Transport Physics of Density Limits

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→ Or…

“How the Birth and Death of Shear Layers

Determines Confinement Evolution:

From the L→H Transition to the Density Limit”

→ See as above, P.D. et al Phil Trans Roy Soc 381 (OV thru 2022)

→ Many refs. throughout

- Collaborators:

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  George Tynan, Rima Hajjar

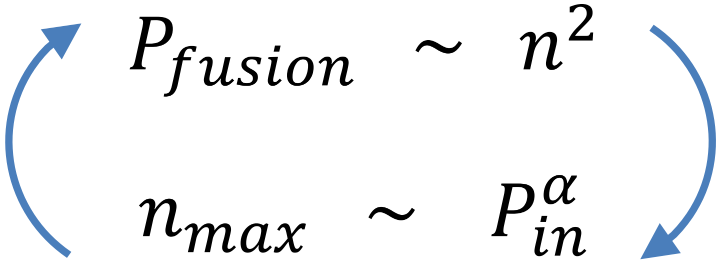
- Ackn:

  Peter Manz, Martin Greenwald, Thomas Eich, Lothar Schmitz,

  Andrew Maris, …

N.B. : Why Study Density Limits?

- Constraint on operating space
- Fusion power gain ~ n^2
- Attractive feedback loop ?! :



$$P_{fusion} \sim n^2$$

$$n_{max} \sim P_{in}^{\alpha}$$

$(0 < \alpha < 1)$

Caveat Emptor

- Dual/Mixed theoretical and experimental approach
- Emphasis on dynamics, micro←→macro connection etc., not scalings
- Emphasis on L-mode density limit
- N.B. Negative Triangularity (NT) experiments open new roads forward (c.f. Sauter, Hong + DIII-D, submitted)
- DL as confinement transition ←→ exploit L→H experience

42 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

N.B. Inhibition of L→H for sufficient NT poses challenge to L→H model

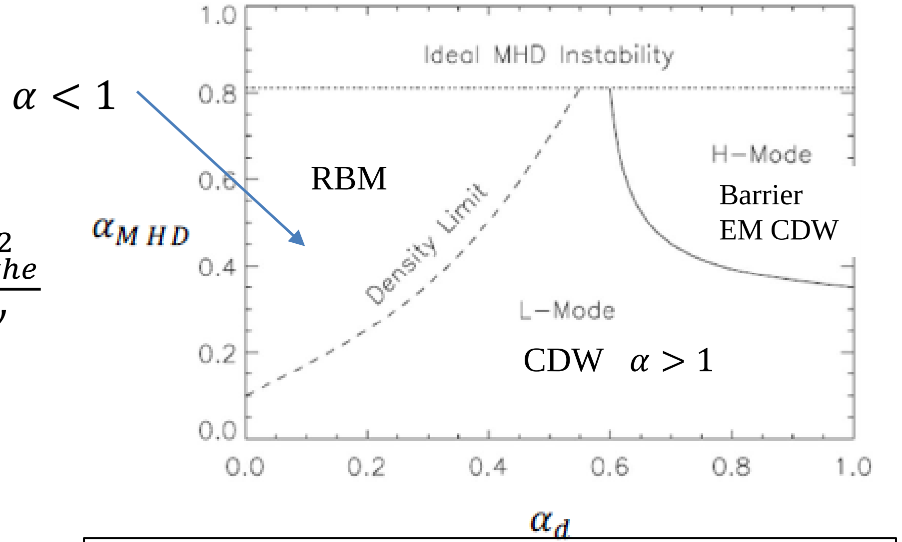
Preview: A Developing Story

From Linear Zoology to Self-Regulation and its Breakdown

1-mode per regime

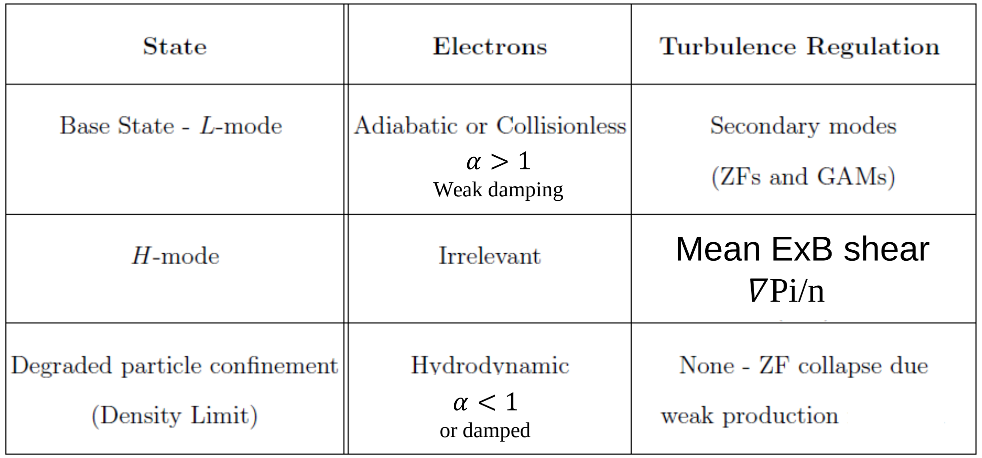
(Drake and Rogers, PRL, 1998)

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



- $\alpha_{MHD} = -\frac{Rq^2 d\beta}{dr}$ → ∇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, et. seq)



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

Secondary modes and states of particle confinement

→ I-mode

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”!?

Outline

- Density Limit Phenomenology

  ←→ Phases and Transitions of Edge Plasma

- Some Theoretical Matters

  ←→ Shear Layers and Their Degradation

- Power ←→ Separatrix Heat Flux Scaling of Density Limit: Dynamical Signatures
- Recent Developments
- To the Future

Phases and Transitions of the Edge Plasma

and

Density Limit Phenomenology

A Brief History of Density Limits → Conventional Wisdom

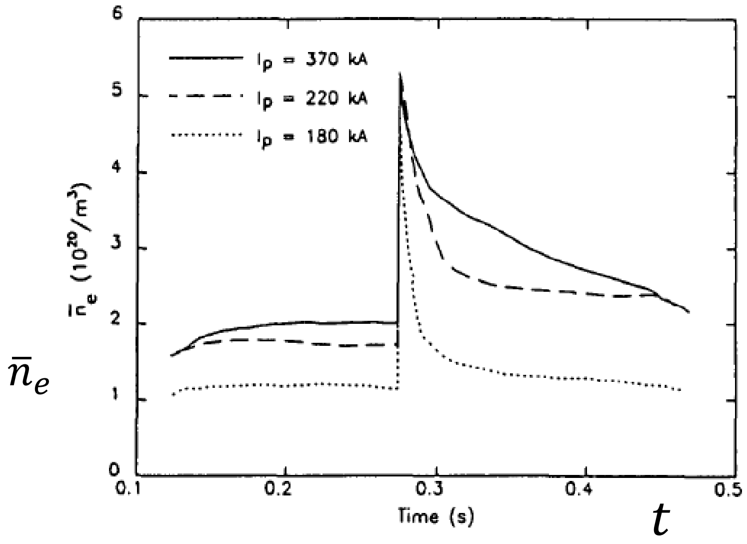
- Greenwald $\bar{n}_G \sim I_p/\, \pi a^2$ (dimensions?)
- High density → edge cooling (transport?!)
- Cooling edge → MARFE (Multi-faceted Axisymmetric Radiation from the Edge) by Earl Marmar and Steve Wolfe

  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…

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



(Alcator C)

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

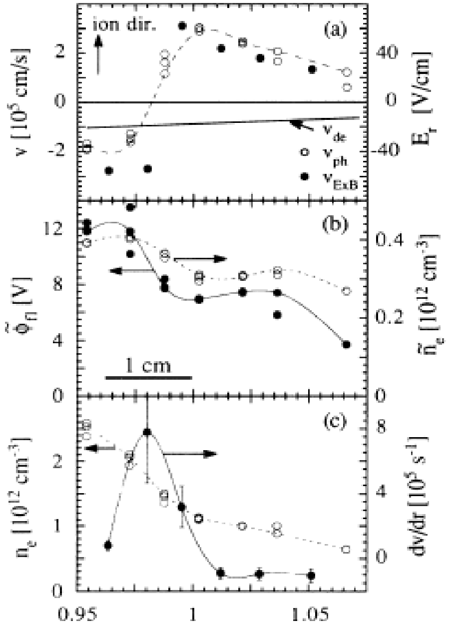
Shear Layer in L-mode? – Universal Feature of Edges

- 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

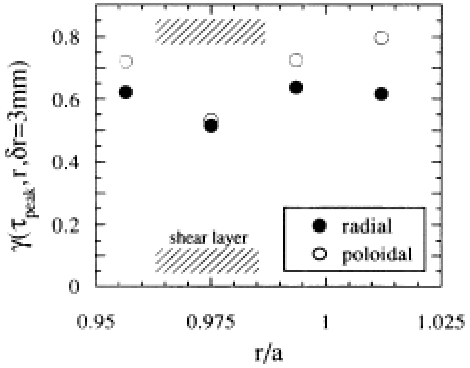
density



V'

FIG. 1. Radial profiles for a discharge with $B_\phi = 2$ T, plasma current of 200 kA, and chord-averaged density of $n_{\text{chord}} = 2\times10^{13}$ 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.

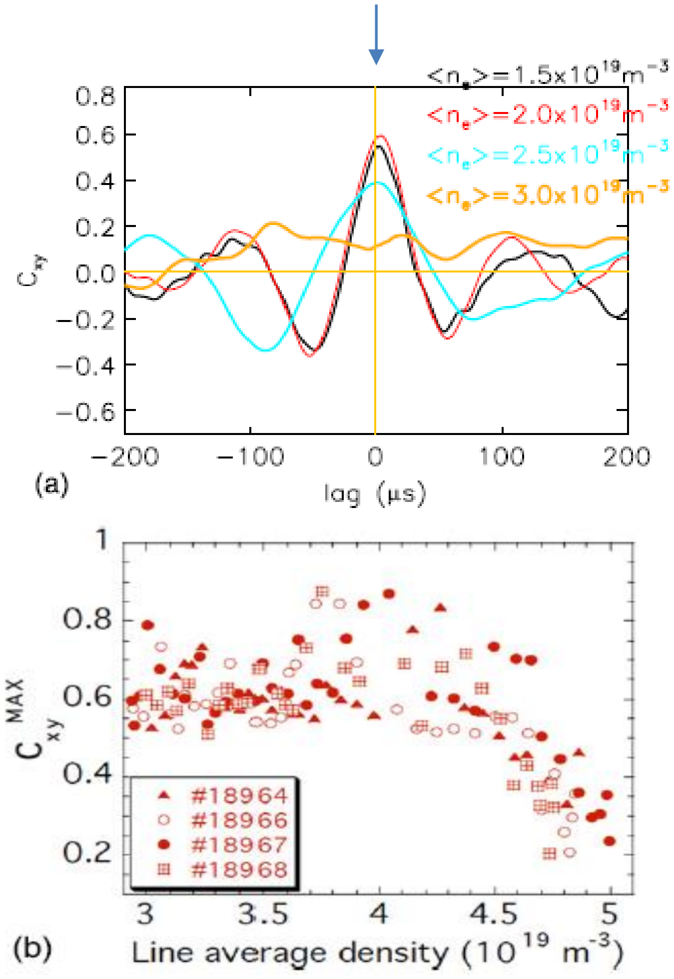
Title: “Evidence for Confinement Improvement by Velocity Shear Suppression of Edge Turbulence”

n.b. not H-mode!

➔ Role of Shear Layer in L→DL ?

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?!

↓

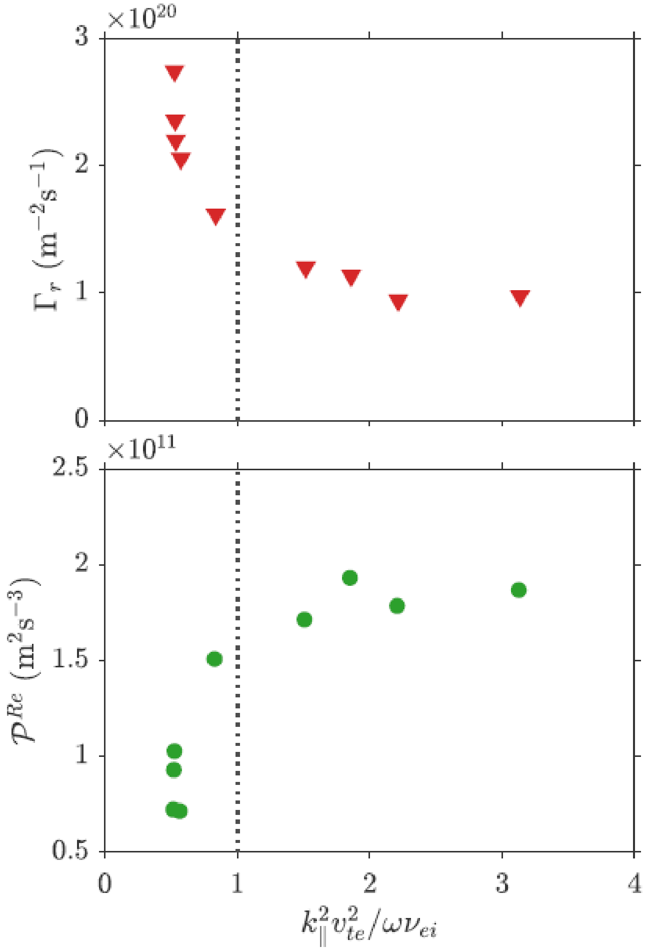
Yes !

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

Reynolds Power (Flow Production)

- Studies of $P_{Re} = -\langle \tilde{v}_r \tilde{v}_\theta \rangle \, \partial \langle V_E \rangle / \partial r$ vs n/n_G

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



Particle flux

surges for $\alpha > 1$

P_{Re} drops for $\alpha < 1$

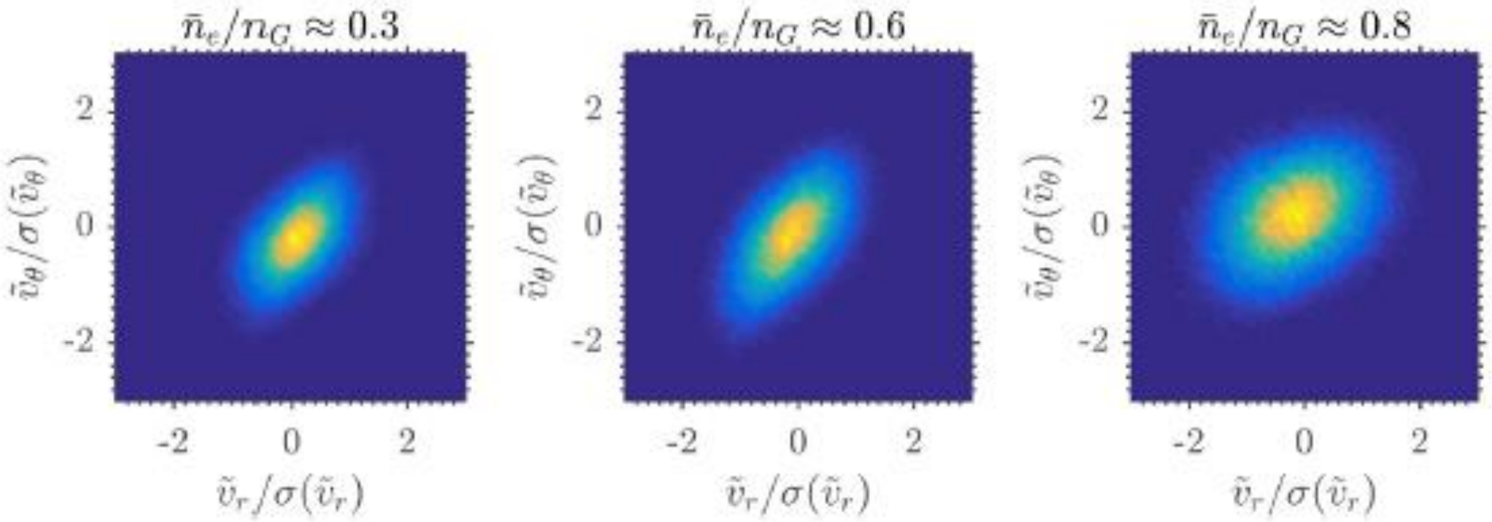
Is DL evolution linked to degradation of edge shear layer ?

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, $\bar{n} \rightarrow n_G$
- $r - r_{sep} = -1cm$
- Note:
  - Tilt lost, symmetry restored as $\bar{n} \rightarrow \bar{n}_g$ ➔ Weakened shear flow production by Reynolds stress as $n \rightarrow n_G$
  - Consistent with drop in P_{Re} observed

An In-depth Look at More Recent Experiments

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

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

N.B. These experiments are ‘theoretically motivated”

J-TEXT – Ohmic

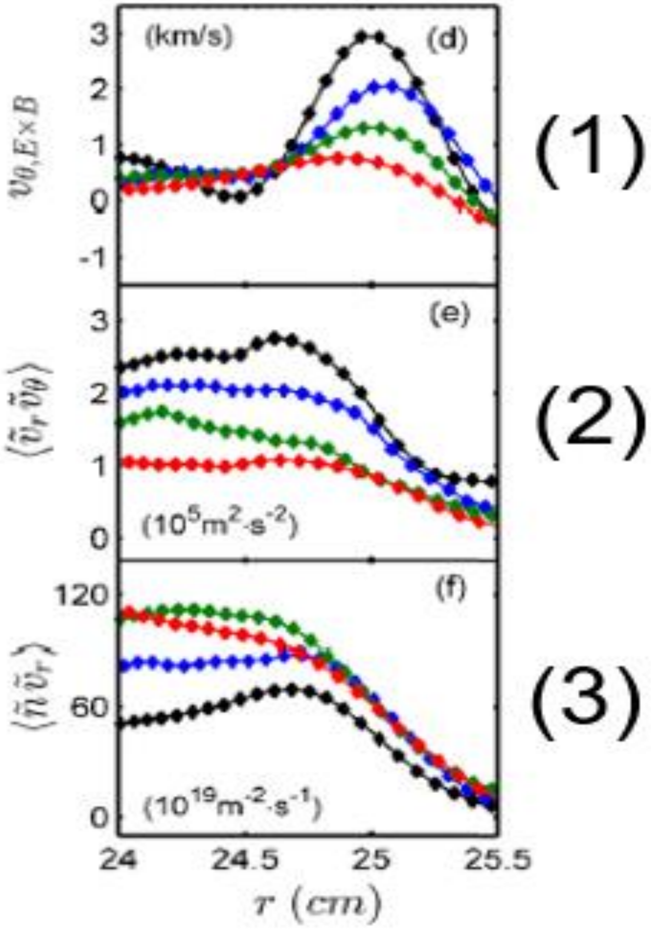
Black - $0.3n_G$

Blue - $0.34n_G$

Green - $0.6n_G$

Red - $0.63n_G$

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



Mean-Turbulence Couplings

- In standard CDW model:

Production ≡ Input from ∇n

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

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

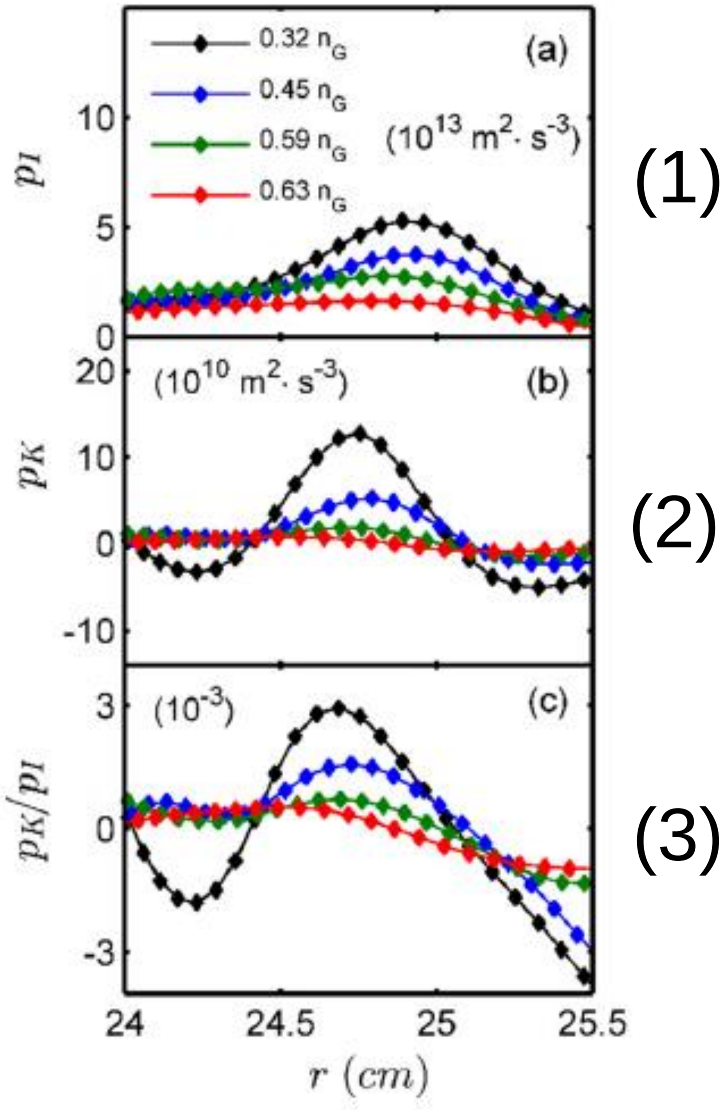
Reynolds Power ≡ Coupling to Zonal Flow

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

- Reynolds power drops as n/n_G rises (see Hong+,’18) (2)
- P_k/P_I drops as n/n_G rises (3)

➔Fate of the Energy ?

➔Where does it go?



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

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

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

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

→ Turbulence Spreading Power

- Turbulence Spreading encompasses “Blob” and “Void” propagation

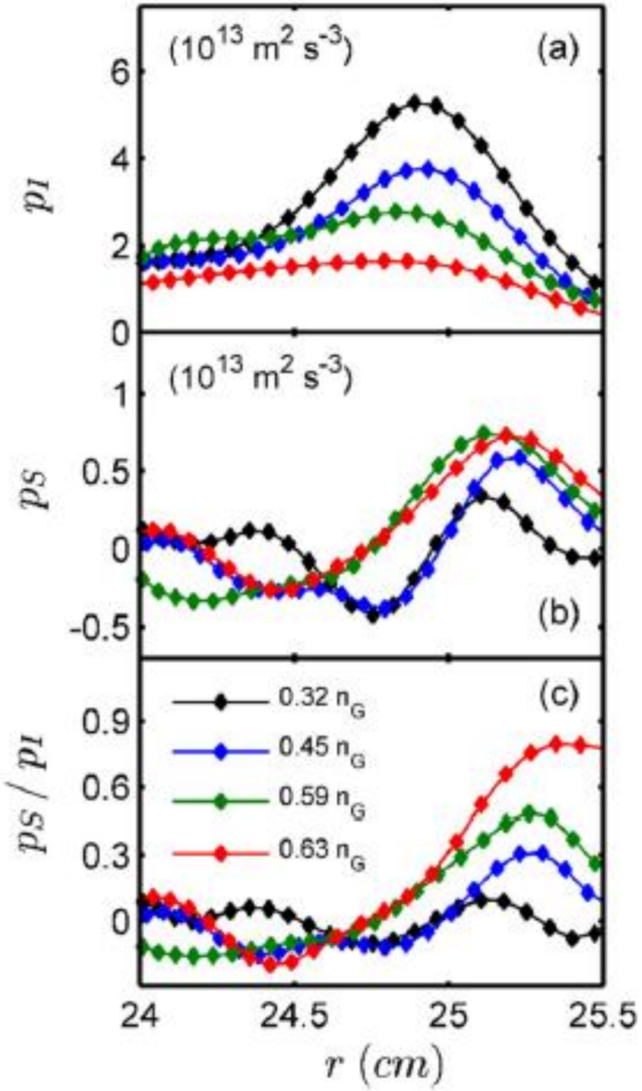
Fate of the Energy, Cont'd

- 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

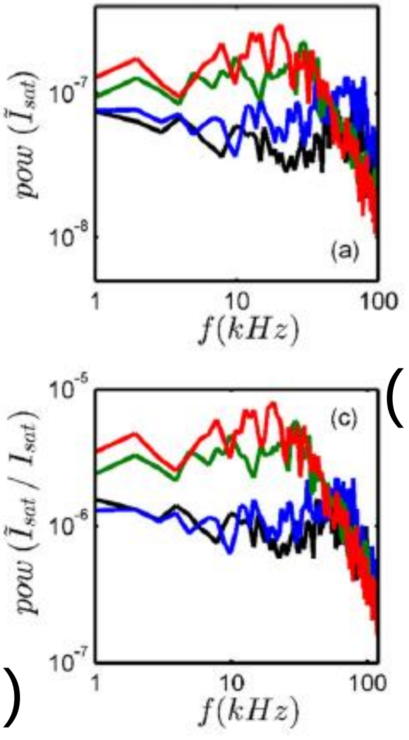


- N.B. Recent result (Long + 2024, submitted): δ(spreading flux) is more robust indicator of DL then δ(particle flux)

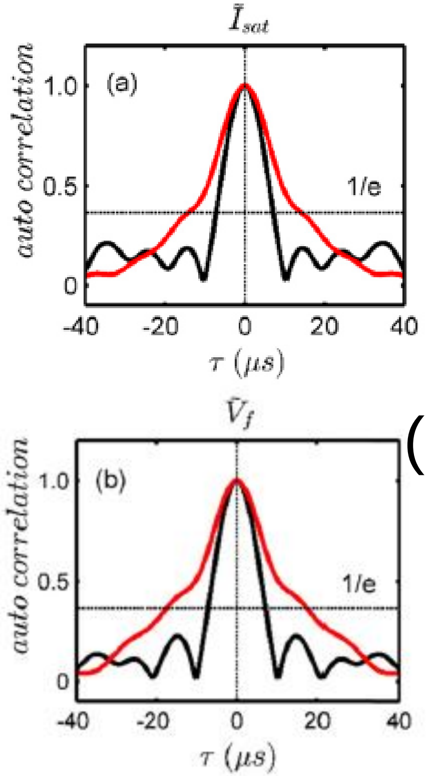
Characteristics of Spreading

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

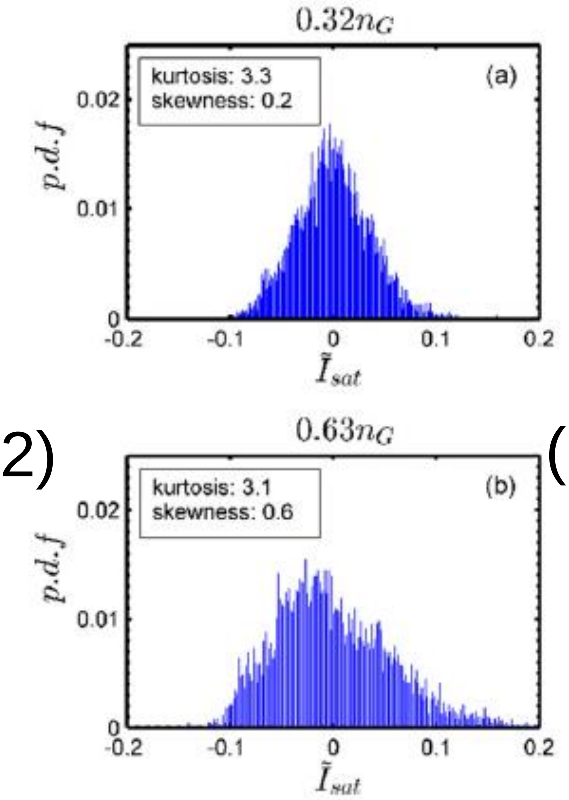
Pdf $\tilde{I}_{sat}$ developes positive skewness as n/n_G increases (3)



(1)



(2)



(3)

See also T. Long, P.D.+ submitted 2023 for $\tilde{n}$ skewness ←→ spreading correlation and in→out symmetry breaking

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

- Blob ejection → recycling → cold neutral influx ➔ cooling + MHD trigger

Is there a key parameter? – Adiabaticity!

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

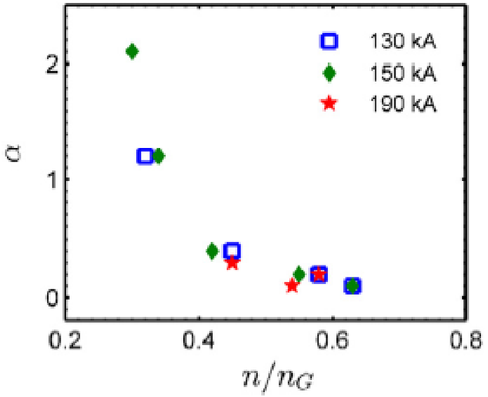
  α drops < 1 as n/n_G increases

- V_E' rises with $\alpha \uparrow$

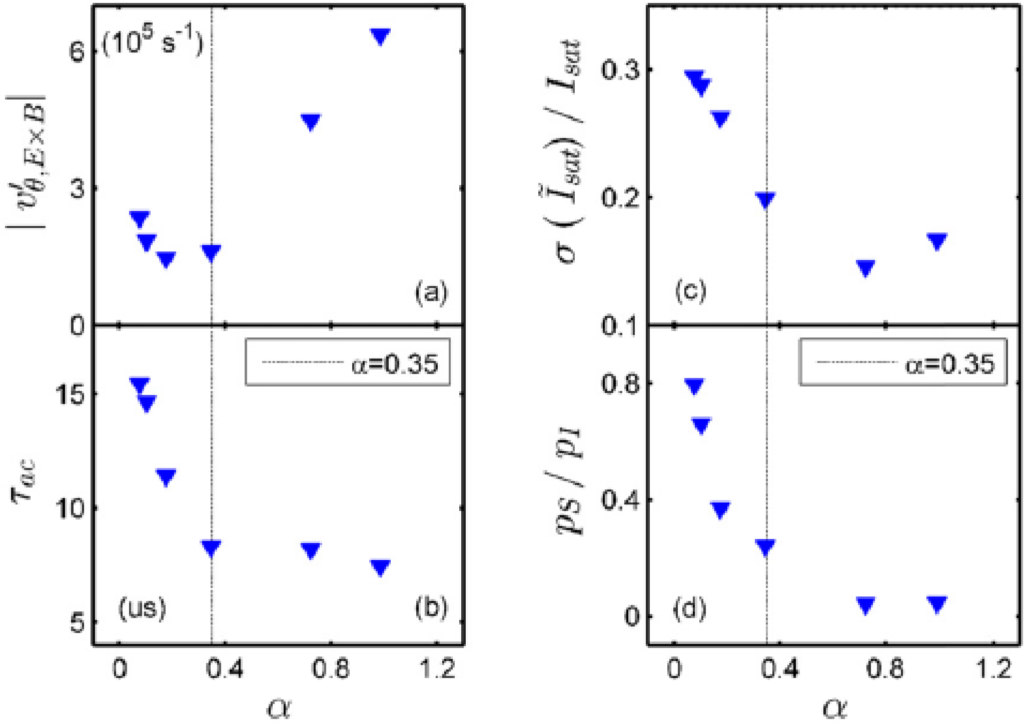
  τ_{ac} decreases with $\alpha \uparrow$

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

  P_s/P_I decreases with $\alpha \uparrow$



N.B. $k_\parallel = 1/Rq$ assumed

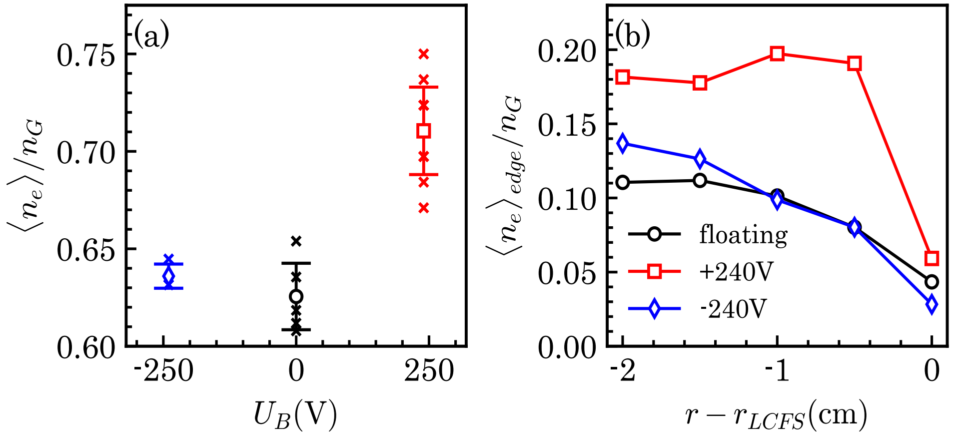


The Obvious Question

- Can driving the shear layer sustain high densities, where L→DL, otherwise ?
- "Driving" ⟶ bias electrode – here (J-TEXT). Not a conventional H-mode
- 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

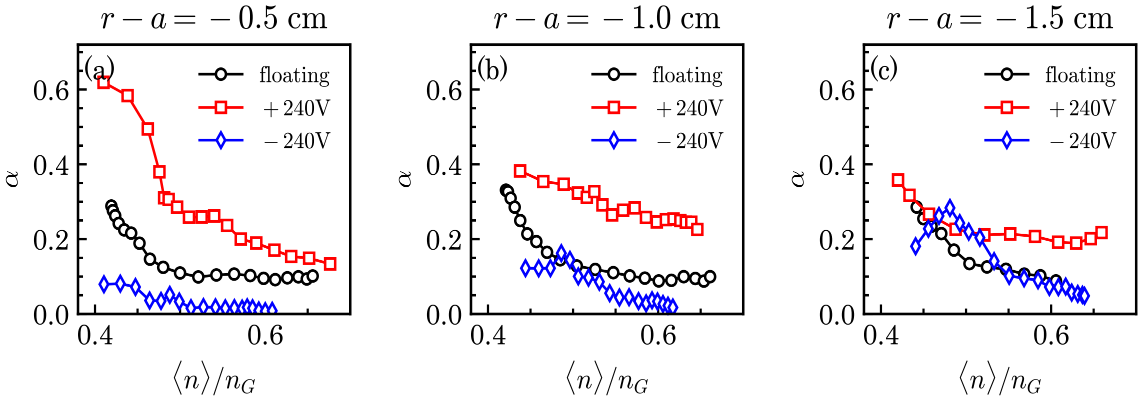
c.f. Rui Ke, P.D. + NF 2022

The Answer – Looks Promising!



- Edge density <u>doubled</u> 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
  - – $\alpha \sim T^2/n$

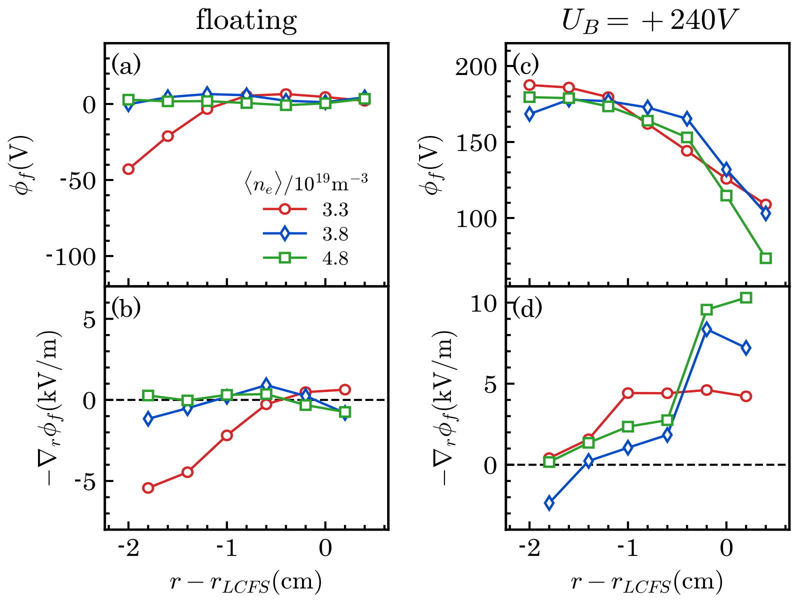
Reduced transport → higher T

- Turbulence spreading quenched by positive bias

The Physics

- Edge Shear Layer produced for +bias

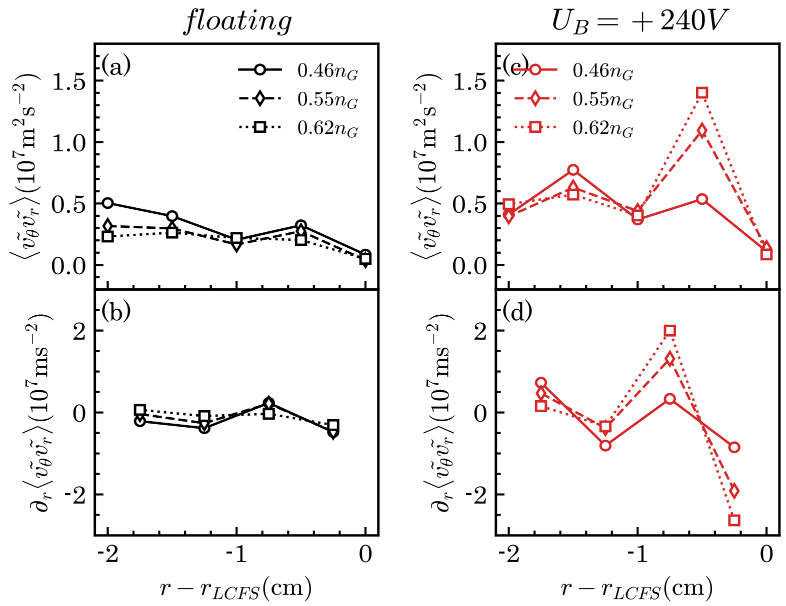
N.B. Not an E_r well



- Reynolds stress, force increase for +bias

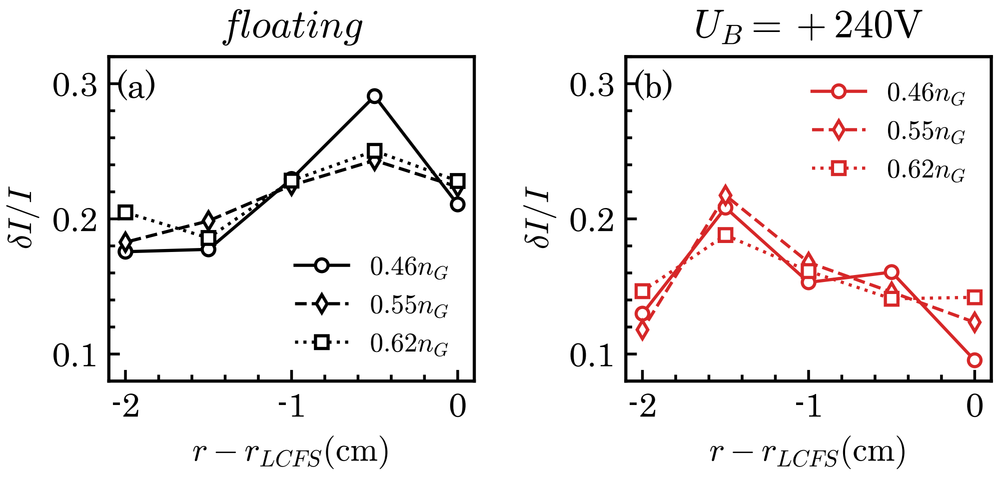
←→ bias effect on eddy alignment

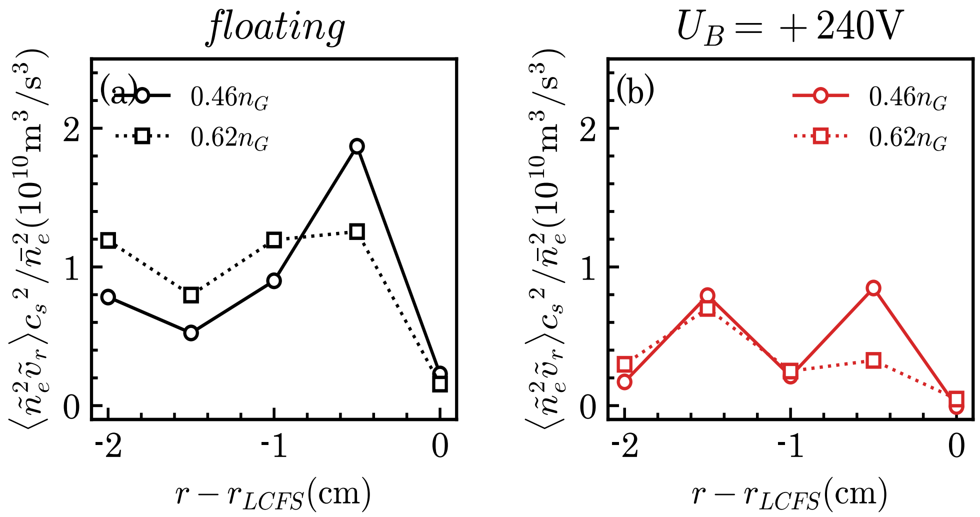
“Shearing” ←→ interplay of bias and Reynolds stress



The Physics

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





- Turbulence spreading quenched by +bias

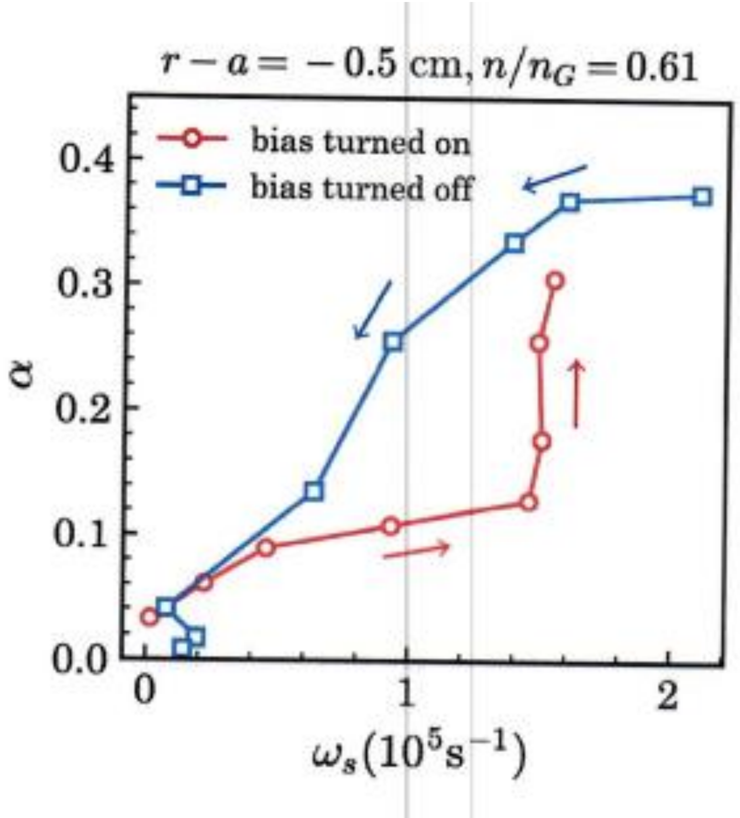
Key Parameter vs Control Parameters

- 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?



Ongoing and Future Work

- Bias experiment with improved probe
- Ip scan vs n/n_G scan ? – obvious ‘Greenwald test’ (Long+ 2024, submitted):

  Ip ramp down explained via $\omega_{shear}\ \tau_{cor}$
- Physics of spreading (Long, PD+ 2023)
  - Spreading ←→ Blob emission
  - Broken symmetry: “Spreading” dominated by large blobs

Some Theoretical Matters

➔ Shear Layer Physics

  - Degradation / Collapse
  - Support → Power

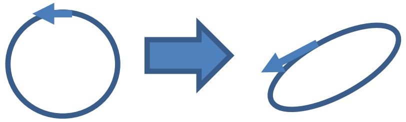
Step Back: Zonal Flows Ubiquitous! Why?

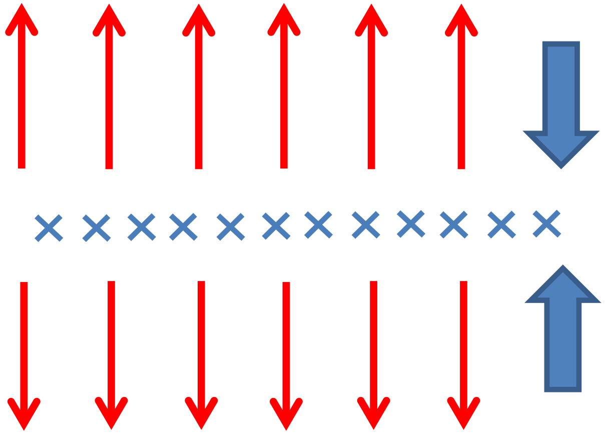
- Direct proportionality of wave group velocity and wave energy density flux

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

  Causality ←→ Eddy Tilting

i.e.





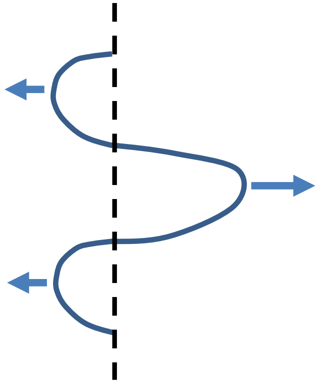
$\omega_k = -\beta\, k_x / k_\perp^2$: (Rossby)

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

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

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 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

N.B. Generic mechanism, not linked to specific "mode"

$\alpha < 1 \nrightarrow$ RBM

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 ↔ $\alpha < 1$ Generic

➔

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

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

Nonlinear Noise

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 #

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) 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

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

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

High B_θ enhances ZF coupling

Limiting reduction of complex ZF, corrugation evolution

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

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

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

High B_θ enhances "noise" for Z.F.

N.B.: I_p enhances modulational growth

Re: Developments:

- Zonal flow and turbulence always 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

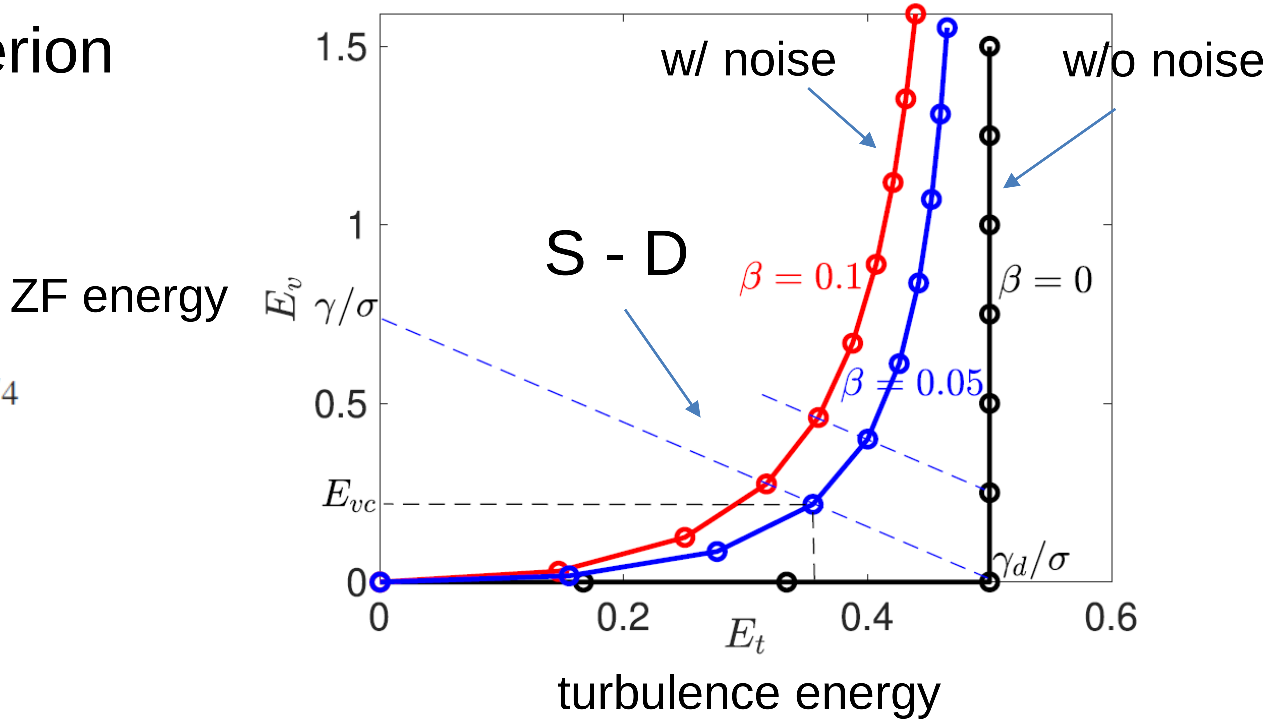
- For collapse limit, criterion without noise is viable approximation to with noise

- Derive shear layer persistence criterion

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

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

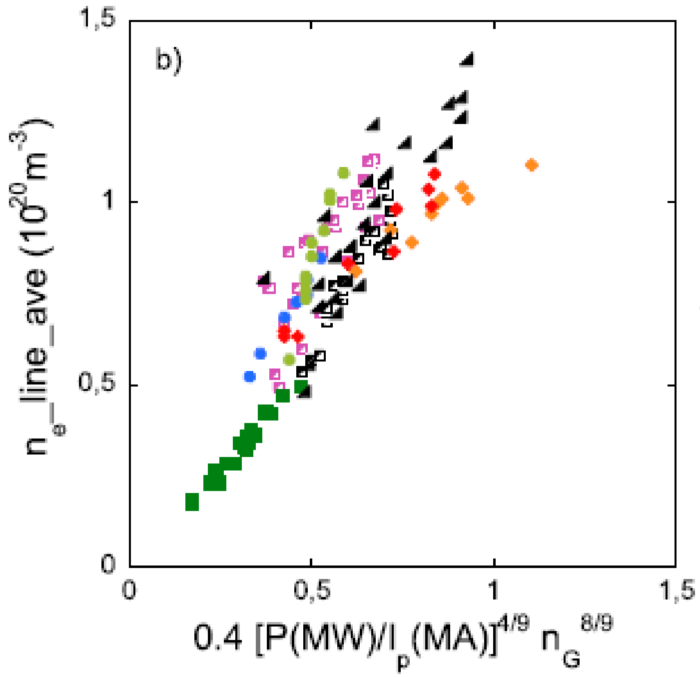
➔ Dimensionless parameter $\frac{\rho_s}{(\rho_\theta L_n)^{\frac{1}{2}}}$



Larger B_θ enhances persistence of ZF

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

- Power Scaling is an old story, keeps returning
- Zanca+ (2019) fits ➔ $\bar{n} \sim P^{0.4}$



Zanca +

- Giacomin+: Simulations recover power scaling
- Observe: $Q_i|_{\mathrm{bndry}}$ will drive shear layer → LH mechanism
- So: P_{scaling} $\leftrightarrow$ shear layer physics: a natural connection

Expanded Kim-Diamond Model

- KD '03 – useful model of L→H dynamics (0D)
- See also Miki, P.D. et al '12, et. seq. (1D)
- Evolve $\varepsilon, V_{ZF}, n, T_i, V_E'$

←→

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

N.B. i) ZeroD → interpret as edge layer
ii) Does not determine profiles
iii) Coeffs for ITG

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

Fluctuation Intensity

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

Zonal Intensity

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

T_i

Q → power

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

n

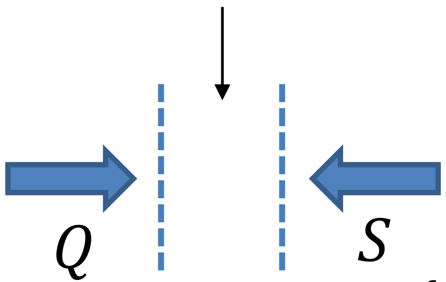
S → fueling

shear

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

Shear (mean)

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



edge layer

Q

heat flux

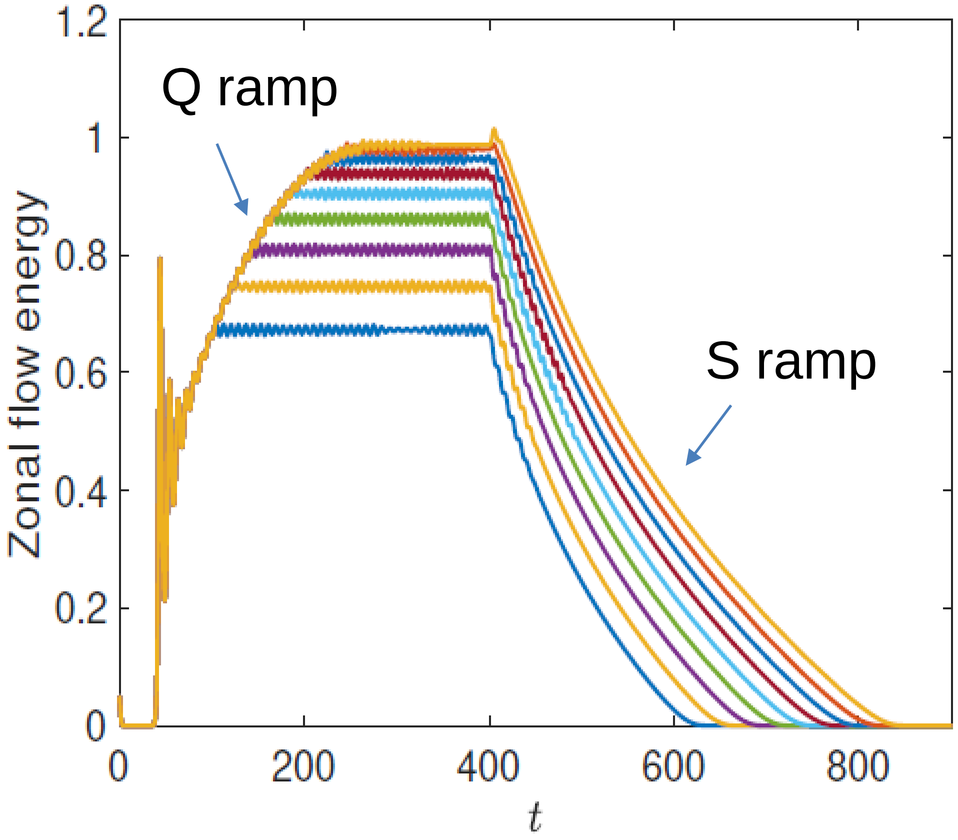
S

fueling

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

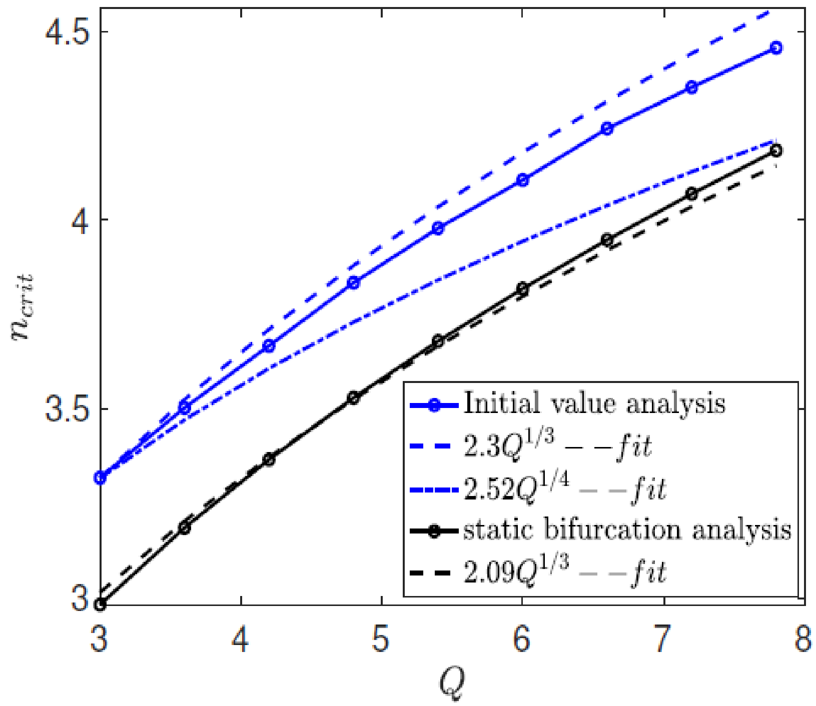
- Look for shear layer collapse
- Q ramp-up to L-mode, followed by S ramp-up
- Oscillations → predator-prey cycles
- n for ZF collapse increases with Q

scaling of n_{crit} emerges



Power Scaling: LDL

- $n_{\text{crit}} \sim Q^{1/3}$
- Distinct from Zanca, but close (model)
- In K-D, with neoclassical screening $n_{crit} \sim I_p \rightarrow I_P^2$
- Physics is $\gamma(Q)$ vs ZF damping
- Shear layer drive underpins power scaling



Physics: Q_i → Turbulence → Reynolds Stress → ZF shear

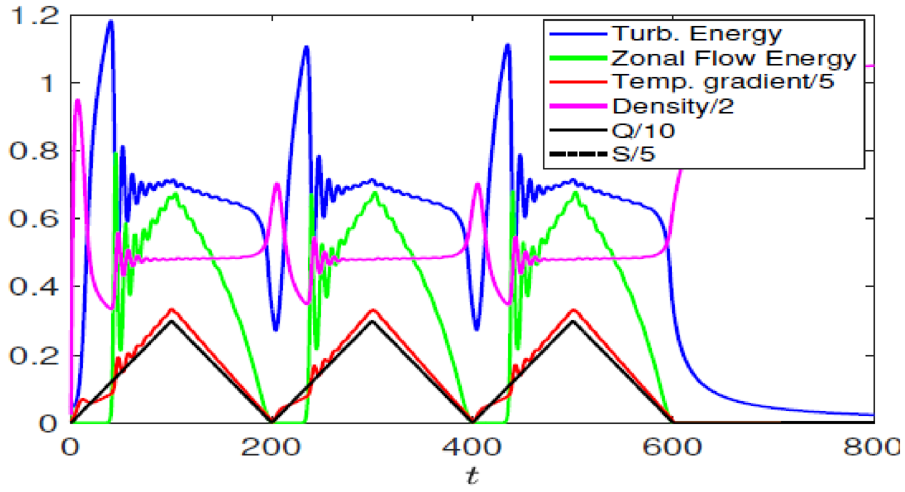
Increased ZF damping → Confinement degradation

NB: Unavoidable model dependence in scalings

Beyond Scalings: L→DL ‘Transition’ Physics

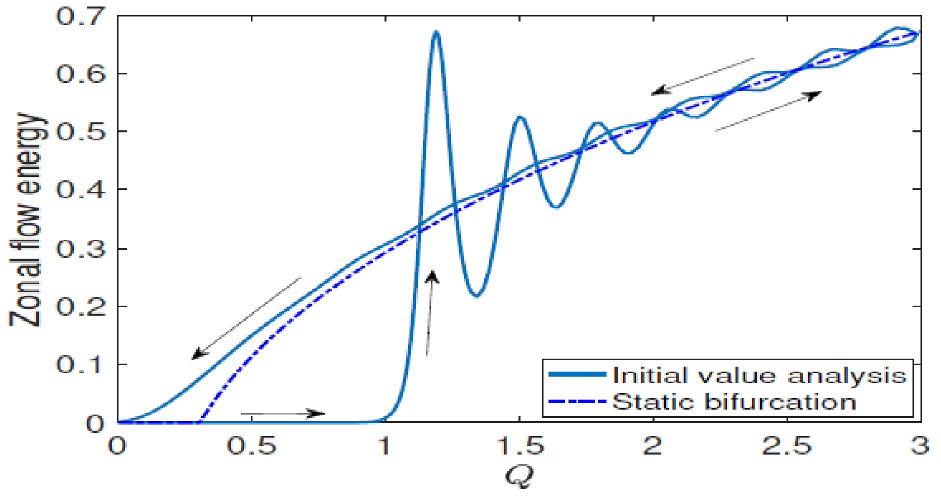
“If it Flux Like a Duck… (M.N. Rosenbluth, after F. Wagner)”

- Hysteresis ! in ε_{ZF} vs Q → Critical slowing down effect
- Expected, given 2 states transport
- Not familiar bistability !
- Physics prediction… beyond scaling



Also:

- Is there torque effect of density limit, i.e. $\nabla P/n$ vs $B_\theta V_\phi$?
- Torque ←→ V_E' → Mean field → Reyn. stress coherence



Recent: NT Density Limit Studies (DIII-D) (Sauter, Hong+ 2023)

Stay Tuned

- $\bar{n} \sim 2\, n_G$ achieved with ~ 10 MW NBI. No disruption
- NT greatly expands dynamic range of L-mode by preventing L→H transition. Allows separation LDL, HDL.
- $\bar{n}$, n_{edge} both scale as P^{α}

$$\bar{n} \quad \rightarrow \quad \alpha \sim 0.3$$

$$n_{edge} \quad \rightarrow \quad \alpha \sim 0.4$$

Caveat Emptor

- Confinement degrades above n_G? – Major question…
- V_E' effects noted

NB: High β_p, peaked density DIII-D does not degrade τ_E above n_G (DIII-D; Ding, Garofalo+ …)

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 ! 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' →

$$\lambda:\ v_D\ * \left\{ \begin{array}{l} \tau_T \\ \tau_{\mathrm{cond}} \end{array} \right.$$

So – instability calculated & inward spreading <u>hypothesized</u>

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

- Experiments needed!

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

N.B. Physics of Back Transition is key to HDL. What degrades ExB shear, absent ELMs

Conclusions: V_E' as Edge Order Parameter

- Density limits as “back-transition” phenomena; V_E' physics crucial
- L-DL mechanism:
  - Shear layer degradation
  - Strong turbulence spreading → Blob emission
- α is key parameter, but not only
- Scalings of L-DL emerge 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 trigger unclear. Back Transition is key.

Speculations / Questions

- Is H-DL due turbulent degradation of V_E' in pedestal? Mechanism?
- Can external means be used to enhance edge density?
- Is there a L-mode edge with $\alpha > 1$ and $n > n_G$?
- Collisionless regimes? - $\nabla \mathrm{n}$ TEM.
- D-L-H triple point, ala' phase transitions?
- New states:
  - Neg. Tri. at high n, P ? Features of edge plasma?
  - Power – Density feedback loop in burning plasma?
- Origin of confinement degradation at high density?

Thank You !

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