Electric Field Profile as the Order Parameter for the Edge Plasma: From L→H Transition to Density Limit

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<u>Or</u>

How the Birth and DEATH of Shear Layers Determines Confinement Transitions

→ Transport Physics of Density Limit

<u>Or</u>

Old L→H Wine in New Bottles

Collaborators:

Theory: Rameswar Singh, R. Hajjar, M. Malkov

(NF 2021, PoP 2018, PPCF 2021, NF – in preparation)

Experiments: Ting Long, Rui Ke, and J-TEXT and SWIP Teams
Rongjie Hong, G. Tynan and HL-2A Teams

(NF 2021, NF 2018, NF – submitted 2022)

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Outline

- 40 years of H-mode → the Lessons
- ‘Phases’ and Transitions of the Edge plasma → V_E' as Order Parameter
- OV of Density Limit Phenomenology (L-mode)
- Reality: Some Recent Experiments
- Theory: L→ DL-Back Transition Model, Power Scaling Physics (K-D returns!)
- The H-mode Density Limit – Thoughts
- Conclusion

40 Years of H-mode - Lessons

- Saved MFE from Goldston scaling

Also:

- 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
- Need for transport regulation, not transport elimination

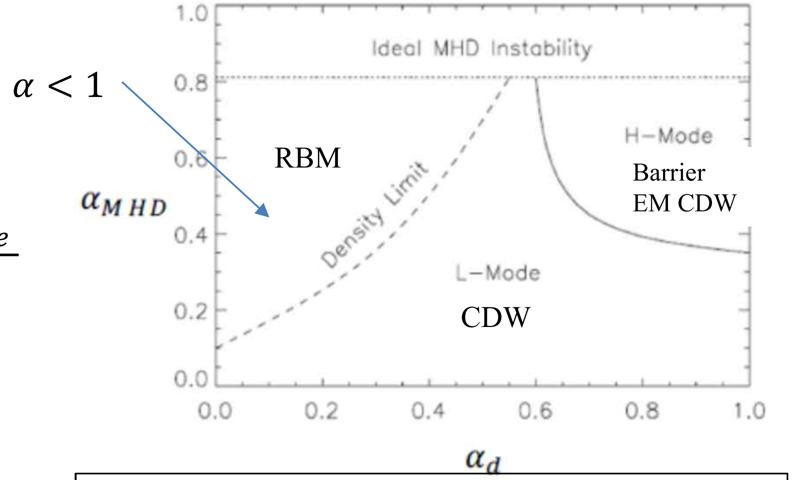
Phases and Transitions of the Edge Plasma

Preview: A Developing Story

From Linear Zoology to Self-Regulation and its Breakdown

1-mode per
regime

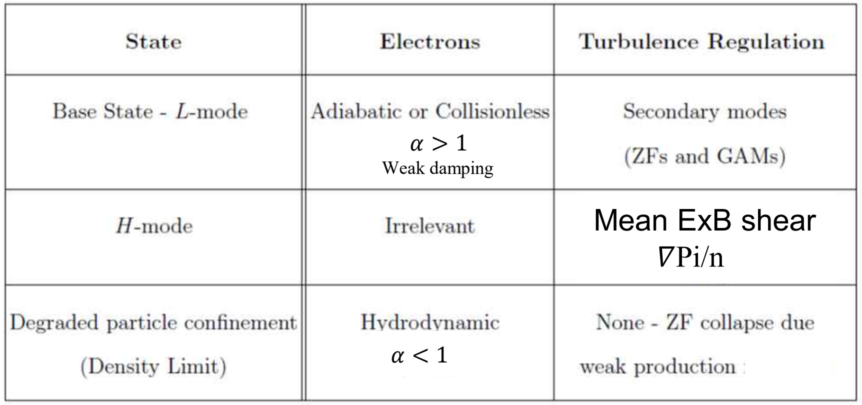
(Drake and Rogers, PRL, 1998)



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

- $\alpha_{M\,HD} = -\frac{Rq^2 d\beta}{dr} \longrightarrow$ ▽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)



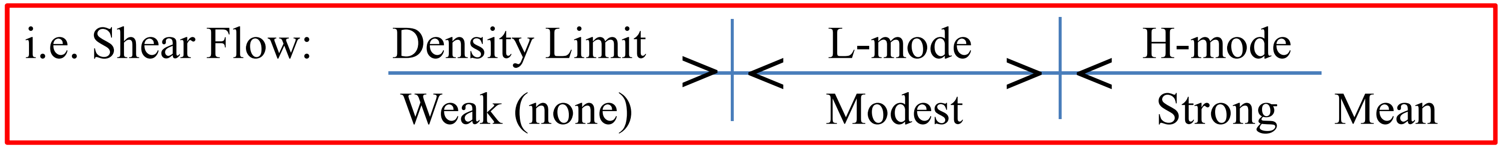
State	Electrons	Turbulence Regulation
Base State - *L*-mode	Adiabatic or Collisionless $\alpha > 1$ Weak damping	Secondary modes (ZFs and GAMs)
H-mode	Irrelevant	Mean ExB shear ∇Pi/n
Degraded particle confinement (Density Limit)	Hydrodynamic $\alpha < 1$	None - ZF collapse due weak production

→ 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"!?

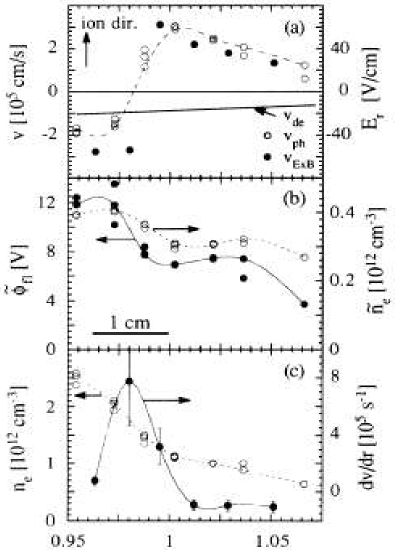
Shear Layer in L-mode?

- 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

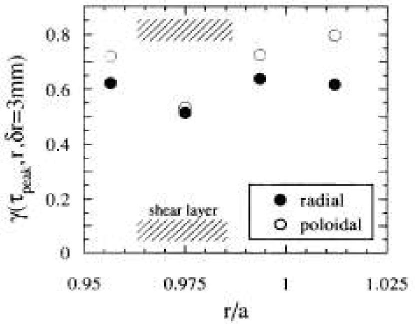
density



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), $v_{E,\times B}$ 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 $r/a\simeq0.02$.

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 ?

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, …

A Brief History of Density Limits
→ Conventional Wisdom

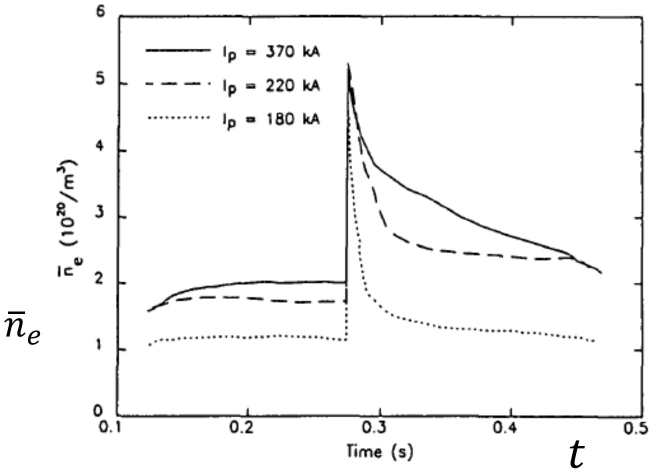
- High density → edge cooling (transport?!)
- Cooling edge → MARFE (Multi-faceted Axisymmetric Radiation from the Edge) by Earl Marmar and Steve Wolfe

  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…

- 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)

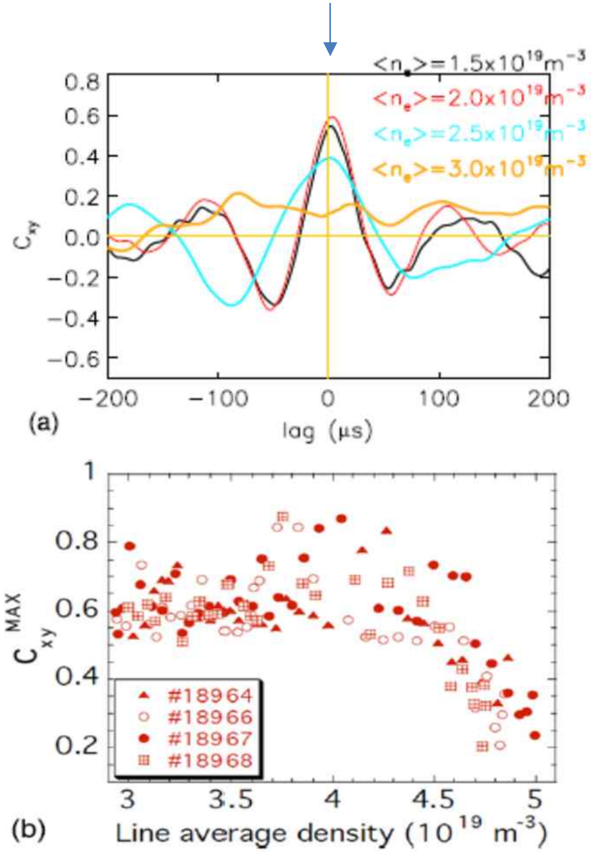


(Alcator C)

- 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?!

↓

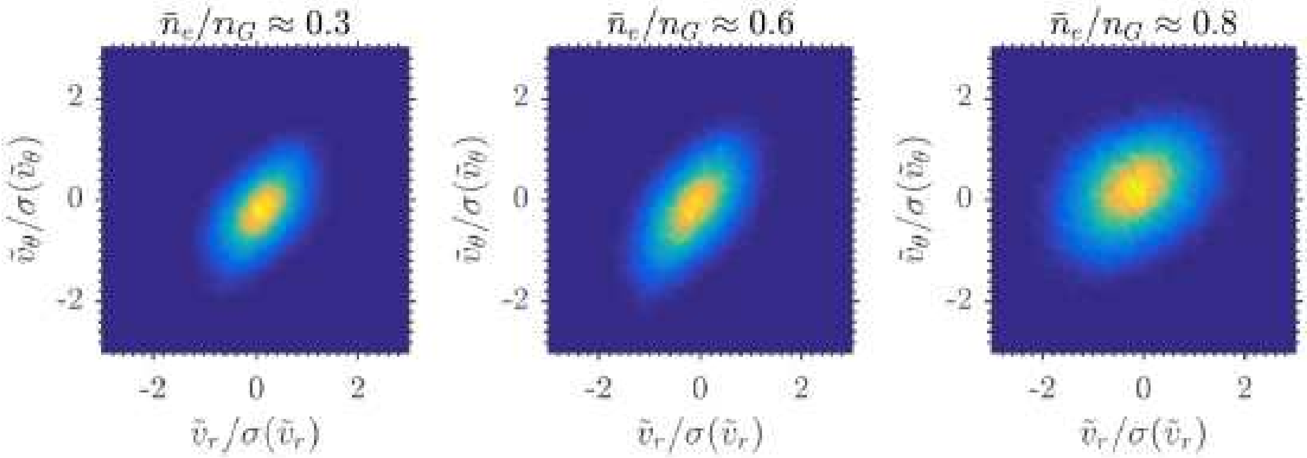
Yes !

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

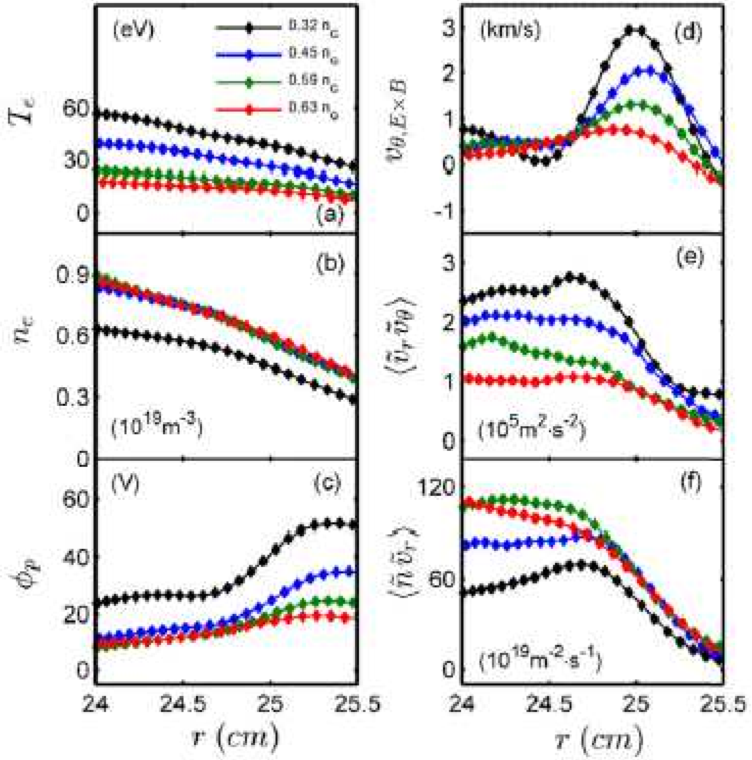
An In-depth Look at New Experiments

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

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

J-TEXT – Ohmic

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



Mean-Turbulence Couplings

- In standard CDW model:

Production ≡ Input from ∇n

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

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

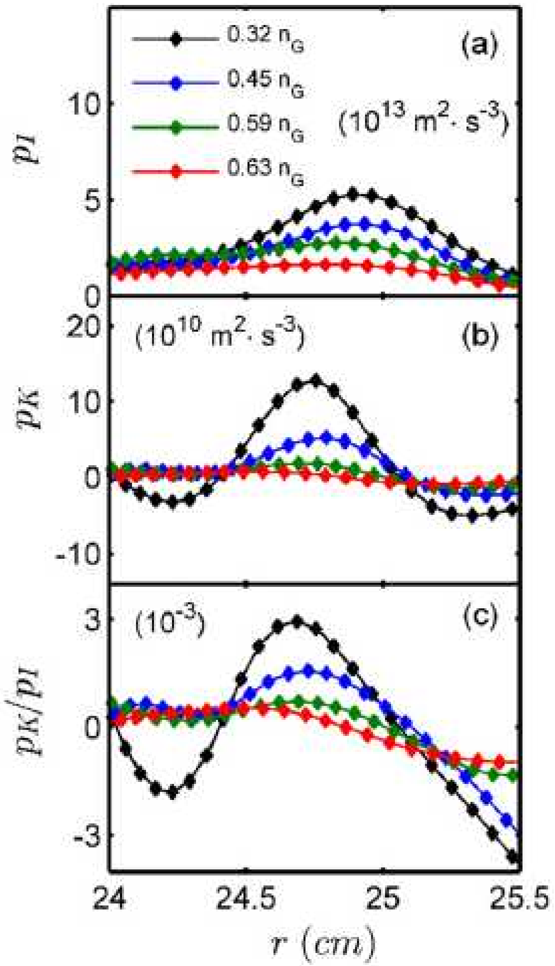
Reynolds Power ≡ Coupling to Zonal Flow

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

– 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 internal energy flux → Turbulence spreading

$$\boxed{P_S = -\partial_r \langle \tilde{v}_r \varepsilon_I \rangle = -\partial_r \langle \tilde{v}_r \tilde{n}^2 c_s^2 \rangle / 2n^2} \longrightarrow \text{Turbulence Spreading Power}$$

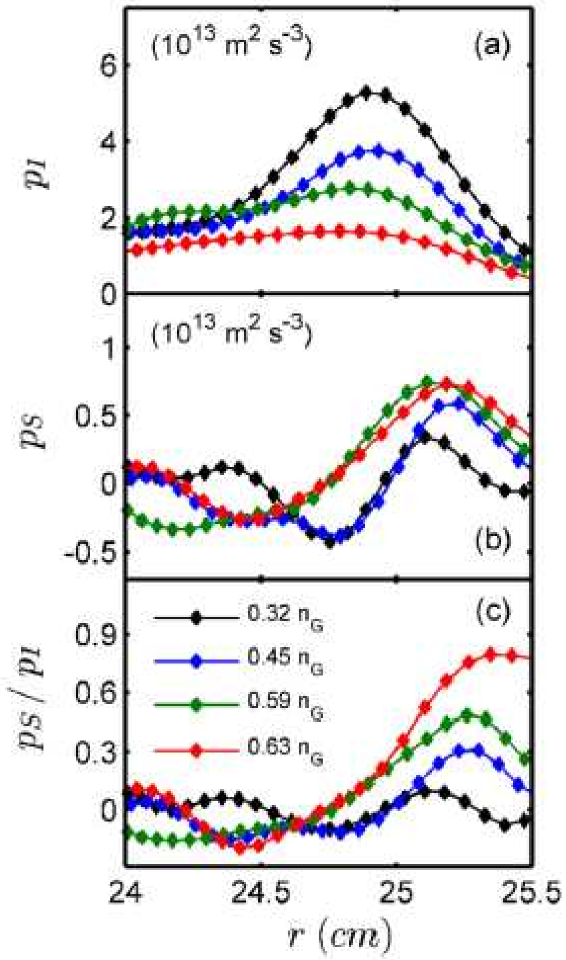
Fate of the Energy, Cont'd

- Turbulence Spreading !
  - 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

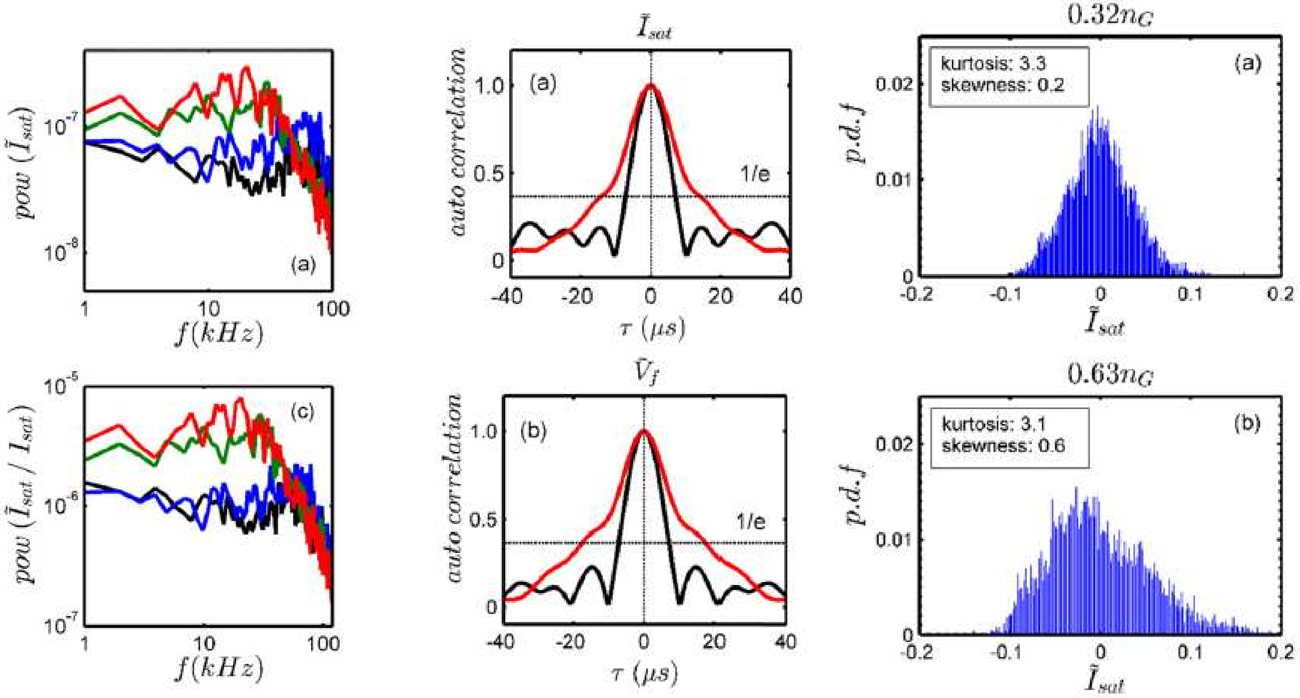
Energy diverted from shear layer to spreading at L→DL



Characteristics of Spreading

- Low frequency content of $\tilde{I}_{\mathrm{sat}}/I_{\mathrm{sat}}$ increases
- $\tilde{I}_{\mathrm{sat}}$ autocorrelation time increases

Pdf $\tilde{I}_{\mathrm{sat}}$ develops positive skewness as n/n_G increases



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 $\alpha \;=\; k_\parallel^2 V_{the}^2\,/\omega\nu$

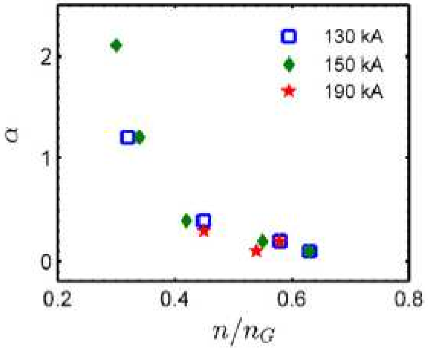
  α drops < 1 as n/n_G increases

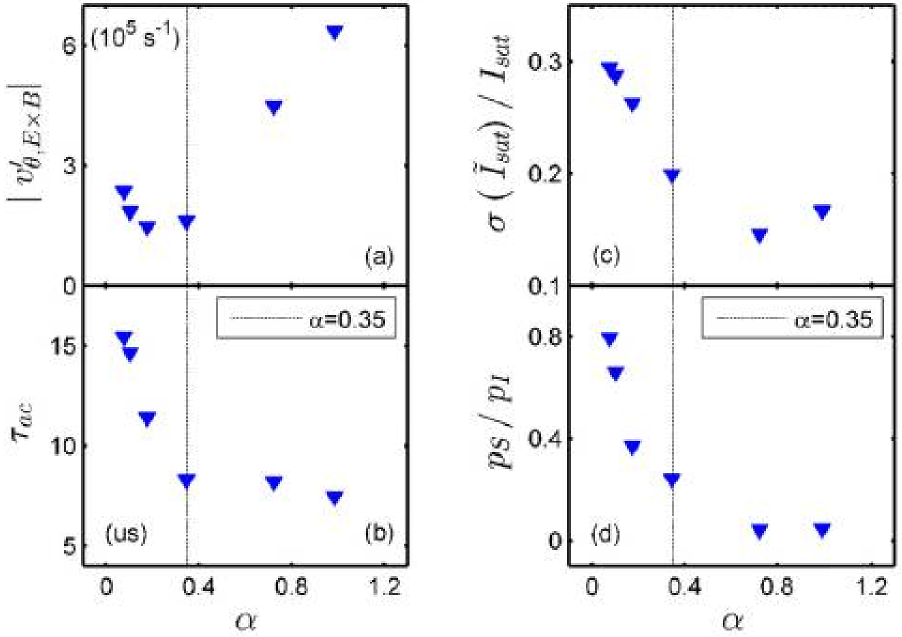
- V_E' rises with $\alpha\uparrow$

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

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

  P_s/P_I decreases with $\alpha\uparrow$

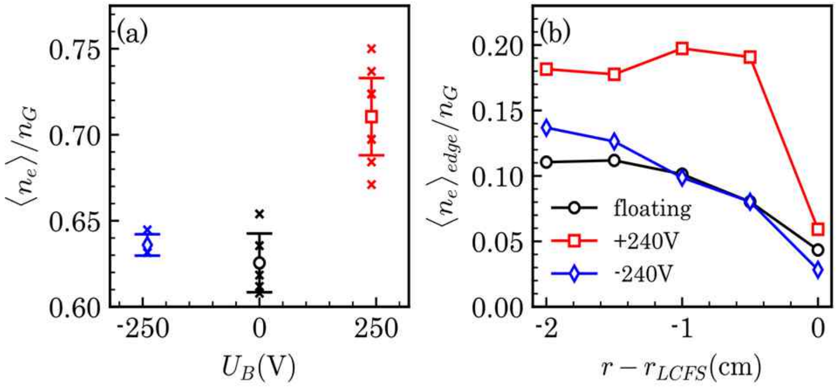




The Obvious Question

- Can driving the shear layer sustain high densities, where L→DL, otherwise ?
- "Driving" → bias electrode – here (J-TEXT)
  - → power scan → Theory (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

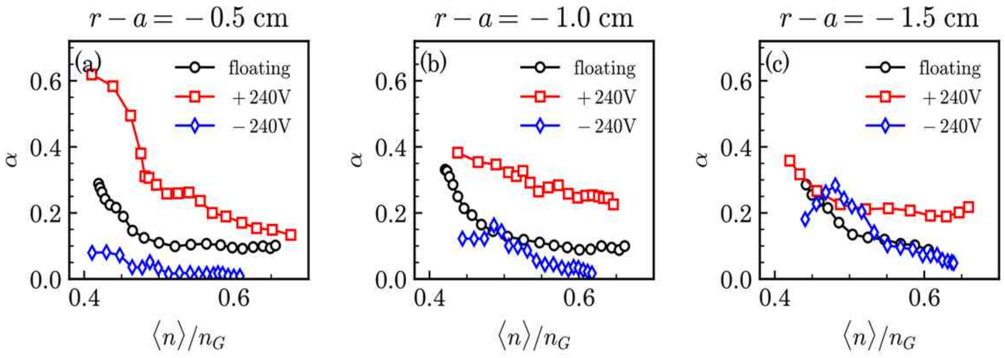
The Answer – Looks Promising!



- Edge density <u>doubled</u> for +240V bias
- $\bar{n}_{\max,\text{bias}} > \bar{n}_{\max,\text{float}}$
- Note: $\bar{n}_{\max,\text{float}} \sim 0.7 n_G$

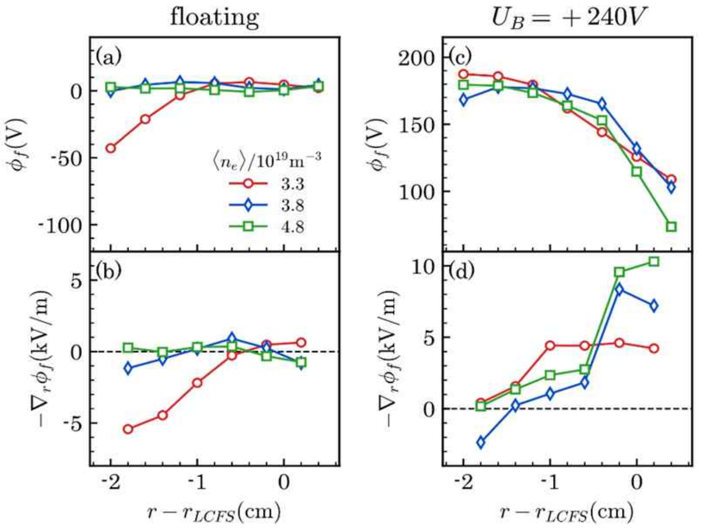
  Experiment limited by graphite probe sputtering

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

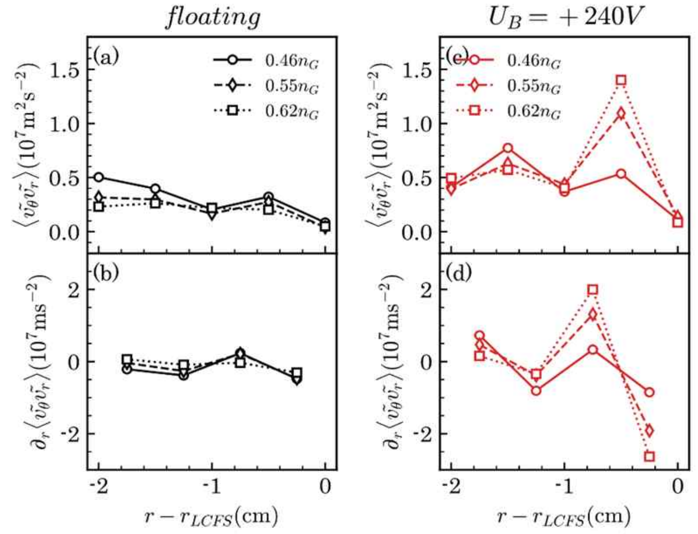


The Physics

- Edge Shear Layer produced for +bias

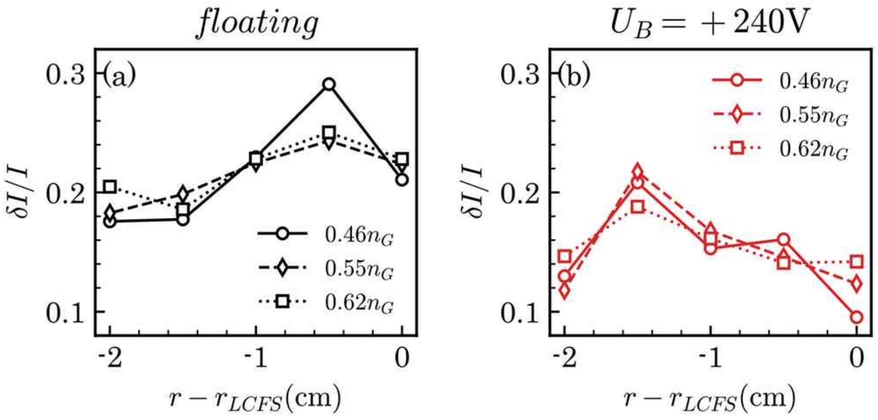


- Reynolds stress, force increase for +bias

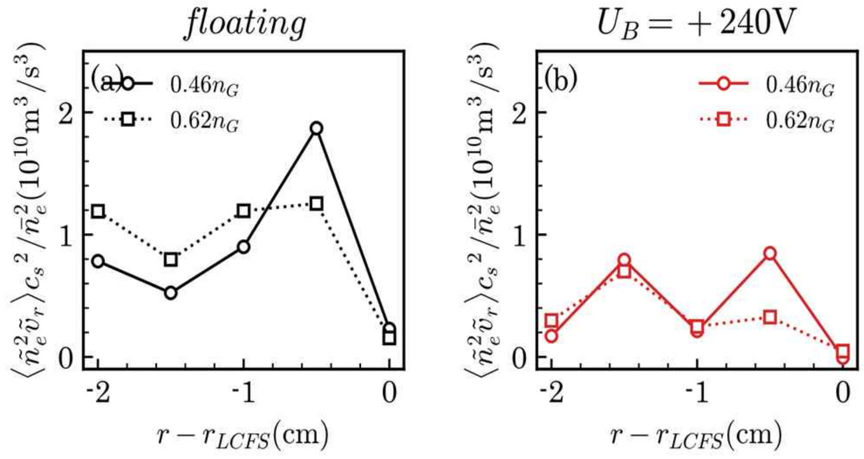


The Physics, Cont’d

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



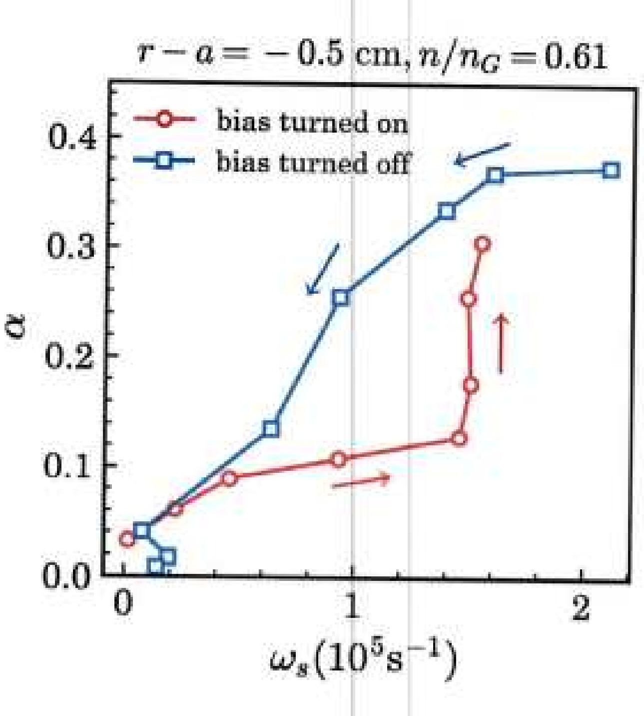
- Turbulence spreading quenched by +bias



Key Parameter?

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

  → shear ↑ → turbulence ↓ → heat transport ↓



Coming Attractions

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

Some Theoretical Matters

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

➔

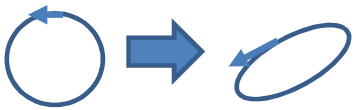
Step Back: Zonal Flows Ubiquitous! Why?

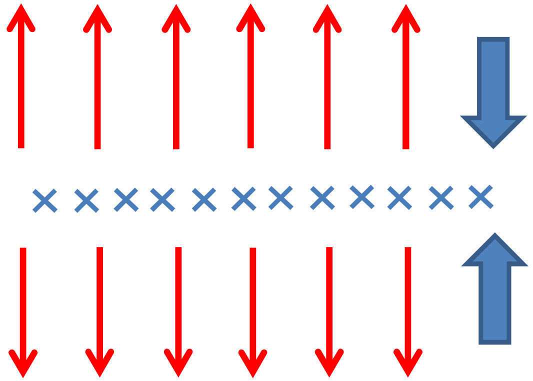
- Direct proportionality of wave group velocity and wave energy density flux

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

  Causality ←→ Eddy Tilting

  i.e.





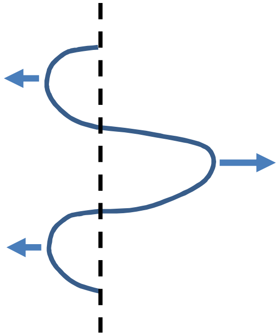
$\omega_k = -\beta\ k_x / k_\perp^2$: (Rossby)

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

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

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. $\alpha < 1$)

- $\omega_r = \left[\frac{|\omega_{*e}|\widehat{\alpha}}{2k_\perp^2\rho_s^2}\right]^{1/2}$ → 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 not arise as direct consequence of causality

➔ ZF generation not ‘natural’ outcome in hydro regime!

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

Desperately Seeking Greenwald

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

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 <u>lower</u> for larger I_p

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

Current Scaling, cont'd

- Shear flow drive:

incoherent
emission

S → polarization NL

emission from 'drift-mode' interaction

production

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

neoclassical response

  - Production ←→ beat drive
  - Response (neoclassical)

- Rosenbluth-Hinton '97 et seq

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 #

Current Scaling, cont'd

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

production factor

Production ↔ τ_c

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

Screening in the Plateau Regime!? (Relevant)

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

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

- 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

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

$$\frac{\partial E_t}{\partial t} = \gamma E_t - \overset{\text{shear}}{\sigma E_v E_t} - \overset{\text{satn.}}{\eta E_t^2}$$

$$\frac{\partial E_v}{\partial t} = \underset{\text{modulation growth}}{\sigma E_t E_v} - \underset{\text{damping}}{\gamma_d E_v} + \underset{\underline{\text{nonlinear noise}}}{\beta E_t^2}$$

High B_θ enhances ZF coupling

$$\left.\begin{array}{l} \sigma \sim \epsilon_{neo}^{-1} \sim B_\theta^2 \sim I_p^2 \\ \\ \beta \sim \epsilon_{neo}^{-2} \sim B_\theta^4 \sim I_p^4 \end{array}\right\} *$$

High B_θ enhances noise

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

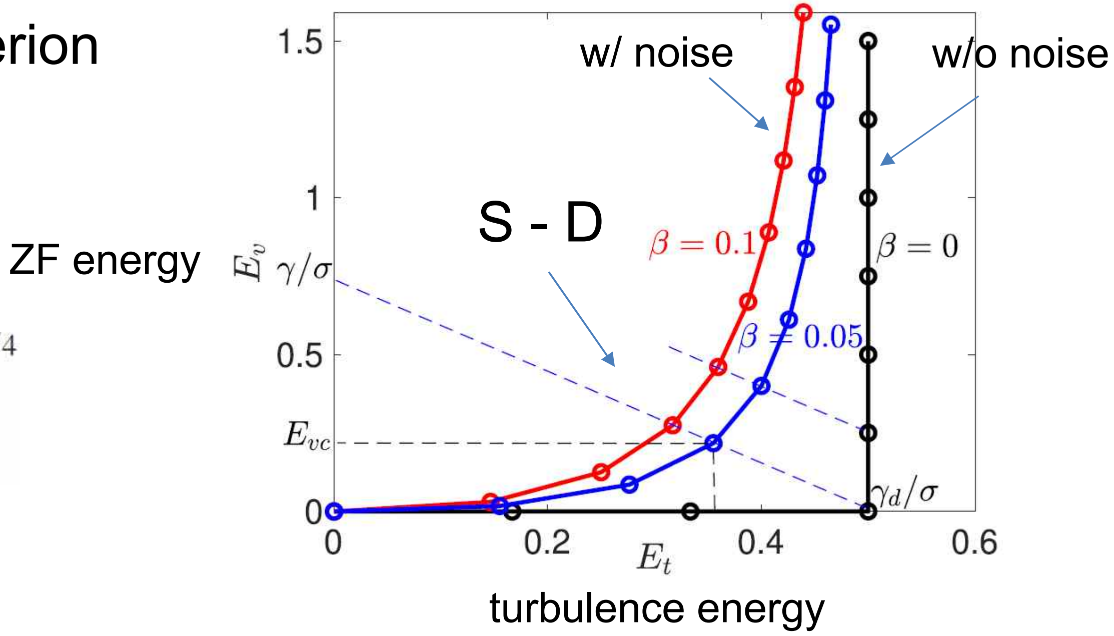
Criterion for Shear Layer Collapse

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

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

$$\alpha t \quad . = \left[\frac{\eta}{\Omega_\mathrm{i}} \frac{\gamma_\mathrm{d}}{2k_x^2\rho_\mathrm{s}^2\Theta\Omega_\mathrm{i}^2} \frac{\hat{\alpha}}{q_\perp^2\rho_\mathrm{s}^2} \frac{\left(1+q_\perp^2\rho_\mathrm{s}^2\right)^3}{q_y^2\rho_\mathrm{s}^2}\right]^{1/4}$$

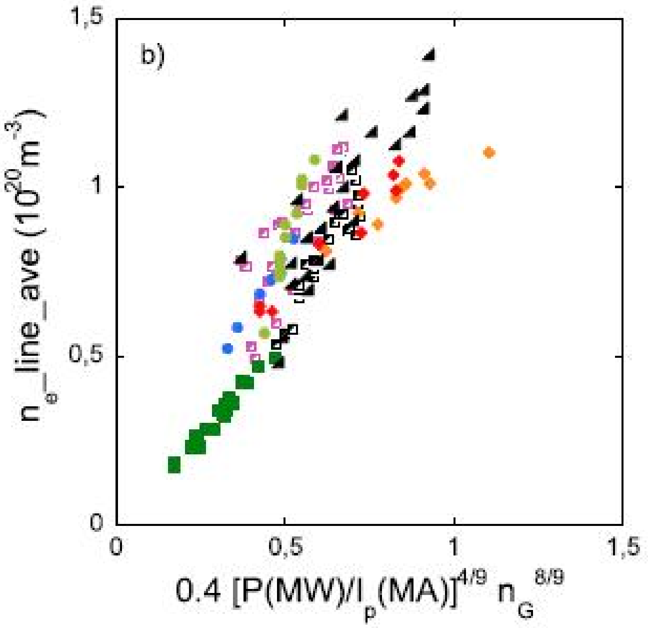
➔ Dimensionless parameter $\frac{\rho_s}{(\rho_\theta L_n)^{\frac{1}{2}}}$



Larger B_θ enhances persistence of ZF

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

- Scaling is an old story, keeps returning
- Zanca (2019) fits ➔ $\bar{n} \sim P^{+4/9}$



- Ricci + Simulations…
- $Q_i|_{\text{bndry}}$ will drive shear layer → familiar from LH mechanism
- P_{scahg} ↔ 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 $\varepsilon, V_{ZF}, n, T_i$
- Run Model in 'L-mode'
- Coeffs derived for ITG

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

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

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

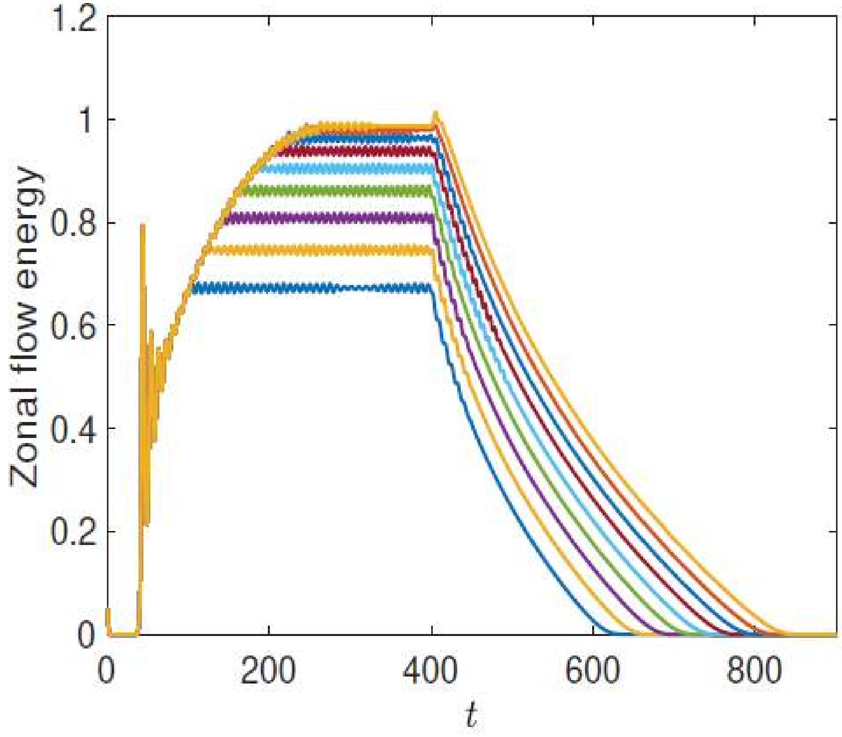
$$\frac{\partial n}{\partial t} = -d_1 \frac{\mathcal{E} n}{1 + d_2 \mathcal{V}^2} - d_3 n + S$$

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

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

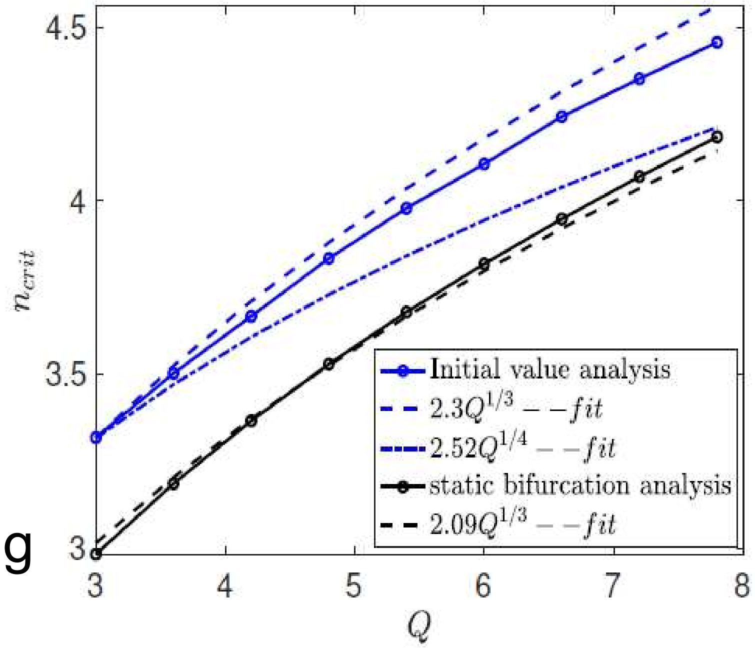
L → DL Studies

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



Power Scaling

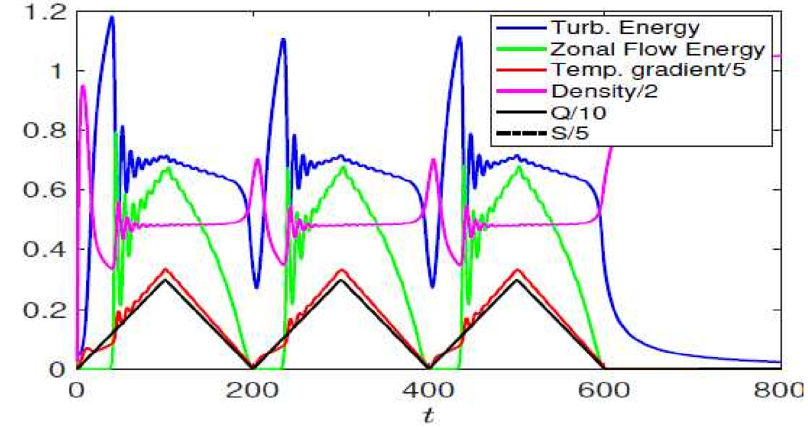
- $n_{\text{crit}} \sim Q^{1/3}$
- Distinct from Zanca, but close
- In K-D, with neoclassical screening $n_{\text{crit}} \sim I_p$
- Physics is $\gamma(\nabla T)$ vs ZF damping
- Shear layer physics seems to imply power scaling

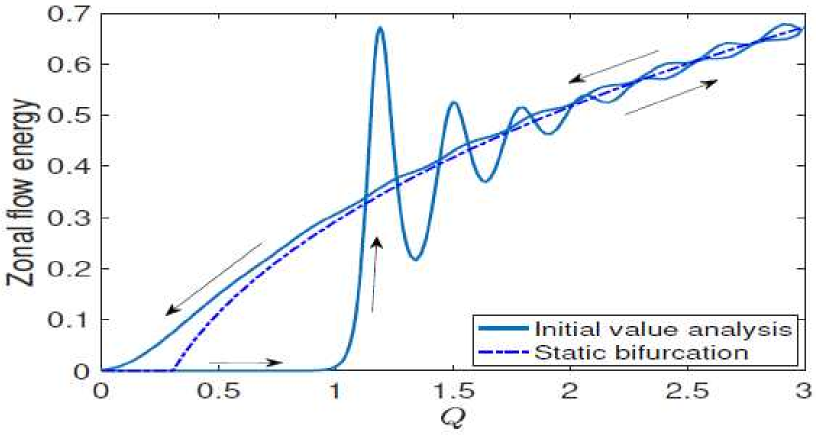


If it Flux Like a Duck… (M.N. Rosenbluth, after F. Wagner)

- Hysteresis ! in ε_{ZF} vs Q
- Expected, given 2 states transport
- Recall J-TEXT....
- 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_{G}
- Key issue ! N.B. Gentle “pump-and-puff” (Mahdavi) has beat Greenwald
- Candidates
  - AUG: α_{MHD} at separatrix (Eich, Manz)
  - Goldston, Brown: Conduction broadens SOL, reduces V_E' → instability & inward spreading hypothesized
- Experiments needed!

c.f. Dog + Tail problem !?

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
- Hysteresis evident in L-DL dynamics

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 $n_{\alpha t}\ \ (Q)$?
  - – Neg. Tri. ?

Thank You !

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