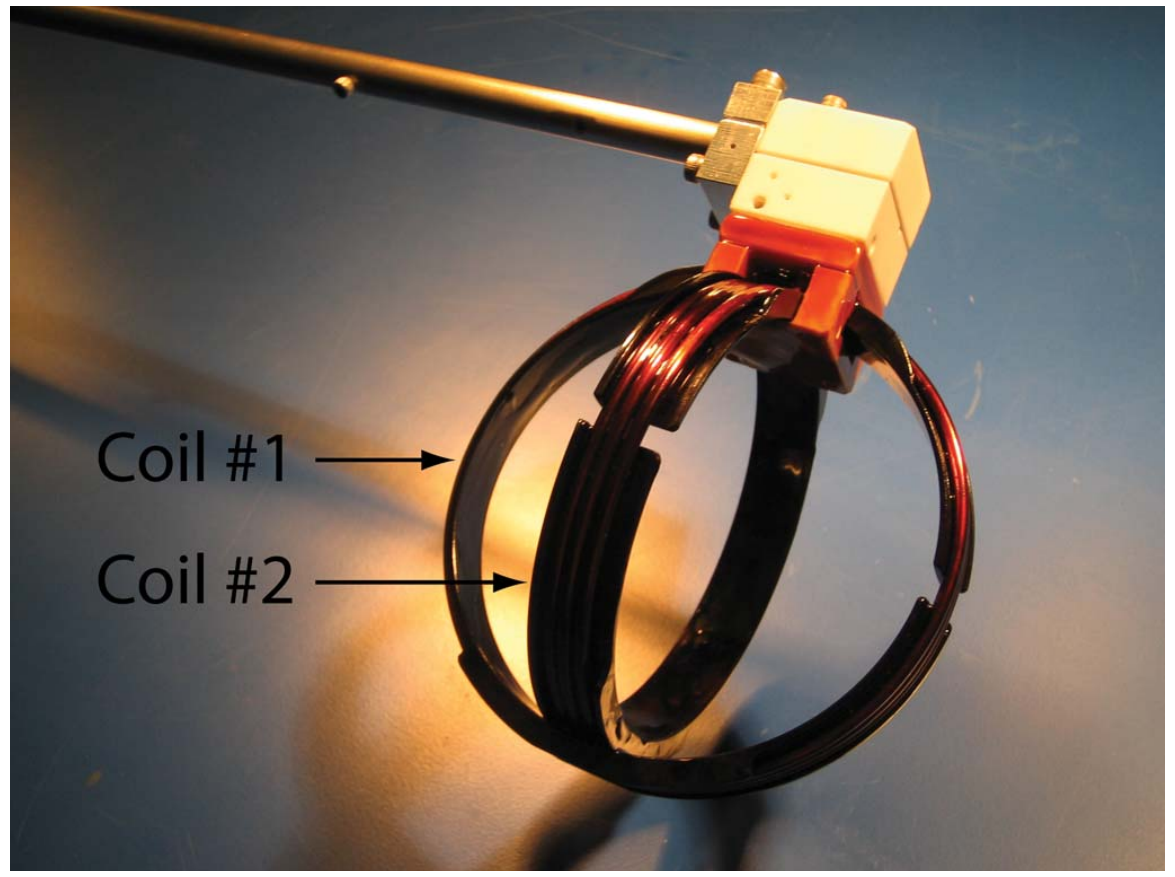
Review: Gekelman, et al., PoP 18, 055501, (2011)

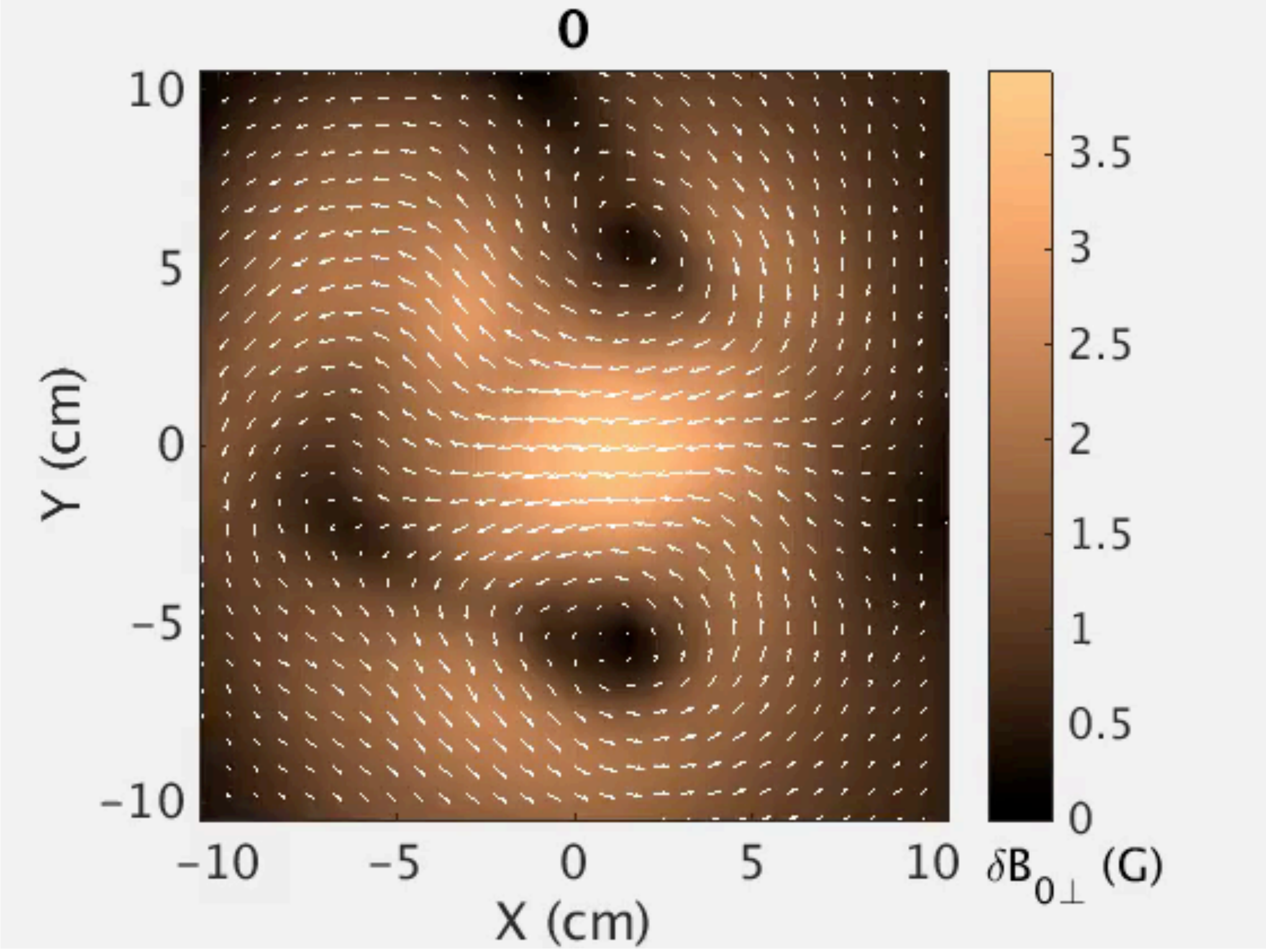
Nonlinear studies of Alfvén waves in LAPD

- Series of experiments exploring three-wave interactions and decay instabilities. Motivations include studying MHD turbulence in the lab
- Collision of two antenna-launched shear Alfvén waves:
  - Two co-propagating AWs produce a quasimode [Carter, et al., PRL, 96, 155001 (2006)]
  - Two co-propagating KAWs drive drift waves, lead to control/ suppression of unstable modes (in favor of driven stable mode) [Auerbach, et al., PRL, 105, 135005 (2010)]
  - Two counter-propagating AWs, one long wavelength ($k_\parallel \approx 0$), produce daughter AW (building block of MHD turbulent cascade) [Howes, et al., PRL, 109, 255001 (2012)]
  - Two counter-propagating AWs nonlinearly excite an ion acoustic wave [Dorfman & Carter, PRL, 110, 195001 (2013)]
- Parametric instability of single large-amplitude shear wave [Dorfman & Carter, PRL, 116, 195002 (2016)]

Large amplitude Alfvén wave generation



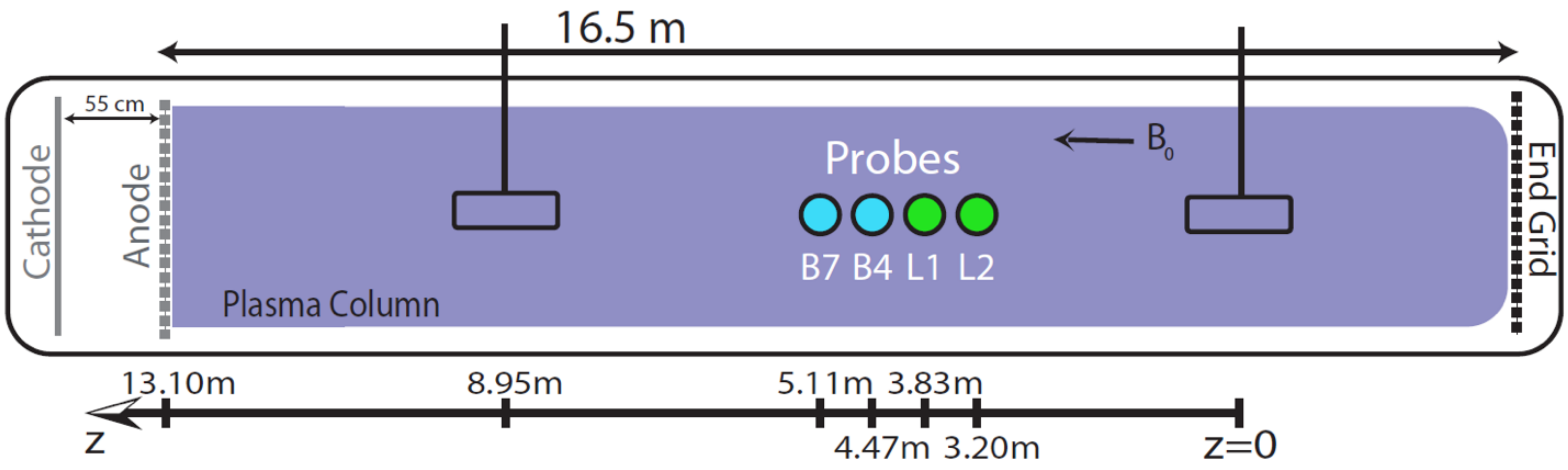




- Antennas can generate AWs with δB/B ~ 1% (~10G or 1mT); large amplitude from several points of view:
  - Wave beta is of order unity $\beta_w = \frac{2\mu_o p}{\langle \delta B^2 \rangle} \approx 1$
  - Wave Poynting flux ~ 200 kW/m^2, same as discharge heating power density
  - From GS theory: stronger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

Nonlinear excitation of sound waves by AWs

- Study three-wave process at heart of parametric decay by interacting two frequency-detuned, counter-propagating AWs



[Dorfman & Carter, PRL 110, 195001 (2013)]

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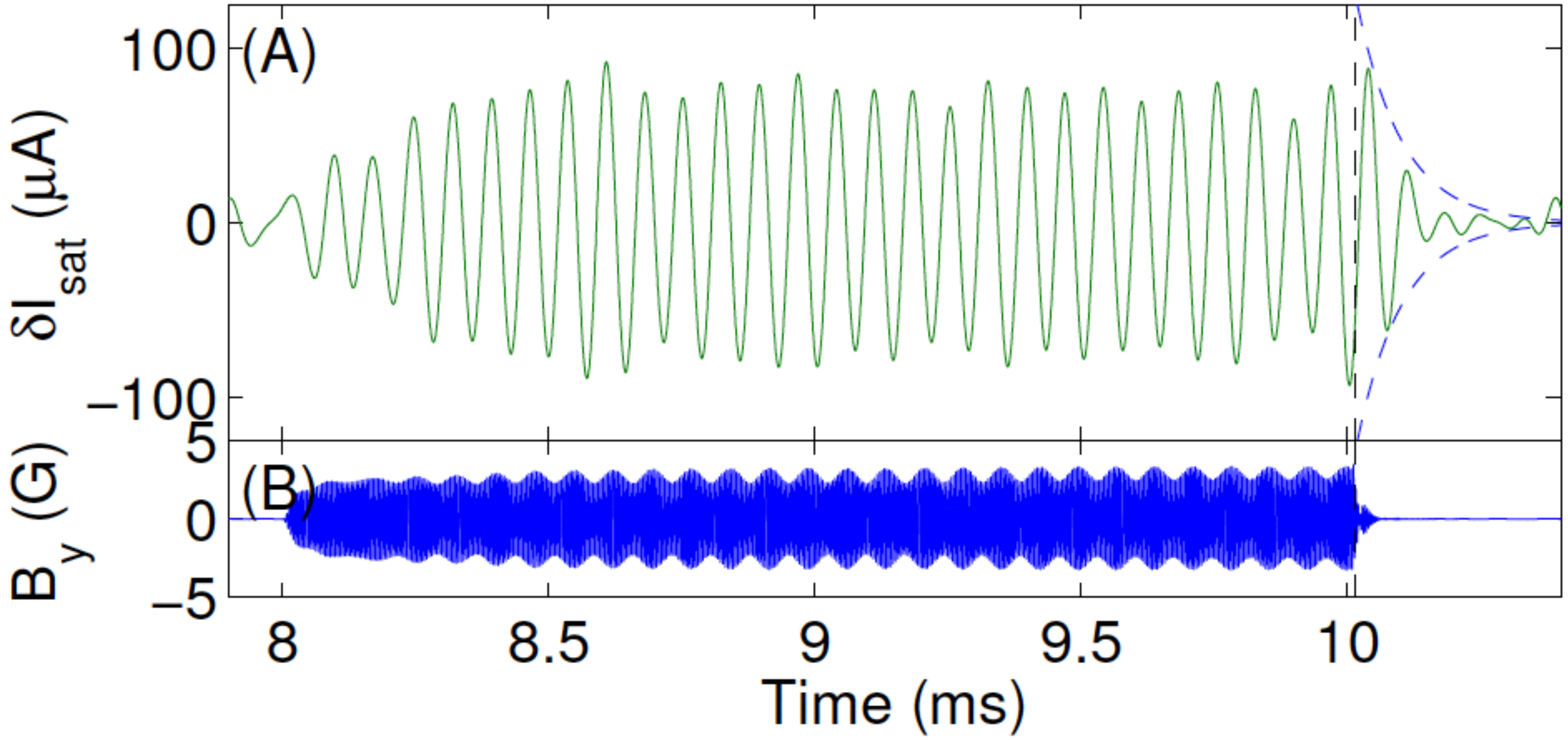
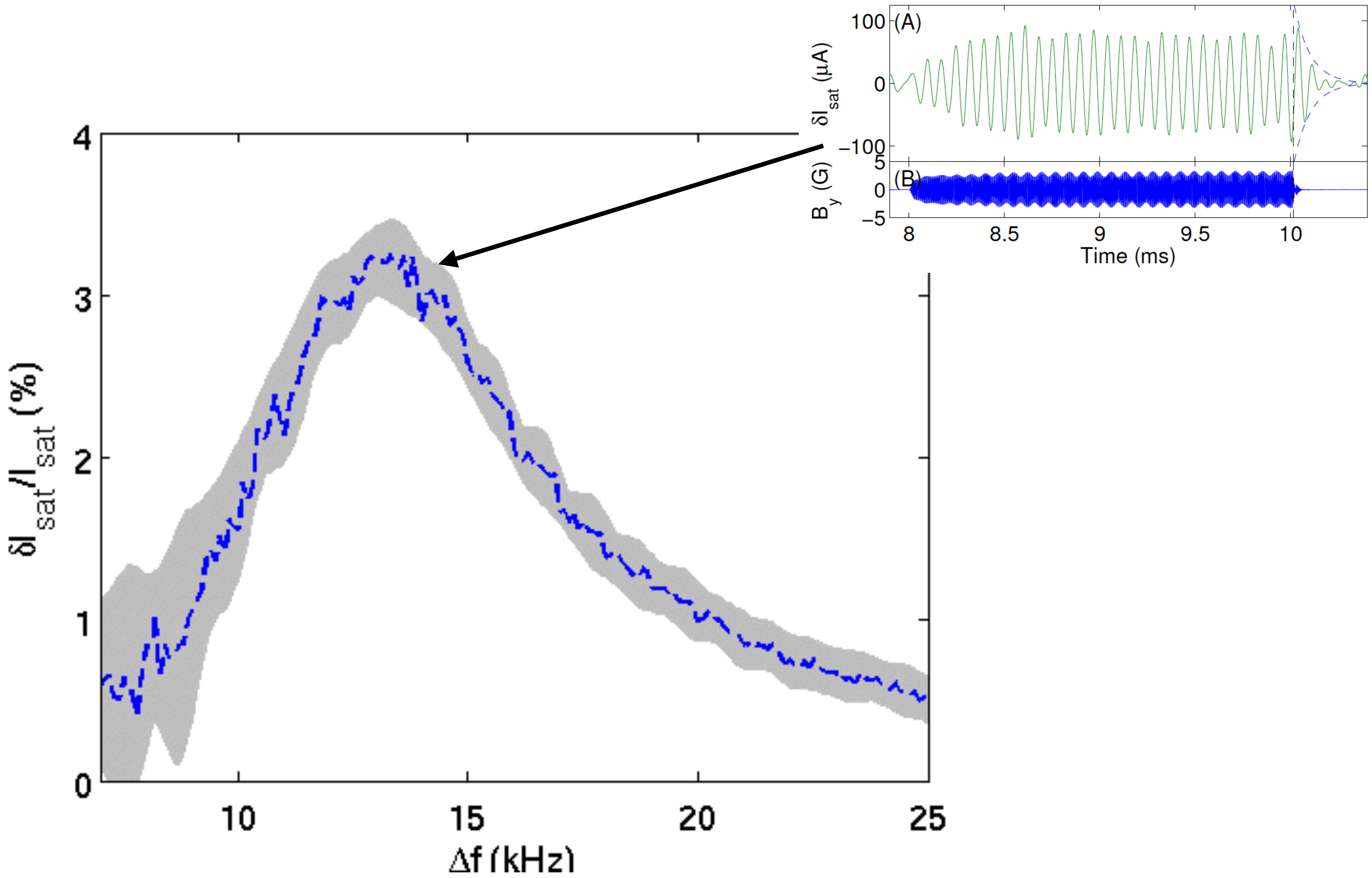


- Nonlinear response at beat frequency observed; response persists after nonlinear drive is turned off: evidence for excitation of damped linear wave

[Dorfman & Carter, PRL 110, 195001 (2013)]

Variation of nonlinear response with beat frequency: consistent with resonance with linear wave



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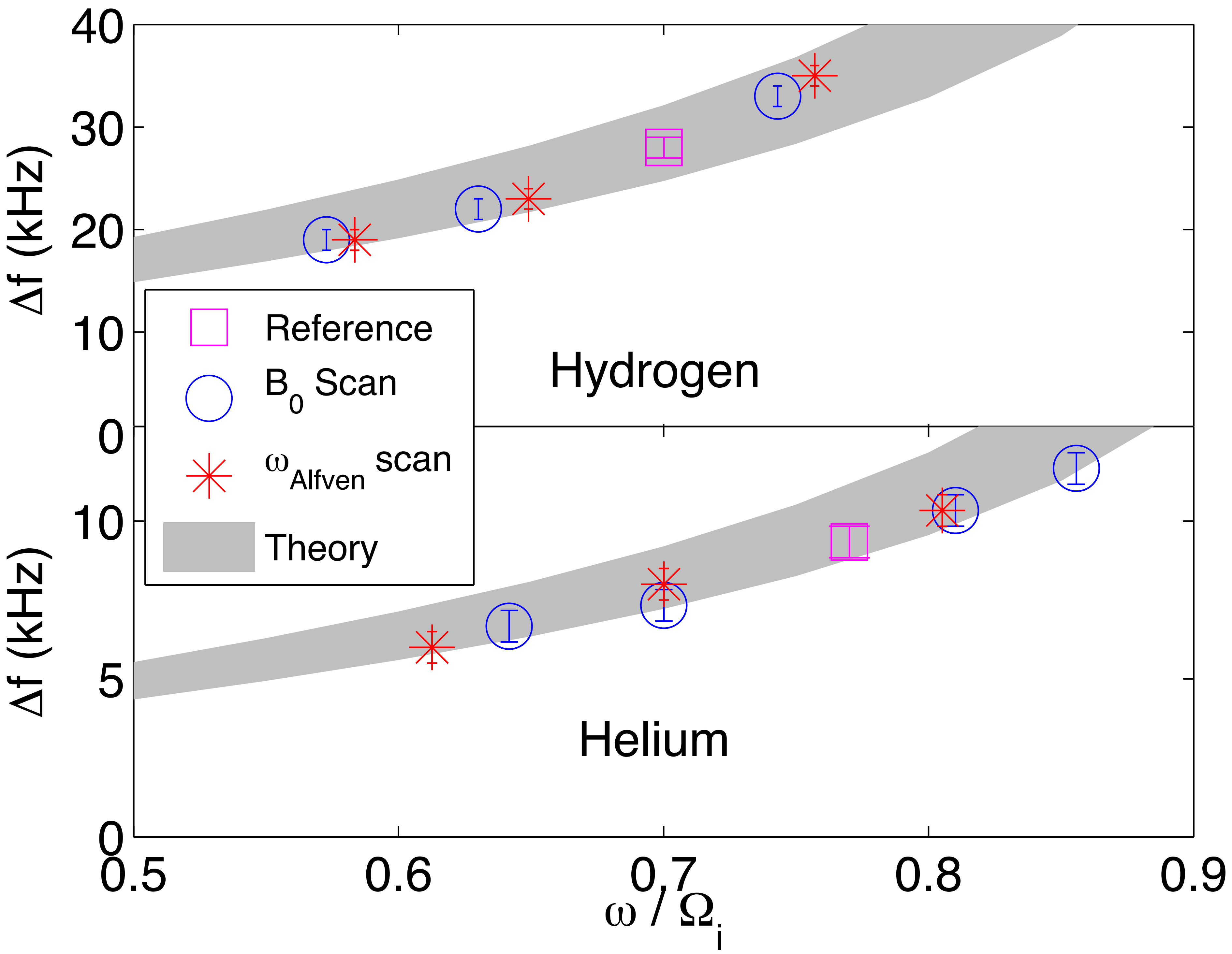
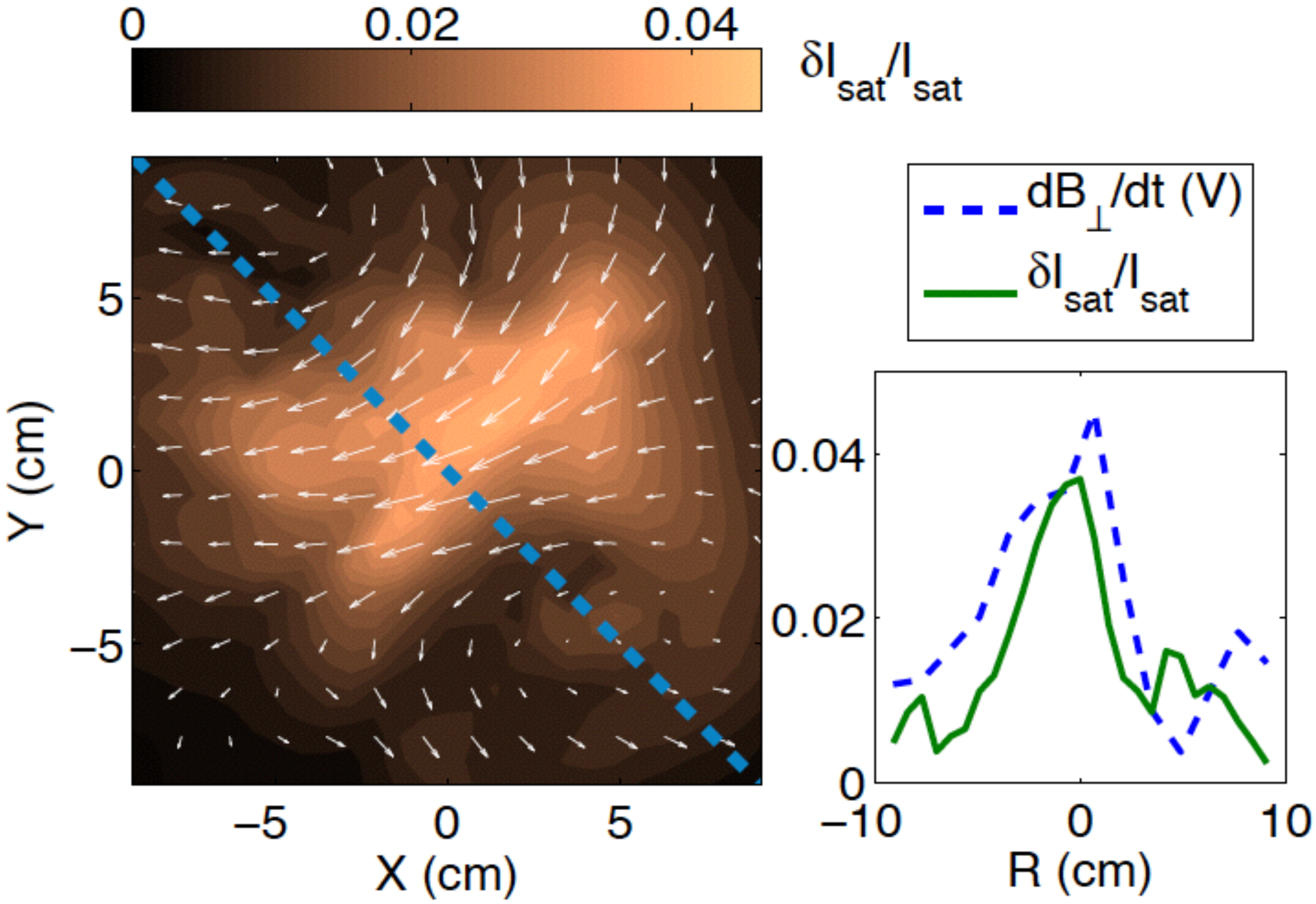


$$\Delta\omega = \frac{2\omega\sqrt{\beta}}{\sqrt{1 + (k_\perp \rho_s)^2 - \left(\frac{\omega}{\Omega_i}\right)^2}}$$

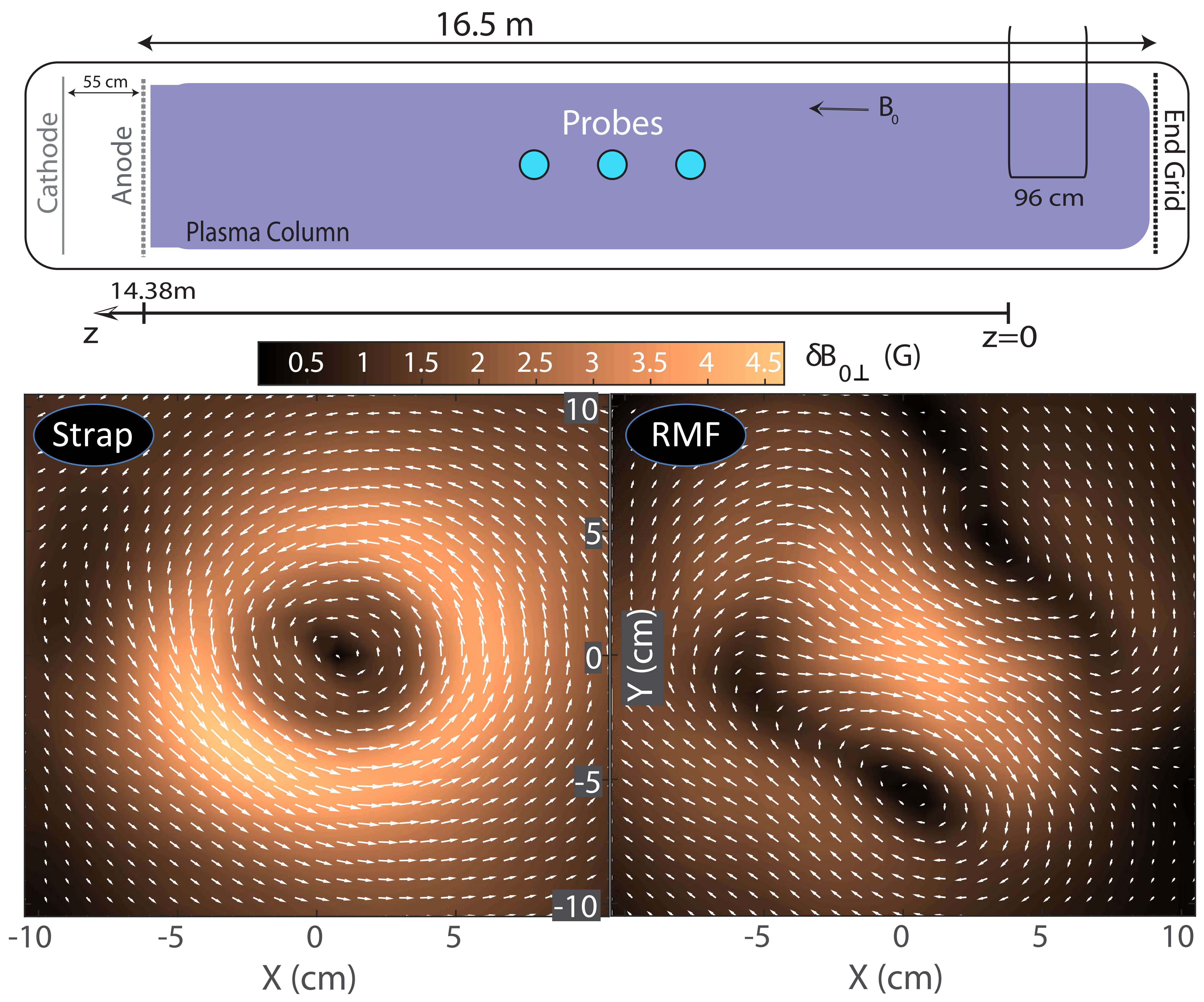
- Beat-wave response peaks at beat frequency consistent with simple fluid model (three-wave matching KAW + KAW → Sound Wave)
- Direct measurement of mode wavenumber confirms production of sound waves

Spatial pattern of driven wave consistent with parallel ponderomotive drive



- Driven mode peaks near spatial maximum of magnetic field fluctuation of beating Alfvén waves

Observation of a parametric instability of KAWs

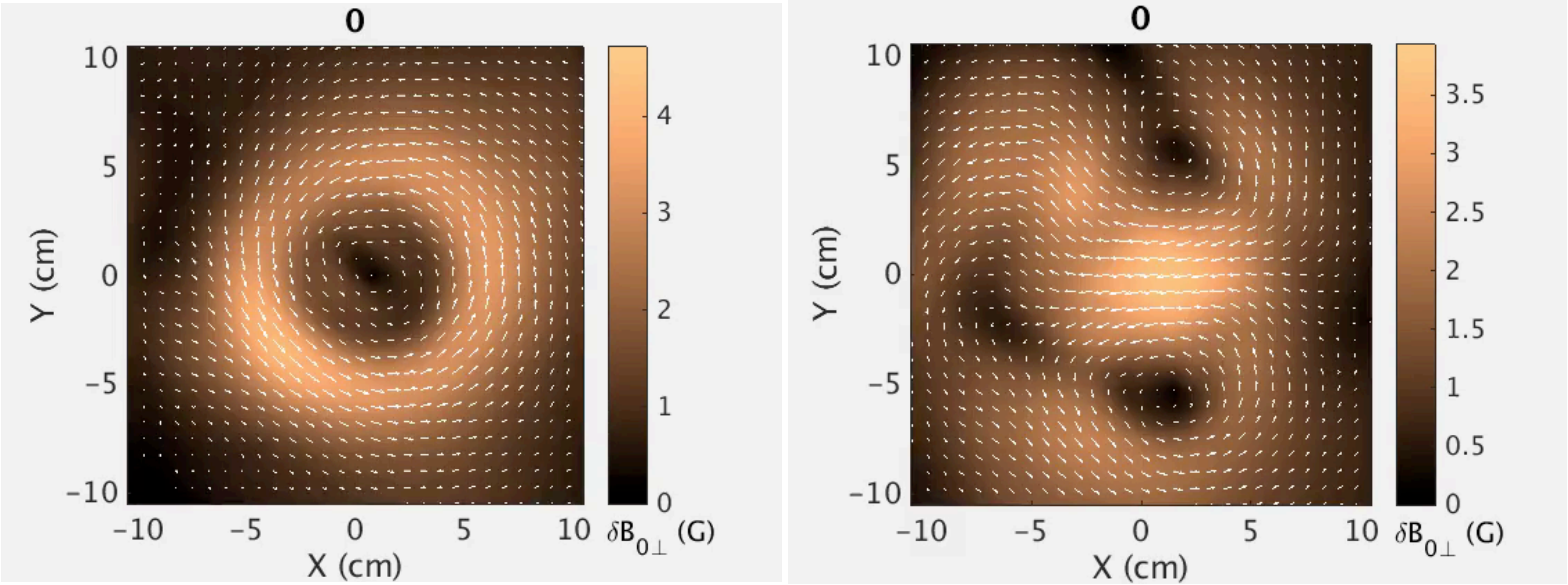


Pump wave spatial patterns (two different kinds of antennas)

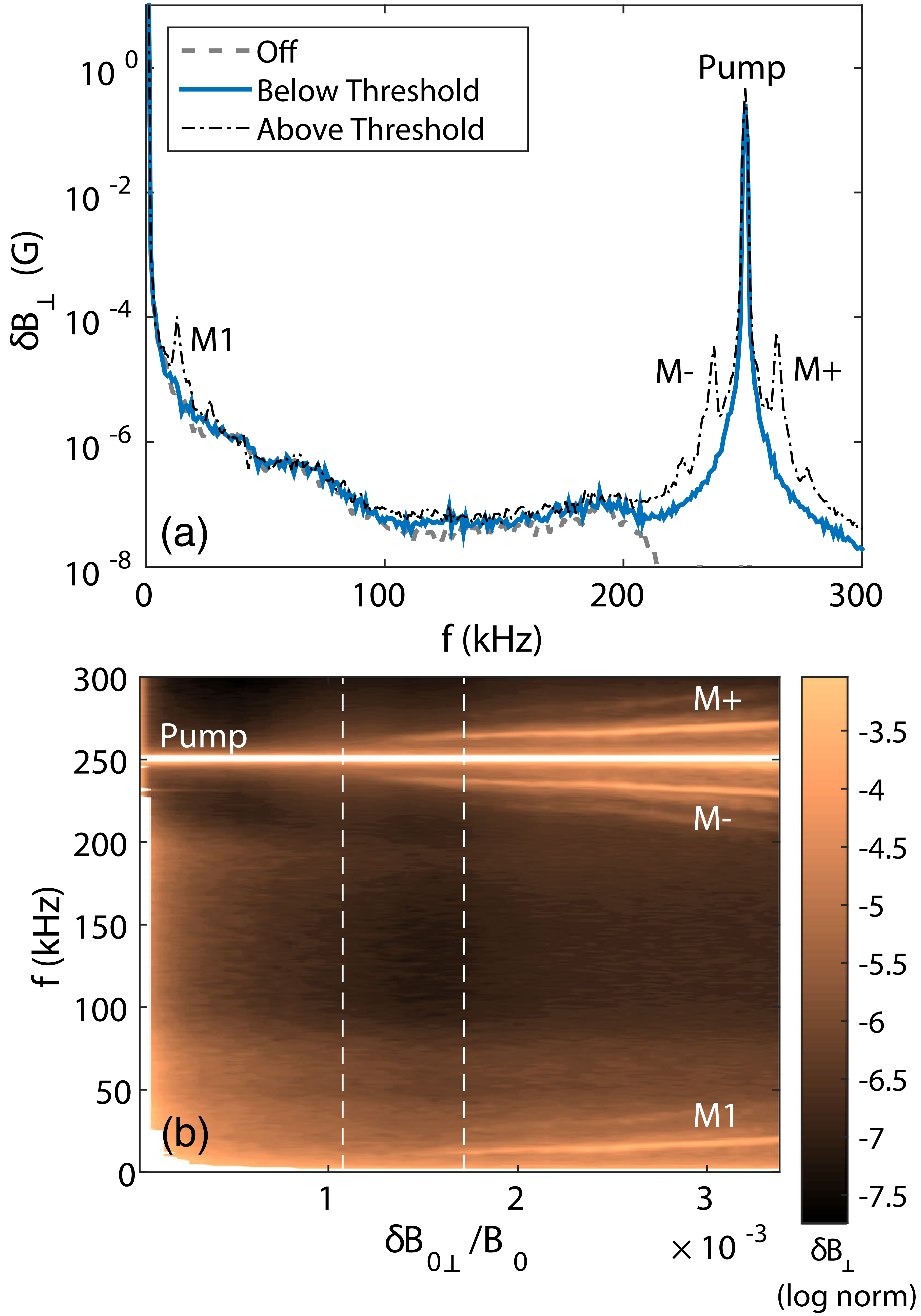
- Single, large amplitude KAW launched. Above an amplitude threshold and frequency, observe production of daughter modes.

[Dorfman & Carter, PRL, 116, 195002 (2016)]

Pump waves: linearly and circularly polarized

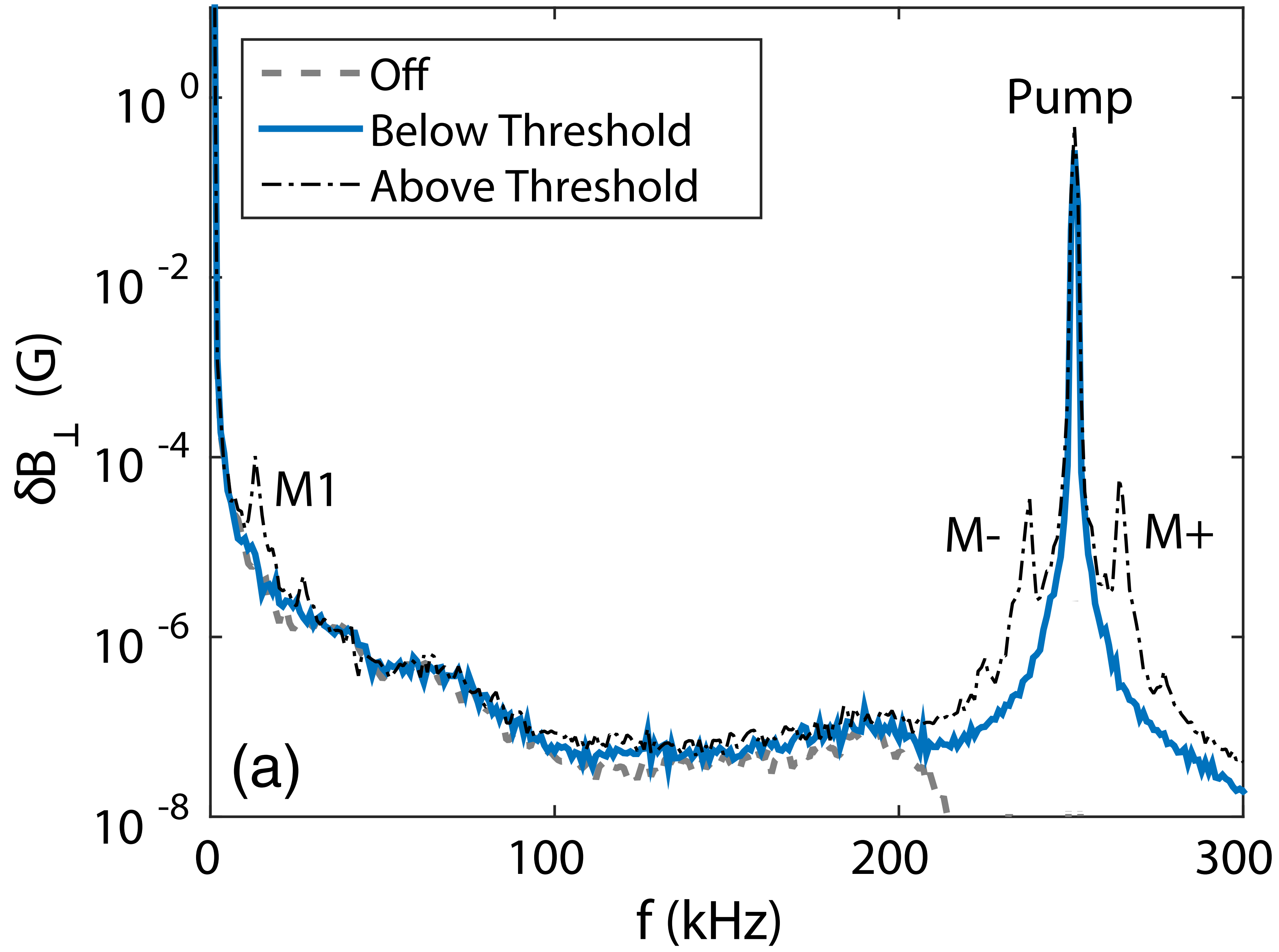


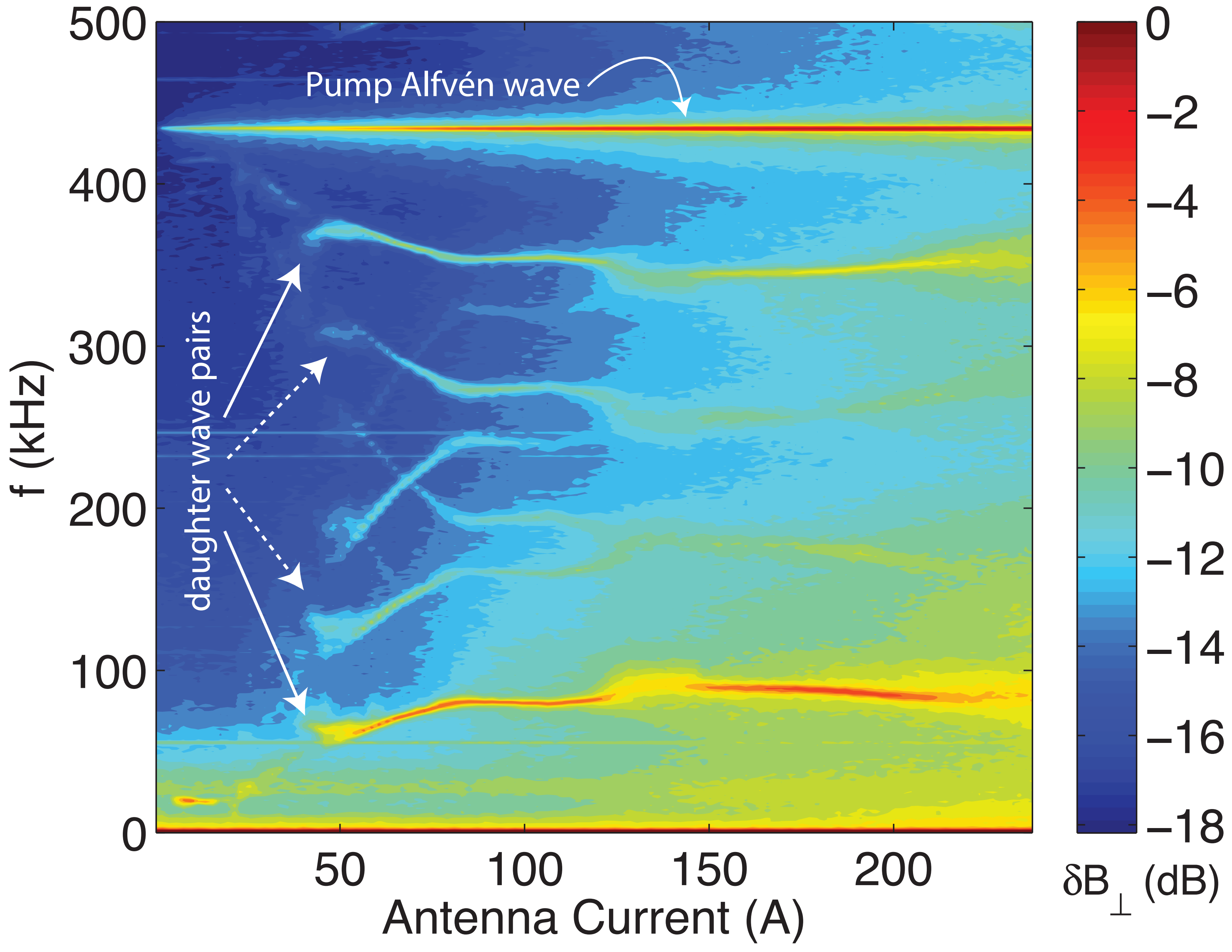
Production of sidebands and low frequency mode



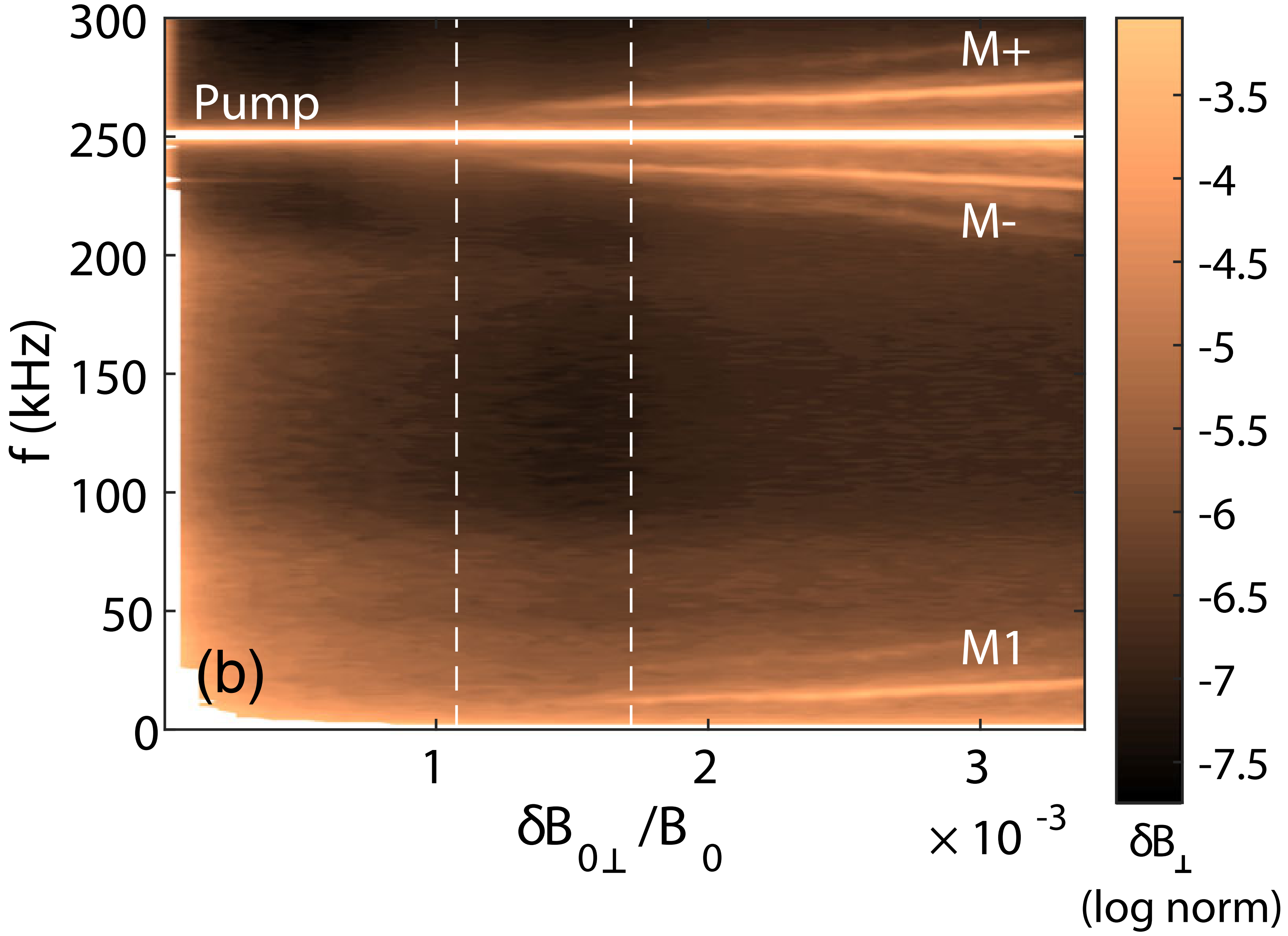
- Production of daughter waves observed: threshold both in wave amplitude and in frequency (only observed for $f \gtrsim 0.5\ f_{ci}$)
- All three daughter waves co-propagating with pump (need dispersive AWs)
  - Modes satisfy three-wave matching rules

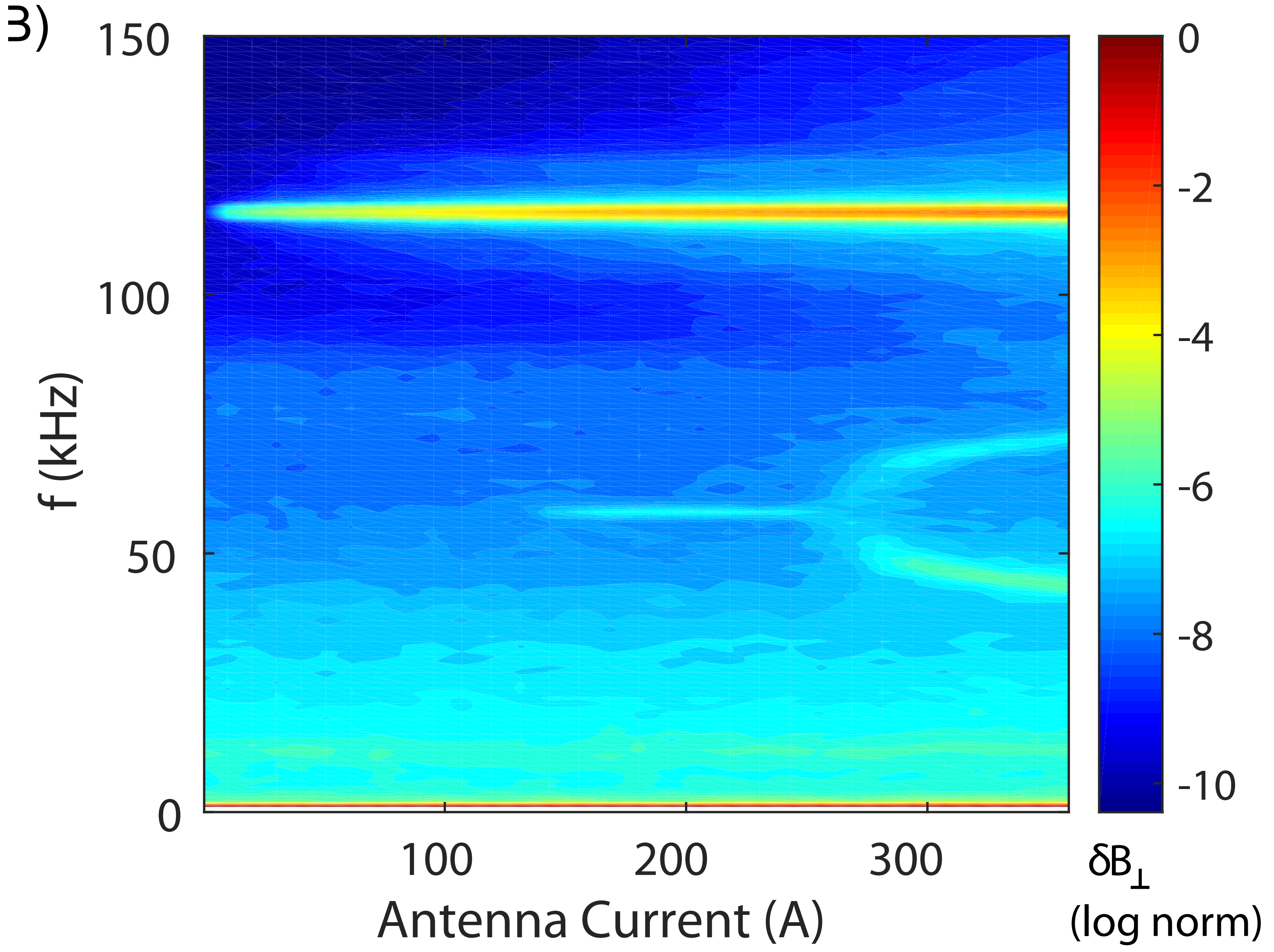
Production of sidebands and low frequency mode



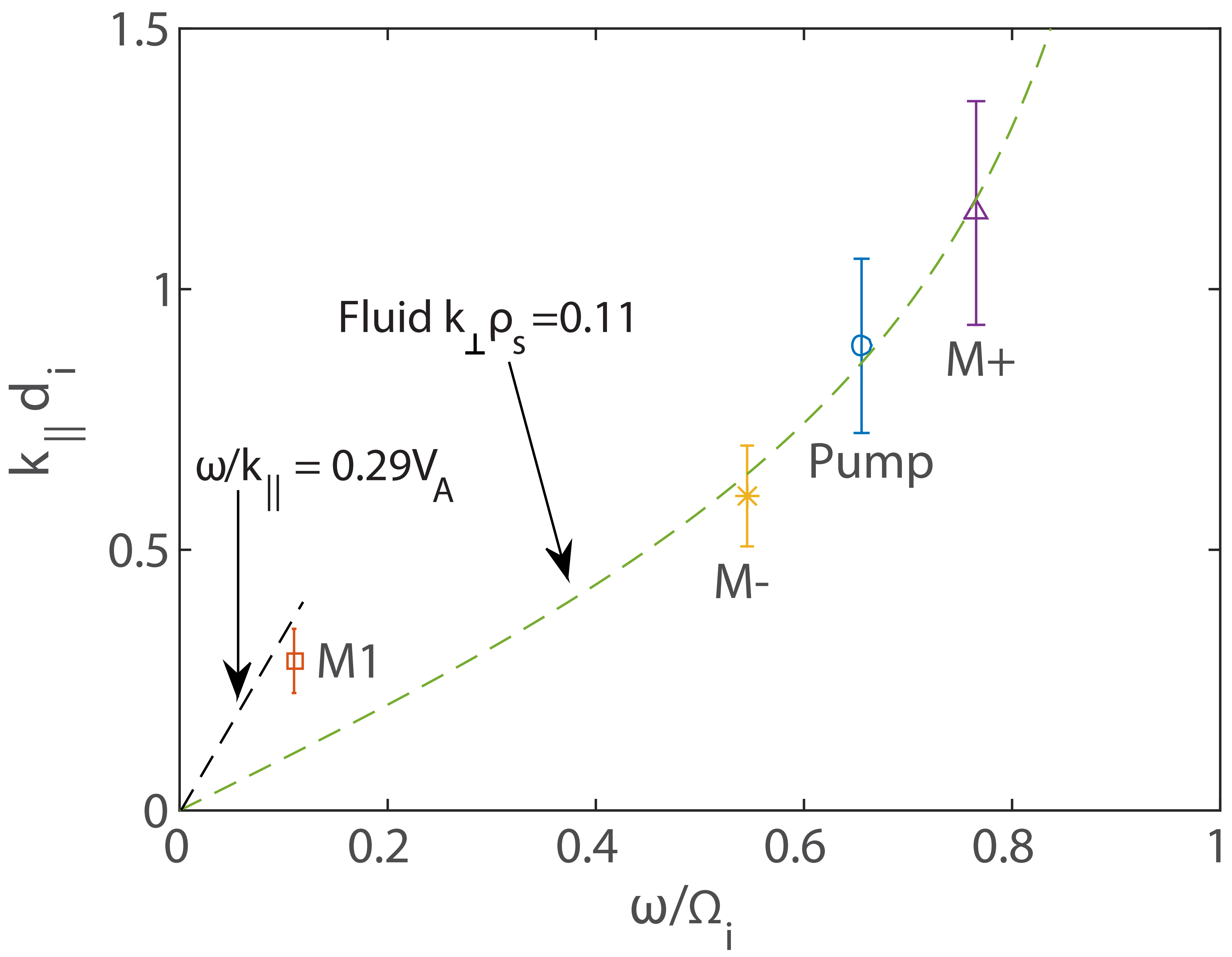


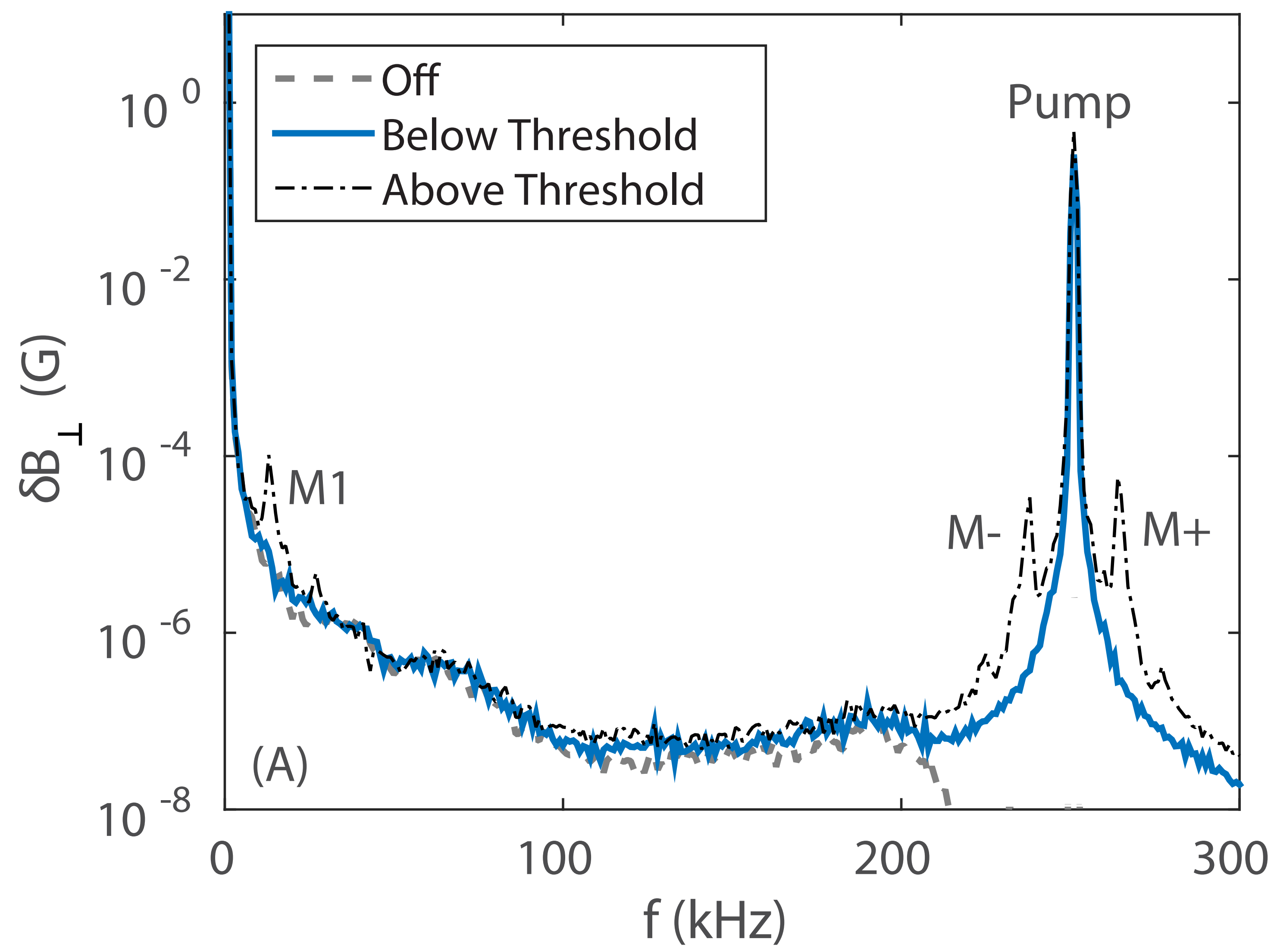
Variety of behaviors observed as plasma parameters are changed





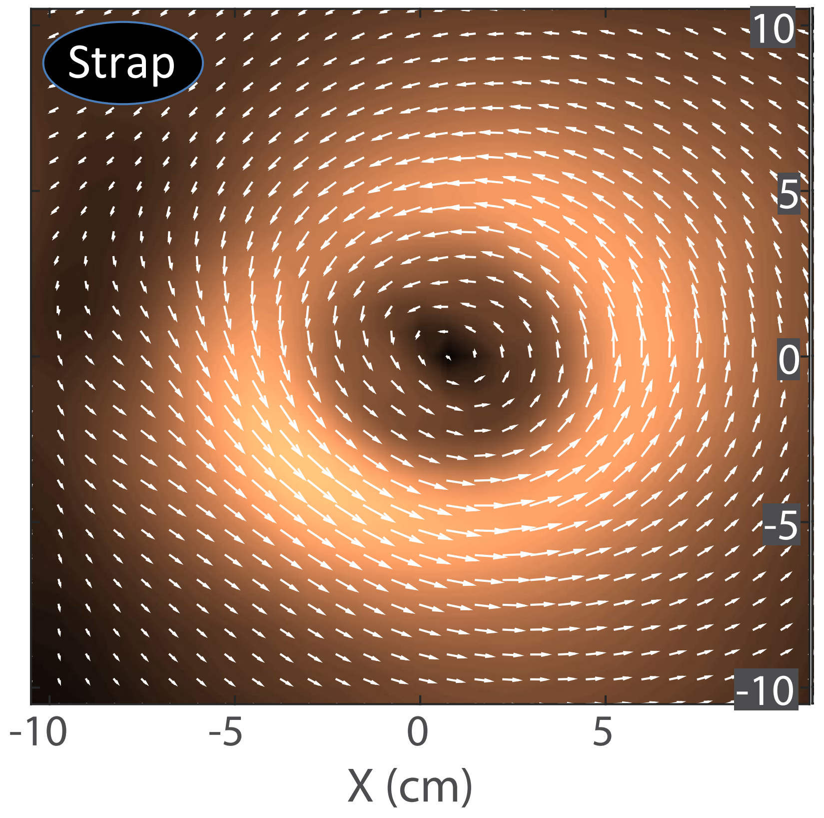
Sidebands are KAWs, low frequency mode is quasimode



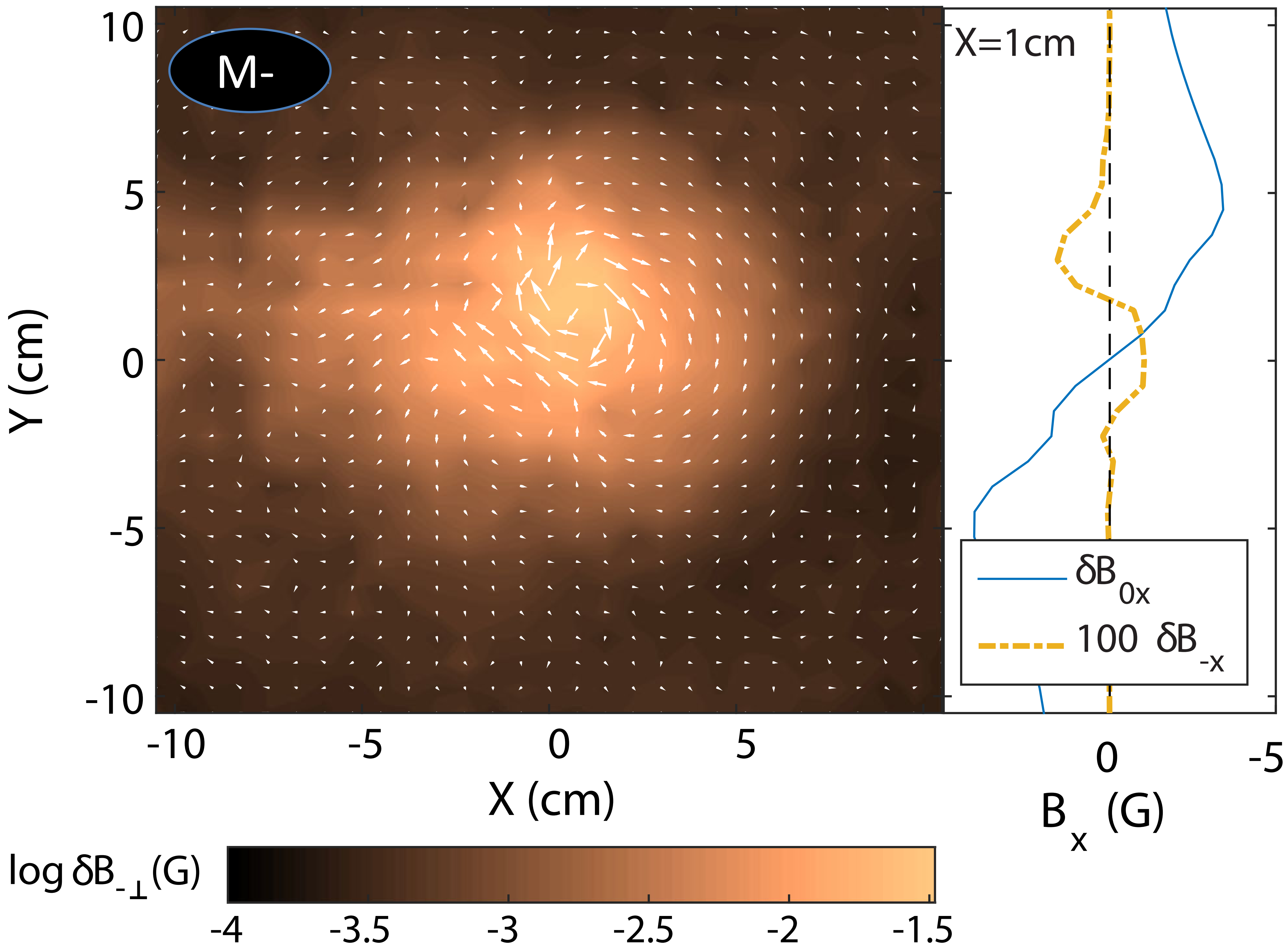


- Sideband waves are consistent with KAW dispersion relation
- Low frequency mode is a non-resonant mode/quasimode: phase speed inconsistent with sound wave or KAW
- Participant modes consistent with **modulation decay instability**

Daughter quasimode located on pump current channel, inconsistent with parallel ponderomotive drive



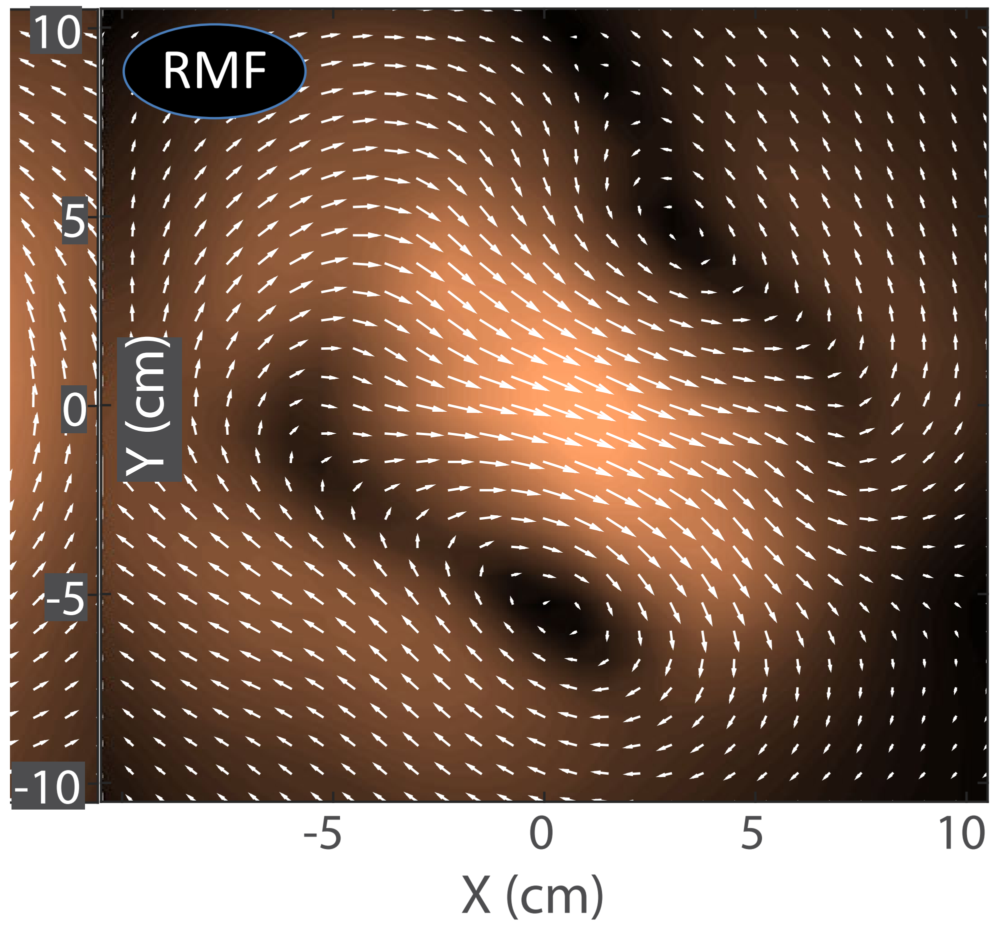
Pump



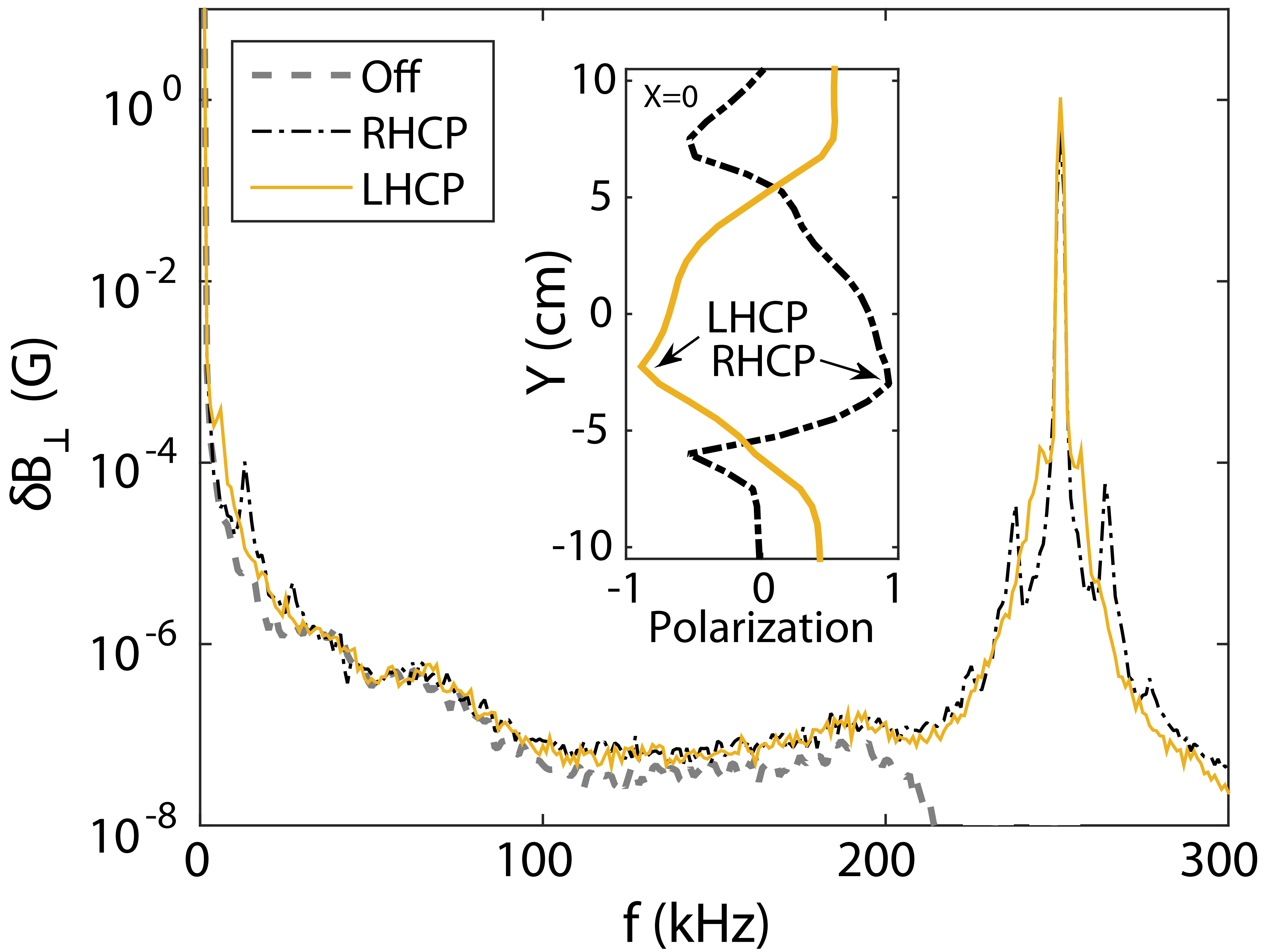
daughter

- Perpendicular nonlinearity? Importance of $k_\perp$ of pump, daughters

Parametric instability changes with pump polarization

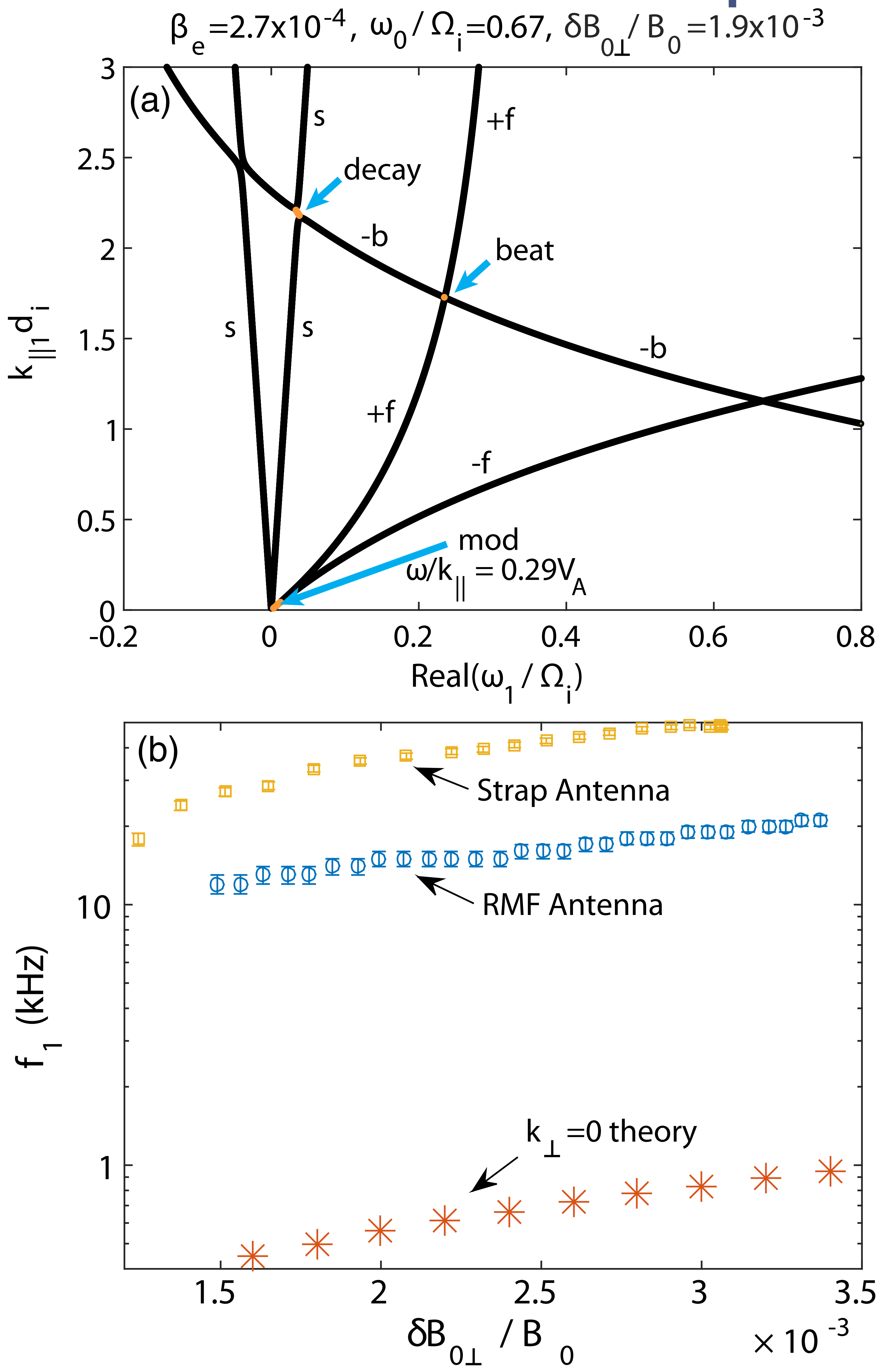


Pump



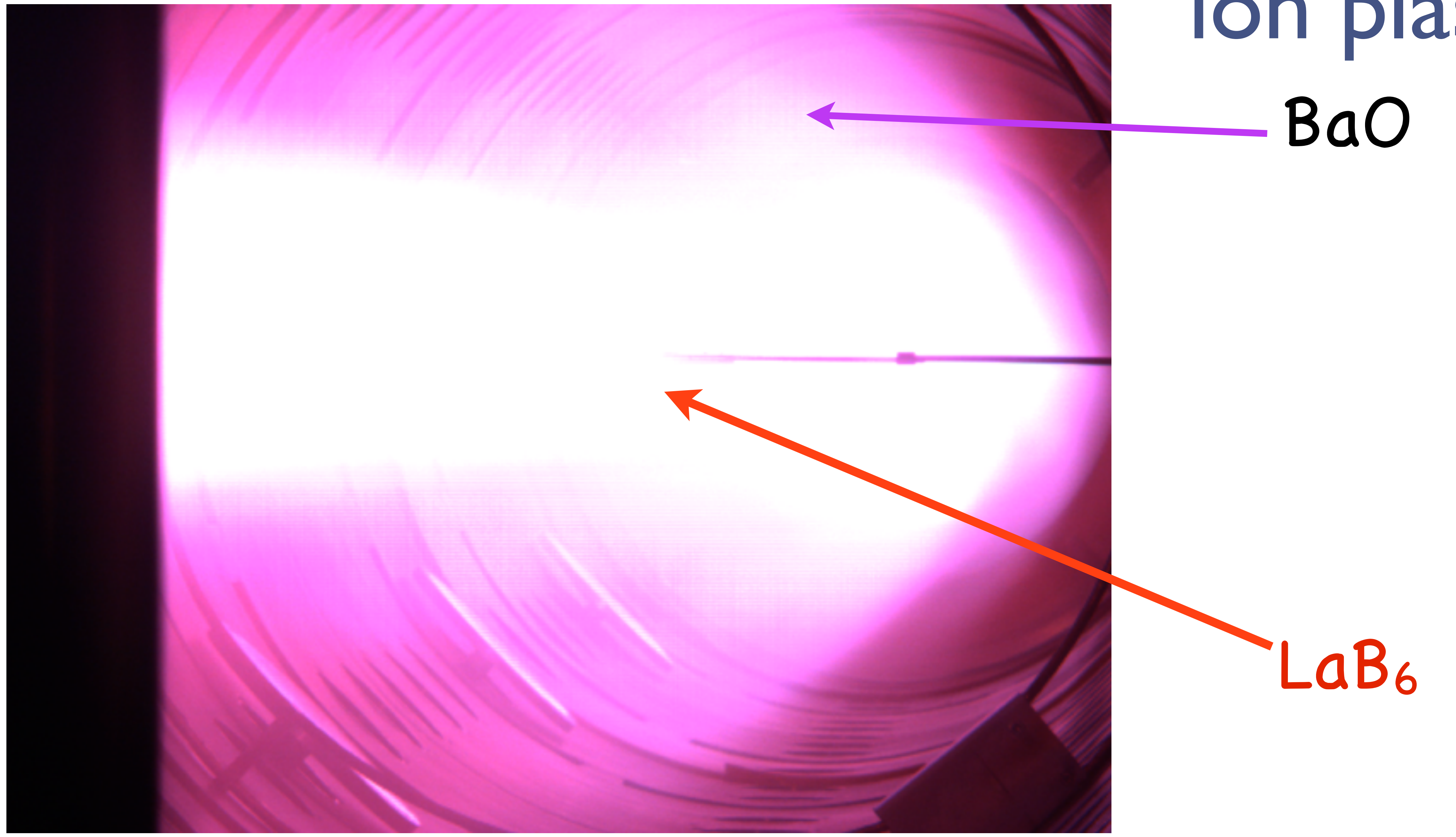
- "Rotating Magnetic Field" antenna: allows control of pump wave polarization (note: not purely CP/not a plane wave)
- Change in daughter frequency/amplitude with change from dominant LHCP to RHCP

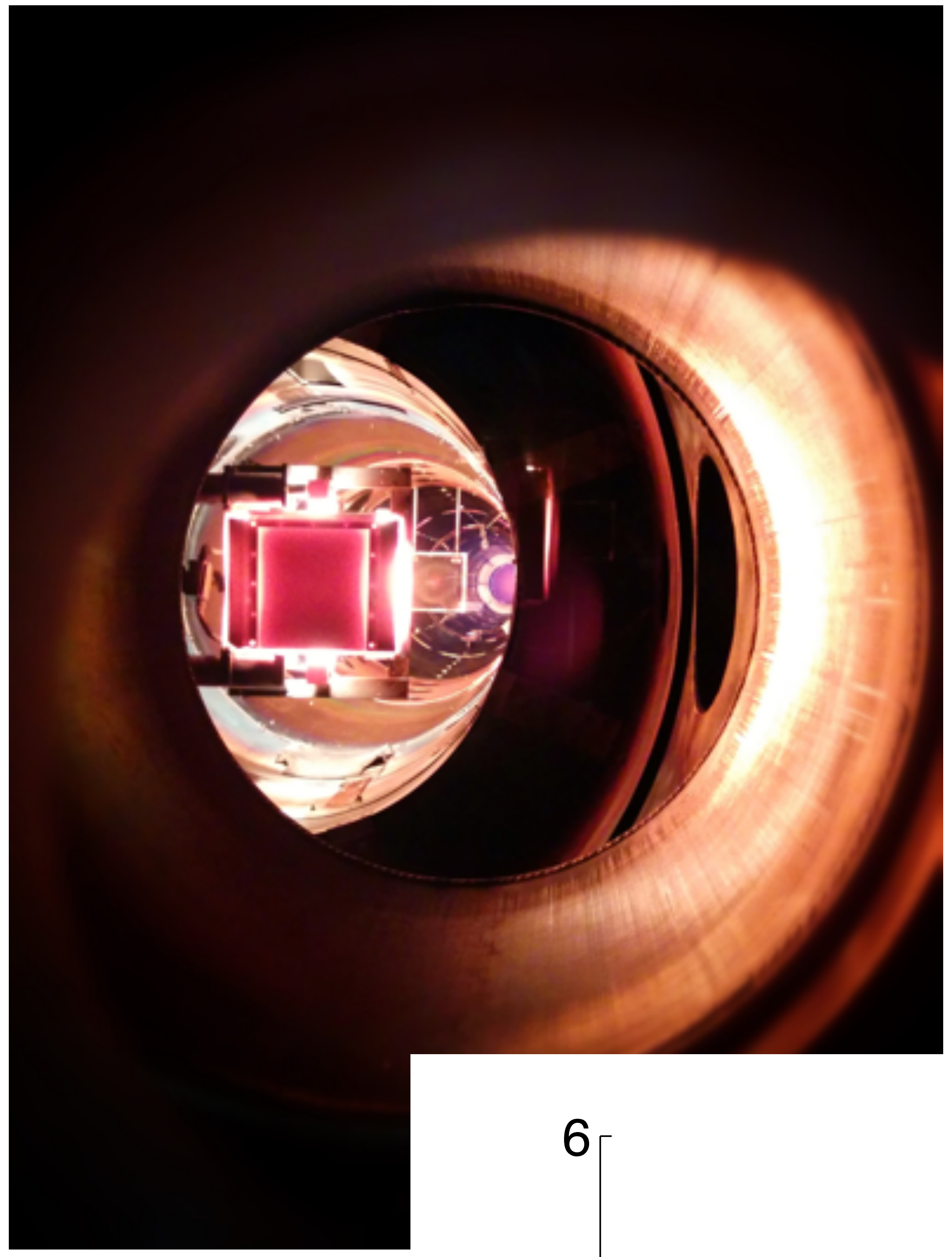
Theory: qualitatively consistent with $k_\perp$=0 modulation decay theory (with important quantitative differences)

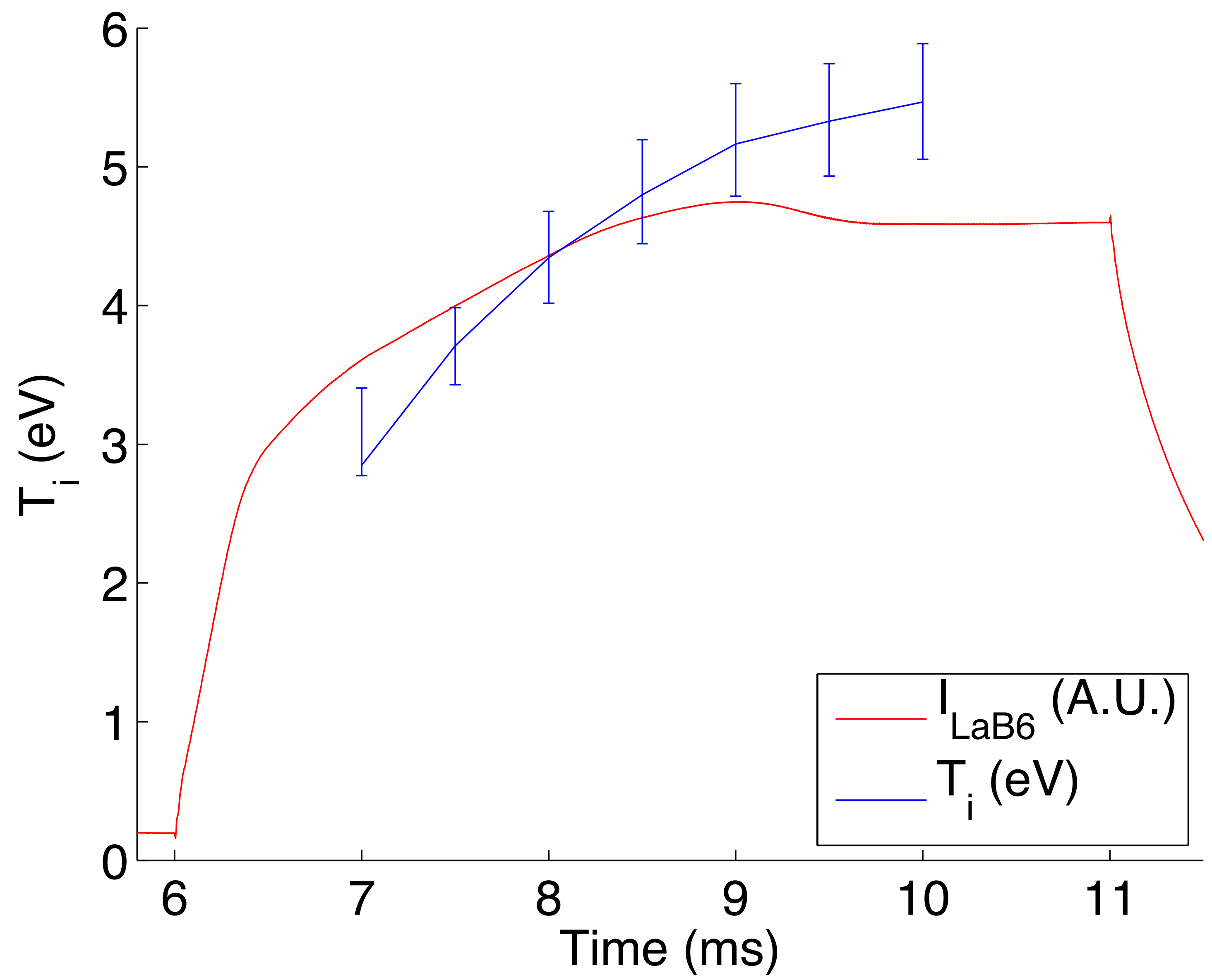


- Theory for $k_\perp$=0 parametric instabilities (Wong & Goldstein; Hollweg) solved for LAPD parameters
- Modulational decay instability predicted to be unstable with consistent phase velocity for M1 (low frequency daughter)
- Mode frequency and growth rate too low for experiment, but scales consistently with amplitude (importance of finite $k_\perp$?)
- Parametric decay (sound wave production) predicted to have higher growth rate but we have not observed it!

New plasma source enables study of much higher pressure (high β), warm ion plasmas





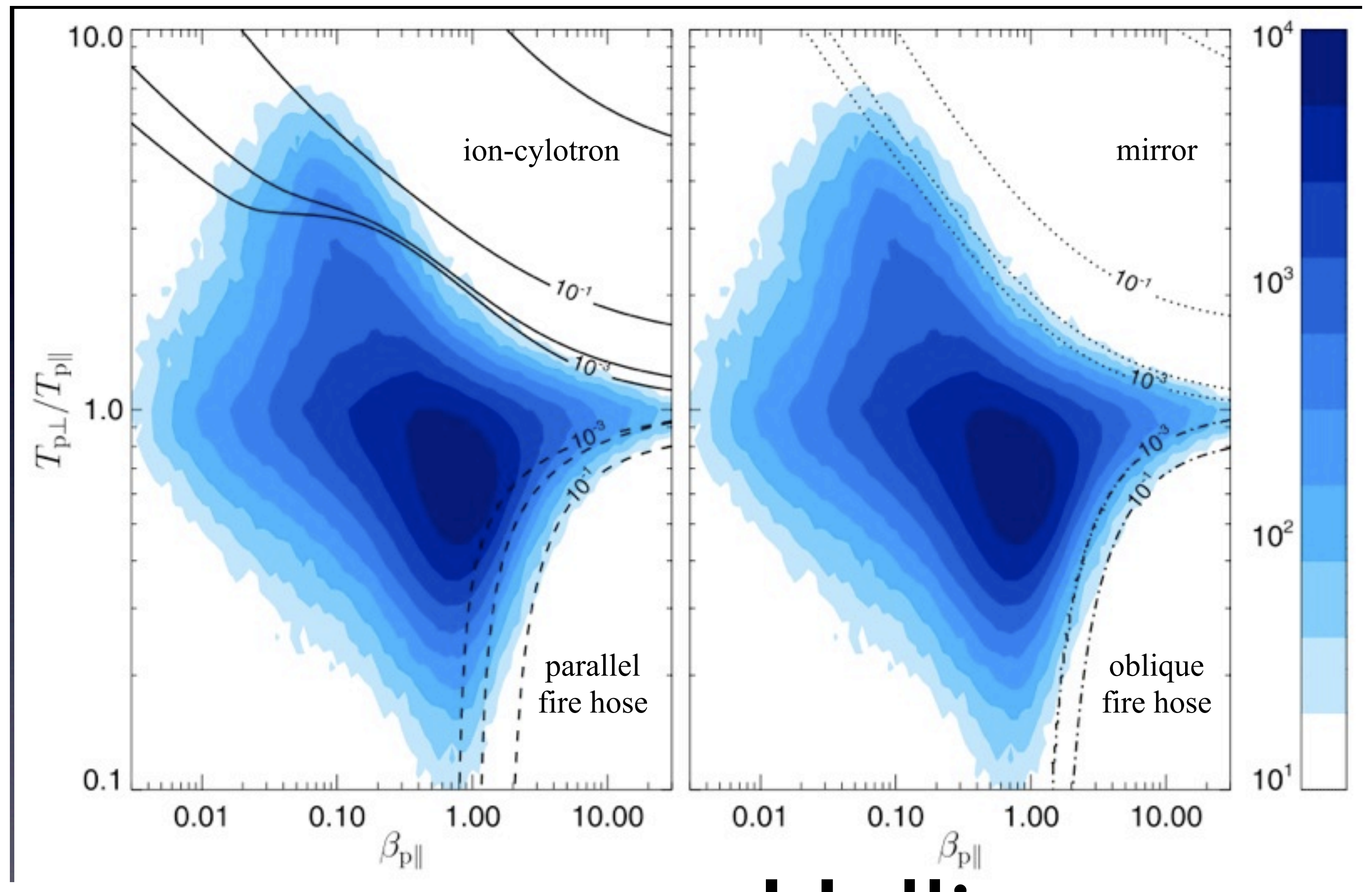


- Second source: LaB6 cathode (1800K) much better electron emitter (smaller ~20cm square source at opposite end)
- Order of magnitude increase in density, hotter electrons and ions (through collisional coupling)
- With lowered field, can get magnetized plasmas with β ~ 1

Solar wind campaign: physics of high beta, warm ion plasmas

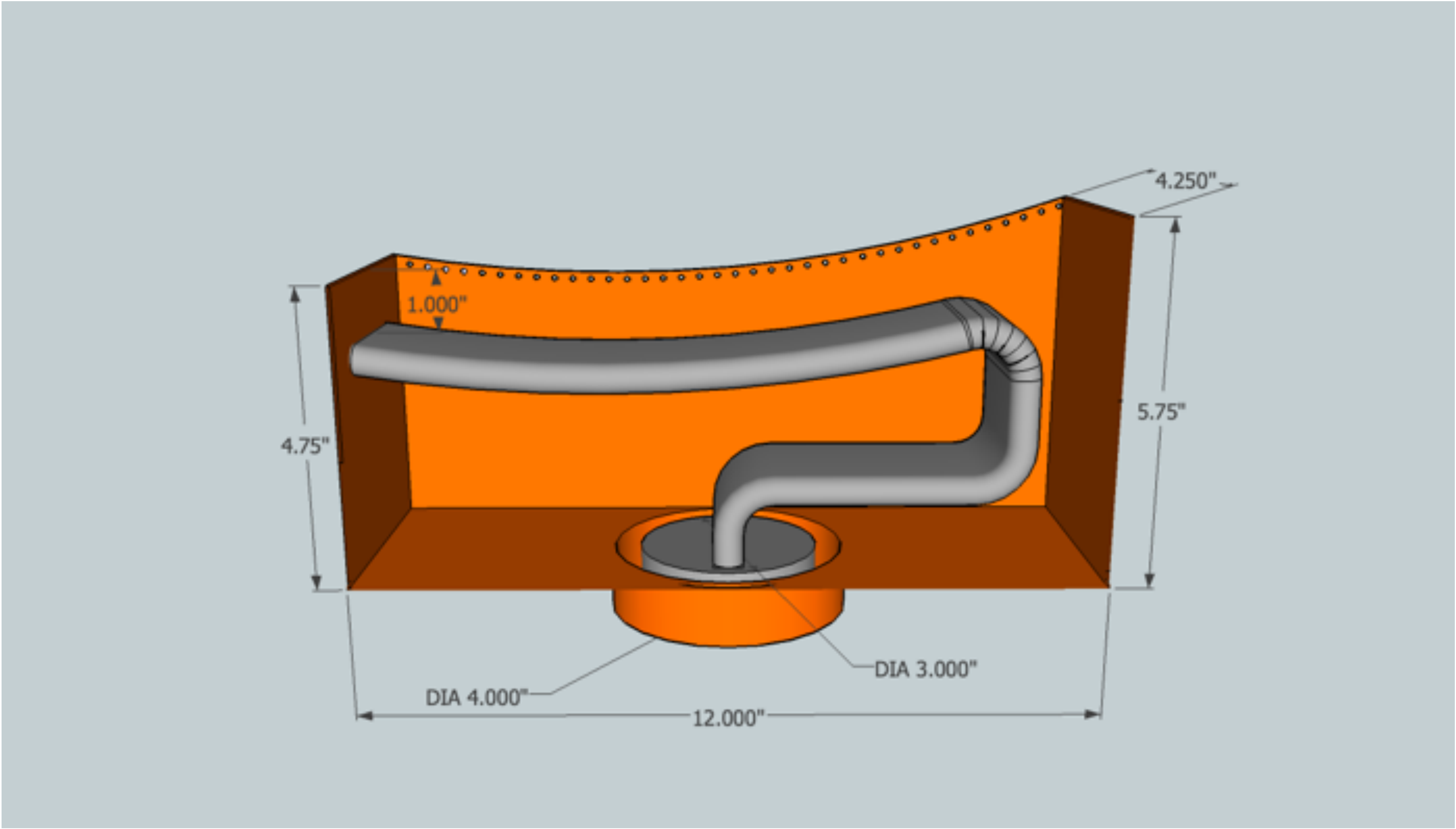
- Kinetic instabilities, waves and turbulence at high plasma beta ($v_A \sim v_{th,i}$) with warm ions
- Warm ions provide opportunity to study ion kinetic effects in waves and instabilities: e.g. FLR effects on Alfvén wave propagation; ion cyclotron absorption; modification to nonlinear Alfven wave interactions
- With lower field, plasma beta can be increased substantially to study, e.g., modifications to Alfvén wave dispersion and damping (e.g. ion Landau/Barnes damping). **Can temperature anisotropy driven instabilities (mirror and firehose) be observed in these plasmas?**

Campaign Leader: Greg Howes (U. Iowa)

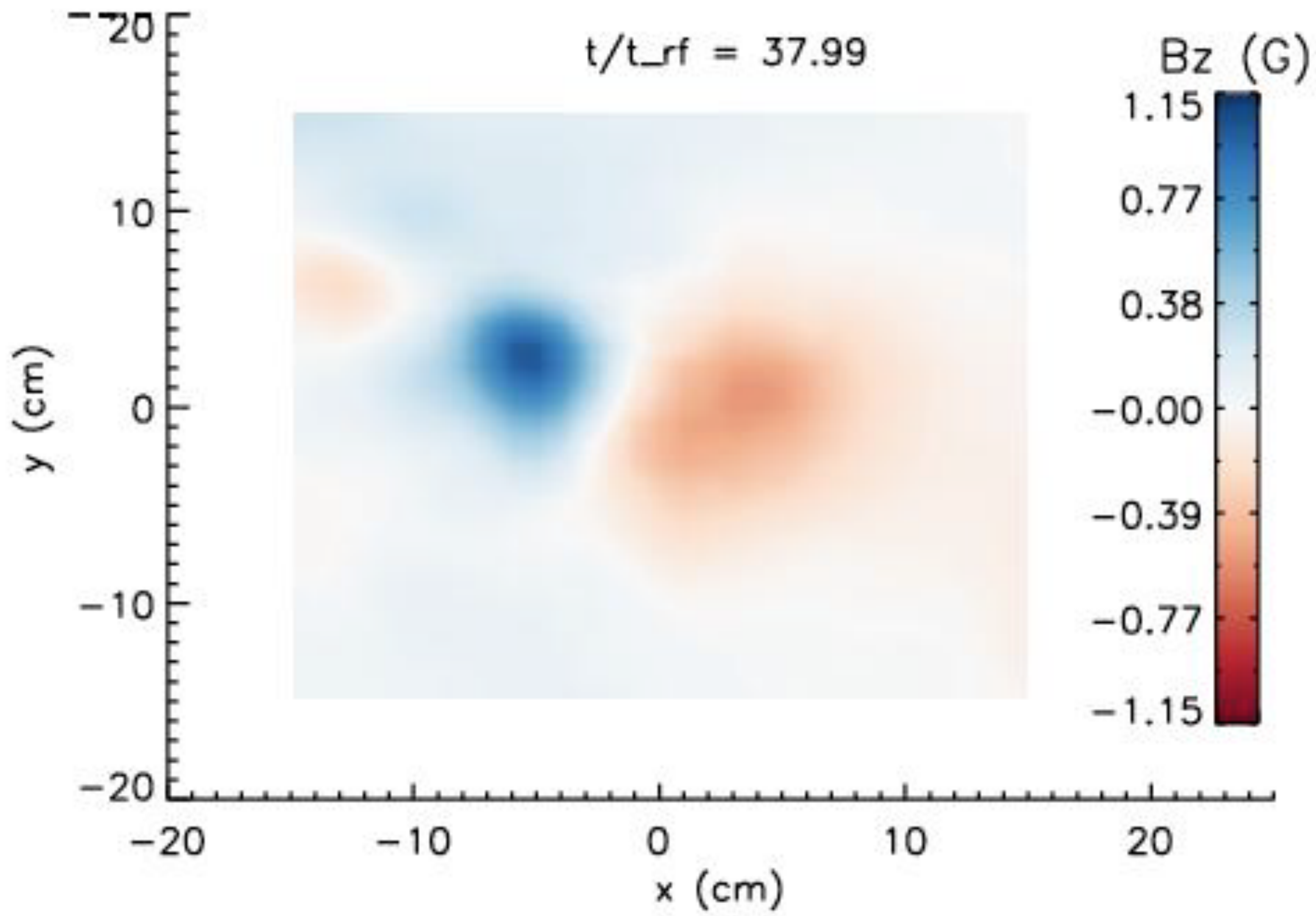


Hellinger, et al., 2006

Can we generate anisotropy in LAPD? Perpendicular Ion heating via ICRH

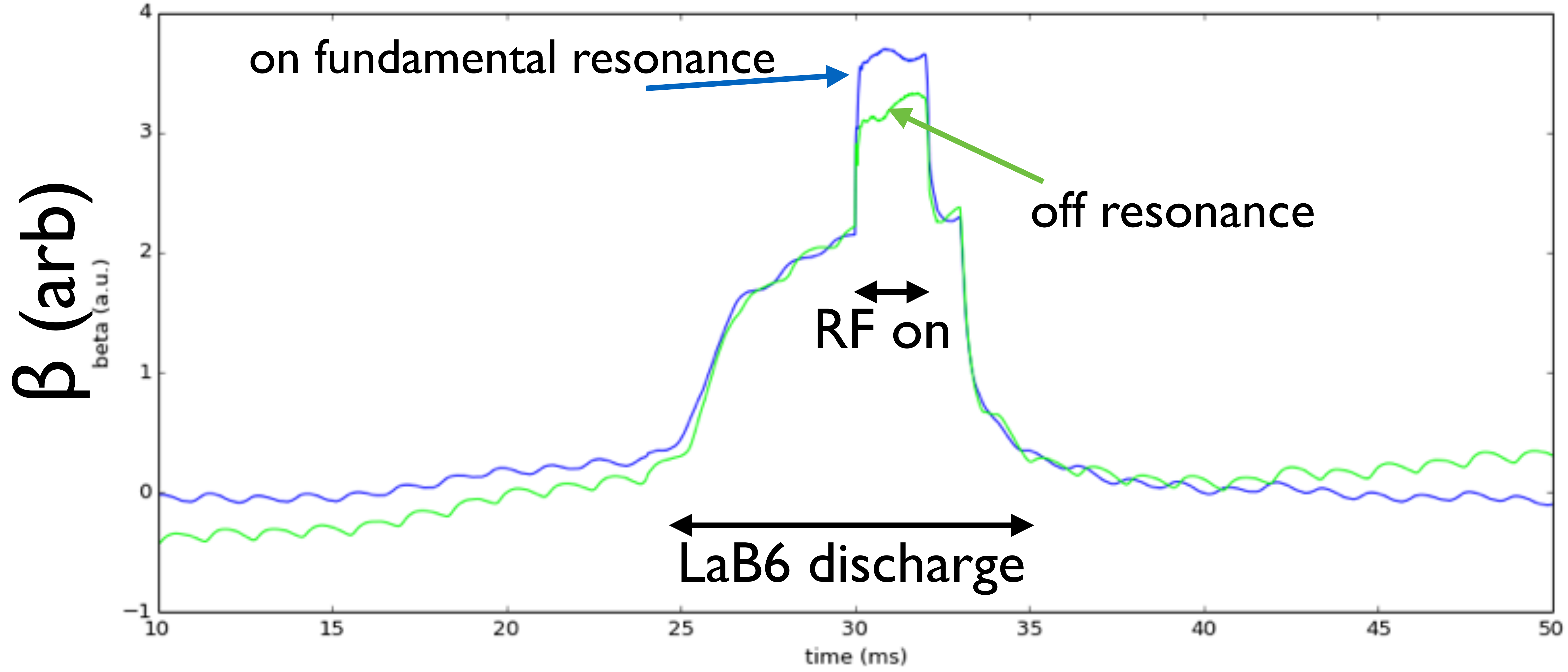


fast wave antenna



- High power (~200 kW) RF driver and fast wave antenna available.
- Initial experiments: good coupling (~30G wave amplitude), some evidence of ion heating via fundamental minority resonance (H in He plasma)

Can we generate anisotropy in LAPD? Perpendicular Ion heating via ICRH



- Diamagnetic loop measurements show on-resonance effect (more convincing measurements/analysis forthcoming!)
- Can ICRH drive temperature anisotropy, get to mirror instability threshold? (Collisions?)

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