Modification of turbulence and transport with continuous variation of edge flow and shear in LAPD

T.A. Carter, D. Schaffner, B. Friedman, G. Rossi,
M.V. Umansky[2], D. Guice, S. Vincena, J.E. Maggs

Dept. of Physics and Astronomy, UCLA
[2]Lawrence Livermore National Laboratory

UCLA

Summary/Outline

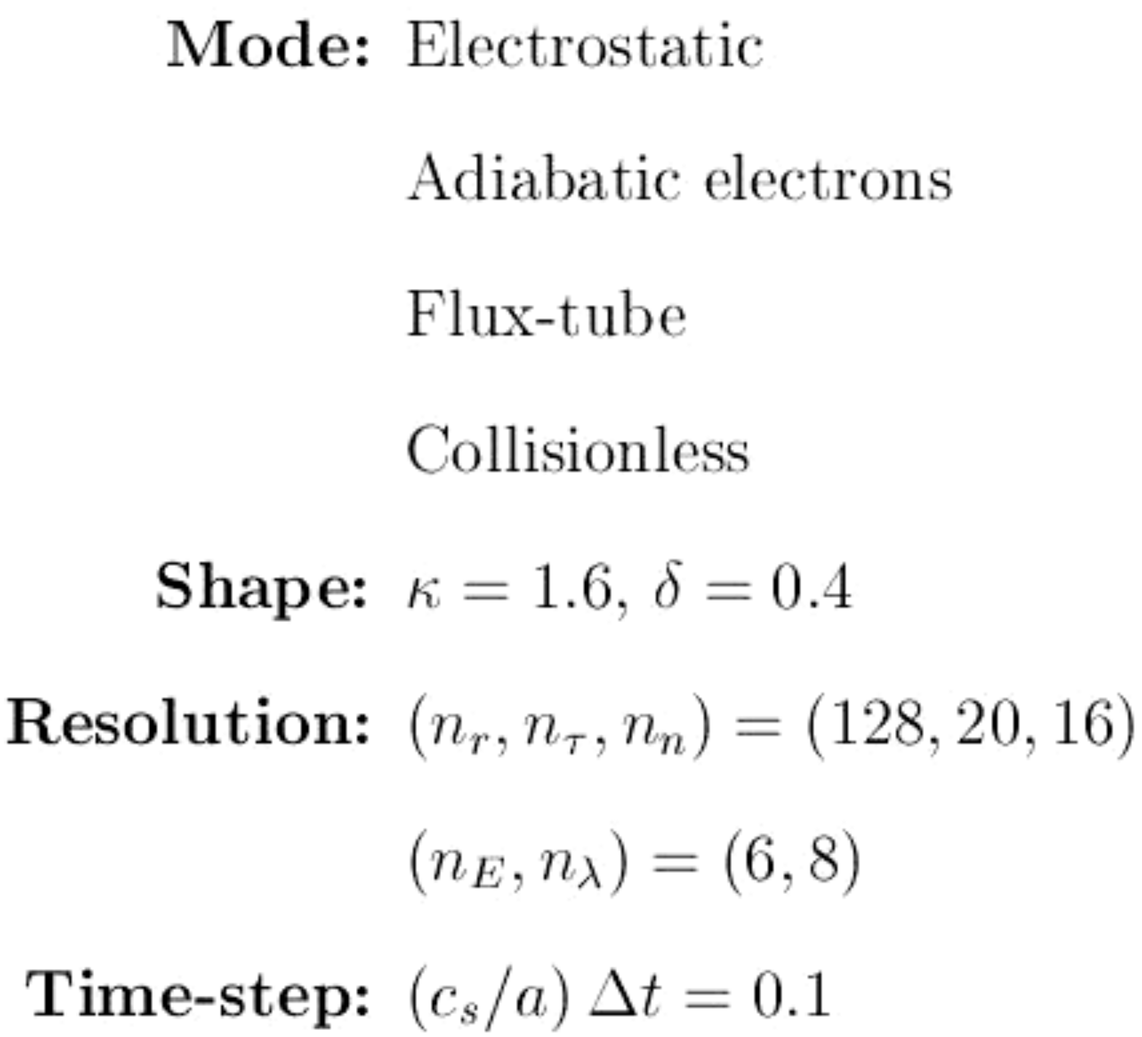
- Documented the response of pressure-gradient driven turbulence to continuous variation of flow shear in LAPD [Schaffner, et al., PRL 109, 135002 (2012)]
    - Continuous control of edge flow through biasing; variation includes zero-shear and zero-flow states, flow reversal
    - Particle transport decreases with increased shearing, enhanced at low flow shear, independent of flow direction
    - Transport reduction due to turbulent amplitude reduction; near complete suppression for shearing rate comparable to no-shear autocorrelation rate
- Two-fluid simulations with BOUT++ code: good qualitative match to measurements; saturated state of turbulence consistent with action of a nonlinear instability. [Friedman, et al., arXiv:1205.2337, PoP submitted]

Why is fusion so difficult?: turbulence causes leakage of heat and particles across confining magnetic field

- Free energy source from pressure gradient: interchange modes, drift waves
- Movie shows electrostatic potential
- Small scales across B, long wavelength along B

Gyrokinetic simulation by Jeff Candy, Ron Waltz (GA)

Why is fusion so difficult?: turbulence causes leakage of heat and particles across confining magnetic field



Mode: Electrostatic

Adiabatic electrons

Flux-tube

Collisionless

Shape: $\kappa = 1.6,\ \delta = 0.4$

Resolution: $(n_r, n_\tau, n_n) = (128, 20, 16)$

$(n_E, n_\lambda) = (6, 8)$

Time-step: $(c_s/a)\,\Delta t = 0.1$

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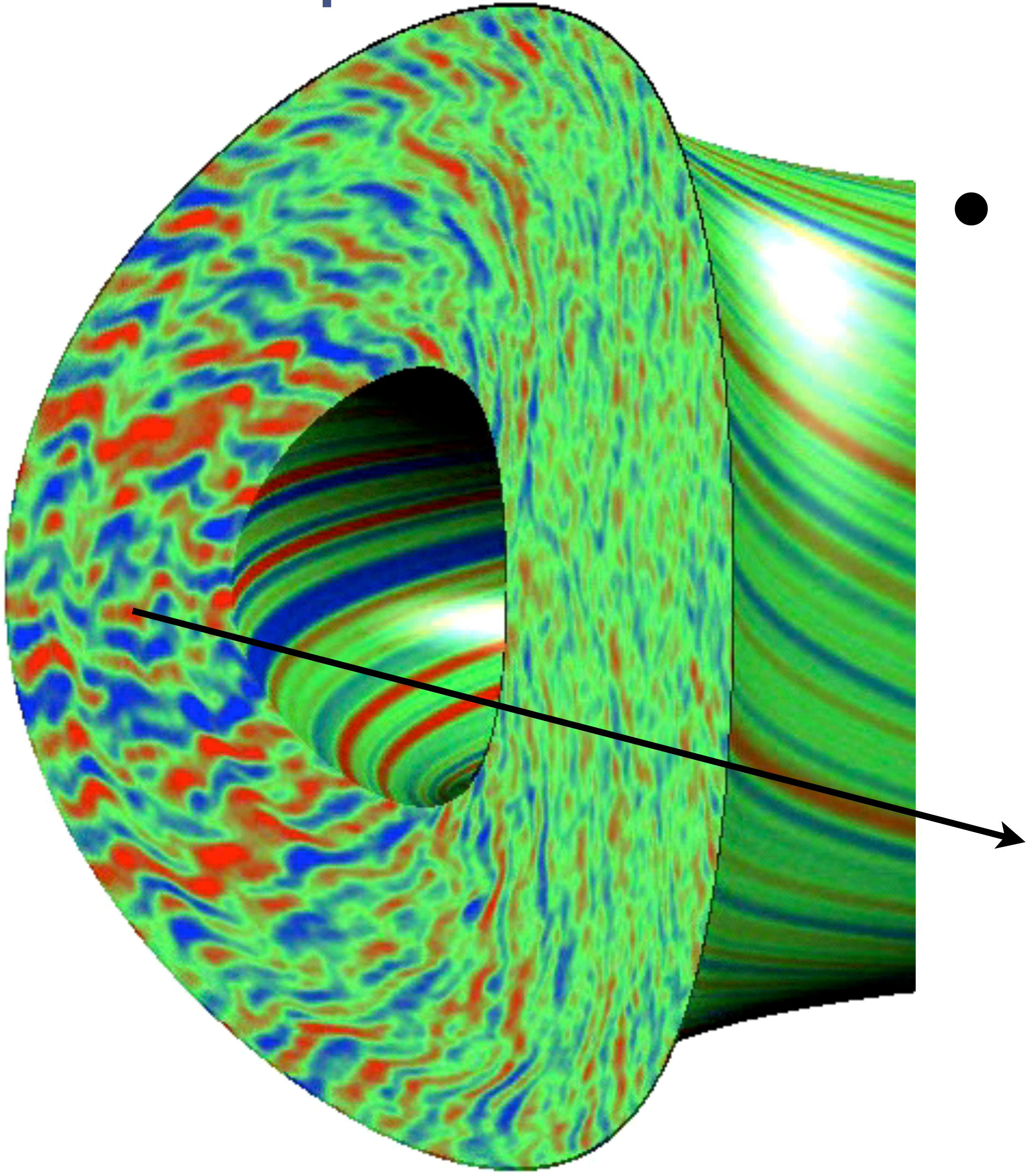

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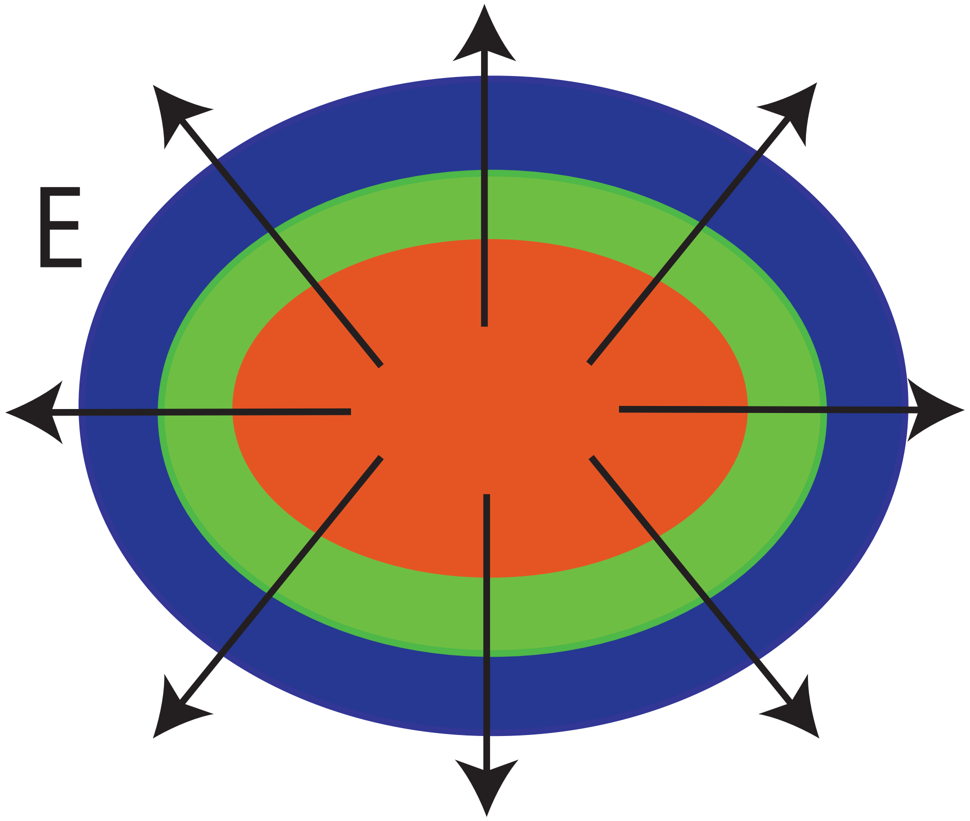

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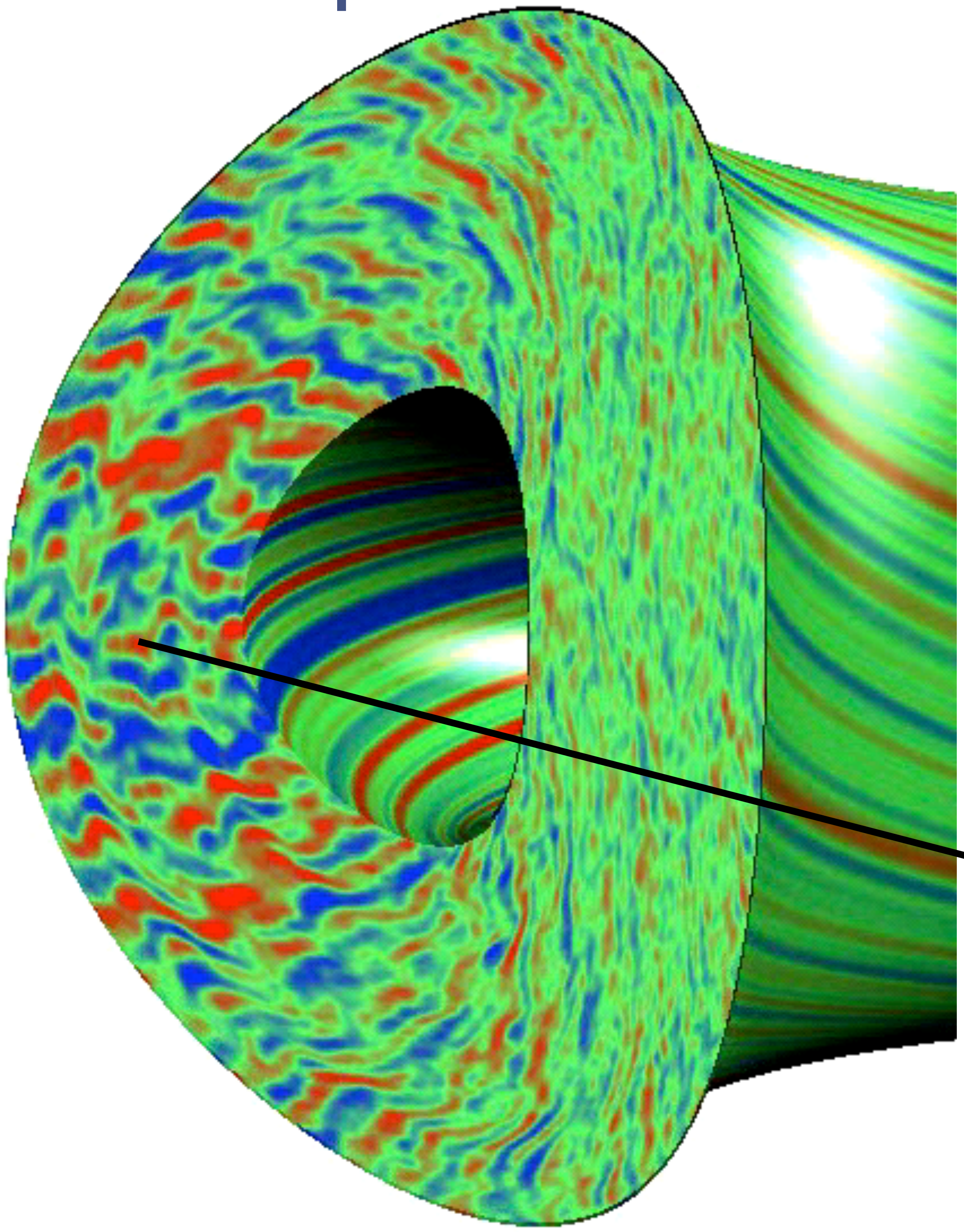
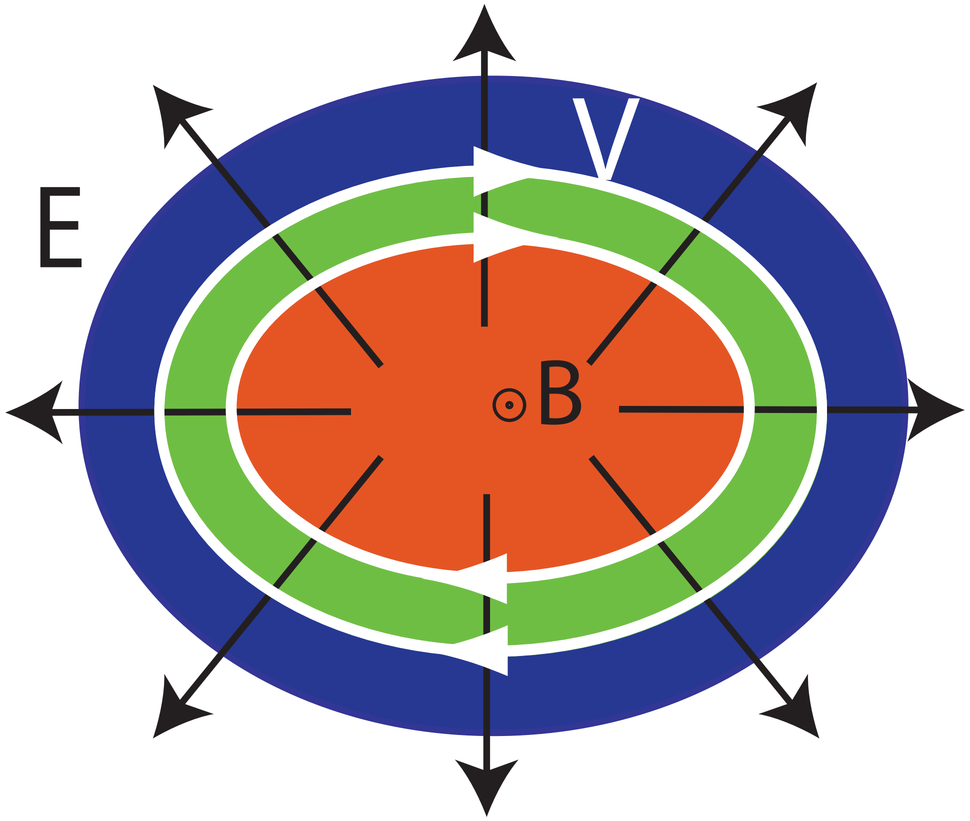


Gyrokinetic simulation by Jeff Candy, Ron Waltz (GA)

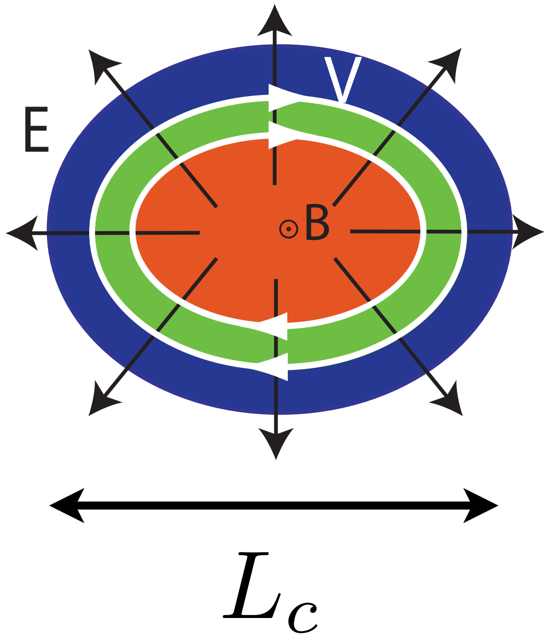
$$v_{\mathrm{drift}} = \frac{\vec{E} \times \vec{B}}{B^2}$$

- Movie shows electrostatic potential
- Contours of potential are contours of ExB flow



Turbulent diffusion estimate

- Turbulent diffusion: random walk by eddy decorrelation



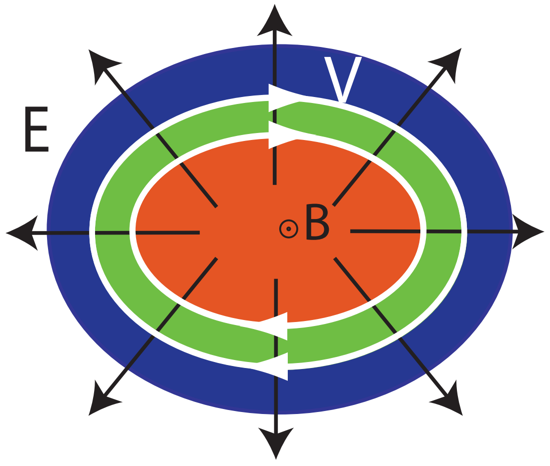
$$D \sim \frac{(\Delta x)^2}{\Delta t} \sim \frac{L_c^2}{\tau_c}$$

Eddy size

Eddy "turnover" time

Turbulent diffusion estimate

- Turbulent diffusion: random walk by eddy decorrelation



$$L_c \sim 10\rho_s$$

$$D \sim \frac{(\Delta x)^2}{\Delta t} \sim \frac{L_c^2}{\tau_c}$$

Eddy size

Eddy "turnover" time

$$\tau_c \sim \frac{L_c}{v} \qquad v \sim \frac{E}{B} \sim \frac{\phi}{L_c}\frac{1}{B}$$

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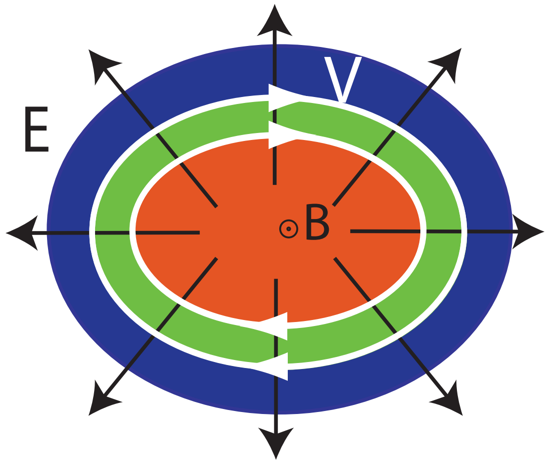

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$$D \sim \frac{(\Delta x)^2}{\Delta t} \sim \frac{L_c^2}{\tau_c}$$

Eddy size (arrow to L_c^2)

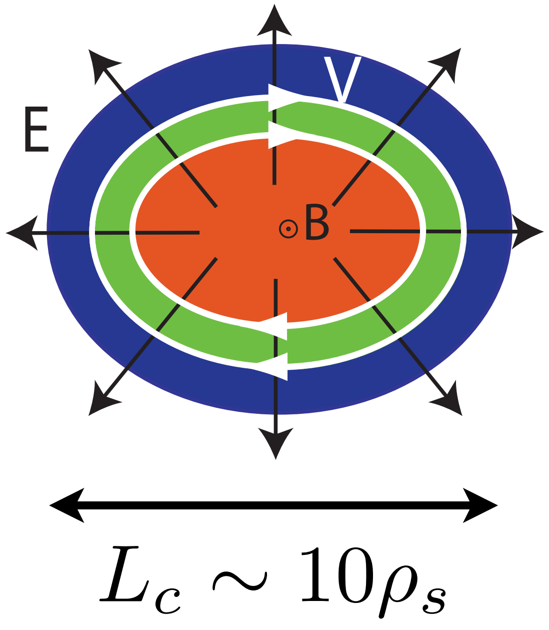
Eddy "turnover" time (arrow to τ_c)

$$\tau_c \sim \frac{L_c}{v} \qquad v \sim \frac{E}{B} \sim \frac{\phi}{L_c}\frac{1}{B}$$

$$\boxed{D \sim \frac{\phi}{B} \sim \frac{T}{B}}$$

Bohm diffusion

Turbulent diffusion estimate



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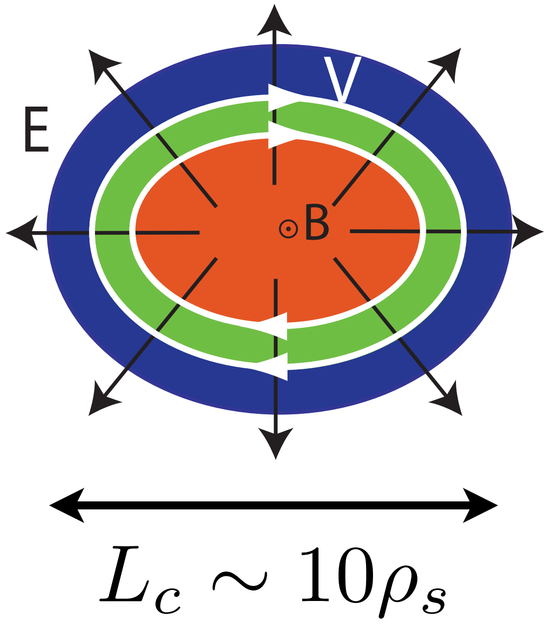
Bohm diffusion

Classical diffusion: $D_{\text{class}} \sim \rho^2\nu \sim T^{-1/2} \quad (\nu \sim T^{-3/2})$

Turbulent diffusion estimate



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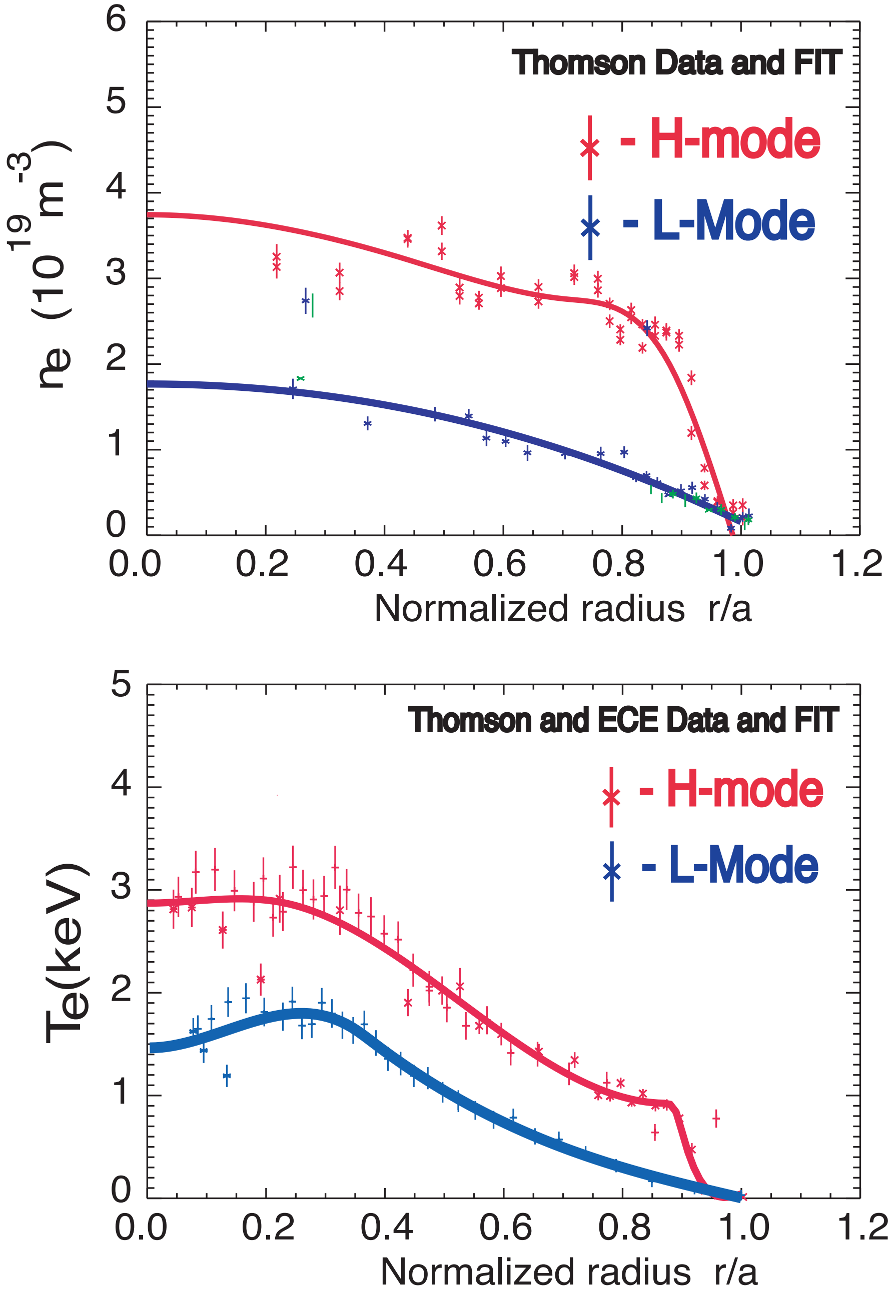
Bohm diffusion

Classical diffusion: $D_{\text{class}} \sim \rho^2 \nu \sim T^{-1/2} \quad (\nu \sim T^{-3/2})$

- Turbulent diffusion coefficient orders of magnitude larger than classical (not shown here)
- More importantly: scaling with T is opposite. As T goes up (more heating power is added) confinement degrades. Consistent with so-called "low-confinement" mode or L-mode in experiments.

Improved confinement due to edge flow layer: the H-mode



Data from DIII-D

- H-mode [Wagner, 82]: factor of two improvement in energy and particle confinement (basis for ITER Q=10)
- Signature is edge transport barrier, with steepened gradients (“pedestal”)

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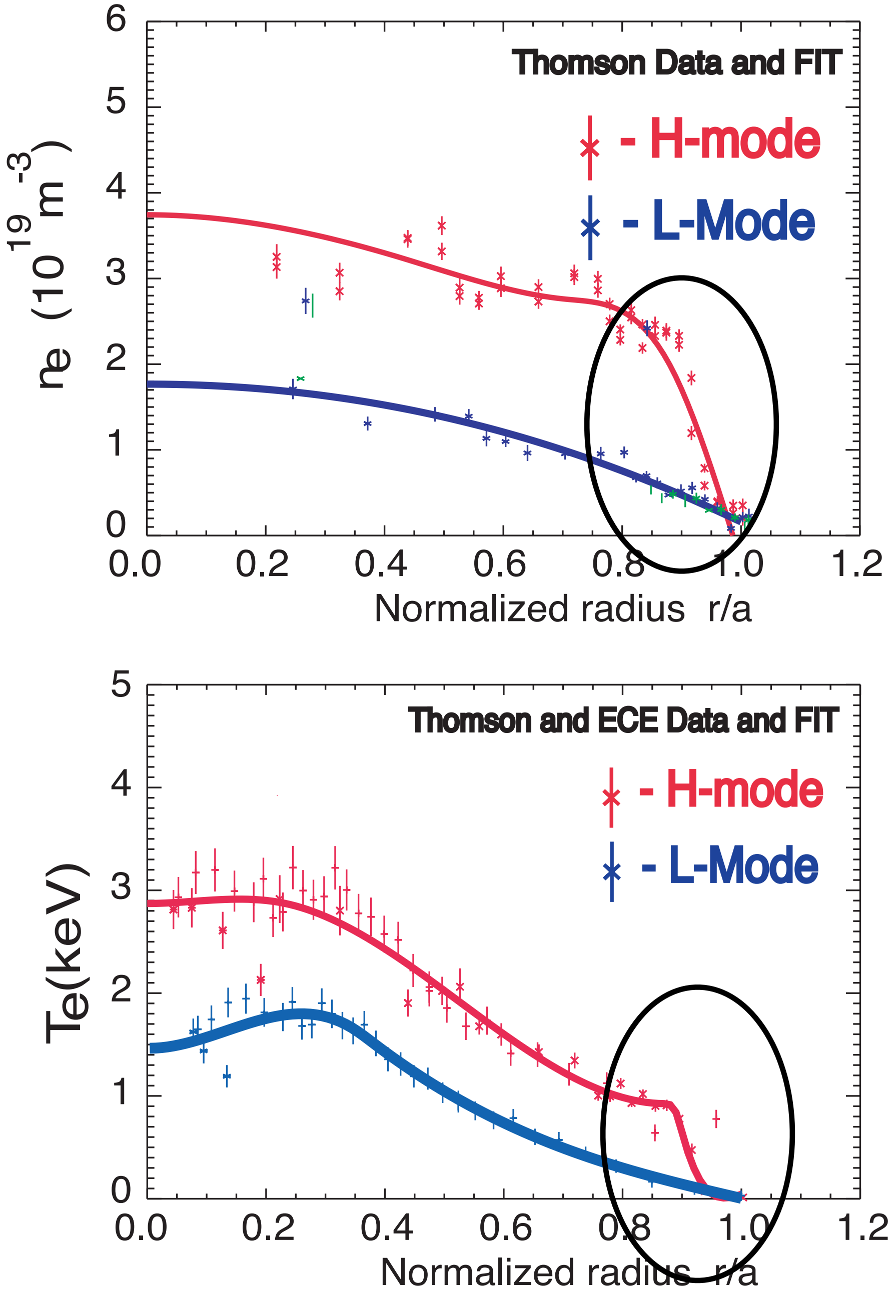

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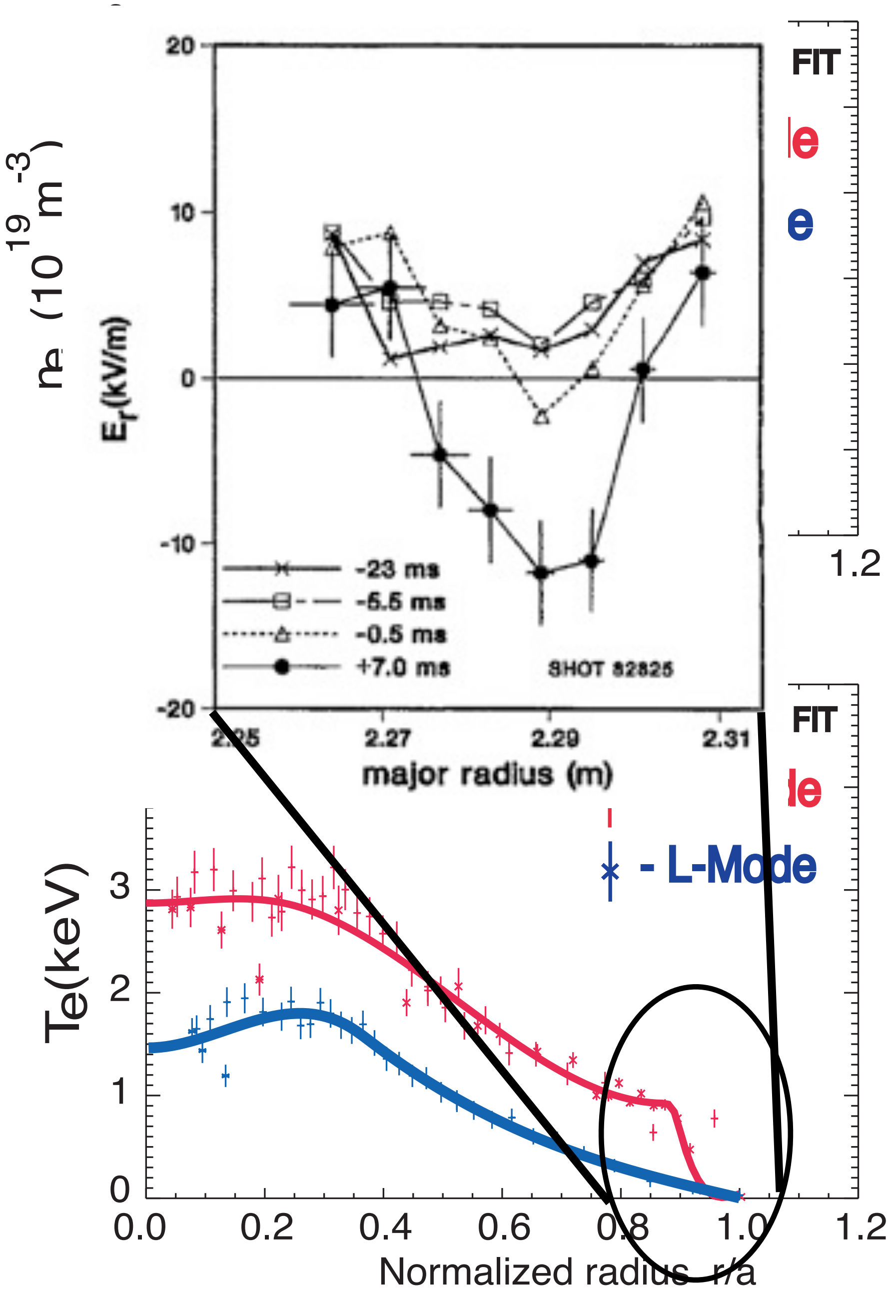

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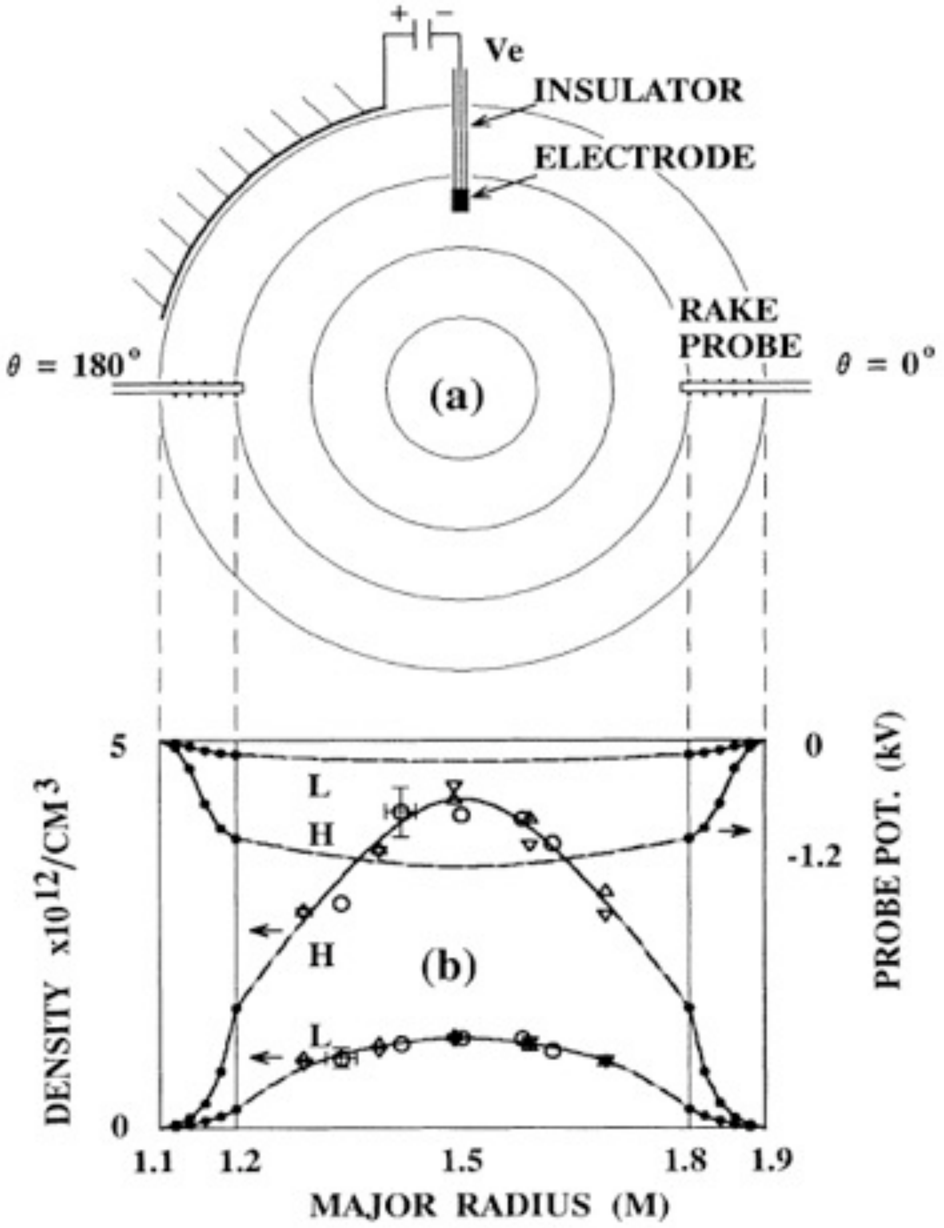

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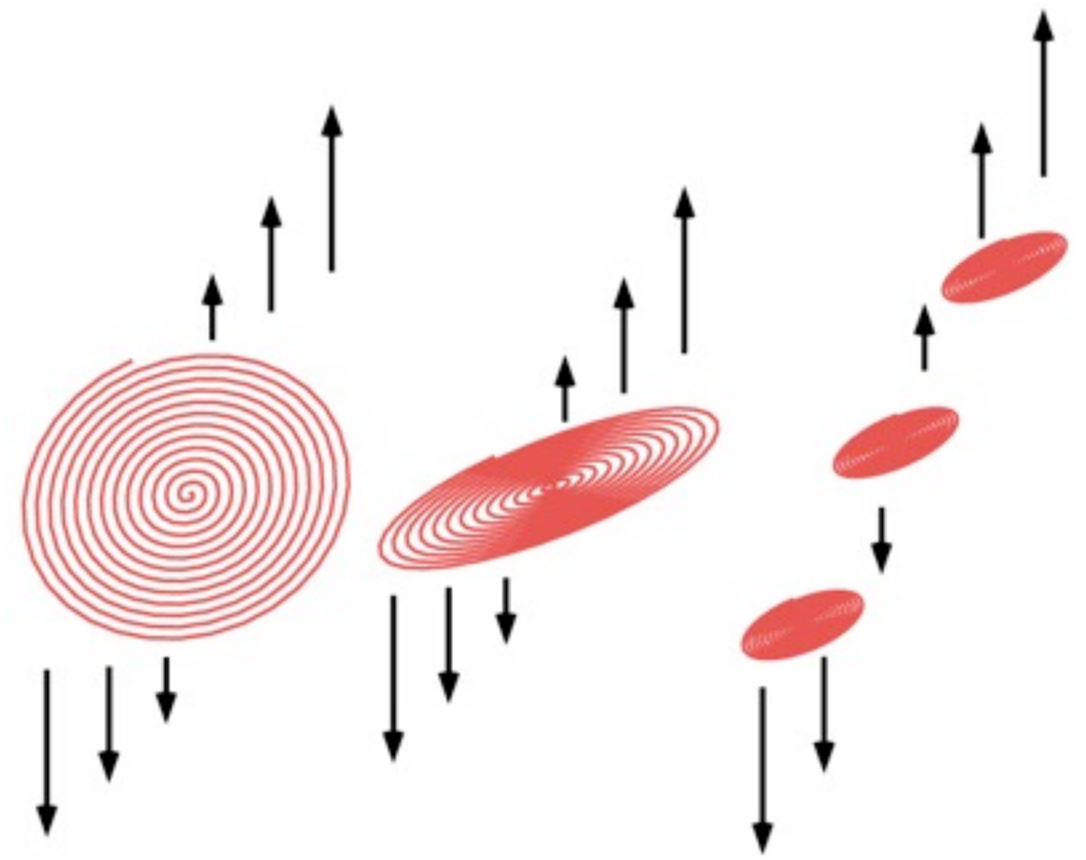
- Signature is edge transport barrier, with steepened gradients (“pedestal”)
- During H-mode, localized cross-field flow (“E_r well”) with strong shear develops spontaneously in the barrier region [e.g., Burrell, 97] (source of flow??)
- Experiments on CCT at UCLA [Taylor, 89] demonstrated the link between flow and improved confinement by directly controlling the edge flow using biasing

Secret to H-mode?: Turbulent transport reduction by sheared flow



- Biglari, Diamond, Terry (BDT 90): transport modified by radial decorrelation or "shearing apart" of eddies
- Shearing dynamically important if shearing rate comparable to eddy turnover time

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

- Turbulent particle flux depends on fluctuation amplitudes and cross-phase between density and electric field fluctuations; both are predicted [BDT; Ware; ...] and observed [Burrell; Moyer; Boedo; Silva; Carter….] to be modified by shearing

Motivation for basic experiment investigating shear suppression of transport

- Large body of work demonstrating shear suppression of turbulent transport in experiment and simulation [see, e.g., Burrell 97, Tynan 09, Terry 00...]

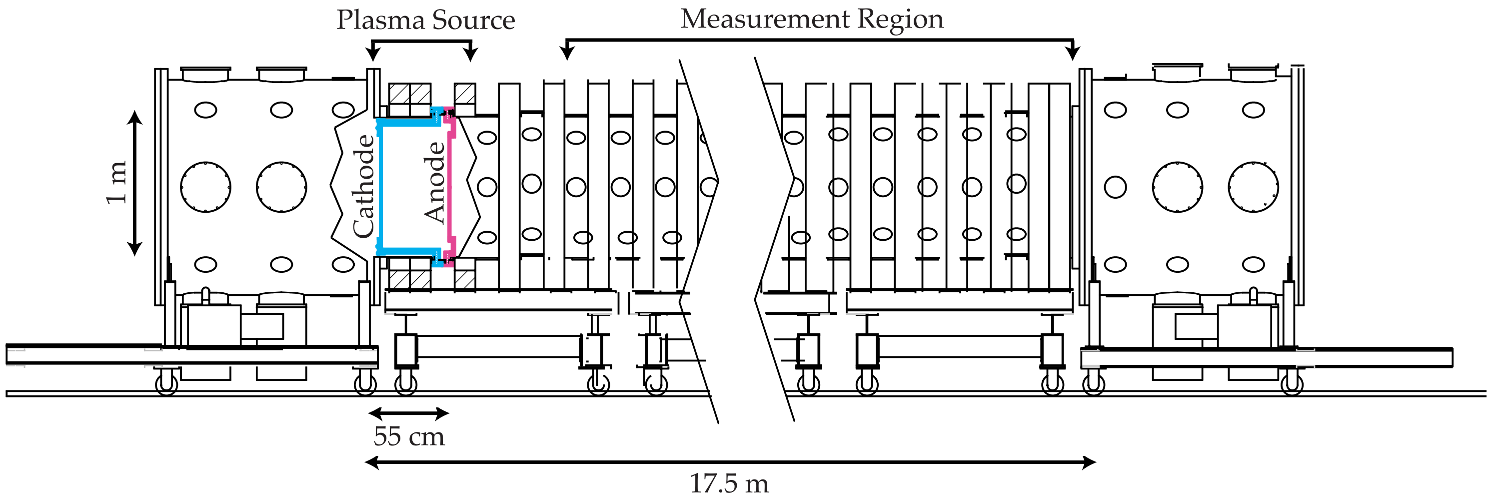
- However, fundamental questions remain about mechanism for transport reduction: decorrelation models (e.g. BDT) underpredict suppression (by an order of magnitude). New ideas: nonlinear spectral shift [Staebler], enhanced coupling to damped eigenmodes by shear flow [Terry], etc.

- Role of shear-driven instabilities?: parallel velocity gradient instability in tokamaks [Barnes, Highcock, et al.]; Kelvin-Helmholtz, Rotational interchange in linear devices

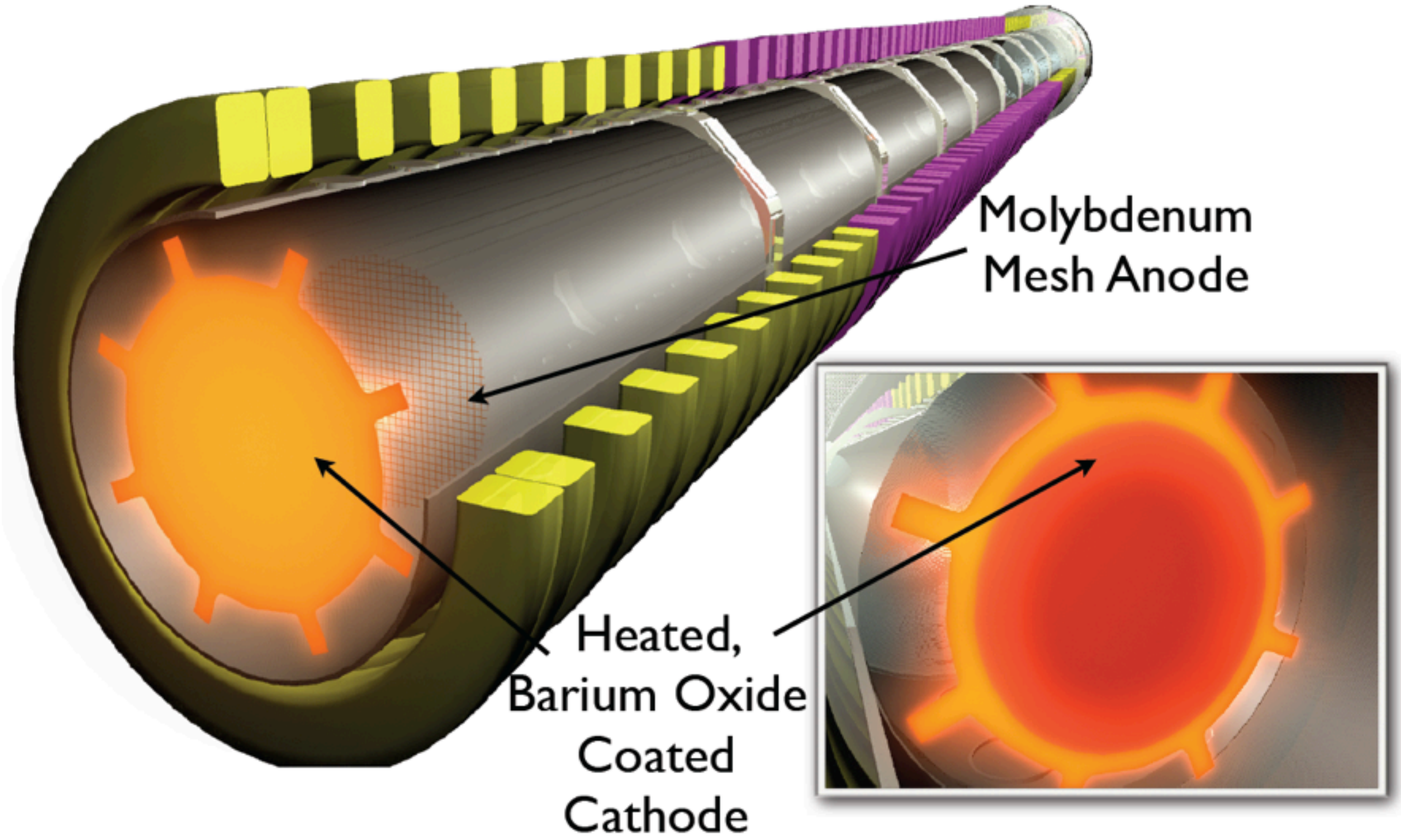
- Predicting transport in current and future devices (ITER) requires validation of models against experiment: predicting shear suppression accurately is absolutely critical

The LArge Plasma Device (LAPD) at UCLA

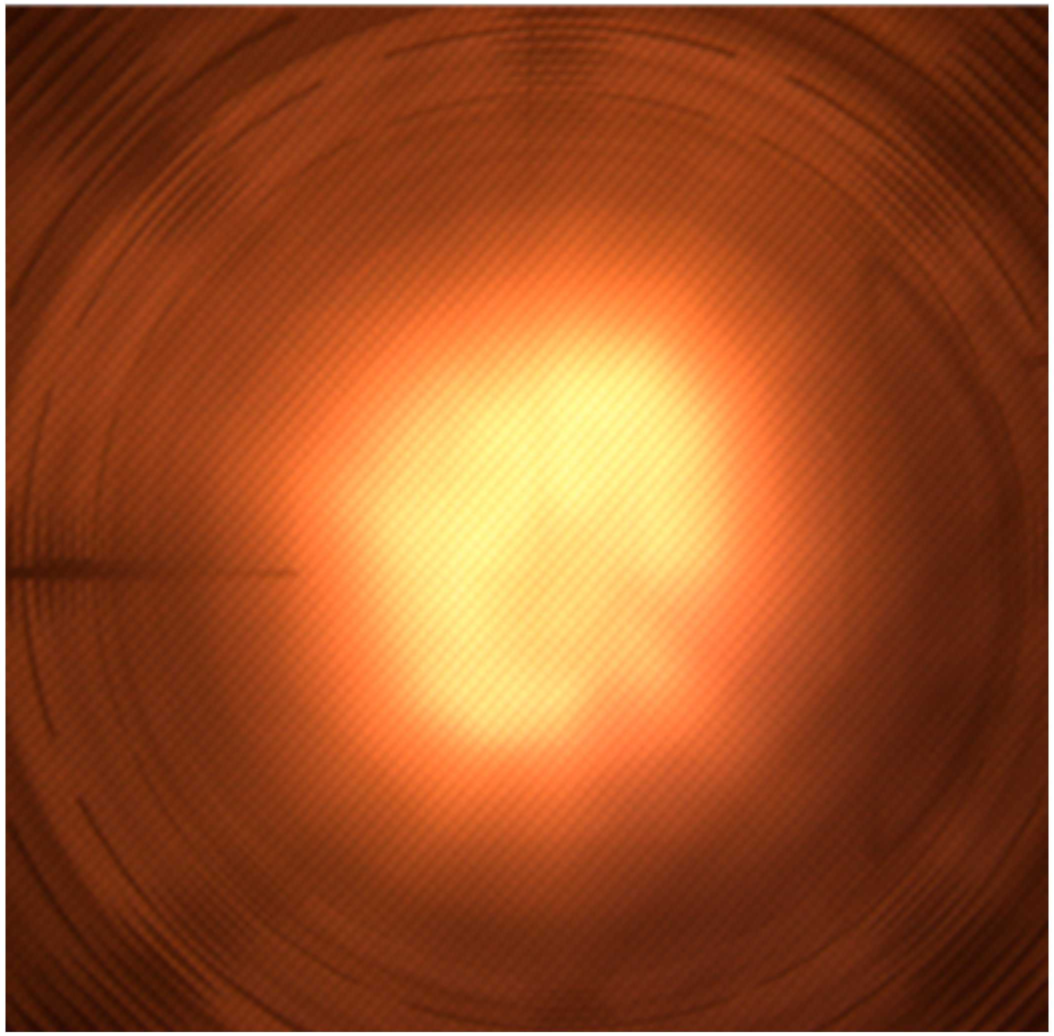
- US DOE/NSF sponsored user facility (http://plasma.physics.ucla.edu)
- Solenoidal magnetic field, cathode discharge plasma
- $0.5 < B < 2\,\mathrm{kG}, n_e \sim 10^{12}\,\mathrm{cm}^{-3}, T_e \sim 5\,\mathrm{eV}, T_i \sim 1\,\mathrm{eV}$
- Large plasma size, 17m long, D~60cm (1kG: ~300 ρ_i, ~100 ρ_s)
- High repetition rate: 1 Hz

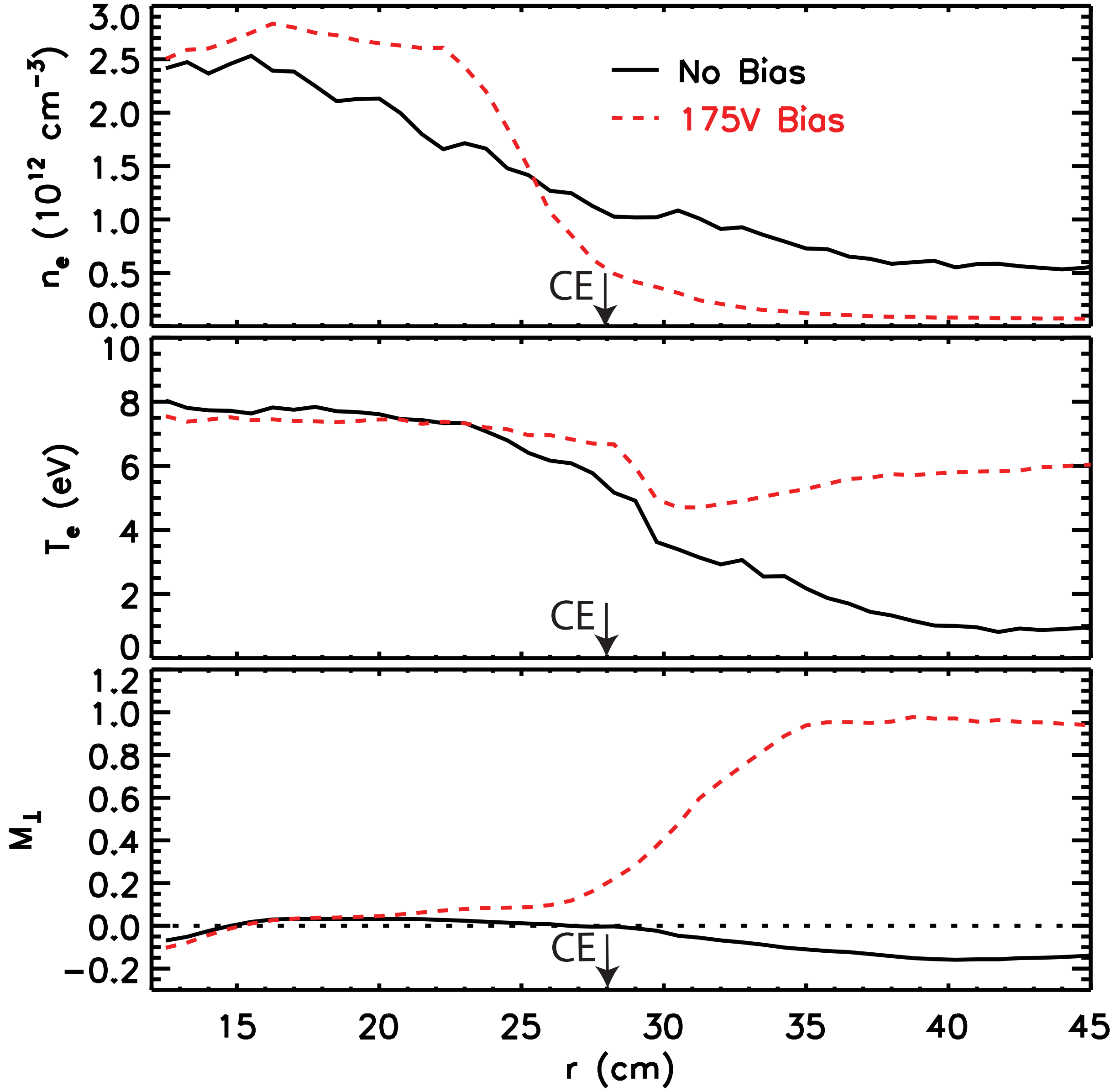


LAPD Plasma source



Example Plasma Profiles

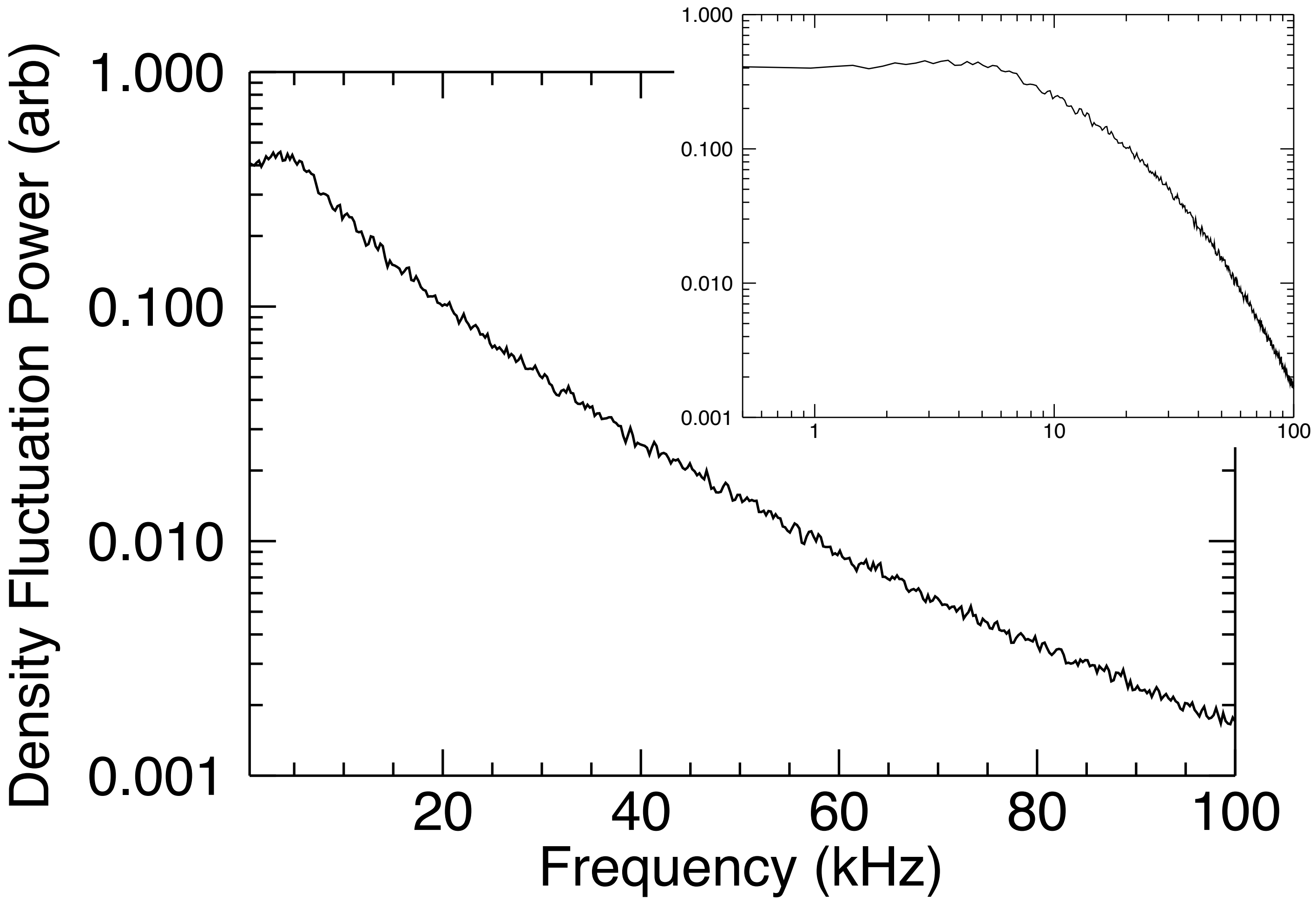


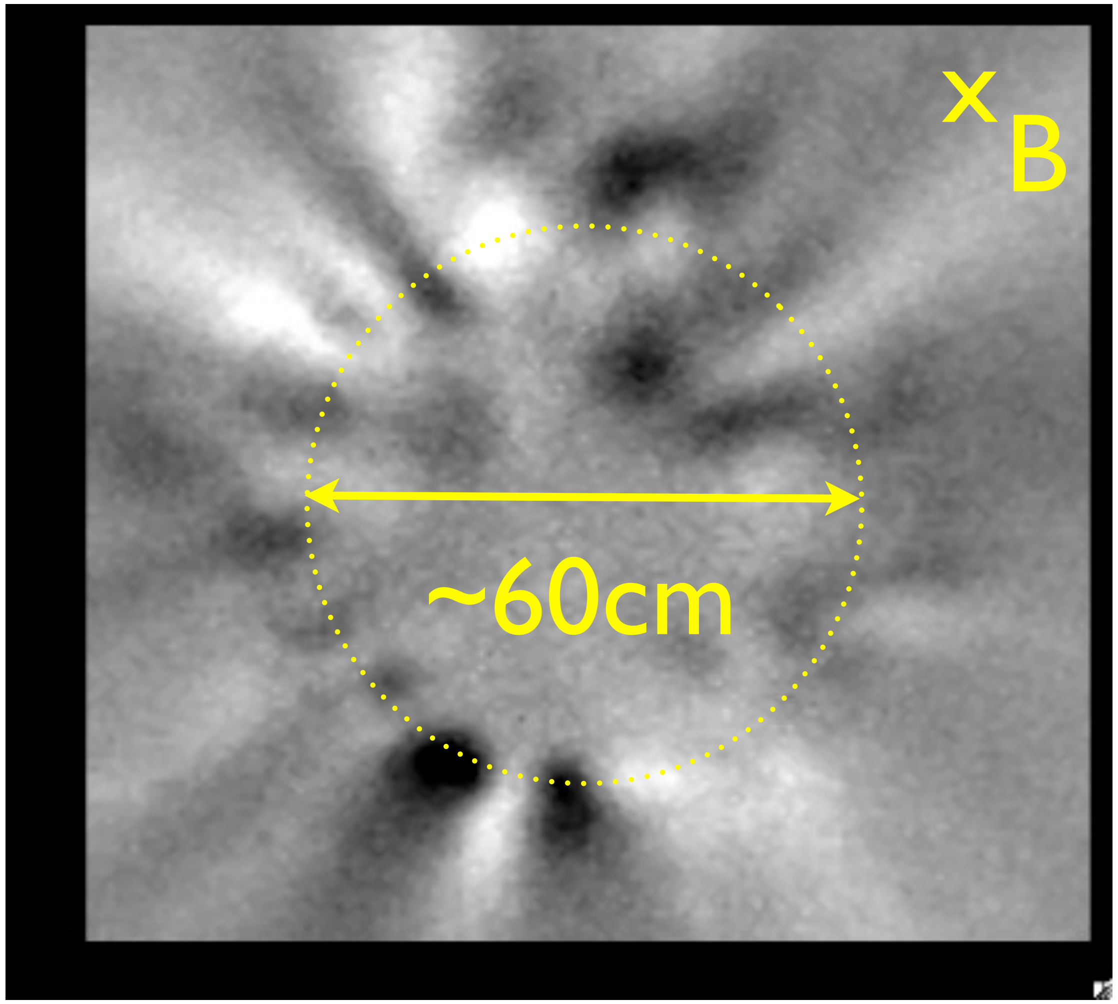


- Low field case (400G) (also shown: with particle transport barrier via biasing*); generally get flat core region with D=30-50cm
- Broadband turbulence generally observed in the edge region (localized to pressure gradient)

* Carter, et al, PoP 16, 012304 (2009)

Turbulence and transport in LAPD





- Broadband turbulence observed in edge (free energy from pressure gradient (drift waves) and driven flow (e.g. KH)). Exponential spectrum observed [Pace 2008]

- Large plasma size allows perp. transport to compete with parallel losses; profile set by perp transport; confinement modification apparent in profile changes

Visible light imaging of LAPD turbulence

Fast framing camera (~50k frames per second, ~10ms total time), visible light (neutral He), viewed along B

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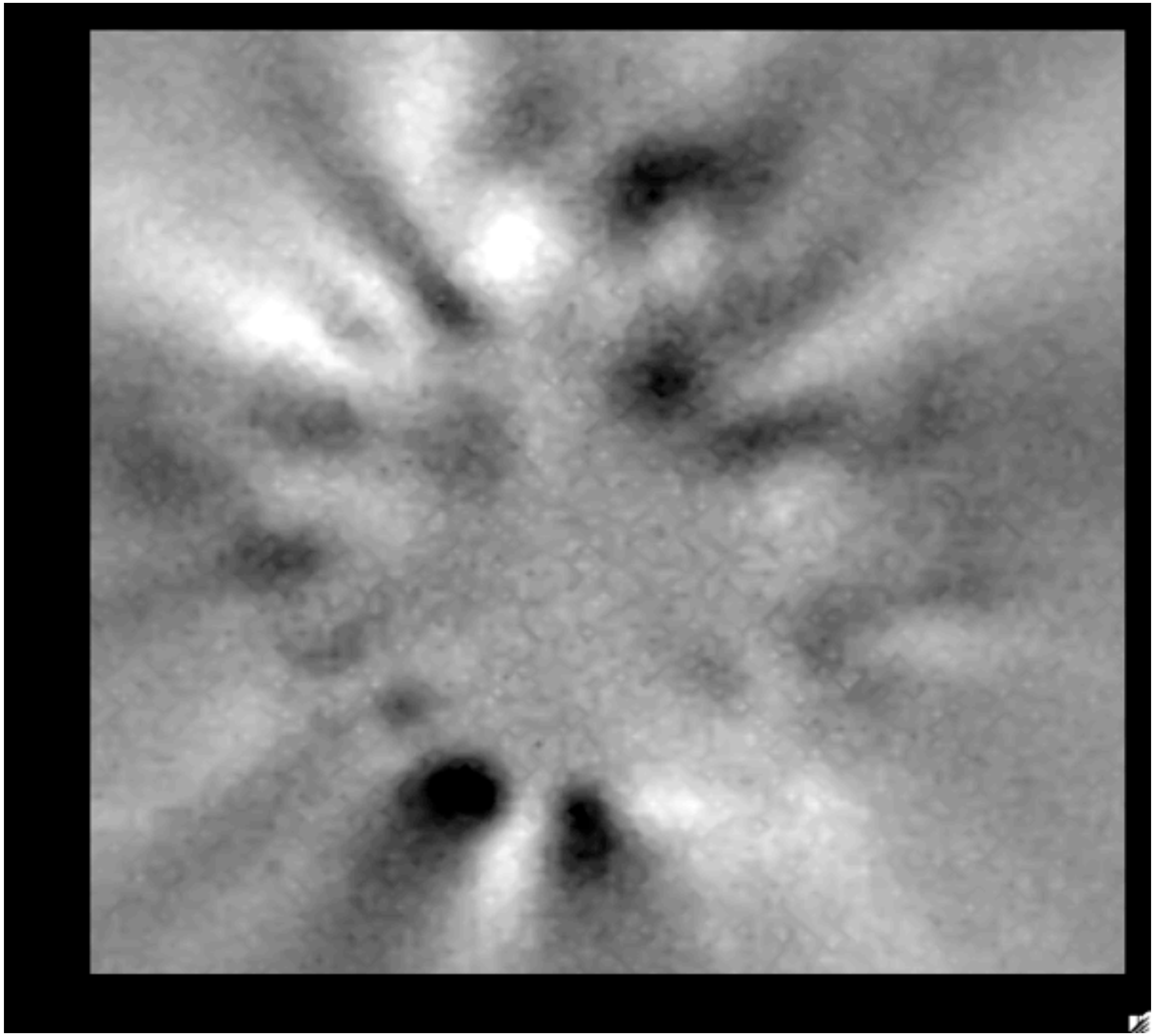
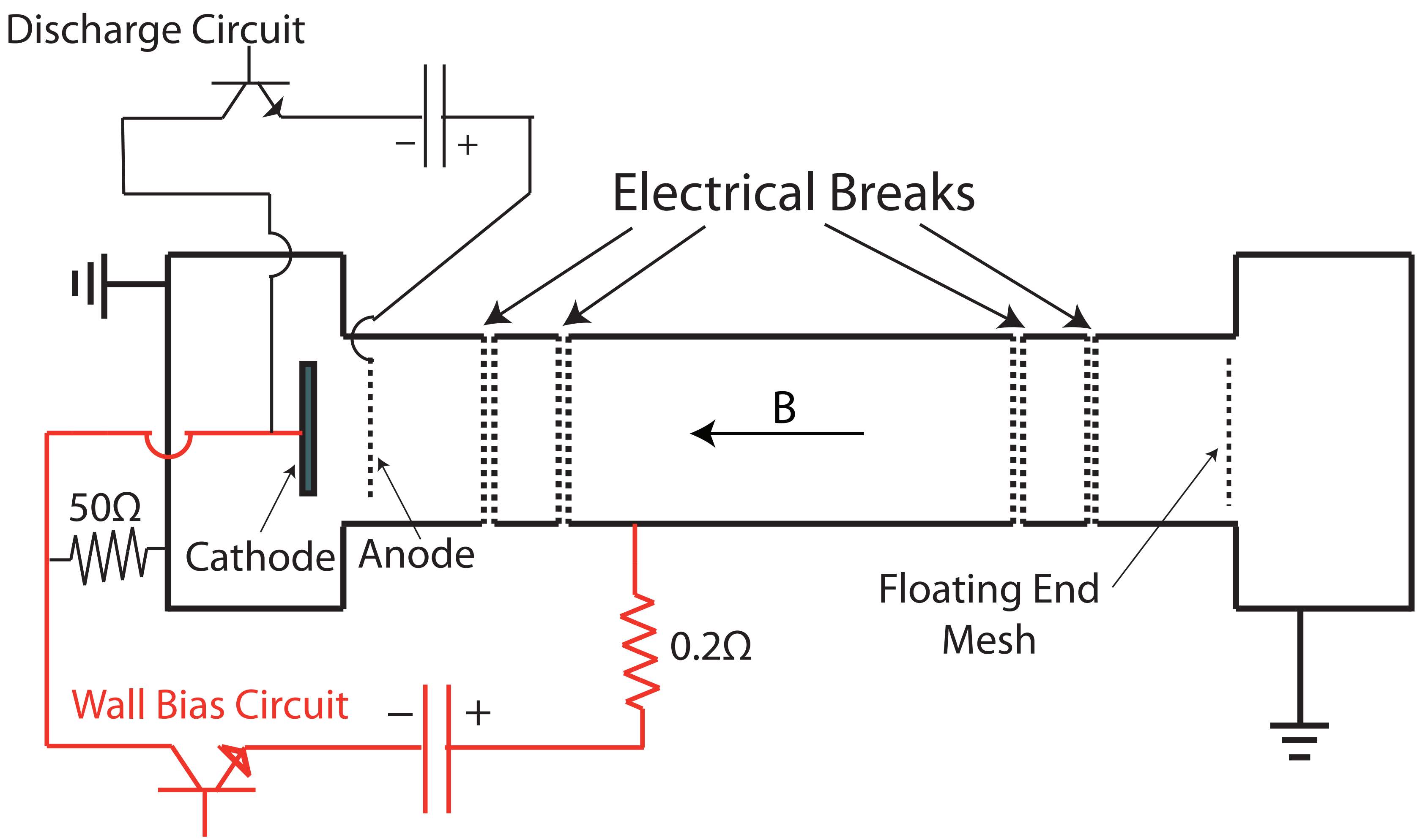


Fast framing camera (~50k frames per second, ~10ms total time), visible light (neutral He), viewed along B

Using biasing to drive cross-field flow

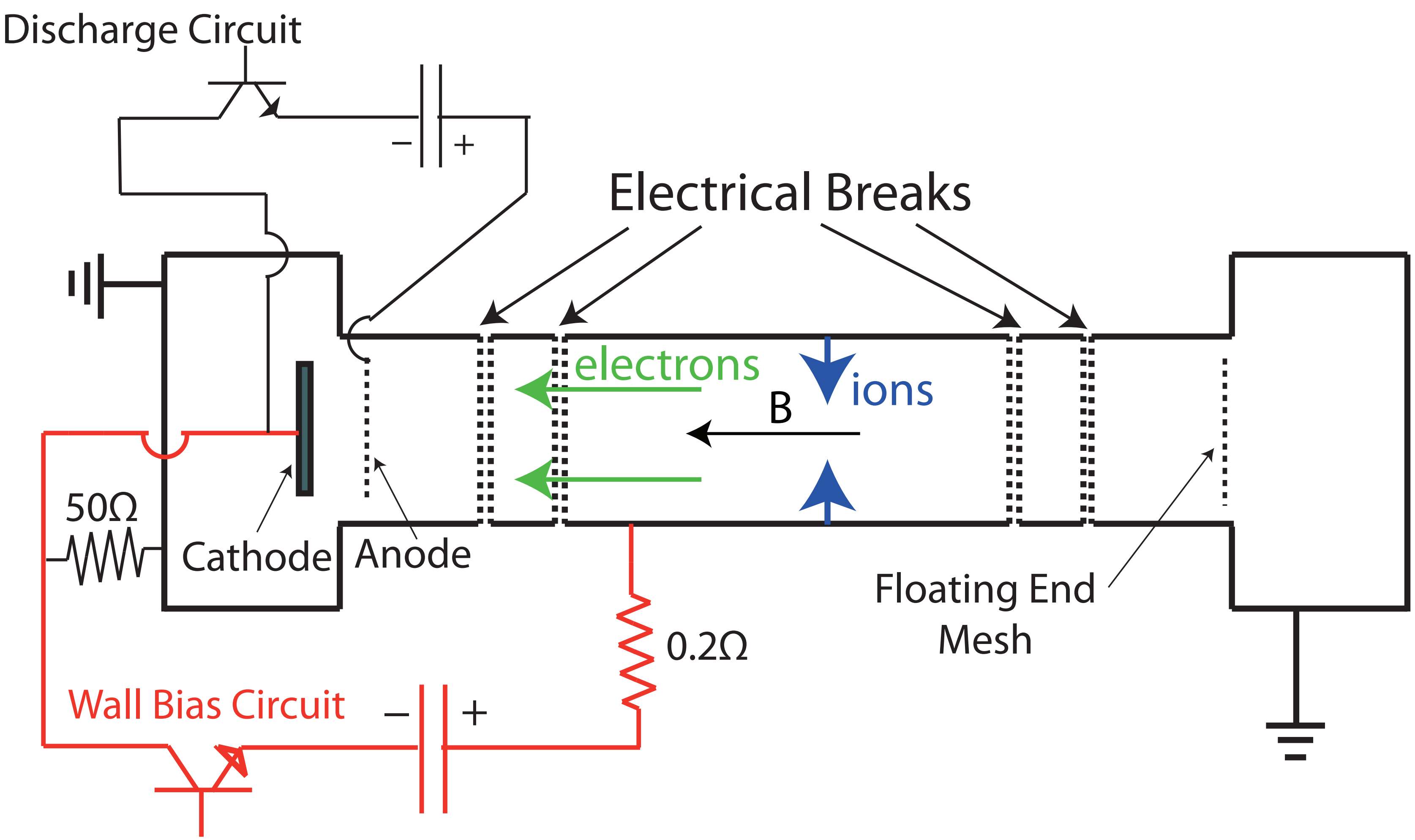
- Electrode immersed in plasma, biased relative to chamber wall (tokamak) or plasma source (LAPD)
- Cross-field current driven (e.g. via Pedersen conductivity), provides torque to spin up plasma
- Following CCT, technique used widely to drive flow and generate transport barriers: tokamaks (including ISTTOK), stellarators, RFPs, mirror machines ... [Weynants 92, Sakai 93, Boedo 02, Silva 06, …]
- LAPD biasing experiments provide combination of precise flow control and extensive measurements to provide detailed response of turbulence to shearing required to validate theoretical models and simulations

Wall-bias-driven rotation in LAPD



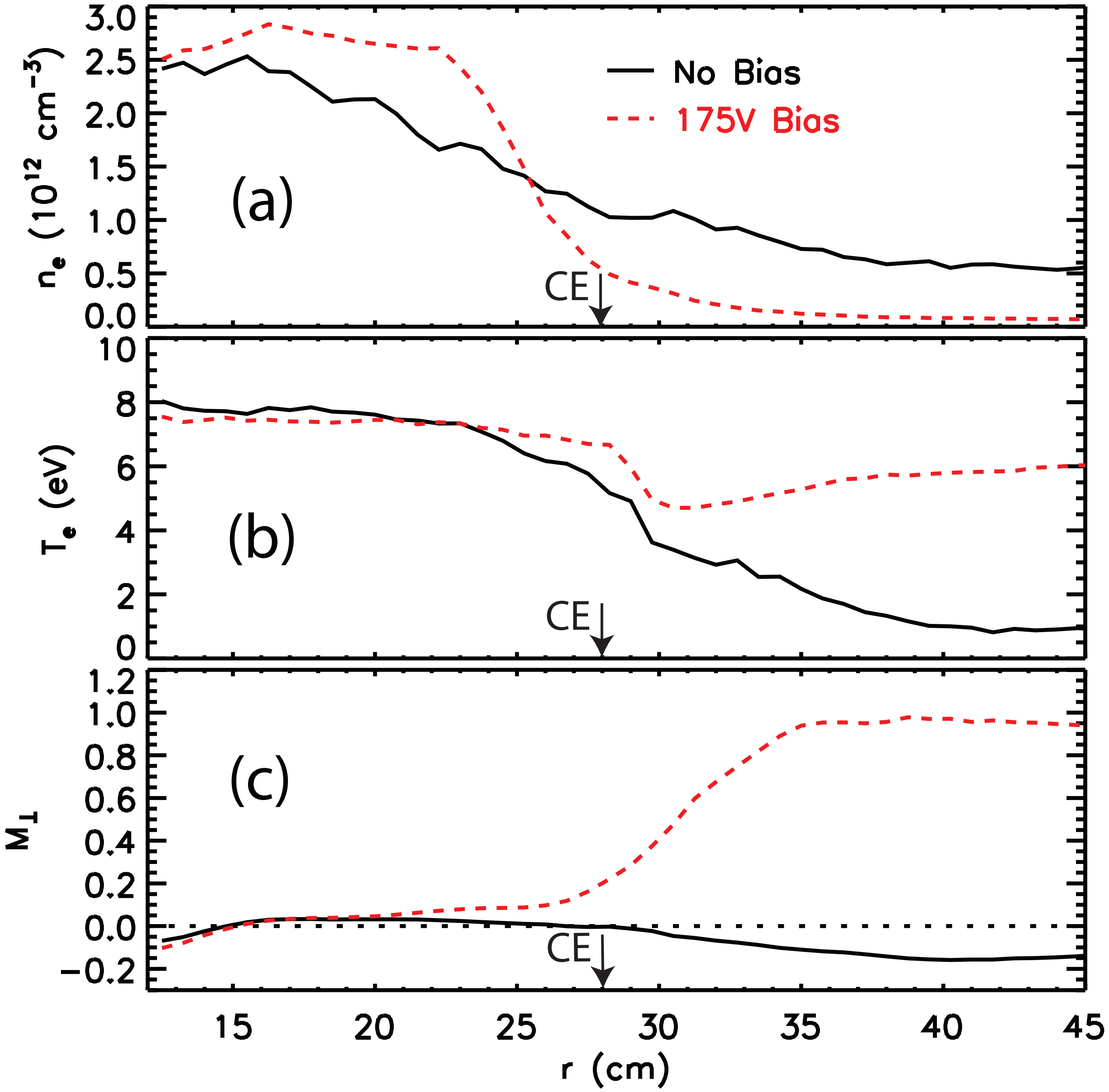
- Apply voltage to (floating) wall of chamber relative to cathode

Wall-bias-driven rotation in LAPD



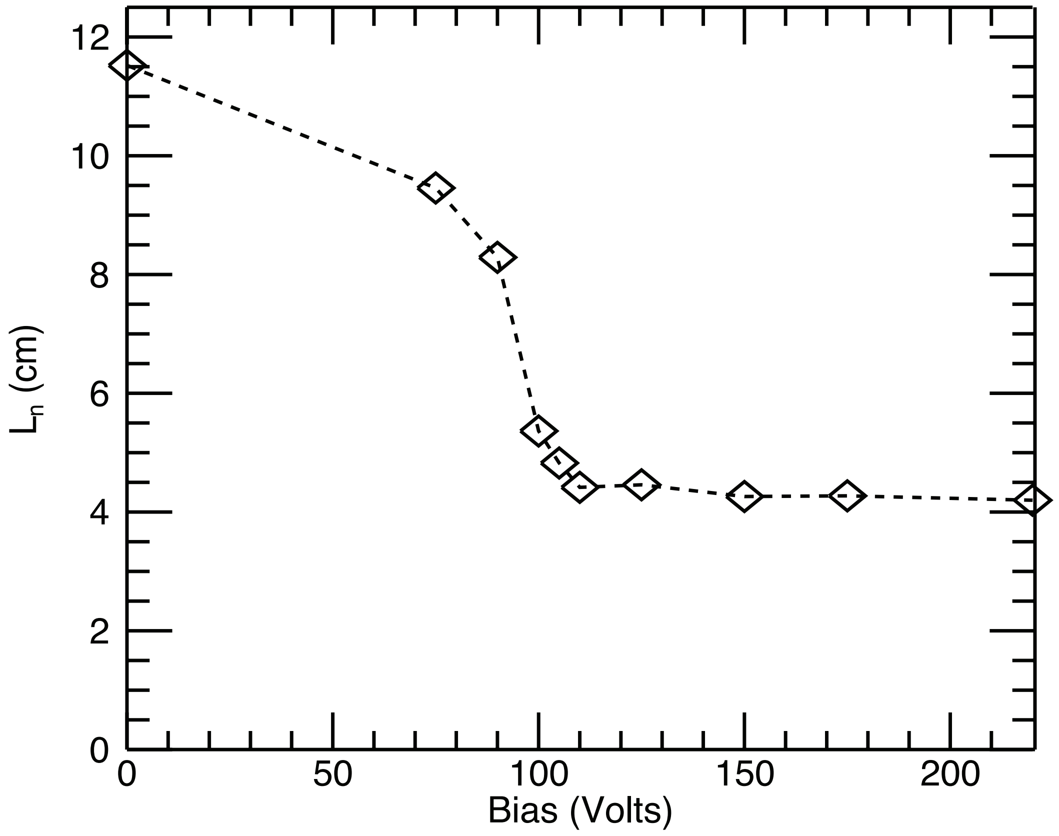
- Apply voltage to (floating) wall of chamber relative to cathode
- Radial current in response to applied potential (cross-field ion current due to ion-neutral collisions) provides torque to spin up plasma, generates radial electric field

Transport barrier/profile steepening observed with biasing



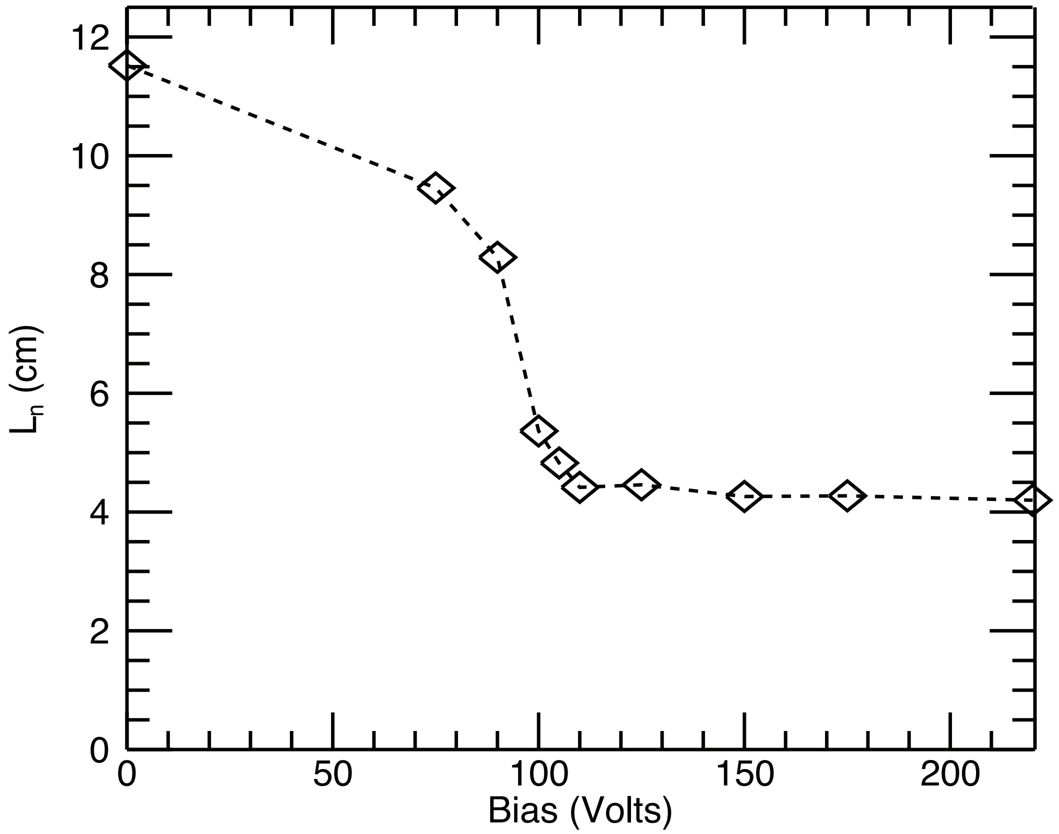
- As bias exceeds a threshold, confinement transition observed (“H-mode” in LAPD)
- Detailed transport modeling shows that transport is reduced to classical levels during biasing (consistent with Bohm prior to rotation) [T.A. Carter, et al., PoP 16, 012304 (2009), J.E. Maggs, et al., PoP (2007)]

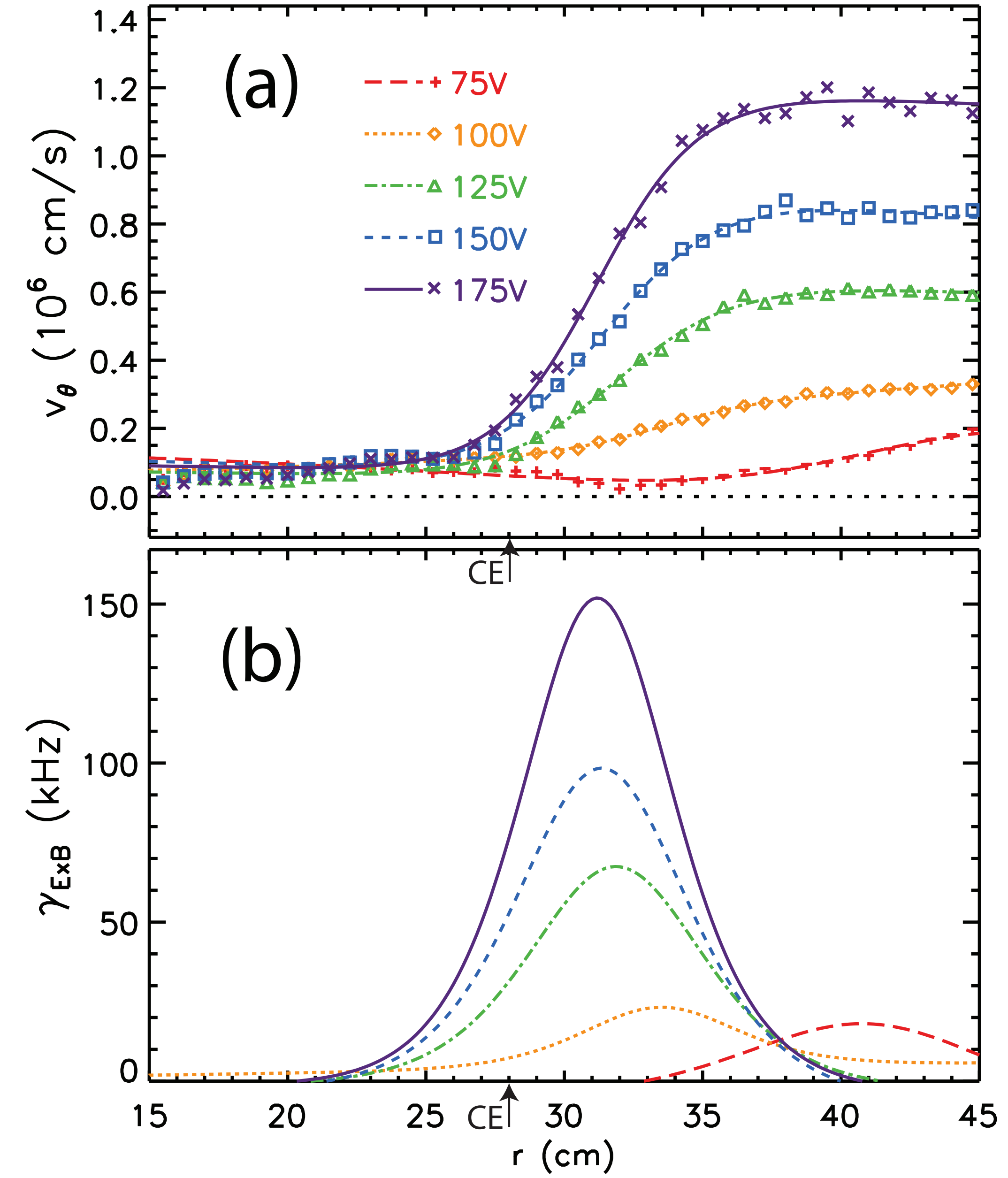
Threshold for transition is observed, appears to be due to radial flow penetration



- Profile steepening observed for bias above a threshold value

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

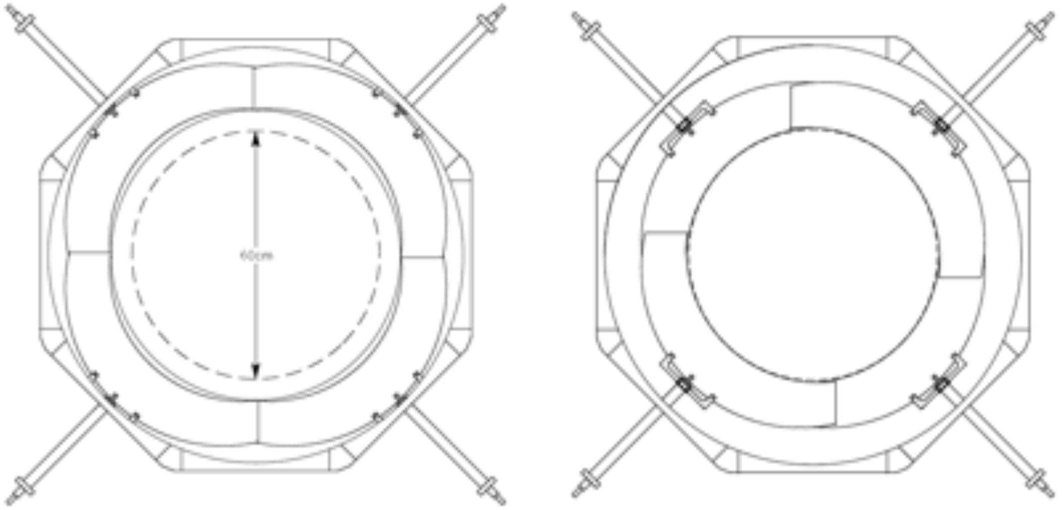


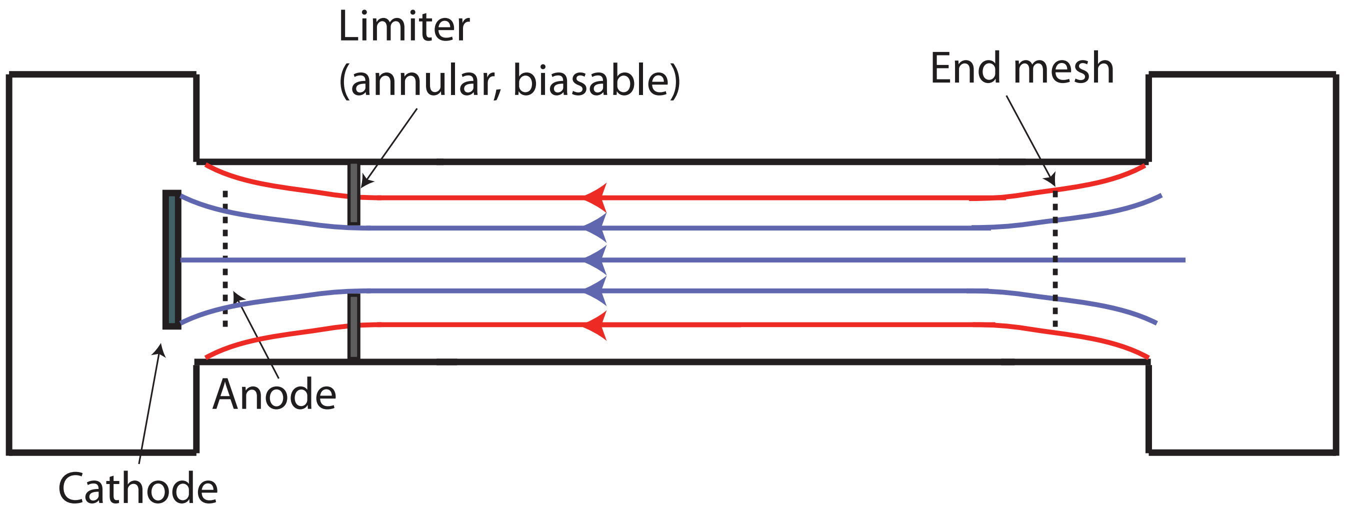


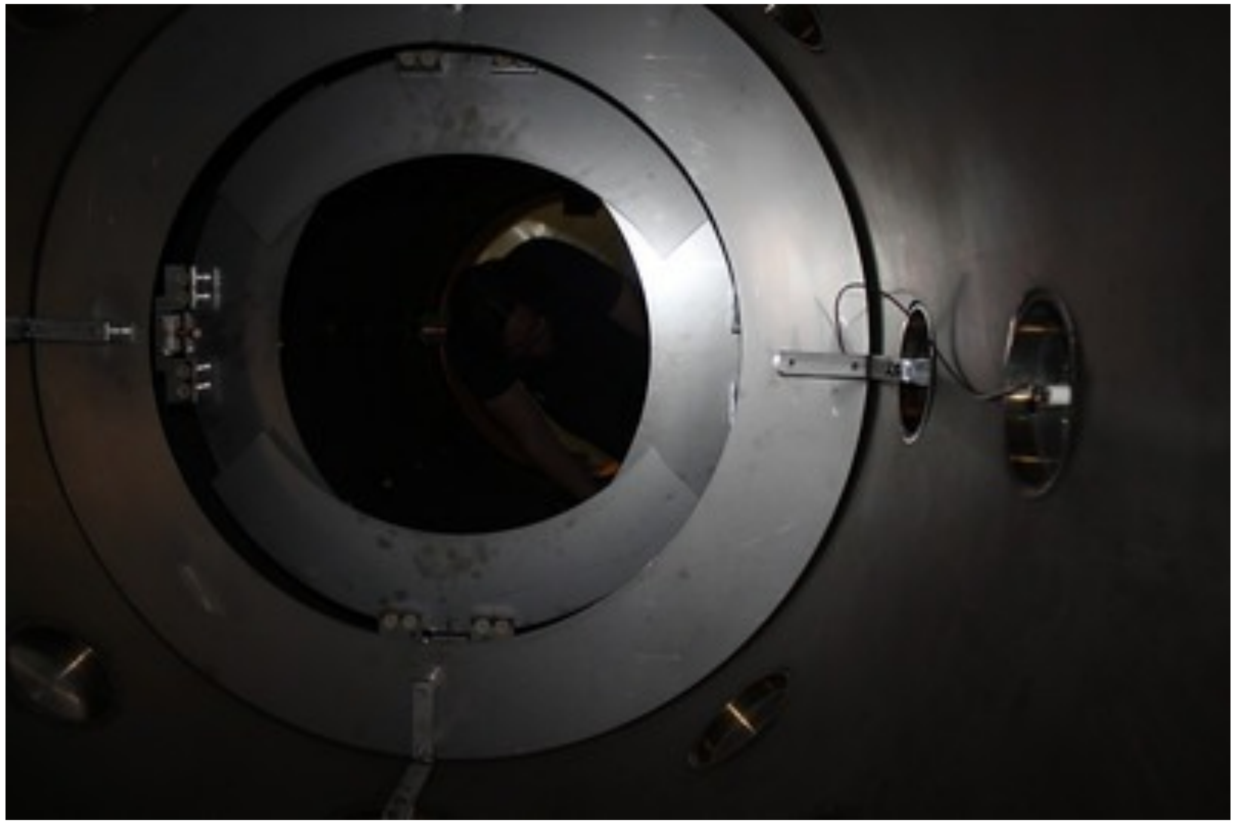
- Flow remains confined to far edge until threshold is exceeded

- Shearing rate large (compared to turbulent autocorrelation) at threshold

New variable aperture, biasable limiter enables extension of driven flow studies

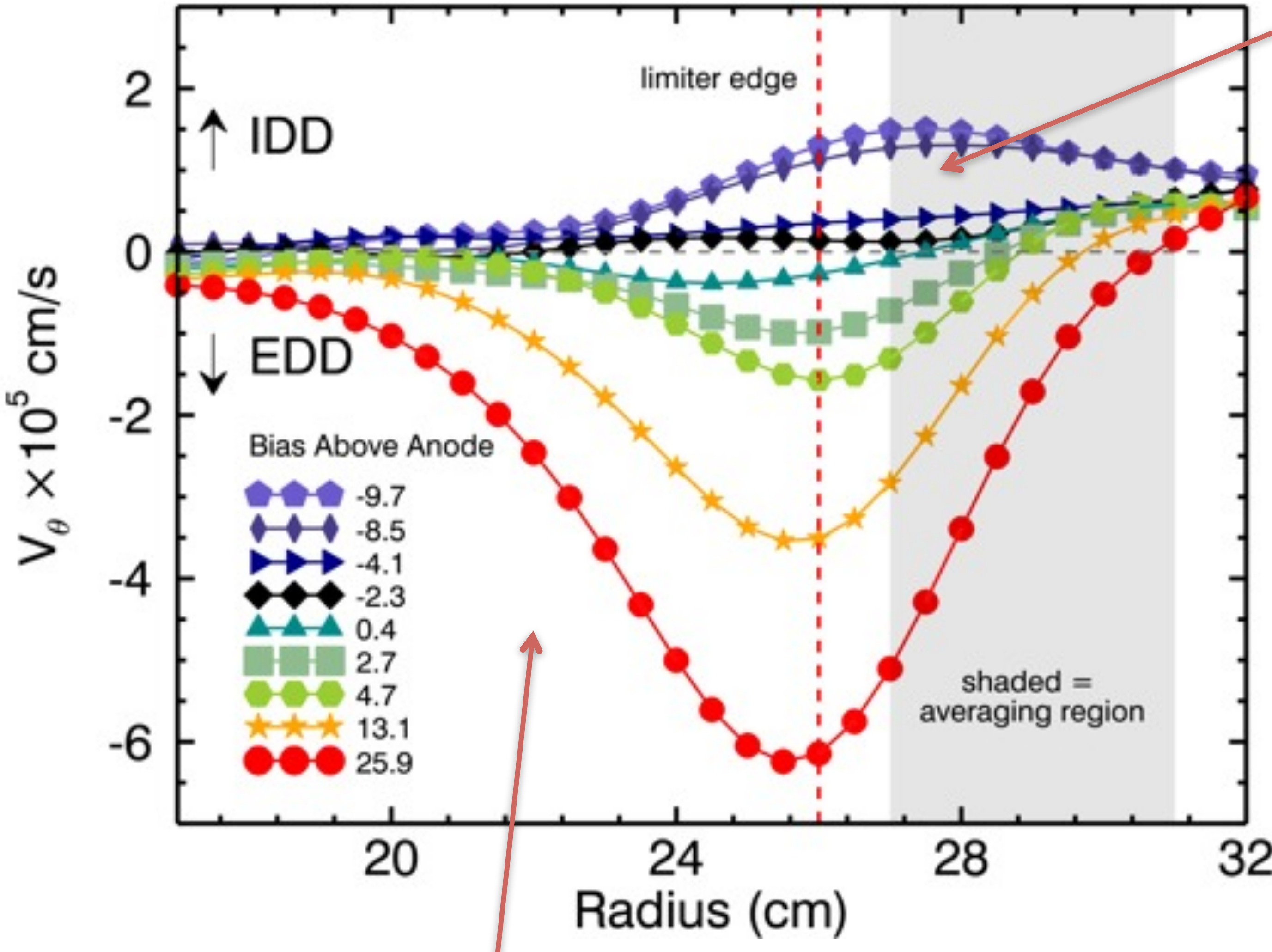






- Variable aperture, for these studies set to 52cm diameter
- Biased relative to the plasma source cathode

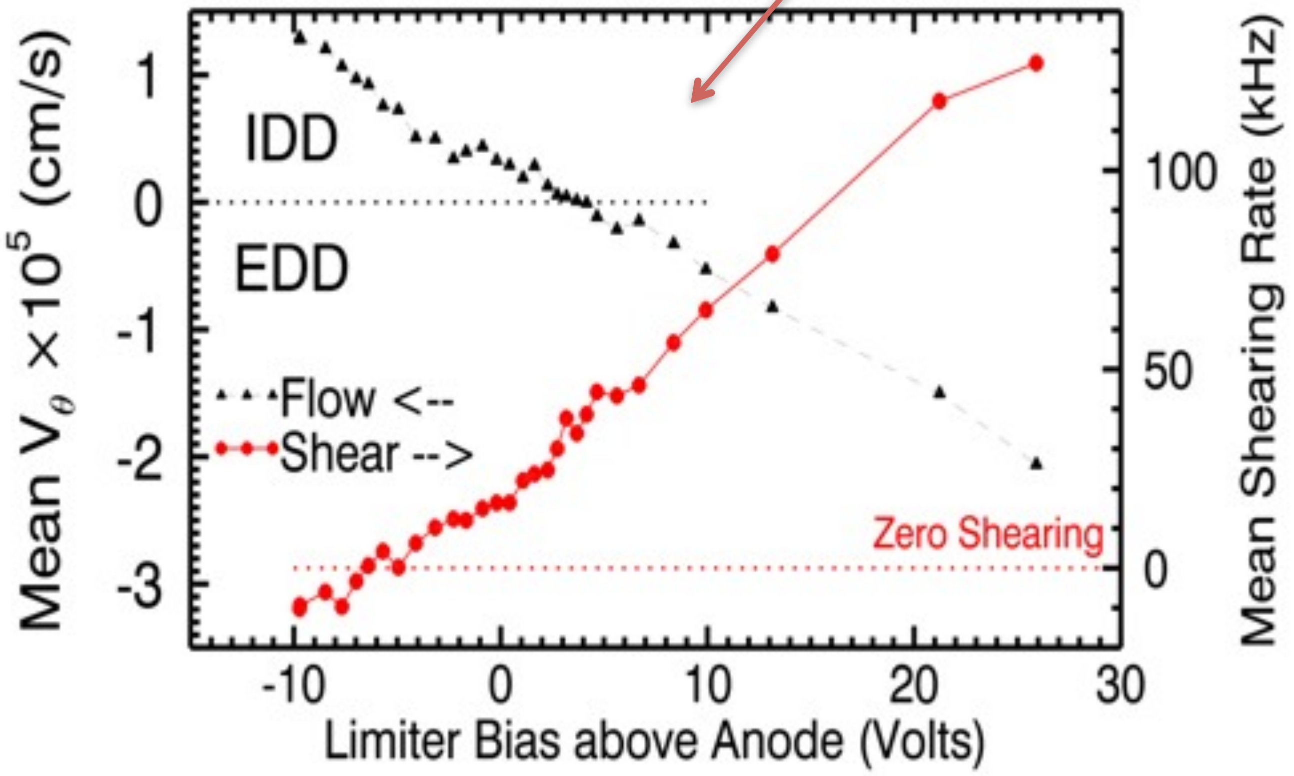
Continuous control on edge flow/shear is achieved, including flow reversal and zero shear state



Spontaneous (unbiased) flow in IDD

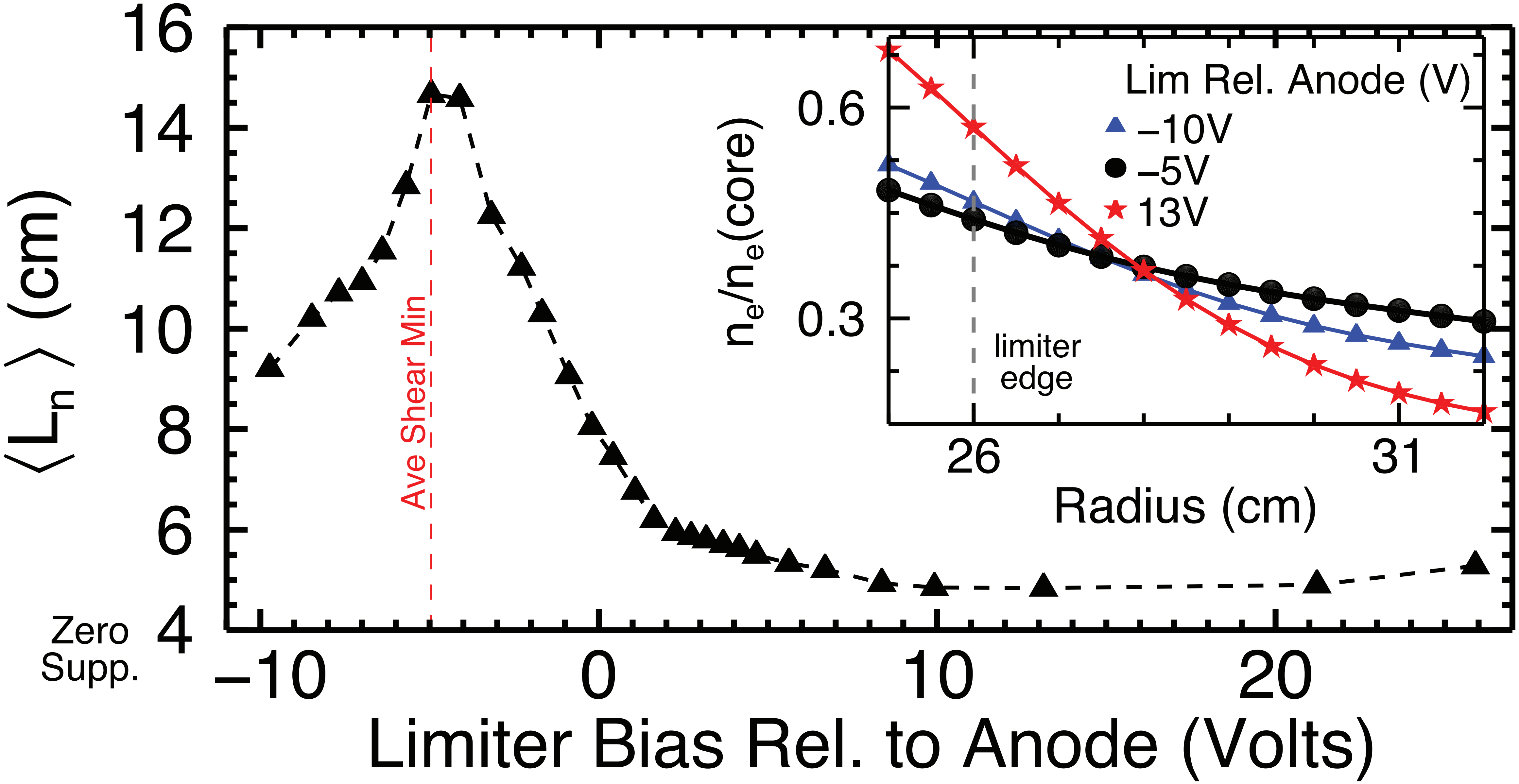
Biasing drives flow in EDD, opposing spontaneously induced flow

Average edge flow velocity and shearing rate scale linearly with limiter bias



Confinement enhanced in both flow directions; degraded at low shear

$$L_n = |\ln \frac{dn}{dr}|^{-1}$$



Effect of driven rotation on turbulence: visible imaging

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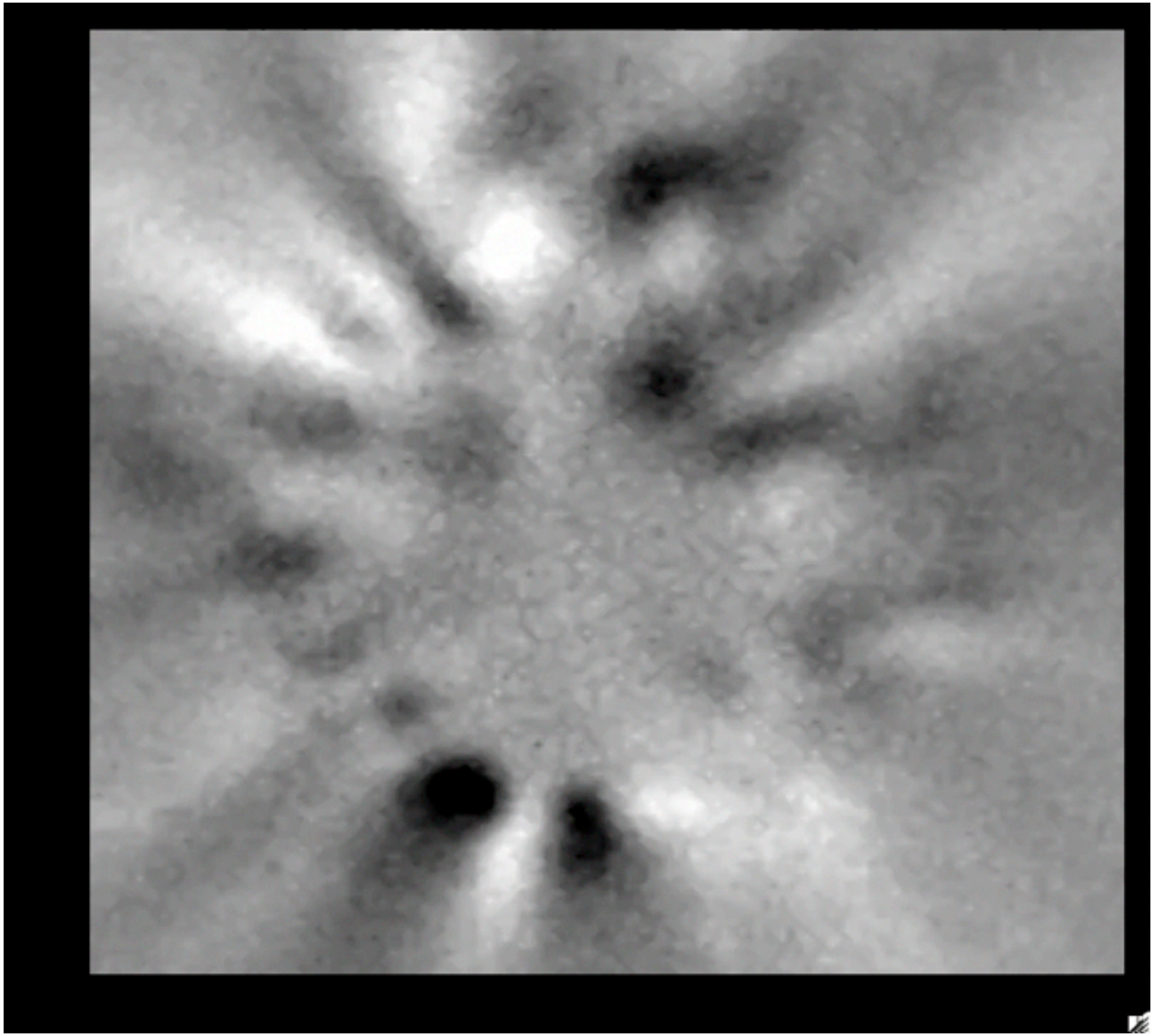
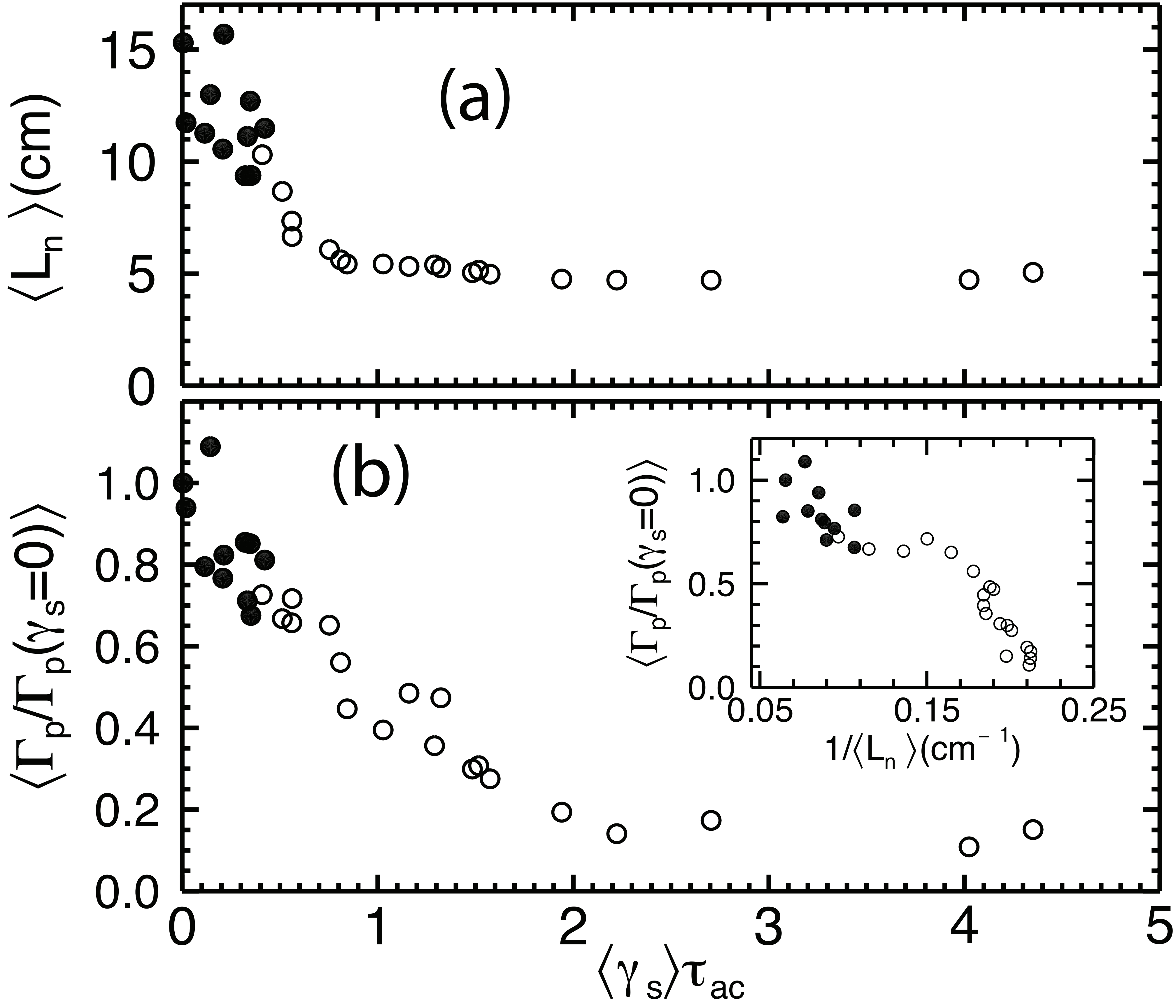
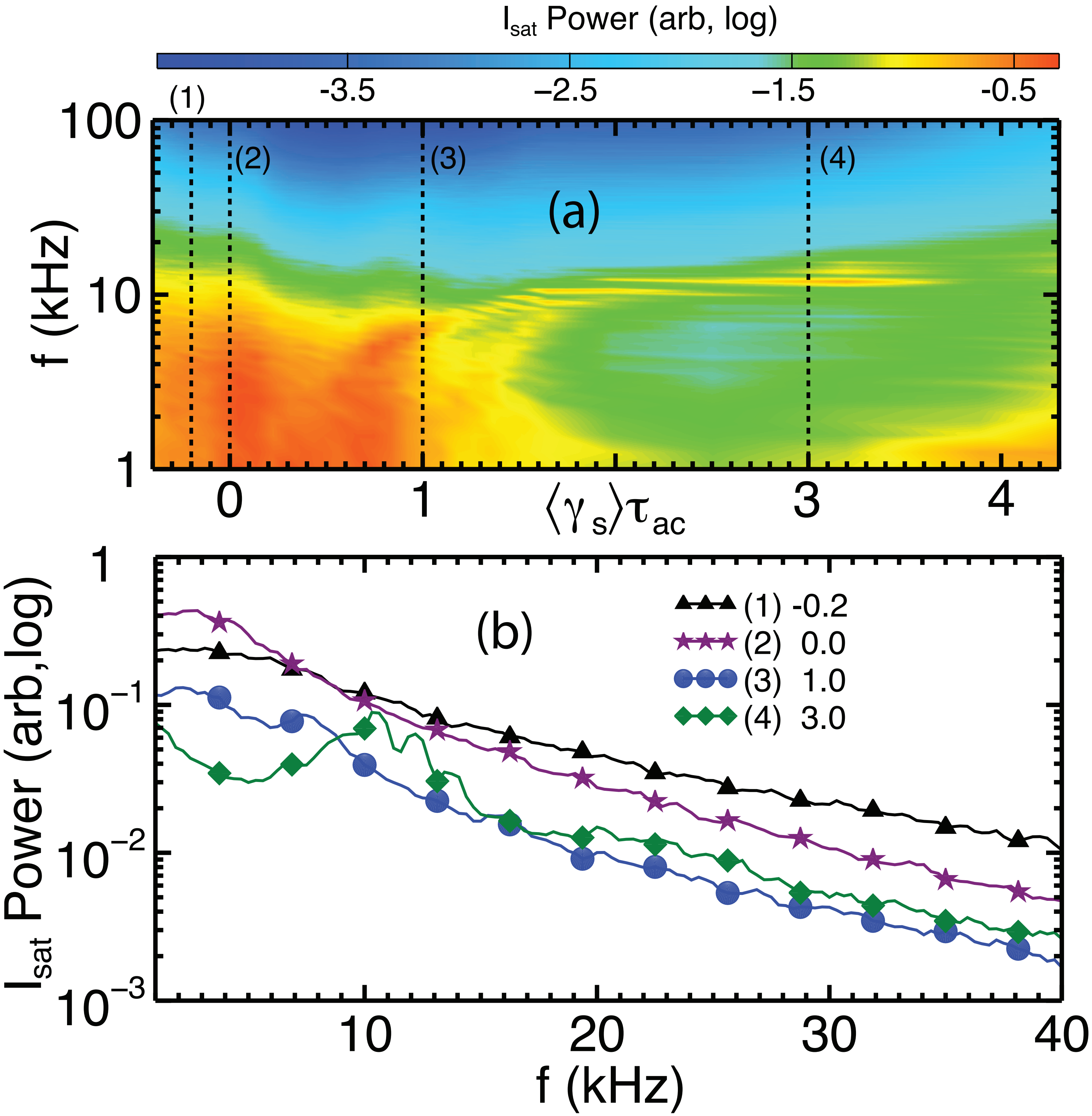


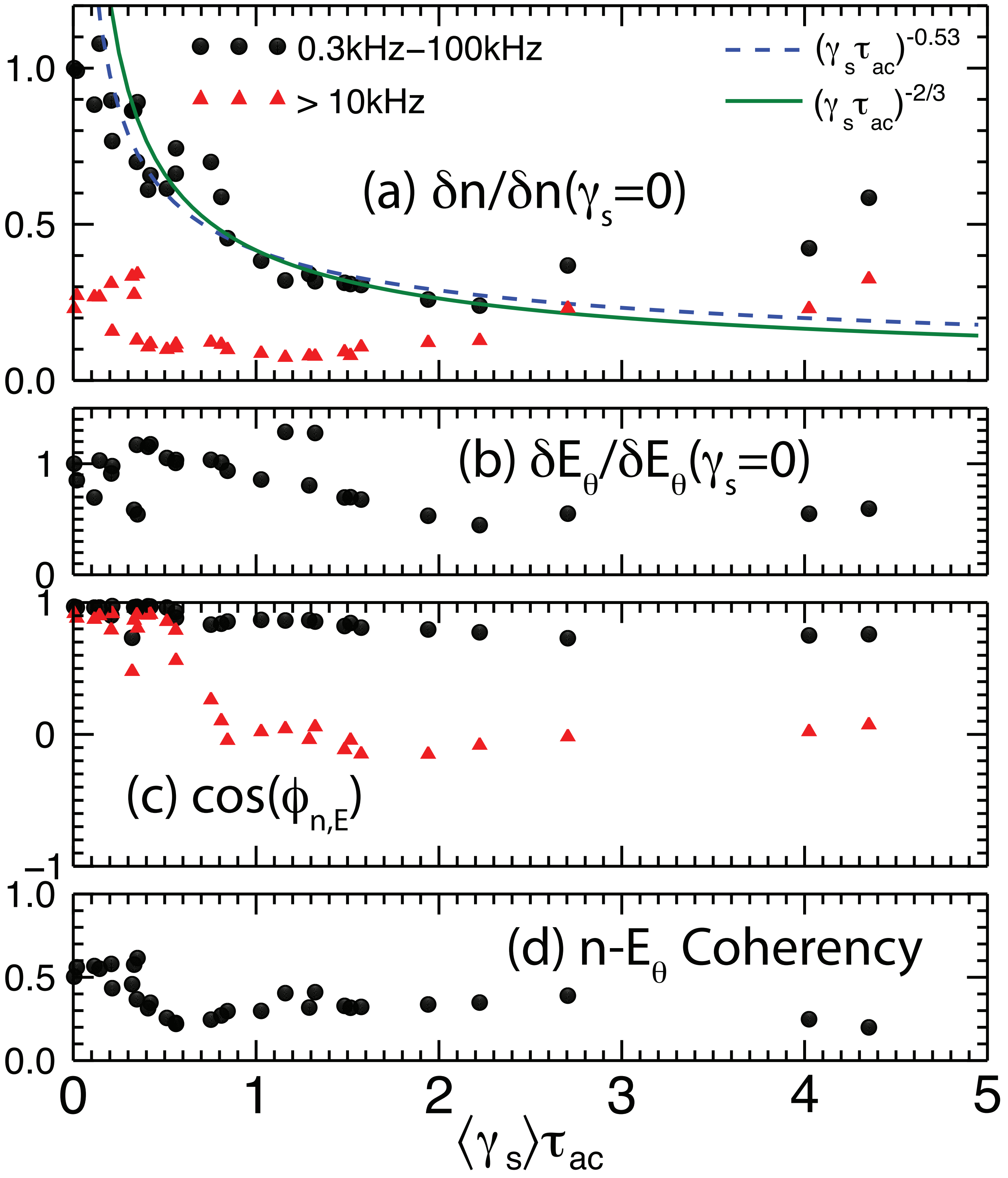
Profile steepens, flux decreases with shearing rate



Fluctuation power is reduced with increased shearing and enhanced at low shear

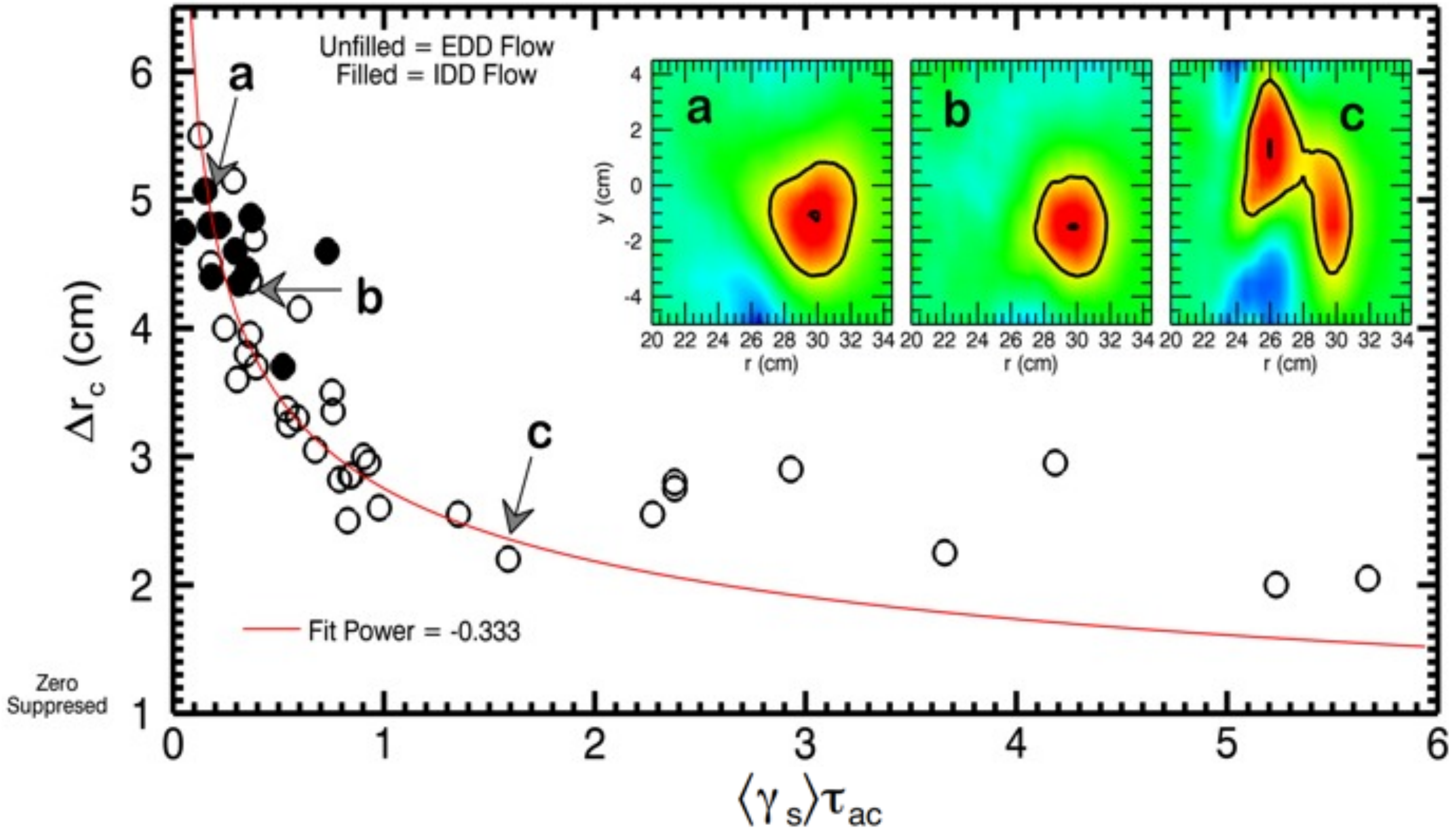


Turbulent amplitude reduction dominates transport suppression



- Density fluctuations drop substantially, electric field reduction weaker
- Crossphase largely unchanged (distinct from previous results: due to lower shear?)
- Coherent mode emerges, but causes no net transport
- Compares well with BDT, but shouldn't apply!

Radial correlation length decreases with shear



- Again, fits BDT theory surprisingly well; however, trend in gradient scale length is similar
- Coherent mode dominates at higher shearing

Simulation of LAPD turbulence

- Using BOUT++ 3D Braginskii two-fluid turbulence code. LAPD plasmas are reasonably collisional: $\lambda_{e,i}$ ~ 20 cm, λ_{DW} ~ 20m even though v_{φ} ~ $v_{th,e}$
    - Collisionless effects important in LAPD: e.g. damping of kinetic Alfvén waves; interested in exploring models with kinetic effects (Landau/gyrofluid, gyrokinetic)
- Verified against linear instability [Popovich PoP 17, 102107 (2010)]
- Initial comparisons to LAPD data [Popovich PoP 17, 122312 (2010), Umansky PoP 18, 055709 (2011)]
- Convergence study performed [Friedman Con. Plas. Phys. 52, 412 (2012)]

BOUT++ Model Equations

$$\partial_t N = -\mathbf{v}_E \cdot \nabla N_0 - N_0 \nabla_\| v_{\|e} + \mu_N \nabla_\perp^2 N + S_N + \{\phi, N\},$$

$$\partial_t v_{\|e} = -\frac{m_i}{m_e}\frac{T_{e0}}{N_0}\nabla_\| N - 1.71\frac{m_i}{m_e}\nabla_\| T_e + \frac{m_i}{m_e}\nabla_\| \phi - \nu_e v_{\|e} + \{\phi, v_{\|e}\},$$

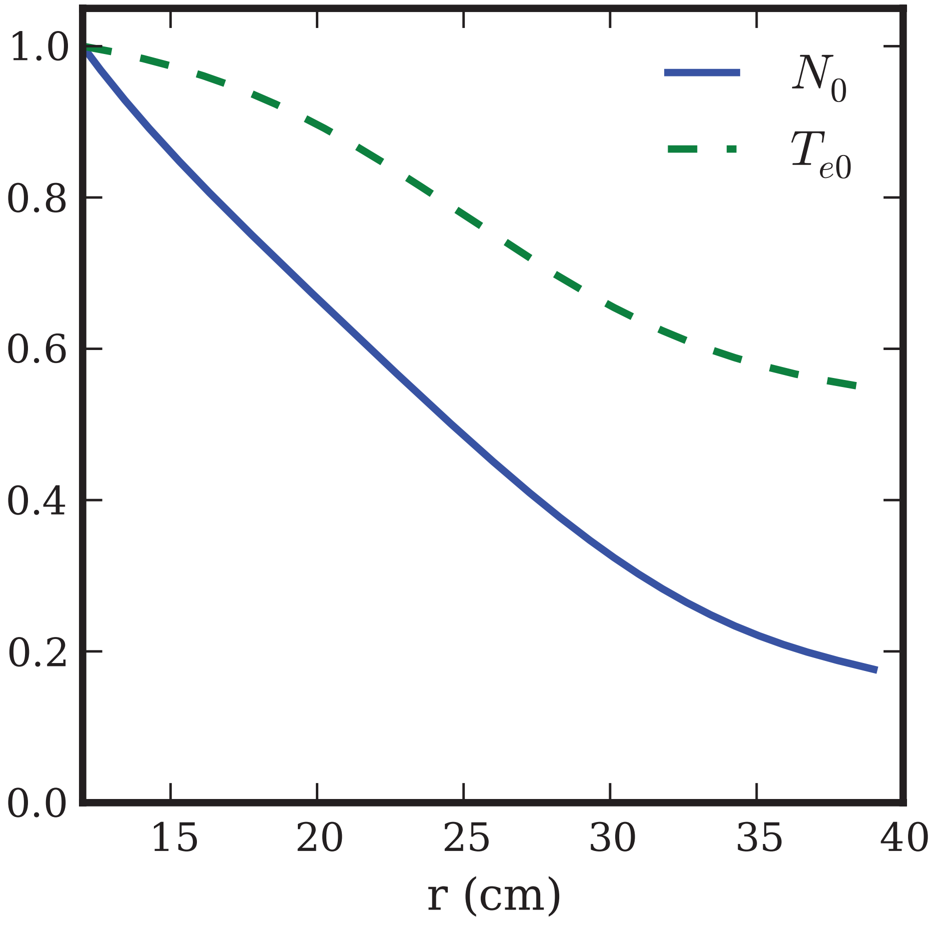
$$\partial_t \varpi = -N_0 \nabla_\| v_{\|e} - \nu_{in}\varpi + \mu_\phi \nabla_\perp^2 \varpi + \{\phi, \varpi\},$$

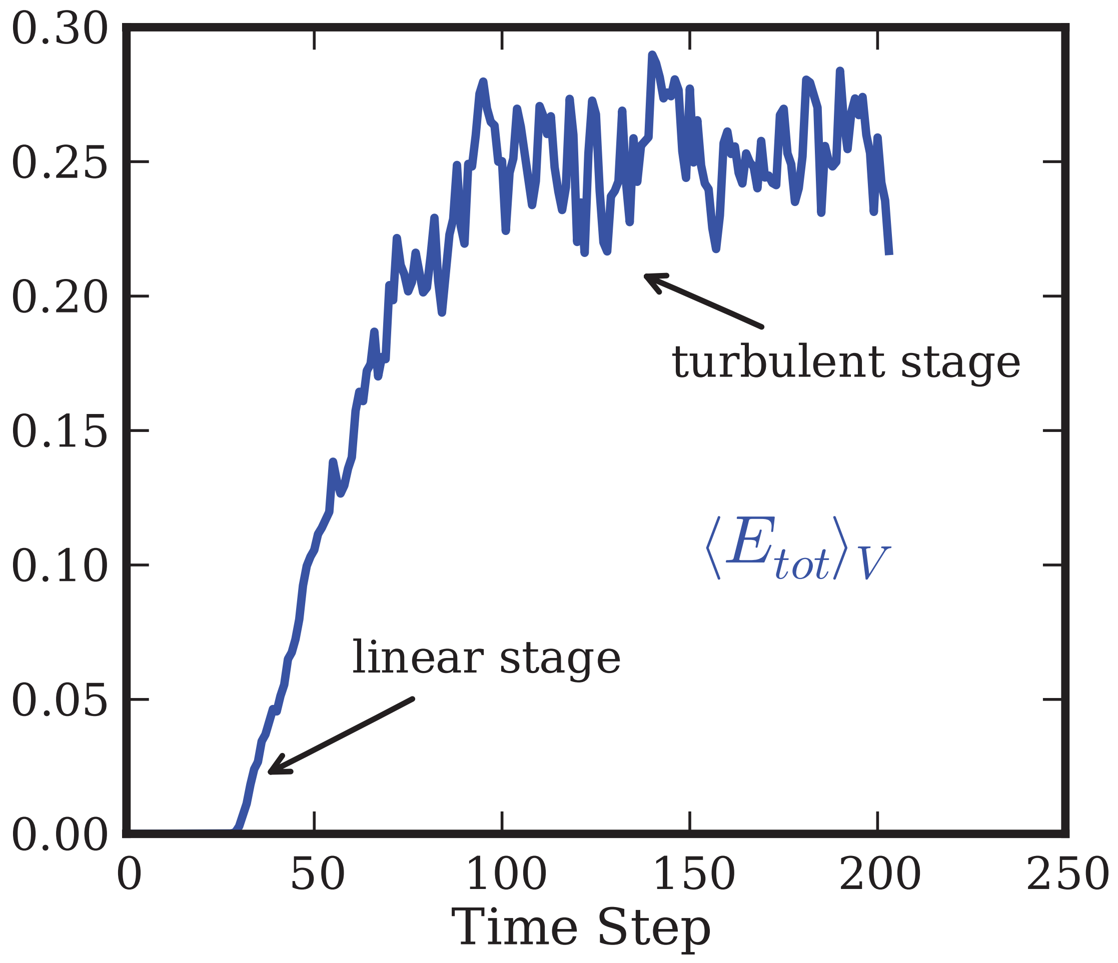
$$\partial_t T_e = -\mathbf{v}_E \cdot \nabla T_{e0} - 1.71\frac{2}{3}T_{e0}\nabla_\| v_{\|e} + \frac{2}{3N_0}\kappa_{\|e}\nabla_\|^2 T_e$$

$$-\frac{2m_e}{m_i}\nu_e T_e + \mu_T \nabla_\perp^2 T_e + S_T + \{\phi, T_e\}.$$

- Electrostatic (correlated magnetic fluctuations in expt (drift Alfvén waves), but small)
- Artificial viscosity, diffusion used (close to Braginskii values for viscosity, but scalar)

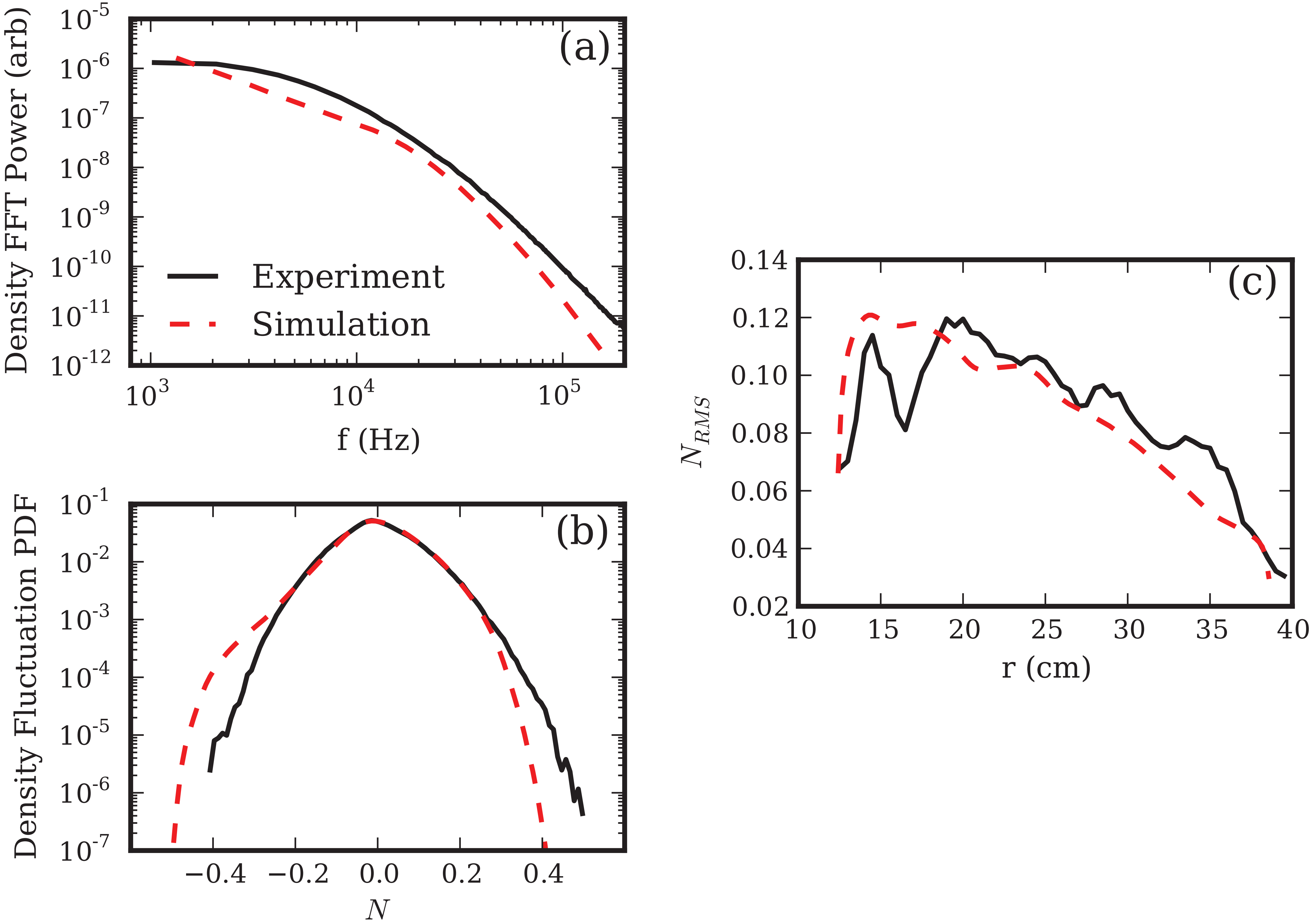
Experimentally consistent profiles used in BOUT++ simulation



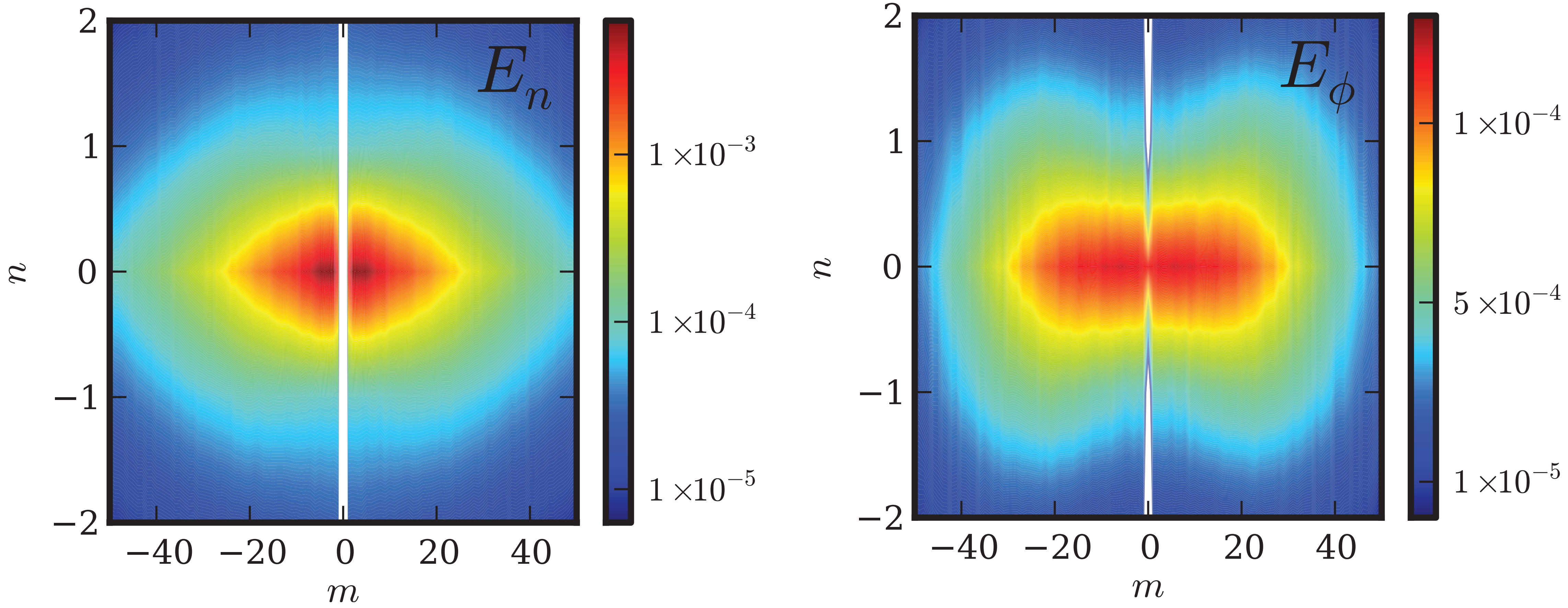


- Density and temperature: fits from experimental data
- FLAT mean potential profile (relevant to no flow experimental case); zonal flows allowed to develop
- Periodic boundary conditions used (simulations with sheath boundary conditions underway)

Not perfect, but encouraging similarity to experimentally measured fluctuation characteristics

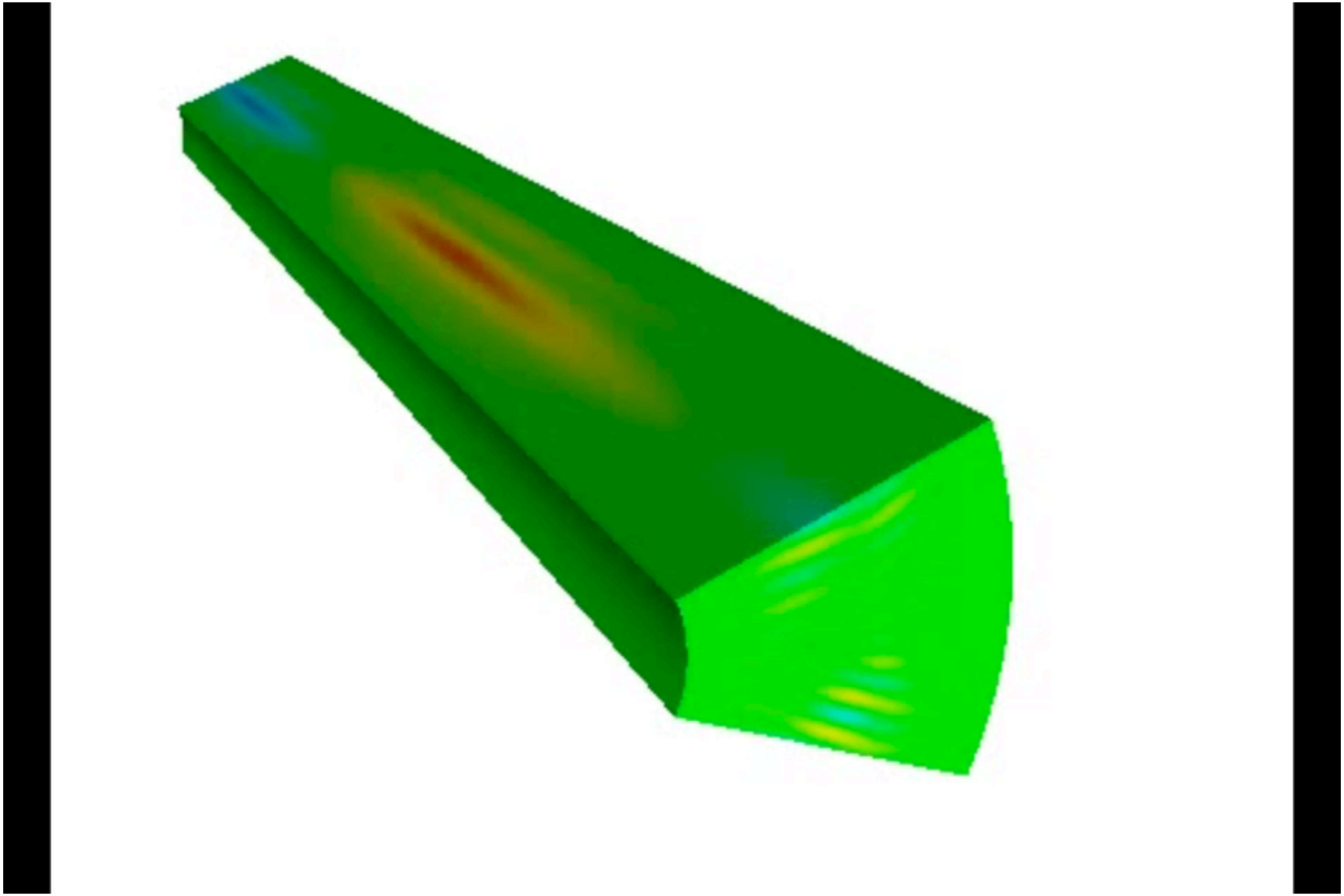


Surprising result: saturated turbulence dominated by flute-like (n=0) fluctuations (not consistent with linear drift waves)

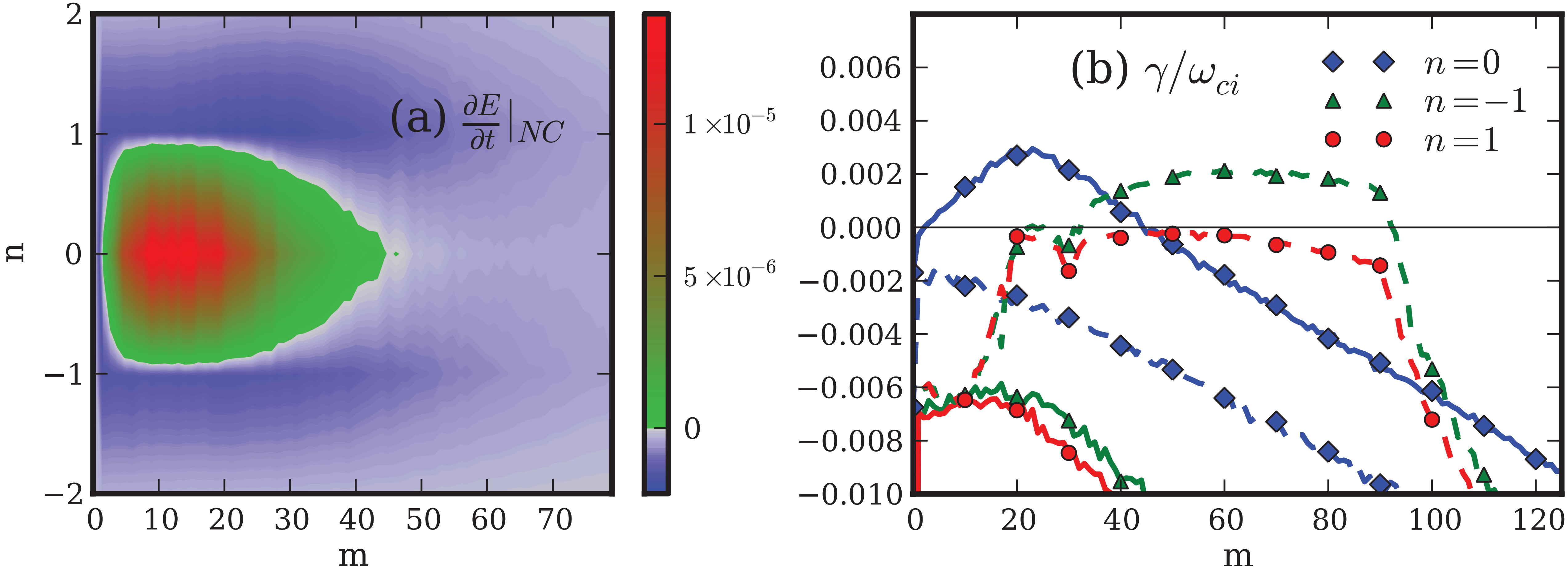


- Density and temperature: fits from experimental data
- FLAT potential profile (relevant to no flow experimental case)
- Periodic boundary conditions used (simulations with sheath boundary conditions underway)

BOUT++ turbulence visualization: clear transition to flute-like modes

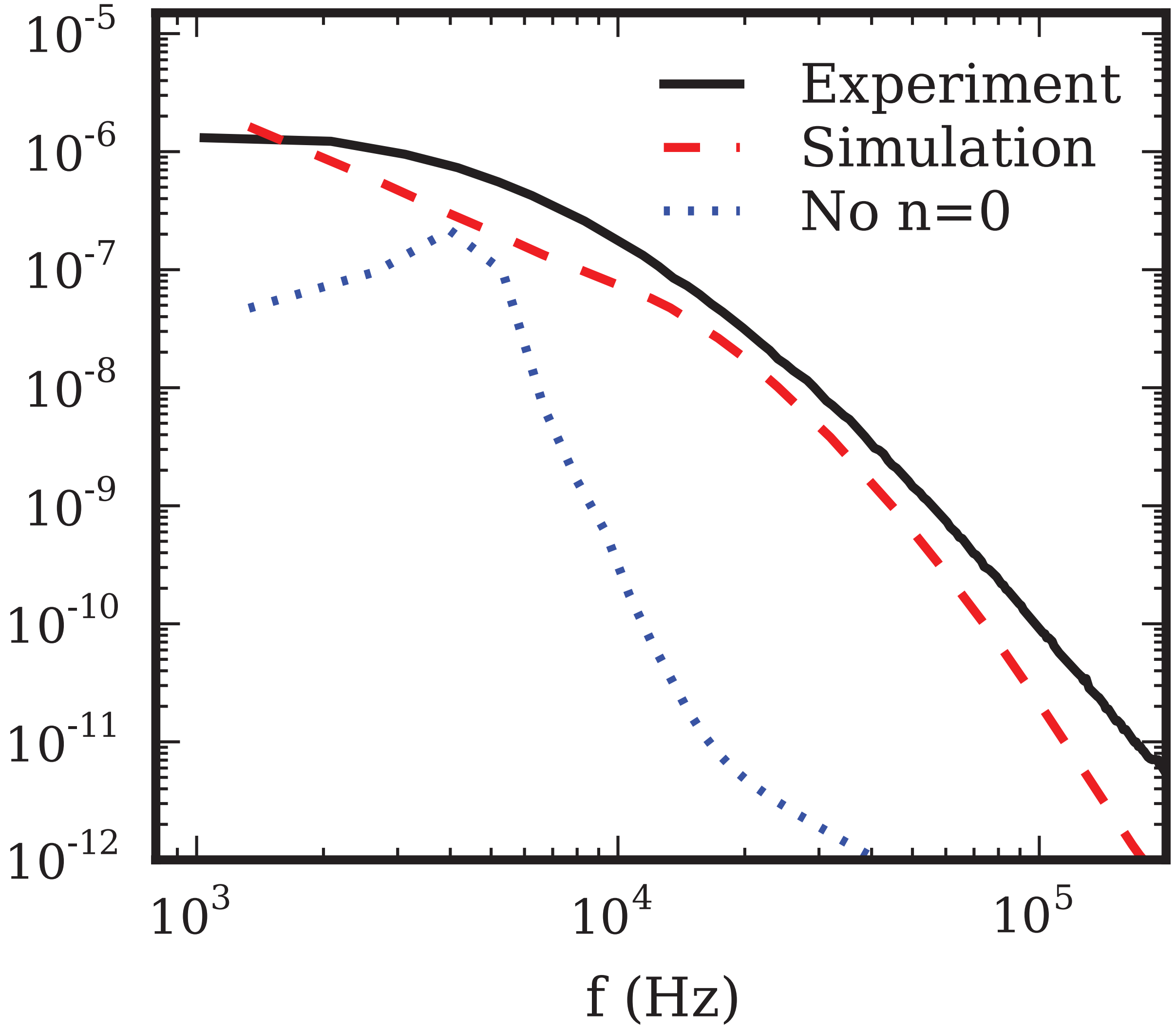


Direct energy injection into n=0 in nonlinear phase: n=1 modes are energy sink, not source!



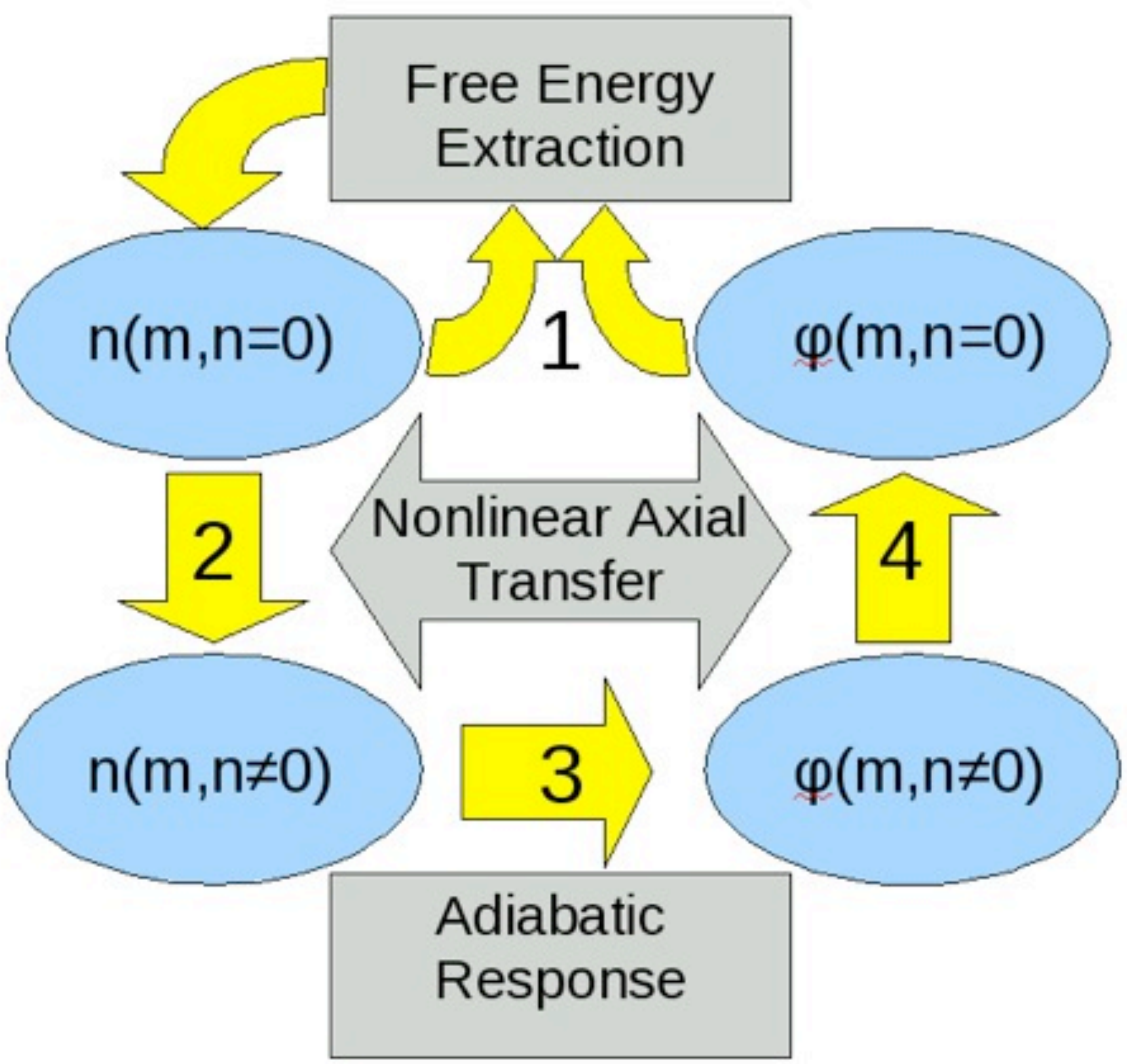
- Energy dynamics of turbulence evaluated: energy injection from pressure gradient (and effective growth rate) positive for n=0, negative for n=1 in saturated phase
- Nonlinear instability dominates even though linear instability is present!

If n=0 modes removed artificially, very different saturated spectrum produced



- Spectrum more coherent (peak near fastest growing linear mode)
- Zonal flows are not removed

Nonlinear instability mechanism



- Similar NL instability observed previously in tokamak edge simulations [Drake, Biskamp, Scott, ...]
- May call into question the use of linear/quasilinear theory to predict edge transport behavior?
- Future work: effect of axial boundary conditions

Friedman, et al. arXiv:1205.2337

Summary/Outline

- Documented the response of pressure-gradient driven turbulence to continuous variation of flow shear in LAPD [Schaffner, et al., PRL 109, 135002 (2012)]
  - Continuous control of edge flow through biasing; variation includes zero-shear and zero-flow states, flow reversal
  - Particle transport decreases with increased shearing, enhanced at low flow shear, independent of flow direction
  - Transport reduction due to turbulent amplitude reduction; near complete suppression for shearing rate comparable to no-shear autocorrelation rate
- Two-fluid simulations with BOUT++ code: good qualitative match to measurements; saturated state of turbulence consistent with action of a nonlinear instability. [Friedman, et al., arXiv:1205.2337, PoP submitted]