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Intermittency and convective transport in edge turbulence.

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Intermittency and convective transport in edge turbulence

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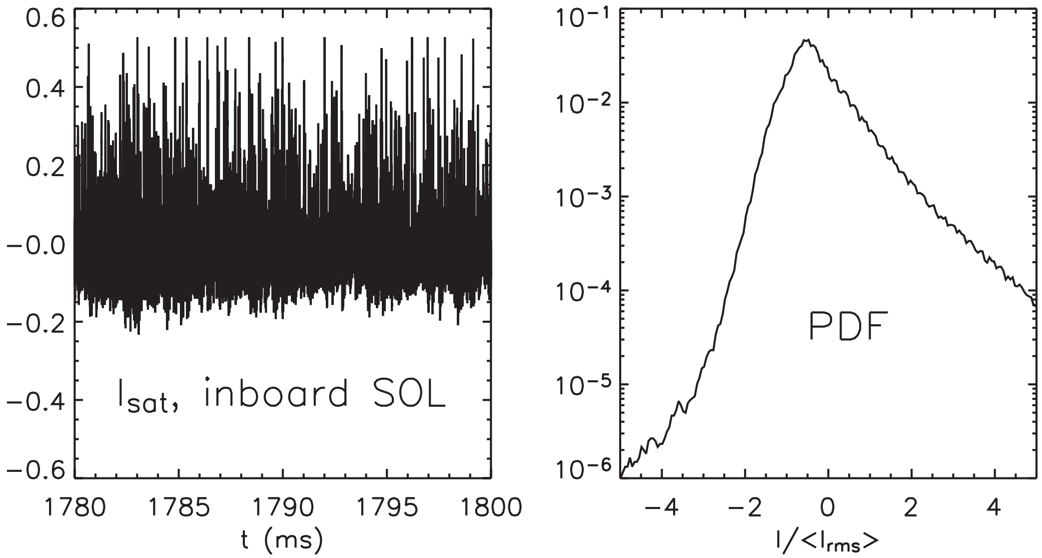
What is intermittent turbulence?

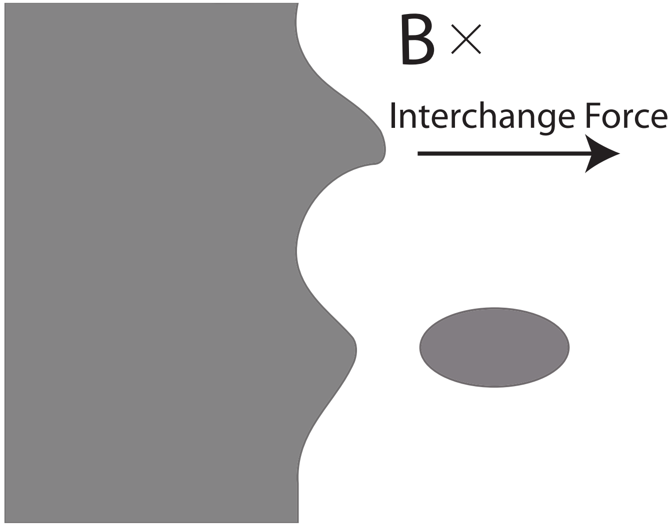


- Patchy in space or bursty in time, non-Gaussian amplitude PDF: above signal full of positive going events

- Intermittent turbulence observed in the edge of nearly all magnetically confined devices (tokamak scrape-off-layer, linear devices, etc) [G.Y. Antar, et al., Phys. Plasmas 10, 419 (2003)]

- Due to existence and propagation of filamentary (field-aligned) structures (often called “blobs” and “holes”) [F. Chen, Sci. Amer. 217, 76 (1967)]

Structure propagation can be explained by polarization by drift-currents



- Imagine a “blob” (filament, really) torn off of the plasma edge

[S.I. Krasheninnikov, Phys. Lett. A 283, 368 (2001)]

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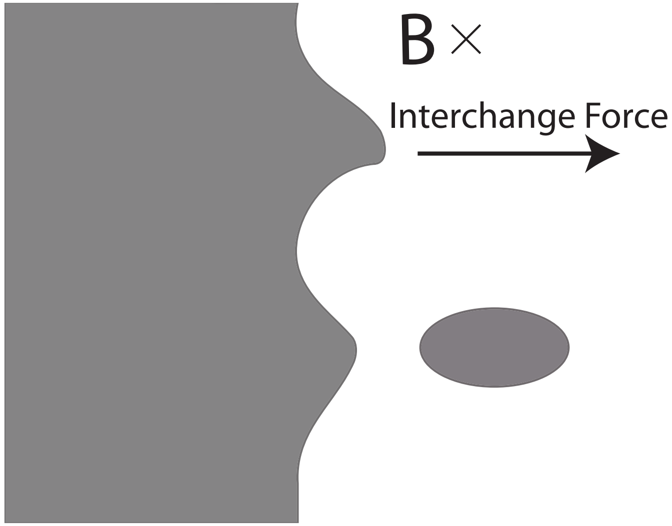

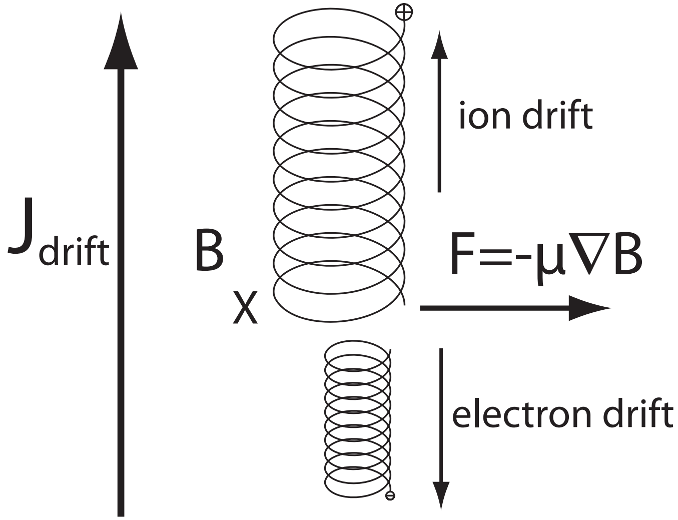

- Imagine a "blob" (filament, really) torn off of the plasma edge
- Vertical currents associated with particle drifts charge the edge of the structure (balanced by parallel losses)

[S.I. Krasheninnikov, Phys. Lett. A 283, 368 (2001)]

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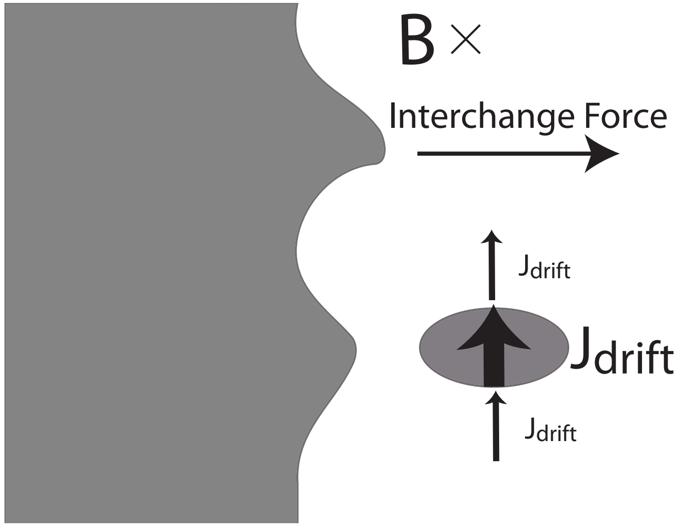

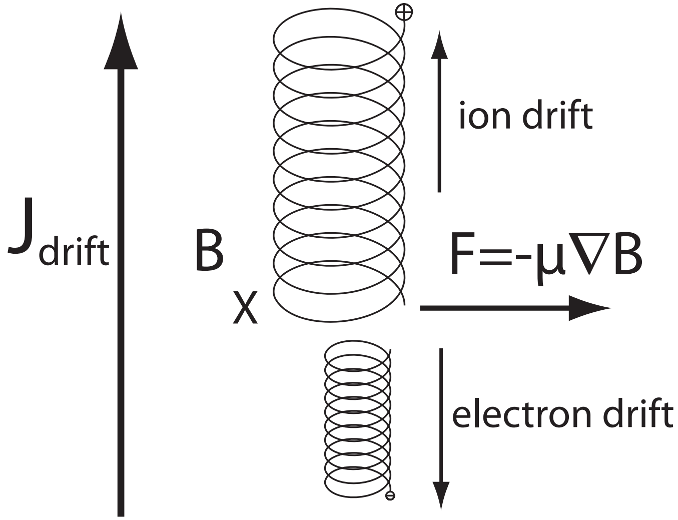

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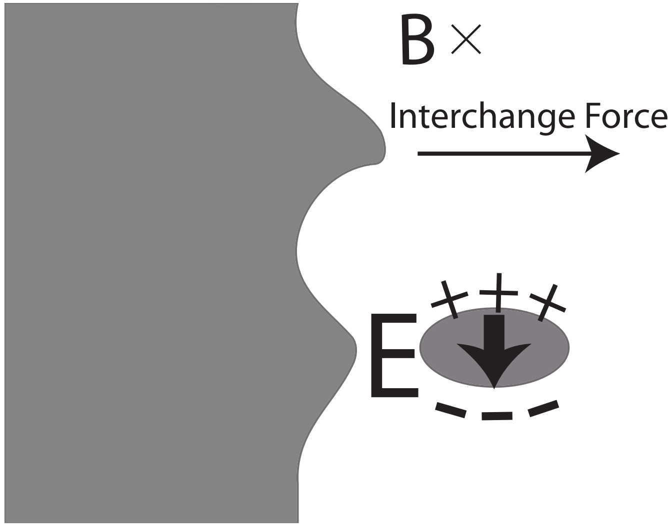

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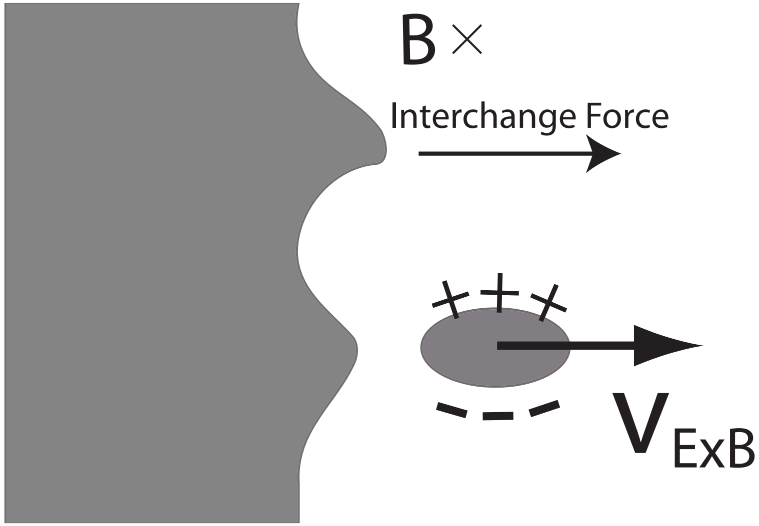
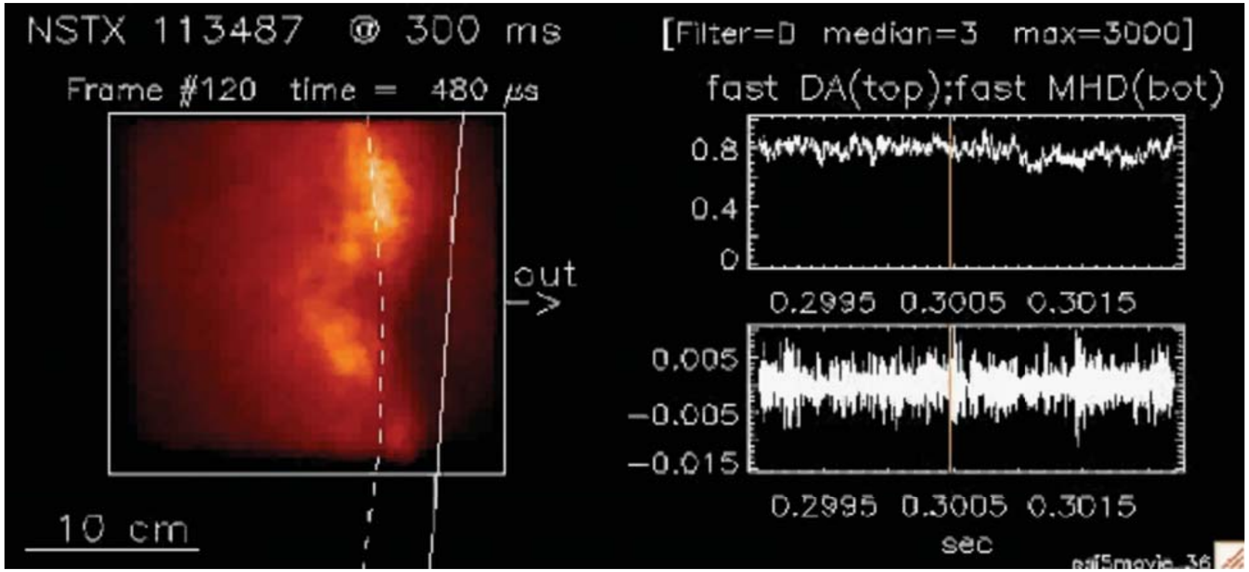


- Imagine a “blob” (filament, really) torn off of the plasma edge
- Vertical currents associated with particle drifts charge the edge of the structure (balanced by parallel losses)
- Polarized blob moves across the field (and out of the plasma edge) by ExB drift

[S.I. Krasheninnikov, Phys. Lett. A 283, 368 (2001)]

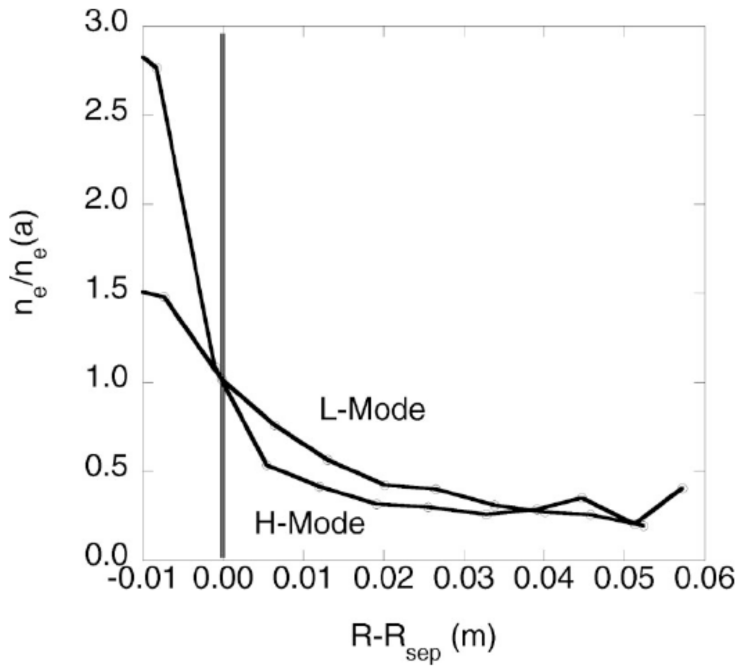
Gas puff imaging (GPI) data show ejection of structures from the plasma boundary



- Movie of neutral emission (enhanced by gas puff), measurements by S. Zweben (PPPL)
- Shows "blobs" ejected from plasma edge (cause "spikes" in signal as they pass by measurement location)

Why do we care?

- Intermittent convection of "blobs" accounts for substantial fraction of particle transport in the edge of tokamaks



- Flat density profiles observed in tokamak SOL (inconsistent with diffusive transport)
- Measurements of transport flux in DIII-D indicate >50% of flux due to blob transport

[J.A. Boedo, et. al., Phys. Plasmas 8, 4826 (2001)]

Why do we care?

- Intermittent convection of "blobs" accounts for substantial fraction of particle transport in the edge of tokamaks
- May be linked to unexplained "density limit" disruptions in tokamaks
  - Dramatic increase in convective particle transport as limit approached in Alcator C-Mod
  - ITER is designed to operate below this limit

[M. Greenwald, Plasma Phys. Control. Fusion 44, R27 (2002).]

Why do we care?

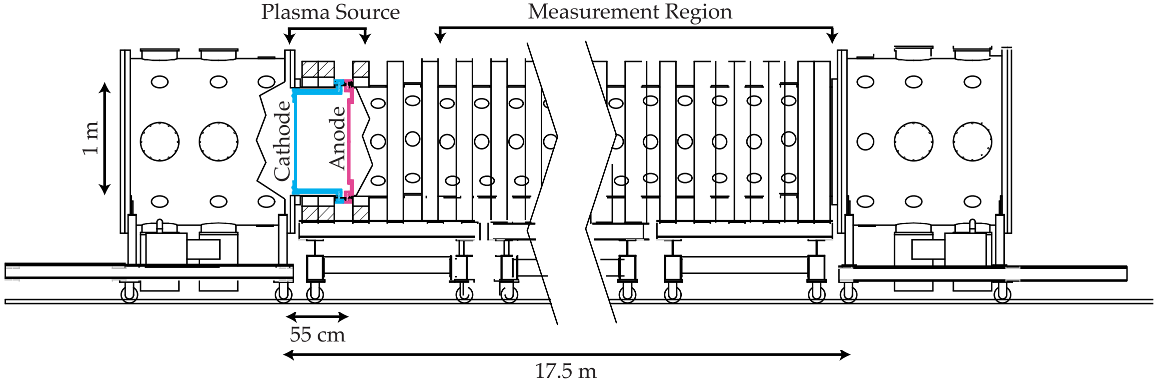
- Intermittent convection of "blobs" accounts for substantial fraction of particle transport in the edge of tokamaks
- May be linked to unexplained "density limit" disruptions in tokamaks
- Intermittent turbulence has relevance to other plasmas: e.g. magnetosphere, interstellar medium
  - Coherent structures in magnetosphere associated with drift-Alfvén waves [D. Sundkvist, et. al., Nature 436, 825 (2005)]

Studies of properties of intermittent turbulence, coherent structures

- Questions:
  - What is the spatial structure of the objects (typical size, are they polarized as expected, etc)?
  - What is the typical ejection velocity? (consistent with drift charging?)
  - How/why are the structures created? (What are primary ingredients of structure creation, how is creation localized in the plasma, etc?)
- Studies ongoing on a number of confinement devices, focus here on my own work on a linear magnetized plasma at UCLA

[T. Carter, Phys. Plasmas 13, 010701 (2006)]

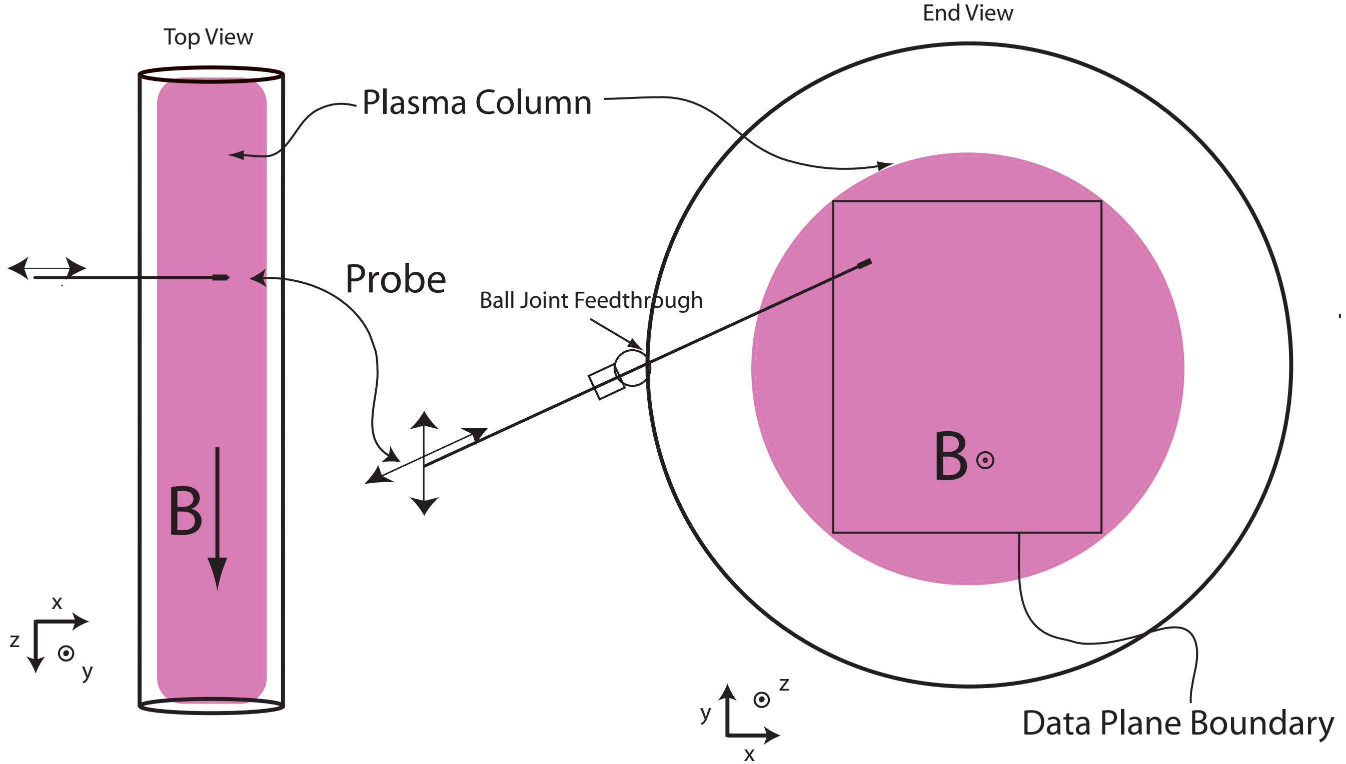
The LArge Plasma Device (LAPD) at UCLA



- US DOE/NSF sponsored user facility (available to international users…)
- 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 (~300 ρ_i, ~100 ρ_s)
- High repetition rate: 1 Hz (10^5 shots a day instead of ~20 on a tokamak)
- Similar parameters to tokamak far edge plasmas: can study basic processes relevant to fusion plasmas

Measurement methodology in LAPD

- Use physical probes to measure local density, temperature, potential, magnetic field, flow
    - e.g. Langmuir probe: electrode biased to collect current from the plasma (determine density, temperature, potential)
- Use high rep rate (1Hz) to make detailed spatial measurements of average quantities over many discharges



Measurement methodology in LAPD

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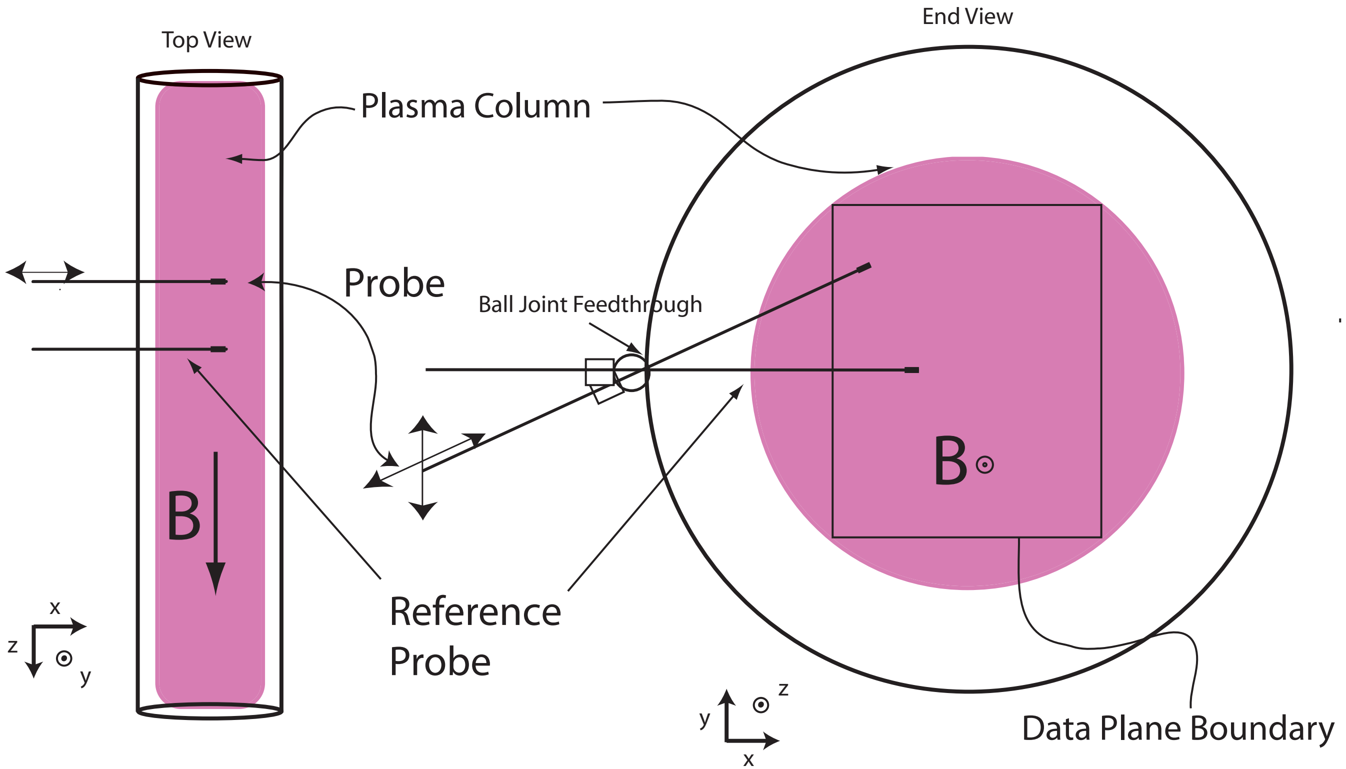
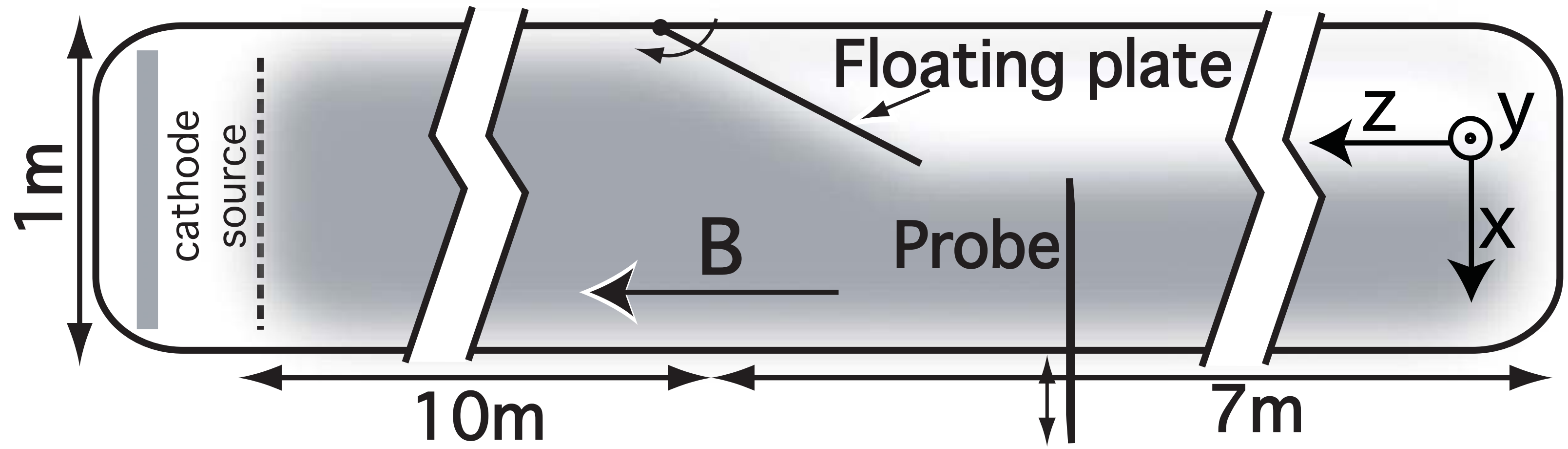
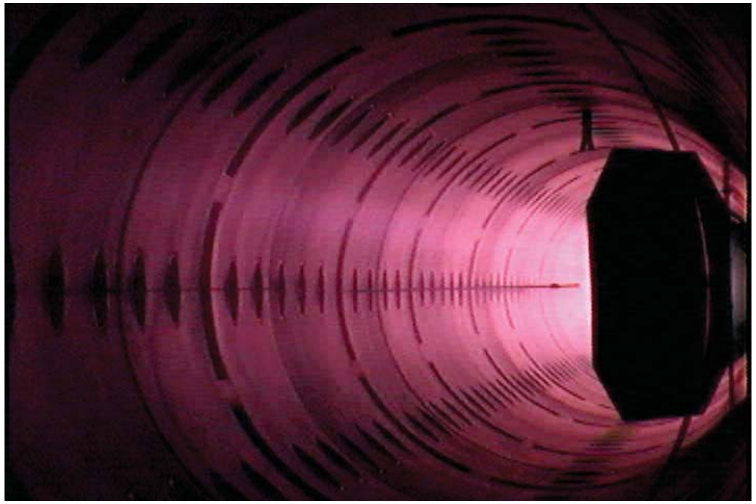
- Use correlation techniques to make detailed statistical measurements of turbulence (structure, etc)



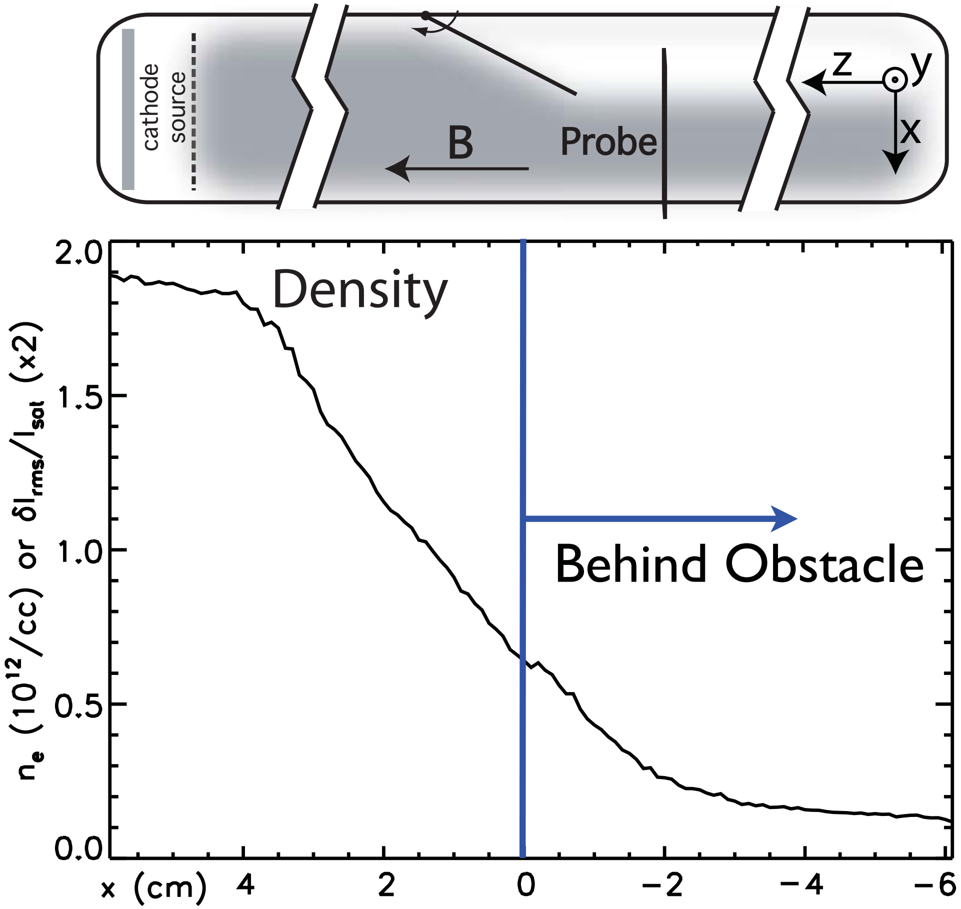
Limiter-produced density gradients in LAPD





- Floating plate (10m from source) partially closed
- Steep density gradient behind limiter
- Vertical limiter edge - flows, but not rotation

Simulated tokamak boundary in LAPD: strong turbulence in steep density gradients



- Obstacle (limiter) terminates discharge, no ionization source behind (x<0); cross-field transport fills this in

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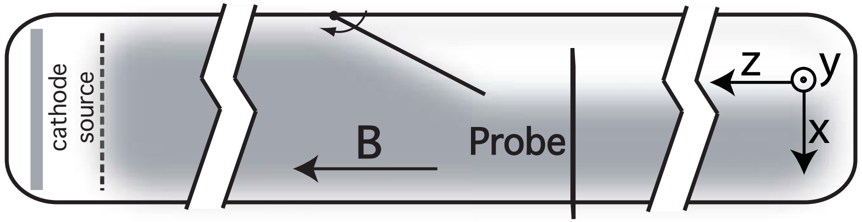
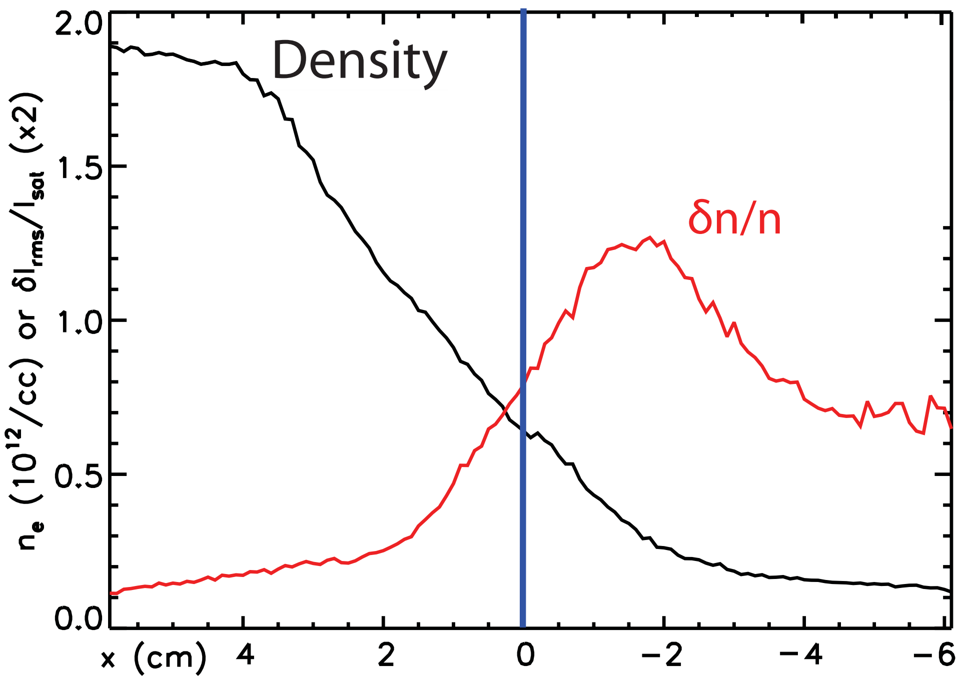
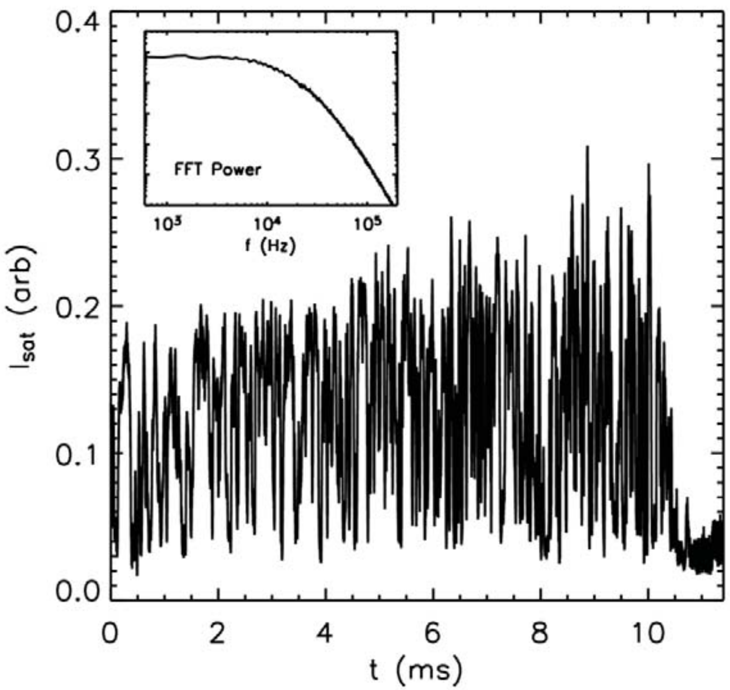


$$\frac{\delta n}{n} \sim 1$$





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- Strong, broadband turbulence in gradient region

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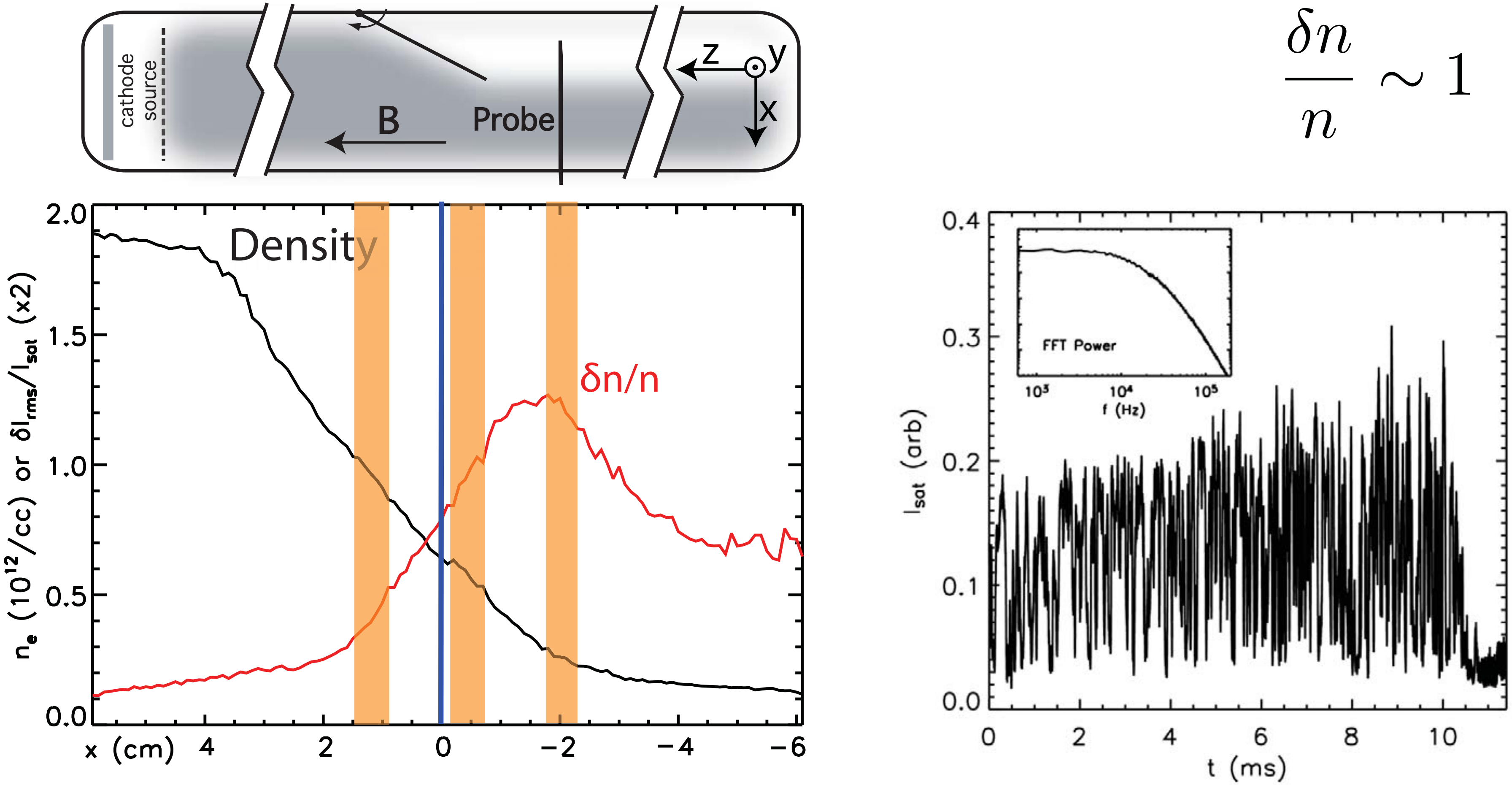

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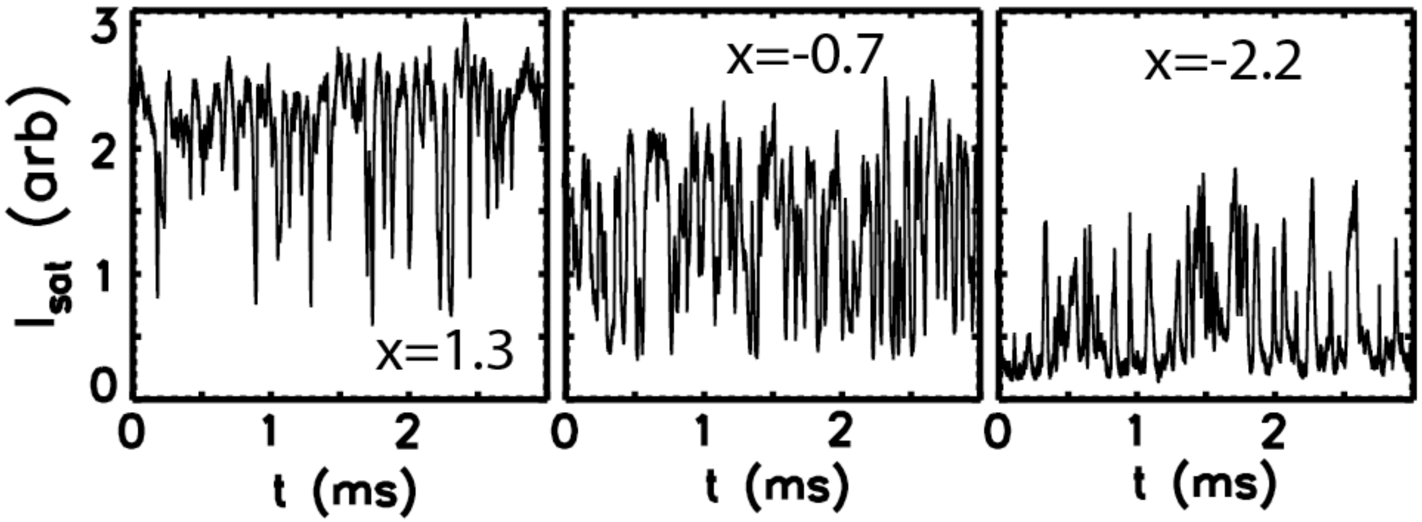
Strong intermittency and observation of both "blob" and "hole" structures



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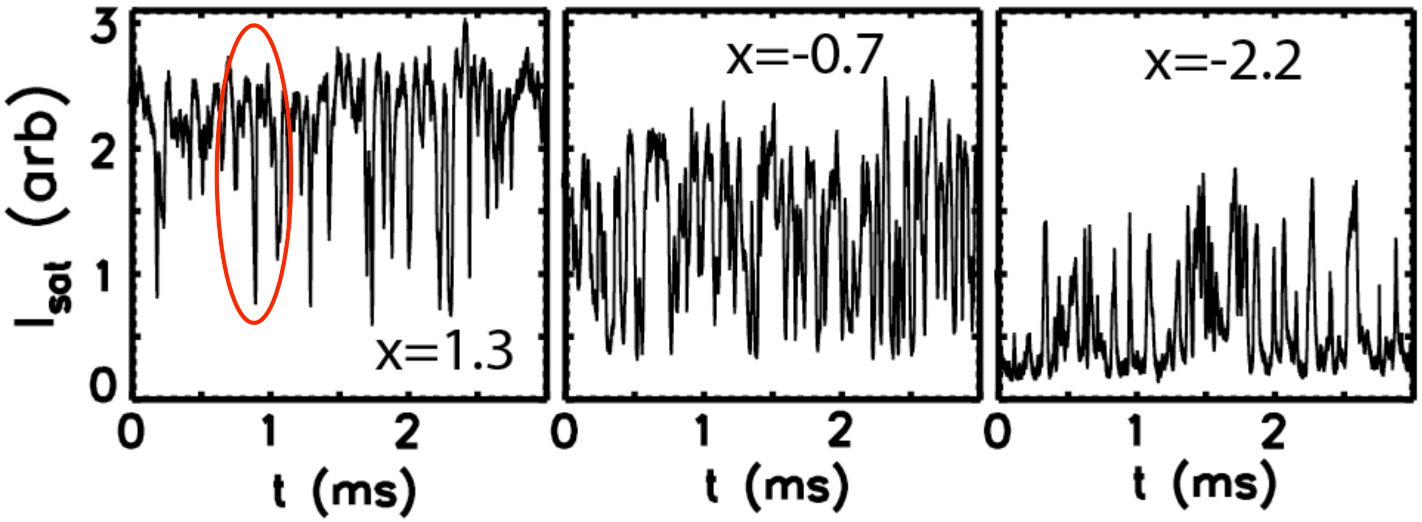

- Density depletion events (or “holes”) dominant on core side of gradient

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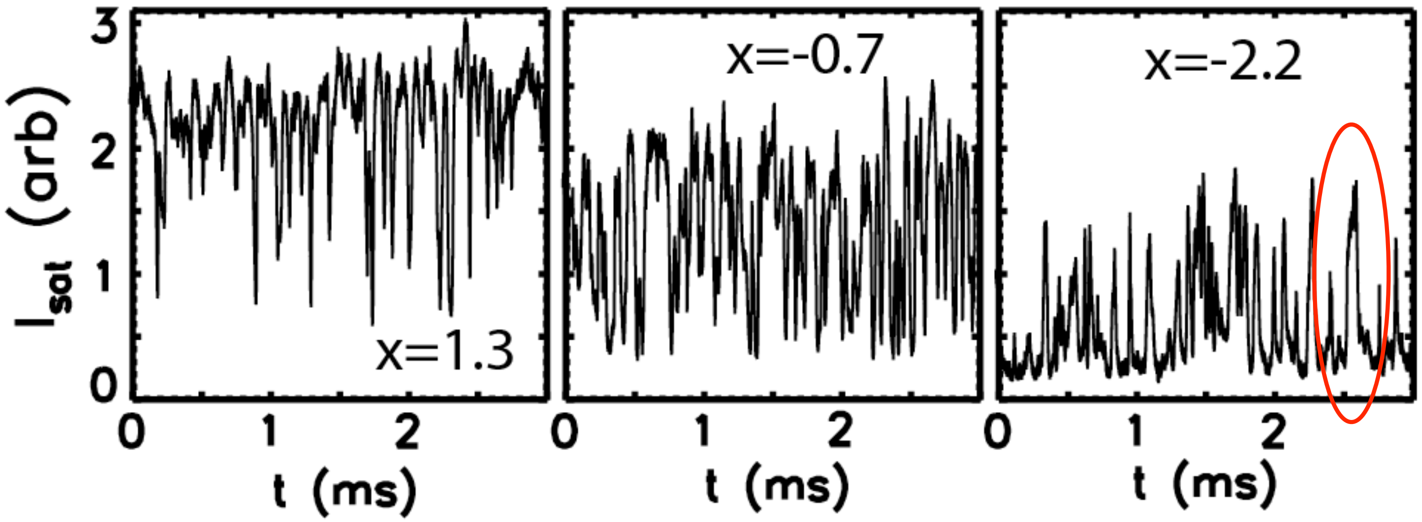
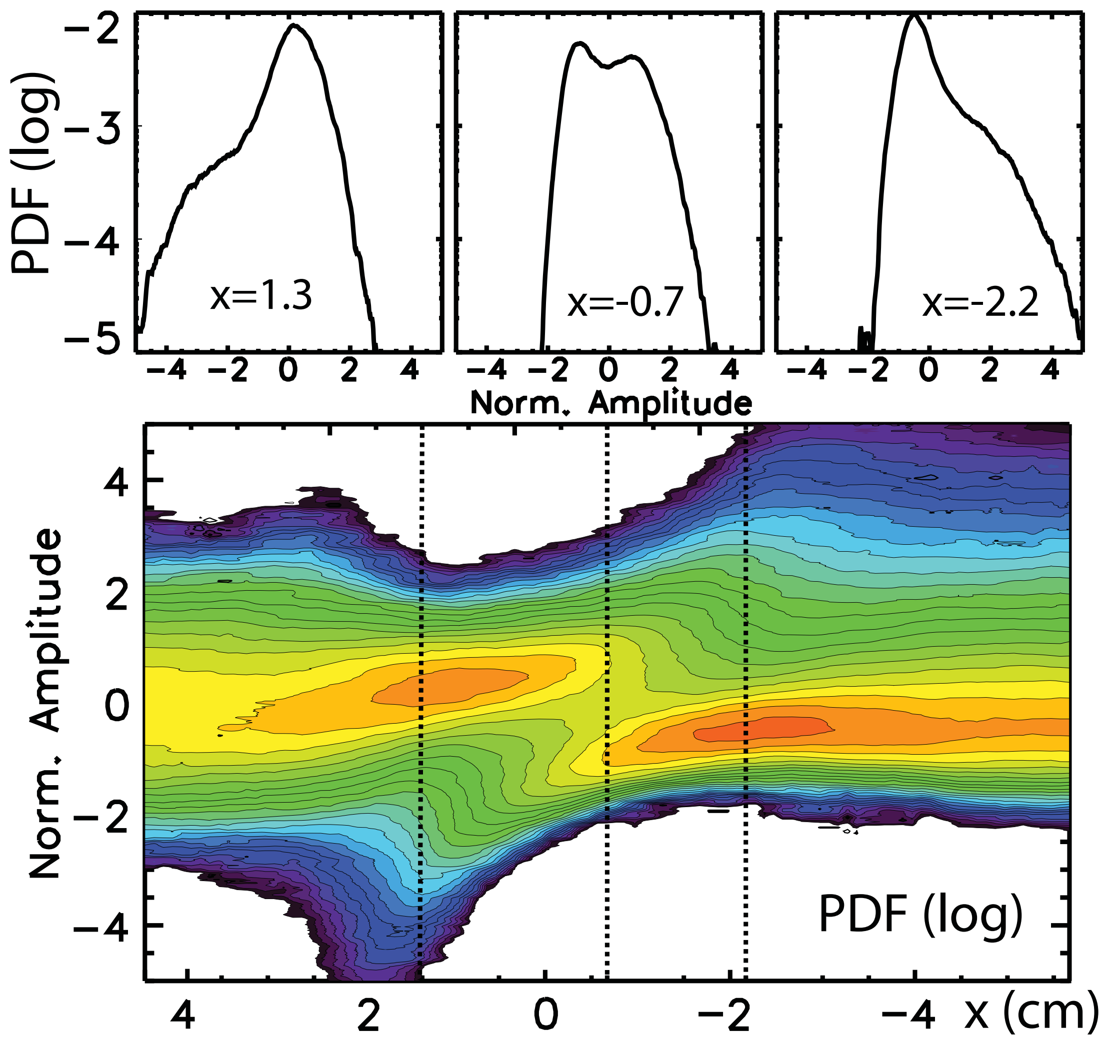


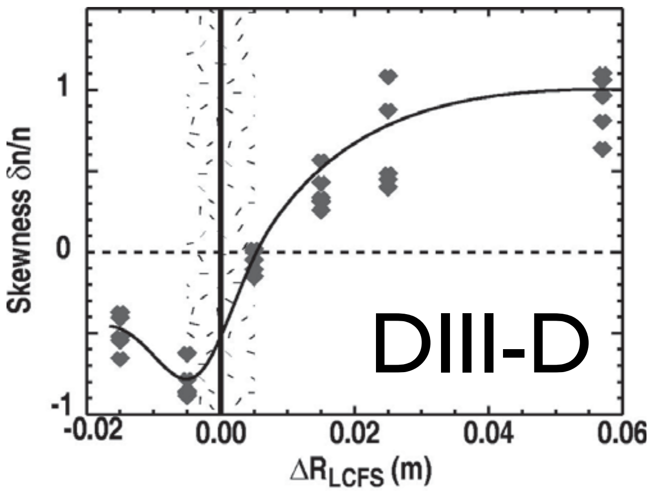
- Density depletion events (or "holes") dominant on core side of gradient
- Density enhancement events (or "blobs") dominant in limiter shadow

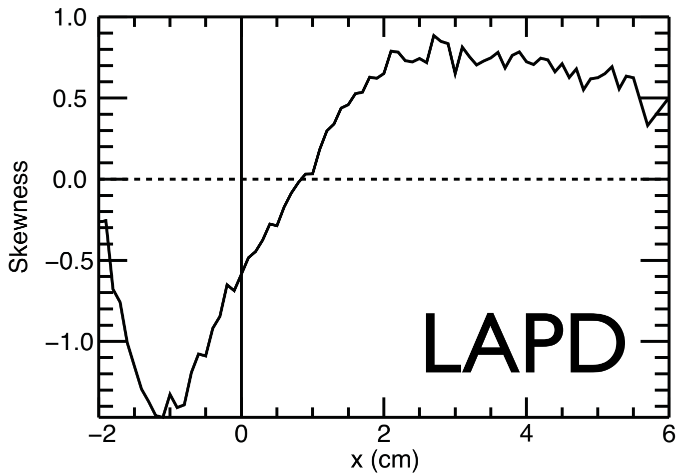
Fluctuation amplitude PDF is highly non-Gaussian



- Hole signature spatially localized, blob-dominated PDF extends into low density region

LAPD data very similar to tokamak data, allows for studies not possible in tokamak





- Density fluctuation measurements in DIII-D exhibit trends in PDF strikingly similar to LAPD observations

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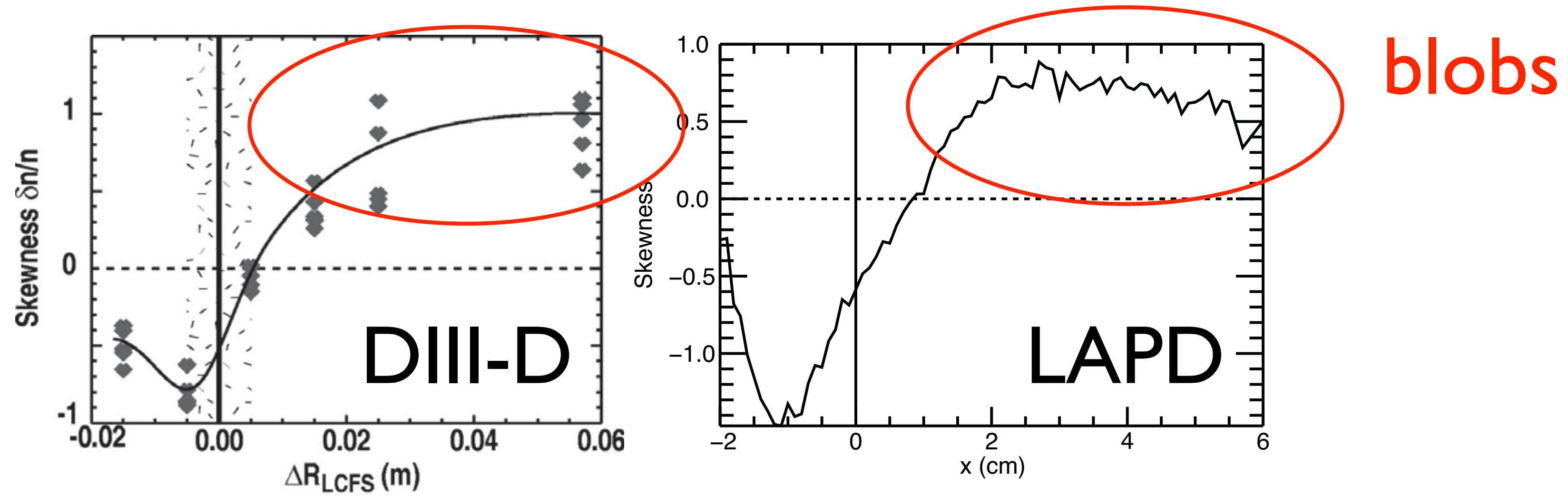

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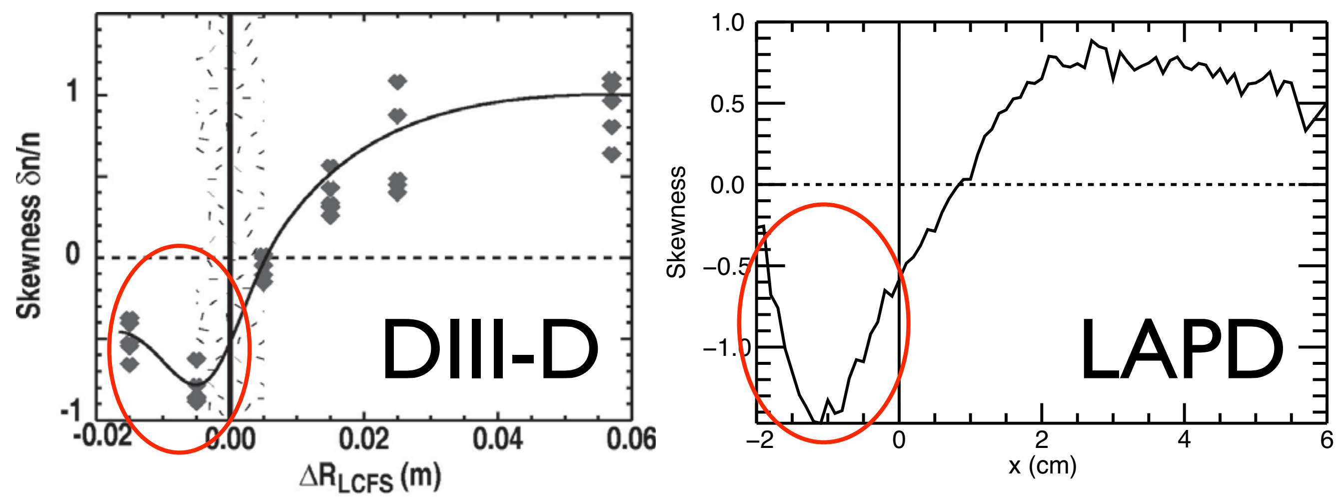

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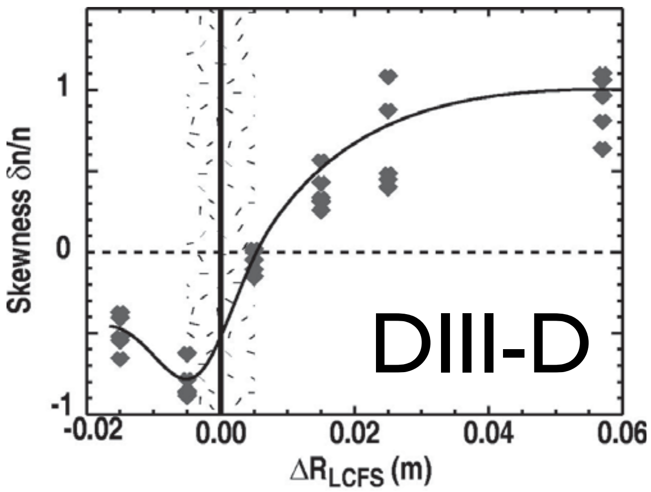
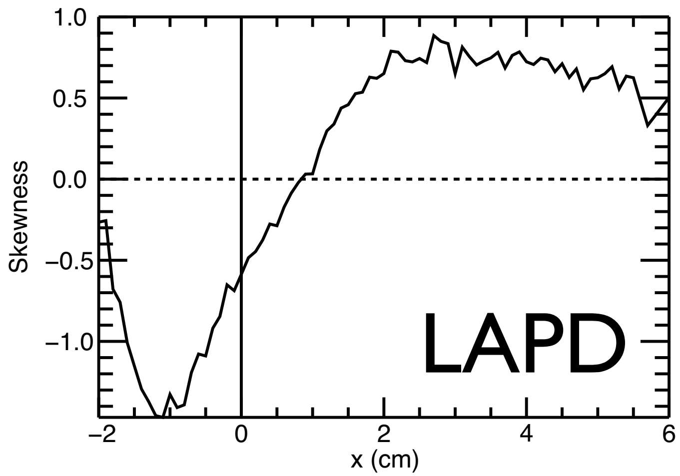
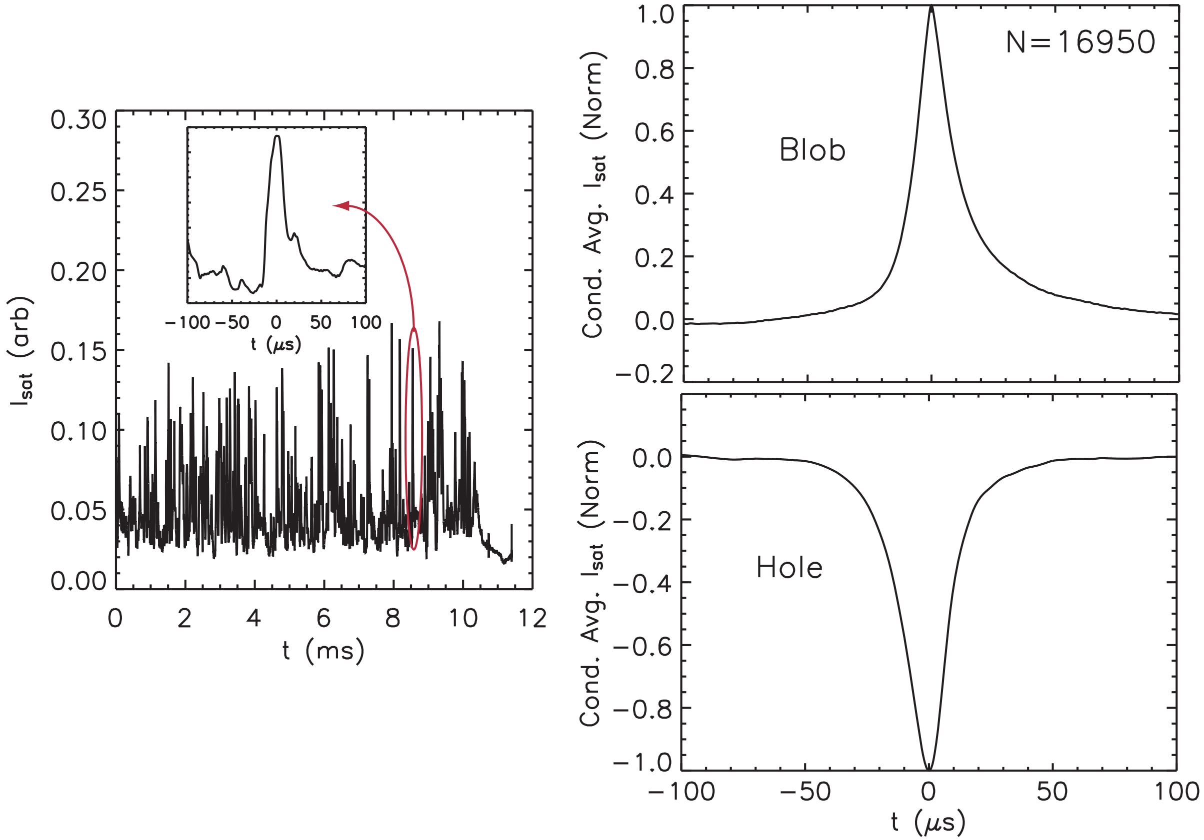




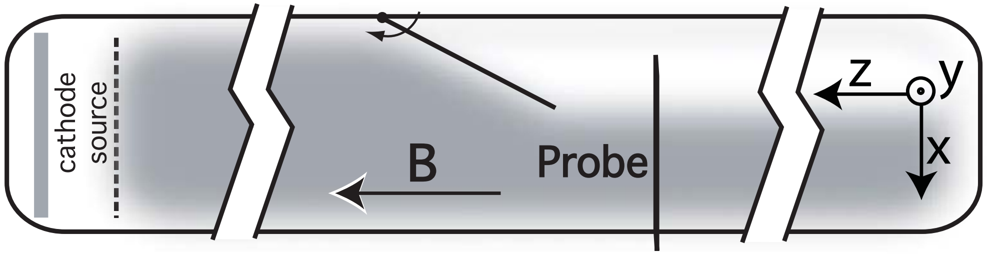
- Density fluctuation measurements in DIII-D exhibit trends in PDF strikingly similar to LAPD observations
  - evidence for blob and hole production, on similar spatial scales (gyroradii similar in two experiments)
- Detailed measurements can be done which are not possible in tokamak
  - Measurement of cross-field structure of blobs, holes
  - Magnetic field scaling of blob size

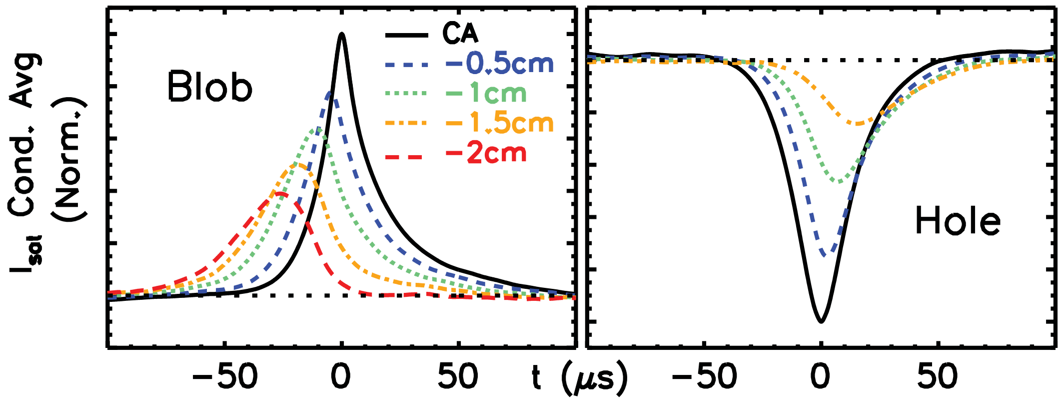
Conditional averaging used to study properties of blob and hole structures



- Time asymmetry in blob event - seen consistently in experiment [Antar, et. al.] and in simulations [D'Ippolito, et. al.]
- Hole event more symmetric, maybe slightly opposite asymmetry

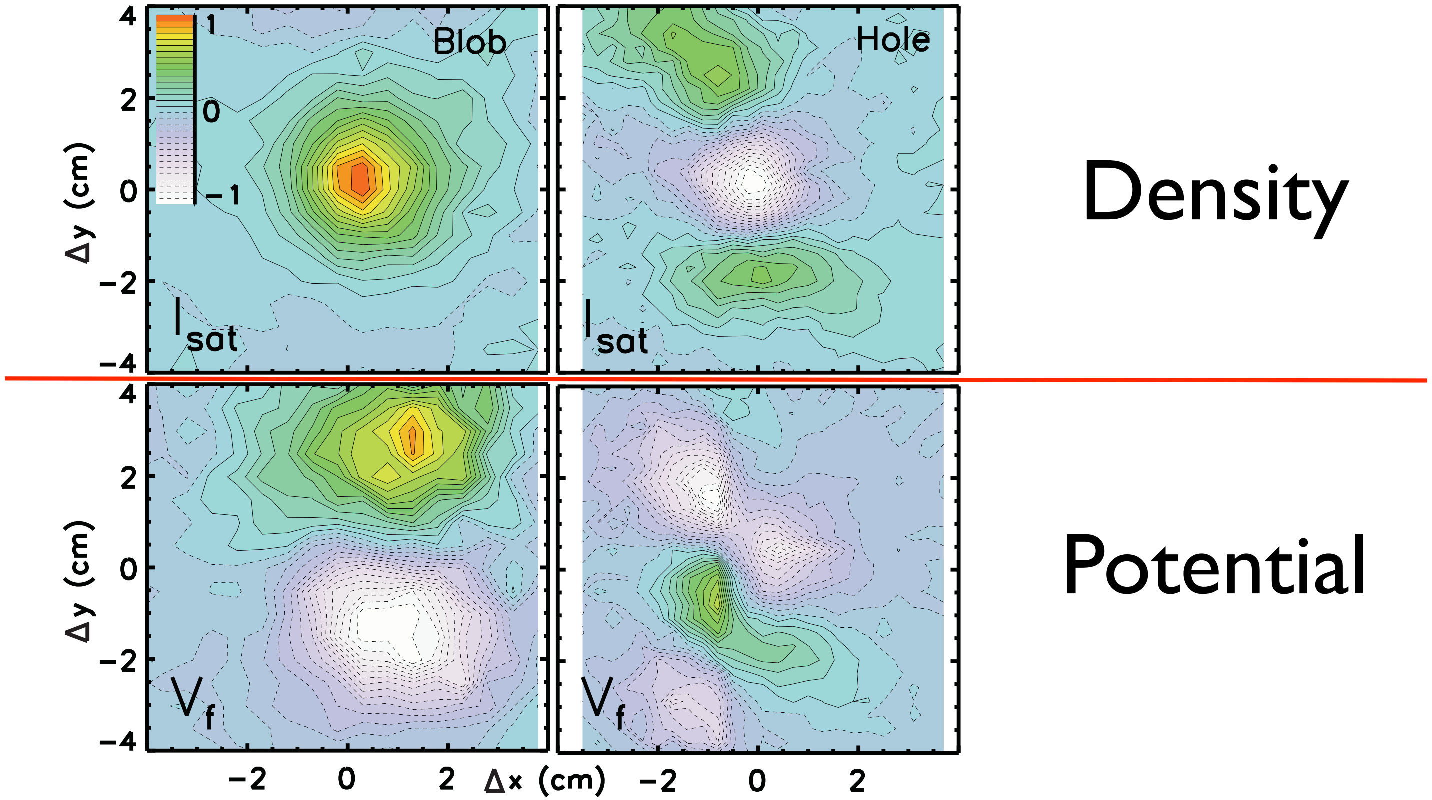
Cross-conditional averaging shows blobs propagate out of plasma, holes back in





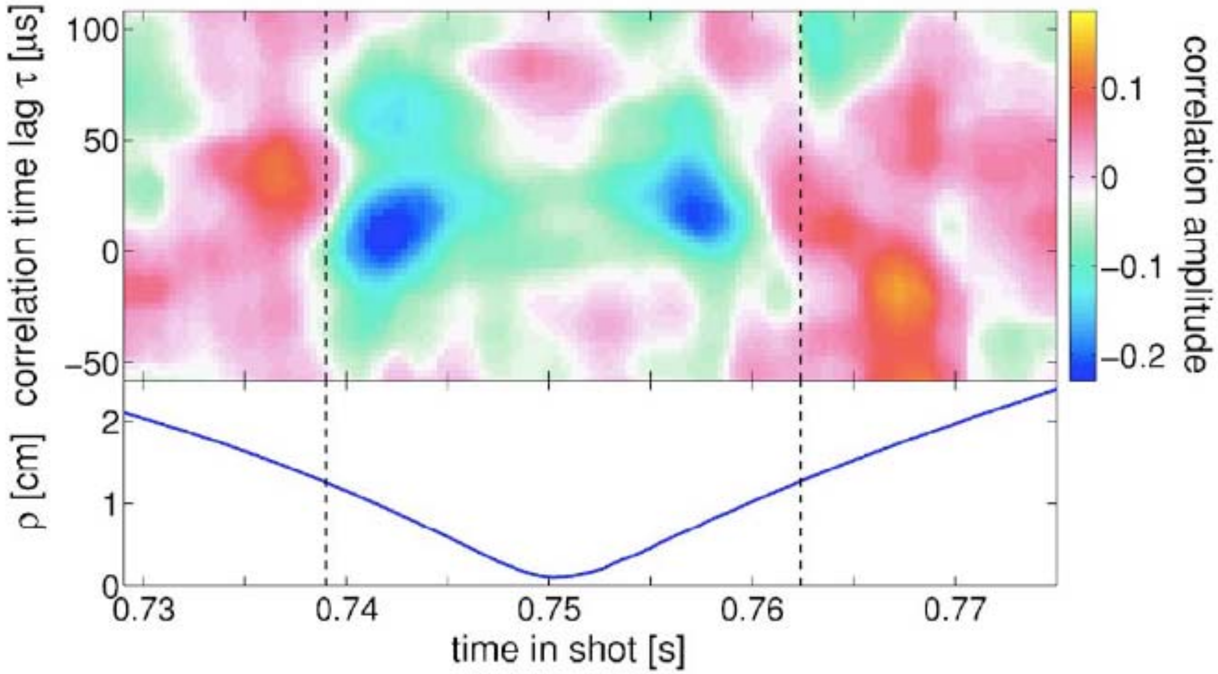
- Linear array of Langmuir tips, arranged on the x-axis
- $V_{blob} \approx 940\ \mathrm{m/s} \ \sim \dfrac{C_s}{10}$
- However - need to know 2D structure to interpret 1D velocity measurement (e.g. could be vertical propagation of tilted structure)

2D structure measurement: blobs are polarized filaments, holes are not isolated structures



- 2D cross-conditional average, using two triple Langmuir probes (separated by 60cm along the field)
- Derived blob velocity consistent with linear array, $V_{ExB} \approx 980$ m/s
- Hole structures do not appear to be detached - instead are likely part of extended nonlinear drift wave structure

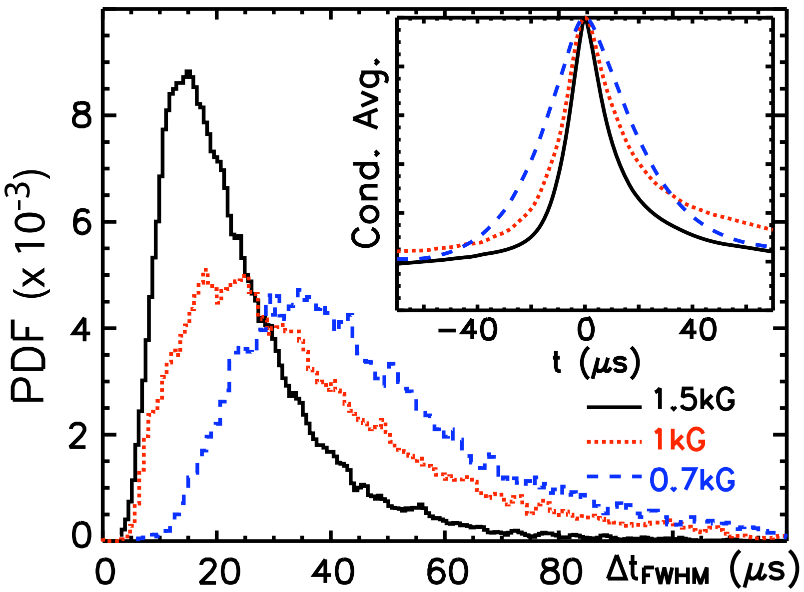
Probe imaging of polarized filaments in Alcator C-Mod

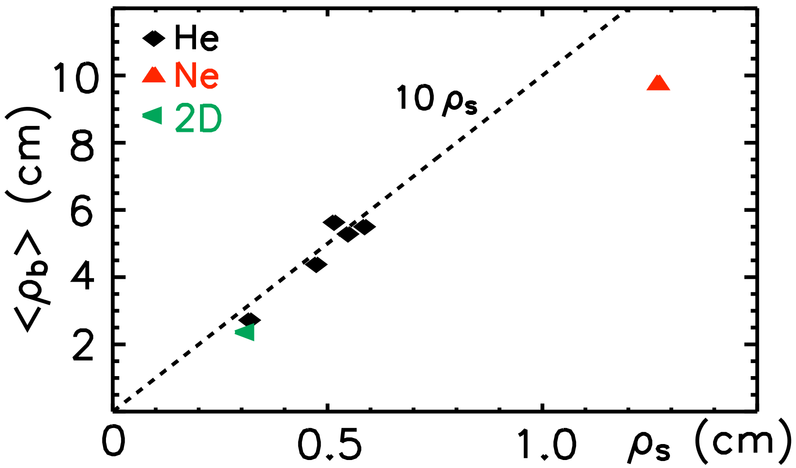


- Cross-correlation between plunging Langmuir probe (measuring floating potential) and GPI measured density fluctuation (effective 1D measurement, but structure sweeps by in time)
- Dipole potential structure associated with blob
- Difference with LAPD: strong poloidal flow also present, get tilted dipole pattern

[O. Grulke, et. al., Phys. Plasmas 13, 012306 (2006)]

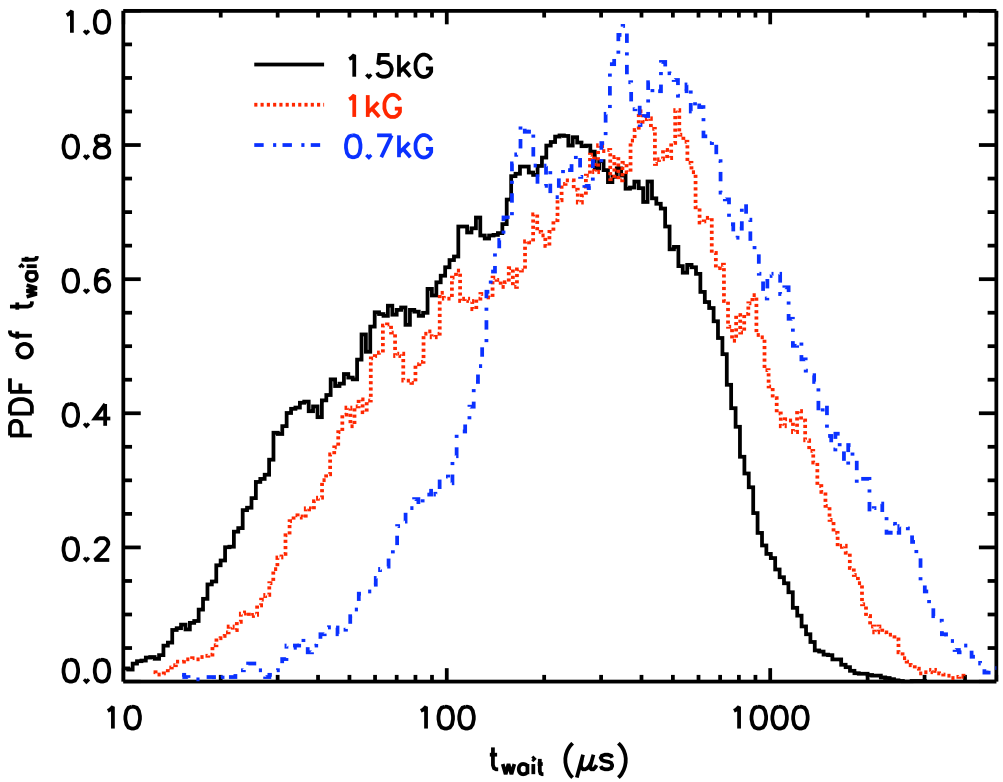
Blob size in LAPD scales with sound gyroradius





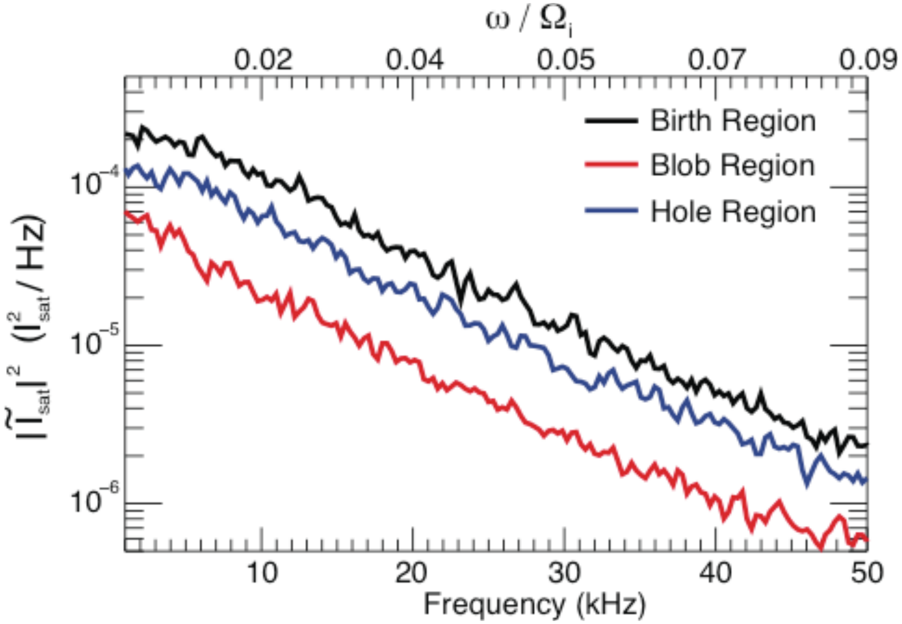
- PDF of event time width: time width of blob events increases with decreasing field
- Average blob size, computed using time width and linear array measured velocity: $\langle \rho_b \rangle \sim 10\rho_s$
- Gyroradius scaling predicted theoretically [D'Ippolito]
- However, note that average blob size is comparable to gradient scale length (indirect scaling?)

Waiting time PDF: blob creation is broadband



- Waiting time: time between consecutive blob events
- Waiting time is broadband (consistent with power spectrum of turbulence in gradient region)
- Waiting time increases with decreasing field, some signs of increased coherency

Closer look at power spectrum of intermittent turbulence: exponential spectrum



- Common spectral feature in edge turbulence literature, although often (mis-)interpreted as power law
- Exponential spectrum consistent with presence of blobs/spikes/pulses/structures in data
- Time width of blob sets characteristic frequency

[D.C. Pace, et. al., Phys. Rev. Lett., in press]

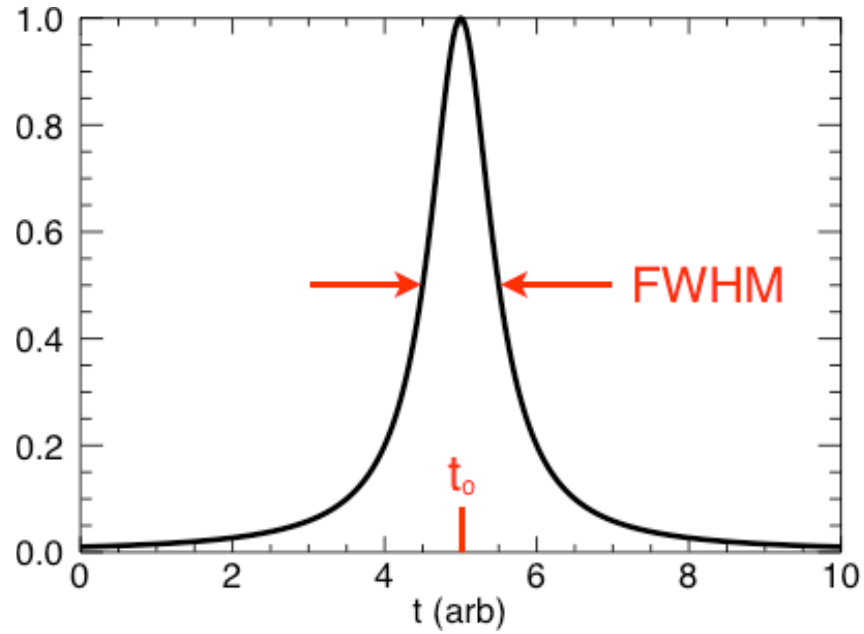
Lorentzian pulse shape gives corresponds to exponential power spectrum

Lorentzian pulse in time, $g(t)$, given by,

$$g(t) = \frac{\tau^2}{(t - t_o)^2 + \tau^2} \, ,$$

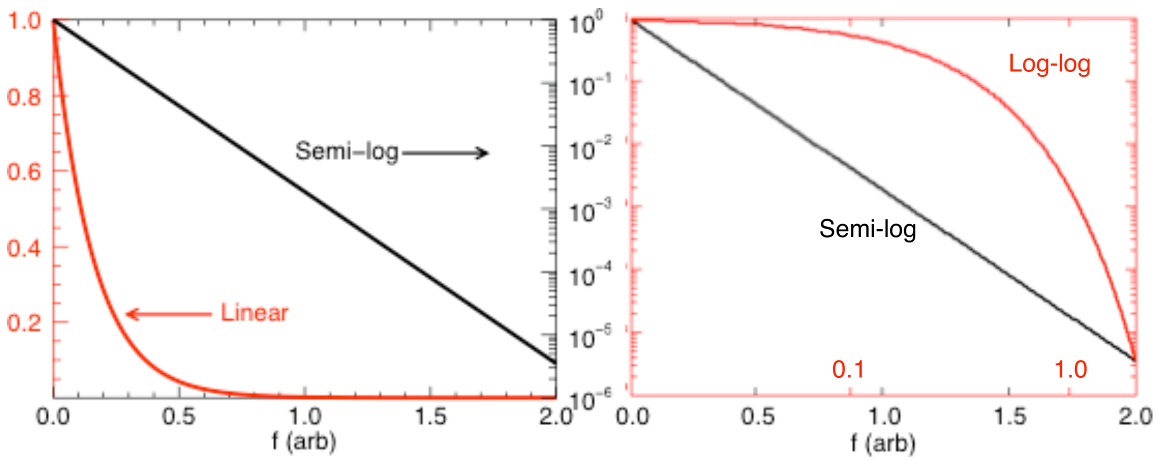
t_o = Initial Time

τ = Time Width
= ½ FWHM



with corresponding Fourier transform,

$$\tilde{g}(\omega) = (\pi\tau) \exp\left(-\omega\tau + i\omega t_o\right) \, ,$$

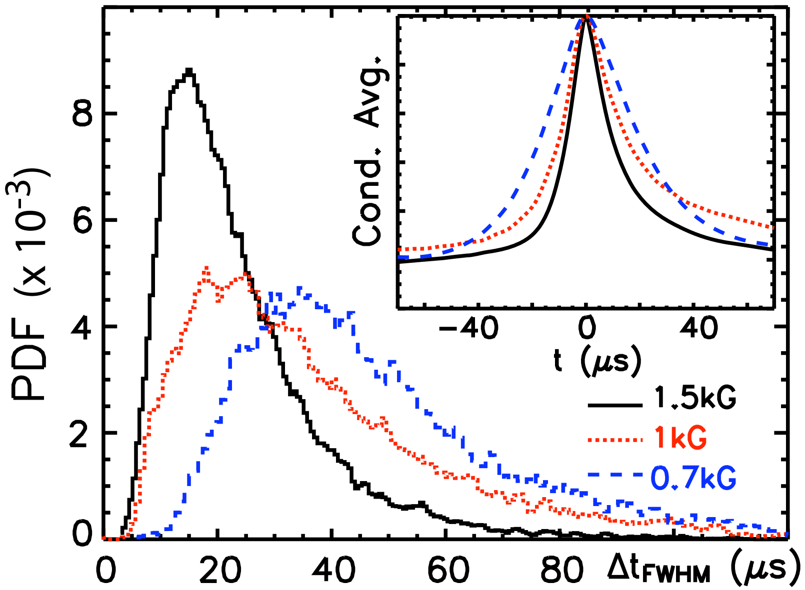


and resulting power spectrum,

$$|\tilde{g}(\omega)|^2 = \left(\frac{2\pi^2}{f_s}\right)^2 \exp\left(\frac{-2f}{f_s}\right)$$

$$f_s = \frac{1}{2\pi\tau}$$ = Scaling Frequency

Slope of exponential spectrum gives time width of events



- Fit to spectrum consistent with pulse width PDF

Fit gives $\tau_{\mathrm{HW}} = 7.0\mu\mathrm{s}$, peak of PDF near $7.5\mu\mathrm{s}$

- Only possible with relatively narrow pulse width PDF (seems to be the

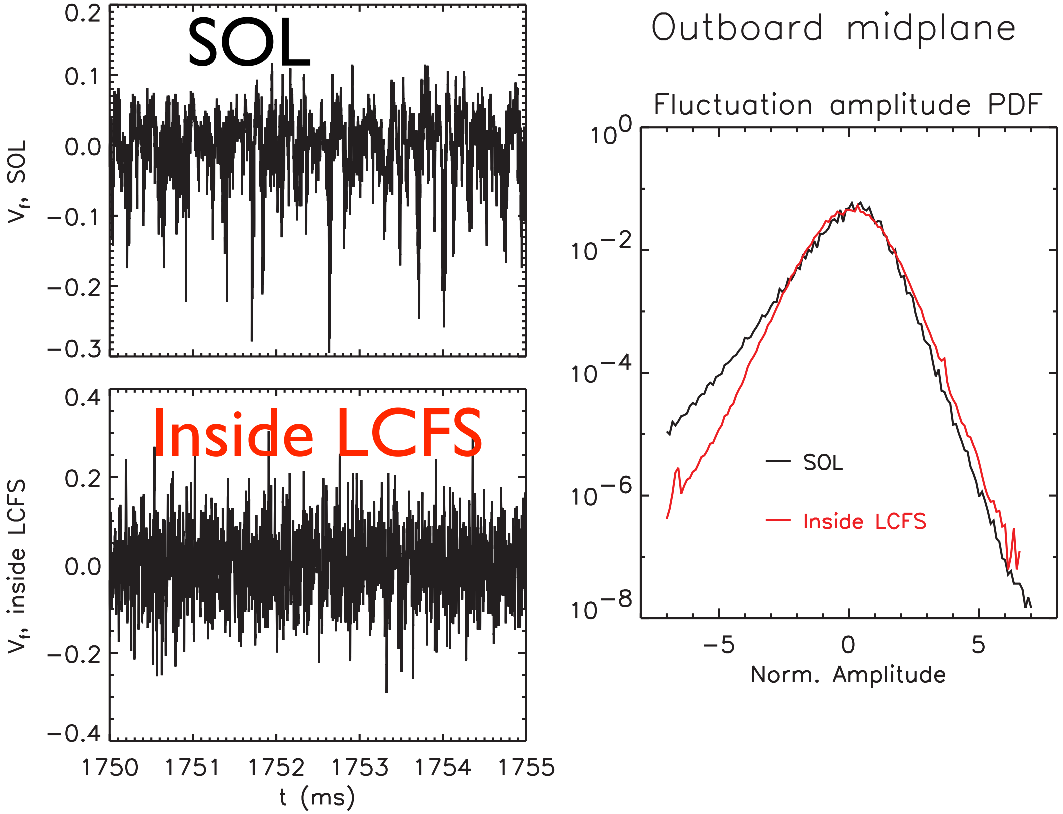
- While creation of blobs is broadband, time-width of blobs (set by size and velocity) is more well defined
- What process sets size and velocity?

Open questions

- Experimental arrangement in LAPD is free of interchange forces (no magnetic curvature, no rotation (straight vertical edge)): What is polarization mechanism?
  - ➡ One proposal is "Neutral wind" [Krasheninnikov, et al., Phys. Plasmas 10, 3020 (2003)]
  - ➡ Effective interchange force provided by difference between interaction with warm (charge exchange generated) neutrals flowing out of the plasma and cold neutrals (from recycling) flowing back in
  - ➡ Reasonable agreement with blob velocity in LAPD and other linear machines [Vineta: Windisch, et al., Phys. Plasmas 13, 122303 (2006)]
  - ➡ May also act in tokamak edge?

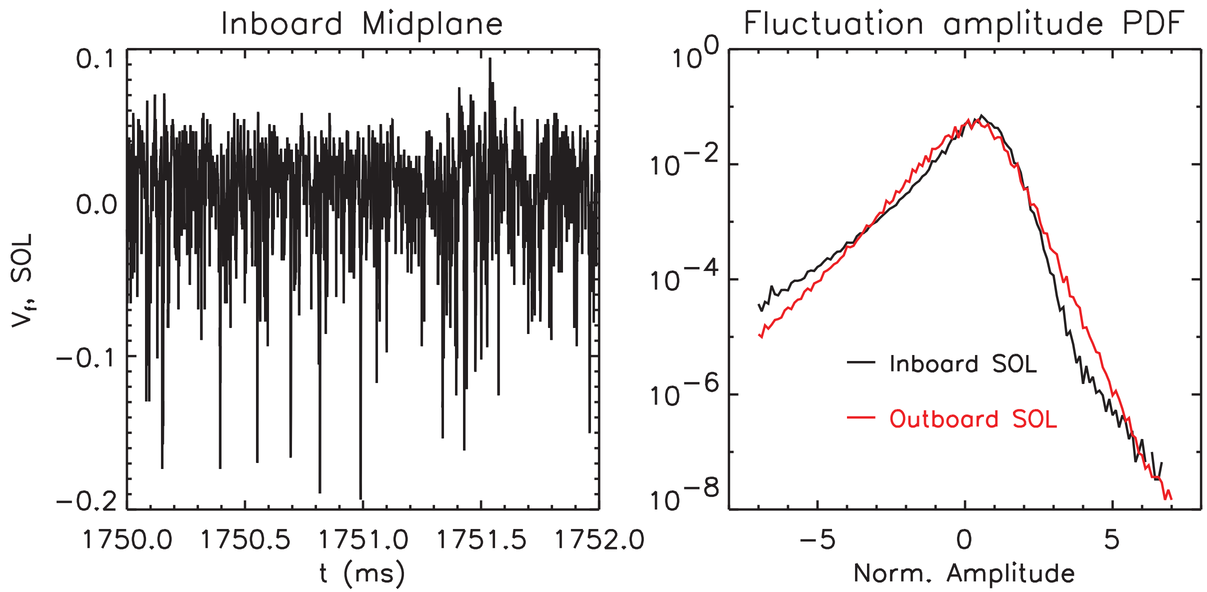
Another polarization mystery(?): intermittency on the inboard side of a tokamak

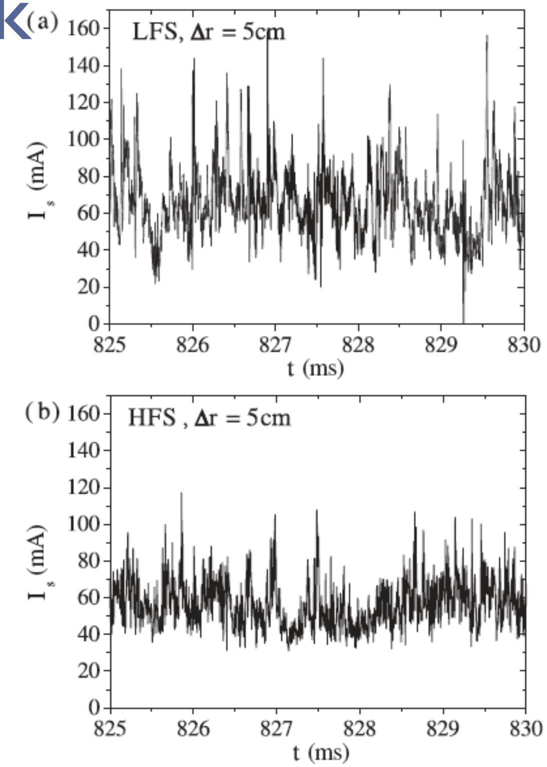
potential



- Data from Electric tokamak at UCLA (large aspect ratio, circular, limited tokamak)

Another polarization mystery(?): intermittency on the inboard side of a tokamak





- Strong intermittent turbulence observed on HFS (inboard) - however no interchange drive (good curvature) (also seen on T-10 [G.S. Kirnev, et al., Nucl. Fusion 45, 459 (2005)])
- Might be driven through connection to the outboard side (e.g. NOT seen in diverted tokamaks like Alcator C-Mod [N. Smick, et al., J. Nucl. Mat. 337, 281 (2005)])
- Also may be role for rotation, neutral wind in polarizing HFS blobs?

Open questions

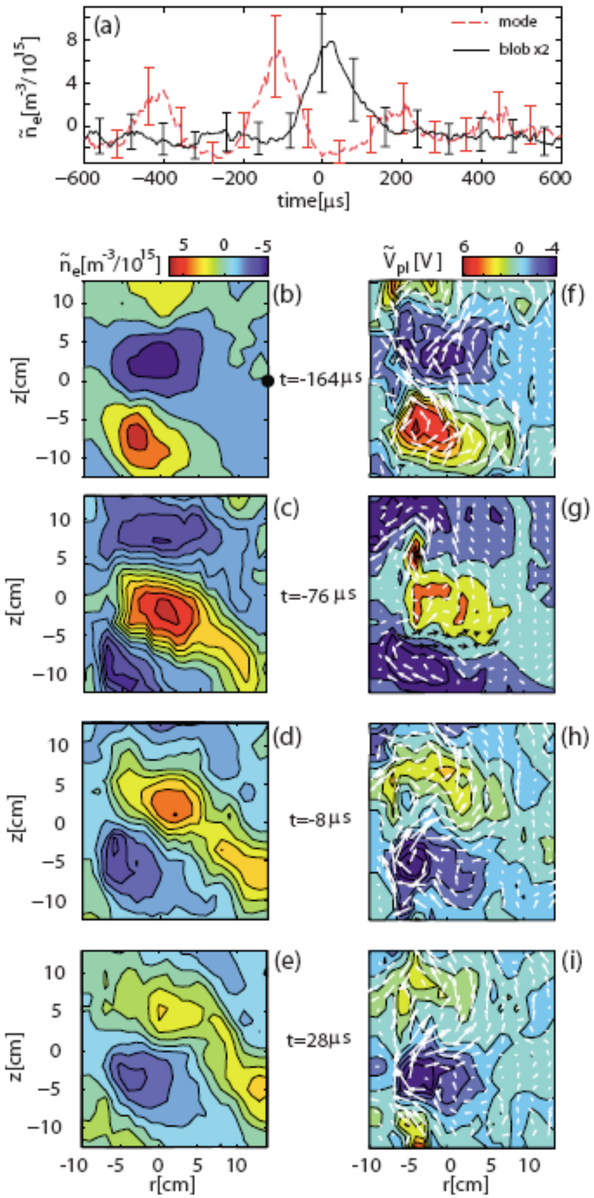
- Experimental arrangement in LAPD is free of interchange forces (no magnetic curvature, no rotation (straight vertical edge)): What is polarization mechanism?
- What is the generation mechanism of the coherent structures by edge turbulence?

➡ Generation localized in linear devices, tokamaks to boundary (separatrix, limiter edge), not found everywhere where strong turbulence exists

➡ Common feature in boundary region of all of these devices: sheared flow layer

➡ Role of sheared flow in generation of structures?

Evidence for role of shear flow in blob generation



- Measurements on TORPEX, basic toroidal plasma facility
- Observe blob generation by shear flow: shears off the tip of interchange driven fingers to form blob
- However: a number of simulations show blob formation without explicit shear flow (although may be self generated?) [Scott, Naulin, Xu, ...]
- Possibly: shear required for driving blobs (hence enhancing particle transport), but larger shear shuts the process of (H-mode)

[Furno, et al., Phys. Plasmas 15, 055903 (2008)]

Open questions

- Experimental arrangement in LAPD is free of interchange forces (no magnetic curvature, no rotation (straight vertical edge)): What is polarization mechanism?
- What is the generation mechanism of the coherent structures by edge turbulence?
- How is the size and velocity of the structures determined?

➡ A number of devices see blob size ~ few-10 ρ_s and speed a fraction (~1/10) of the sound speed

➡ Coincidence or something fundamental about the generation of these structures?

Open questions

- Experimental arrangement in LAPD is free of interchange forces (no magnetic curvature, no rotation (straight vertical edge)): What is polarization mechanism?
- What is the generation mechanism of the coherent structures by edge turbulence?
- How is the size and velocity of the structures determined?
- What is the connection to the tokamak density limit?

➡ Recent support for connection from devices other than C-Mod (DIII-D, T-10), but questions remain

Open questions

- Experimental arrangement in LAPD is free of interchange forces (no magnetic curvature, no rotation (straight vertical edge)): What is polarization mechanism?
- What is the generation mechanism of the coherent structures by edge turbulence?
- How is the size and velocity of the structures determined?
- What is the connection to the tokamak density limit?
- Is there a connection to other cases of production of filamentary structures, such as ELMs?

➡ Is an ELM an electromagnetic version of a blob?

Open questions

- Experimental arrangement in LAPD is free of interchange forces (no magnetic curvature, no rotation (straight vertical edge)): What is polarization mechanism?
- What is the generation mechanism of the coherent structures by edge turbulence?
- How is the size and velocity of the structures determined?
- What is the connection to the tokamak density limit?
- Is there a connection to other cases of production of filamentary structures, such as ELMs?

We've made progress on understanding intermittent turbulence, but plenty of work remains for eager young minds….