How the Birth and Death of Shear Layers Determines Confinement Evolution: From the L→H Transition to the Density Limit

P.H. Diamond

U.C. San Diego, USA

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See: “How the Birth … to the Density Limit”

in Phil. Trans. Roy. Soc. ~ January 2023

by P.D., Rameswar Singh, Ting Long, Rongjie Hong, Rui Ke,

Zheng Yan, Mingyun Cao, George Tynan

→ OV of Work and Related 2018→Present

→ Combines Experiment and Theory

40 Years of H-mode – Lessons (1982 →)

- Saved MFE from Goldston scaling
- Introduced transport barrier, bifurcation → state ‘phases’ and transitions
- Role of flow profile in confinement (BDT ’90)
- Dynamical feedback loops → Predator-Prey cycles, Zonal flows, etc. (PD+’94,05; K-D ‘03)
- Consequences of marked transport reduction

  ➔ Strong interest in turbulent pedestal states
- Applications elsewhere → Density Limit

Phases and Transitions of the Edge Plasma

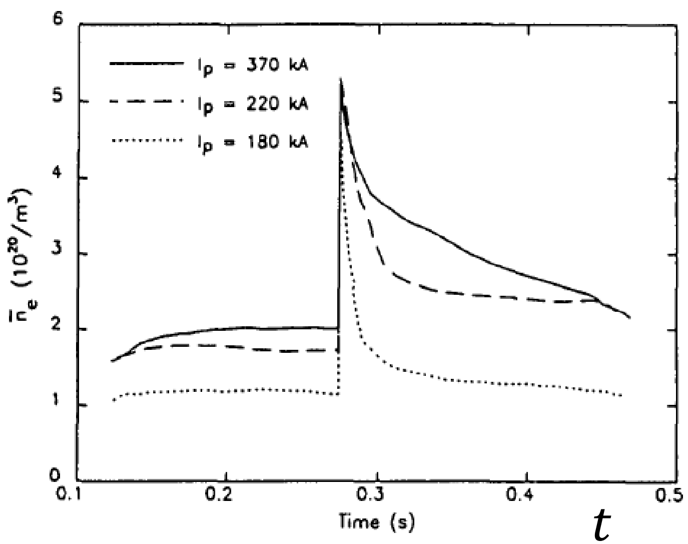
and

Density Limit Phenomenology

N.B. Fusion power gain ~ n^2 → Reactors: high density

- Conventional Wisdom: Radiation + MHD (Rebut → Gates…)
- Argue: Edge Particle Transport is fundamental
  - ‘Disruptive’ scenarios <u>secondary</u> outcome, largely consequence of <u>edge cooling,</u> following fueling vs. increased particle transport
  - $\bar{n}_g$ reflects fundamental limit imposed by <u>particle transport</u>
- An Important Experiment (Greenwald, et. al. ‘88)

$\bar{n}_e$



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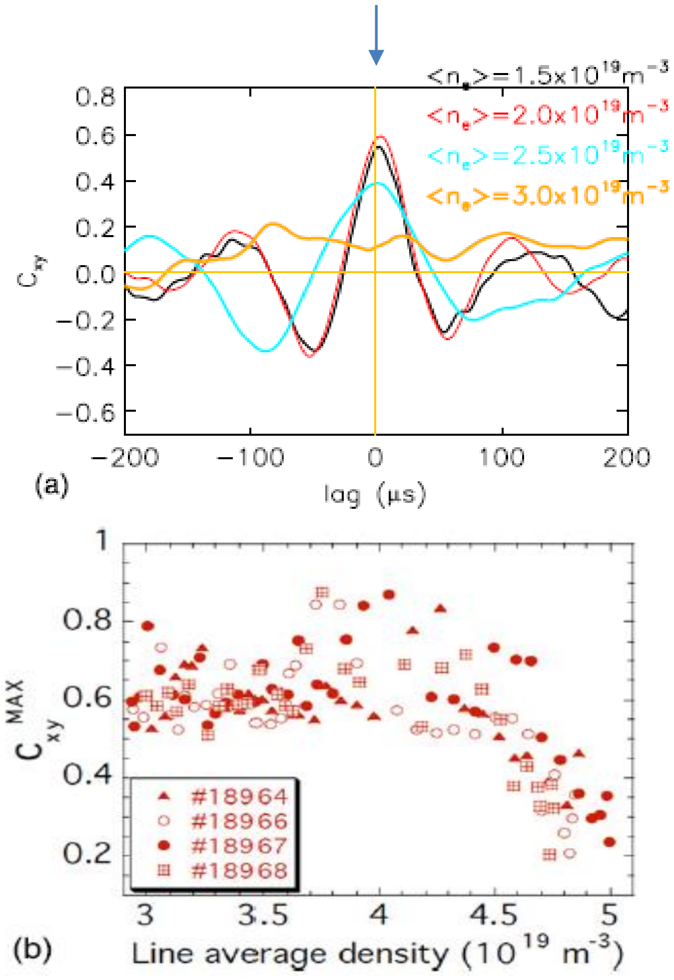
(Alcator C)

  - Density decays <u>without disruption</u> after shallow pellet injection
  - $\bar{n}$ asymptote scales with I_p
  - Density limit enforced by transport-induced relaxation
  - Relaxation <u>rate</u> not studied
  - Fluctuations?

Toward Microphysics: Recent Experiments - 1

(Y. Xu et al., NF, 2011)



$\bar{n}$

See also: Pedrosa '07, Hidalgo '08 …

LRC vs $\bar{n}$

- Decrease in maximum correlation value of LRC (i.e. ZF strength) as line averaged density $\bar{n}$ increases at the edge (r/a=0.95) in both TEXTOR and TJ-II.
- The reduction in LRC due to increasing density is also accompanied by a reduction in edge mean radial electric field (Relation to ZFs).

Is density limit related to edge shear decay?!

↓

Yes !

Reynolds work (Flow production) drops as $n \to n_g$ (Hong+ '18)

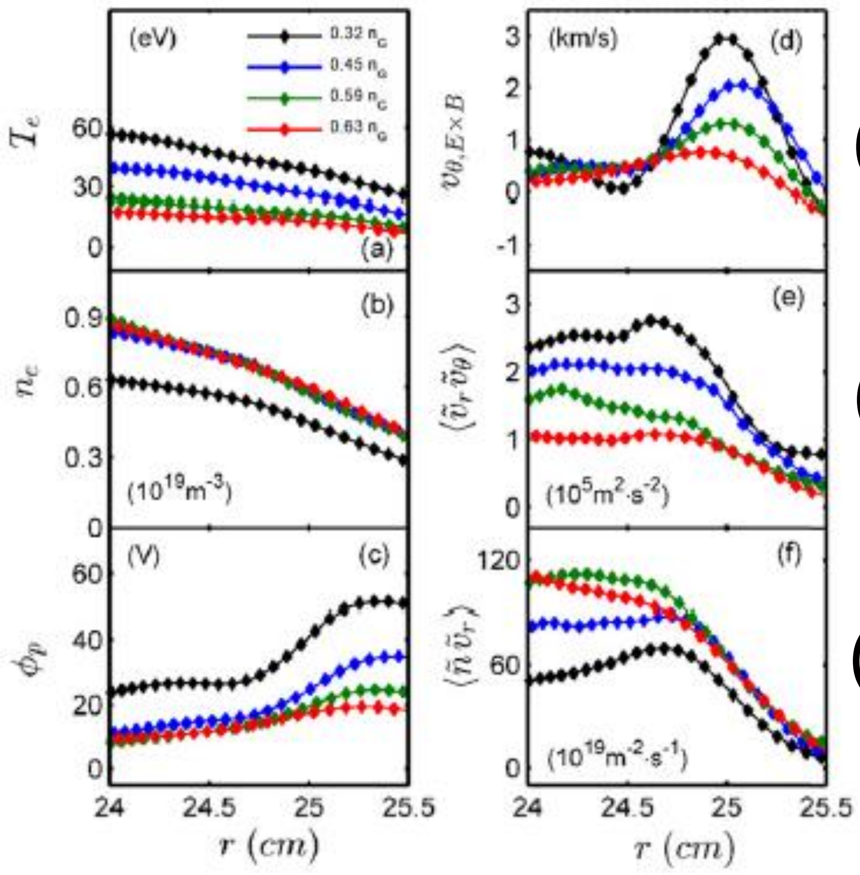
An In-depth Look at New Experiments

Ting Long, P.D. et. al.   2021 NF

Rui Ke, P.D., T. Long et. al. 2022 NF

J-TEXT – Ohmic

- $B_T \sim 1.6 - 2.2\,T$ $\frac{n}{n_G} \sim 0.7$ $n_G \sim 6.4 \rightarrow 9.3 \times 10^{19} m^{-3}$
- $I_p \sim 130 - 190\,kA$ $\bar{n} \sim 2.0 - 5.3 \times 10^{19} m^{-3}$
- Principal Diagnostics: Langmuir Probes
  - Shear layer <u>collapses</u> as n/n_G increases (1)
  - Turbulence particle flux increases (2)
  - Reynolds force decays (3)
  - Velocity fluctuation PdF → symmetry



(1)

(2)

(3)

Mean-Turbulence Couplings

- In standard CDW model:

Production ≡ Input from ∇n

$$\delta n = \tilde{n}/n_0$$

$$P_I = -c_s^2 \langle \tilde{V}_r \delta n \rangle \left(\frac{1}{n_0} \frac{\partial \langle n \rangle}{\partial r} \right)$$

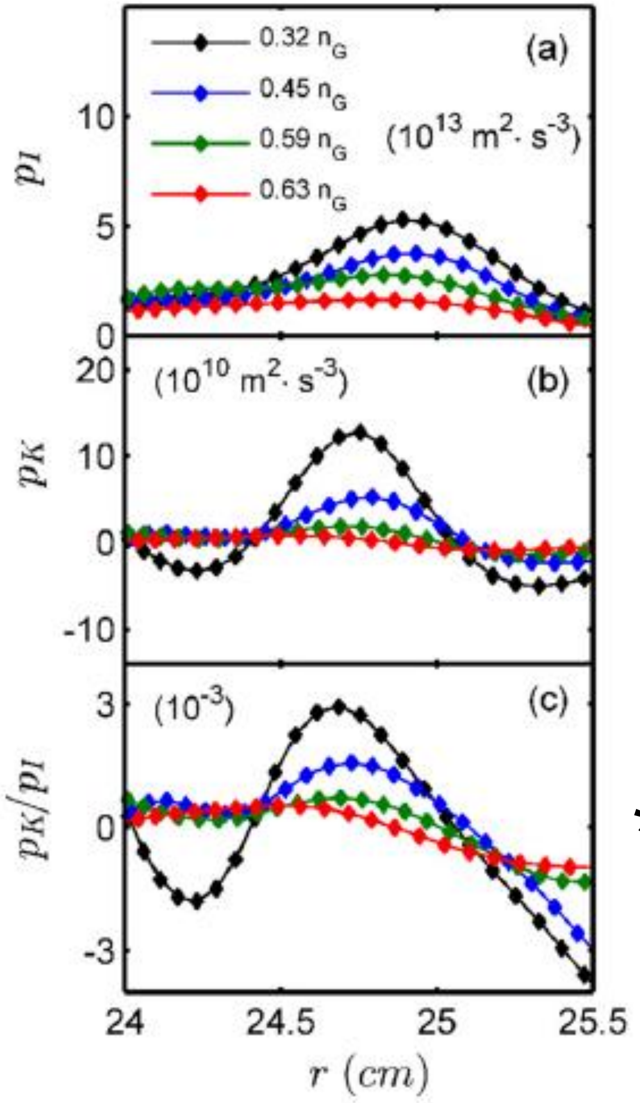
Reynolds Power ≡ Coupling to Zonal Flow

$$P_k = -\langle \tilde{V}_r \tilde{V}_\theta \rangle \langle V_E \rangle'$$

– Reynolds power drops as n/n_G rises (see Hong+,'18)

– P_k/P_I drops as n/n_G rises *

➔ Fate of the Energy ?



*

Fate of the Energy ?

- Turbulence Energy Budget

Triplet, Production

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial}{\partial r}\langle v_r \varepsilon \rangle = P_I - \text{Dissipation}$$

Spreading

$$\varepsilon = \varepsilon_k + \varepsilon_I \qquad \varepsilon_I = \frac{c_s^2}{2}\langle (\tilde{n}/n_0)^2 \rangle$$

- Then P_S → Power coupled to fluctuation energy flux → <u>Turbulence spreading</u>

$$P_S = -\partial_r \langle \tilde{v}_r \varepsilon_I \rangle = -\partial_r \langle \tilde{v}_r \tilde{n}^2 c_s^2 \rangle / 2n^2$$

→ Turbulence Spreading Power

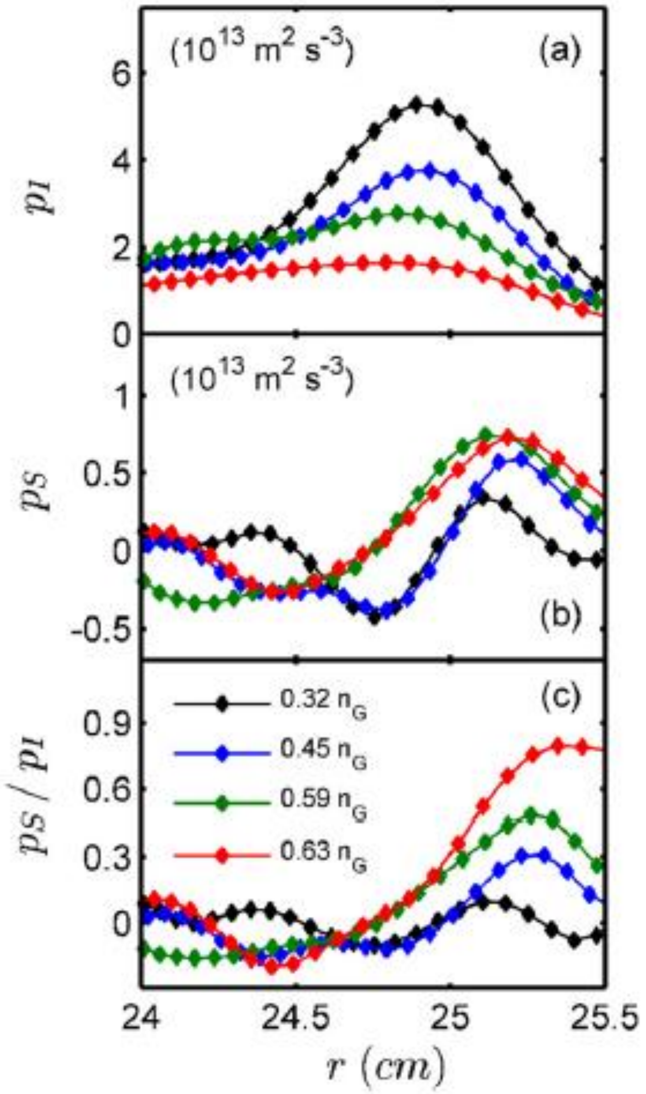
Fate of the Energy, Cont'd

- Turbulence Spreading !
  - Reynolds power drops
  - P_s increases; transitions $P_s < 0$ to $P_s > 0$
- Where does the shear layer energy go?

$(P_k/P_I)_{peak} \times (P_s/P_I)_{peak} \sim 0.3, 0.5, 0.4, 0.4 \times 10^{-3}$ as $n/n_G \uparrow$

$\approx$ constant

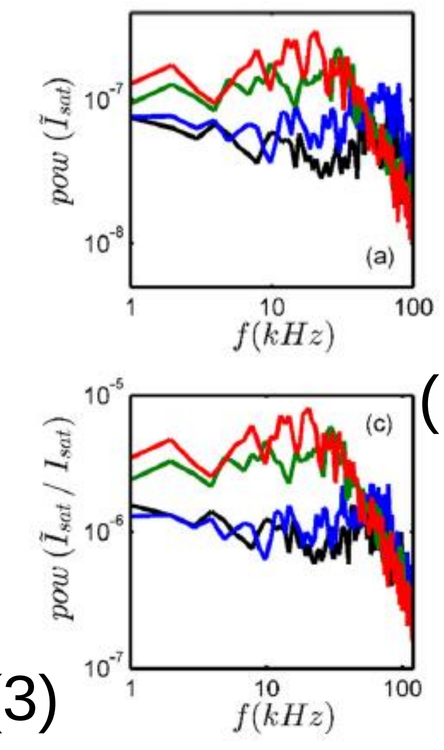
Energy diverted from shear layer to spreading at L→DL



Characteristics of Spreading

- Low frequency content of $\tilde{I}_{sat}/I_{sat}$ increases (1)
- $\tilde{I}_{sat}$ autocorrelation time increases (2)

Pdf $\tilde{I}_{sat}$ developes positive skewness as n/n_G increases (3)



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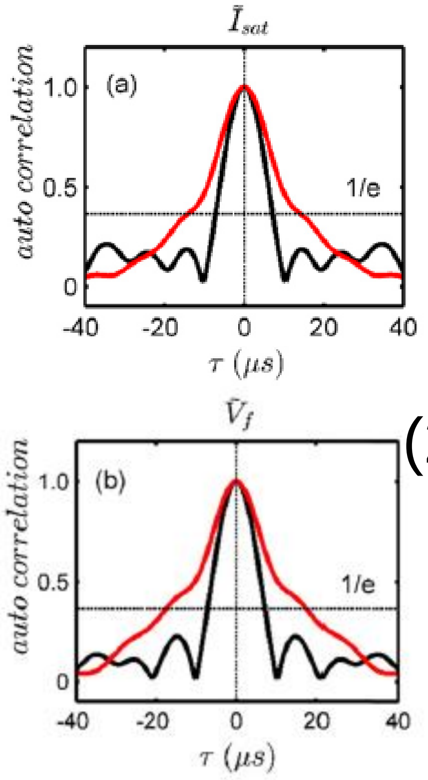

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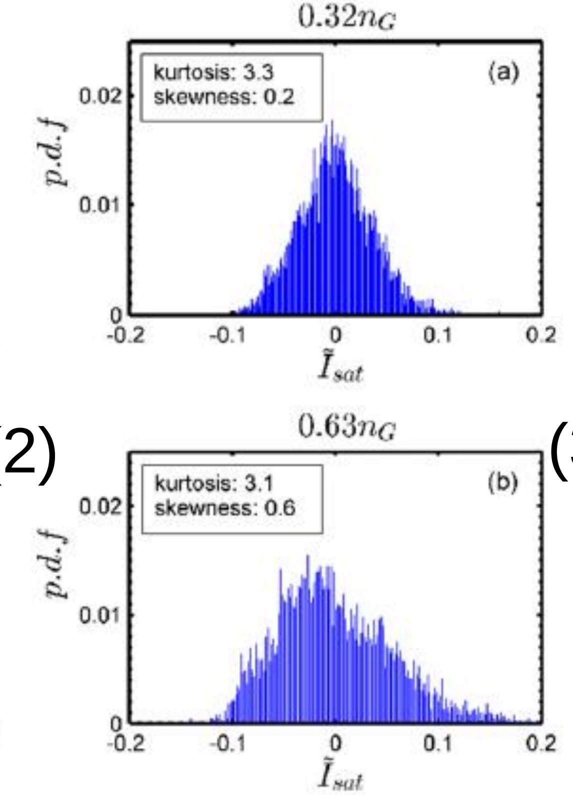


(3)

See also T. Long; AAPPS-DPP ‘22 for $\tilde{n}$ skewness ←→ spreading correlation

Characteristics of Spreading, Cont'd

- Enhanced turbulent particle transport events accompany L→DL back transition
- Events are quasi-coherent density fluctuations. Diffusive model of spreading dubious
- Localized over-turning events, small avalanches, "blobs", …

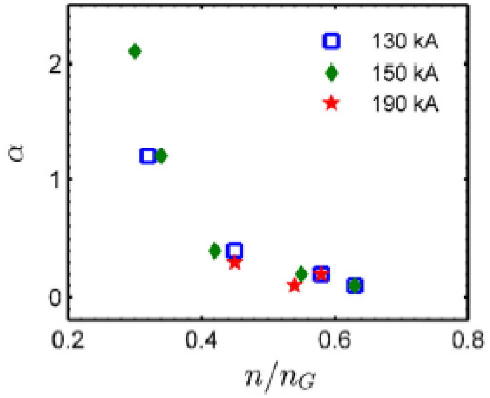
N.B. "The limits of my language means the limits of my world."

- Ludwig Wittgenstein

Is there a key parameter? – Adiabaticity!

- Adiabaticity $\alpha = k_{\parallel}^2 V_{the}^2 / \omega\nu$

  α drops < 1 as n/n_G increases

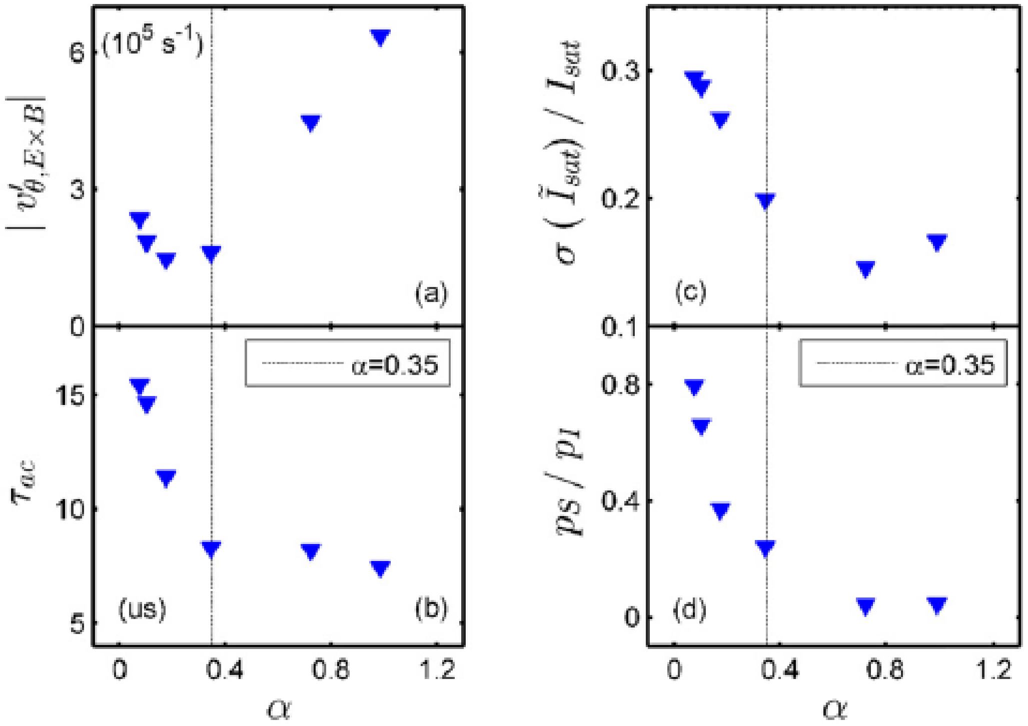


- V_E' rises with $\alpha \uparrow$

  τ_{ac} decreases with $\alpha \uparrow$

  $\sigma(\tilde{I})/I$ decreases with $\alpha \uparrow$

  P_s/P_I decreases with $\alpha \uparrow$

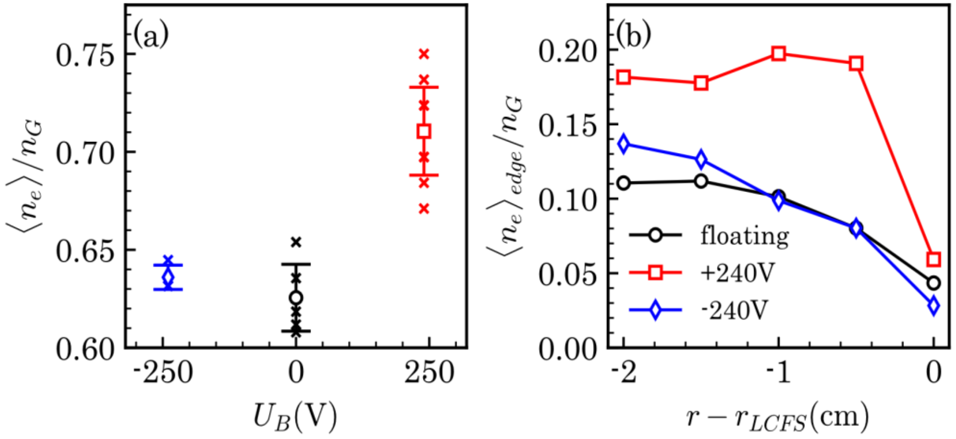


The Obvious Question

- Can driving the shear layer sustain high densities, where L→DL, otherwise ?
- “Driving” ⟶ bias electrode – here (J-TEXT) (c.f. Singh, P.D.)
- Long history of bias-driven shear layers in L→H saga – R.J. Taylor, et. seq.
- Recent: Shesterikov, Xu et. al. 2013 - Textor
- Electrode → $J_r \rightarrow V_\theta \rightarrow V_E'$ etc.
- New Here?
  - High Density
  - Gas Puffing → push on DL
  - Analysis

The Answer – Looks Promising!

- Edge density doubled for +240V bias



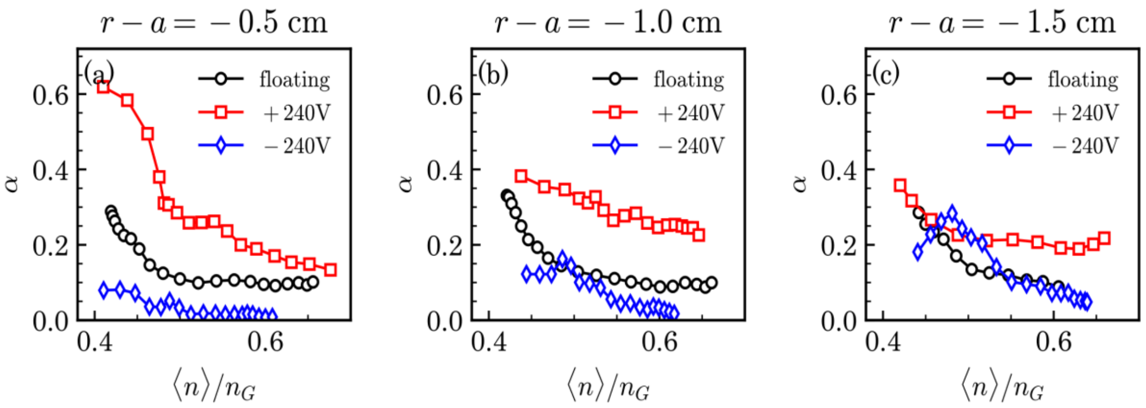
- $\bar{n}_{\text{max,bias}} > \bar{n}_{\text{max,float}}$

- Note: $\bar{n}_{\text{max,float}} \sim 0.7 n_G$

Experiment limited by graphite probe sputtering

- Key parameter?
  - – α systematically higher with +bias
  - – $\alpha \sim T^2/n$

Reduced transport → higher T



- Turbulence spreading quenched by positive bias

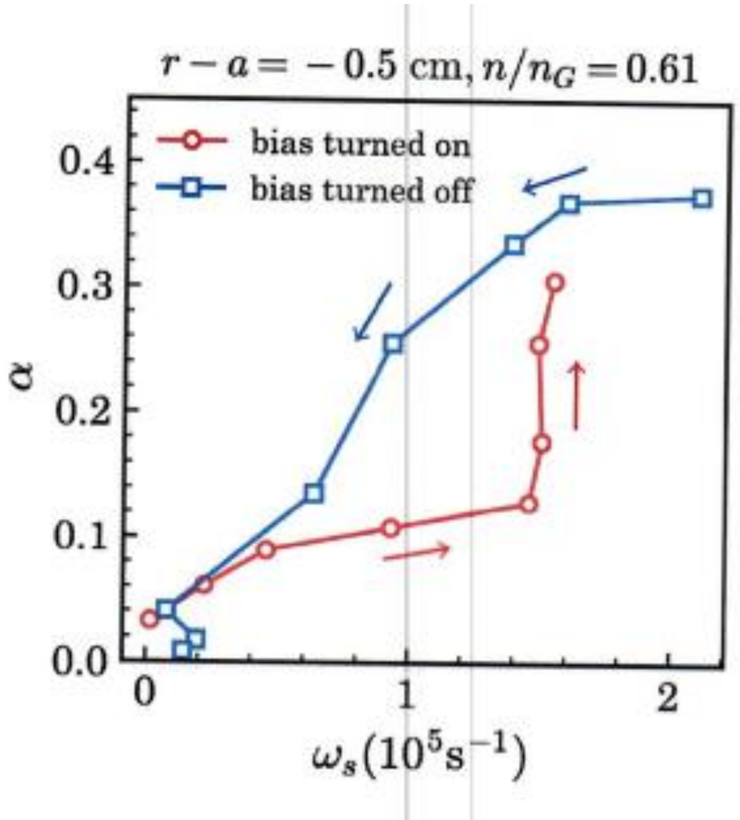
Key Parameter vs Control Parameters

- α vs ω_{shear} exhibits hysteresis loop
- Cntr clockwise rotation → ω_{shear} 'leads' α
- Is α unique 'key parameter'?
- For drift waves, $\alpha \sim T^2/n$

  → shear ↑ → turbulence ↓ → heat transport ↓

  → α increases

- Is ω_{shear} the control parameter?



Theory:

Desperately Seeking Greenwald

- How $\alpha > 1 \rightarrow \alpha < 1$ – Back-Transition Mechanism
- Origin of Current Scaling
- Dimensionless Parameter?

N.B. :
- Zonal flow collapse as $\alpha > 1 \rightarrow \alpha < 1$ well understood via wave energy-momentum flux connection (Hajjar, PD, Malkov 2018)
- See also Numata +, Ghantous +, Camargo + simulations

What of the Current Scaling?

- Obvious question: How does shear layer collapse scenario connect to Greenwald scaling $\bar{n} \sim I_p$?
- Key physics: shear/zonal flow response to drive is 'screened' by neoclassical dielectric

i.e. $-\ \epsilon_{neo} = 1 + 4\pi\rho c^2/B_\theta^2$

– ρ_θ as screening length

– effective ZF inertia lower for larger I_p

N.B.: Points to ZF response as key to stellarator.

Current Scaling, cont'd

- Shear flow drive:

emission from 'drift-mode' interaction → production

incoherent emission

S → polarization NL

$$\frac{d}{dt}\left[\left\langle\left(\frac{e\phi}{T}\right)^2\right\rangle_{ZF}\right] \approx \frac{\sum_k |S_{k,q}|^2 \tau_{c_{k,q}}}{|\epsilon_{neo}(q)|^2}$$

neoclassical response

  - Production ←→ beat drive
  - Response (neoclassical)

- Rosenbluth-Hinton '97 et seq (extended)

Increasing I_p decreases ρ_θ and off-sets weaker ZF drive

$$\left(\frac{e\hat{\phi}}{T}\right)_{ZF} \approx \int \frac{S_{k,q}}{\left(1 + 1.16\frac{(q(r))^2}{\epsilon^{1/2}}\right) q_r^2 \rho_i^2}\, dt$$

classical — neo — zonal wave #

Revisiting Feedback in Reduced Model (c.f. Singh, P.D. PPCF '21)

- How <u>combine</u> noise, neoclassical dielectric and feedback dynamics? → back to Predator-Prey…

Limiting reduction of complex ZF, corrugation evolution

shear, satn.

$$\frac{\partial E_t}{\partial t} = \gamma E_t - \sigma E_v E_t - \eta E_t^2$$

$$\frac{\partial E_v}{\partial t} = \sigma E_t E_v - \gamma_d E_v + \beta E_t^2$$

modulation growth, damping, <u>nonlinear noise model</u>

$$\sigma \sim \epsilon_{neo}^{-1} \sim B_\theta^2 \sim I_p^2$$

$$\beta \sim \epsilon_{neo}^{-2} \sim B_\theta^4 \sim I_p^4$$

} *

High B_θ enhances ZF coupling

High B_θ enhances "noise" for Z.F.

N.B.: I_p enhances modulational growth

Re: Developments:

- Zonal flow and turbulence <u>always</u> co-exist *
- Zonal flow energy increases with current
- Turbulence energy never reaches 'old' modulation threshold
- Zonal cross-correlation import TBD

cf: extends P.D. et. al. '94; Kim, PD '03

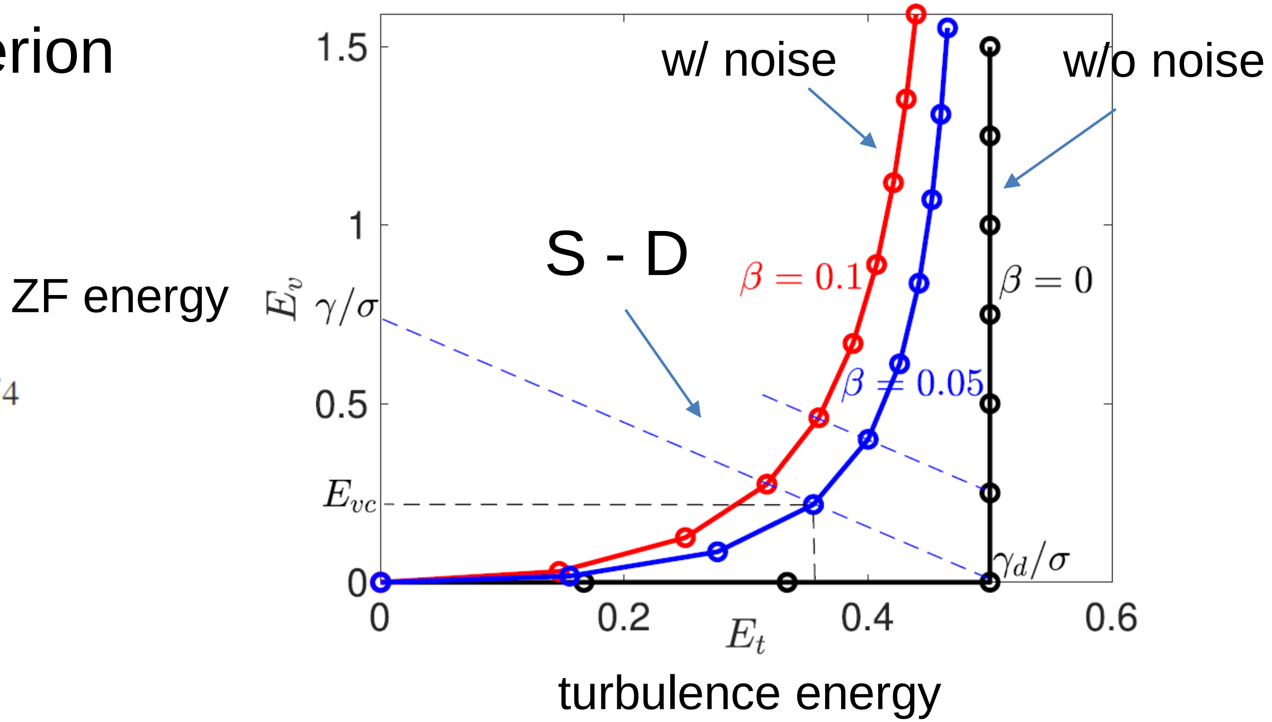
Criterion for Shear Layer Collapse

- For <u>collapse limit</u>, criterion without noise is good approximation to <u>with</u> noise
- Derive shear layer persistence criterion

$$\frac{\rho_s}{(\rho_\theta L_n)^{\frac{1}{2}}} > \text{crit.}$$

$$\text{crit.} = \left[\frac{\eta}{\Omega_i}\frac{\gamma_d}{2k_x^2\rho_s^2\Theta\Omega_i^2}\frac{\hat{\alpha}}{q_\perp^2\rho_s^2}\frac{\left(1+q_\perp^2\rho_s^2\right)^3}{q_y^2\rho_s^2}\right]^{1/4}$$

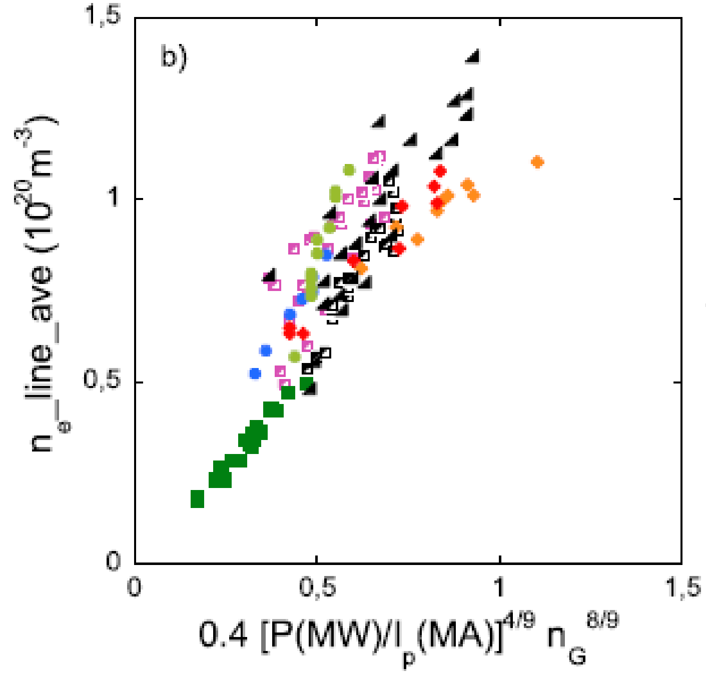
➔ Dimensionless parameter $\frac{\rho_s}{(\rho_\theta L_n)^{\frac{1}{2}}}$



Larger B_θ enhances persistence of ZF

Power Scaling and Physics of L-mode Density Limit (Singh, P.D. PPCF 2022)

- Power Scaling is an old story, keeps returning
- Zancat (2019) fits ➔ $\bar{n} \sim P^{1/4}$



Zanca +

- Ricci + Simulations…
- $Q_i|_{\text{bndry}}$ will drive shear layer → LH mechanism
- $P_{\text{scaling}} \leftrightarrow$ shear layer physics?

Expanded Kim-Diamond Model

- KD '03 – useful model of L→H dynamics
- See also Miki, P.D. et al '12, et. seq.
- Evolve $\varepsilon, V_{ZF}, n, T_i$

←→

- Treats mean and zonal shearing
- Separates density and temperature contributions to P_i
- Heat and particle sources

$$\frac{\partial \mathcal{E}}{\partial t} = \frac{a_1 \gamma(\mathcal{N}, \mathcal{T}) \mathcal{E}}{1 + a_3 \mathcal{V}^2} - a_2 \mathcal{E}^2 - \frac{a_4 v_z^2 \mathcal{E}}{1 + b_2 \mathcal{V}^2}$$

$$\frac{\partial v_z^2}{\partial t} = \frac{b_1 \mathcal{E} v_z^2}{1 + b_2 \mathcal{V}^2} - b_3 n v_z^2 + b_4 \mathcal{E}^2$$

$$\frac{\partial \mathcal{T}}{\partial t} = -c_1 \frac{\mathcal{E} \mathcal{T}}{1 + c_2 \mathcal{V}^2} - c_3 \mathcal{T} + Q$$

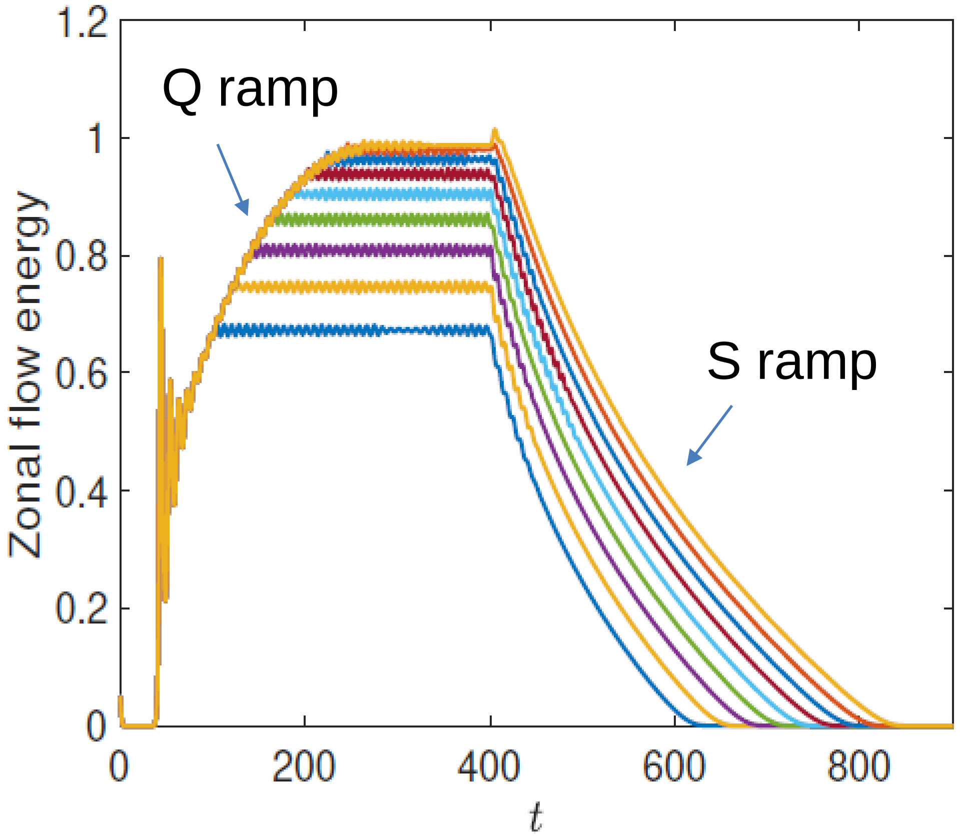
$$\frac{\partial n}{\partial t} = -d_1 \frac{\mathcal{E} n}{1 + d_2 \mathcal{V}^2} - d_3 n + S$$

$$V_E' = -\rho_i v_{thi} L_n^{-1} (L_n^{-1} + L_T^{-1})$$

$$\mathcal{V} \equiv \frac{V_E' a}{\rho^* v_{thi}} = -\frac{n_0}{n} \mathcal{N} \left(\frac{n_0}{n} \mathcal{N} + \frac{T_0}{T} \mathcal{T} \right)$$

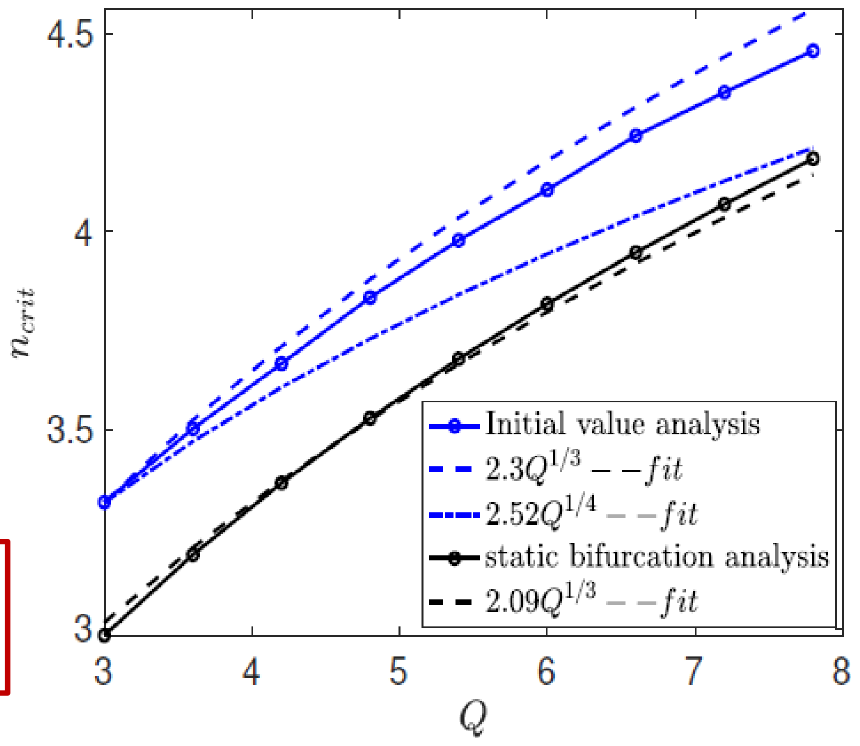
L → DL Studies: Shear Layer Physics ←→ Power Scaling

- Look for shear layer collapse
- Q ramp-up to L-mode, followed by S ramp-up
- Oscillations → predator-prey
- n for ZF collapse increases with S
- Q scaling n_{crit} emerges



Power Scaling

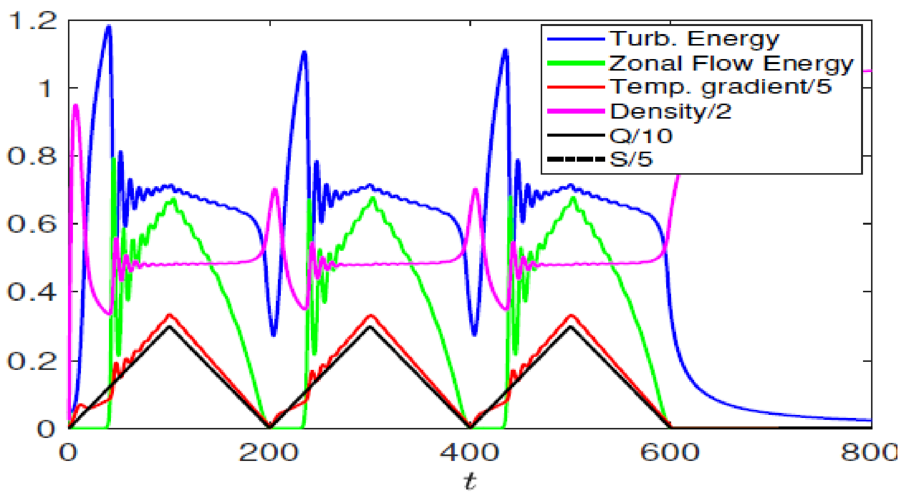
- $n_{\text{crit}} \sim Q^{1/3}$
- Distinct from Zanca, but close (model)
- In K-D, with neoclassical screening $n_{crit} \sim I_p$
- Physics is $\gamma(\nabla T)$ vs ZF damping
- Shear layer drive underpins power scaling

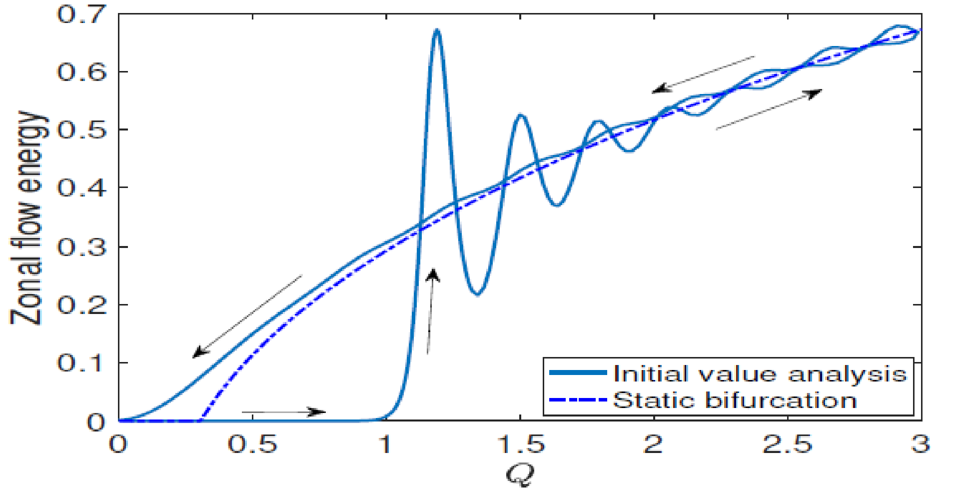


If it Flux Like a Duck… (M.N. Rosenbluth, after F. Wagner)

- Hysteresis ! in ε_{ZF} vs Q → Critical slowing down effect
- Expected, given 2 states transport
- Not familiar bistability !
- Physics prediction… beyond scaling
- Is there torque scaling of density limit, i.e.

  $\nabla P/n$ vs $B_\theta V_\phi$?





From L-DL to H-DL

- H-mode density limit is back transition H→L at high density, usually followed by progression to $n_{\mathrm{Greenwald}}$
- Key issue ! N.B. gentle “pump-and-puff” (Mahdavi) has beat Greenwald ←→ strong shear layer…
- Candidates
  - AUG: α_{MHD} at separatrix (Eich, Manz)
  - Goldston, Brown: Conduction broadens SOL, reduces V_E' →

$$\lambda:\ v_D * \begin{cases} \tau_T \\ \tau_{\mathrm{cond}} \end{cases}$$

So – instability calculated & inward spreading hypothesized

$$\gamma = c_s/(\lambda R)^{1/2} - \phi/\lambda^2$$

- Experiments needed!

c.f. Dog + Tail ? → track inward spreading ?!

Conclusions: V_E' as Edge Order Parameter

- Density limits as back-transition phenomena; V_E' physics crucial
- L-DL mechanism:
  - Shear layer collapse
  - Strong turbulence spreading
- α is key parameter, but not only
- Scalings of L-DL merge from zonal flow physics
  - I_p scaling → neo dielectric
  - P scaling → Reynolds stress, radial force balance
- Novel hysteresis evident in L-DL dynamics
- H→DL back transition triggers unclear

←→ Lessons from L→H transition broadly applicable !

Thank You !

Back-Up

Preview: A Developing Story

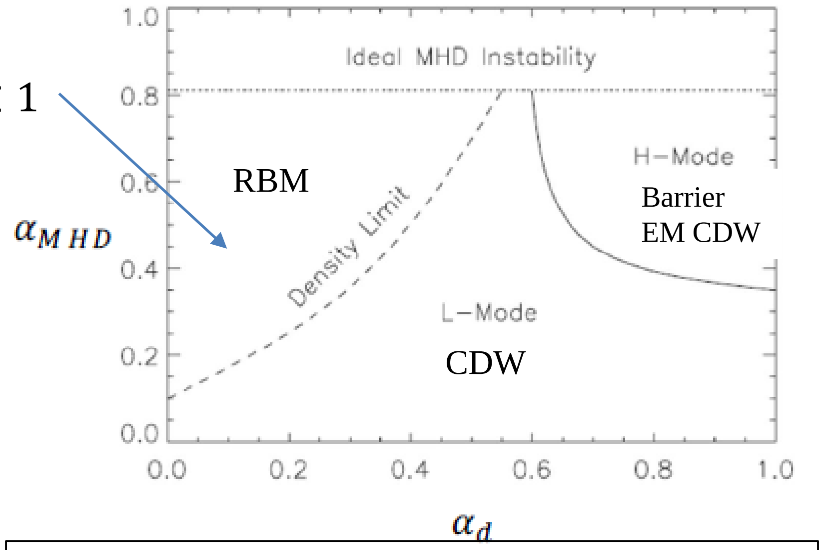
From Linear Zoology to Self-Regulation and its Breakdown

1-mode per regime

(Drake and Rogers, PRL, 1998)

$\alpha < 1$

$$\alpha = \frac{k_\parallel^2 V_{the}^2}{\omega \nu}$$



- $\alpha_{MHD} = -\frac{Rq^2 d\beta}{dr} \rightarrow \nabla P$ and ballooning drive to explain the phenomenon of density limit.
- Invokes yet another linear instability of RBM.
- What about density limit phenomenon in plasmas with a low β?

(Hajjar et al., PoP, 2018)

State	Electrons	Turbulence Regulation
Base State - *L*-mode	Adiabatic or Collisionless $\alpha > 1$ Weak damping	Secondary modes (ZFs and GAMs)
H-mode	Irrelevant	Mean ExB shear ∇Pi/n
Degraded particle confinement (Density Limit)	Hydrodynamic $\alpha < 1$ or damped	None - ZF collapse due weak production

→ I-mode

Secondary modes and states of particle confinement

L-mode: Turbulence is *regulated* by shear flows, but not suppressed.
H-mode: *Mean ExB* shear ↔∇p_i suppresses turbulence and transport.
Density Limit: High levels of turbulence and particle transport, as shear flows collapse.

Unified Picture ➔

i.e. Shear Flow: Density Limit > | < L-mode > | < H-mode
Weak (none) | Modest | Strong Mean

Edge shear – as – order parameter

L➔DL as a "back-transition"!?

A Brief History of Density Limits → Conventional Wisdom

- High density → edge cooling (transport?!)
- Cooling edge → MARFE (Multi-faceted Axisymmetric Radiation from the Edge) by Earl Marmar and Steve Wolfe

  MARFE = Radiative Condensation Instability in Strong B_0

  after G. Field '64, via J.F. Drake '87 : Anisotropic conduction is key
- MARFE → Contract J-profile → Tearing, Island … → Disruption

  after: Rebut, Hugon '84, … , Gates …
- But: more than macroscopics going on…

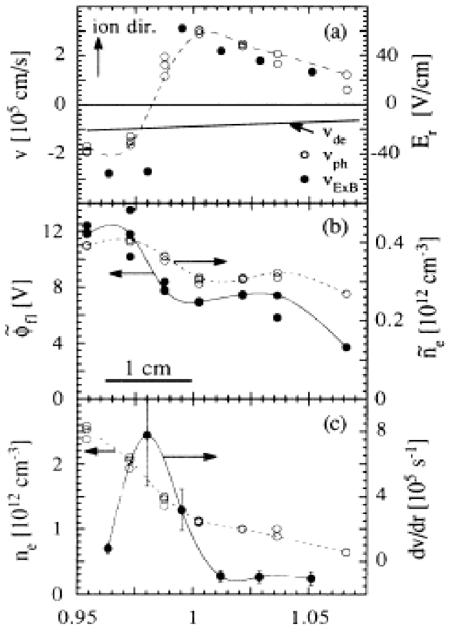
Shear Layer in L-mode?

- Shear layer impacts/regulates edge turbulence even in Ohmic/L-mode, enhanced in H-mode
- Ritz, et. al. 1990

v_{ph} - closed

v_{pl} - open

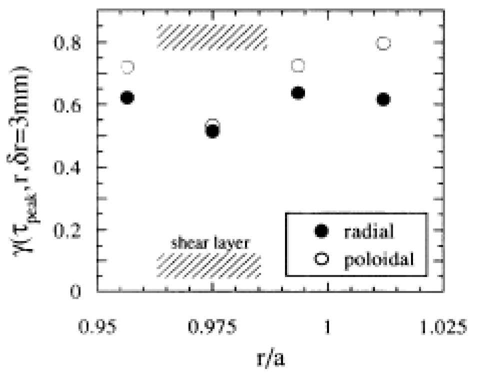
density



V'

FIG. 1. Radial profiles for a discharge with $B_\phi = 2$ T, plasma current of 200 kA, and chord-averaged density of $n_{chord} = 2\times10^{13}$ cm^{-3}. (a) Phase velocity of the fluctuations v_{ph} (closed circles), $v_{E_r\times B}$ plasma rotation (open circles), and drift velocity v_{de}. (b) Density and floating potential fluctuations. (c) Density and velocity shear. The statistical error for individual shots is of order the symbol size and shot-to-shot reproducibility is given by the individual symbols. The systematic error in the plasma position is 0.5 cm or $r/a \simeq 0.02$.

Shear layer



Peak

correlation

FIG. 3. Peak values of the normalized two-point correlation function for poloidally and radially separated probes with fixed separations of $\delta r = 3$ mm.

Title: “Evidence for Confinement Improvement by Velocity Shear Suppression of Edge Turbulence”

n.b. not H-mode!

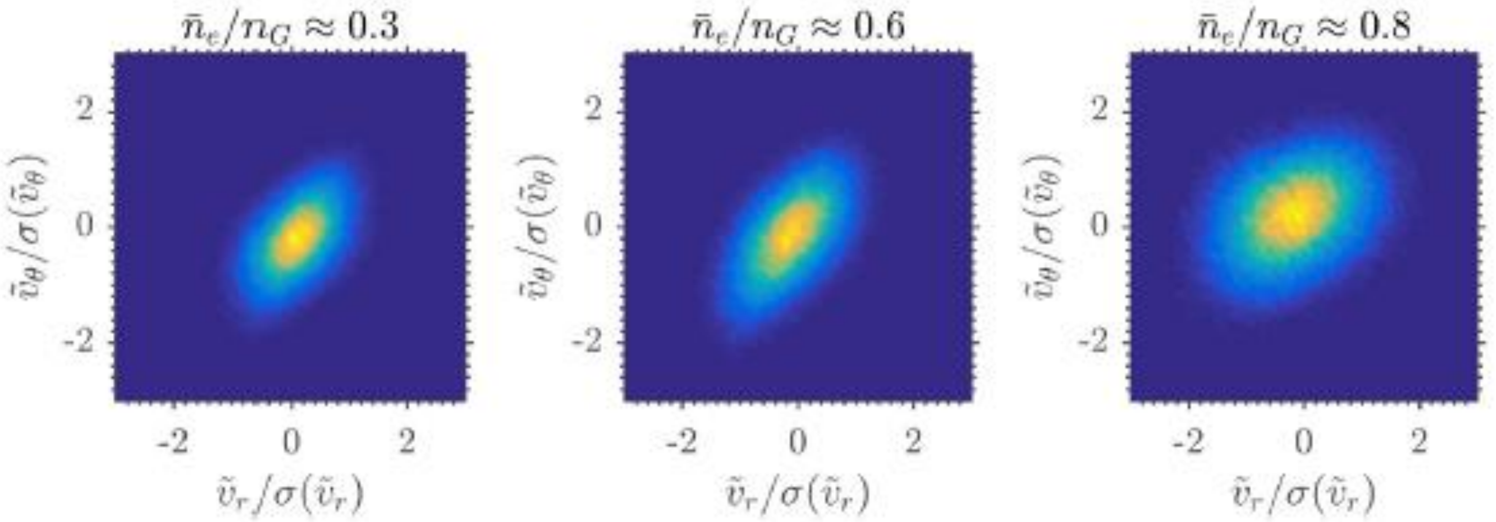
➔ Role of Shear Layer in L→DL ?

Fluctuation + n/n_G $scan$, R. Hong et. al. (NF 2018)

Distribution

Fluctuating

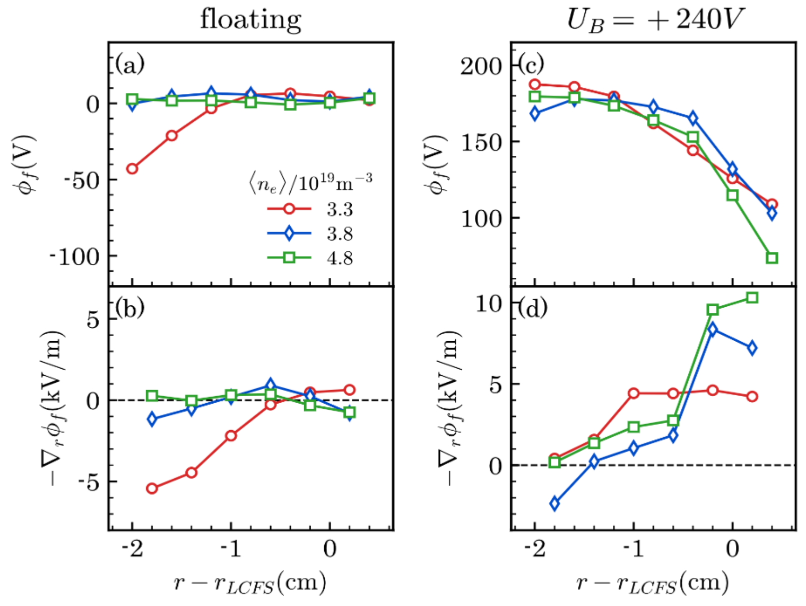
Velocities



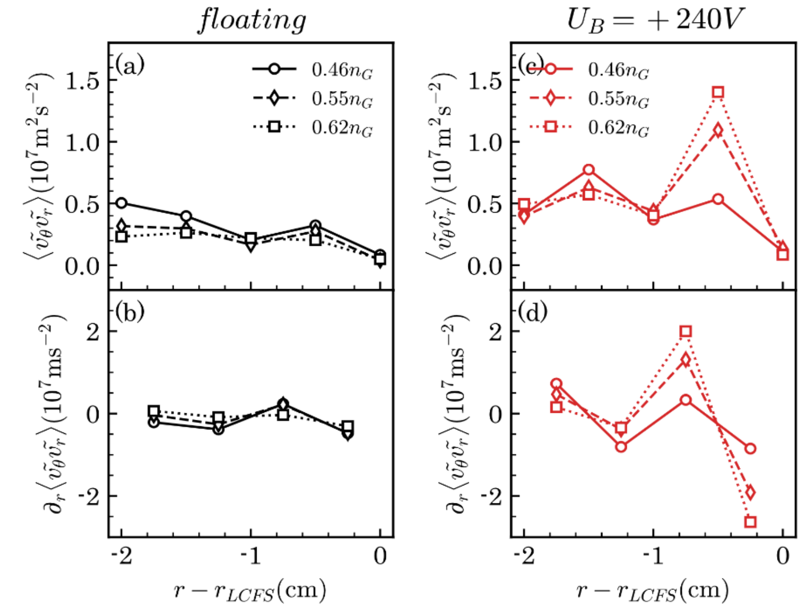
- Joint pdf of $\tilde{V}_r, \tilde{V}_\theta$ for 3 densities, $\bar{n} \to n_G$
- $r - r_{sep} = -1cm$
- Note:
  - Tilt lost, symmetry restored as $\bar{n} \to \bar{n}_g$ ➔ Weakened shear flow production by Reynolds stress as $n \to n_g$
  - Consistent with drop in P_{Re} observed

The Physics

- Edge Shear Layer produced for +bias

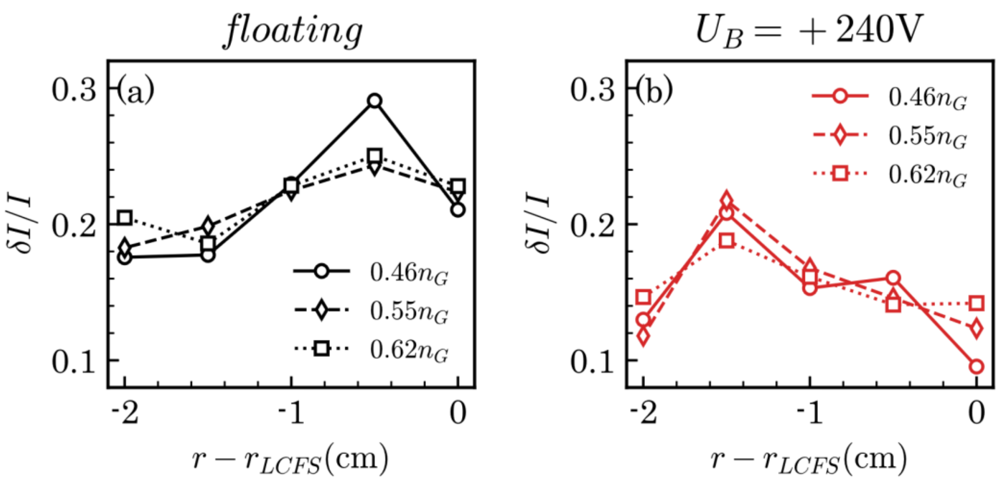


- Reynolds stress, force increase for +bias

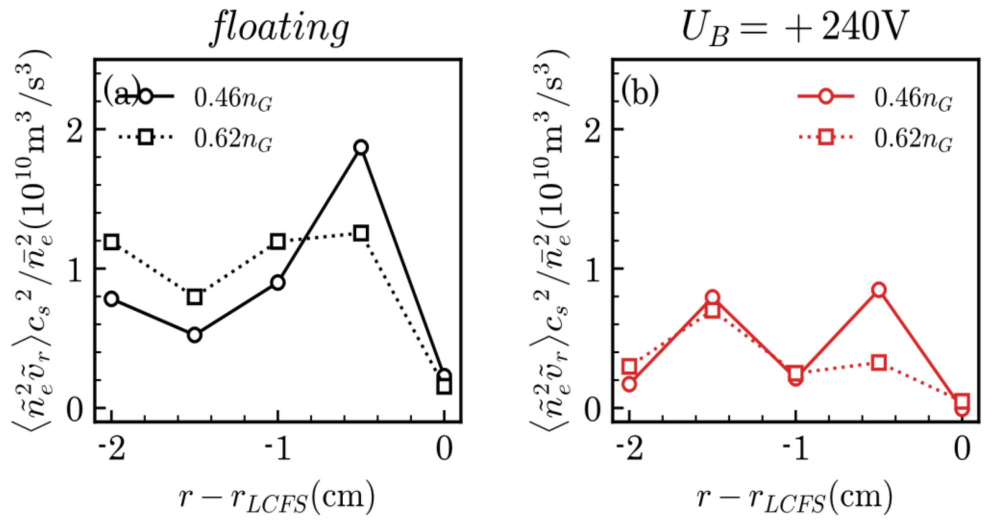


The Physics

- $\delta I/I$ $(\rightarrow \tilde{n}/n)$ fluctuations sharply reduced by +bias



- Turbulence spreading quenched by +bias

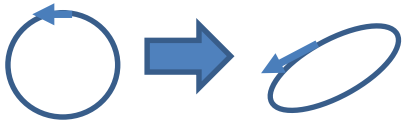


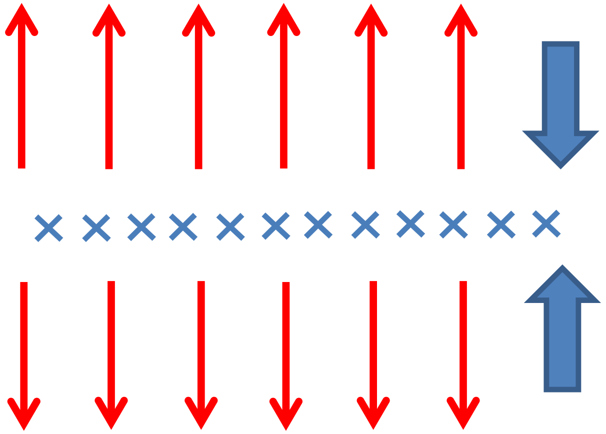
Step Back: Zonal Flows Ubiquitous! Why?

- Direct proportionality of wave group velocity and wave energy density flux

  to Reynolds stress ←→ spectral correlation $\langle k_x k_y \rangle$

  Causality ←→ Eddy Tilting

  i.e. 



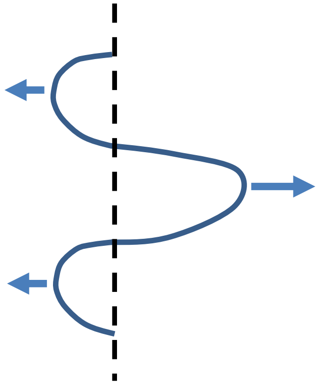
$\omega_k = -\beta \, k_x / k_\perp^2$: (Rossby)

➔ $V_{g,y} = 2\beta \, k_x k_y / (k_\perp^2)^2$

➔ $\langle \tilde{V}_y \tilde{V}_x \rangle = -\sum_k k_x k_y |\phi_k|^2$

So: $V_g > 0 \; (\beta > 0)$ ←→ $k_x k_y > 0$ ➔ $\langle \tilde{V}_y \tilde{V}_x \rangle < 0$

Propagation ←→ Stress



- Outgoing waves generate a <u>flow convergence</u>! ➔ <u>Shear layer spin-up</u>

But NOT for hydro convective cells: (i.e. $\alpha < 1$)

- $\omega_r = \left[\frac{|\omega_{*e}|\hat{\alpha}}{2k_\perp^2\rho_s^2}\right]^{1/2}$ → for convective cell of H-W (enveloped damped)
- $V_{gr} = -\frac{2k_r\rho_s^2}{k_\perp^2\rho_s^2}\,\omega_r$ ←??→ $\langle\tilde{V}_r\tilde{V}_\theta\rangle = -\langle k_r k_\theta\rangle$; direct link broken!

→ Energy flux NOT simply proportional to Momentum flux ➔

↓

→ Eddy tilting ($\langle k_r k_\theta\rangle$) does <u>not</u> arise as direct consequence of causality

➔ ZF generation <u>not</u> 'natural' outcome in hydro regime!

➔ <u>Physical</u> picture of shear flow collapse emerges, as change in branching ratio of vorticity flux to particle flux as α drops

Simulations !?

- Extensive studies of Hasegawa-Wakatani system for $k_{\parallel}^2 V_{the}^2/\omega\nu < 1, > 1$ regimes.

  i.e. Numata, et al '07

  Gamargo, et al '95

  Ghantous and Gurcan '15

  + many others

- All note weakening or collapse of ordered shear flow in hydrodynamic regime ($k_{\parallel}^2 V_{the}^2/\omega\nu < 1$), which resembles 2D fluid/vortex turbulence – i.e. $\alpha < 1$
- Physics of collapse left un-addressed, as adiabatic regime ($k_{\parallel}^2 V_{the}^2 \omega/\nu$) dynamics of primary interest – ZFs
- Shear Layer Collapse $\leftrightarrow$ $\alpha < 1$ Generic

➔

Screening in the Plateau Regime!? (Relevant) N.B. Ions!

$$\left(\frac{\phi_k(\infty)}{\phi_k(0)}\right)^{ZF} = \frac{\epsilon^2/q(r)^2}{\left(\epsilon/q(r)\right)^2 + L} \approx \frac{\epsilon^2/q(r)^2}{L} = \frac{1}{L}\left(\frac{B_\theta}{B_T}\right)^2$$

$$L = \frac{3}{2}\int_0^{1-\epsilon} d\lambda \frac{\int d\theta}{2\pi} h^2 \rho \approx 1 - \frac{4}{3\pi}(2\epsilon)^{3/2}$$

- Favorable I_p scaling of time asymptotic RH response persists in plateau regime. Robust trend.
- Compare to Banana ($L = 1$);

$$\left(\frac{\phi_k(\infty)}{\phi_k(0)}\right)^{ZF} = \left(\frac{B_\theta}{B_T}\right)^2$$

Current scaling but smaller ratio

Speculations

- Is H-DL due turbulent degradation of V_E' in pedestal? Mechanism?
- Can external means (NTV?) be used to enhance edge density?
- Collisionless regimes? - $\nabla \mathrm{n}$ TEM
- D-L-H triple point, ala' phase transitions?
- New states:
  - Fusion power + L-mode $n_{\mathrm{crit}}(Q)$?
  - Neg. Tri. ?

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A Look at Density Limit Phenomenology

→ Greenwald Limit

$\bar{n} = \bar{n}_G \sim I_p/\pi a^2$

→ Line averaged

→ Critical to ITER, CFETR, FPP, …

Coming Attractions

- Re-visit bias experiment with tungsten probe +
- Slow bias ramp ↑↓ → causality, hysteresis
- I_p ramp down (M. Greenwald)
- Theory

Some Theoretical Matters

Current Scaling, cont'd

$$\left(\tilde{V}_E'\right)_Z \approx \frac{S_{k,q}}{\left[\rho_i^2 + 1.6\epsilon_T^{\frac{3}{2}}\rho_{\theta i}^2\right]} \sim P\,\frac{\left(\frac{e\phi}{T}\right)^2}{\rho_{\theta i}^2} \sim B_\theta^2\, P\,\left(\frac{e\phi}{T}\right)_{DW}^2$$

production factor

Production $\leftrightarrow \tau_c$

- <u>Higher current strengthens ZF shear</u>, for fixed drive
- Can "prop-up" shear layer vs weaker production
- Collisionality? – Edge of interest!?