The Ins and Outs of Density Limits

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ABOUND FEST
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→ See recent review:

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

→ Phil Trans Roy Soc 381 (2023)

→ See also Eich and Manz; 2021, 2023

- Collaborators:

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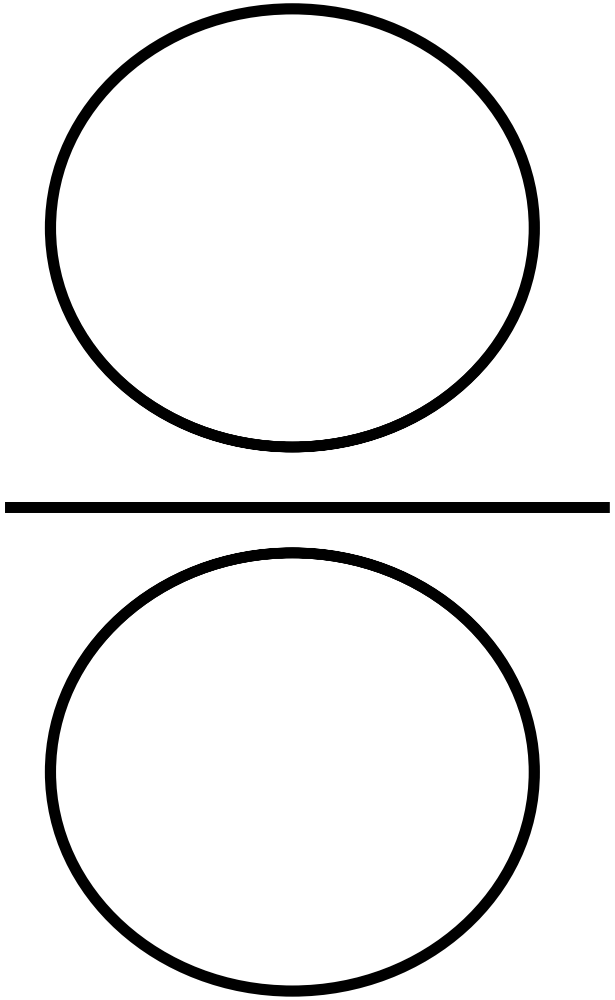
  George Tynan, Rima Hajjar

- Ackn:

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

  Andrew Maris, …

Warning:

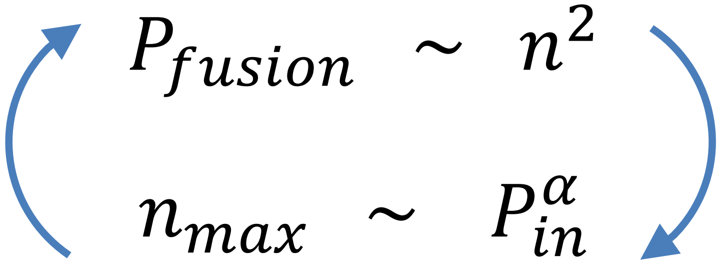


Results from Large Scale Computations

ScoDAC $ spent

N.B. : Why Study Density Limits?

- Constraint on operating space
- Fusion power gain ~ n^2 → burning plasma will be high density
- Attractive feedback loop ?! :



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

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

$$(0 < \alpha < 1)$$

n.b. Power dependence density limit

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 → both L, H

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

Outline

- Issues in Density Limit Physics
- Status of Theory
- Critical Experiment

  In → Out

- HDL → Back Transition Trigger?

  Out → In

- Wish List for Computation

Preview: A Developing Story

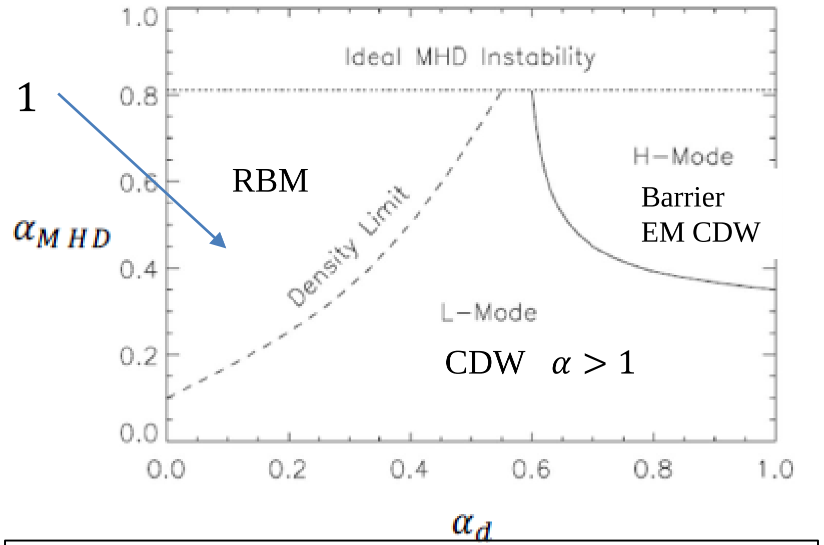
From Linear Zoology to Self-Regulation and its Breakdown

1-mode per regime

(Drake and Rogers, PRL, 1998)

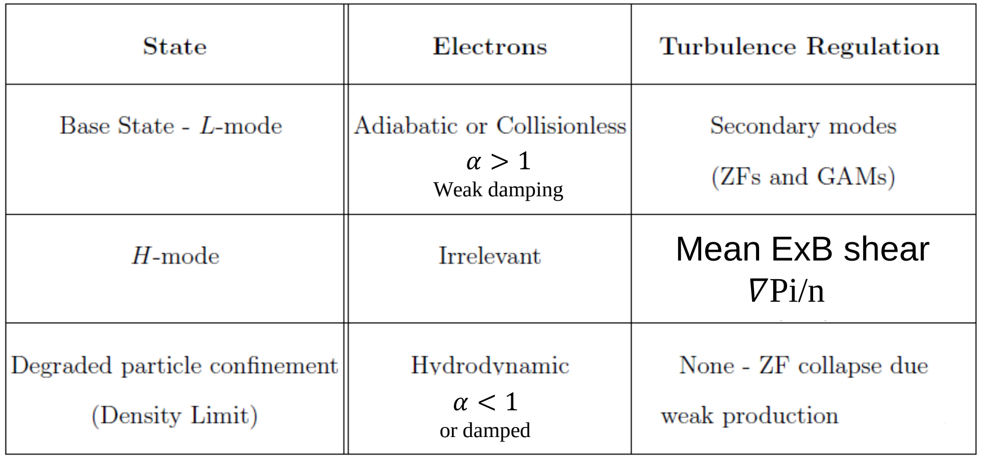
$\alpha < 1$

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



- $\alpha_{MHD} = -\frac{Rq^2 d\beta}{dr} \rightarrow \bigtriangledown$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

→ 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"!?

Issues in Density Limit Physics

- Physics of increased particle transport, cooling approaching n_g
- Micro-Macro connection:

  Progression transport → MARFE → Disruption

- Physics of Current Scaling?
- Physics of Power Scaling?
- Origin of confinement degradation at high n i.e. $n > n_g$ (DIII-D NT)?

Status of Theory

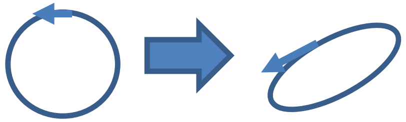
Edge ExB Shear: Zonal Flows Ubiquitous! Why?

- 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.



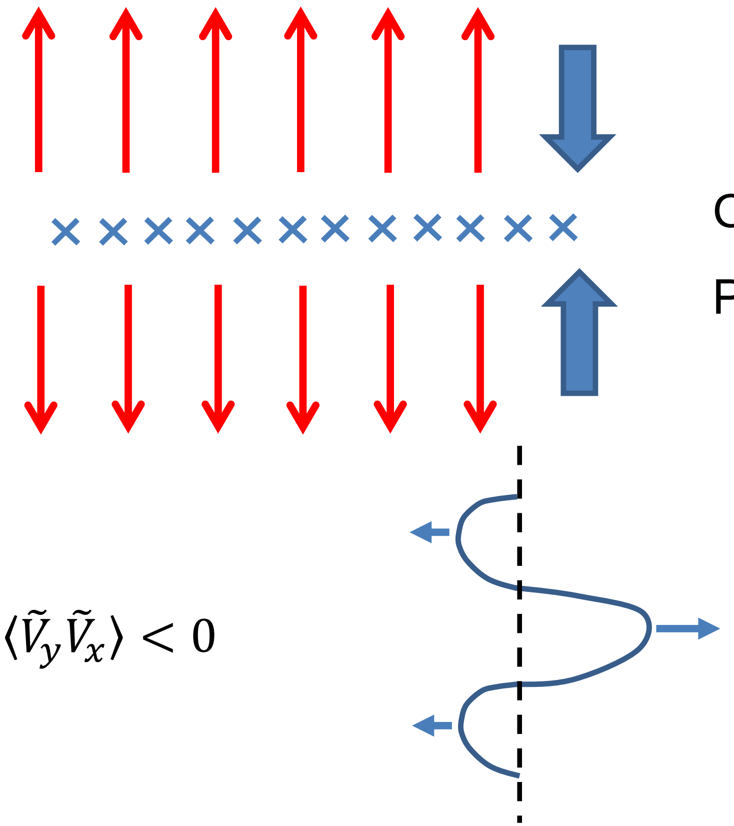
$\omega_k = -\beta \, k_x / k_\perp^2$: (Rossby)

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

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

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

Propagation ←→ Stress



Cf: Held, Vallis in GFD

P.D. + Kim '90

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

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

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

- $\omega_r = \left[\frac{|\omega_{*e}|\widehat{\alpha}}{2k_\perp^2\rho_s^2}\right]^{1/2}$ → 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 <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

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

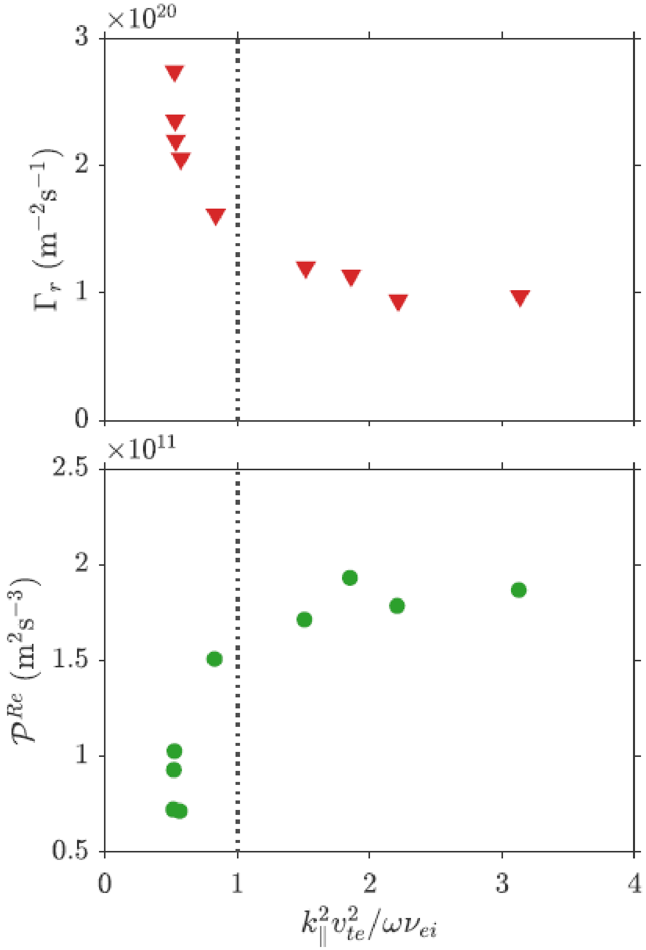
$\alpha < 1 \;\nRightarrow\;$ RBM

Adiabaticity ≠ Collisionality

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 ?

(Hong+, 2018 NF)

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.

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

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

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

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” 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

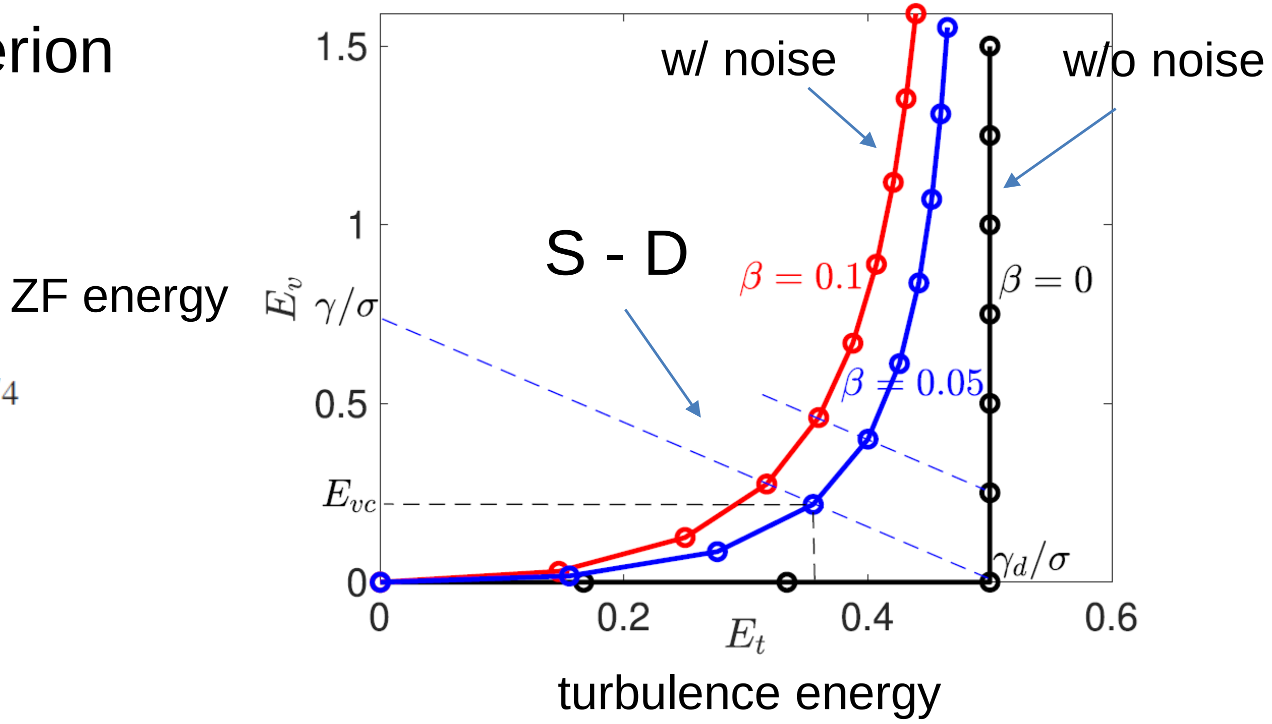
Criterion for Shear Layer Collapse

- For collapse limit, criterion without noise is viable approximation to with noise
- Derive shear layer persistence criterion

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

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

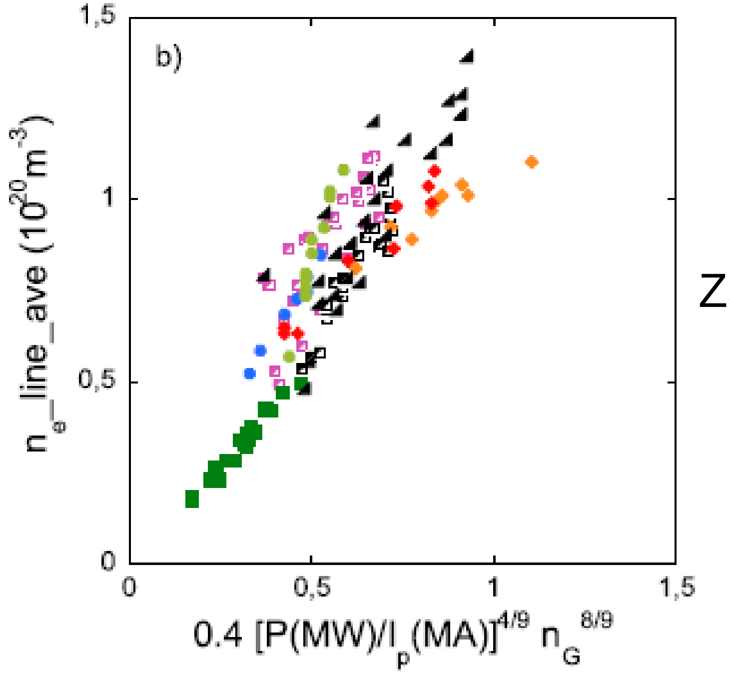
➔ Dimensionless parameter $\frac{\rho_s}{(\rho_\theta L_n)^{\frac{1}{2}}}$



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 ➔ $\bar{n} \sim P^{1/4}$



Zanca +

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

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

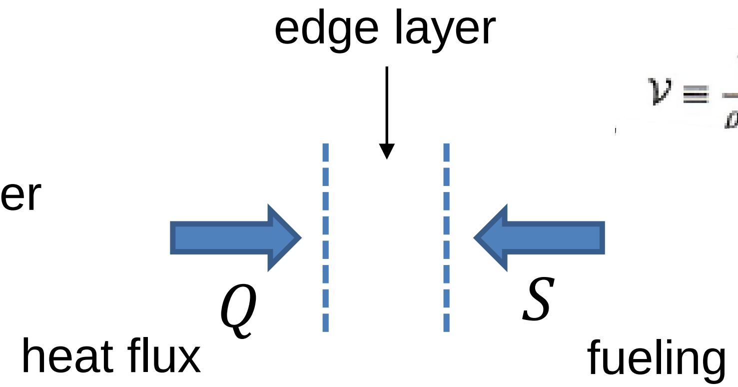
n

S → fueling shear

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

Shear (mean)

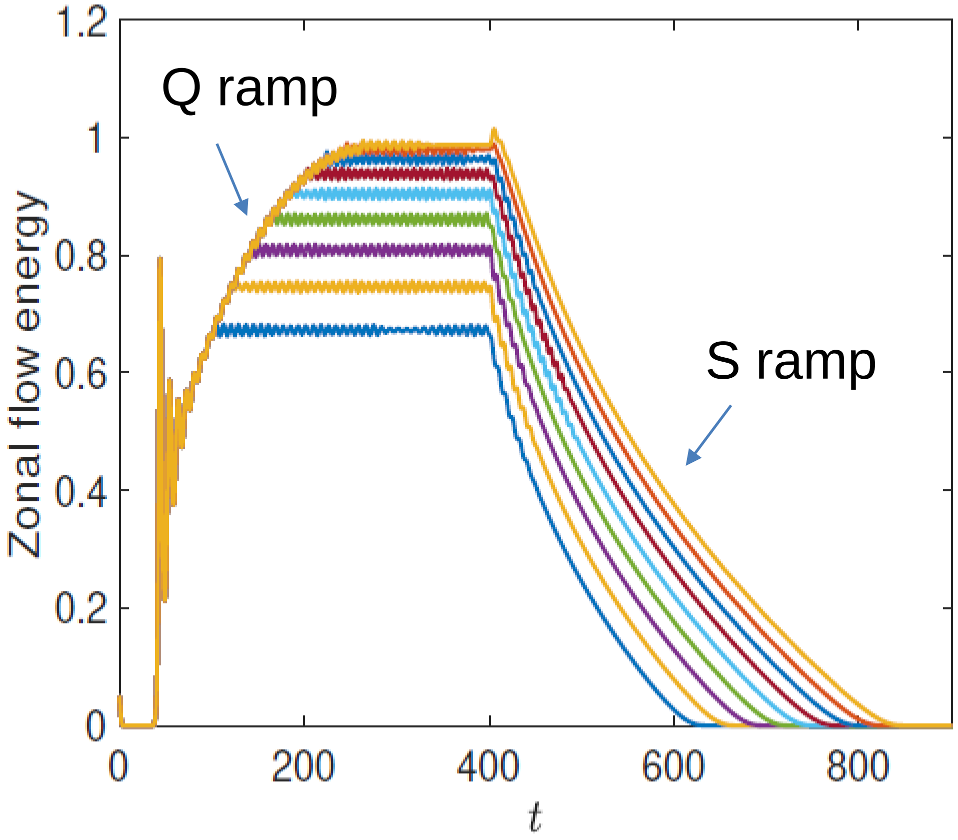
$$\mathcal{V} \equiv \frac{V_E' a}{\rho^* v_{thi}} = -\frac{n_0}{n} \mathcal{N} \left(\frac{n_0}{n} \mathcal{N} + \frac{T_0}{T} \mathcal{T} \right)$$



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

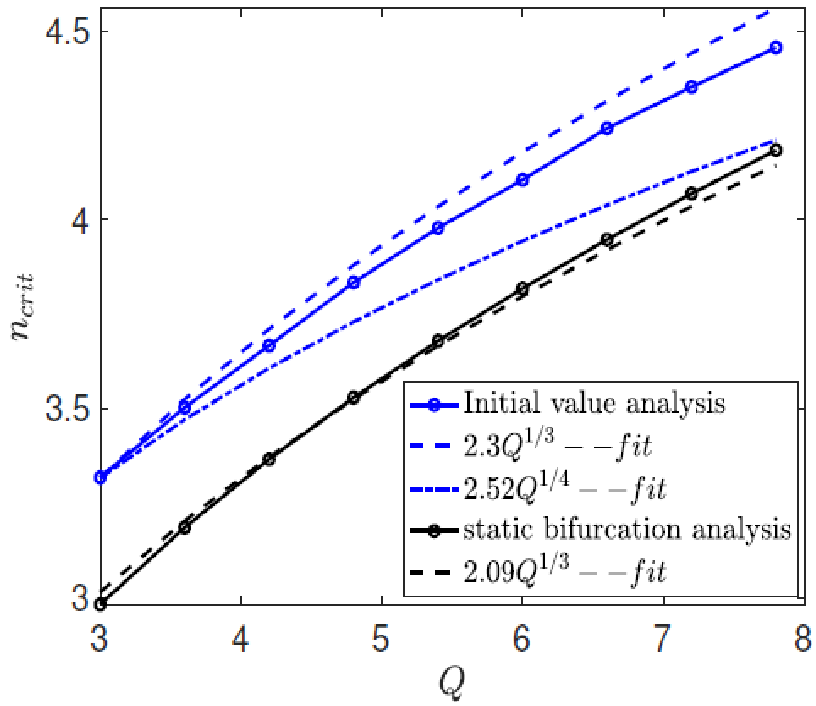
- Look for shear layer collapse
- Q ramp-up to L-mode, followed by S ramp-up
- Oscillations → predator-prey cycles
- n for ZF collapse increases with Q

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)"

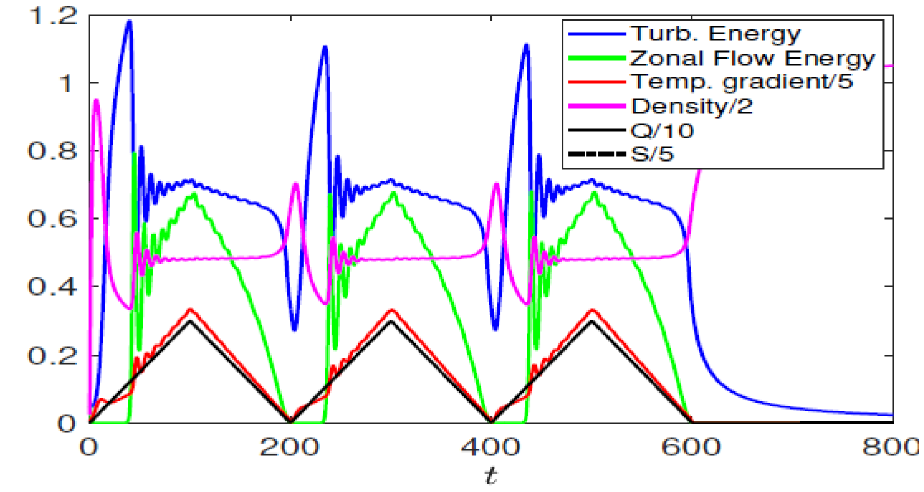
- Hysteresis ! in ε_{ZF} vs Q → Critical slowing down effect
- Expected, given 2 states transport
- Not familiar bistability ! → slow mode
- Physics prediction… beyond scaling

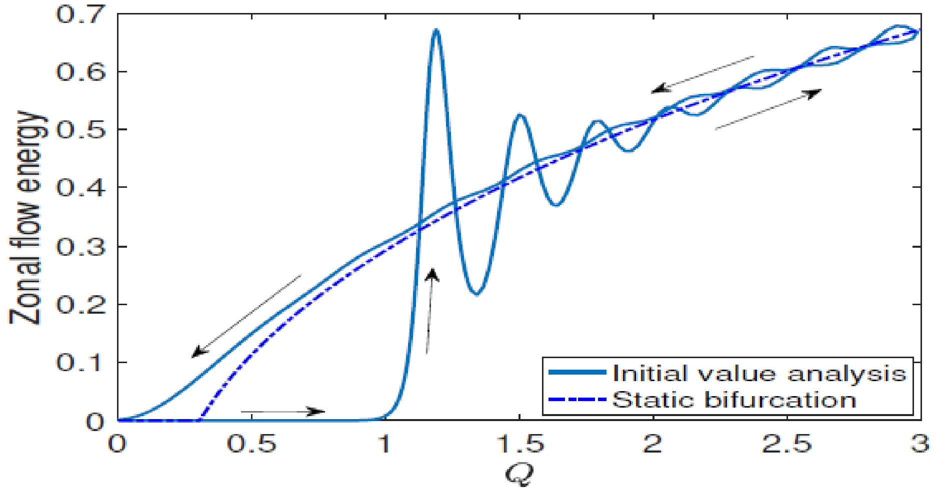
Also:

- 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





Critical Experiments

i) NT – Expanding the Dynamic Range of Power for LDL

(R. Hong+, in prep.)

ii) Bias Probe – Separating Power, V'_E, α

(R. Ke, P.D.+ NF 2022)

Critical Experiment I:
NT Density Limit Studies (DIII-D) (Sauter, Hong+ 2024)

Stay Tuned

- $\bar{n} \sim 2\, n_G$ achieved with ~ 10 MW NBI.
- 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}

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

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

Caveat Emptor

- Confinement degrades above n_G? – Major question…
- Disruption for $\alpha \leq 1$ at resonant q ! → $\alpha(r)$!?

NB: High β_p, <u>peaked density</u> DIII-D dose not degrade τ_E above n_G (DIII-D; Ding, Garofalo+ … c.f. Nature 2024)

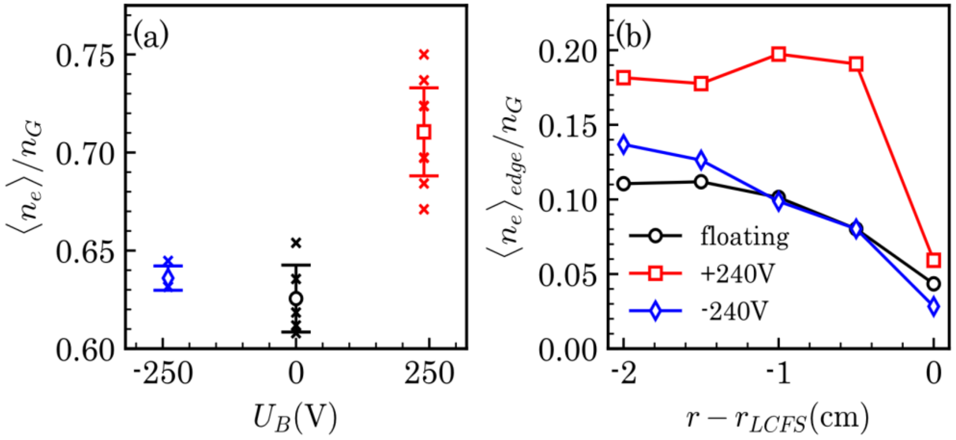
- Further NT DL experiments coming soon. Includes torque scan.

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. Drive an edge ExB shear layer
- New Here?
  - High Density
  - Gas Puffing → push on DL
  - Analysis

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

The Answer – Looks Promising!

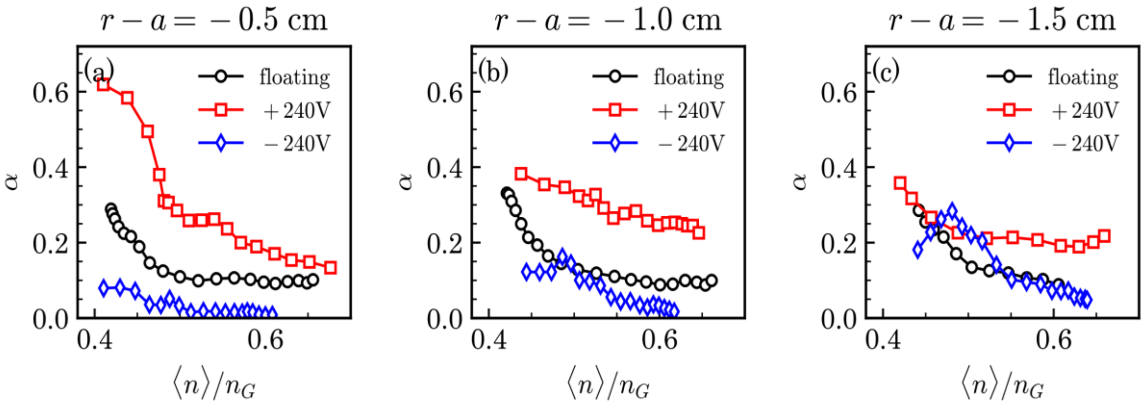


- Edge density doubled for +240V bias

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

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

Experiment limited by graphite probe sputtering



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

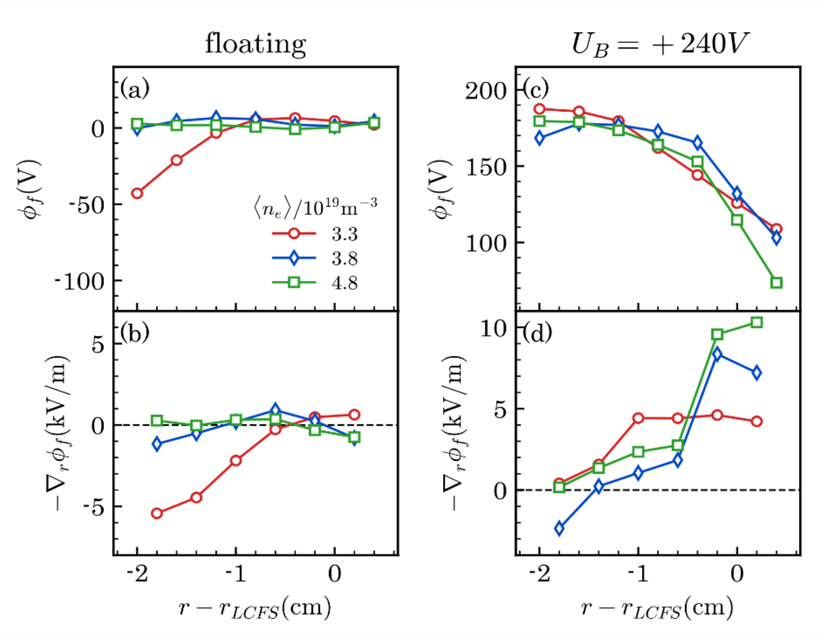
Reduced transport → higher T

- Turbulence spreading quenched by positive bias

The Physics

- Edge Shear Layer produced for +bias

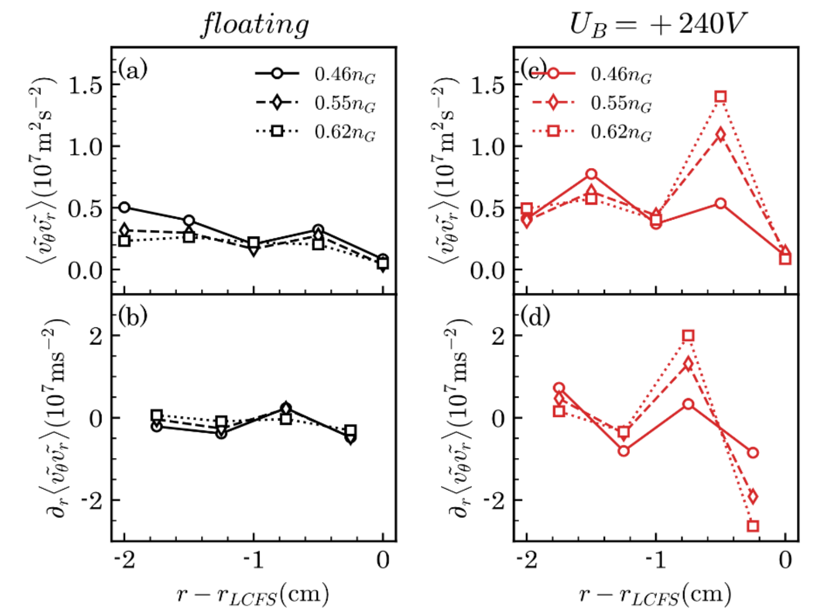
N.B. Not an E_r well



- Reynolds stress, force increase for +bias

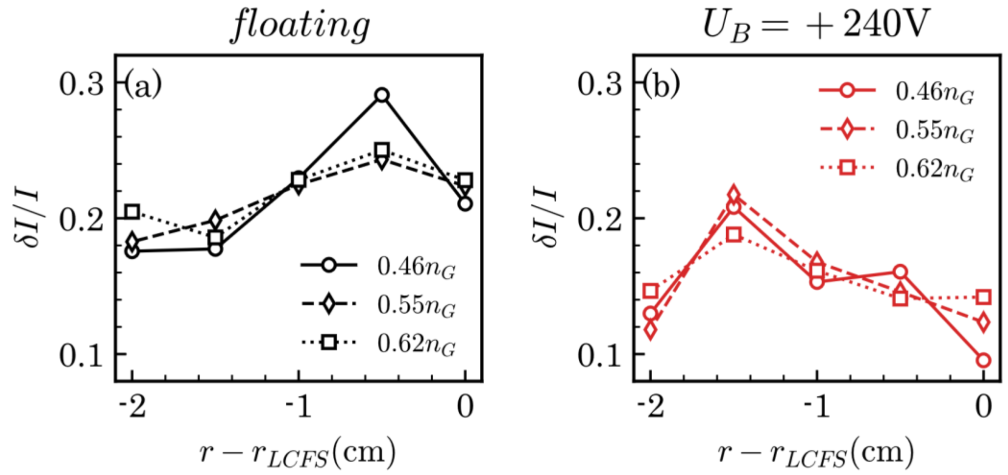
←→ bias effect on eddy alignment

“Shearing” ←→ interplay of bias and Reynolds stress

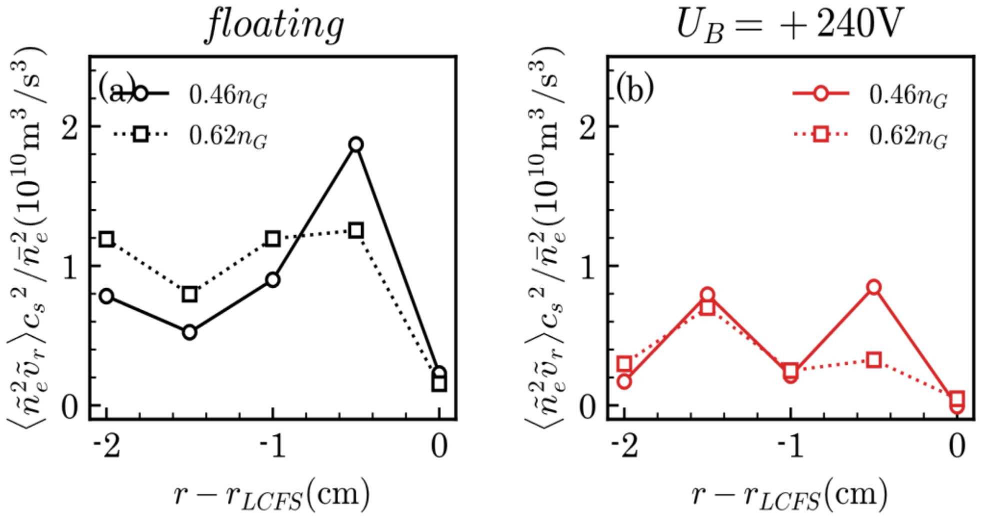


The Physics

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



- Turbulence spreading quenched by +bias



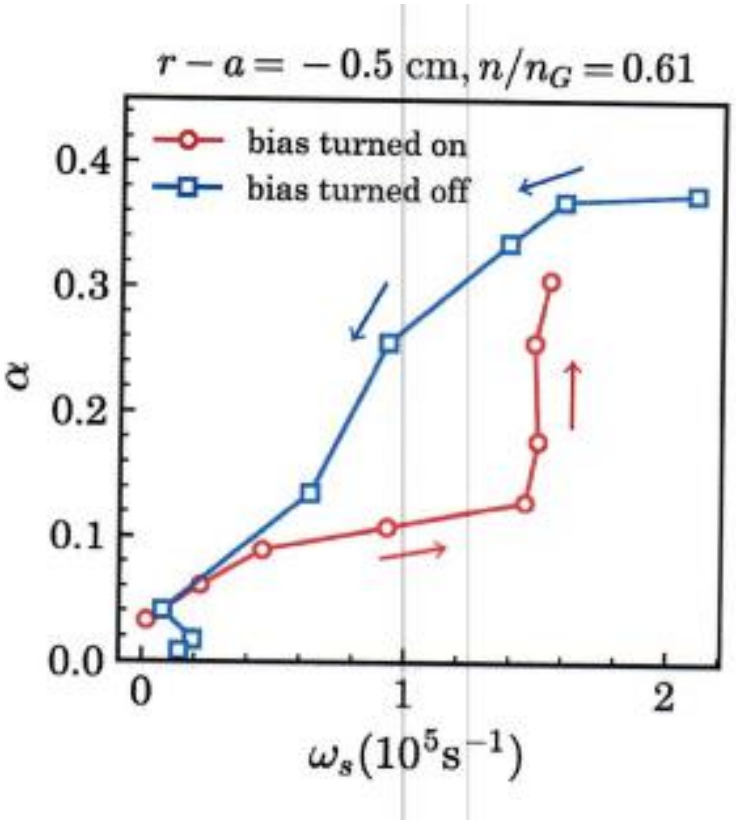
$$\langle \tilde{v}_r \tilde{n} \tilde{n} \rangle$$

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):

  Ip ramp down explained via $\omega_{shear}\ \tau_{cor}$
- Physics of spreading (Long, PD+ 2024)
  - Spreading ←→ Blob emission
  - Broken symmetry: “Spreading” dominated by large blobs

From L-DL to H-DL – More shear layer degradation

- H-mode density limit is <u>back transition</u> H→L at high density,

  usually followed by progression to $n_{\text{Greenwald}}$

- Key issue: Gentle "pump-and-puff" (Mahdavi) has beat Greenwald
  ←→ strong shear layer… Not a clear boundary…
- Candidates
  - AUG: α_{MHD} at separatrix (Eich, Manz)
  - Goldston, Brown: Conduction broadens SOL, reduces V_E' →

$$\lambda:\ v_D * \begin{cases} \cancel{\tau_T} \\ \underline{\tau_{\text{cond}}} \end{cases}$$

(collisionality !)

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

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

γ_{Int} V_E'

- 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

L-DL to H-DL, Cont'd

- SOL scenario
  - Do SOL turbulence levels increase in conduction dominated regime. Critical n?
  - Is there inward spreading from SOL → pedestal ?! ETB penetration ?!
  - Critical pedestal fluctuation level to degrade ETB?
- α_{MHD} scenario
  - Does $\nabla P|_{sep} \sim \nabla P_{crit}$ drive pedestal fluctuations
  - E_r decay → pedestal stochastization
  - Collisionality dependence?

Computation Wish List – 2 Numerical Experiments

- High n ped. + fueling
  - $\nabla P|_{sep} \rightarrow \nabla P_{crit}$ response
  - Inward propagation due resp
  - Evolution of V_E'
- Return of local SOL turbulence in conductive regime?
  - Is it possible for turbulence to penetrate pedestal?
  - Conditions to degrade/destroy V_E'

Speculations / Questions

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

More Thoughts for ABOUND

- Edge shear layer evolution during gas puff → cooling, spreading (Blobs) response
- Grand Challenge: Integrate Transport + MHD (“Causality Simulation”)
  - When does enhanced transport trigger condensation + island growth ?
  - Combine: turbulence + radiation + MHD
  - Recovery for small perturbations ?! – Necessary for credibility
- Physics of Power Dependence → mean shear, ZF? Negative Triangularity desirable ←→ DIII-D comparisons
- Need combine GK + BOUT

Thank You !

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