Studies of waves, turbulence and transport in the Large Plasma Device

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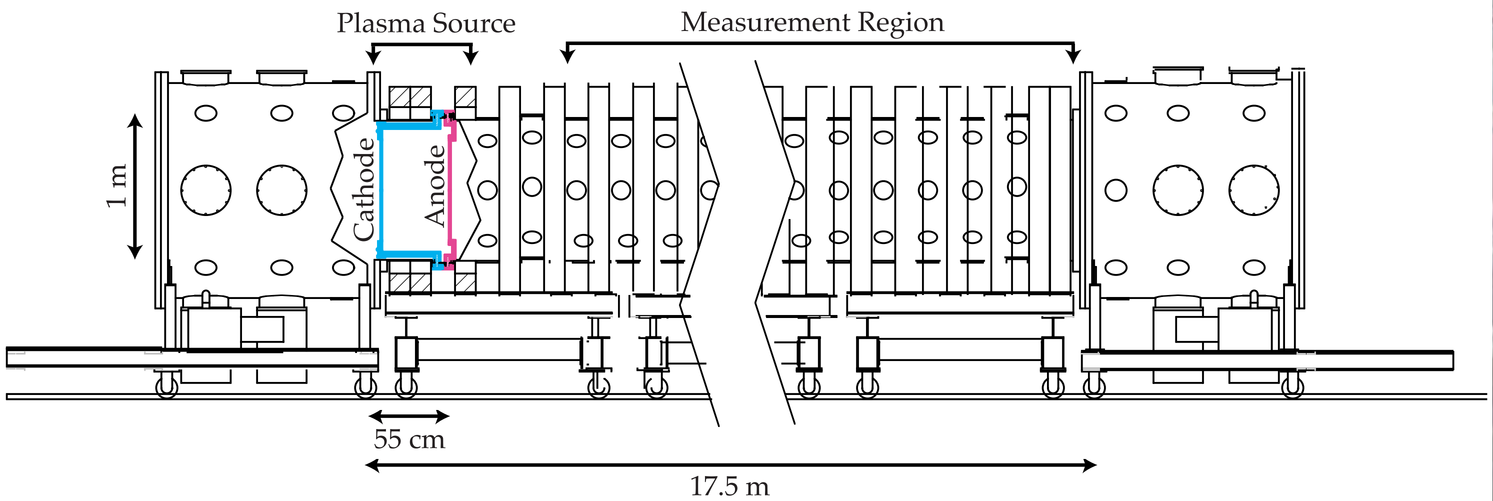
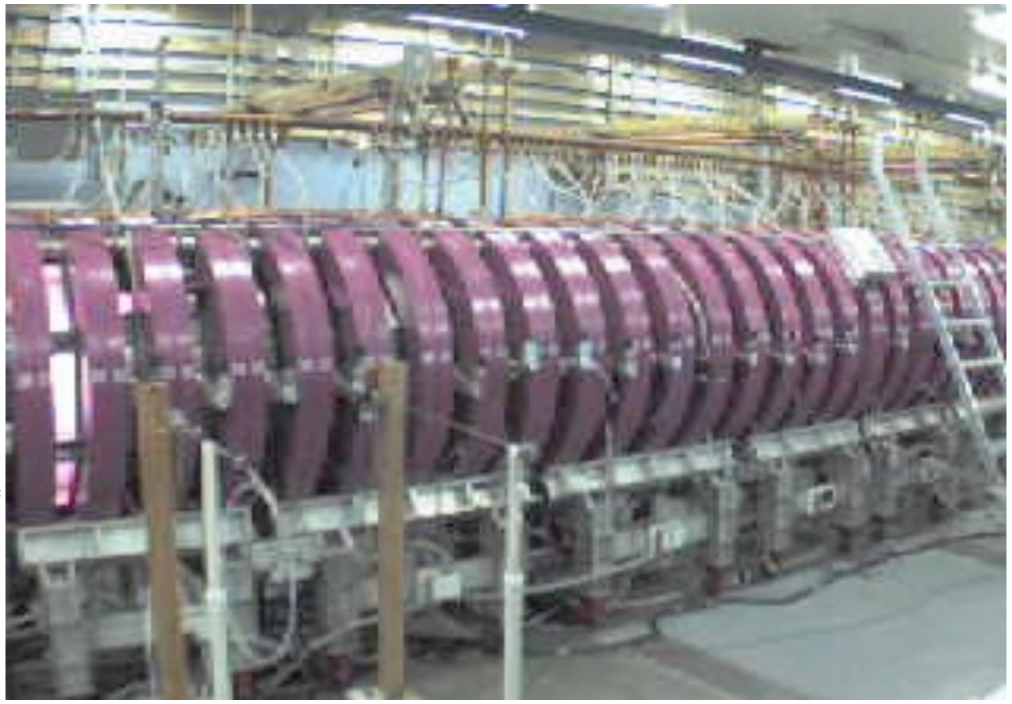
Summary/Outline

- Large Plasma Device (LAPD): Flexible, well-diagnosed experiment for studying basic physical processes (motivations from space, astro, fusion), target for code validation
  - Examples: kinetic/inertial Alfvén waves; fast ion interaction with turbulence, waves; suppression of turbulent transport via sheared flow
- Control of gradient-driven instability through nonlinear interaction with 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 (synchronized?) in favor of driven second mode, overall fluctuation amplitude reduced

The LArge Plasma Device (LAPD) at UCLA



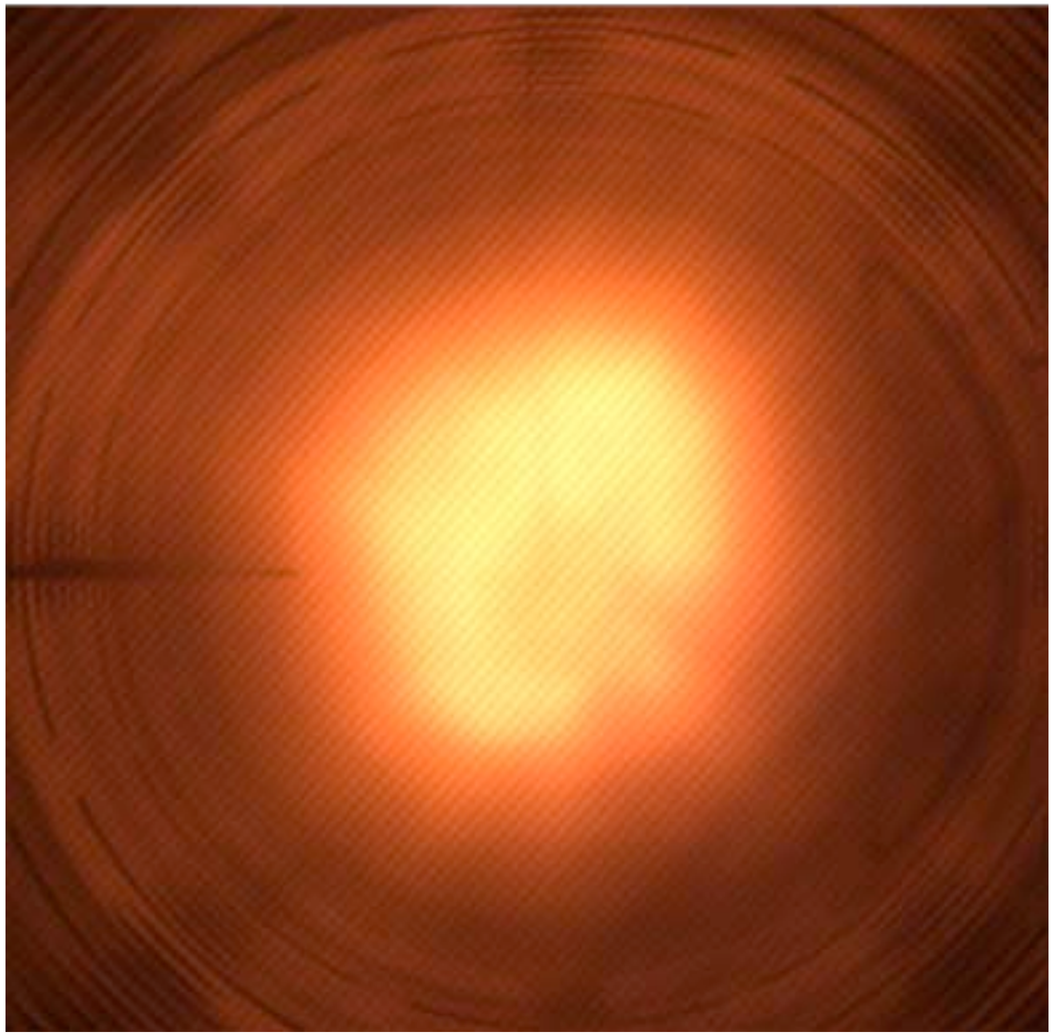


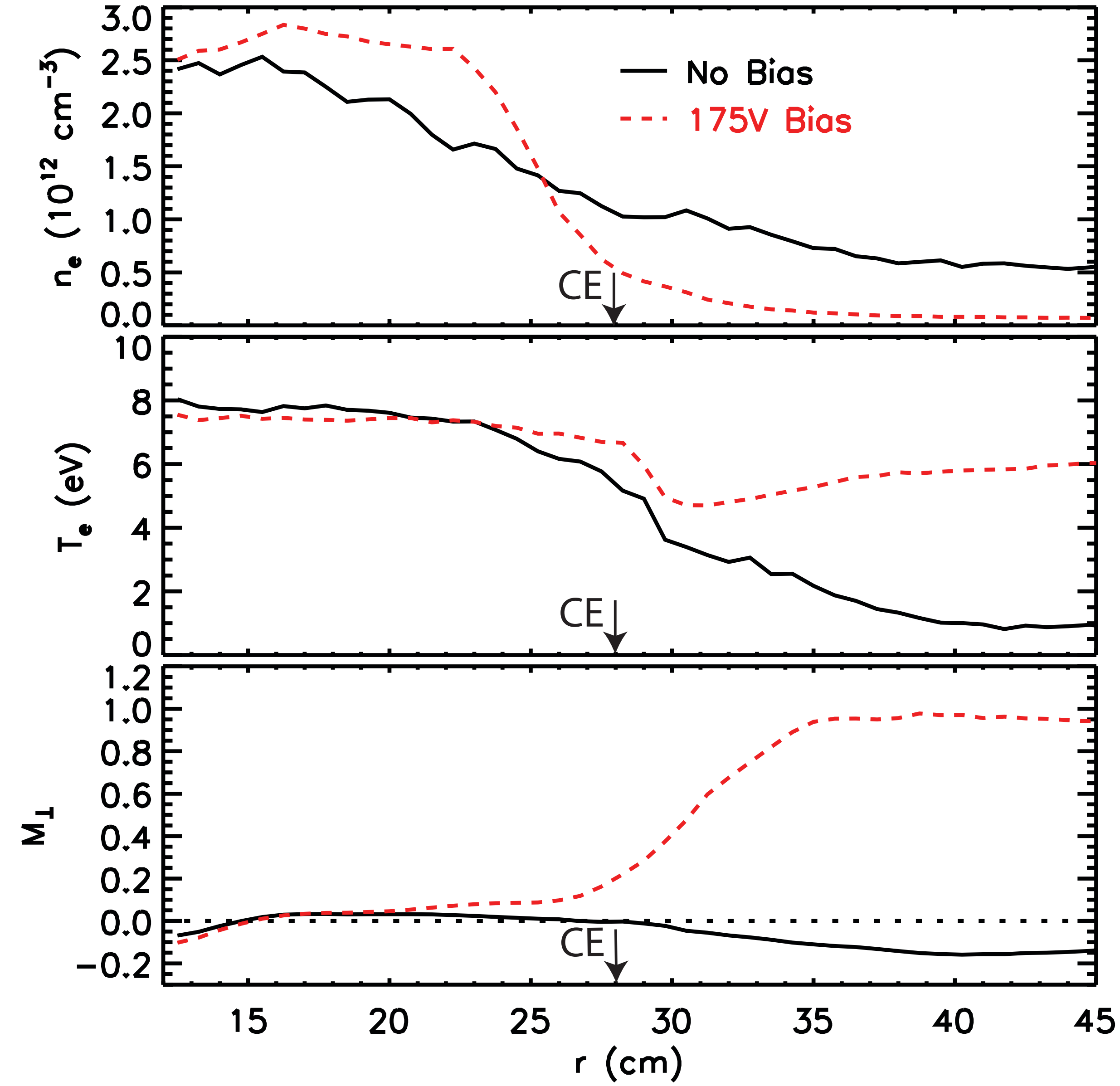
- US DOE/NSF sponsored user facility
- Solenoidal magnetic field, cathode discharge plasma
- $0.5 < B < 2\,\mathrm{kG}, n_e \sim 10^{12}\,\mathrm{cm}^{-3}, T_e \sim 5\,\mathrm{eV}, T_i \sim 1\,\mathrm{eV}$
- Large plasma size, D~60cm (1kG: ~300 ρ_i, ~100 ρ_s)
- High repetition rate: 1 Hz
- Similar parameters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

Example LAPD Users and Research Areas

- Basic Physics of Plasma Waves: e.g. linear properties of inertial and kinetic Alfvén waves (Kletzing, Howes); Alfvén waves in multi-ion plasmas (Vincena, Maggs, Morales)
- Physics of fast ion interaction with Alfvén waves and turbulence (Zhou, Zhang, Heidbrink, Carter, Breizman, …)
- Electron Phase Space Holes (Chen, Kinter, Pickett)
- Reconnection between flux tubes (Lawrence, Gekelman)
- Alfvén waves and shocks driven by laser blow-off (Niemann, Gekelman)
- Nonlinear interactions between Alfvén waves (Brugman, Auerbach, Carter, Vincena, Boldyrev, Howes)
- Drift-wave turbulence and transport (Pace, Schaffner, Friedman, Popovich, Carter, Maggs, Morales, Horton)

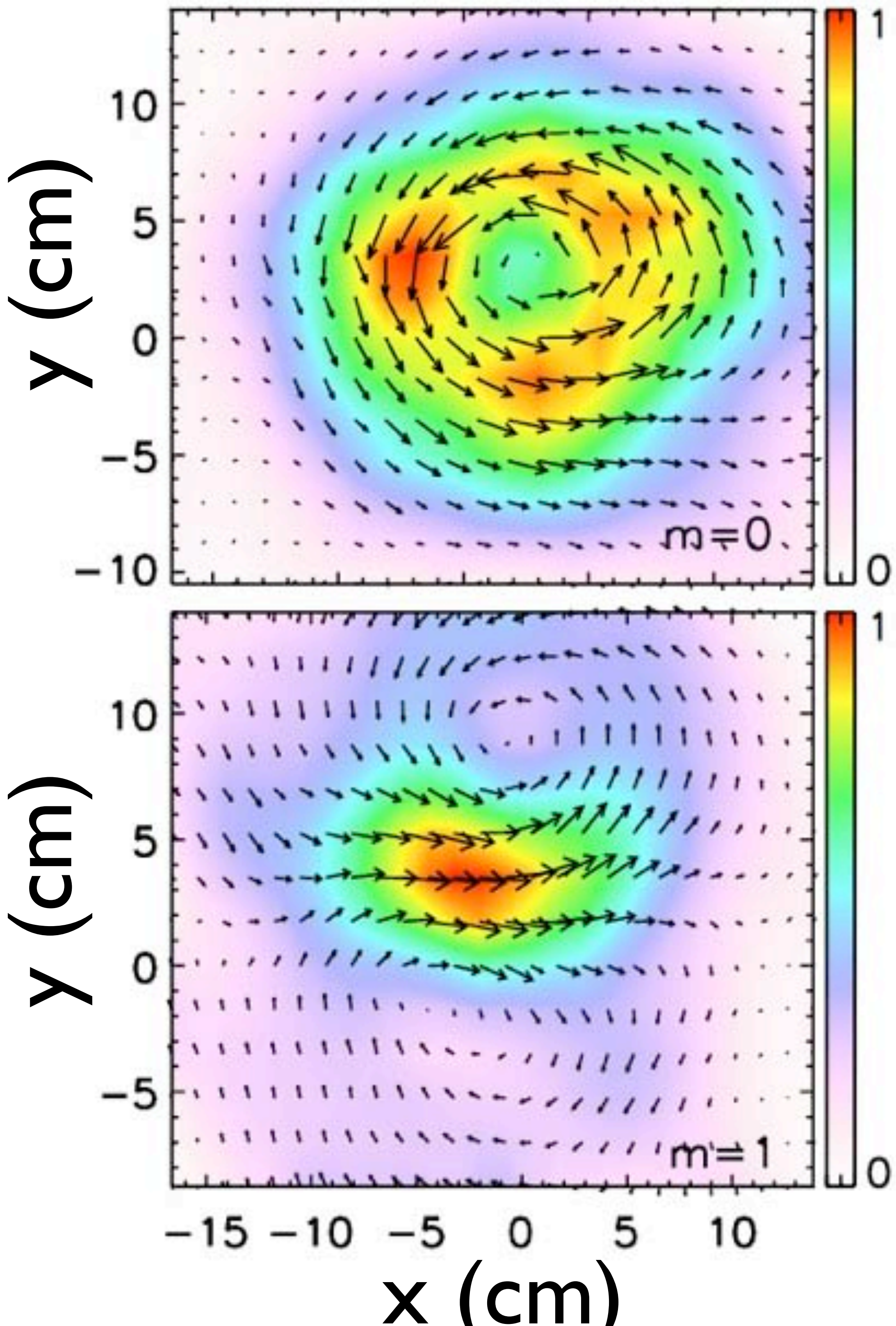
Example Profiles





- Low field case (400G) (also shown: after bias-induced confinement transition); generally get flat core region with D=30-50cm
- Broadband turbulence generally observed in the edge region

Example data: Alfvén wave eigenmodes

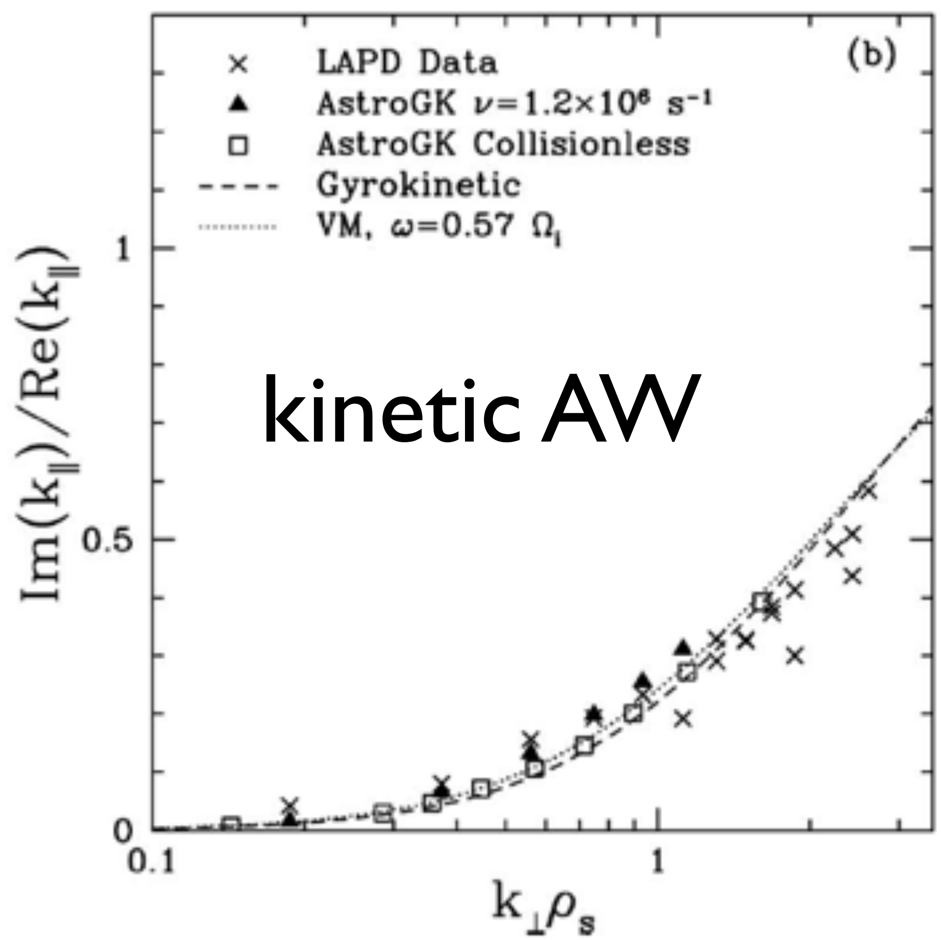


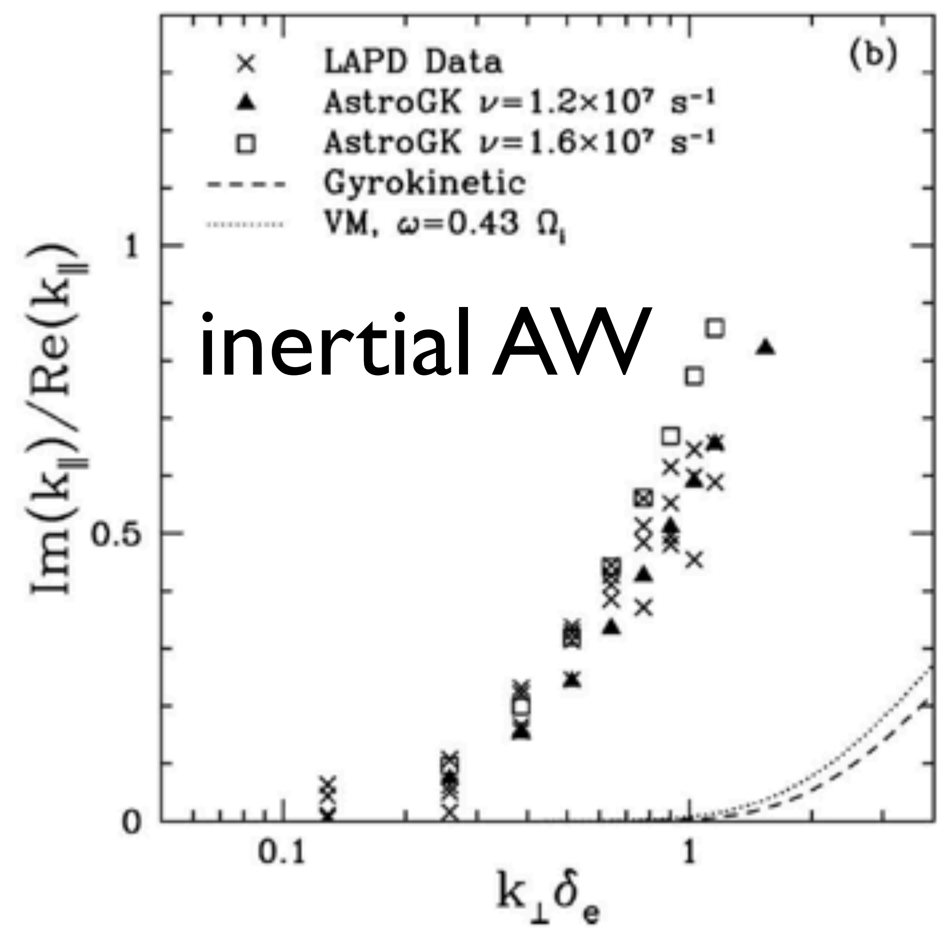
- Alfvén wave maser (plasma source is resonant cavity)
- Correlation techniques used to extract structure
- ~12 hour overnight data run (measurements at ~1600 spatial locations, 10-20 shots per location)

J.E. Maggs, G.J. Morales, T.A. Carter, Phys. Plasmas 12, 013103(2005)

Dispersion and damping of AWs

- Recent studies of dispersion/damping for very high $k_\perp$ AWs (U. Iowa: Kletzing, Bounds, et al) ,Compared to AstroGK simulation (Howes)

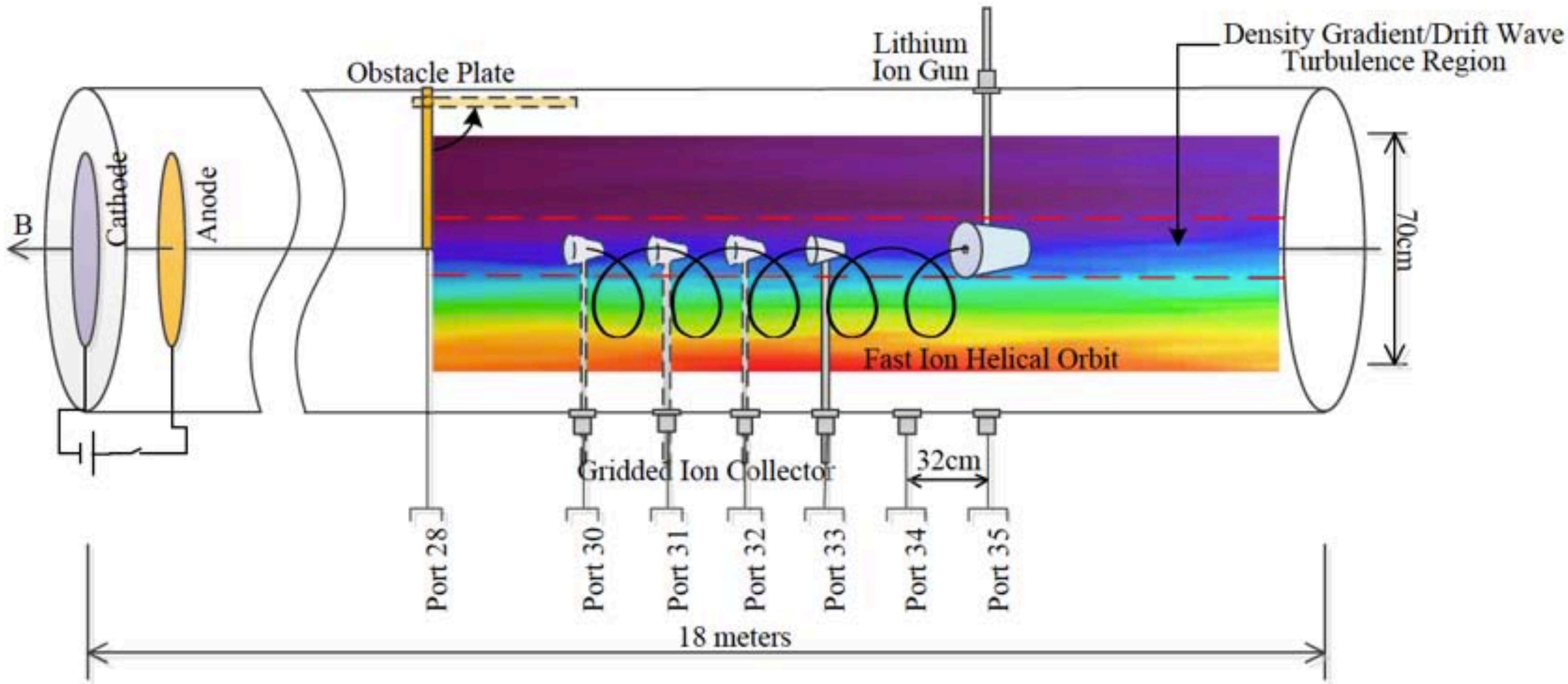




Kletzing, et al, PRL 104, 095001 (2010)

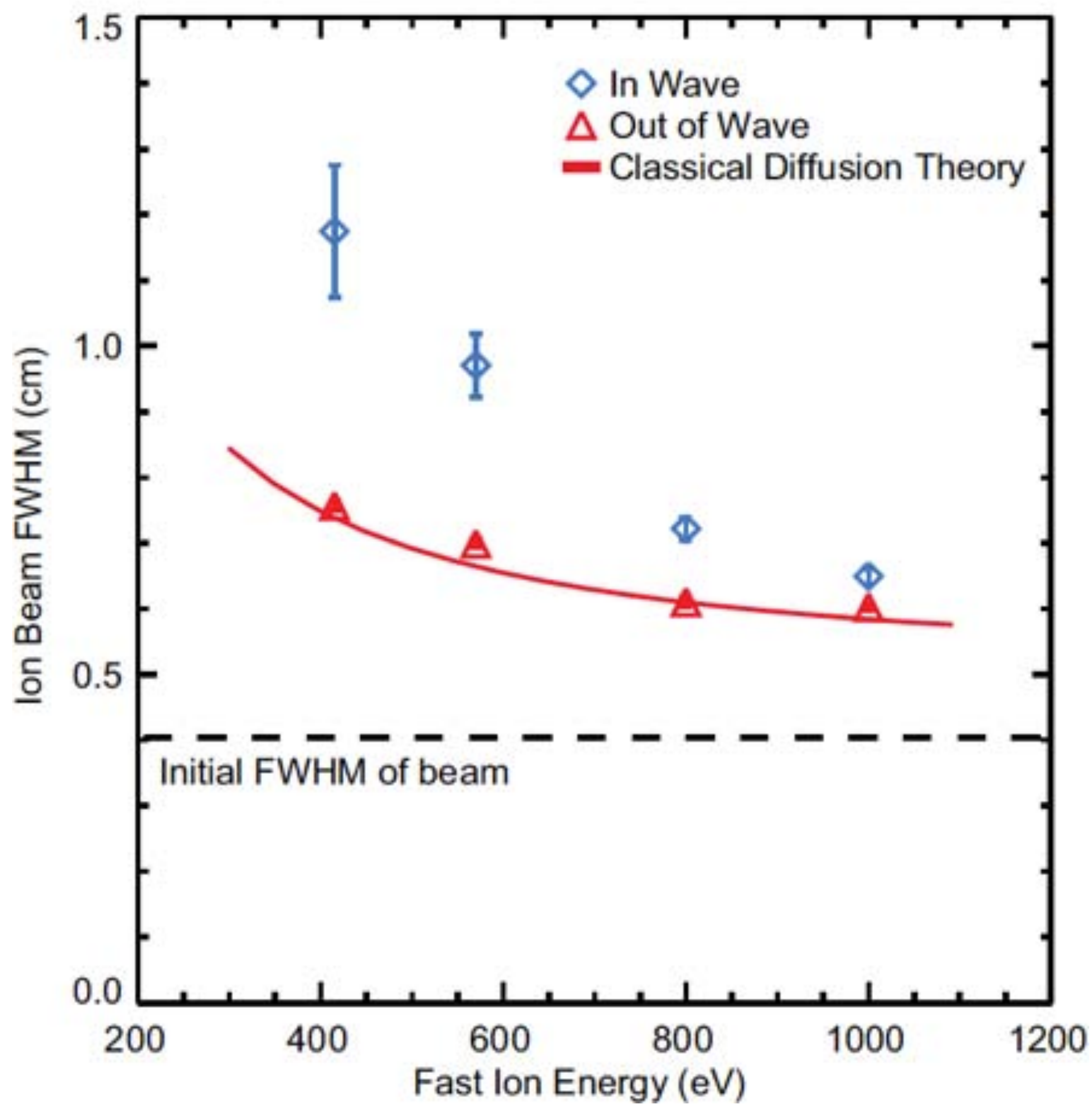
Nielson, Howes, et al, PHYSICS OF PLASMAS **17**, 022105 (2010)

Fast ion transport in drift-wave turbulence



- Limiter used to produce localized, strong drift-wave turbulence
- Pass Li beam through turbulence, measure beam spreading
- Coordinated with studies on DIII-D, TORPEX

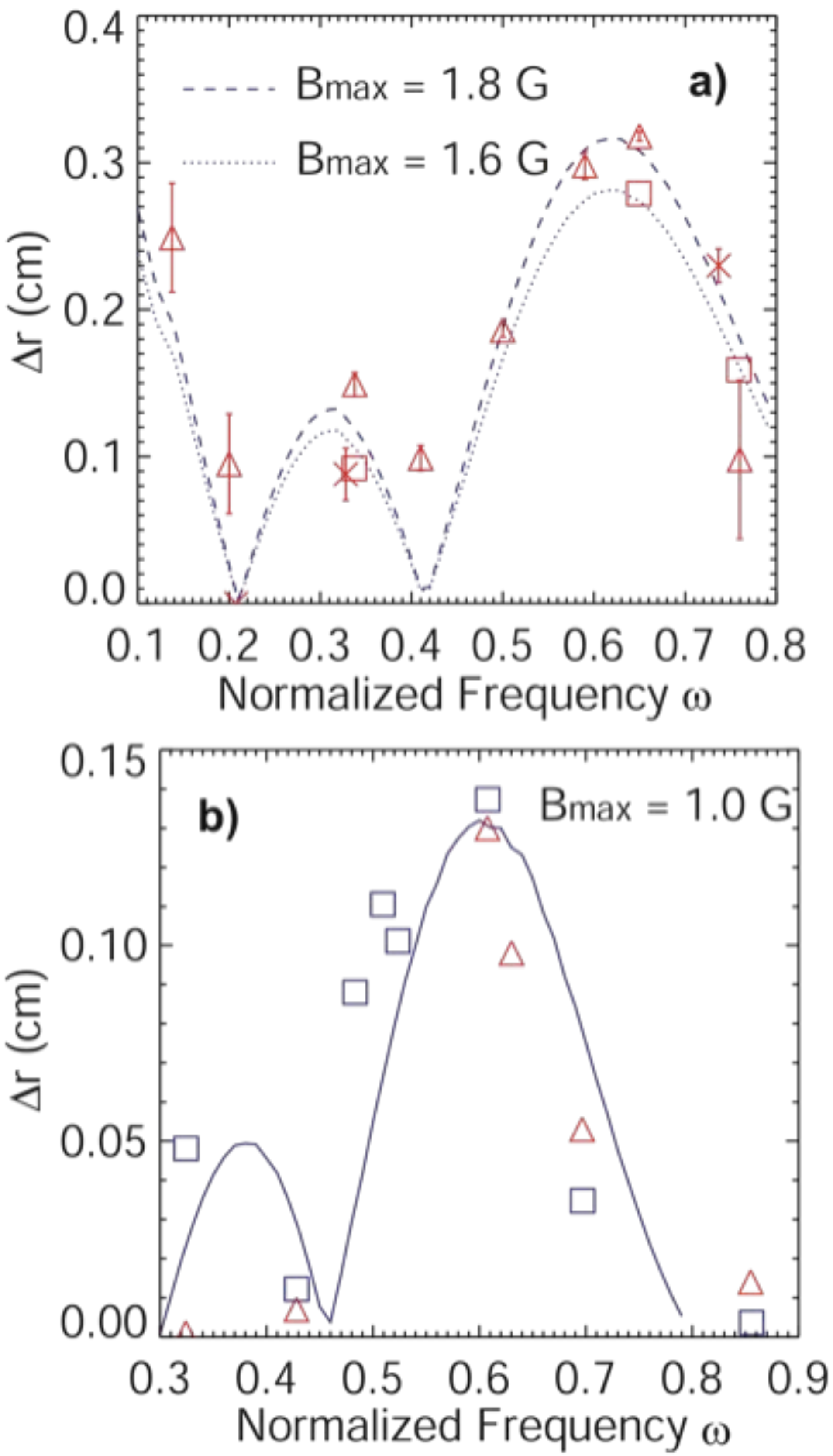
Fast ion transport in drift-wave turbulence



- Beam spreading observed due to turbulence, increases with lower energy, consistent with orbit-averaging picture

[Zhou, et al., submitted]

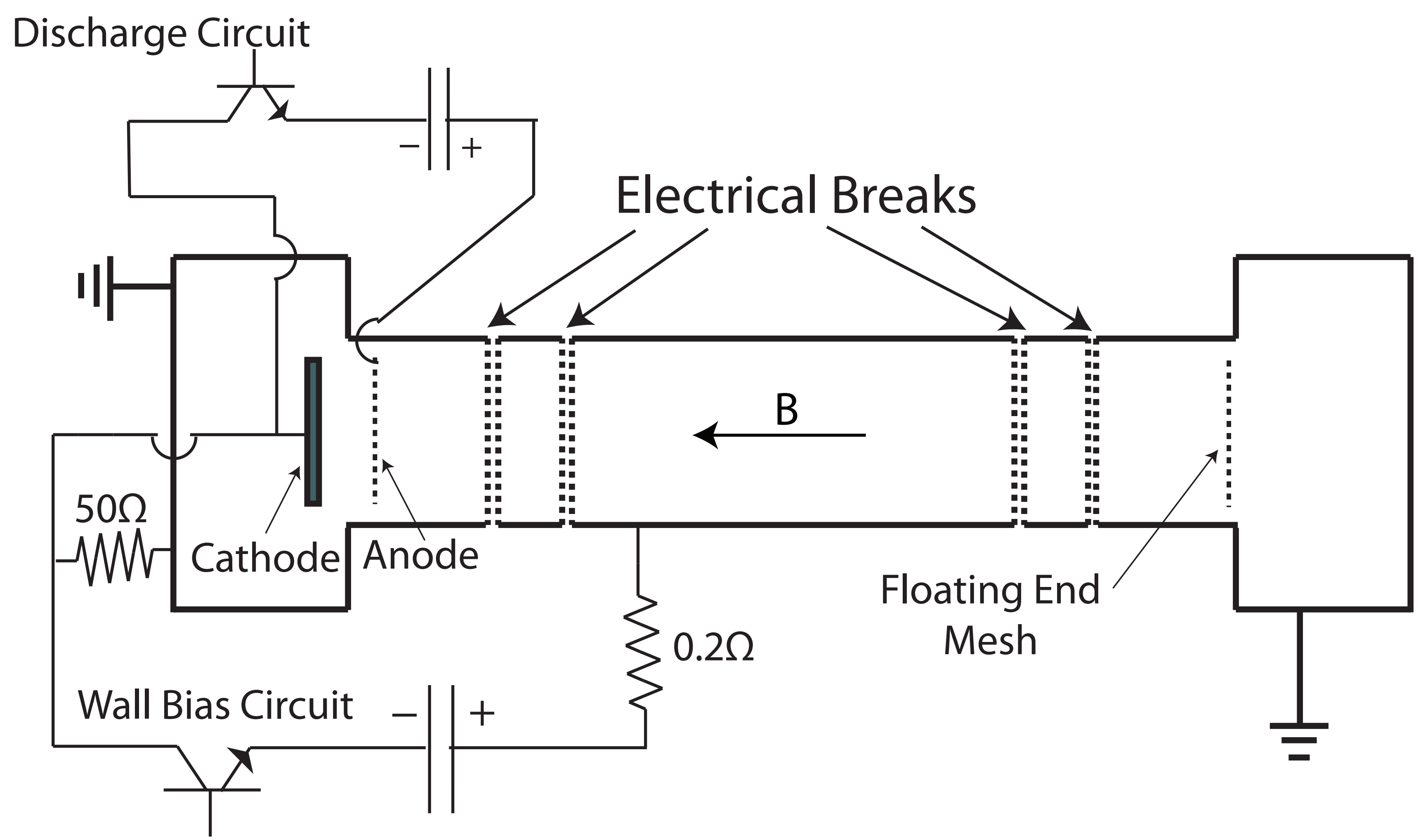
Fast ion/Alfvén wave interaction



- Lithium test ion beam (~1 keV) interacts with antenna launched AWs
- Doppler-shifted cyclotron resonant interaction observed
- Interaction only observed with LHP waves
- Good agreement with theoretical prediction

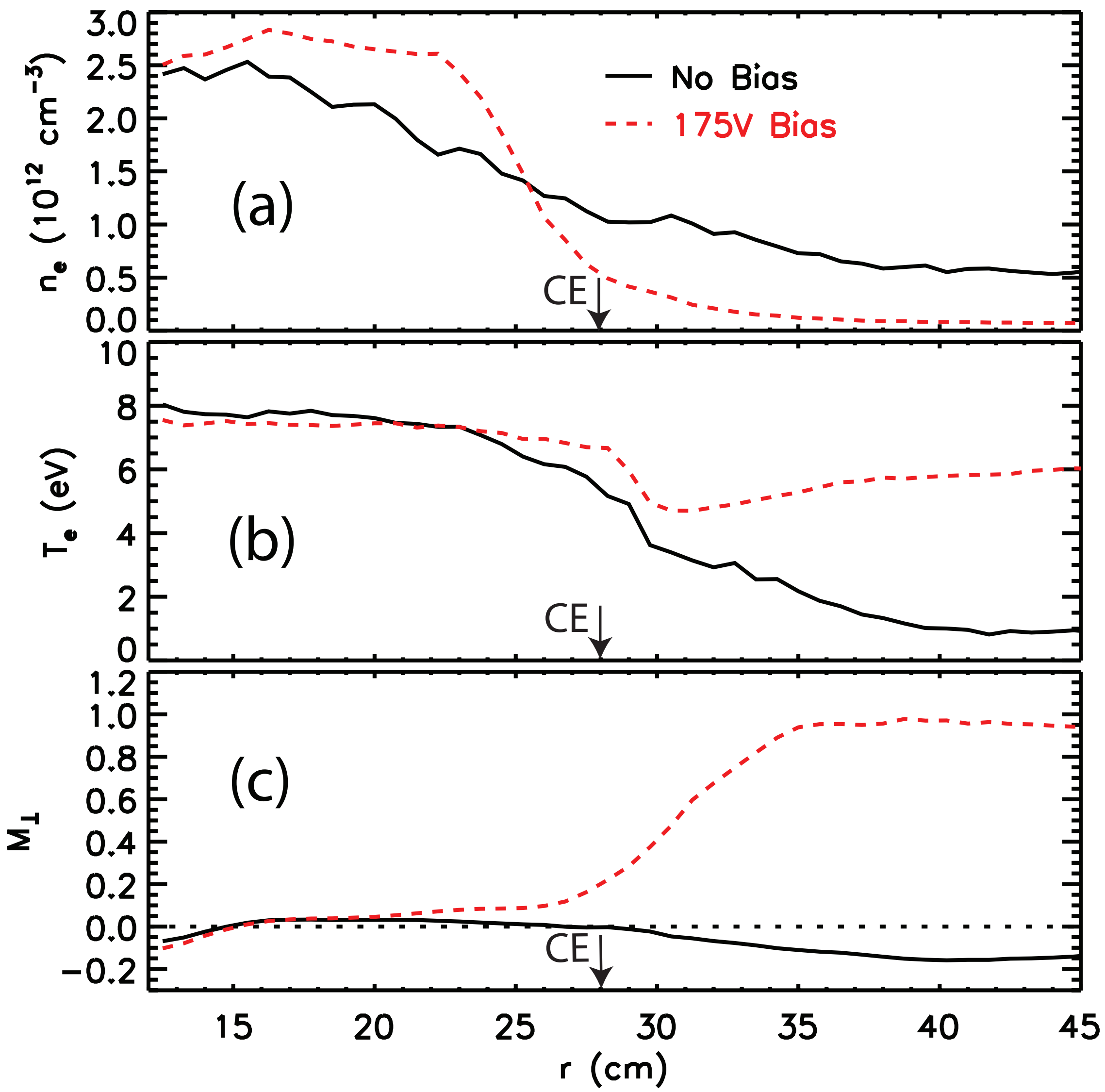
Y. Zhang et al., Phys. Plasmas 16, 055706 (2009)
Y. Zhang et al., Phys. Plasmas 15, 102112 (2008)

Biased rotation in LAPD



- Apply positive bias to (floating) wall of chamber (relative to cathode)
- Radial current in response to applied potential provides torque to spin up plasma
- Cross-field current carried by ions (through ion-neutral collisions)

Dramatic profile steepening observed with biasing

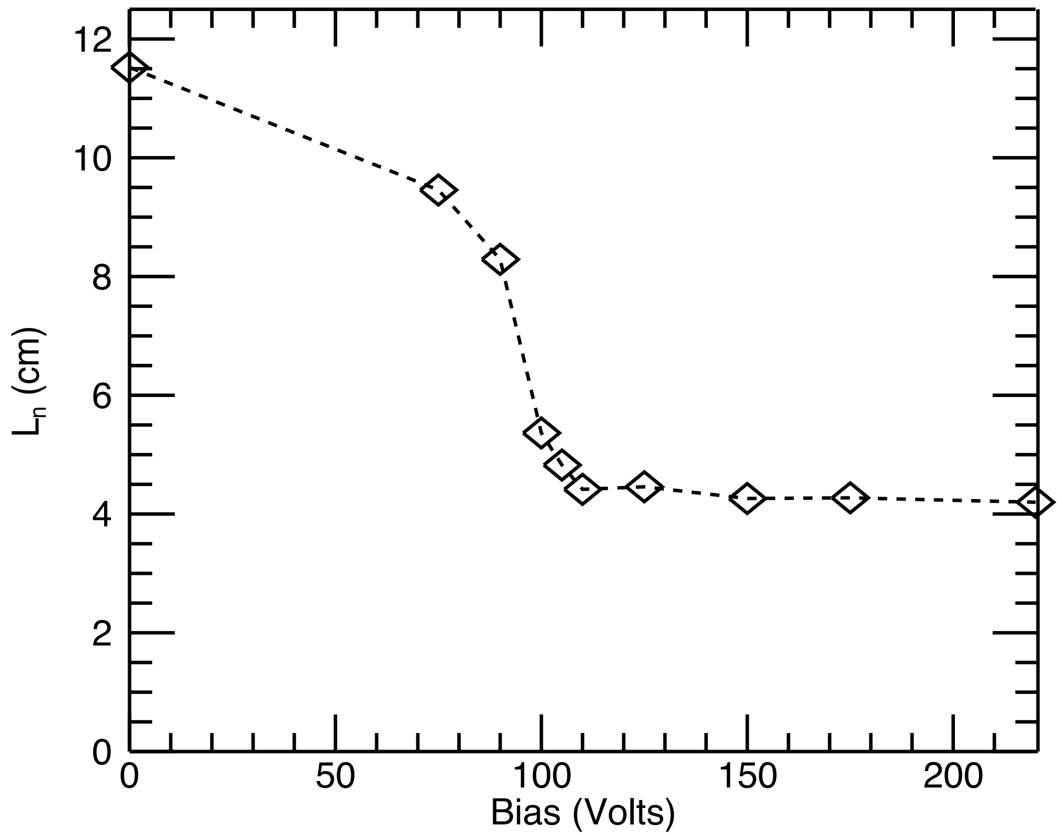


- As bias exceeds a threshold, confinement transition observed (“H-mode” in LAPD)
- Detailed transport modeling shows that transport is reduced to classical levels during biasing (consistent with Bohm transport prior to rotation)

[Maggs, Carter, Taylor, PoP 14, 052507 (2007)]

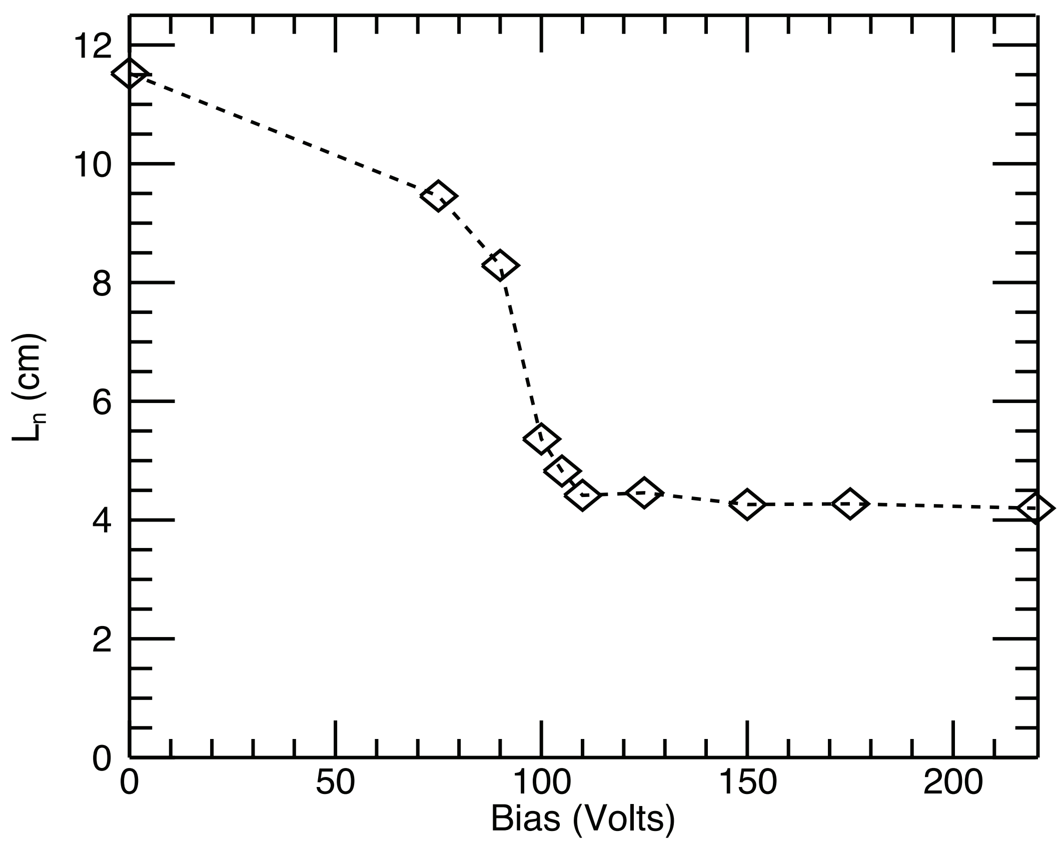
[Carter, Maggs, PoP 16, 012304 (2009)]

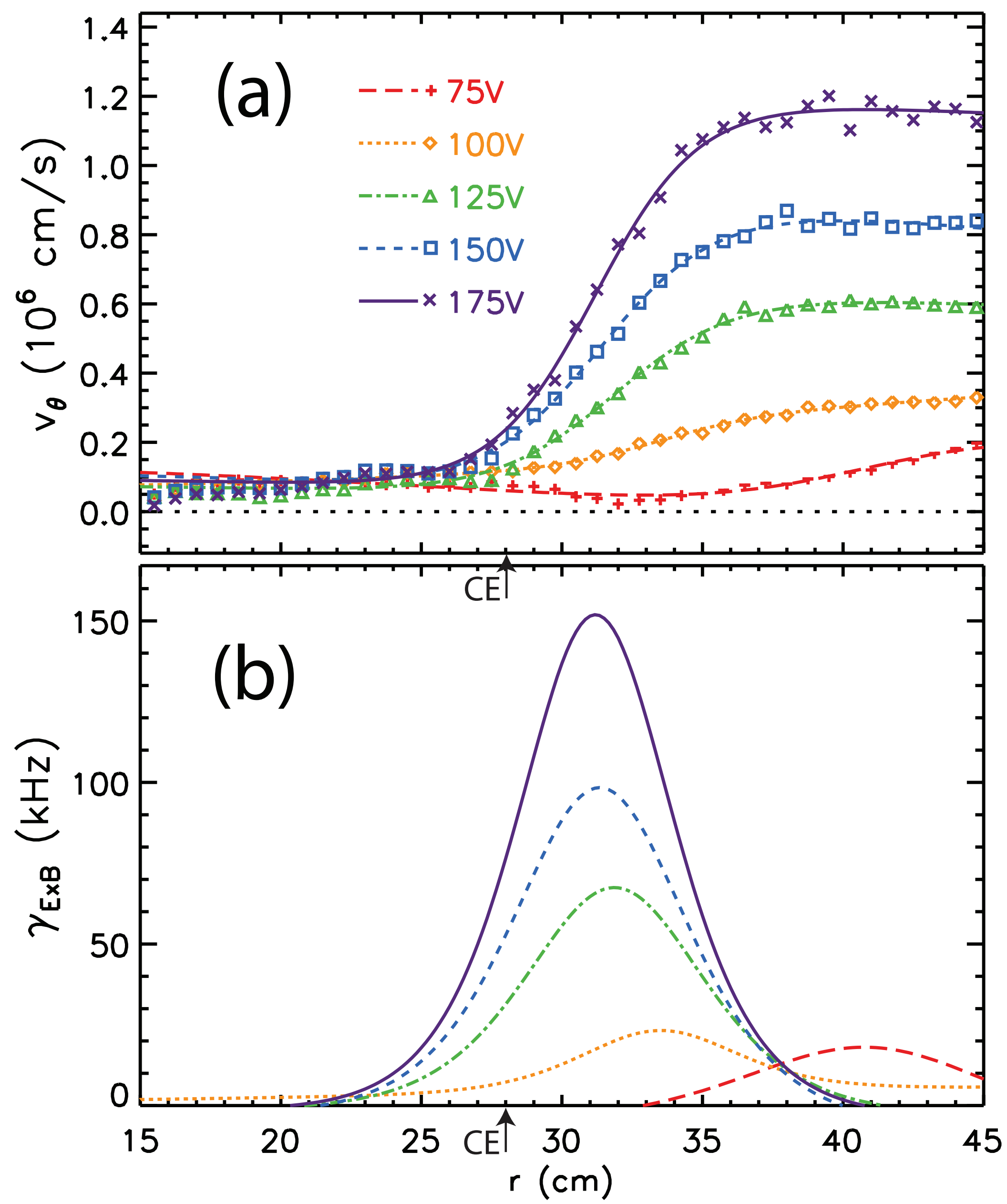
Threshold for bias transition is observed, appears to be due to radial flow penetration



- Profile steepening observed for bias above a threshold value

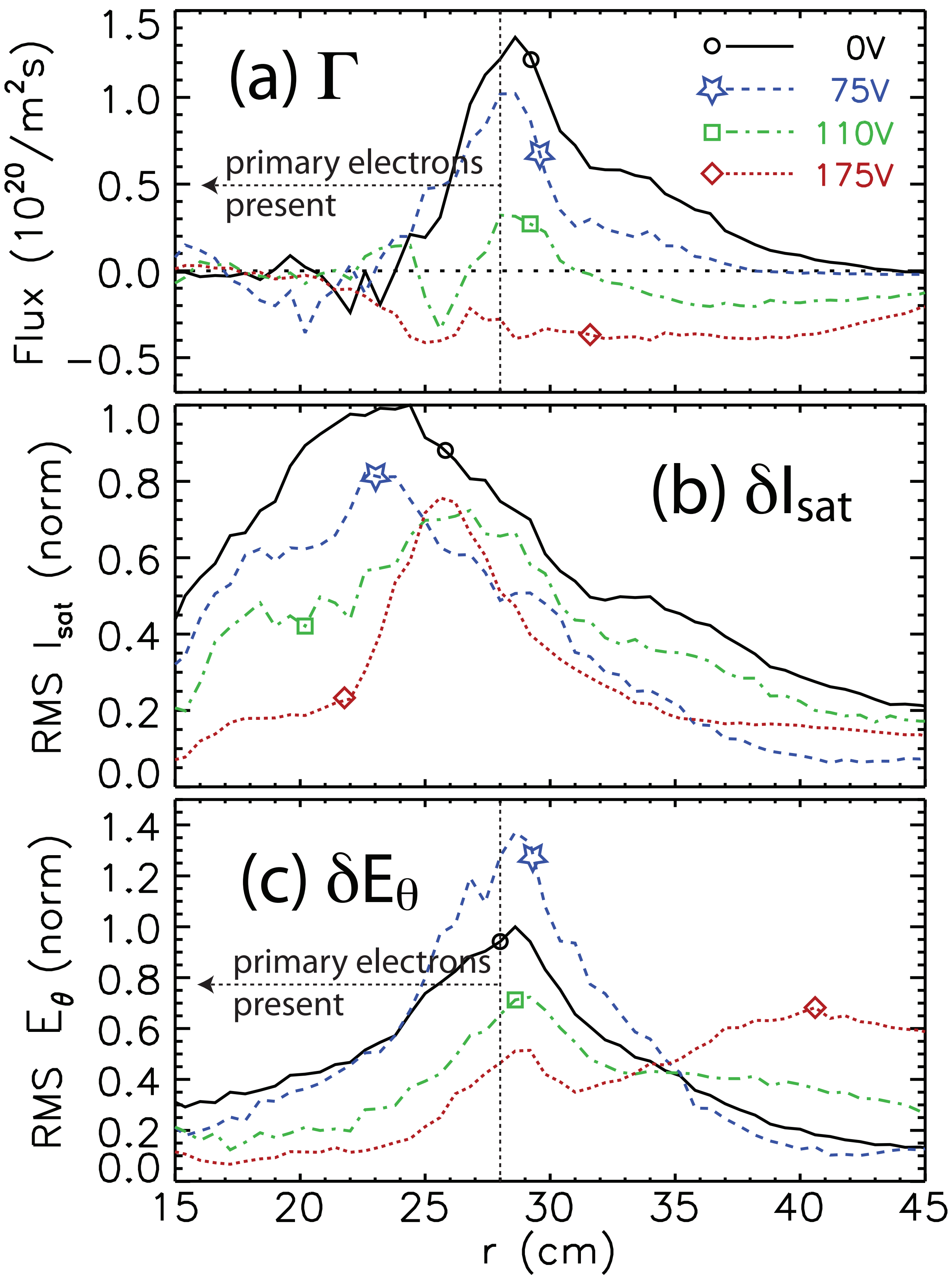
Threshold for bias transition is observed, appears to be due to radial flow penetration





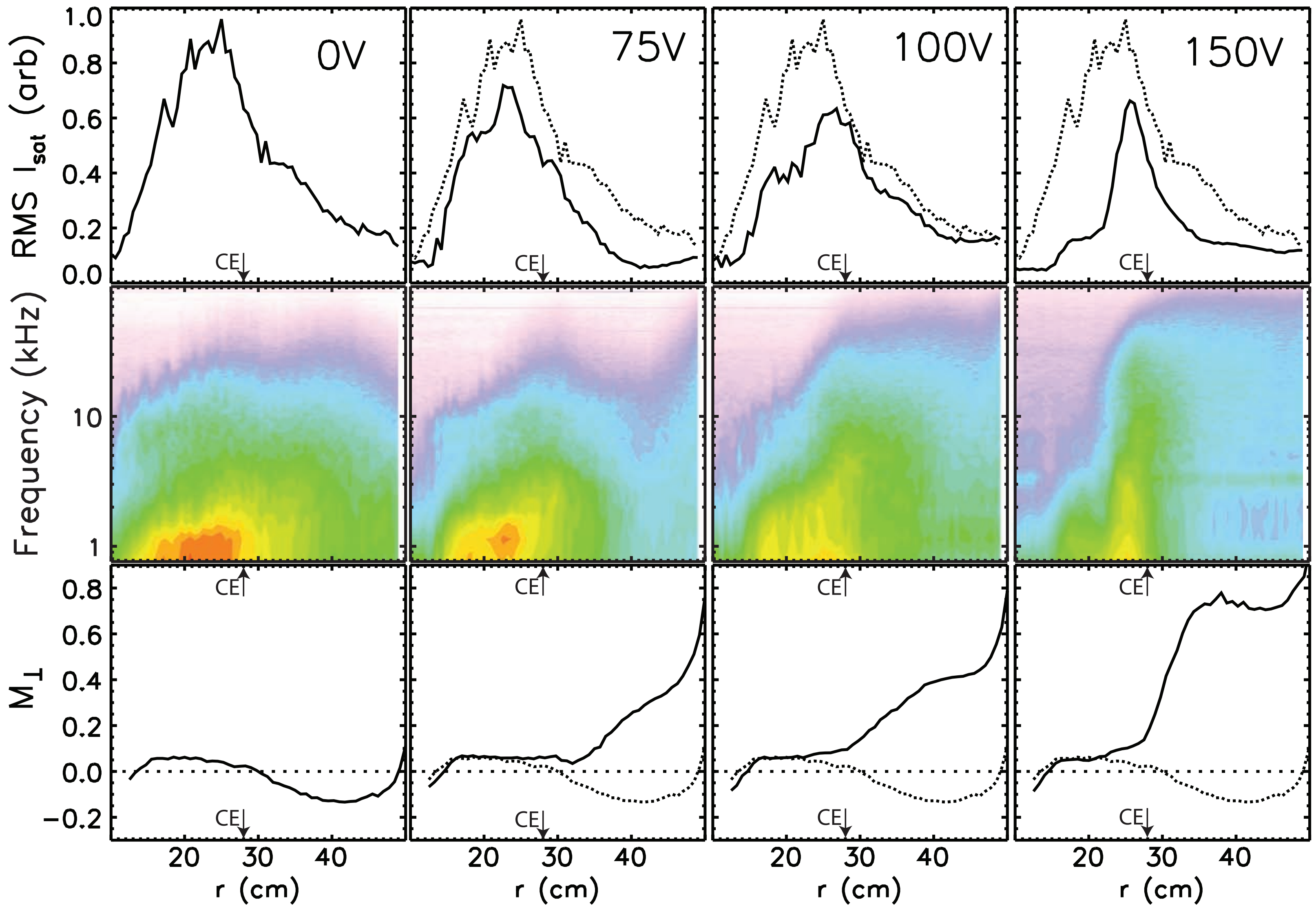
- Profile steepening observed for bias above a threshold value
- Flow remains confined to far edge until threshold is exceeded

Flux probe measurements show suppression of flux at threshold, apparent reversal at larger biases



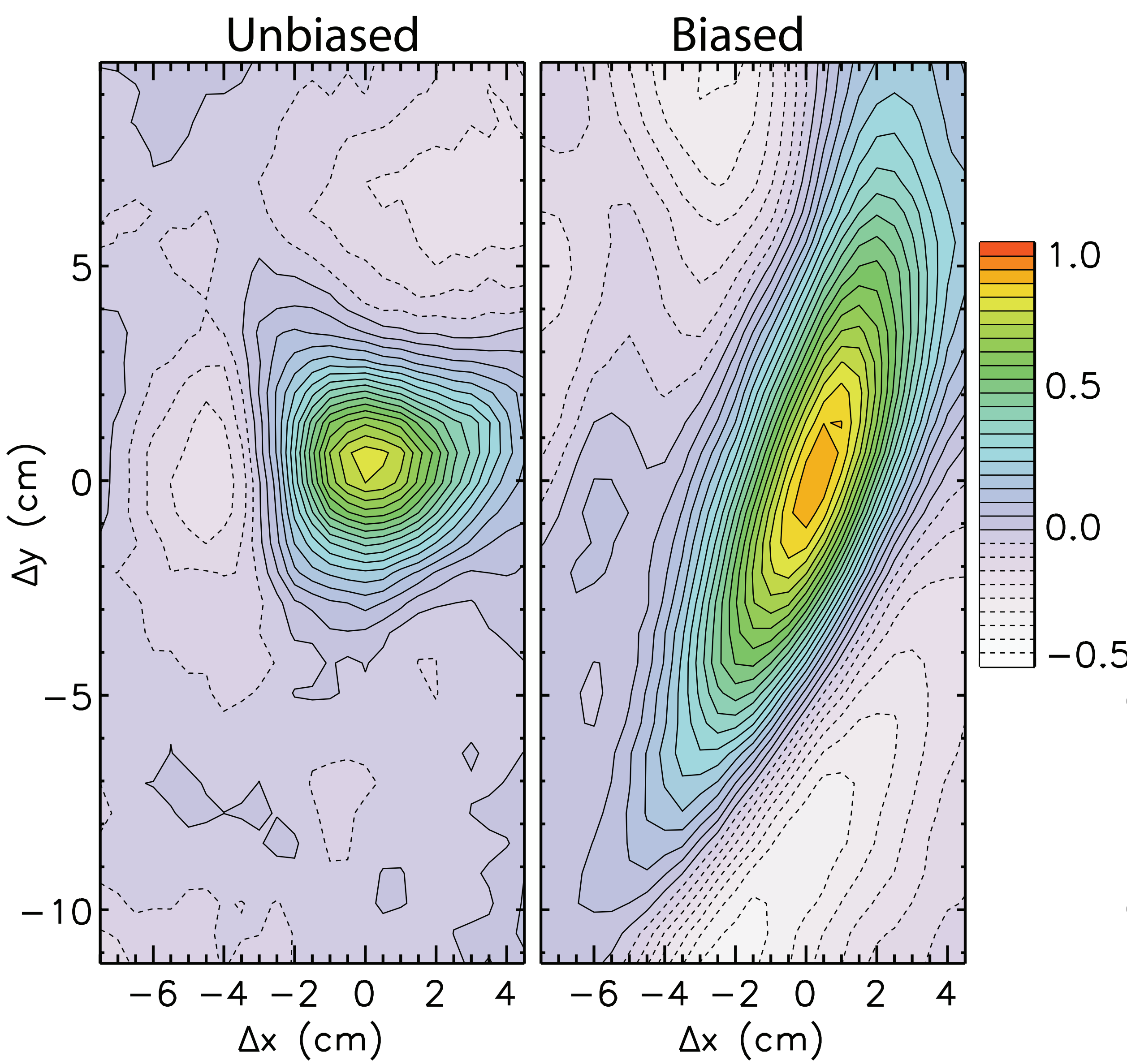
- Flux reduced somewhat below threshold, suppressed once flow and shear penetrate to gradient region
- As bias is increased, flux reverses direction, apparently indicating inward flux
- Electric field fluctuations suppressed more than density, but combination is not enough to explain transport reduction
- Primary electrons from plasma source appear to affect ability to measure electric field (floating potential)

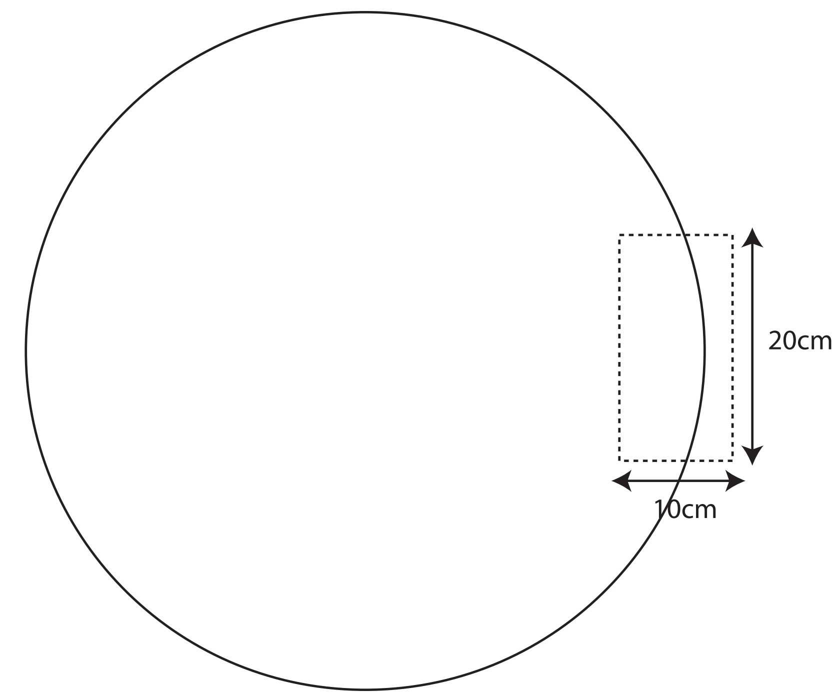
Fluctuation profile modified, but peak amplitude reduced only slightly



- Broadband drift-Alfvén wave fluctuations before biasing
- Fluctuations concentrate on steepened profile, Doppler shift observed

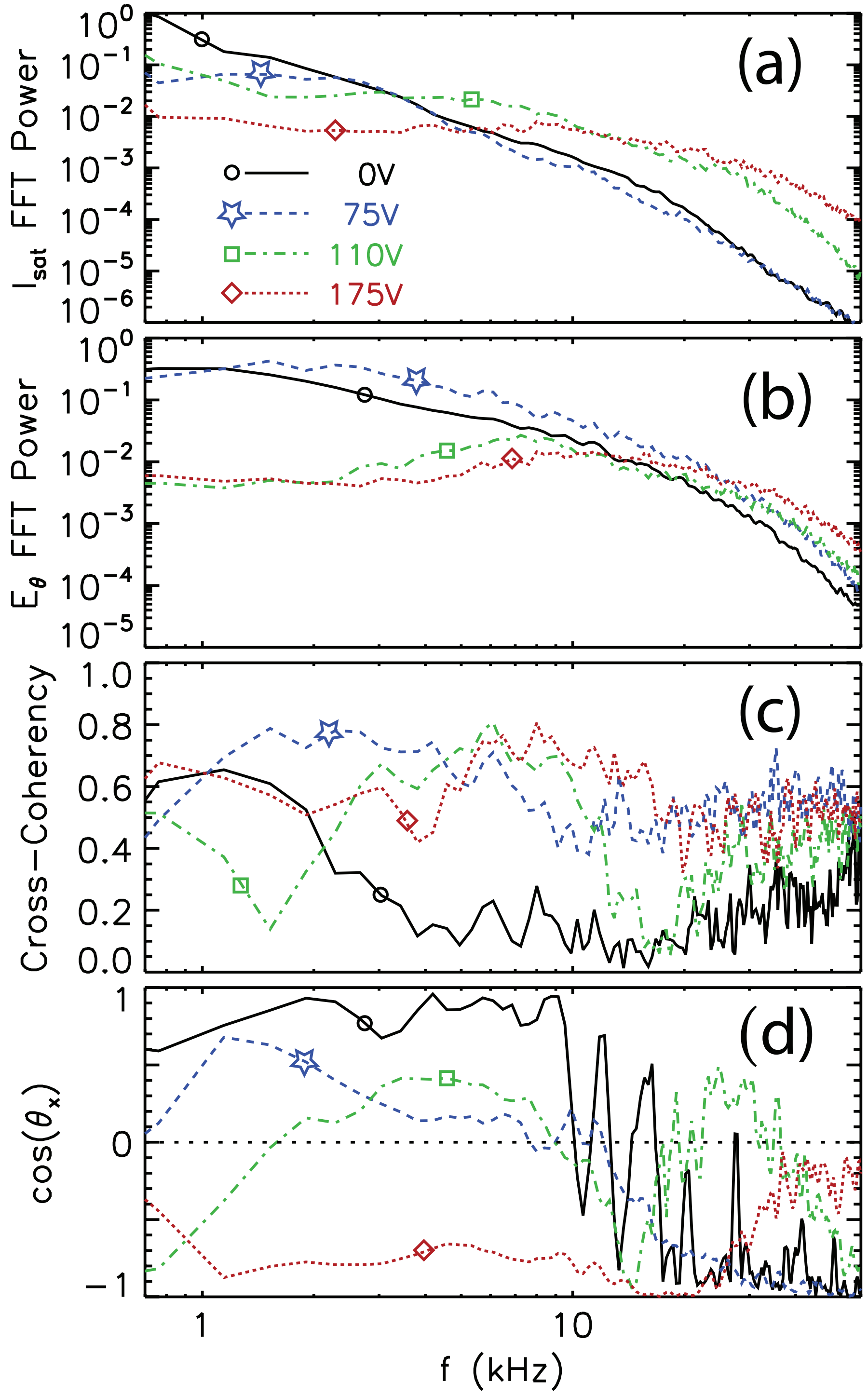
2D Correlation function measurements show dramatic increase in azimuthal correlation, no significant radial decorrelation





- Reference is fixed probe 1m away along field
- No strong evidence for radial decorrelation
- Decreased transport through longer effective transport step time?

Turbulent flux suppression due to modification of density-electric field fluctuation cross-phase

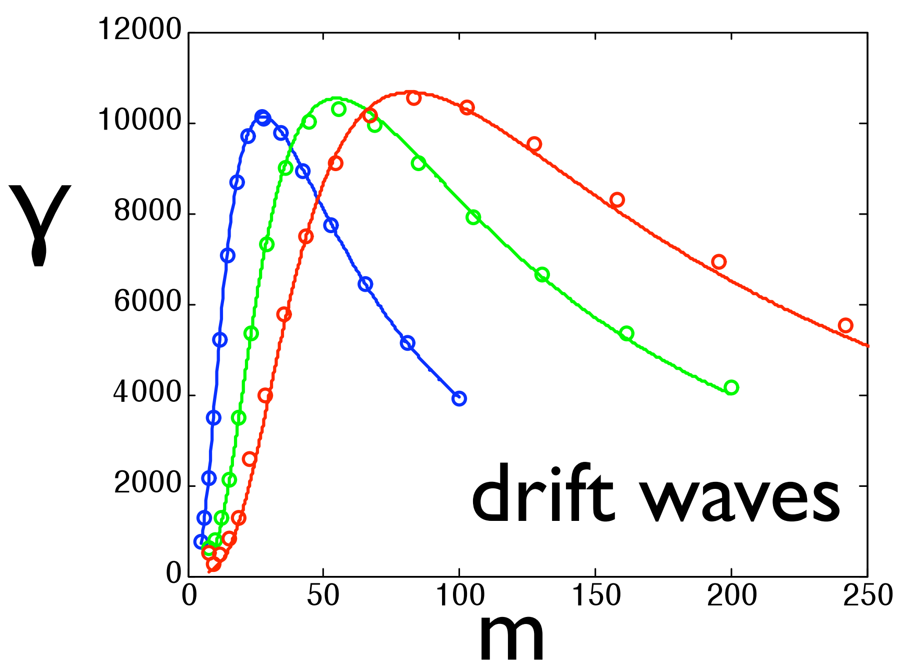


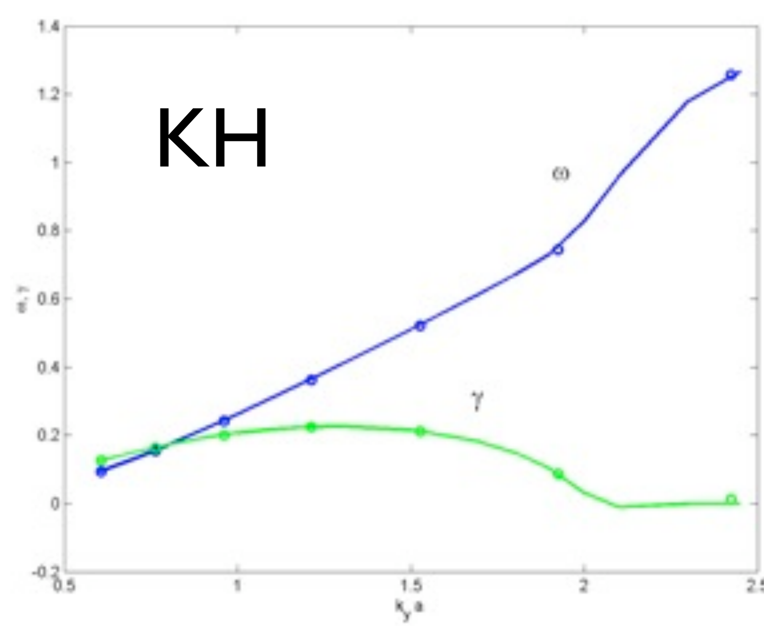
- Some amplitude reduction, but not enough to explain transport modification
- Coherency actually increases with bias
- Cross-phase term suppressed, reversed with increasing bias, explaining observed behavior of the flux

$$\Gamma = \langle \tilde{n}\tilde{v}_r \rangle = \frac{\langle \tilde{n}\tilde{E}_\theta \rangle}{B} = \frac{2}{B}\mathrm{Re}\int_0^\infty \chi_{nE}(\omega)d\omega = \frac{2}{B}\int_0^\infty |\tilde{n}||\tilde{E}_\theta|\gamma(\omega)\cos(\theta_x(\omega))d\omega$$

Modeling LAPD turbulence using BOUT

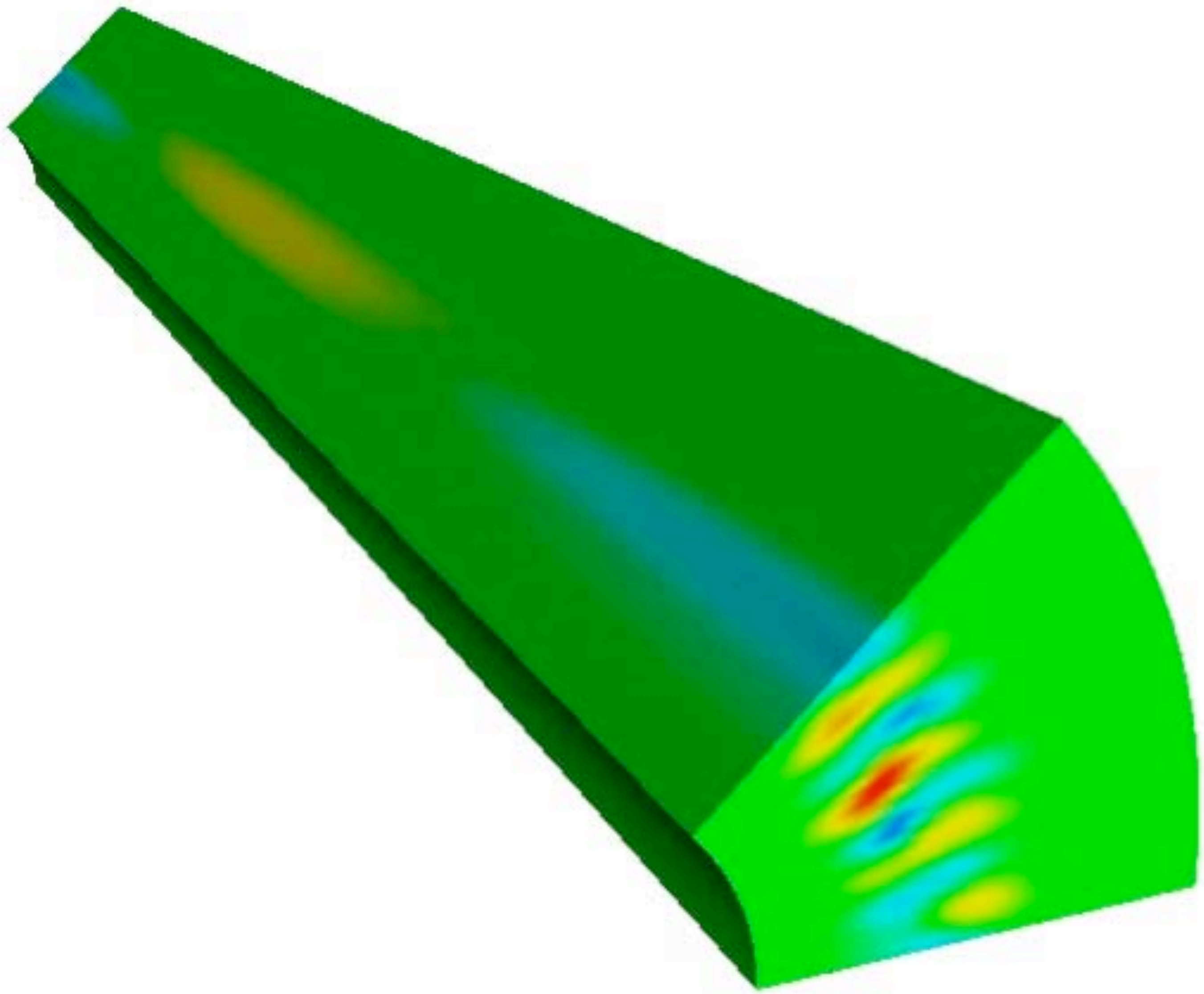
- BOUT/BOUT++: 3D Braginskii fluid tokamak edge simulation code modified to simulate LAPD (P. Popovich, M. Umansky, B. Dudson, B. Friedman)
  - Modified to cylindrical geometry, restored neglected terms to handle strong flows in biased LAPD
  - Verification studies: drift waves, KH, rotational interchange

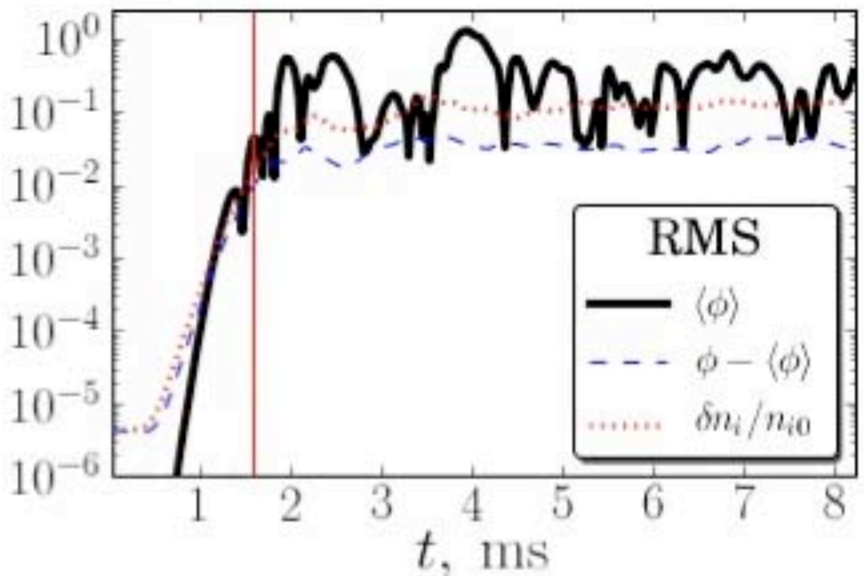


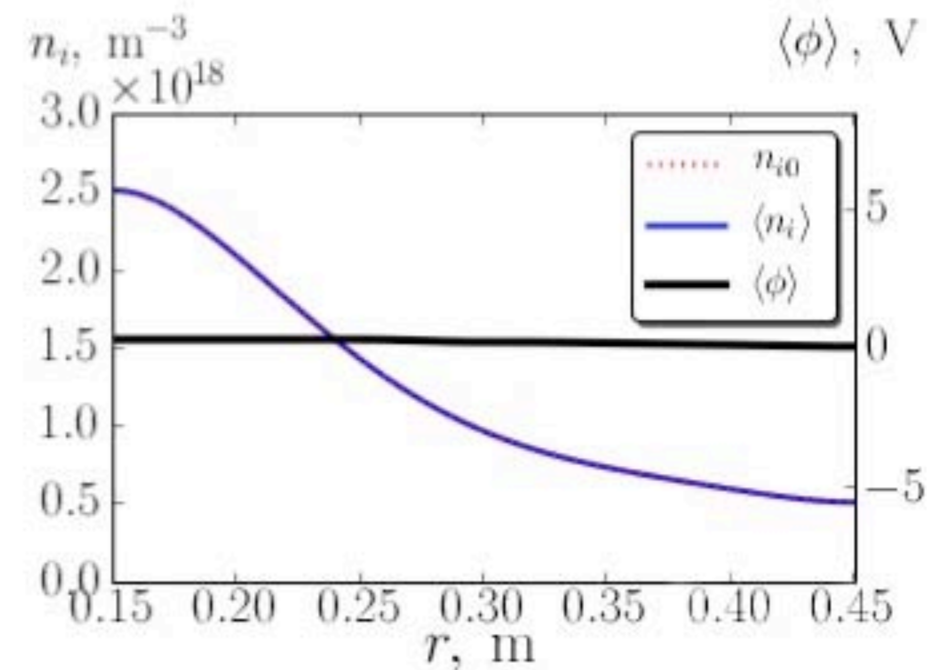


- Measurements provide challenge to BOUT predictions (validation opportunity). Is Braginskii enough to explain LAPD data? (Gyrokinetic/Gyrofluid simulation of LAPD turbulence??)

Nonlinear BOUT LAPD Simulation

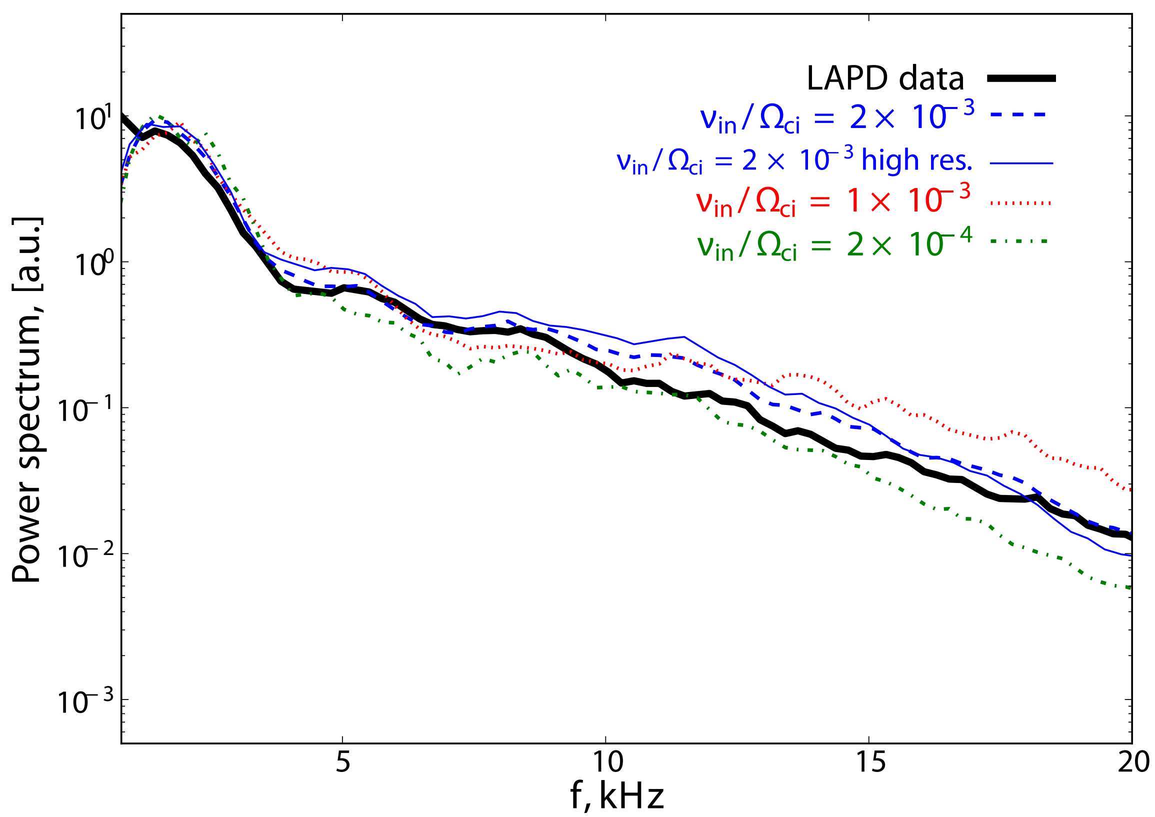


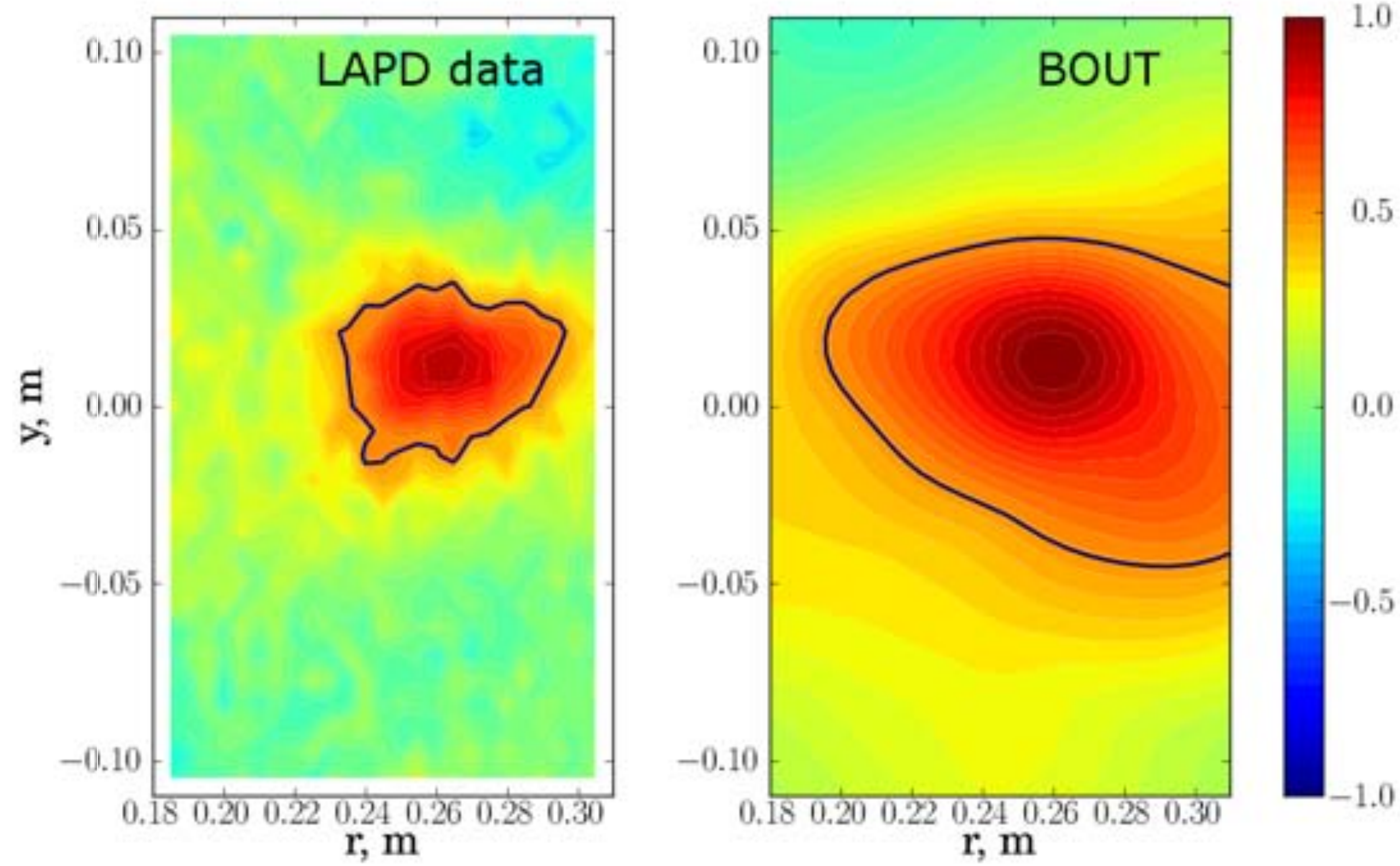




- Simulation uses measured LAPD density profile, but periodic BCs, flows not matched
- Profile fixed by adding ad hoc plasma source

Comparison with measurements: good agreement with spectral shape

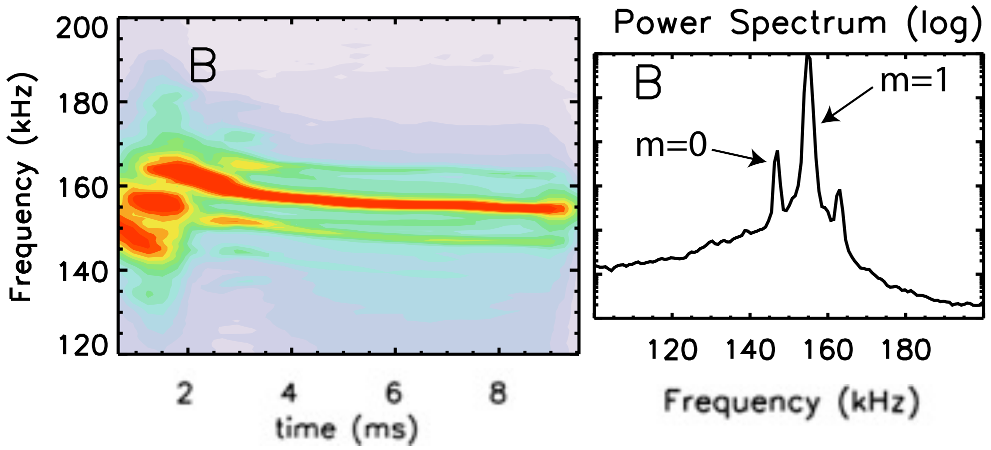




- Correlation function from BOUT comparable but longer correlation length predicted
- Simulation has comparable fluctuation amplitude, intermittency
- Near term focus: what establishes flow profile in LAPD? Studying Reynolds Stress, Boundary drive (collab with Rogers/Ricci)

Alfvén beat wave interactions 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)

Alfvén beat wave interactions in LAPD

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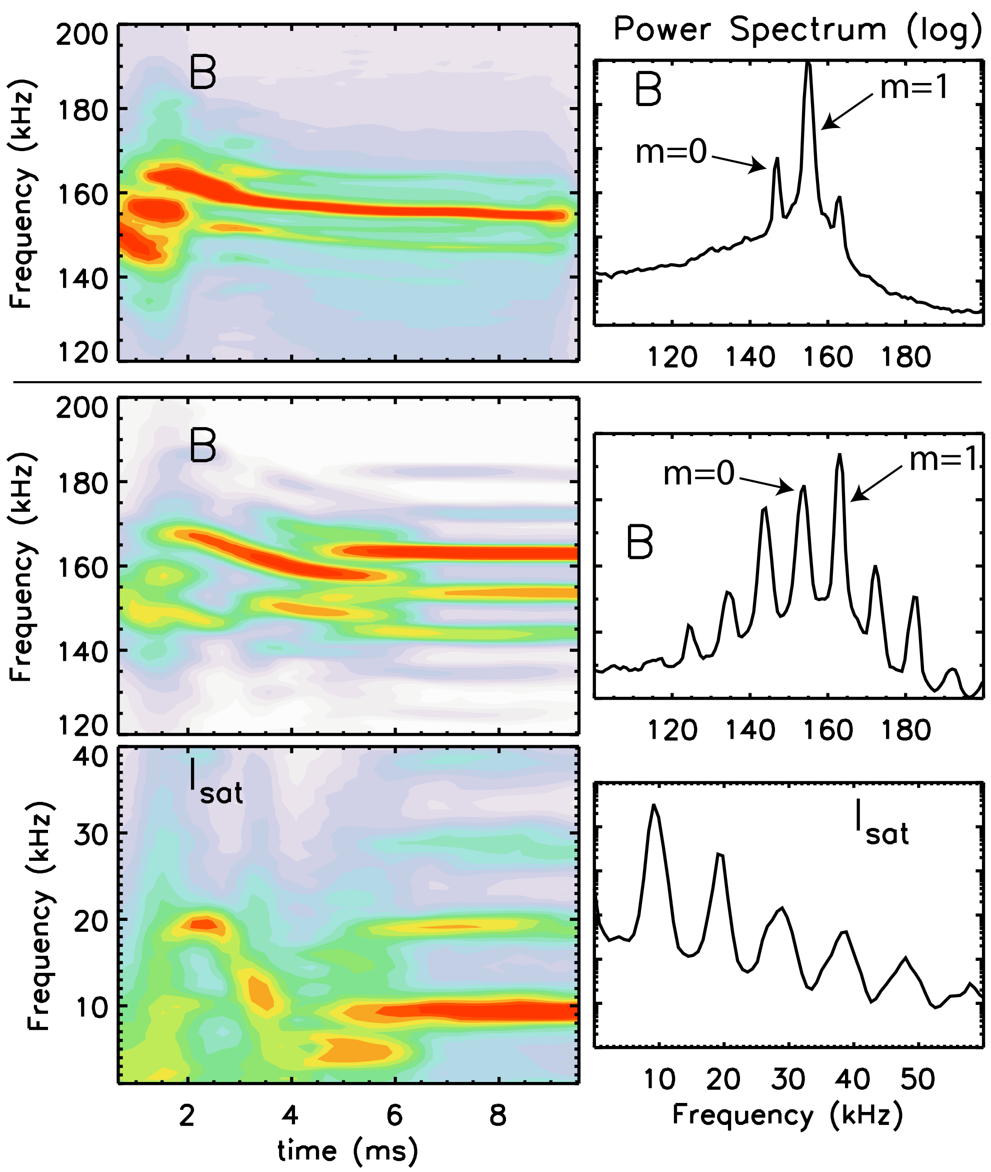
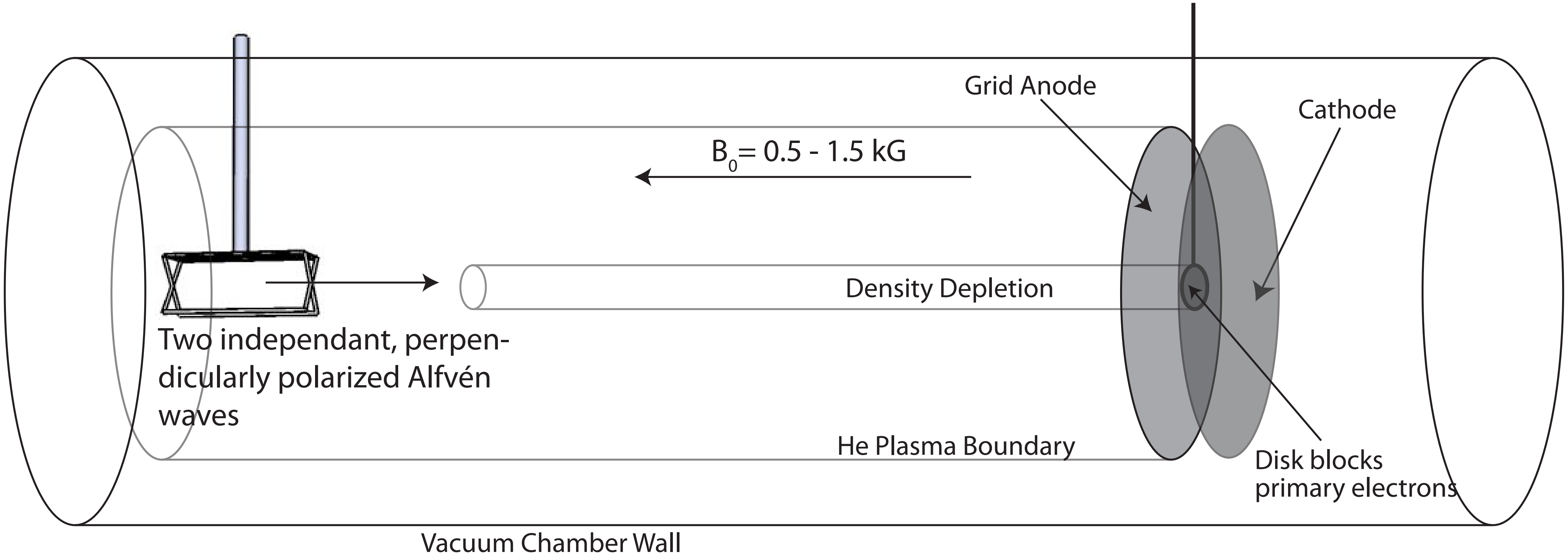


- Can control multimode emission (e.g. current, shortening the plasma column)
- With two strong primary waves, observe beat driven quasimode which scatters pump waves, generating sidebands
- Strong interaction: "pump" $\delta B/B\sim 1\%$, QM $\delta n/n \sim 10\%$

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

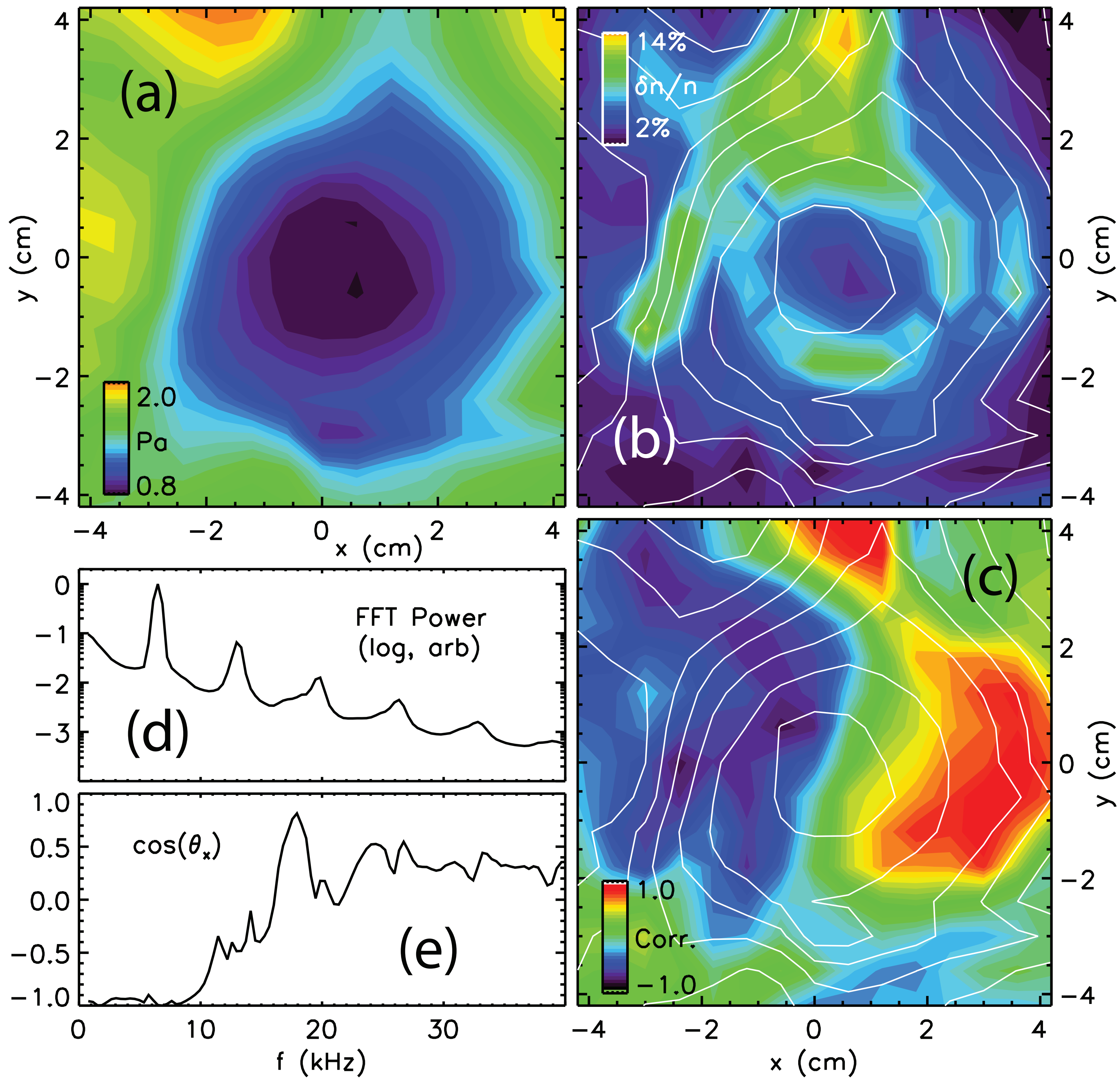
KAW beat-wave/instability interaction experiment



- Density depletion formed by inserting blocking disk into anode-cathode region, blocking primary electrons therefore limiting plasma production in its shadow
- Spontaneous growth of instability on periphery of depletion
- Launch KAWs into depletion, look for interaction

Auerbach, et al., arXiv:1004.0647, PRL accepted

Unstable fluctuations observed on depletion

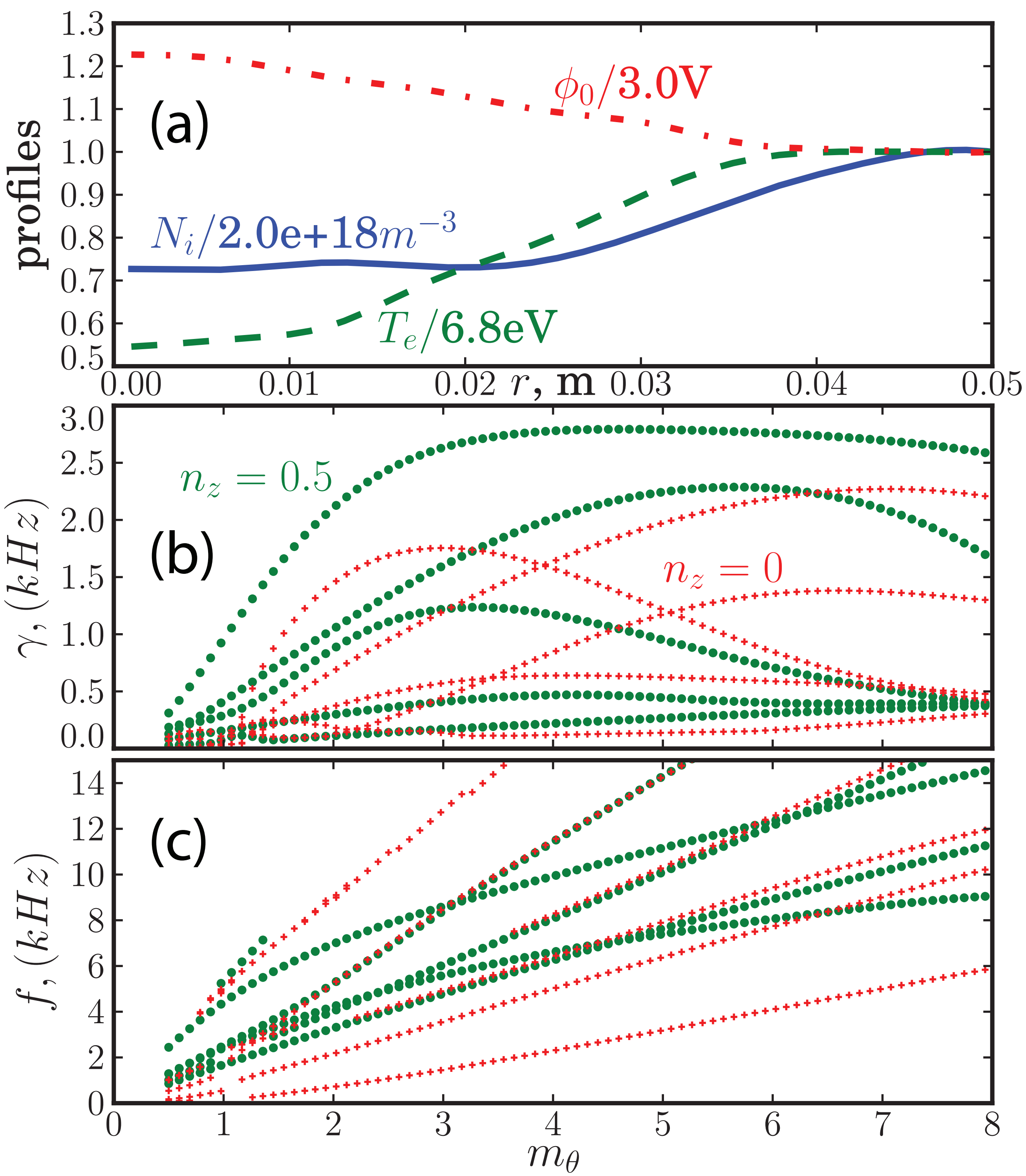


- m=1 coherent fluctuation observed localized to pressure gradient
- Drift-Alfvén wave?

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

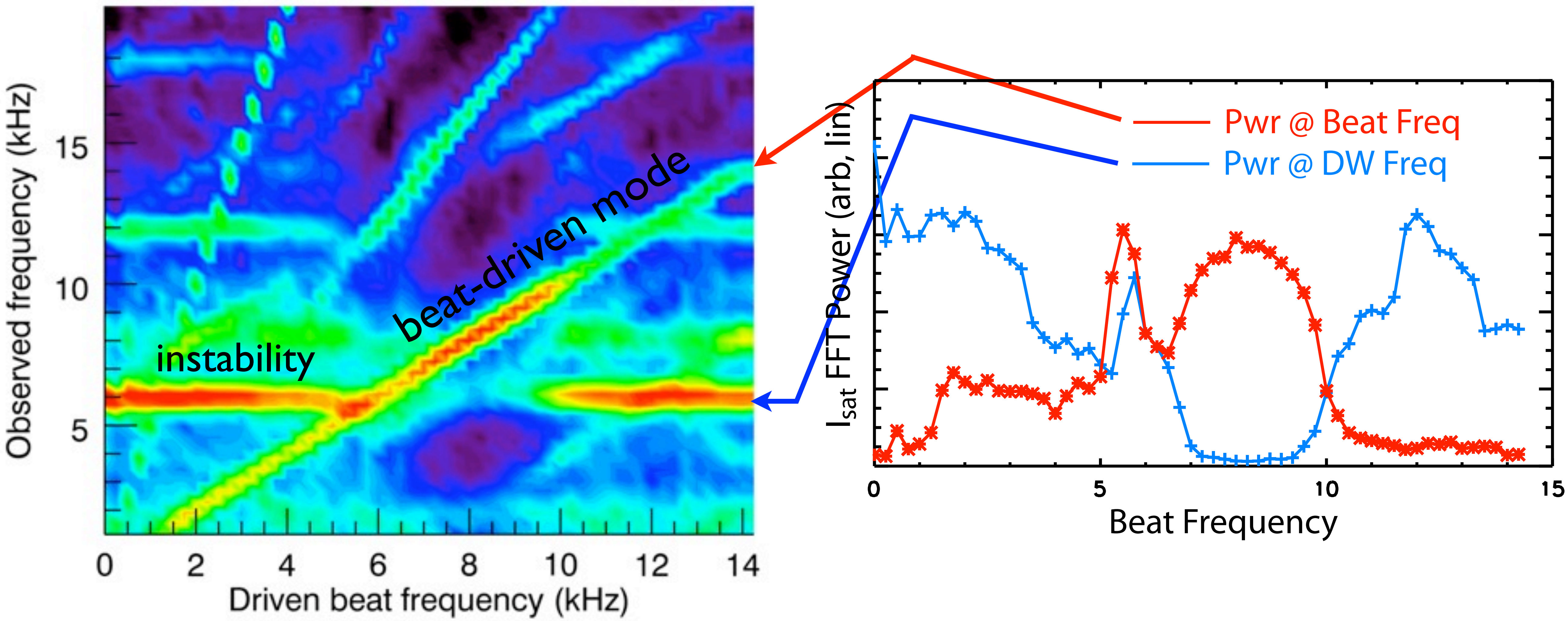
- However, Density-potential cross-phase (~180) inconsistent

Both pressure gradient and shear flow driven modes unstable



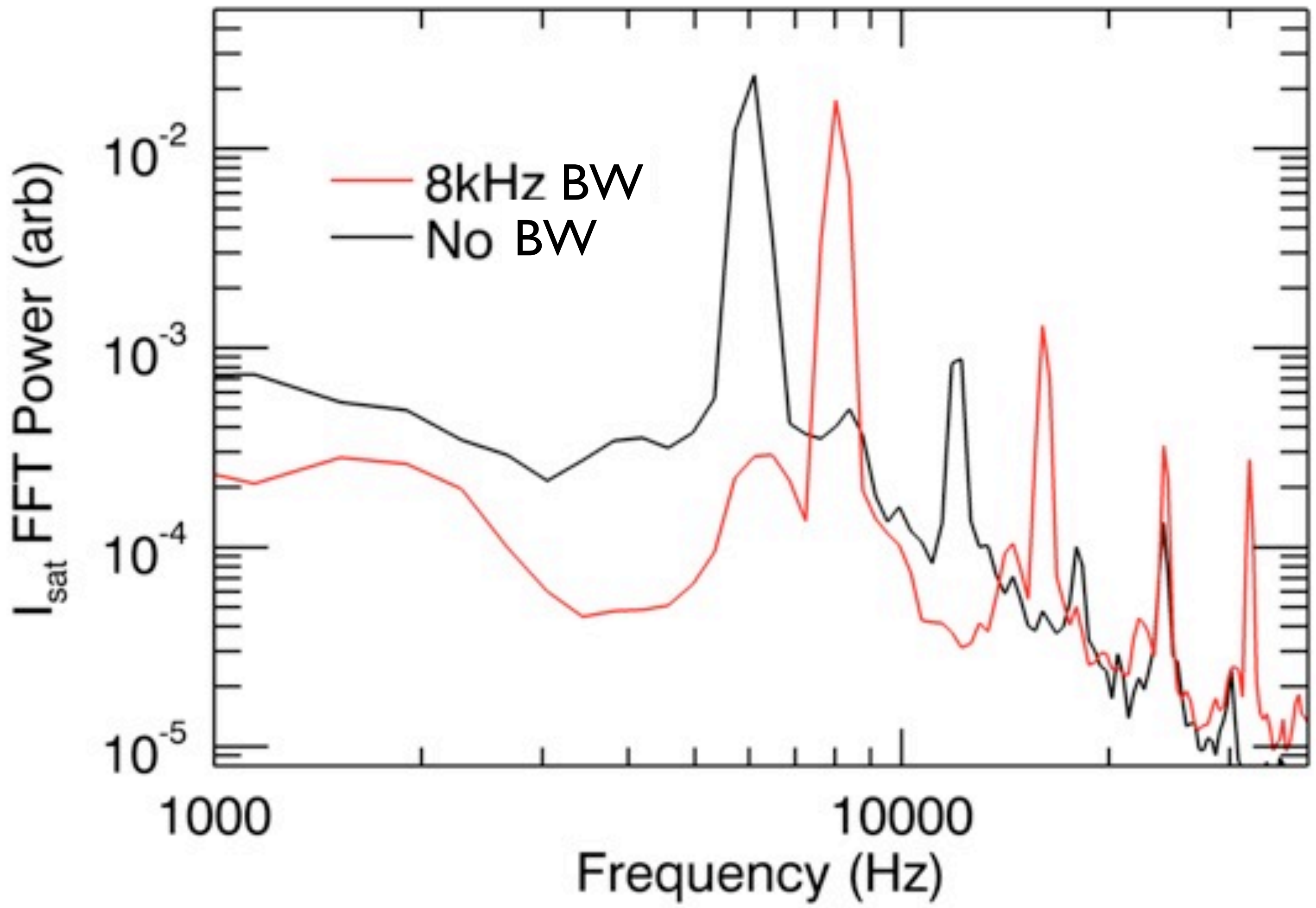
- Flows/potential gradient also present in density depletion
- Drift-wave and flute-like (Kelvin-Helmholtz) unstable on measured profiles (linear Braginskii fluid calculation)
- Nonlinear calculations (BOUT) in progress

Resonant drive and mode-selection/suppression of instability



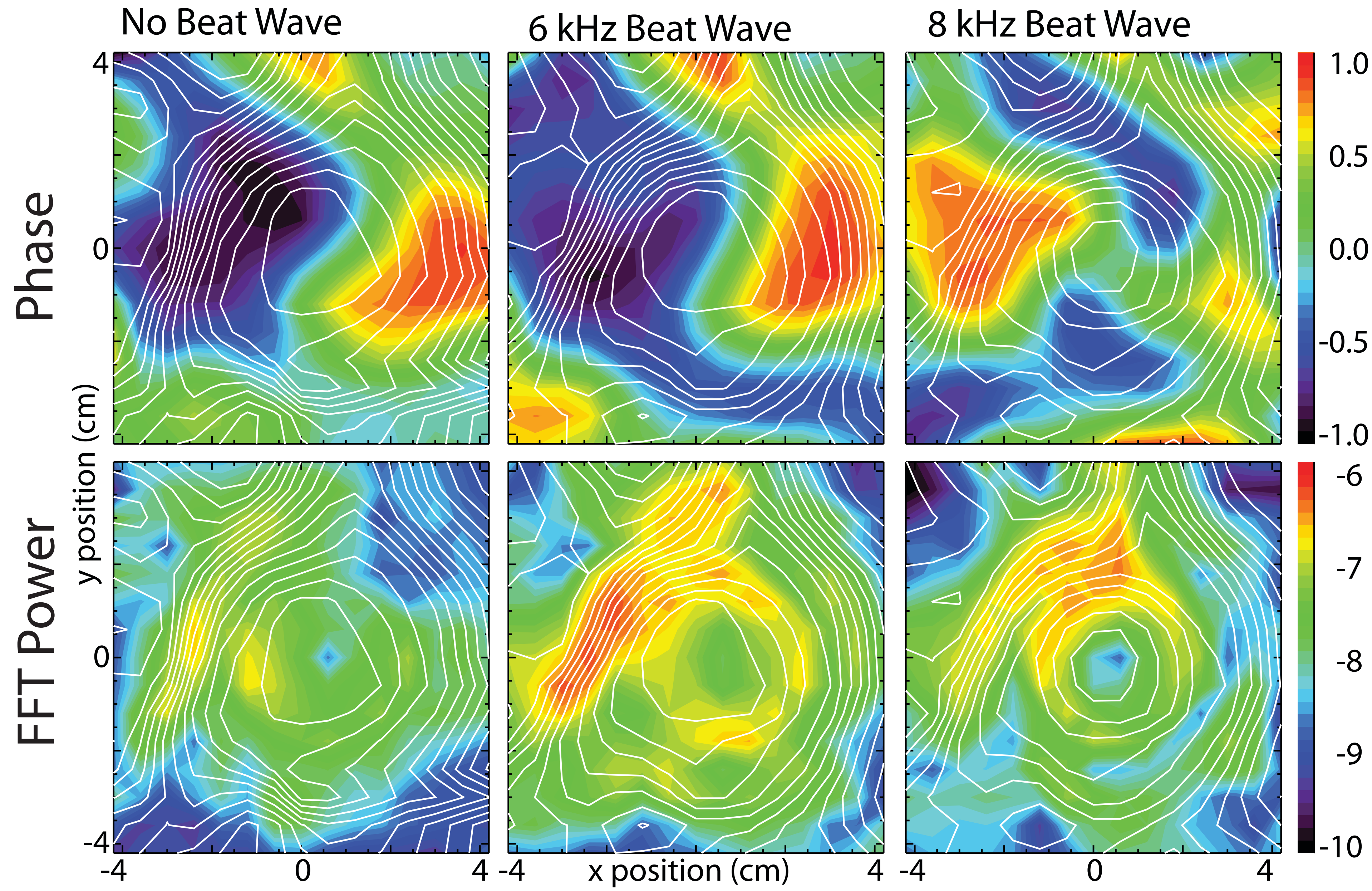
- Beat response significantly stronger than uniform plasma case
- Resonance at (downshifted) instability frequency observed, suppression of the unstable mode observed above (and slightly below)
- Instability returns at higher beat frequency

Suppression of coherent unstable mode and broadband noise



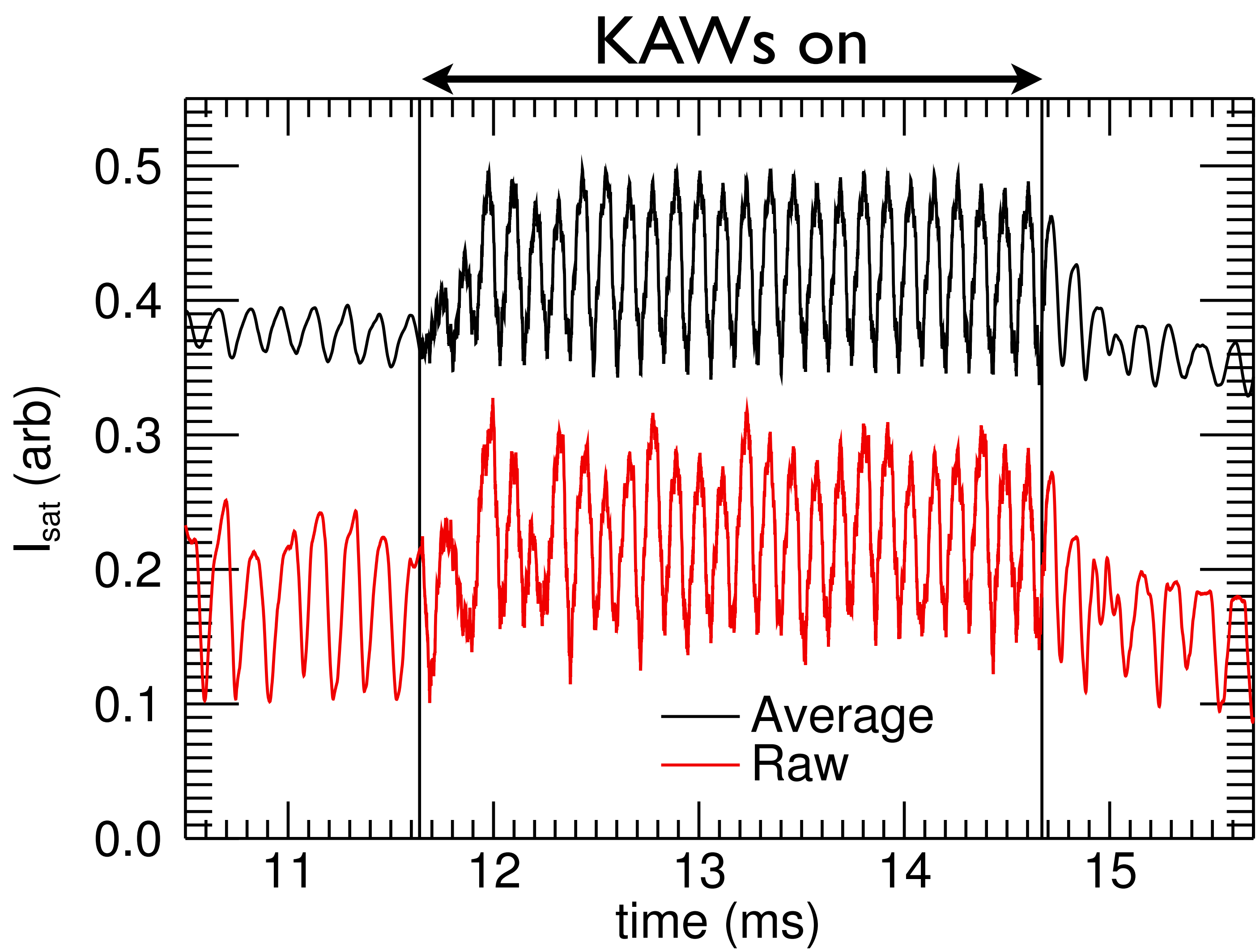
- Suppression for beat-driven wave amplitude comparable to unstable mode amplitude
- With beat wave, quieter at wide range of frequencies (motivates looking at interaction with broadband spectrum)

Structure of beat-driven modes



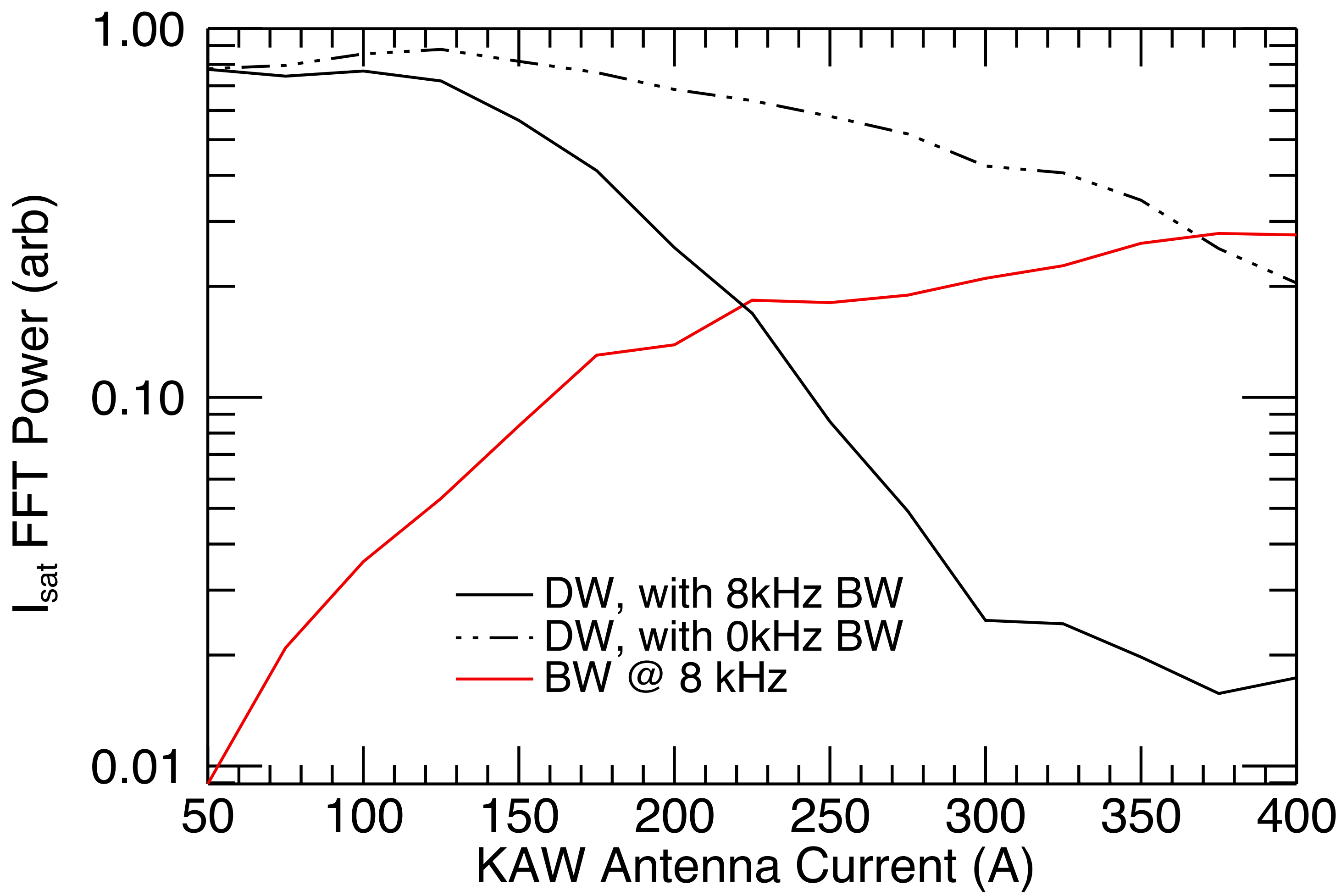
- Beat wave has m=1 (6 kHz peak), m=2 (8 kHz peak)
- Rotation in electron diamagnetic direction (same as instability)

Ring-up/Ring-down observed



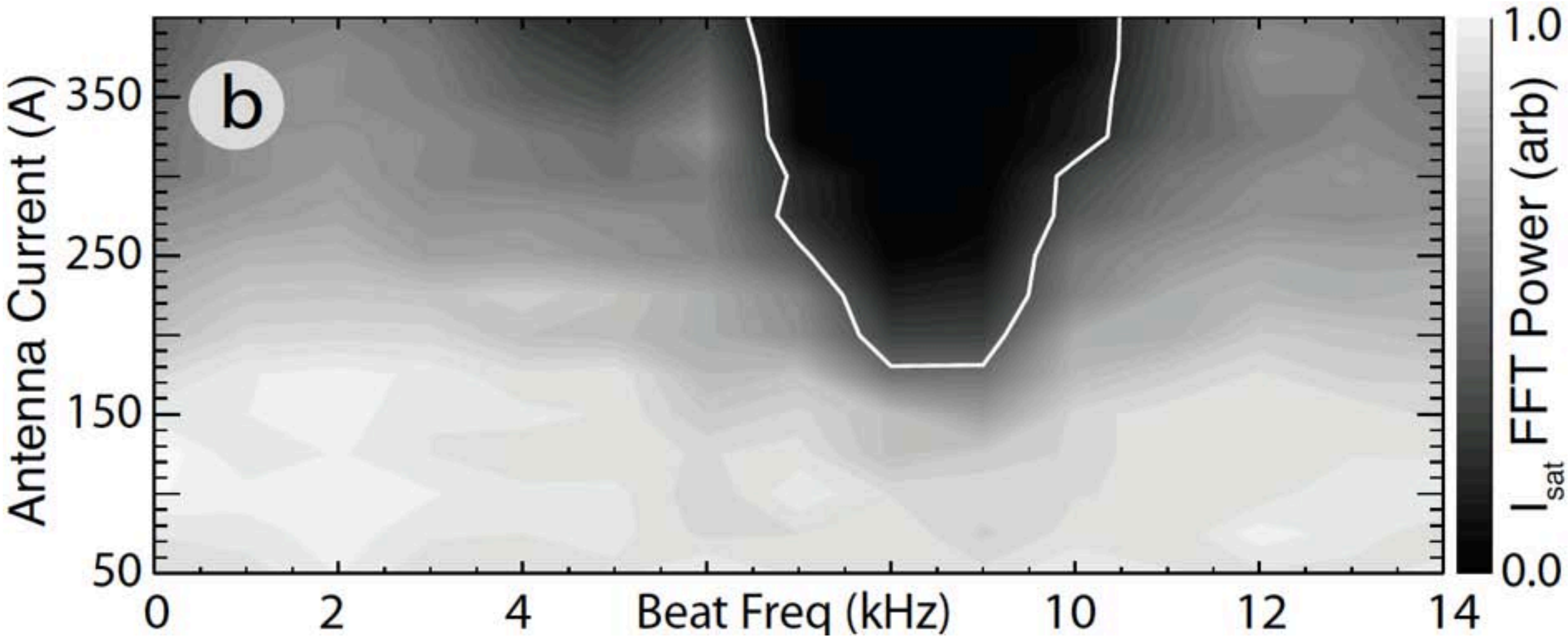
- 8kHz wave persists (rings down) after drive is shut-off; ring-up also observed
- Provides further support for coupling of BW to linear mode (DW/KH)

Threshold for control, saturation of BW observed



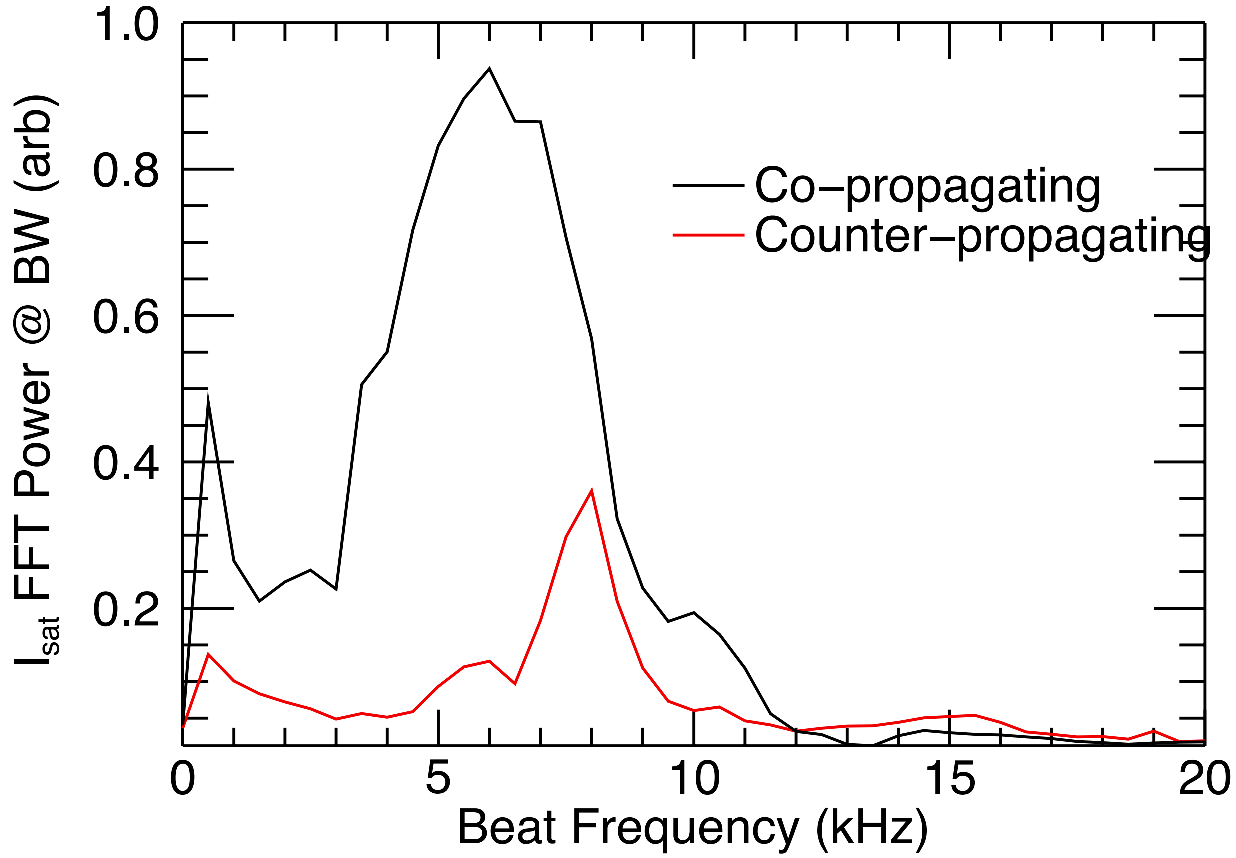
- Modification of DW seen starting at PBW/PDW ~ 10%; maximum suppression for comparable BW power
- Two effects: electron heating from KAWs modifies profiles, causing some reduction in amplitude without BW
- BW response seems to saturate as DW power bottoms out

Frequency width of control depends on amplitude



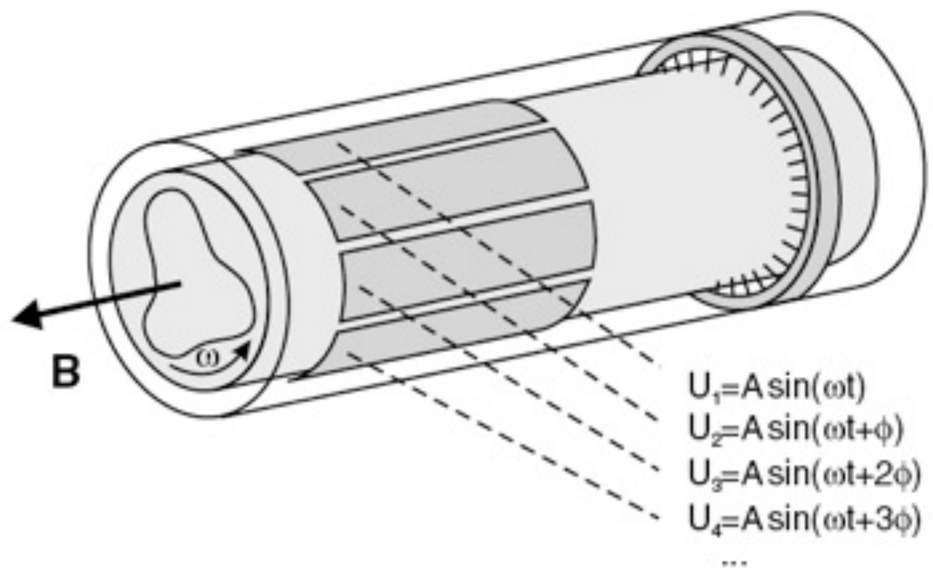
- Window of mode stabilization/control increases with increasing BW drive

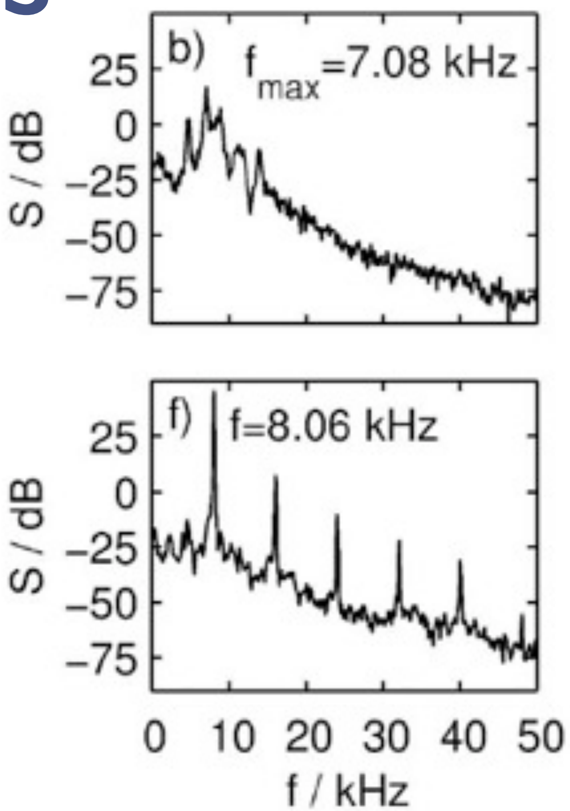
Parallel BW wavelength matters: weak resonant drive/suppression for counter-propagation



- 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…)

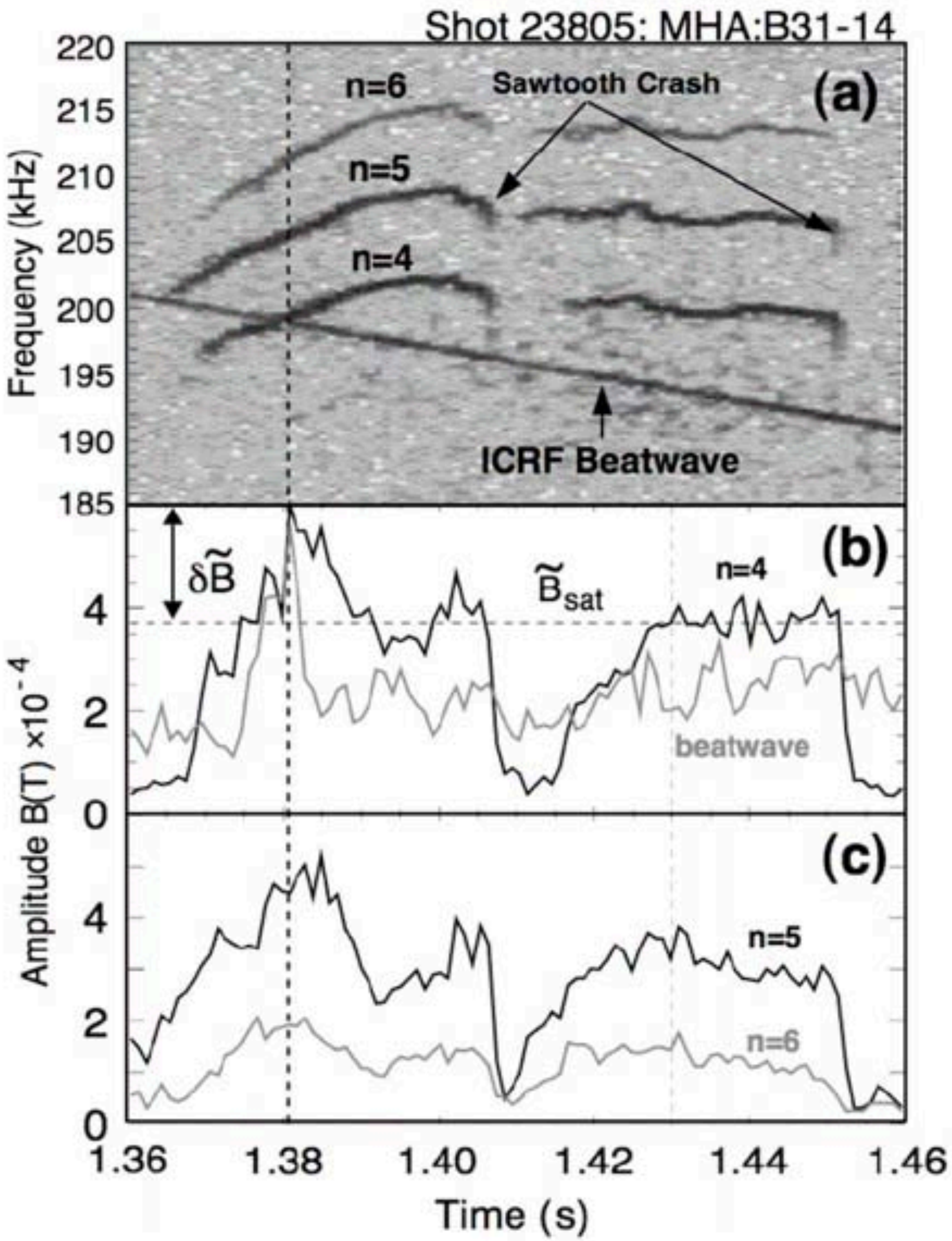
Similar behavior seen using external antenna to excite drift-waves





- Schroder, Klinger, et al, PRL 86, 5711 (2001)
- 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)
- Using AWs likely more portable to fusion devices? Can we suppress/control instabilities using beat waves driven by, e.g., ICRF?

ICRF beat wave control of drift turbulence?



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

- ICRF BWs used to excited TAEs in JET [Fasoli, et al.] and ASDEX [Sassenberg, et al.]
- Explore BW frequency near ITG/TEM/etc mode frequencies, modification of turbulent spectrum, transport?

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