

Turbulence and flow in the Large Plasma Device

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Summary

- Spontaneous Flows in LAPD and their scaling with field
- Connection of flows to Turbulence, Transport
- Using Biasing to Control Flows

Basic Parameters of the Large Plasma Device

- 17 m long, 1 meter diameter, ~60 cm wide plasma
- Magnetic Field Range: 400-2500G
- Density: 1.0×10^{11} to $4.0 \times 10^{12} \text{ cm}^{-3}$
- Pulse Duration ~ 10ms
- Pulse rate – 1Hz



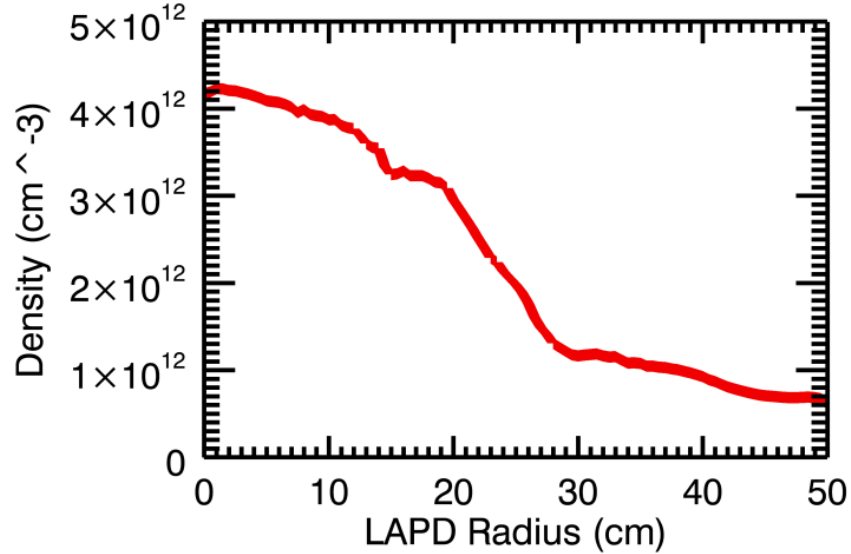
Info/pic from BAPSF: <http://plasma.physics.ucla.edu/bapsf/index.html>

Turbulence and transport in LAPD

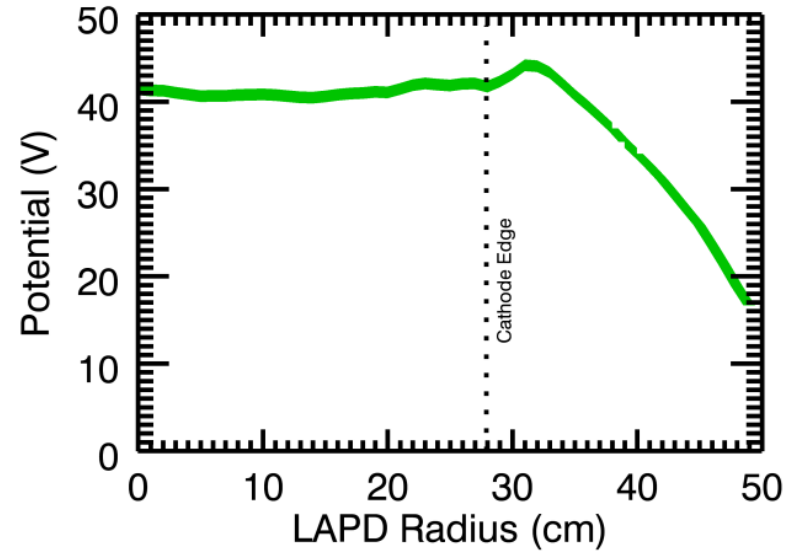
- Larger is better for turbulence studies:
 - Ion gyroradius to plasma size perpendicular to B-Field, (ρ_i/a) , is on the order of 1/100 to 1/300
 - This ratio allows a large number of unstable modes to be supported—edge turbulence is broadband/fully developed
 - Large size allows perpendicular transport to compete with parallel losses; profile is set by perp transport
- Turbulence is EM; Drift-Alfvén wave turbulence observed (coupling occurs at beta realized in LAPD)
- Wall bias can be used to drive strong flow in the edge of LAPD, spontaneous flow observed

Typical LAPD Profiles

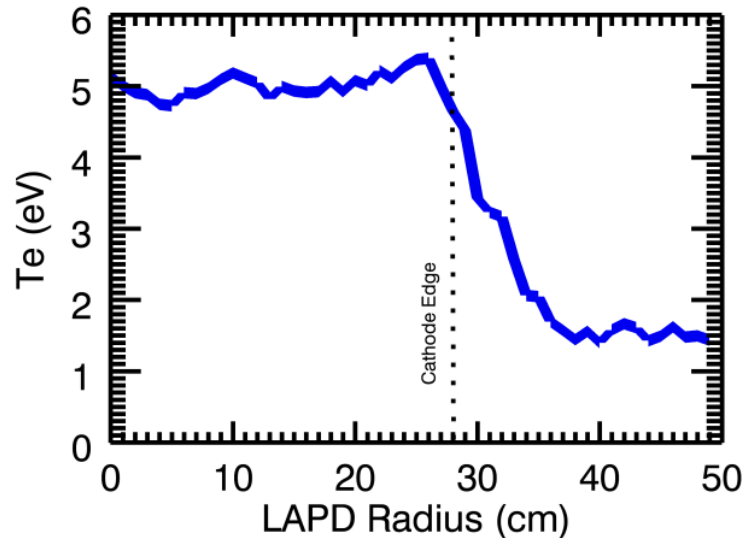
Typical LAPD Density (@1000G)



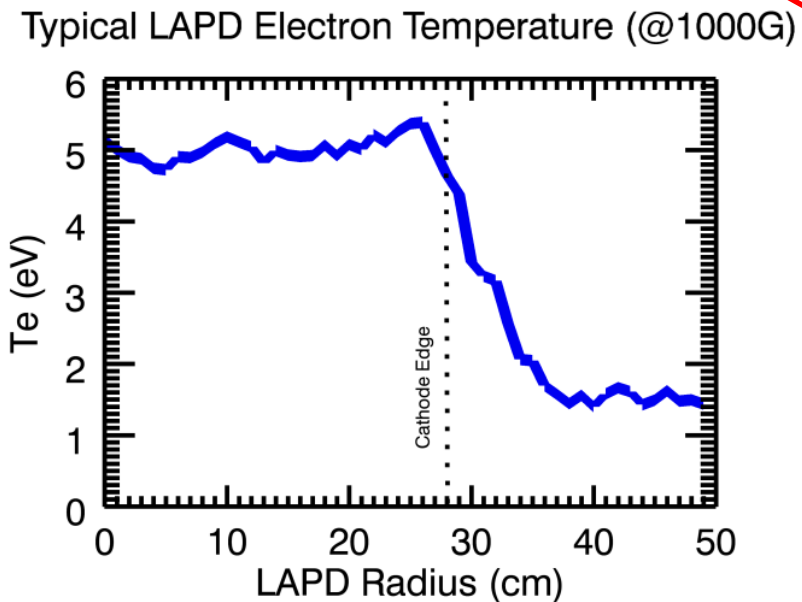
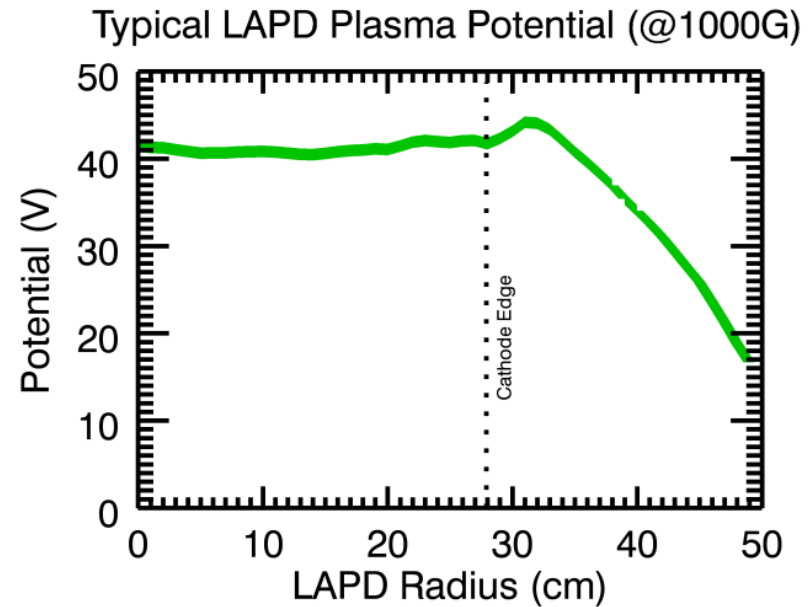
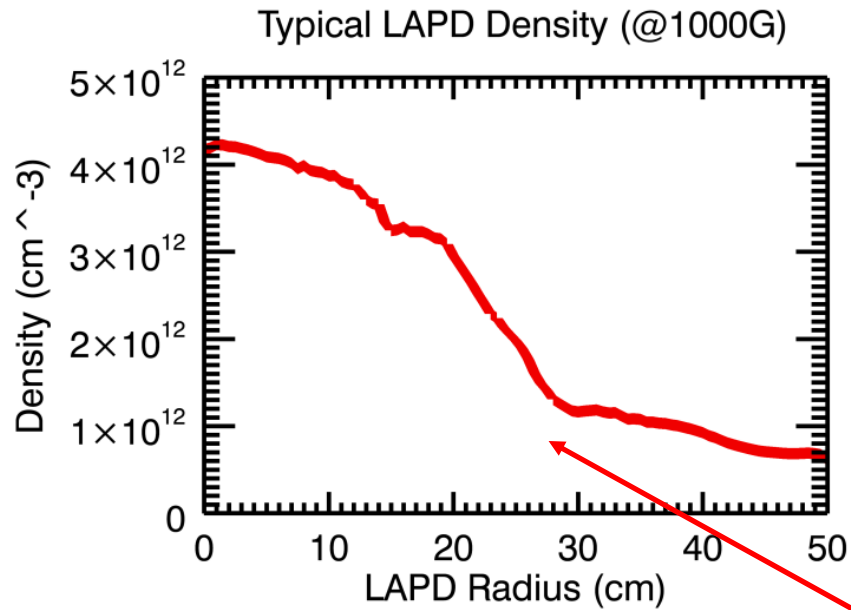
Typical LAPD Plasma Potential (@1000G)



Typical LAPD Electron Temperature (@1000G)

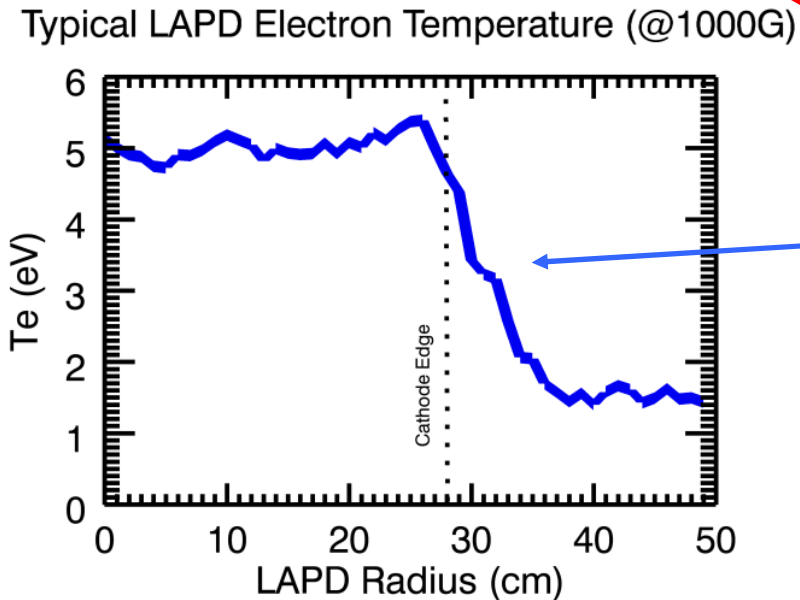
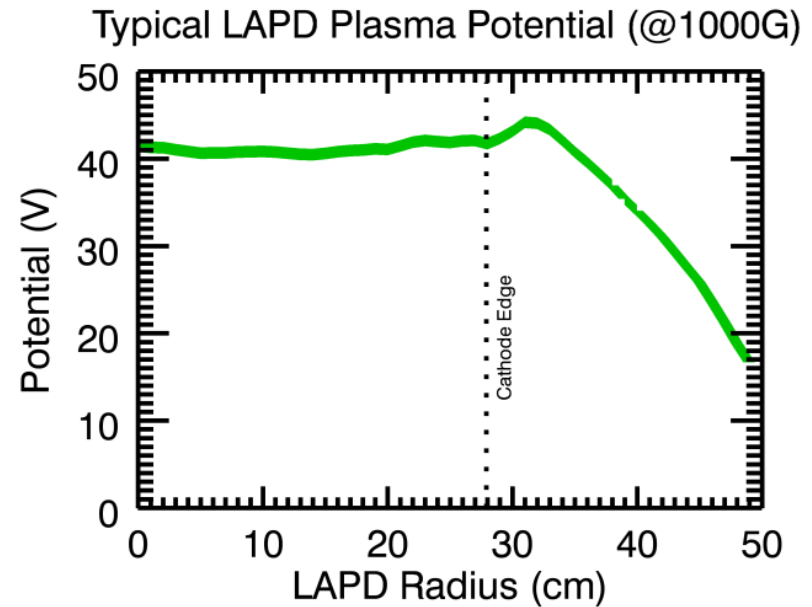
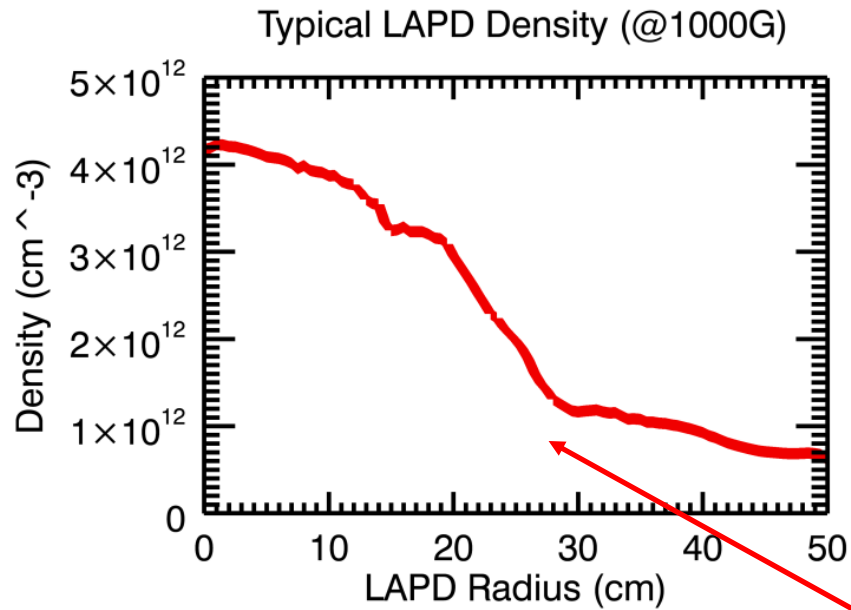


Typical LAPD Profiles



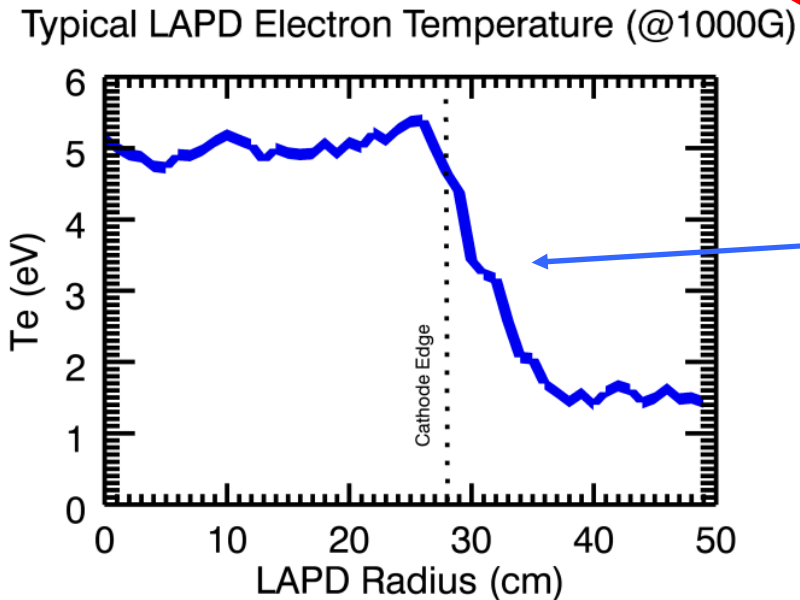
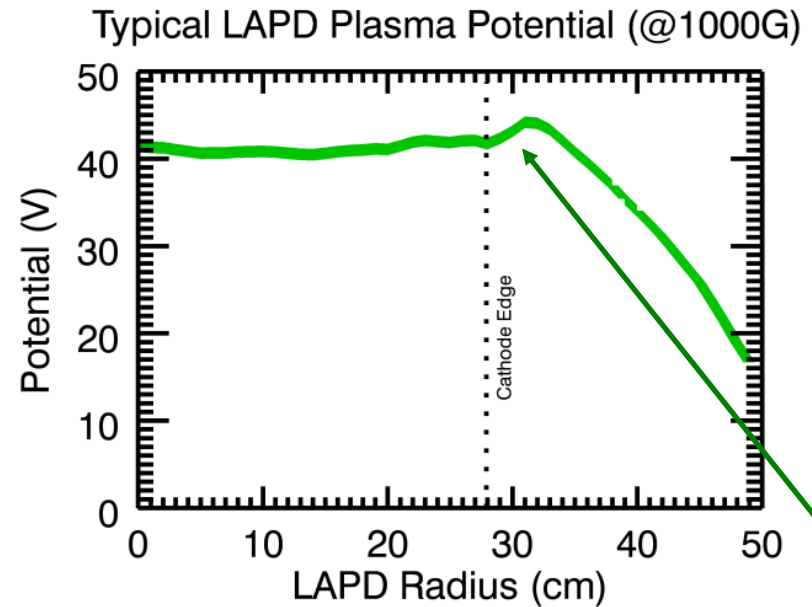
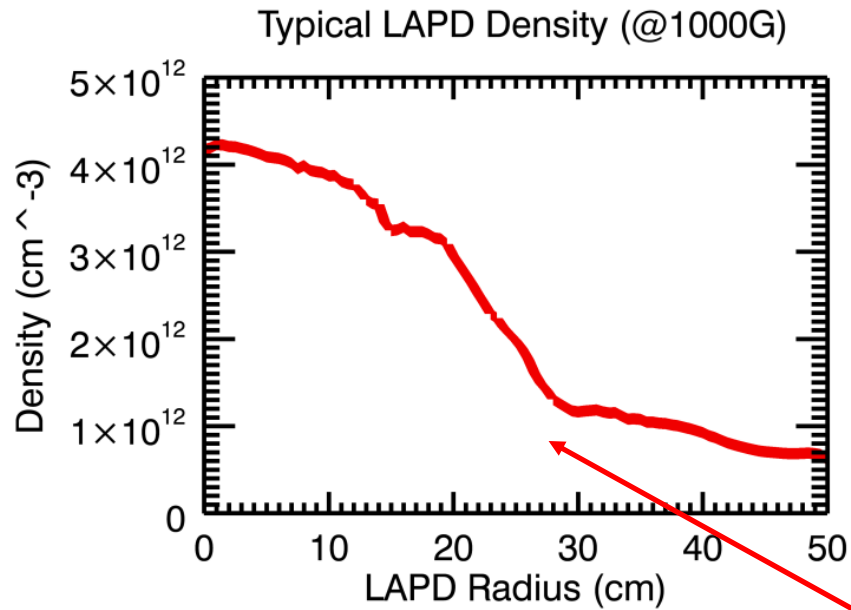
- Density gradient begins about 10cm before cathode edge

Typical LAPD Profiles



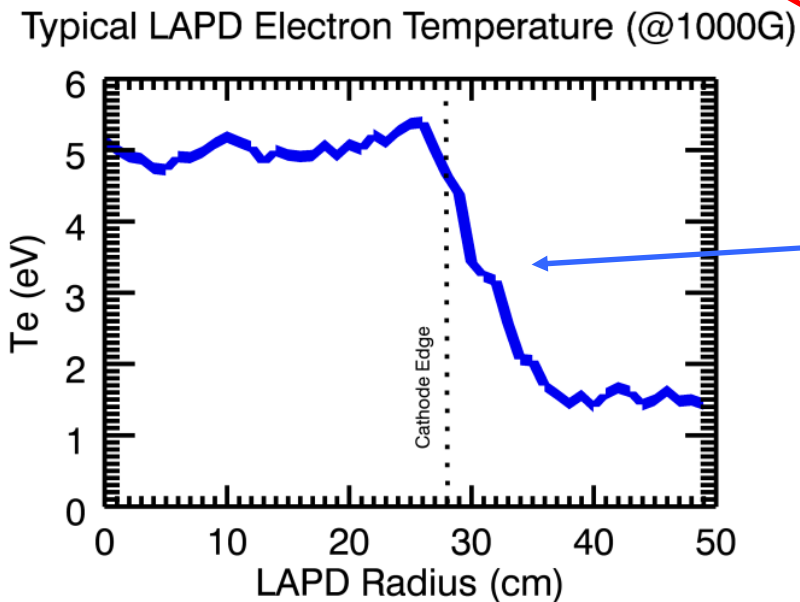
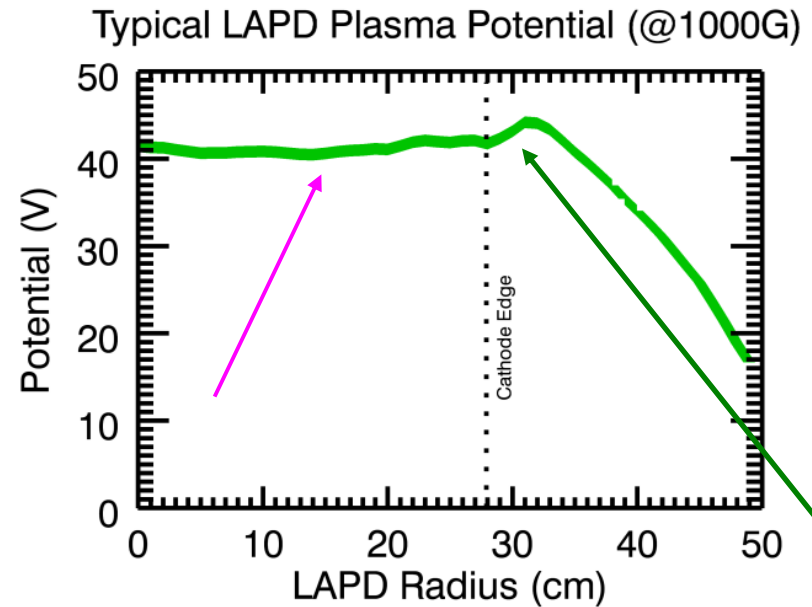
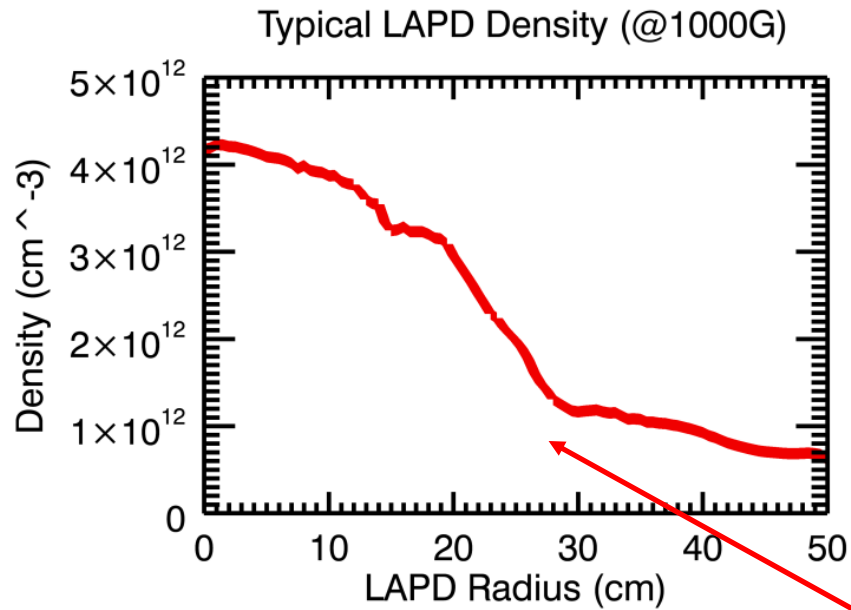
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- Temperature falls off sharply at cathode edge

Typical LAPD Profiles



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- Temperature falls off sharply at cathode edge
- Plasma Potential rises briefly before decreasing toward edge—indicative of shear flow

Typical LAPD Profiles

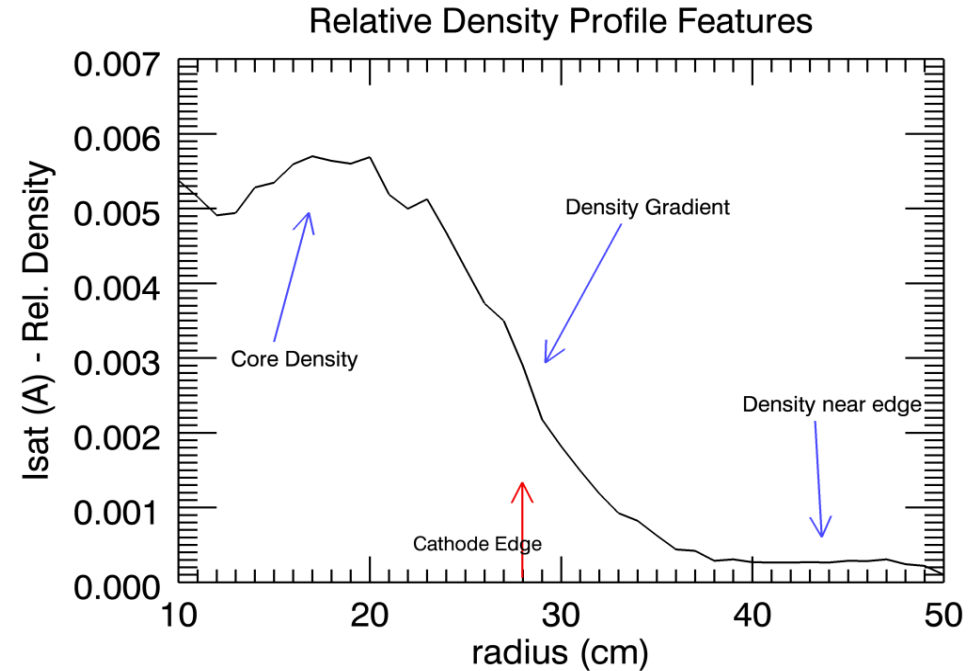
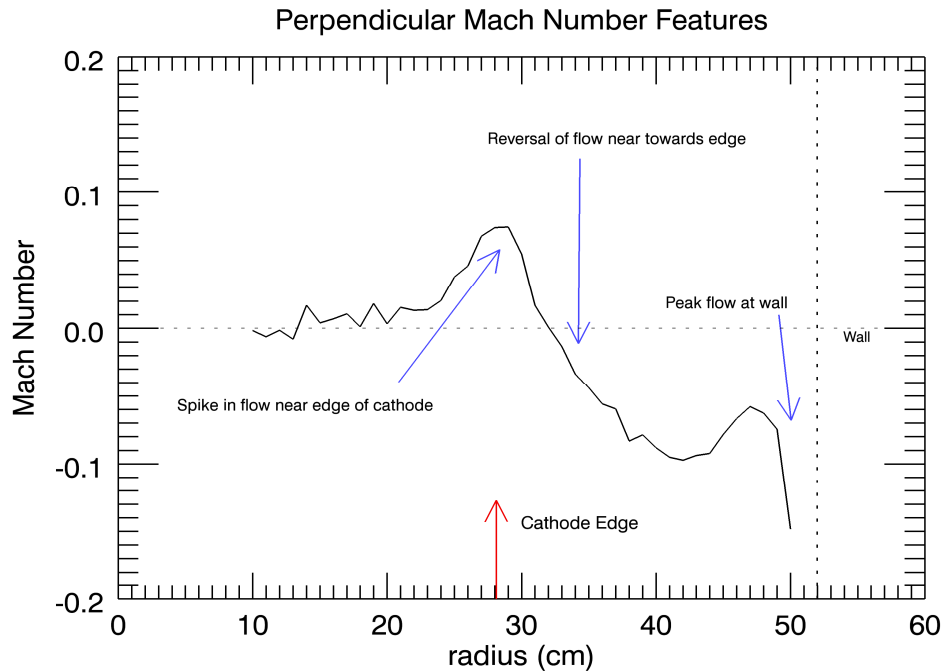


- Density gradient begins about 10cm before cathode edge
- Temperature falls off sharply at cathode edge
- Plasma Potential rises briefly before decreasing toward edge—indicative of ExB flow
- Potential nearly flat within cathode edge region—B.C. might preclude flow in core

Flows and Turbulence/Transport

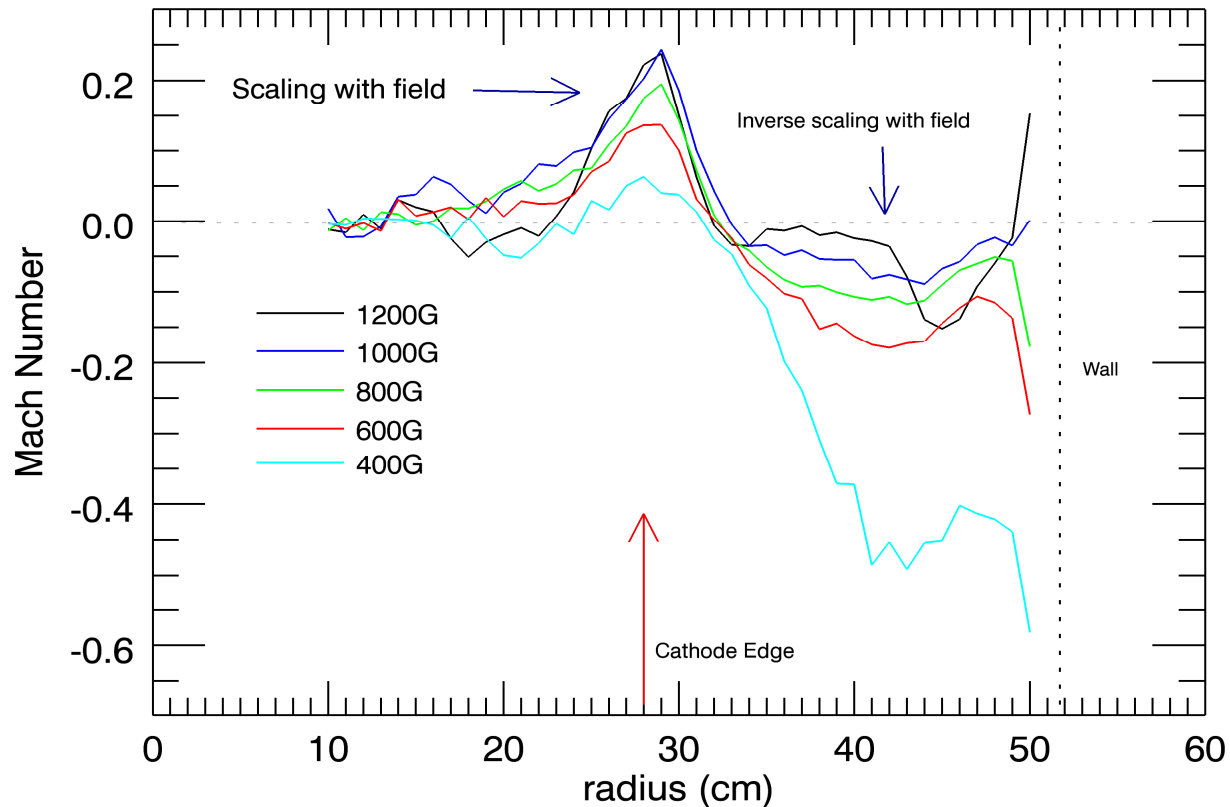
- Flow is critical to stability/transport
- Edge rotation has been linked to H-mode, transport suppression in tokamaks
- LAPD exhibits a plasma with broadband turbulence where spontaneous flows arise; what is role of turbulence? How do flows correlate with transport?
- What is role of boundary processes to flow in LAPD (like in tokamak SOL – flows determined by transport to divertor, magnetic geometry, etc)

Background plasmas exhibit spontaneous flows



- $I_{\text{sat}} \sim$ Density decreases around the cathode edge
- Flows develop near cathode edge and beyond
- Flow measured with 6-sided Mach Probe
- Mach flow assumed zero in core by comparison with ExB flows (removes mach probe asymmetries in measurement)
- Strong flow shear layer develops near cathode—reverses direction near edge

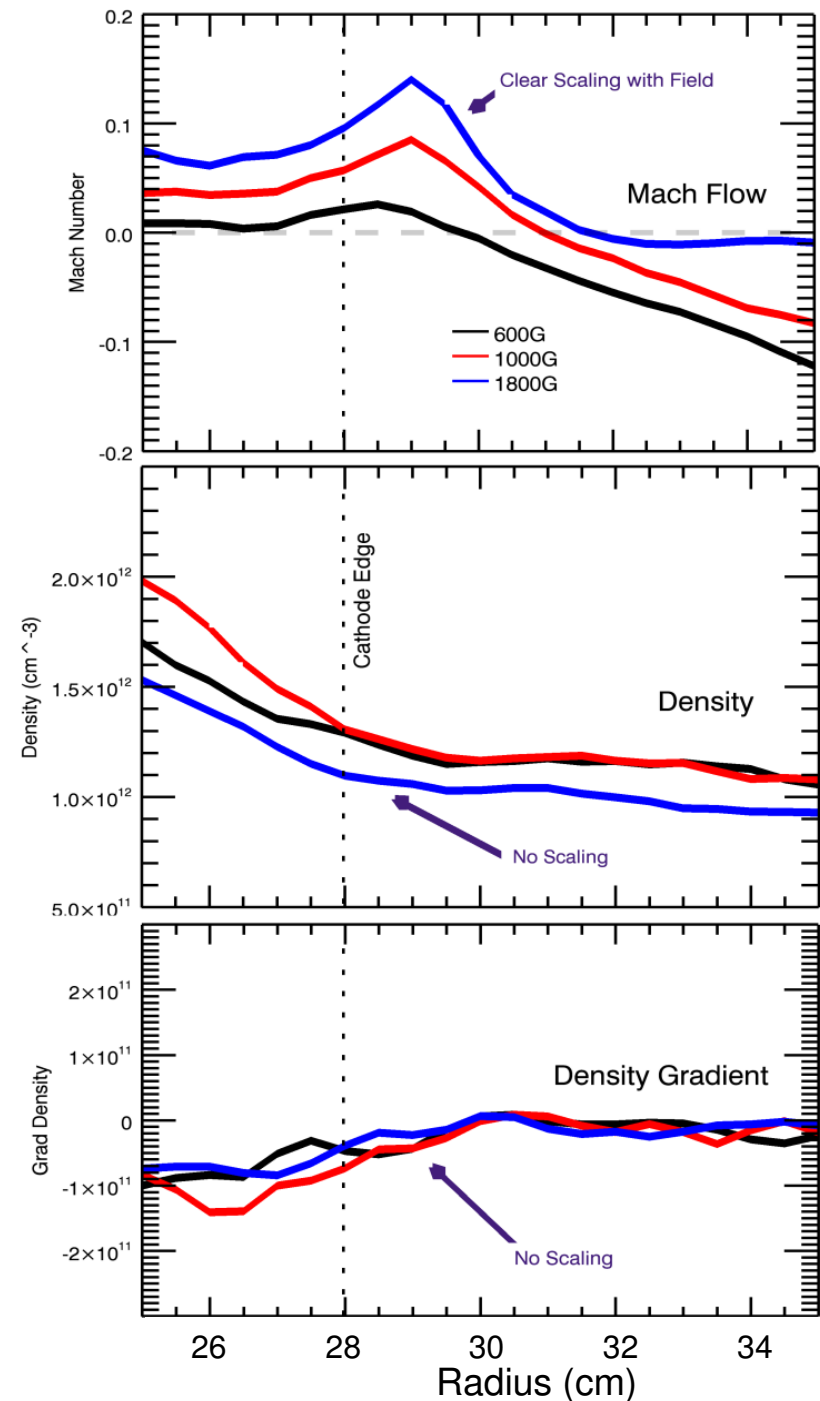
Flows scale with magnetic field



- Peak flow in shear layer near cathode edge increases with field
- Flow near wall in opposite direction, scales inversely with field
- Peak flows occur near or at wall
- Varying trends suggest multiple mechanisms responsible for flows

Shear layer flows/density gradient scaling relationship not clear

- Possible drive for flow is density-gradient driven instabilities
- Shear layer flow shows scaling with magnetic field
- Corresponding density and density gradients do not exhibit same scaling
- No clear correlation between flow scaling and density gradient scaling is observed— *alternative mechanism causes field differentiation?*

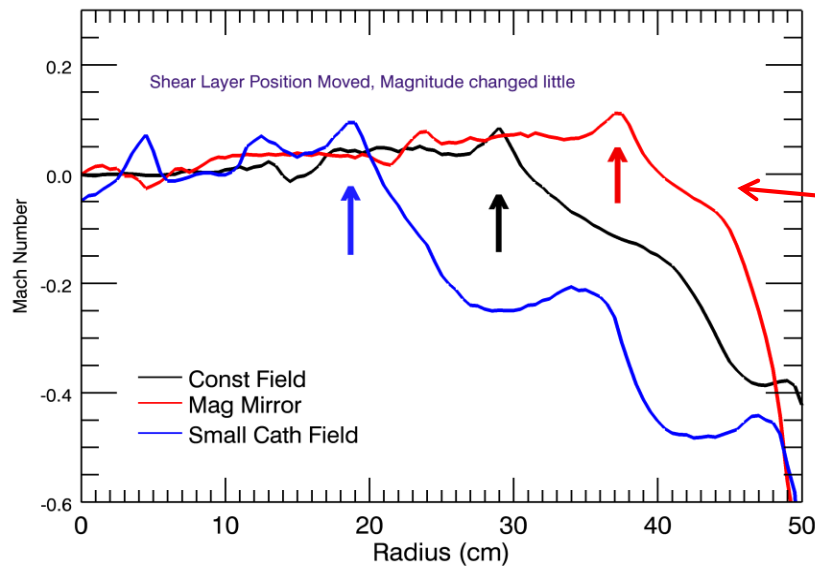
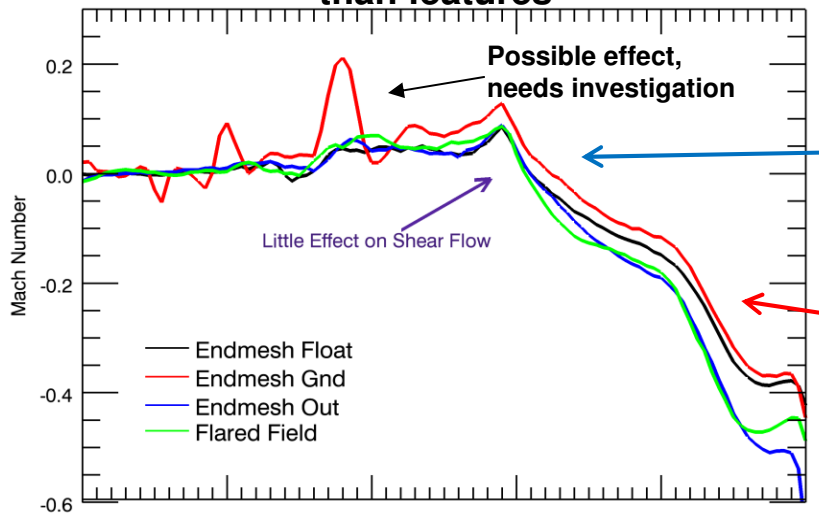


Origin of Spontaneous Flows Not Clear

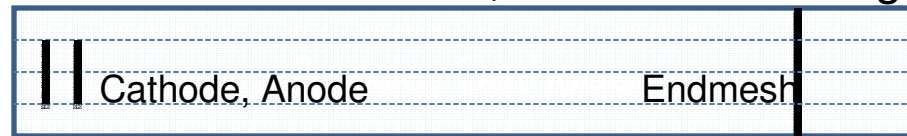
- Edge flows appear to be driven by penetration of electric field from the chamber edge as evidenced by inverse field scaling and flow modification by edge biasing (shown later)
- Shear layer flow in cathode edge/density gradient area seems to be driven by a different mechanism—
turbulence/Reynolds stress or boundary effects?

End boundary changes have some effect on flow

Changing B.C. has minor effect on shear flow, tends to modify size of overall plasma, rather than features



Base Boundary Condition: Constant Field 1000G, Endmesh Floating



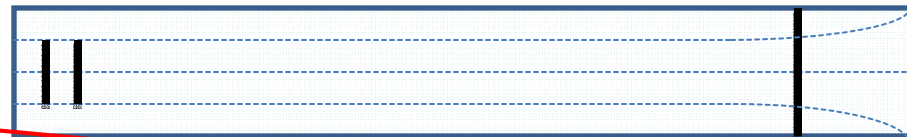
Endmesh Rotated Out



Endmesh Grounded to Chamber



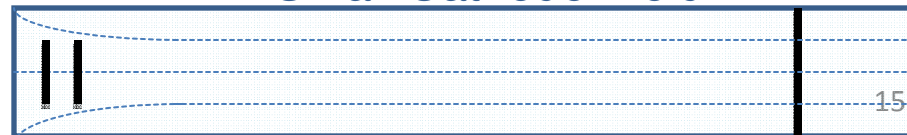
Field Flared at End



Magnetic Mirror



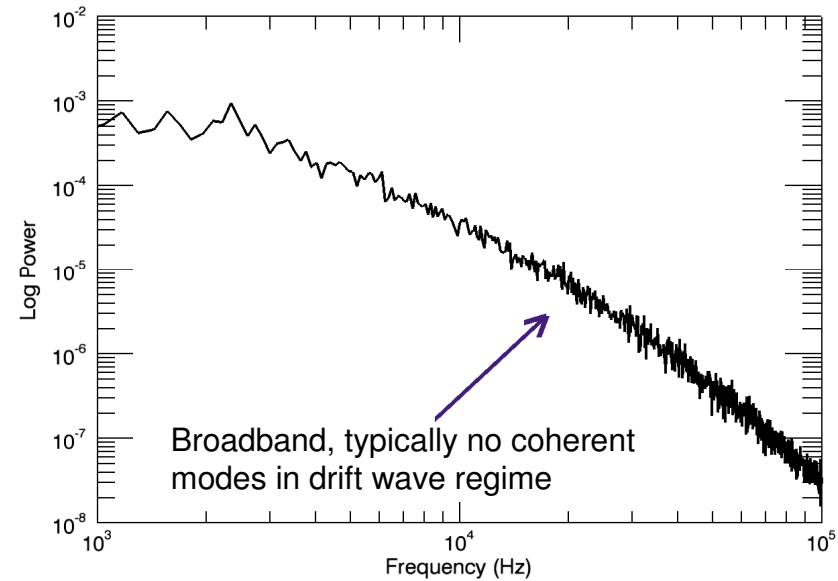
Small Cathode Field



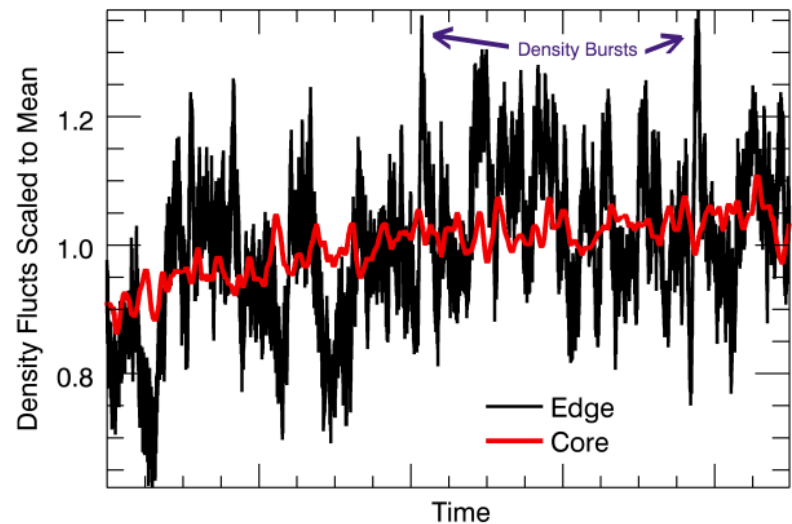
Turbulence Observed in LAPD

- Both broadband spectrums and intermittent turbulence observed in LAPD—
Broadband turbulence near cathode edge/density gradients and intermittent turbulence in edge

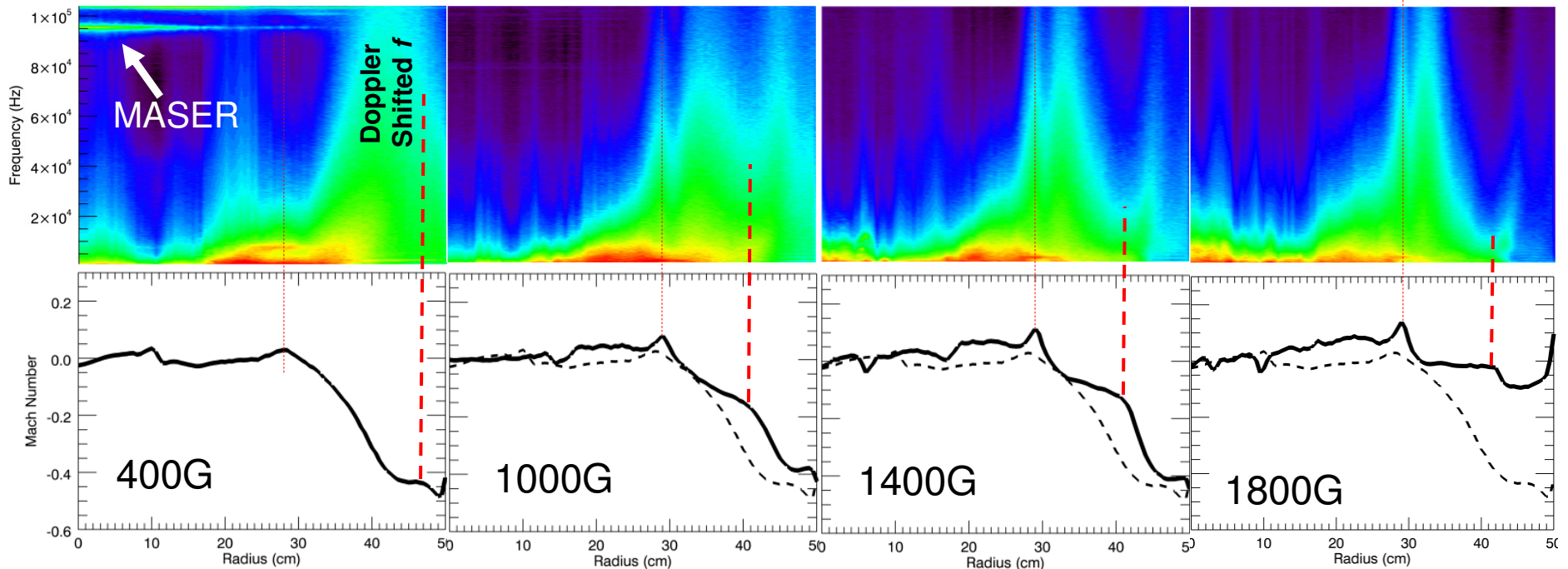
Isat Power Spectrum near Cathode Edge (@1000G)



Isat Traces at Core and Edge (@1000G)



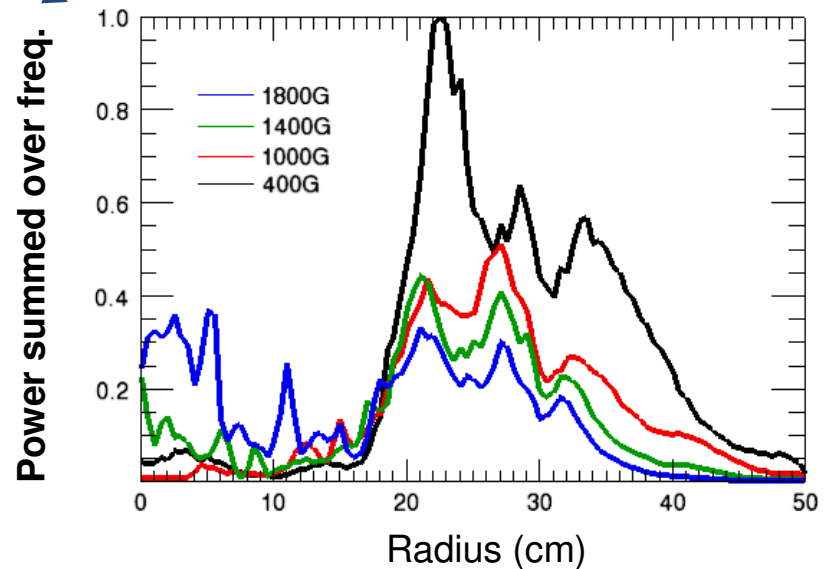
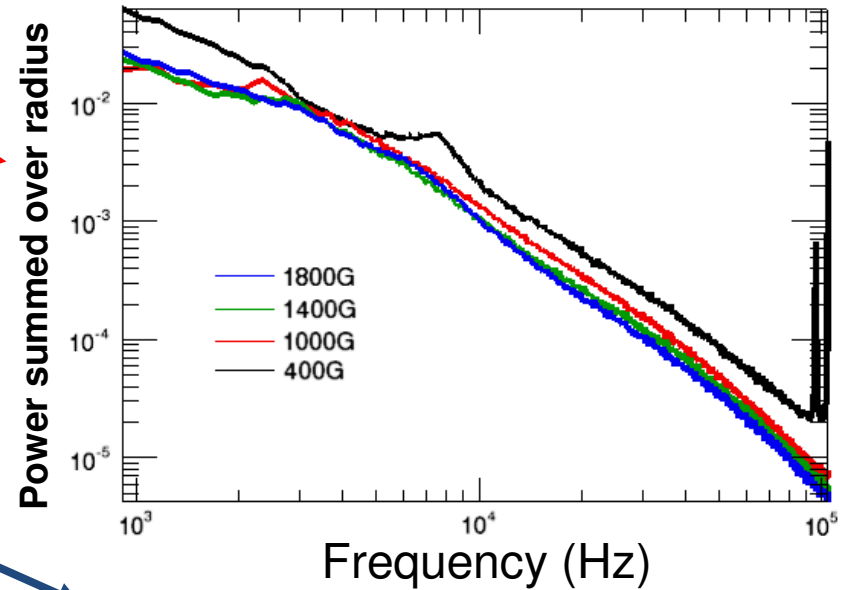
Flows appear to modulate turbulence



- Broadband spectrum peaked in the 10's of kHz range—typical of drift wave frequencies
- Doppler shifting clear in regions of high flow— *should really recast in k-spectrum*
- Spectra show sharp *decreases* in power at points where shear flow is greatest around shear layer peak
- A second decrease in power is observed near inflection point of flow profile—point where density gradient levels off
- Some evidence that turbulence reduced with higher flow shear, but not always observed (such beyond 45 cm)—competition between Doppler shifting and turbulence reduction?

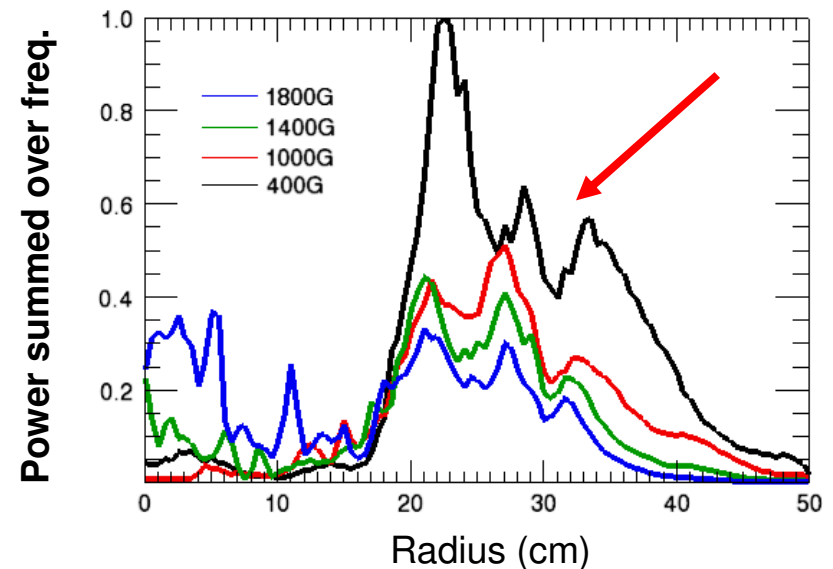
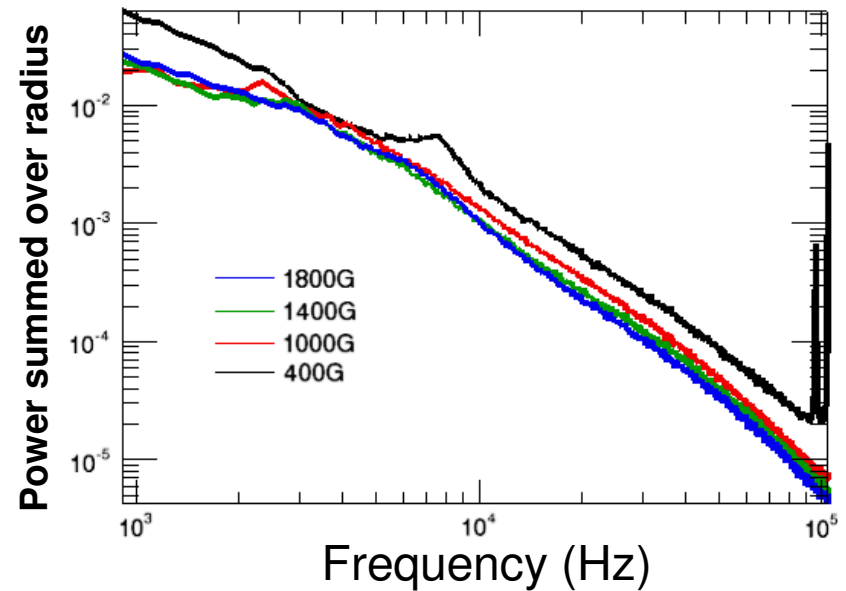
Summed fluctuation power varies with field

- The fluctuation power summed over across all radial positions scales inversely with field frequencies in drift wave regime
- The fluctuation power summed over all frequencies per radial position peaks in the density gradient region, scales inversely with field as well



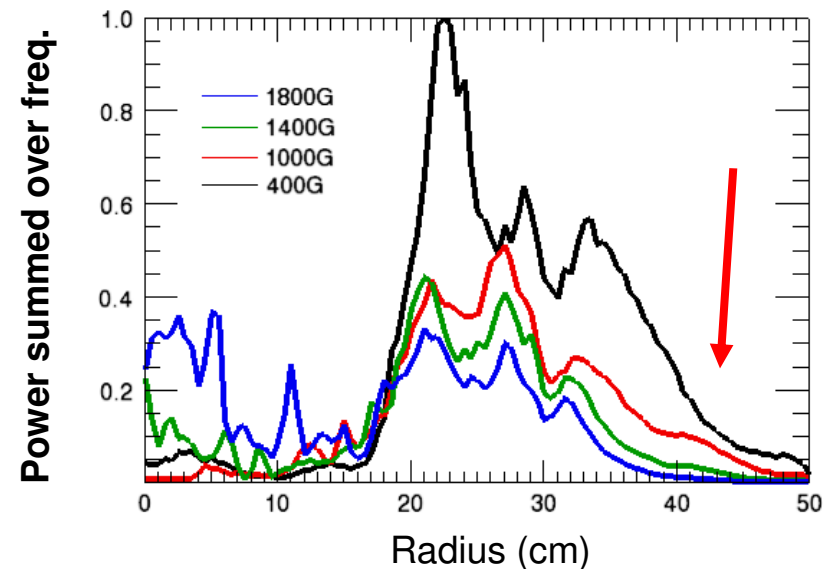
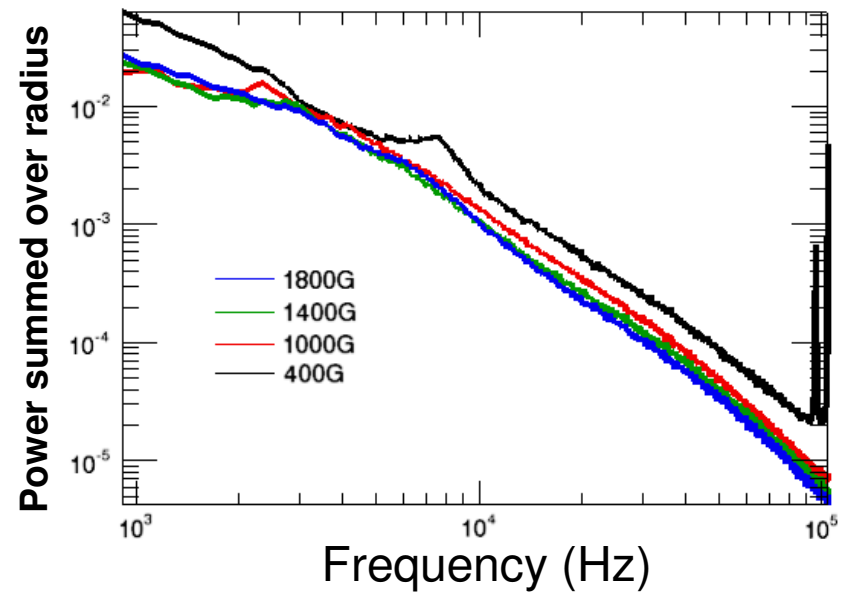
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- Notice the drop in fluctuation power 30cm, approximately where the absolute shear flow is at a maximum (the slope of the mach flow peak)



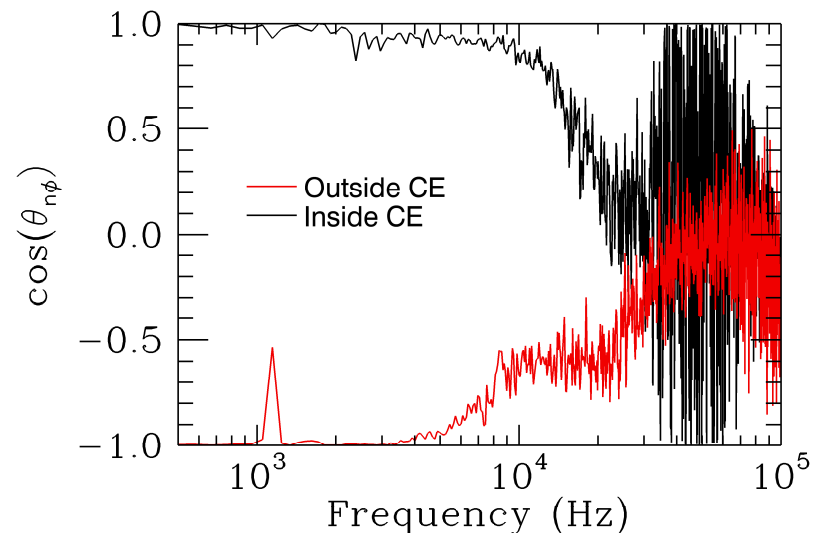
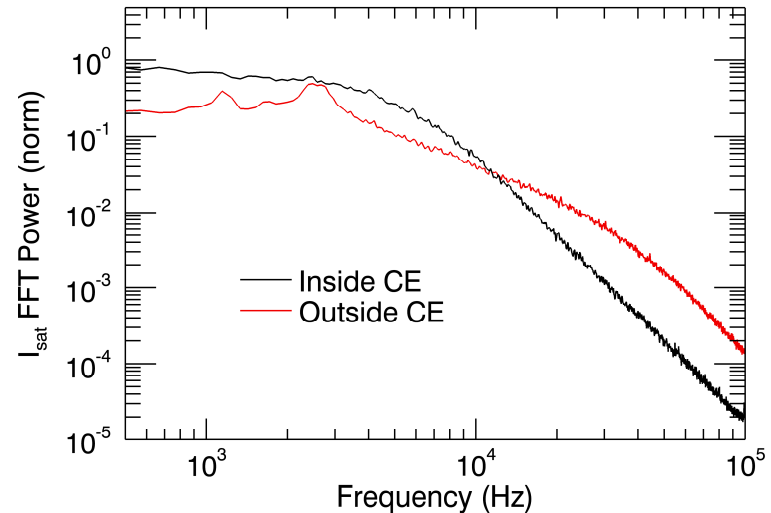
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- Fluctuations beyond 40cm scale inversely with field, despite flow and flow shear scaling with field—Doppler shift winning out over suppression?

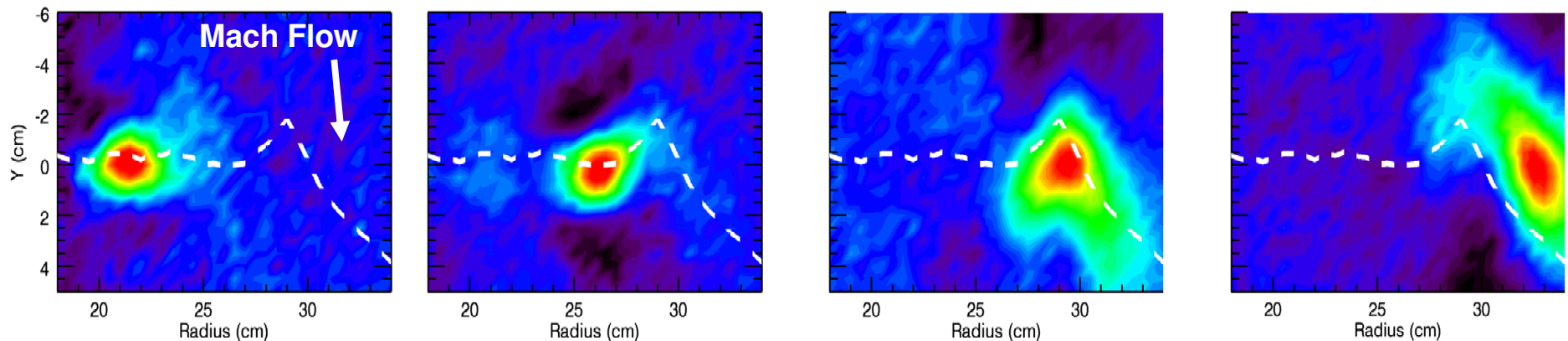


Different modes active inside and outside cathode edge?

- A possible alternative explanation for spectrum observed?
- Evidence for different modes for $r < 28\text{cm}$ and $r > 28\text{cm}$ from power spectra, cross phase
- Drift-wave like cross-phase for $r < 28\text{cm}$
- $R > 28\text{cm}$ density/potential are out of phase. Flow driven or sheath driven mode?

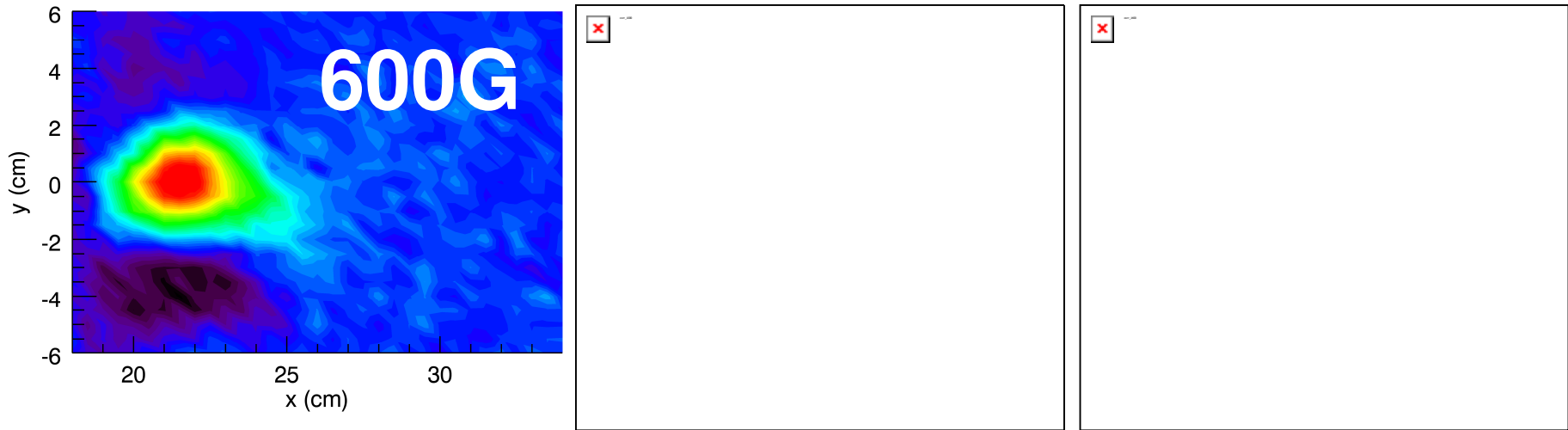


Correlation function size/shape varies with position



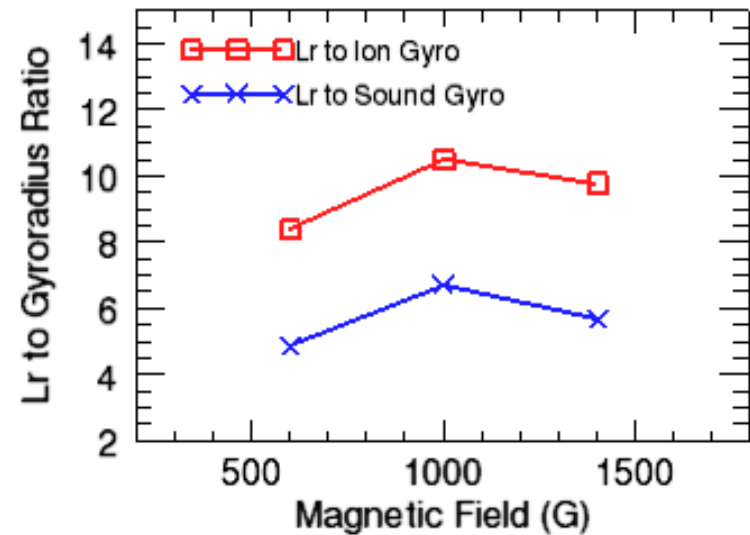
- 2D Correlation function made with two Langmuir tips separated about 1m apart in z, reference tip at varying positions around shear layer, $\sim 20 \times 12$ cm plane
- Shows effect of shear layer flow and edge flow on correlation length
- Correlations functions can be used to extract the k-spectrum of the drift instabilities
 - Back-of-envelope calculation: $M_\theta \approx K_\theta r = 2\pi r / \lambda$, with $\lambda \sim$ azimuthal correlation length
 - $M_\theta \approx 30-40$ —*consistent with predicted fast growing drift wave*

Correlation size scales inversely with field

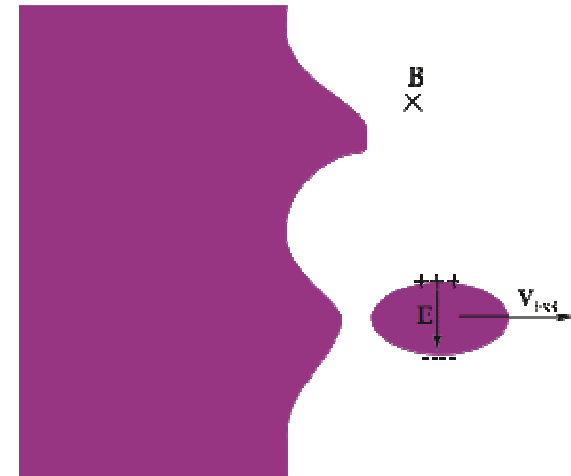
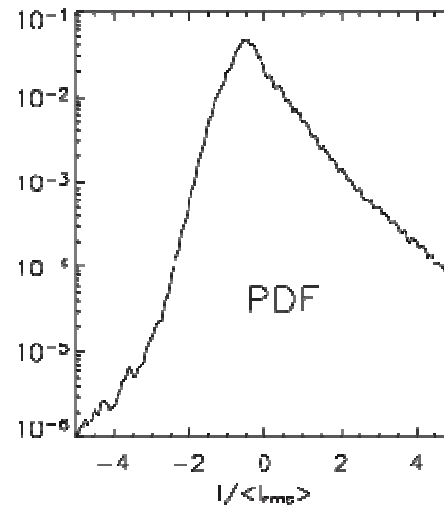
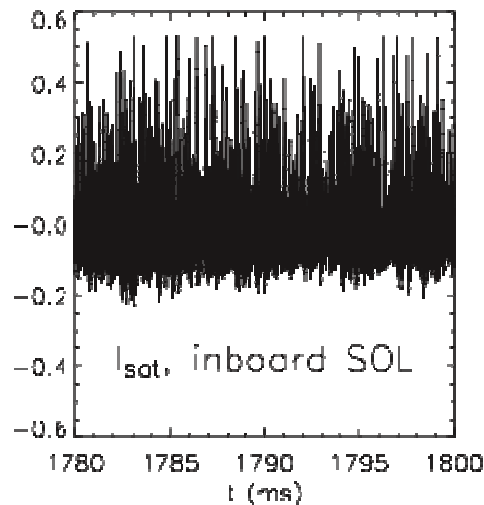


- Both radial and azimuthal correlation lengths decrease with increasing field
- The correlation lengths are approximately
 - 4-6 sound gyroradii and
 - 8-10 ion gyroradii

Approx. Radial Corr. Length to Gyroradius Ratio



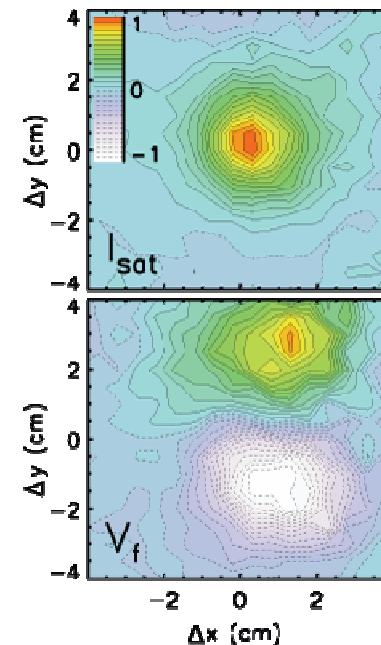
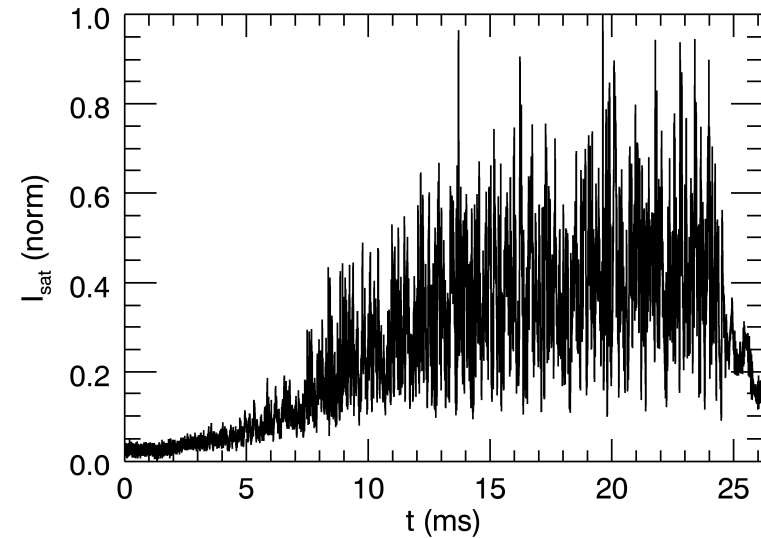
Intermittent turbulence also observed in LAPD



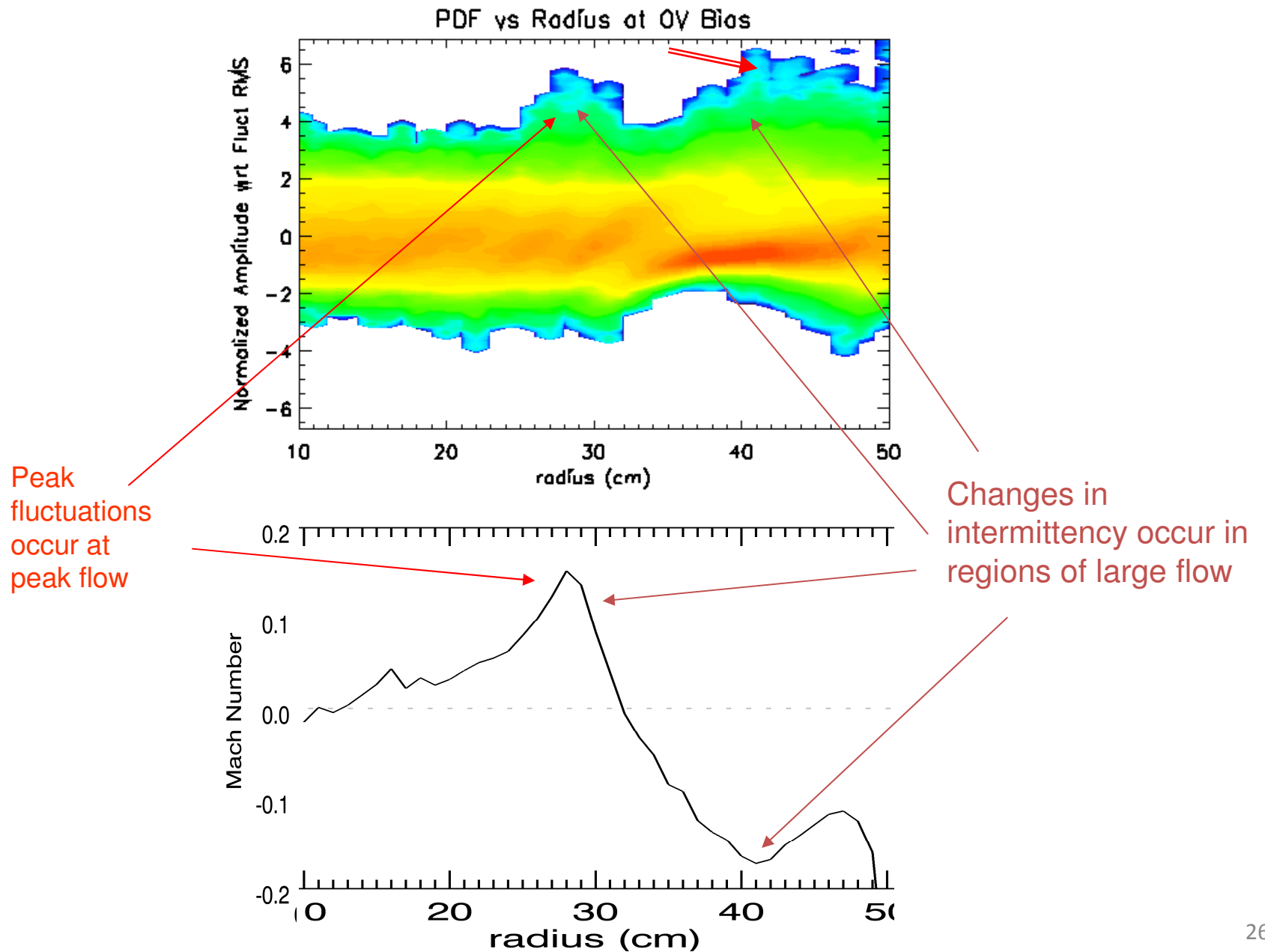
- Patchy in space or bursty in time, non-Gaussian amplitude PDF
- In edge magnetic confinement devices, explained by presence and propagation of structures (seen in nearly all such devices [Antar])
- Propagation of structures tied to polarization by drift-charging [Krasheninnikov] (need interchange force)
- Transport by intermittent convection very important in edge of confinement devices, and may be linked to density limit [Greenwald]

Intermittency seen in signal beyond cathode edge

- Tends to appear beyond cathode edge
- Intermittent convection of blobs contributes to particle transport in LAPD
- Signature of intermittency is a skewed PDF
- **How does intermittent turbulence effect or contribute to plasma flows or vice-versa?**

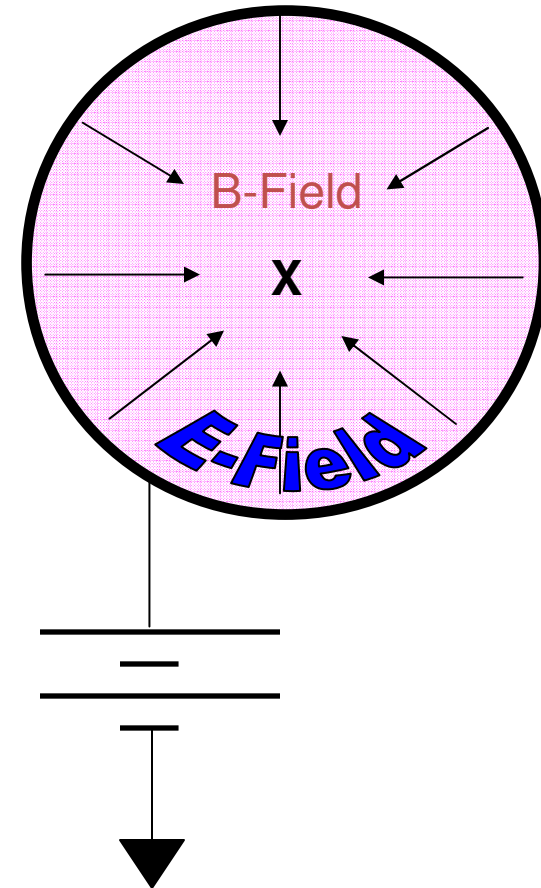


Skewness increases in high flow regions

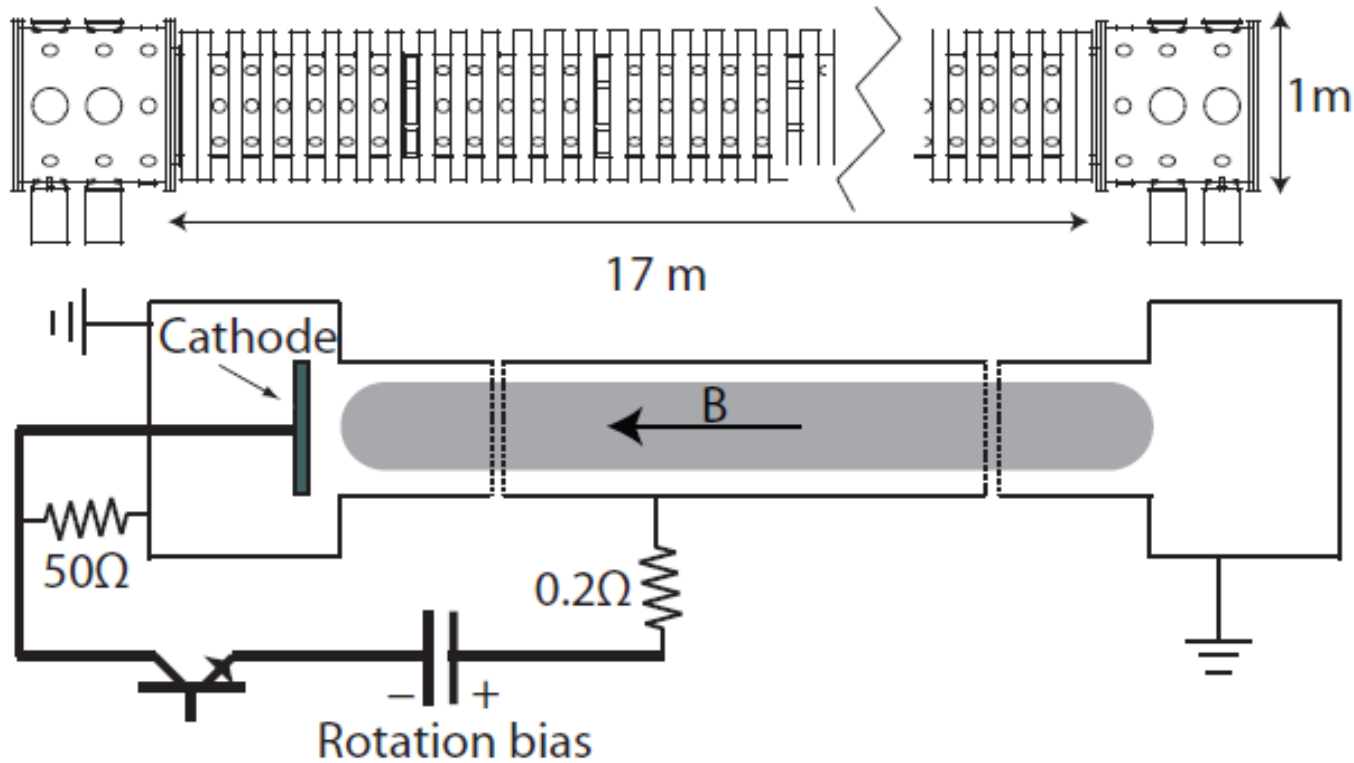


Biasing chamber to modify flows

- Biasing the chamber walls with a voltage larger than plasma potential can be used to directly modify flow profile by establishing strong radial electric fields from the chamber wall
- Comparisons to spontaneous phenomena can be made: flows, spectral turbulence and intermittency



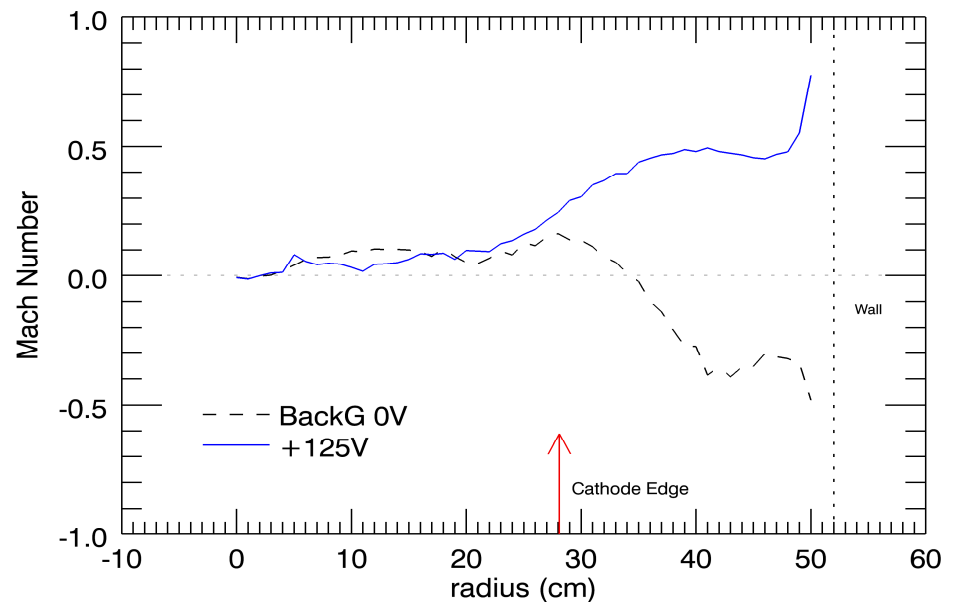
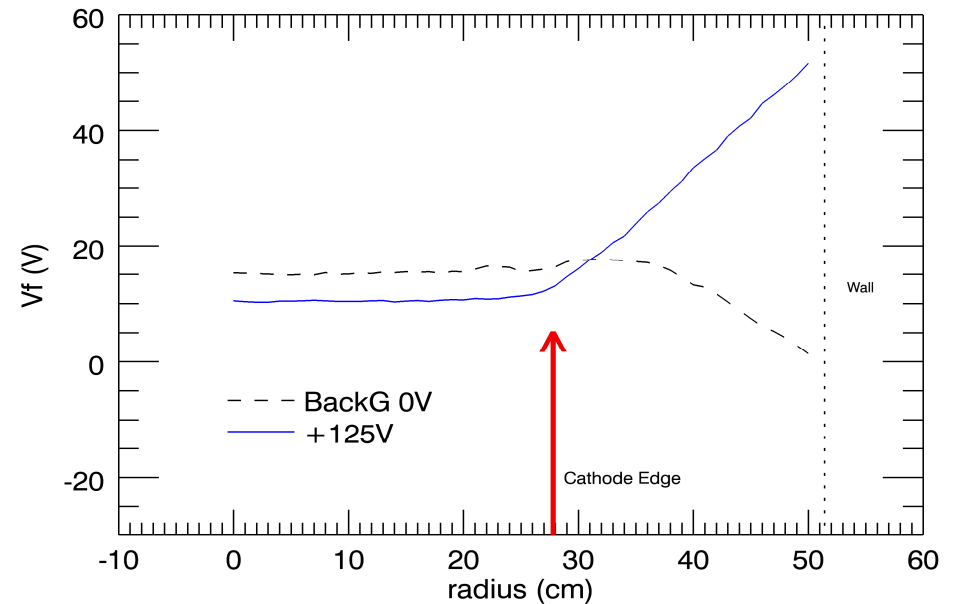
Biasing in LAPD



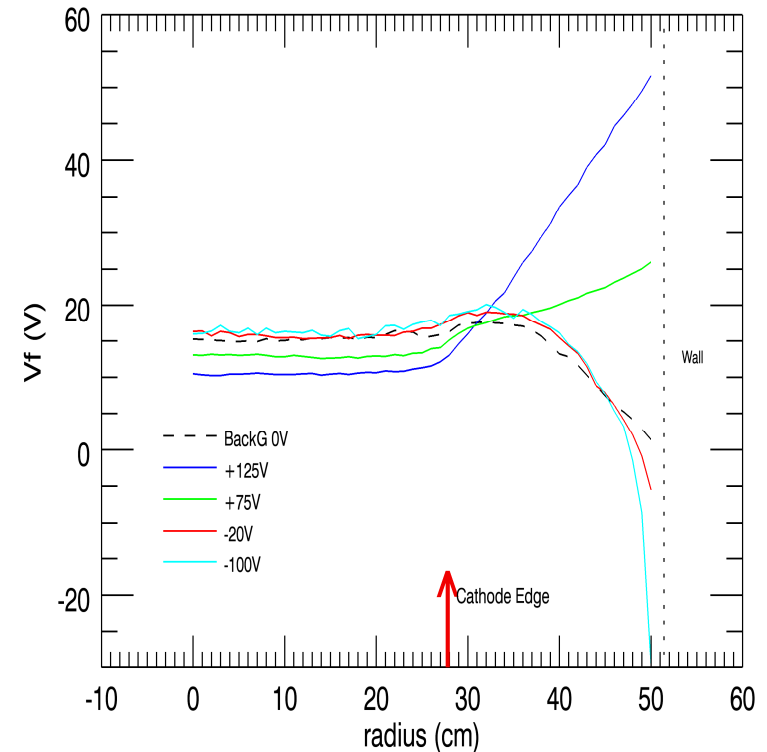
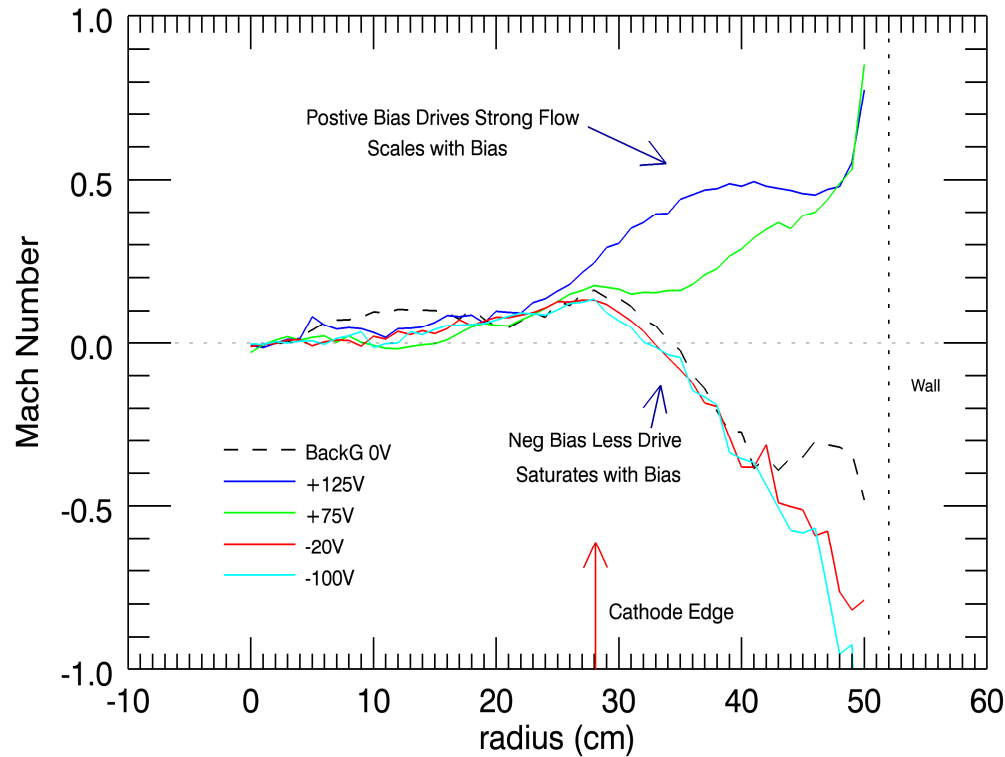
- Apply positive bias to (floating) wall of chamber (relative to cathode)
- Radial current in response to applied potential provides torque to spin up plasma
- Cross-field current carried by ions (through ion-neutral collisions)
- Confinement transition observed with biasing

Biasing modifies profile of potential, flow

- Floating potential increases beyond cathode edge, rather than decrease
- Flows reverse direction compared to unbiased case
- Spontaneous edge flow is in the ion diamagnetic direction (shear layer flow is in electron diamagnetic direction)
- Positive biasing drives flow in electron diamagnetic direction
- Shear layer at cathode less apparent in highly biased plasmas ($\sim +150\text{V}$)

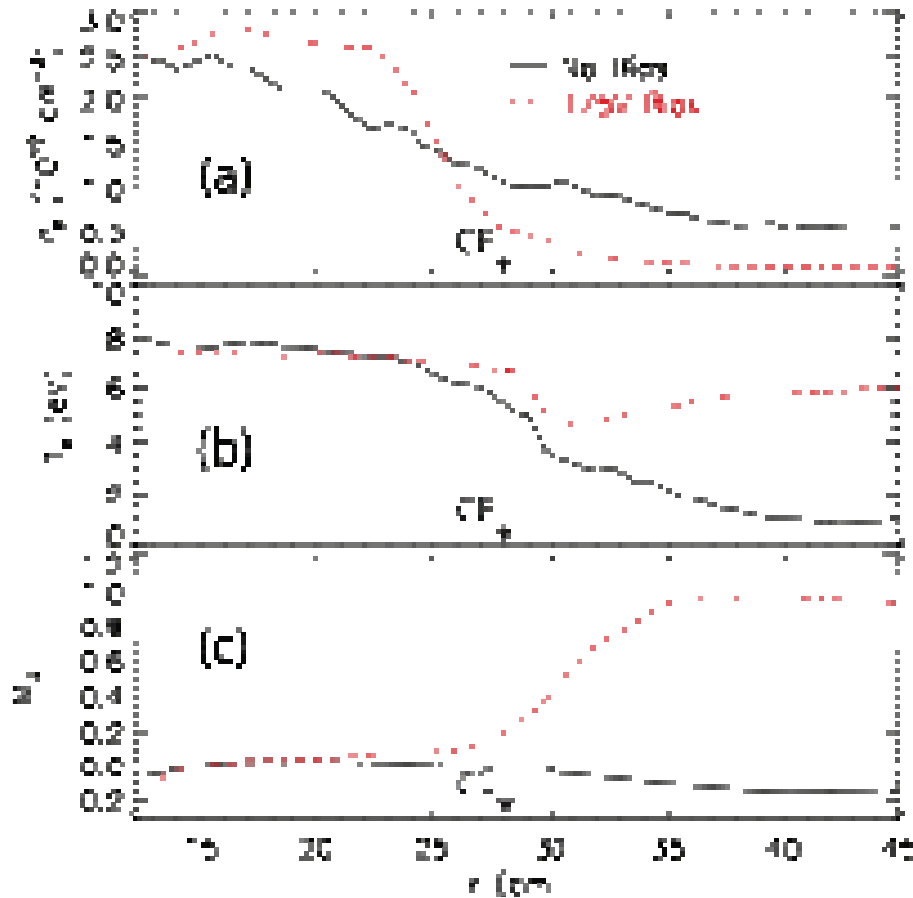


Flows scale with positive bias, not negative bias



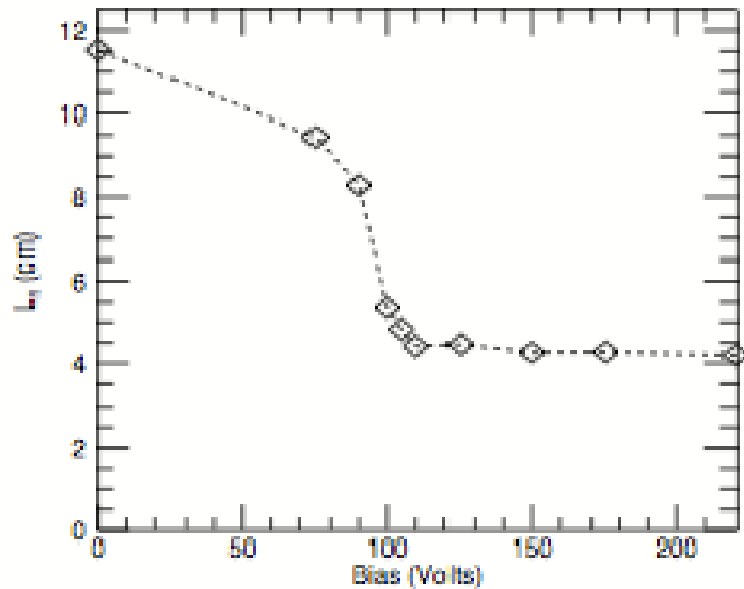
- Flows appear to scale with positive bias (unlimited electron collection current at wall)
- Negative bias does not drive more flow than background except right near wall (limited by ion collection)
- Potential increase to cathode edge scales with positive bias, negative potential doesn't penetrate

Dramatic profile steepening observed with biasing

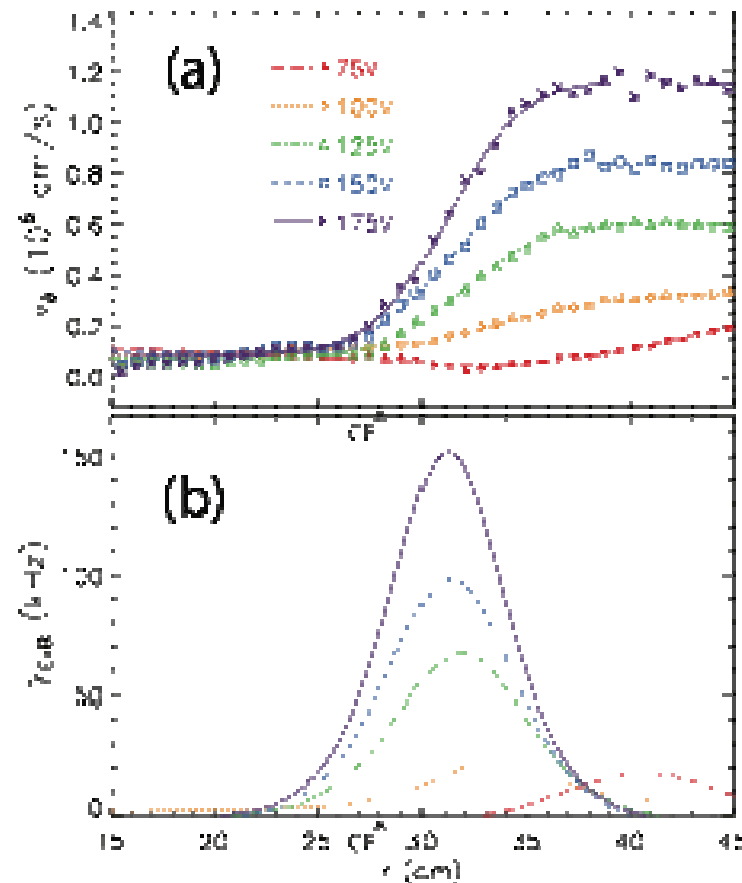


- As bias exceeds a threshold, confinement transition observed (“H-mode” in LAPD)
- Detailed transport modeling shows that transport is reduced to classical levels during biasing (consistent with Bohm prior to rotation) [Maggs, Carter, Taylor, PoP 14, 052507(2007)]

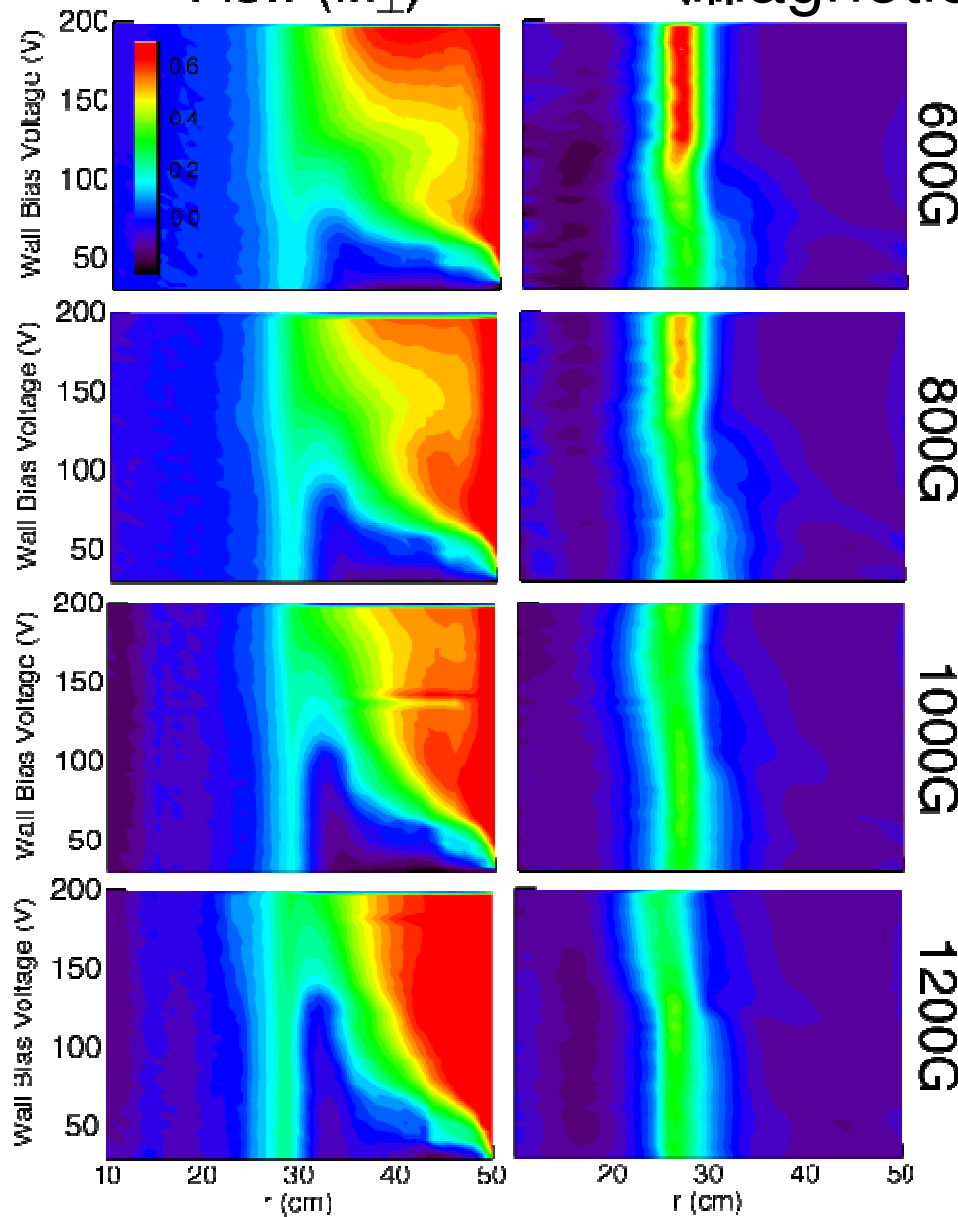
Threshold for bias transition is observed, appears to be due to radial flow penetration



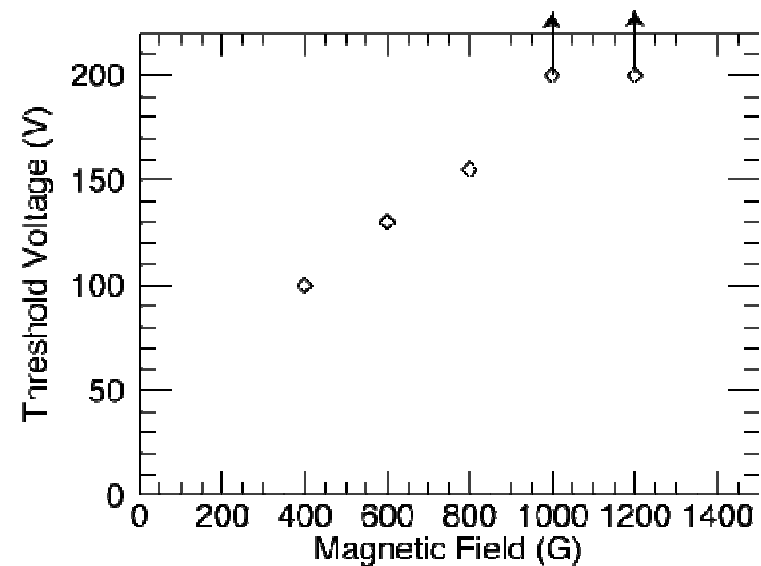
- Flow remains confined to far edge until threshold is exceeded
- Threshold increases with B



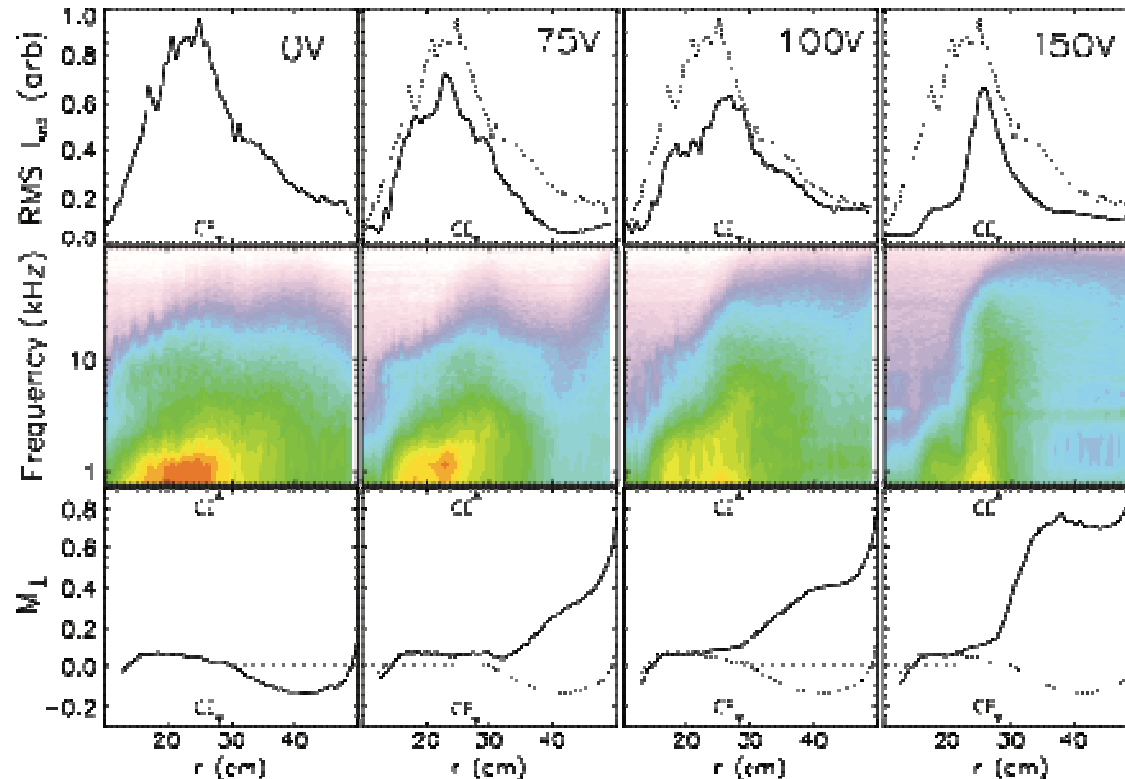
Transition threshold increases with increasing Flow (M_{\perp}) ∇ magnetic field



- Threshold still consistent with radial flow penetration
- Bias current decreases with increasing field

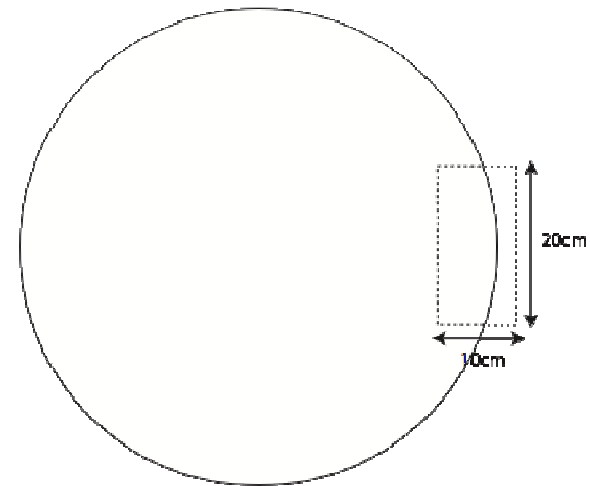
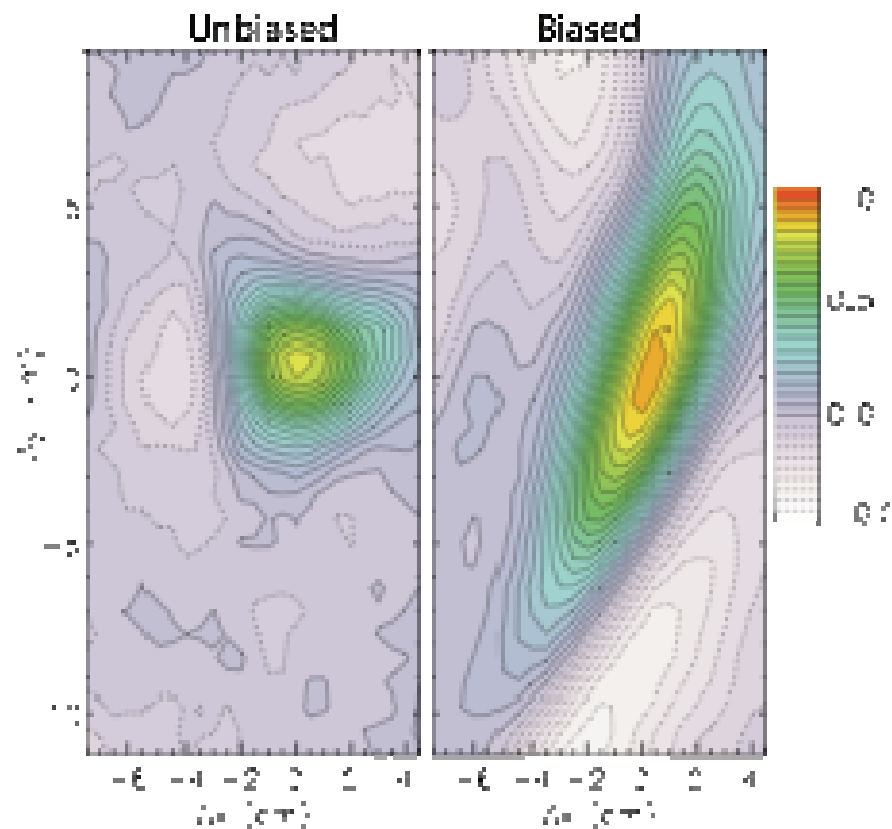


Fluctuation profile modified, but peak amplitude reduced only slightly



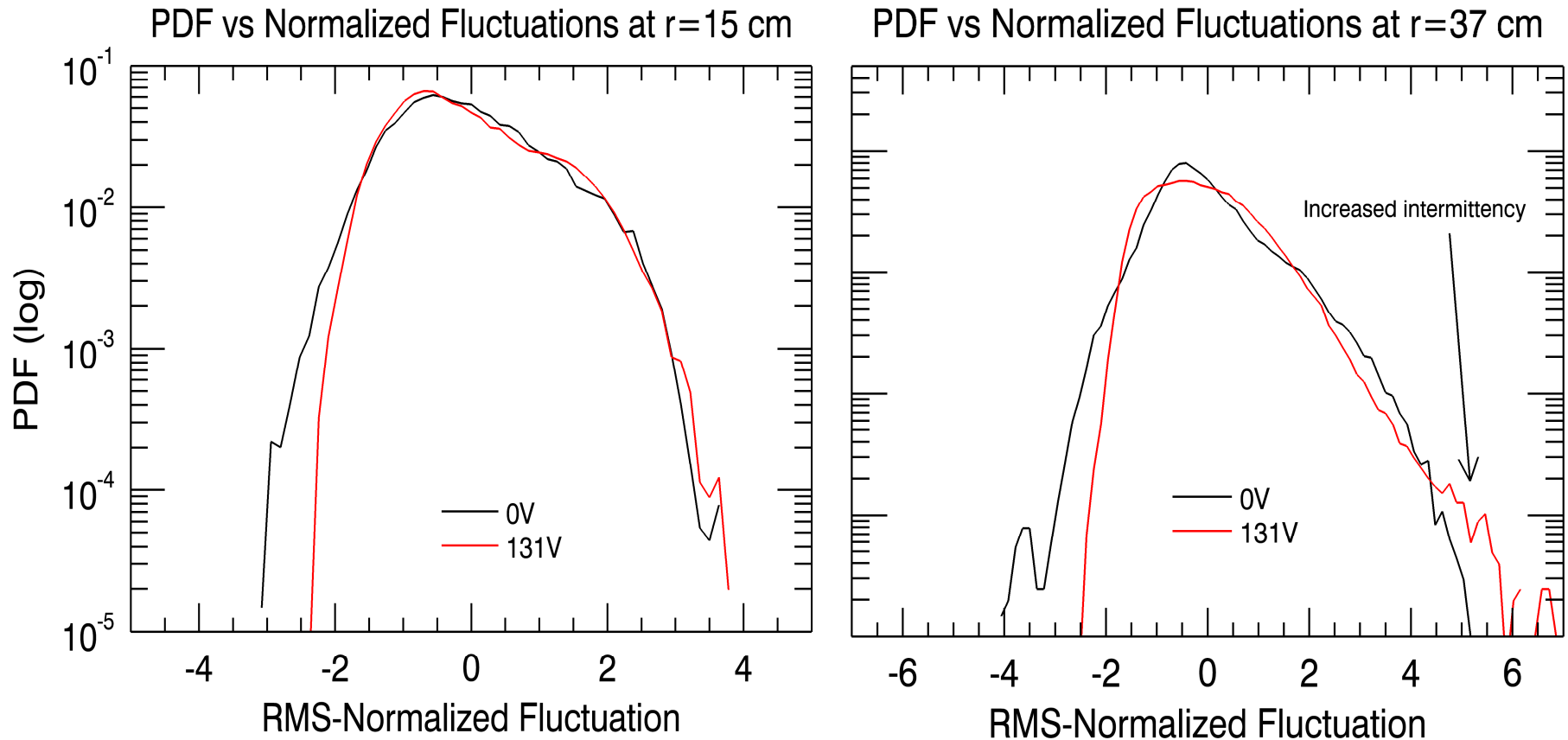
- Broadband fluctuations before and after biasing
- Fluctuations concentrate in space on steepened profile, Doppler shift observed, but strong fluctuations persist

Correlation functions show dramatic increase in azimuthal correlation, no significant radial decorrelation



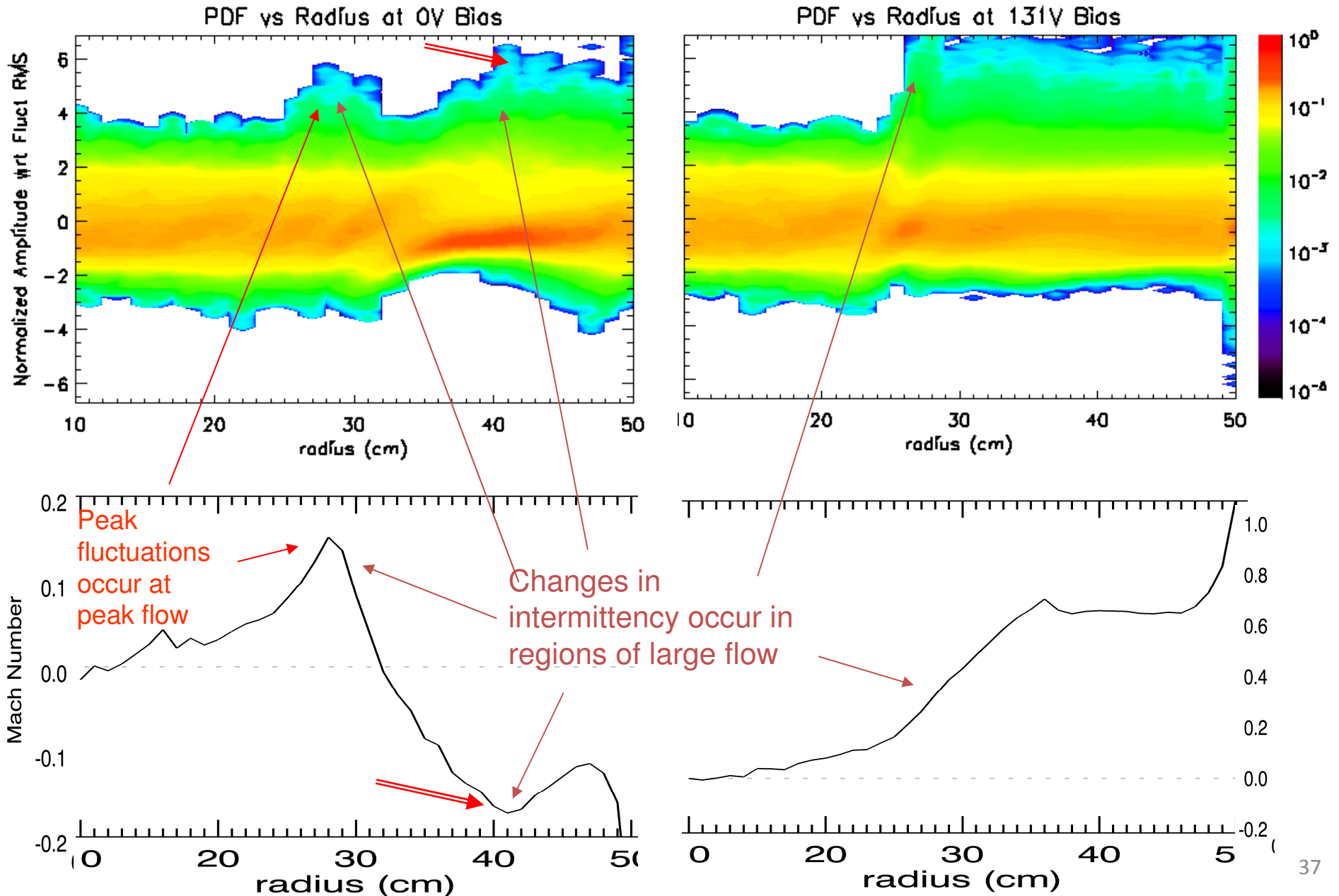
- No strong evidence for radial decorrelation
- Decreased transport through longer effective transport step time?

Intermittency varies with radius, bias



- Intermittency still seen with increasing bias voltage, even increased intermittency in high tail

Biassing increases intermittency observed



Summary

- LAPD parameters provide a fertile environment for study of turbulence, transport and flow
- Spontaneous flows develop in LAPD; flows scale inversely with field at cathode edge, and with field near chamber edge—their origin is still under investigation
- Turbulence in drift-wave mode regime is broadband and generally scales inversely with field
- Sheared flow appears to suppress some turbulent fluctuations, but not all
- End boundary conditions do not appear to have a significant effect on shear layer flows
- Intermittent turbulence is seen in the edge region and appears to have some connection to flow—edge effect still being investigated
- Biasing can be used as a tool to control flow directly to extract more scaling relationships

Future Work

- Continue study of spontaneous and bias driven flows; in particular look at relationship to Reynolds stress
- Examine particle flux and density/potential cross-phase
- Develop k-spectra from correlation functions for connection to observed modes
- Look for turbulence/transport/flow/momentum transfer connections to intermittency in edge
- Further investigation of boundary effect including potential introduction of iris-like limiters in LAPD
- Continue to compare results to simulations such as BOUT, or gyrokinetic code
- *Feedback on possible analyses is welcome! Any suggestions for measurements/calculations useful to theorists/simulators that have been overlooked are greatly appreciated!*