Energy Transport Driven by Electron Temperature Gradients

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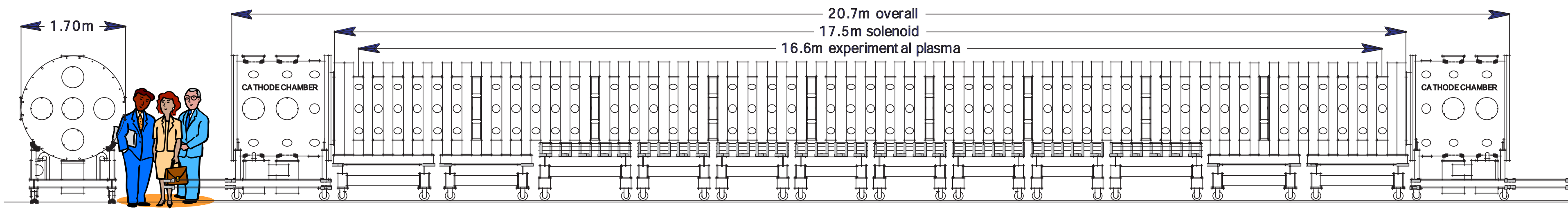
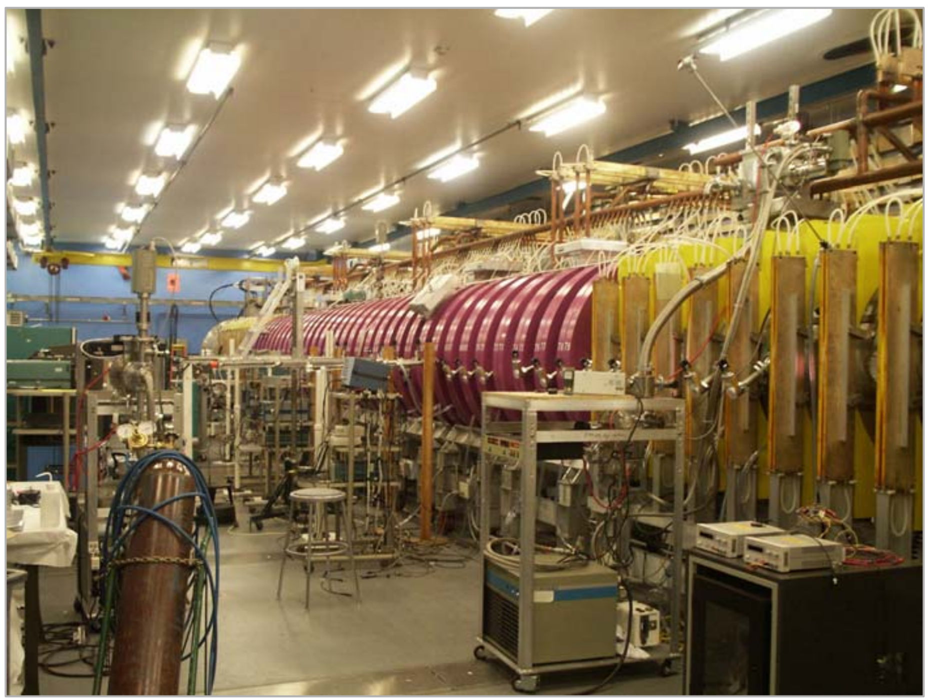
Abstract

An experimental study is made of the heat transport associated with controlled electron temperature gradients established in a large magnetized plasma. The phenomena investigated illustrates processes encountered in magnetic fusion as the development of broadband turbulence and increased electron heat transport closely follows the profile evolution. Axial and transverse electron temperature gradients are established in the LAPD-U device by injecting a narrow electron beam into a cold afterglow plasma. The beam energy is less than the ionization energy of the background neutral gas and the conditions approximate a localized heat source embedded in an infinite, strongly magnetized plasma. For low heating powers and/or short times, classical heat transport prevails and temperature gradients are formed both parallel and perpendicular to the applied magnetic field. As the heating power is increased, flows develop and drift-Alfven waves become unstable. Late in time these features evolve into broadband turbulence and result in anomalous transport that exhibits various spatio-temporal patterns. This study focuses on the properties of the spectral features that trigger the transition from coherent fluctuations to broadband turbulence.

LAPD's Size is Vital to this Transport Study

The Large Plasma Device (LAPD)





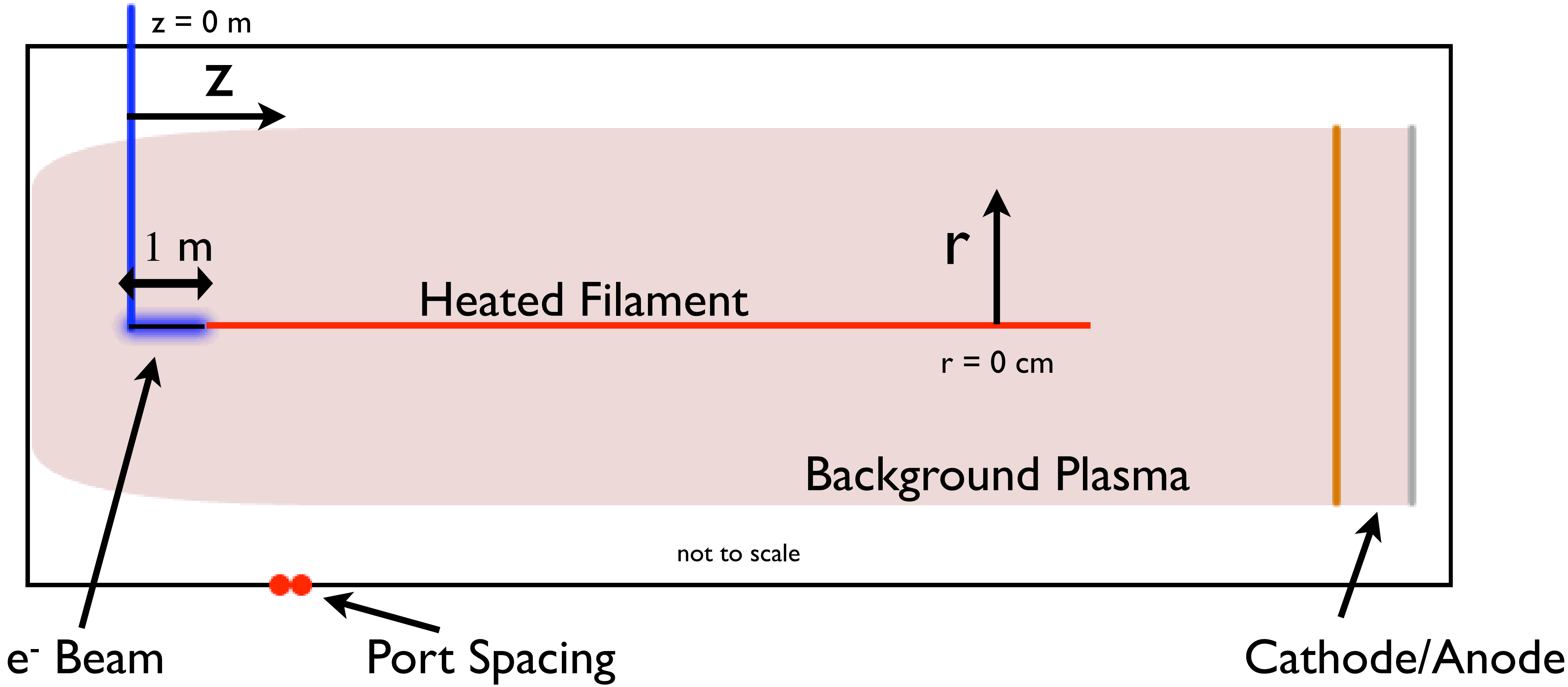
Cathode discharge plasma
Highly Ionized plasmas $n \approx 3 \times 10^{12}$ /cm^3
Reproducible, 1Hz operation
> 4-month cathode lifetime
Up to 2.5kG DC Magnetic Field on axis
Plasma column up to 1000R_{ci} in diameter
Over 450 Access ports, with 50 ball joints
Computer Controlled Data Acquisition
Microwave Interferometers
Laser-Induced Fluorescence
Large variety of probes

* Slide Content by Steve Vincena, LAPD Laboratory

Electron Energy Transport is Studied in a Controlled Environment Allowing for Variation of Relevant Parameters

- Effort concerns the study of a transition from classical transport to a wave-induced, turbulent transport.
  - A controlled temperature filament is generated in a cooler background plasma, $r_{filament} \sim r_{cathode} / 230$
  - Early in the temporal evolution of the system the heat transport is governed (to within experimental uncertainty) by classical effects.
- The system may be approximated as a heated filament in an infinite background plasma.

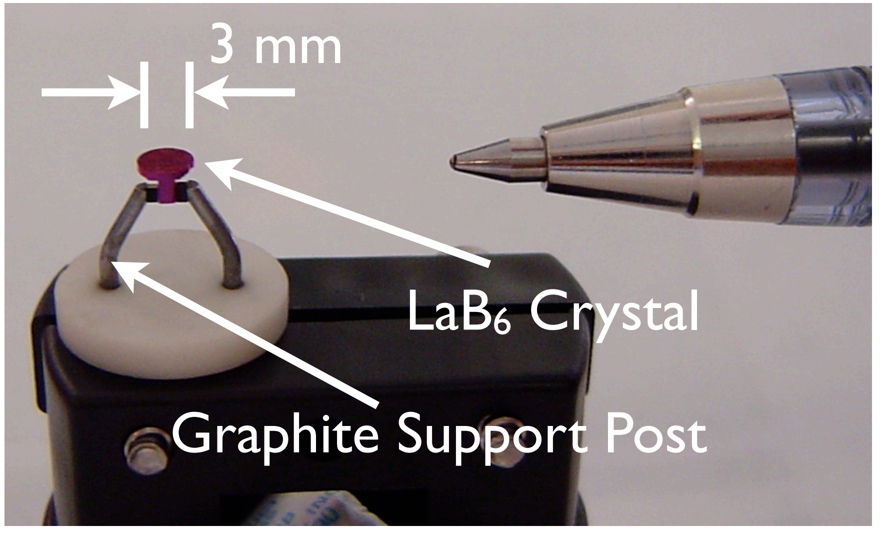
Heat Plume Geometry Leads to Comparable Axial and Radial Heat Transport

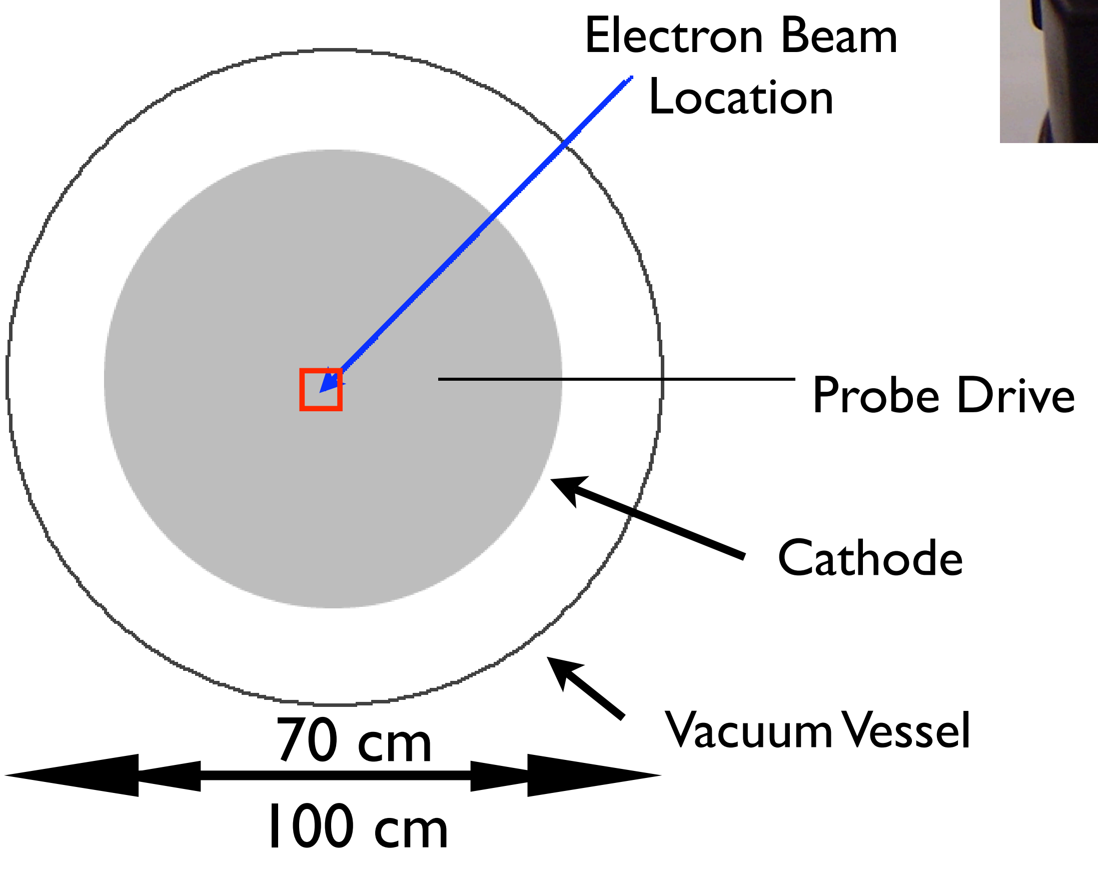


- Radial transport investigated along length of heat plume.
- Beam electrons are thermalized within one meter of emission.
- Probe ports available along entire axial extent: ~ 32 cm spacing with probe ability to reach intermediate axial locations.

Small Electron Beam Generates Heat Source Without Ionization of Background Plasma

- Lanthanum Hexaboride (LaB_6) crystal
- Emission at ~ 1800 °C
- Emission Current > 200 mA



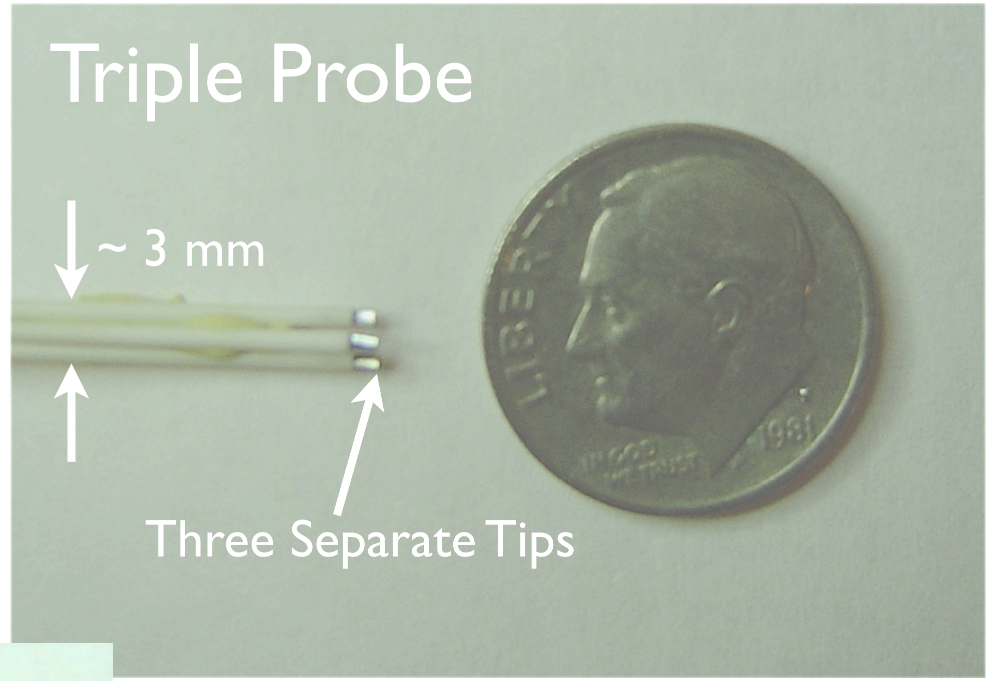


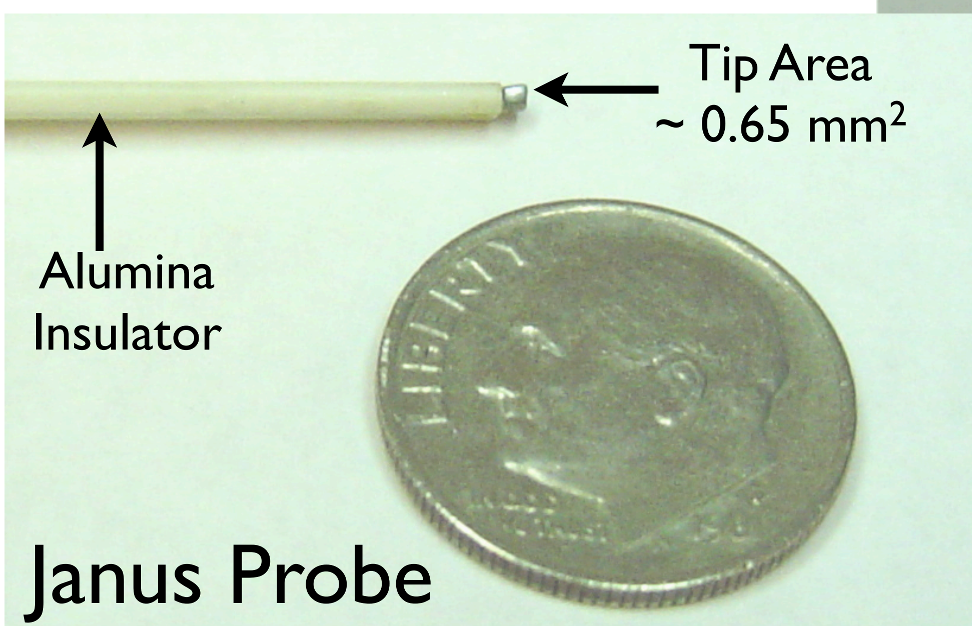
- Small region of interest, area ~ 2.5 x 2.5 cm
- Filament radius on scale of ion gyroradius.
- Filament geometry sets strict requirements on diagnostic design, small Langmuir probes vital to investigation.

Diagnostics Array Provides Measurements of Various System Properties

- Triple Probe: Simultaneous measurement of electron temperature, ion saturation current, and floating potential

- Janus Probe: Provides for ion saturation current and flow along one direction (Mach number)



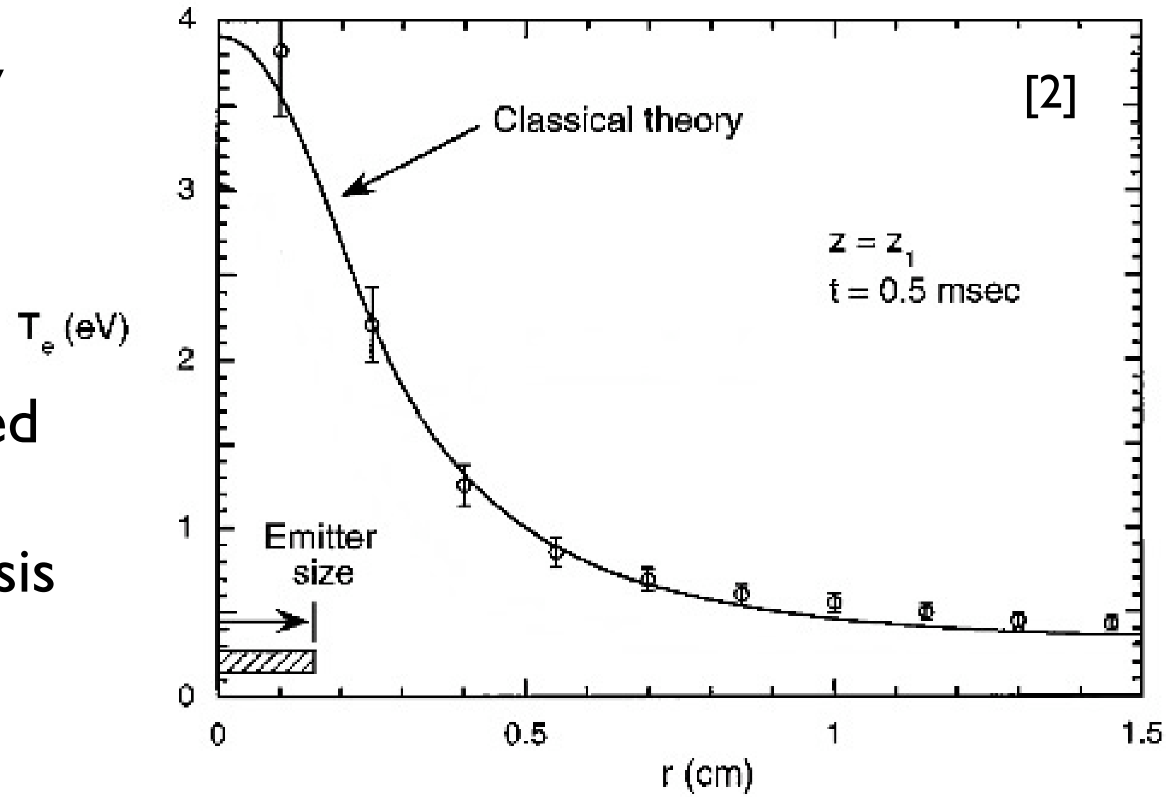


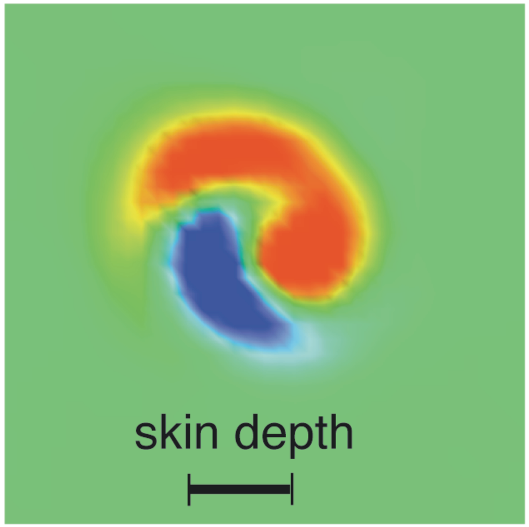
- Single Tip Langmuir Probe: Least perturbative, tip area ~ 0.7 mm^2

- Additional efforts concentrated on heat flux probe and non-perturbative optical measurements

Previous Work

- Formulation of classical theory compiled 50 years ago [1].
- Experimental verification of classical transport accomplished in similar geometry with previous LAPD device and thesis work (Burke) [2].
- Extensive measurements of perpendicular energy transport exceeding classical predictions have been made [3].
- Drift Alfvén mode observed along with anomalous energy transport rates [4].



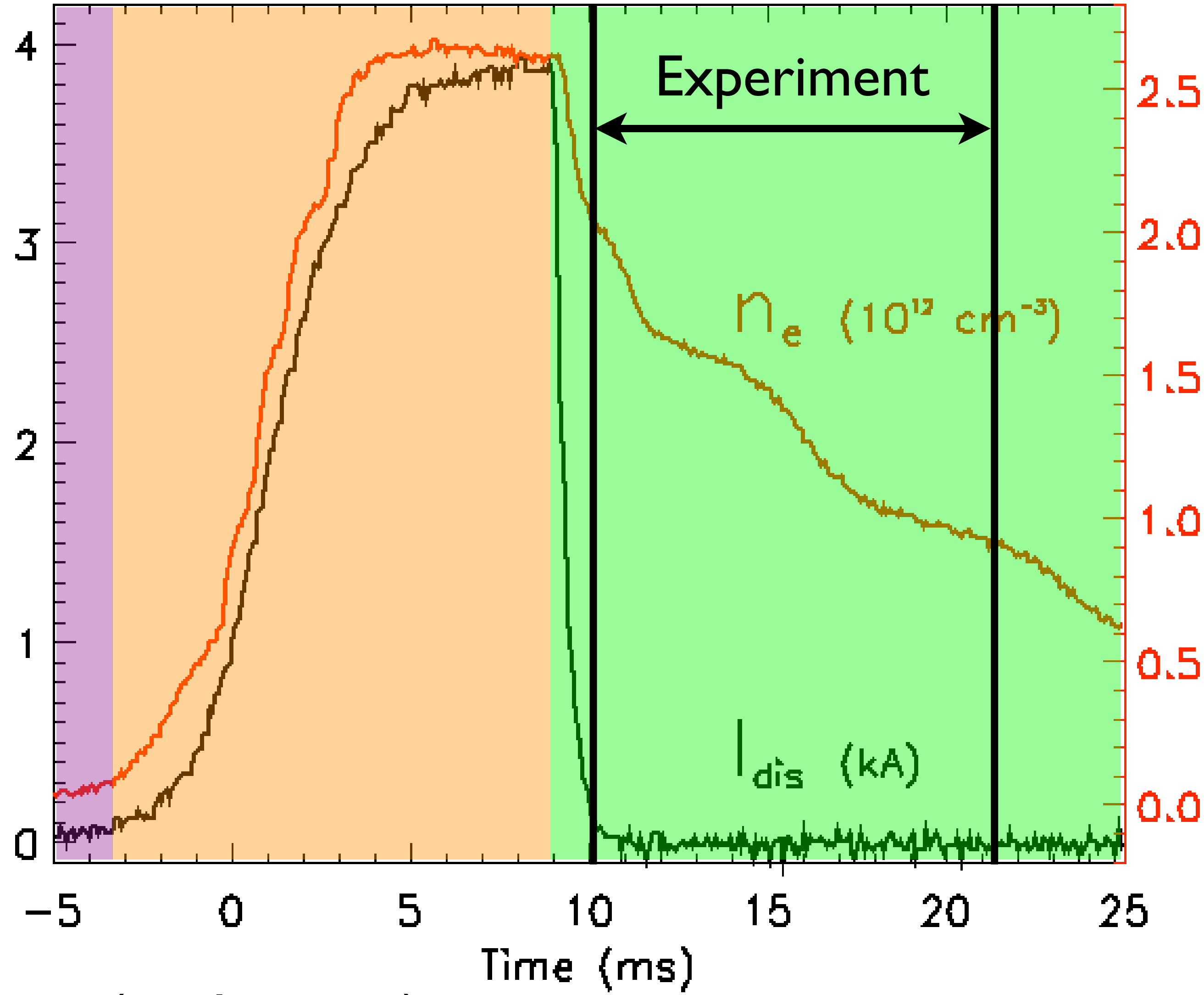


[4]

LAPD Afterglow Provides
Low Temperature and Moderate Density

DC State
- Down state between shots.

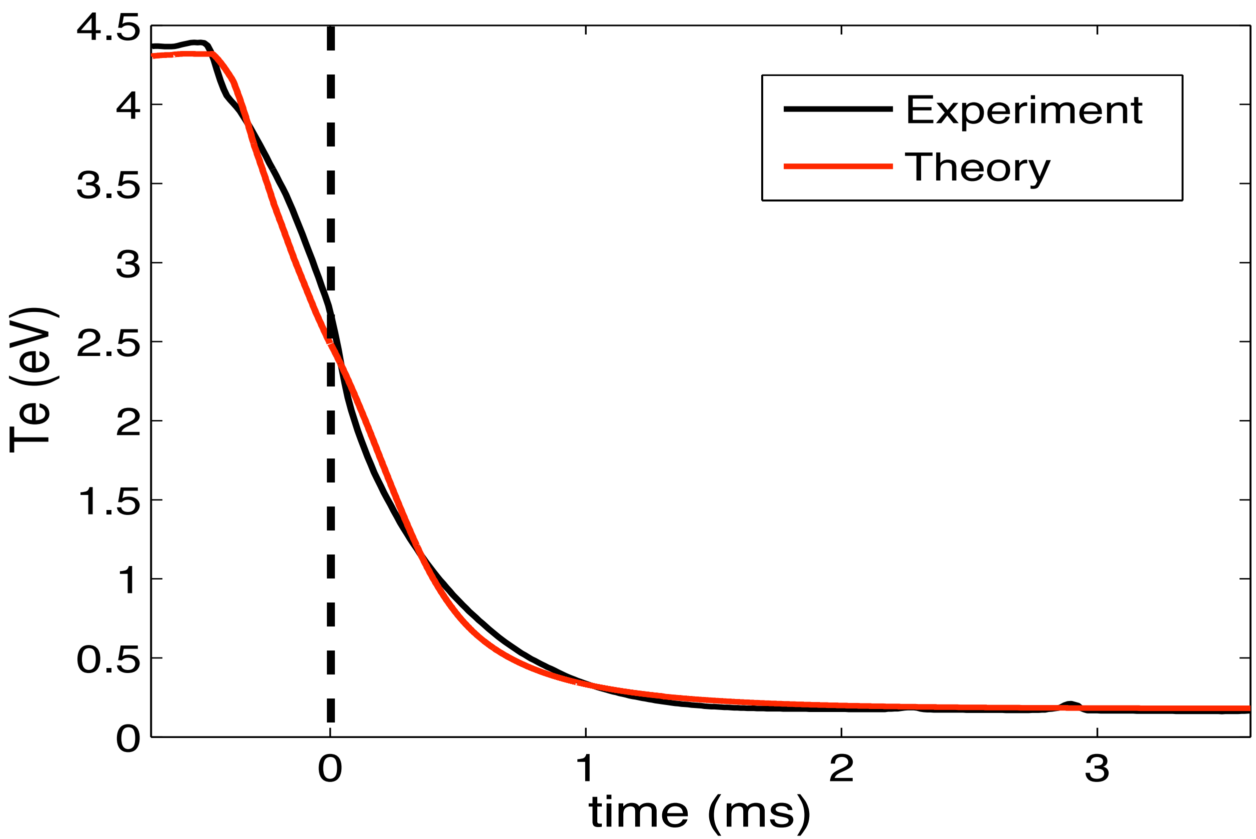
Discharge
- Current ramp up to flat-top.
- Adjustable time length, typically ~ 10 ms.



Afterglow
- Discharge current at zero (no heating).
- Temperature decays rapidly (τ_{decay} ~ 50 μs).
- Significant density maintained for t > 100 ms.

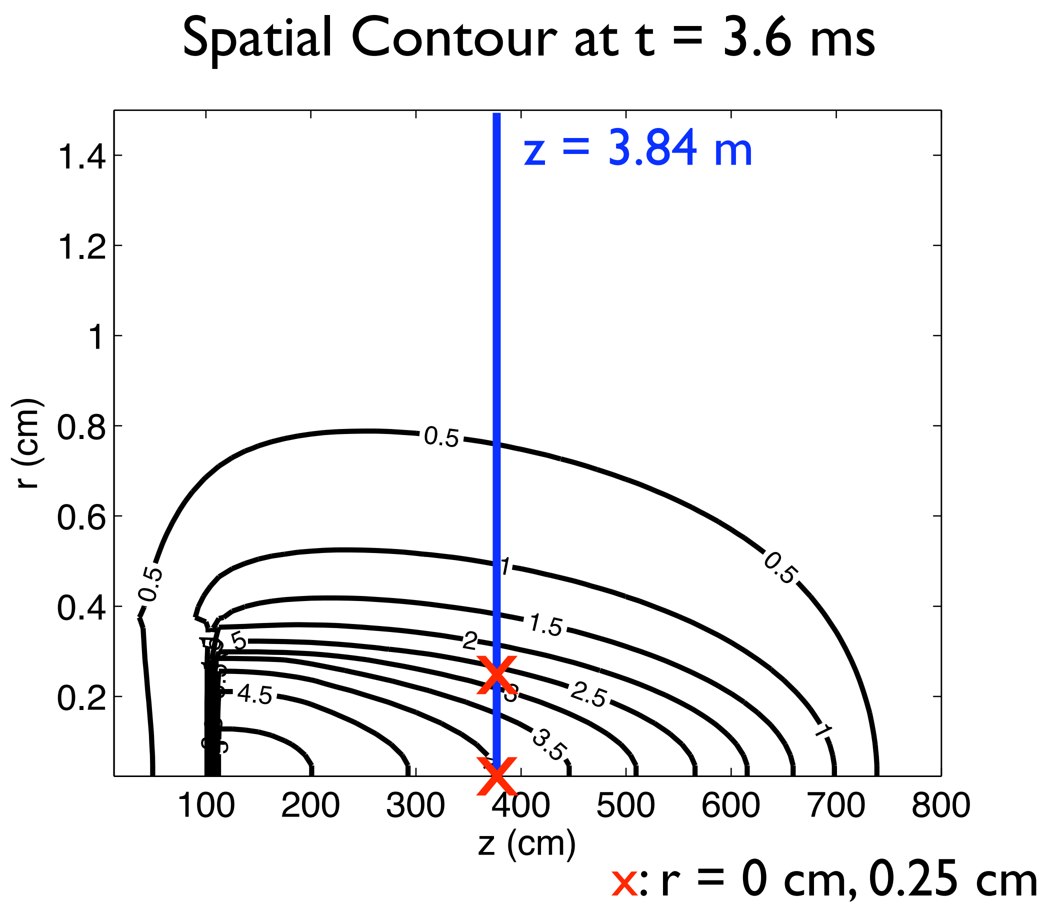
Rapid Temperature Decay in Afterglow Allows for Significant Beam Heating

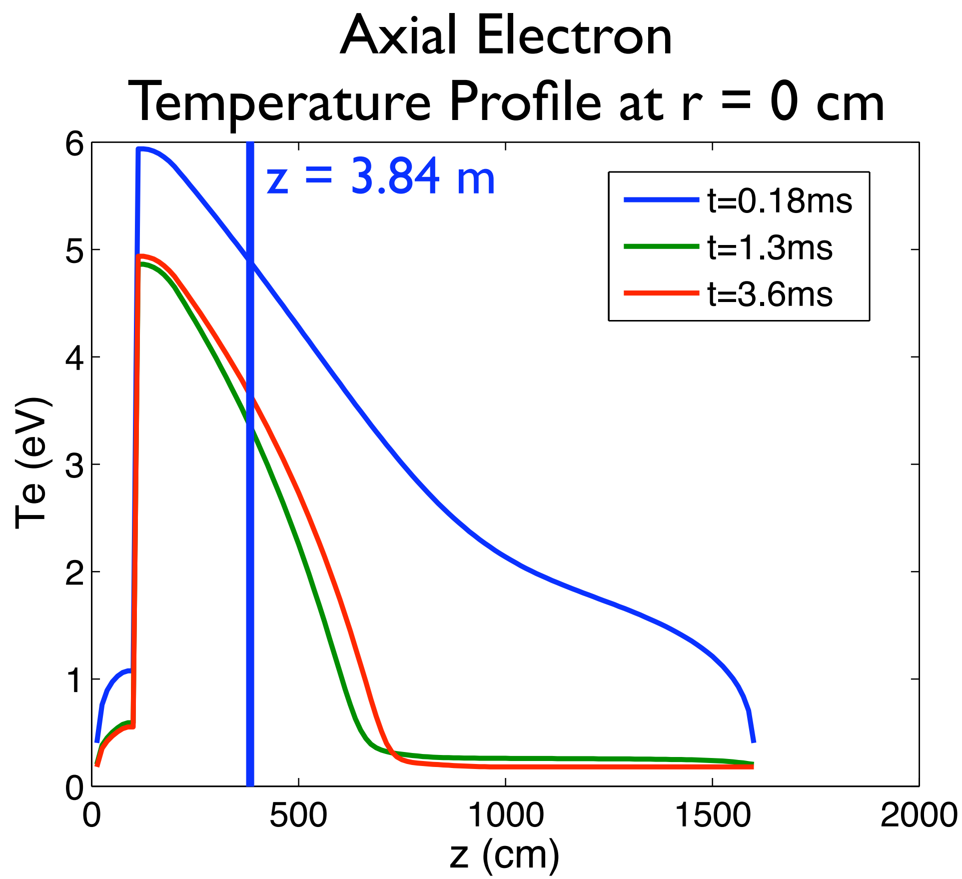
- Beam heating produces $\delta T_e / T_e \sim 5$.
- Beam voltage set below ionization level of ion species.
- Temperature decay in afterglow treated in previous work.



- Time t = 0 ms set according to the beam turn-on.
- Strong agreement between measurement and theory for afterglow behavior.
- Amplitude of initial temperature gradient determined by position of beam turn-on in afterglow decay.

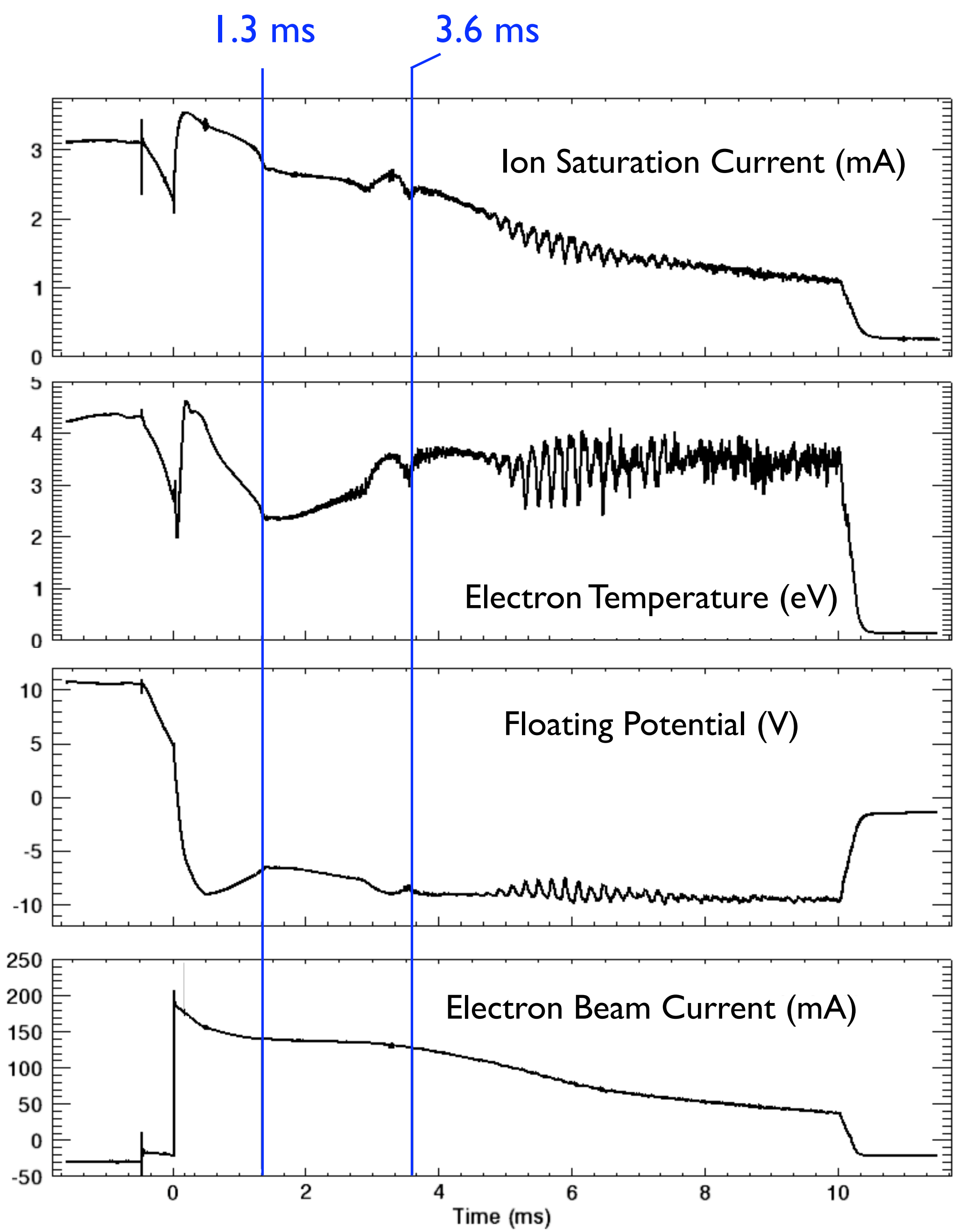
Spatial Profile of Filament Evolves in Time, Requiring Measurements at Multiple Axial and Radial Positions





- System is axisymmetric, the filament center is defined as r = 0 cm.
- Radial profiles taken at various axial locations.

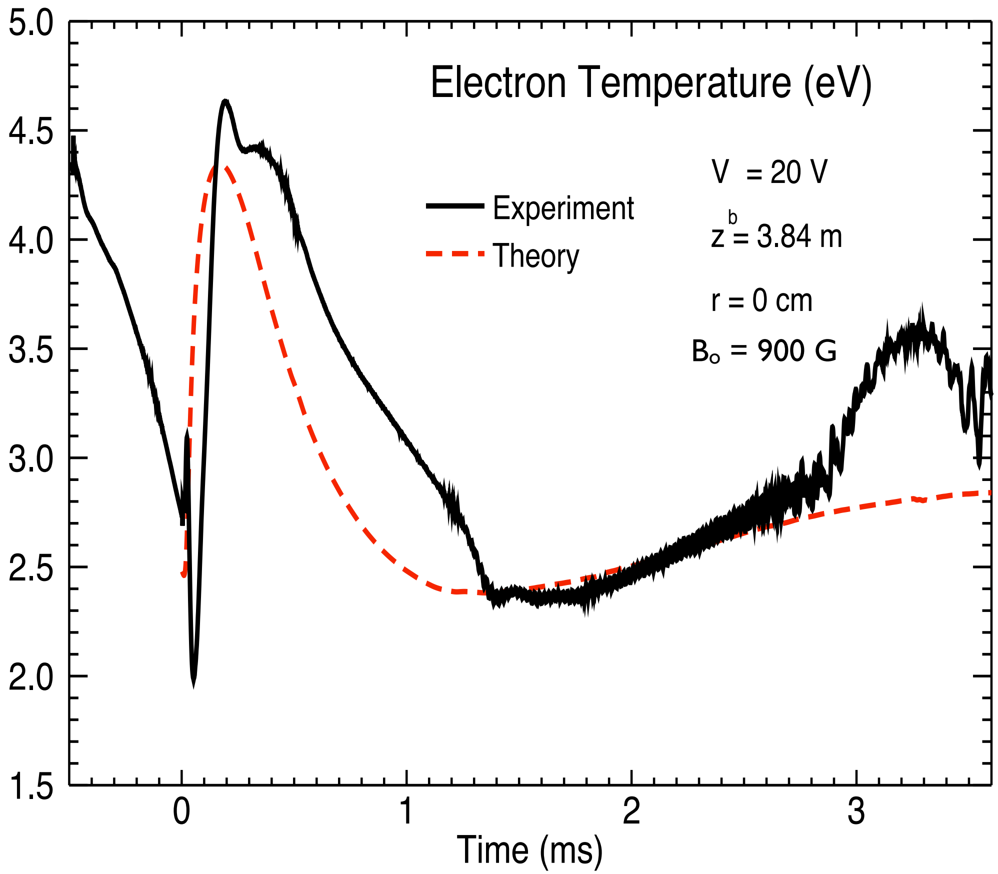
Time Traces Display Separate Regimes of Classical and Turbulent Transport

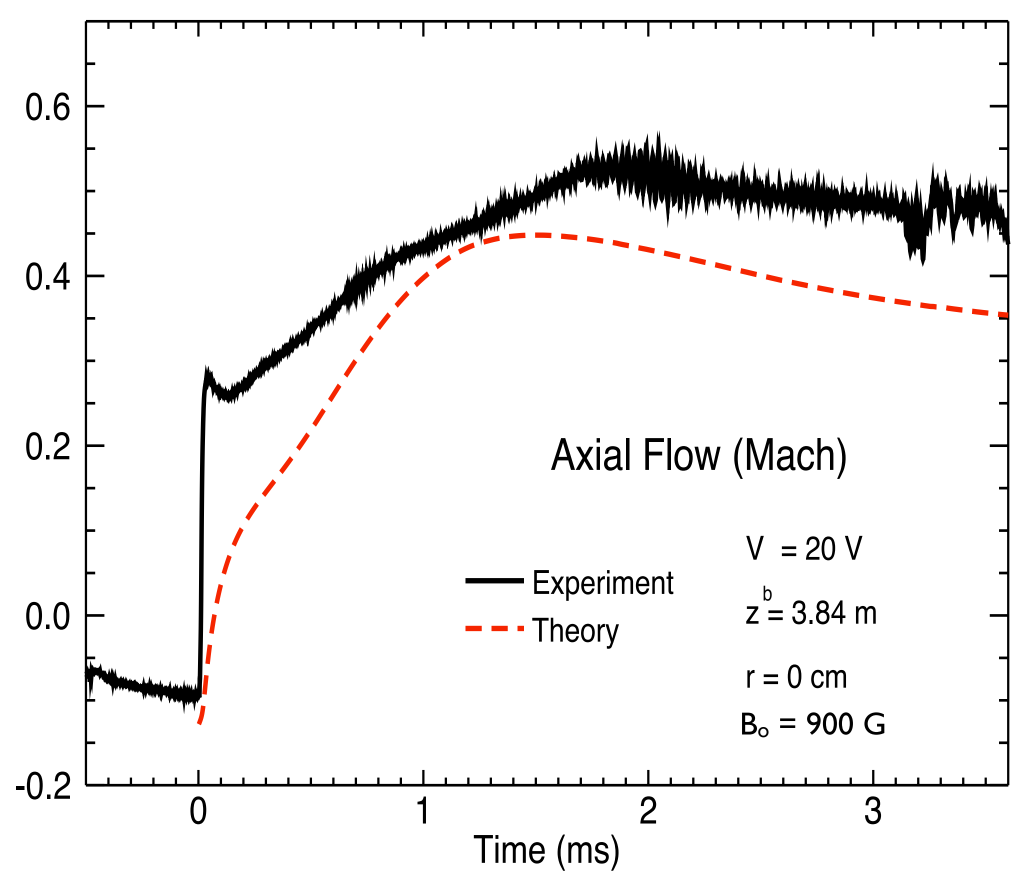


- Classical transport region ($t \lesssim 3.6$ ms) denoted by lack of large amplitude fluctuations.
- Two specific time points chosen for theory comparision
    - t = 1.3 ms : minimum of electron temperature due to retreat of heat plume
    - t = 3.6 ms : recovery of electron temperature due to return of heat plume

z = 3.84 m
r = 0 cm
B_o = 900 G

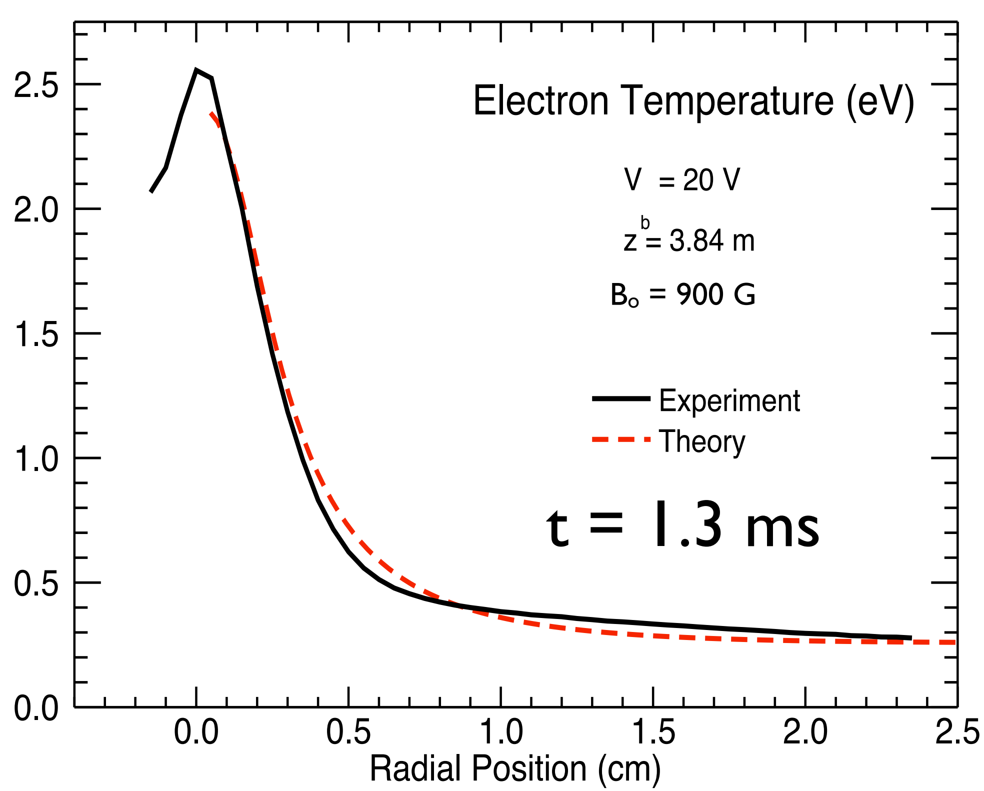
Complementary Theoretical Effort Provides Comparison and Validation of Classical Behavior Early in Time Evolution

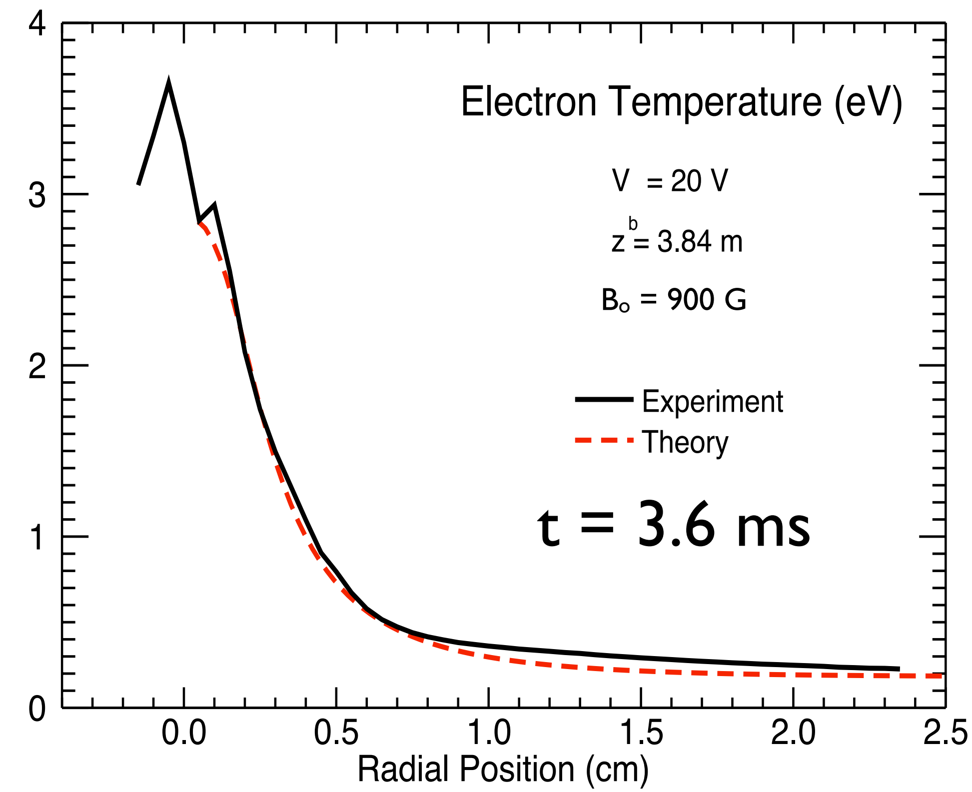




- Theory results produced by 2D, cylindrical geometry Braginskii equation solver.
- Departures from code results may indicate transition from classical transport to a turbulent regime.

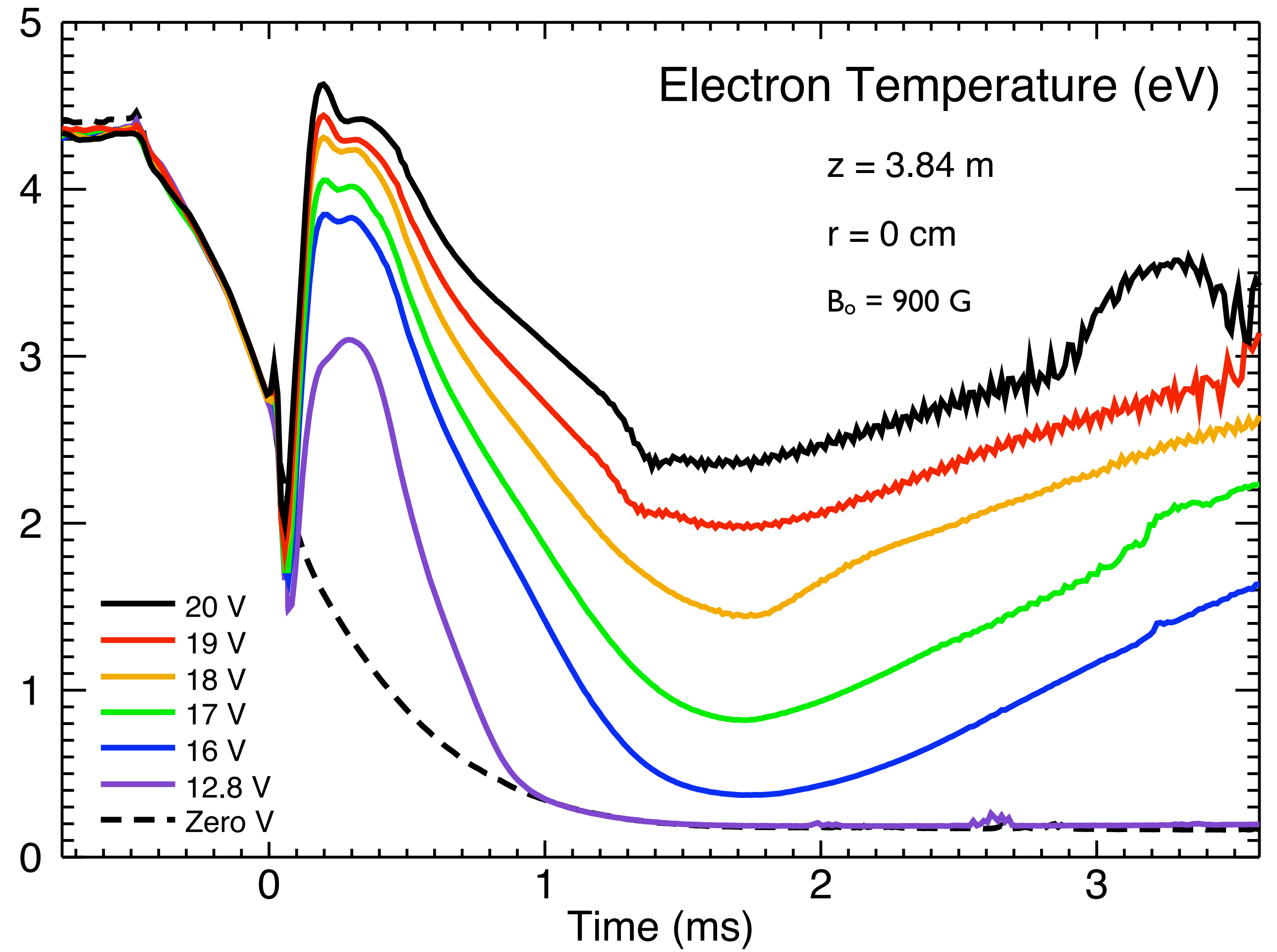
Spatial Profiles of Electron Temperature Show Excellent Agreement and Confirm Initial Classical Transport





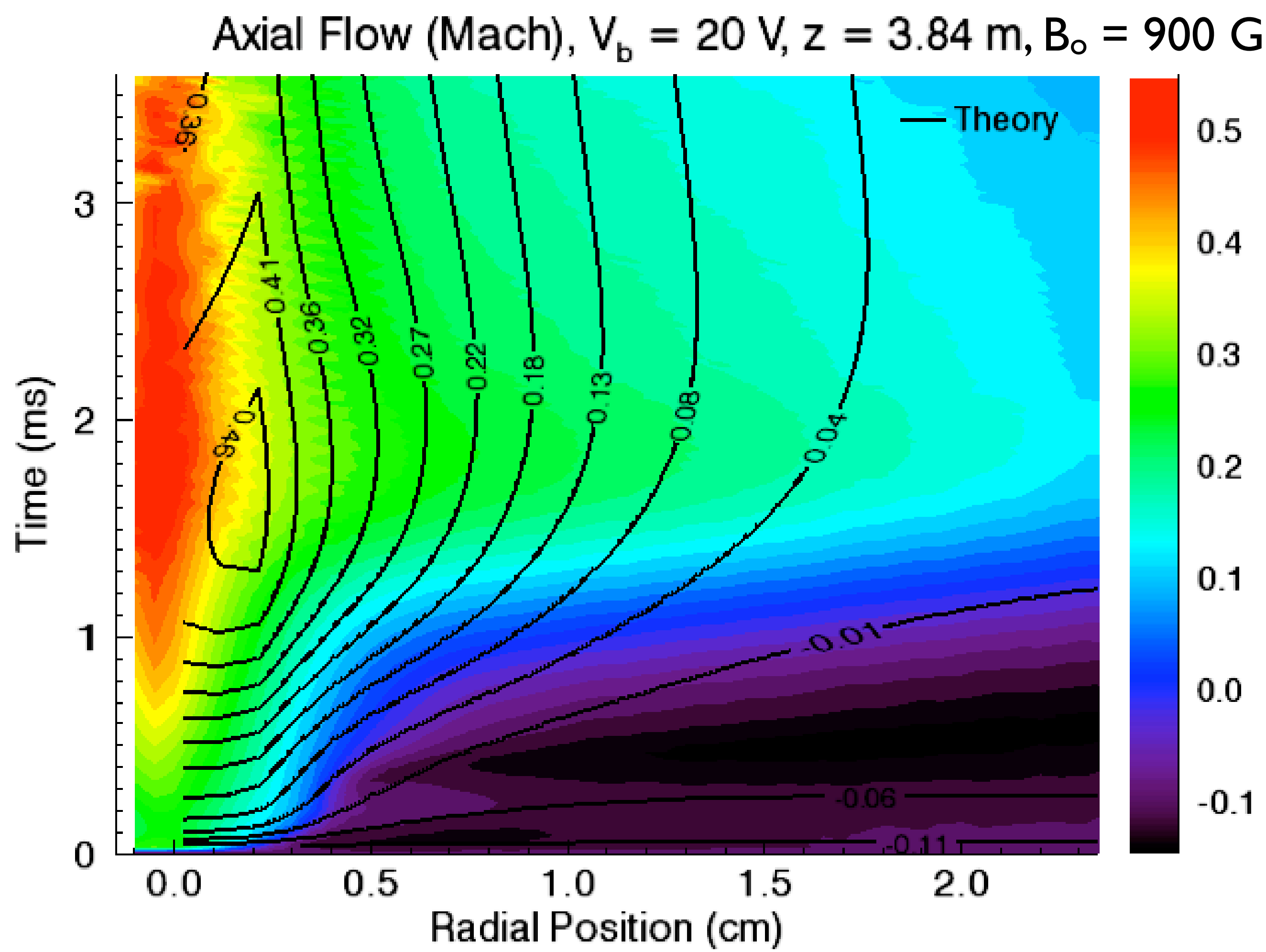
- Experimental values from planar triple probe.
  - Small (~ 1 mm) probe tip dimensions allow for measurements across filament.
  - Probe provides additional measurements of floating potential and ion saturation current.
- Theoretical profiles diverge from experimental results late in time (i.e. $t \gtrsim 3.6$ ms).

Injected Power Variation Significantly Affects Filament Length and Temporal Behavior



- Temporal behavior implies axial extent of heated filament evolves according input power.
- Power scans (variation of electron beam voltage) allow for study of varied temperature gradient amplitude.

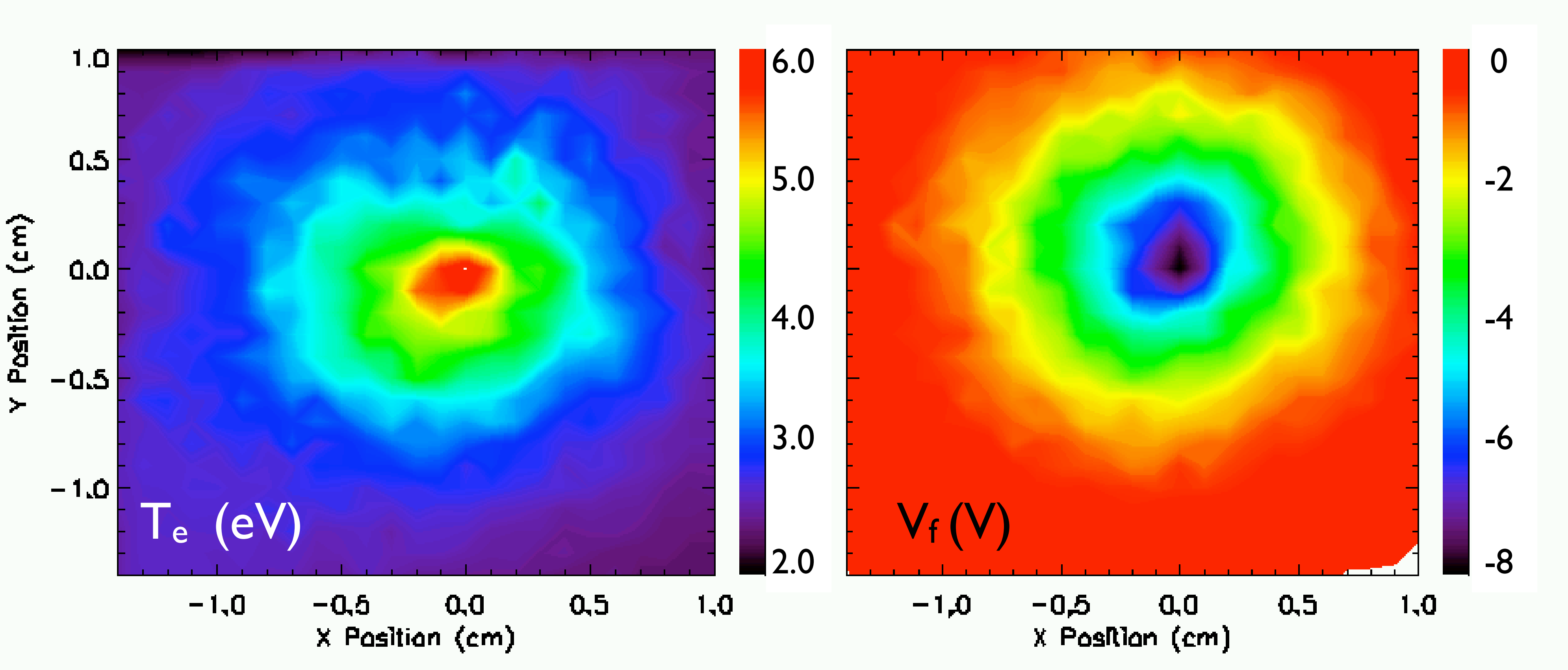
Axial Flow Profiles Extend Radially Further than Electron Temperature



- Measurements indicate increased axial flow values up to r > 2 cm.
- Wide radial extent of axial flow is seen in both measurements and theory results.

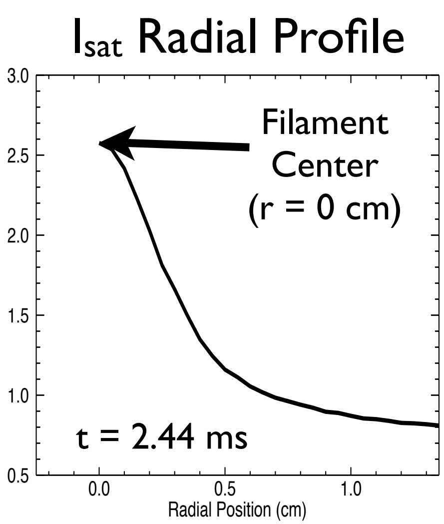
Heat Plume Exhibits Expected Radial Symmetry During Beam Heating

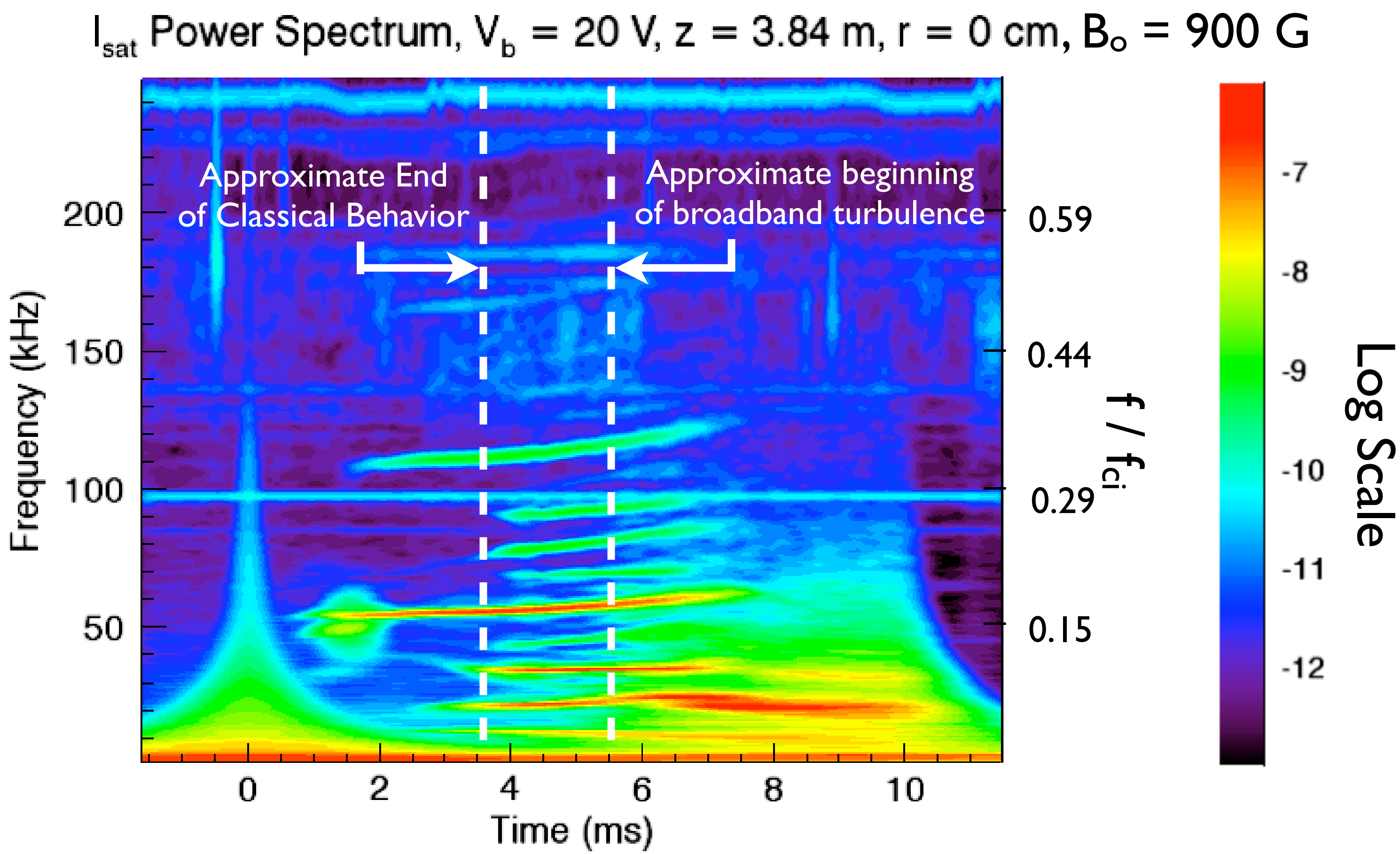
- Electron temperature (T_e) and floating potential (V_f) contours display fluctuations.
- Fine spatial resolution results in apparent, though non-physical, vertical offset in signals (separation between the measuring tips is, d ~ √2 mm).



Helium, B_o = 1.0 kG, t = 9.6 ms, z = 5.12 m

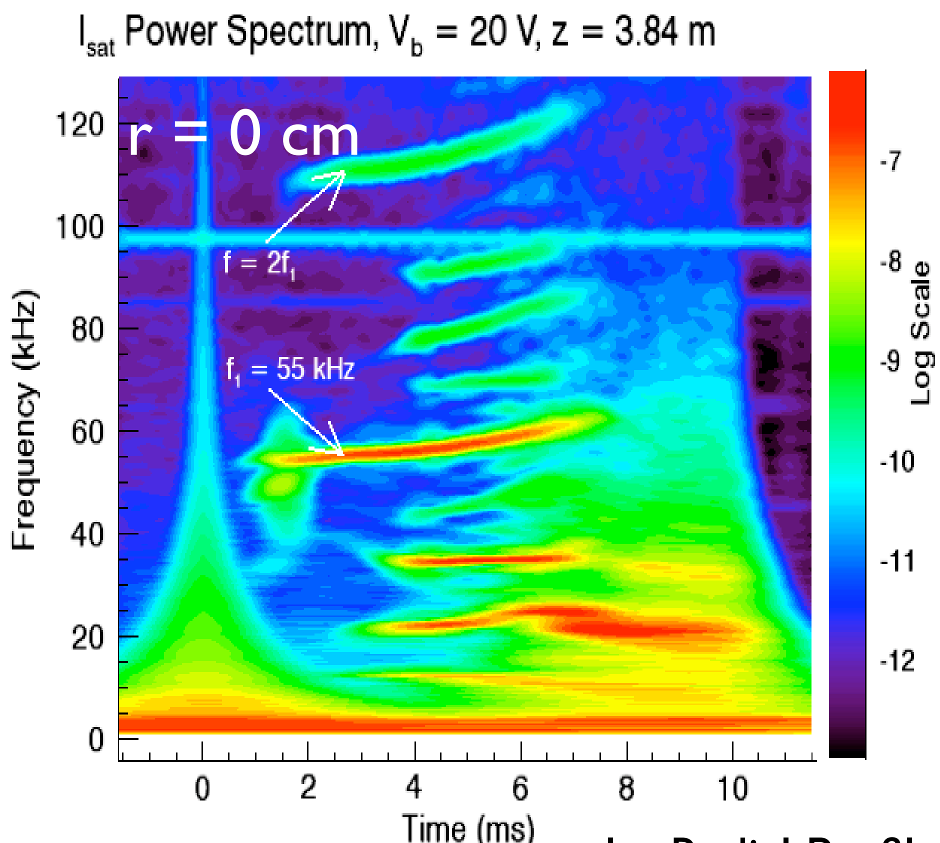
Wavelet Power Spectra Indicate Distinct Temporal Regions of Fluctuation Characteristics

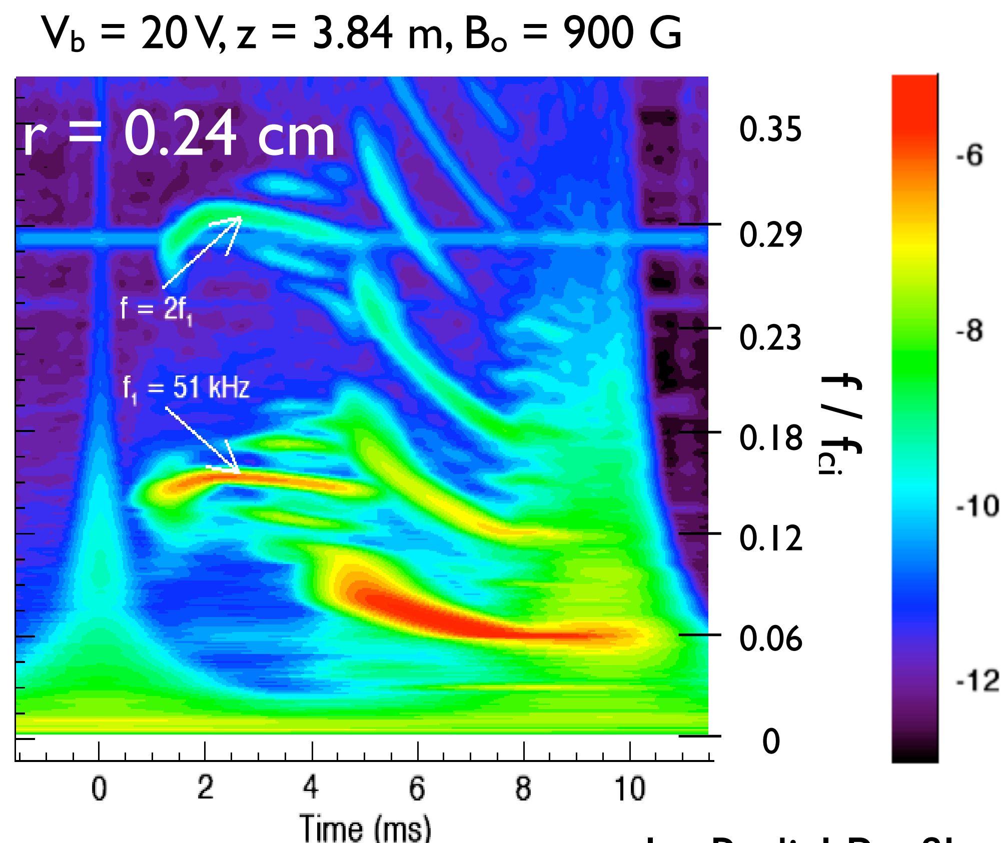


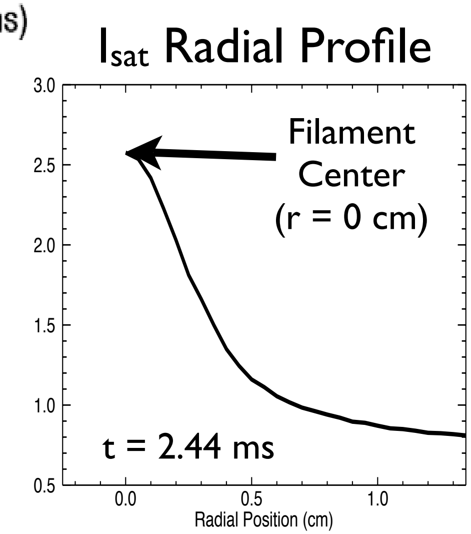


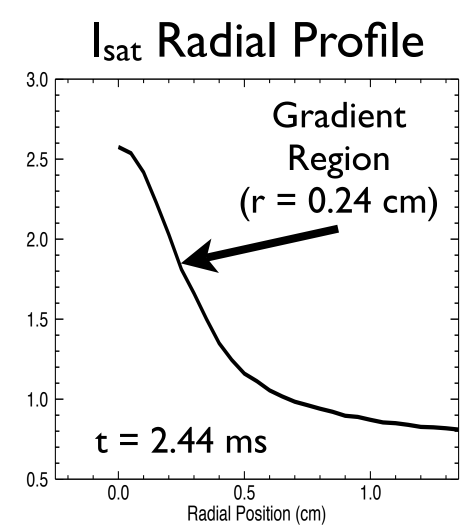
- Wavelet power spectra provide improved time resolution over sliding FFTs.
- Distinct modes and harmonics observed, with mode interaction suggested and causality demonstrated.
- Spectra from different measurements may indicate unique properties of fluctuations.

Power Spectra at Different Radial Positions Indicate Spatially Dependent Frequencies Likely due to Rotation Induced Doppler Shifts

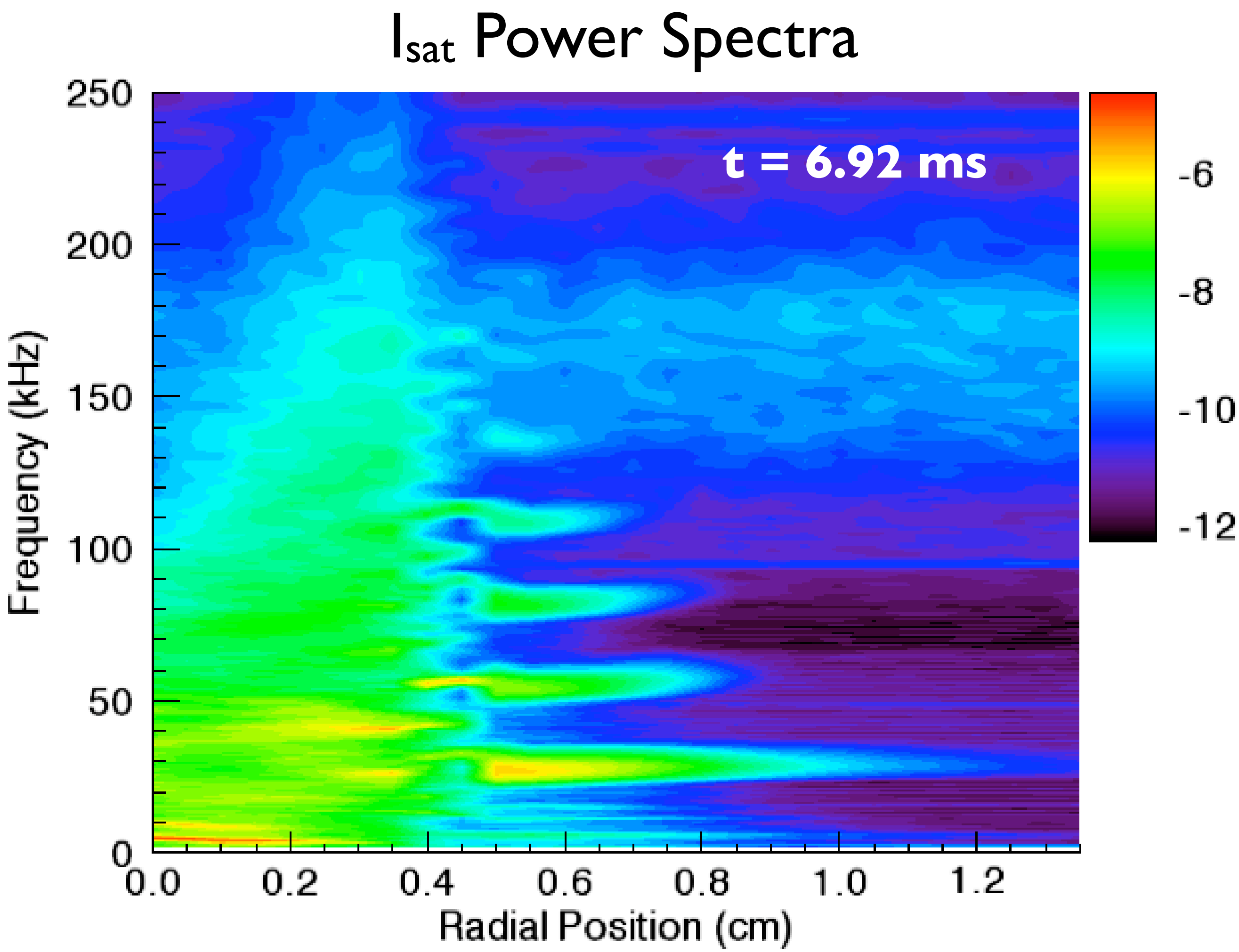








Eigenmode Nature of Spectral Features is Demonstrated

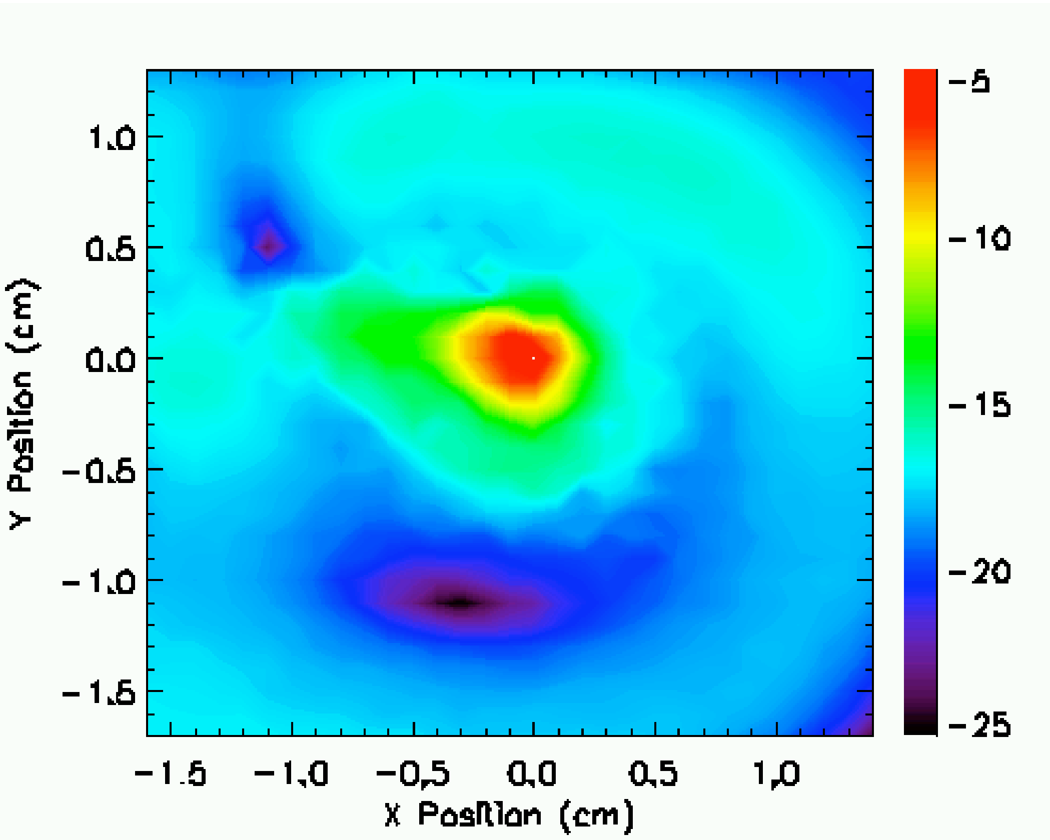


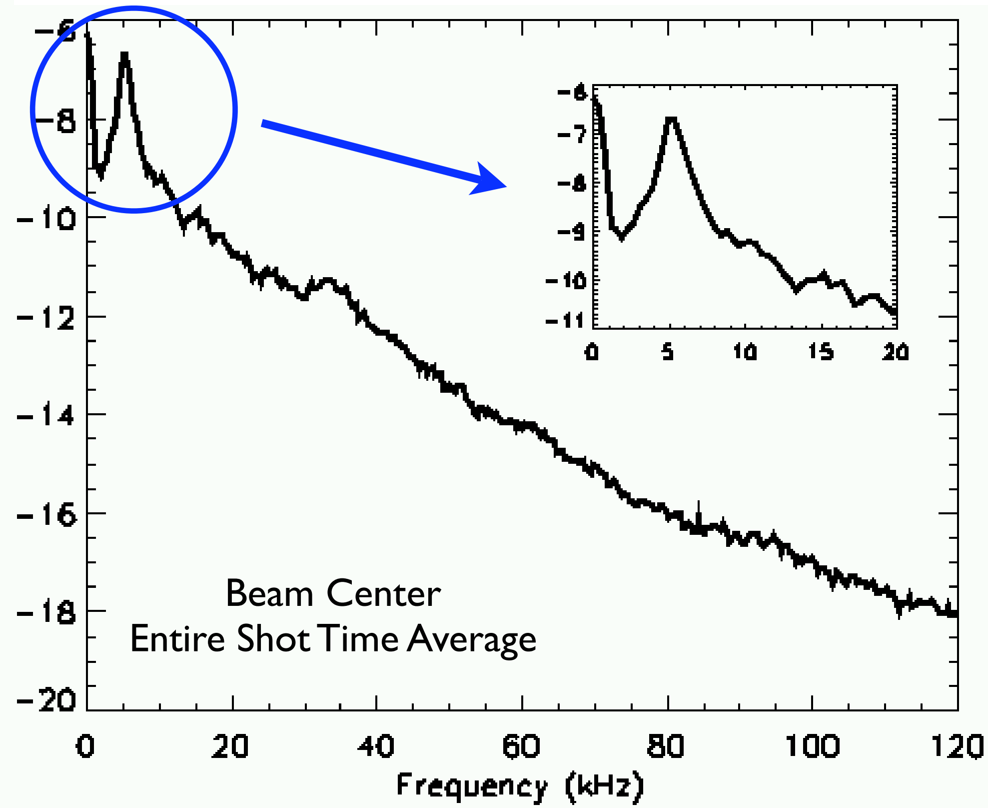
- Spectra calculated across multiple positions and times.
- Filament center displays low frequency, m = 0 mode.
- Gradient region dominated by drift Alfvén, m = 1, mode.
- Broadband feature is easily observed and followed through space and time.

- Movies generated from contours at successive times indicate that filament center moves in time and the Alfvén mode frequency downshifts.

Observed Low Frequency Mode Localized in Filament Center

- Low frequency mode, f ~ 5.7 kHz, observed only at radial locations corresponding to filament center.
- Spatial location coincides with flow profile.

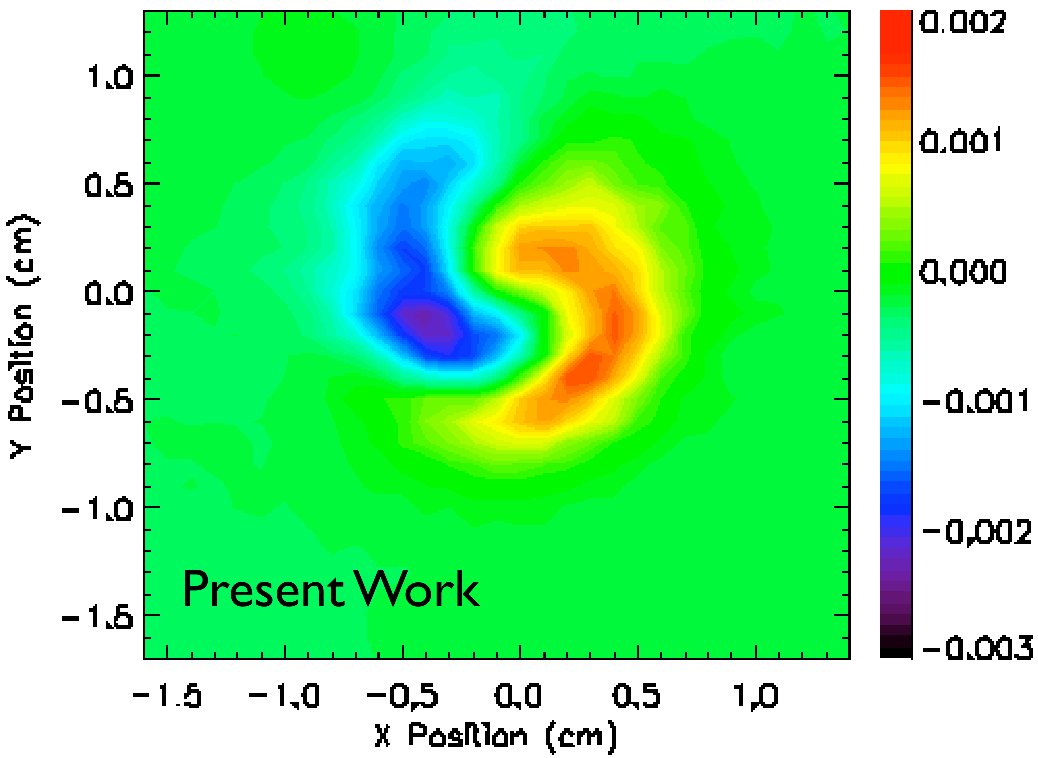




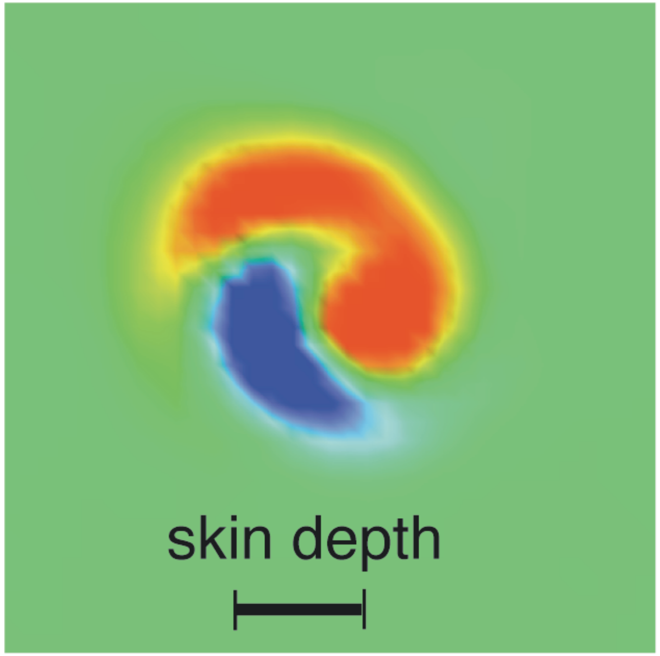
Helium, 20 Shot Average
B_o = 1.0 kG, z = 5.44 m

Observed Drift Alfvén Mode Reproduces Previous Results

- Spiral arms result from m = 1 mode of drift Alfvén wave.
- Earlier paper [4], determined wave structure from fluctuating component of density, ñ / n.
- Auto-covariance of I_{sat} for new results displays similar behavior.



Helium, 20 Shot Average
B_o = 1.0 kG, z = 5.44 m

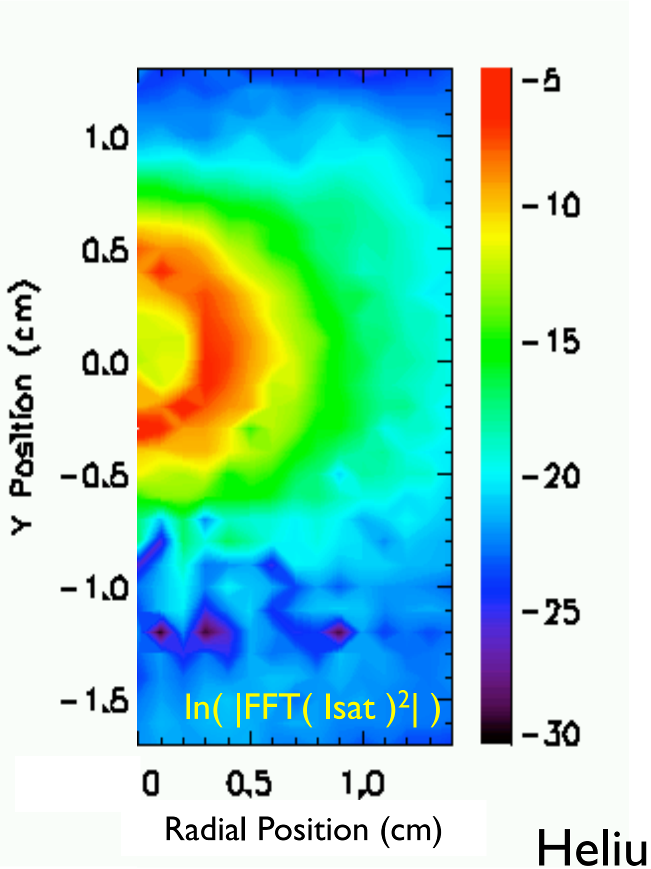


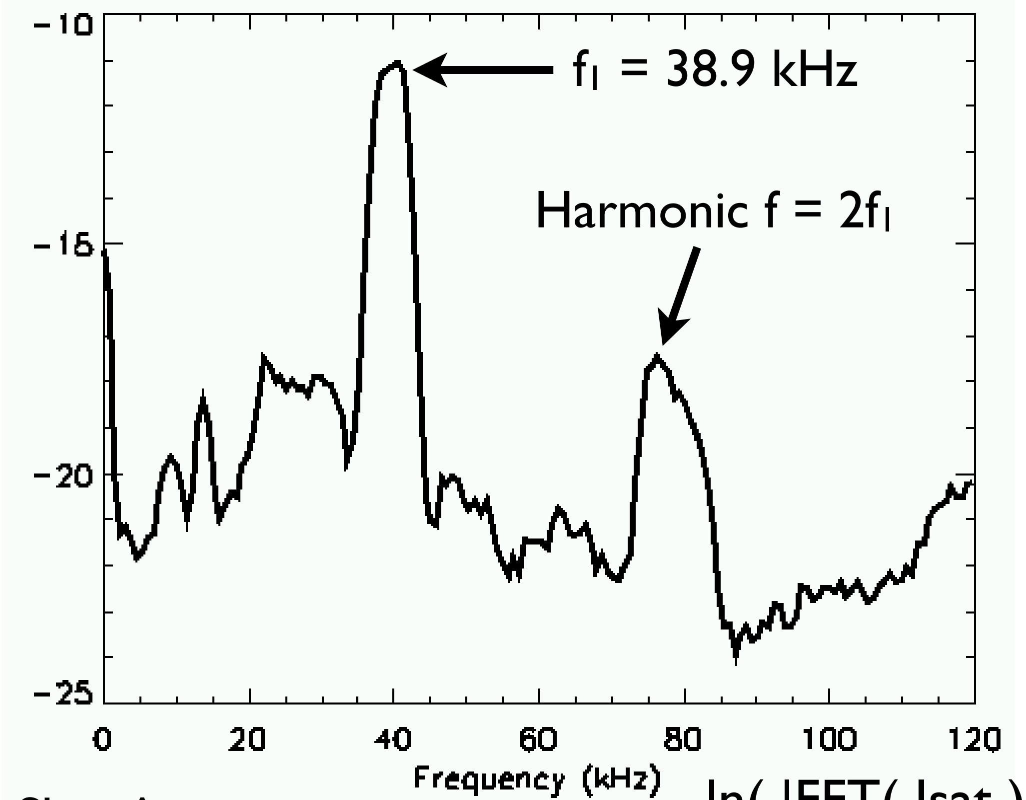
[4]

From Previous Work

Drift Alfvén Mode Localized to Region of Maximum Temperature Gradient

- Drift Alfvén mode, f ~ 38.9 kHz, localized around the filament center.
- Significant difference in type of modes within 5 mm radial extent.
- Mode is prominent in temporal power spectra.





Helium, 20 Shot Average
B_o = 1.0 kG, z = 5.44 m

ln(|FFT(Isat)²|)
r = 0.5 cm, t ~ 2 ms

References and Notes

1. Braginskii, S. I., *Rev. Plasma Phys.* **1**, 205 (1965)

2. A. T. Burke, J. E. Maggs, and G. J. Morales, *Phys. Rev. Lett.* **81**, 3659 (1998)

   Note: Image referenced to the above publication has been altered (removed additional theory trace) by the presenter.

3. Needelman, D. D., Stenzel, R. L., *Phys. Rev. Lett.* **58**, 1426 (1987)

4. A. T. Burke, J. E. Maggs, and G. J. Morales, *Phys. Rev. Lett.* **84**, 1451 (2000)