Microphysics and Macrophysics of the Tokamak (Edge) Density Limit

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Two Themes:

- Microphysics: Edge turbulence as n/n_G increases – shearing layers, Kubo number, Production Ratio

- Macrophysics: Radiative condensation → Strong particle flux → Scalings beyond Greenwald (especially 'power')

- Principal Collaborators:

  Rongjie Hong, Ting Long, Rameswar Singh,

  Jingtong (Peter) Sheng, Ting Wu

- Ackn Collaboration of:

  DIII-D, HL-2A, J-TEXT programs

General Ideas

- Mixed experimental + theoretical approach
- Emphasis on dynamics, micro-macro connection, fluctuation structure
- Focus on L-mode DL
- Toward DL as a confinement transition
- N.B. Focus on edge fueling (relevance)

Preview: From there to here of DL

- Greenwald (1988) scaling → Wrong → Power Scaling, Multiple Limits

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

- Sudo (1990) Scaling (stellarator) → mainstream, albeit incomplete → G + S unification

  $\bar{n} \sim P^{1/2}$ Transport Physics Central

- DL as MHD + Disruption phenomenon → frequently, even usually, not

  Rebut, Gates, White

- DL as a 'Back-Transition' → from heresy to convention
- Radiation triggers MHD → Rad. triggers transport...
- Better Density 'Saturation' than 'Limit' !

Basic Ideas

Why Study Density Limits?

- Interested in max density - both line averaged and edge
- Constraint on operating space

  Lawson # ~ $n\,T\,\tau_E$

- Fusion power gain → $P \sim n^2 \sim \beta^2 B_0^4 R^3$ (MIT favorite)
- Emerging attractive feed back loop for burning plasma

  $P_{\text{fusion}} \sim n^2$ (β^2 + ITG limits on ∇T_i steepening)

  $n_{max} \sim P^{\alpha}$ ($0 < \alpha < 1$, but which P in BP?)

A Brief History of Density Limits → Conventional Wisdom

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

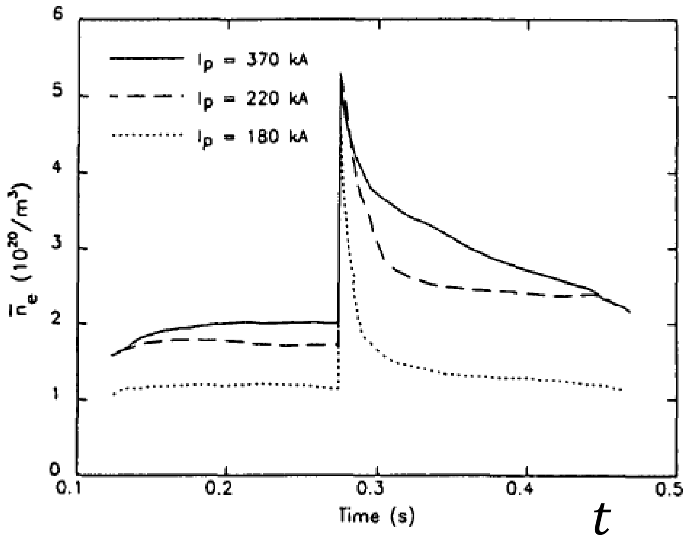
  MARFE = Radiative Condensation Instability in Strong B_0

  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)

$\bar{n}_e$



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(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?

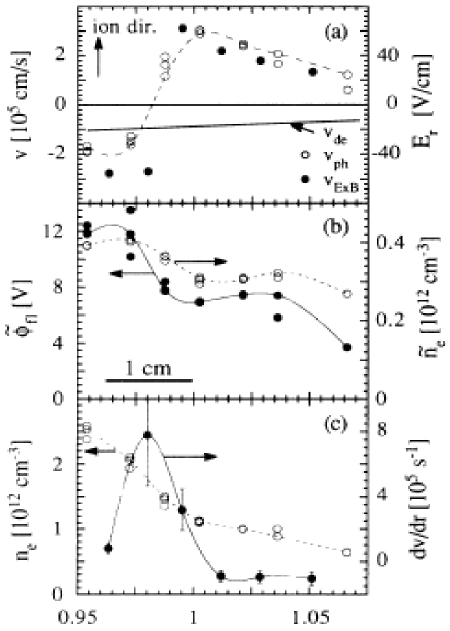
Shear Layer in L-mode? – Universal Feature of Edges

- 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

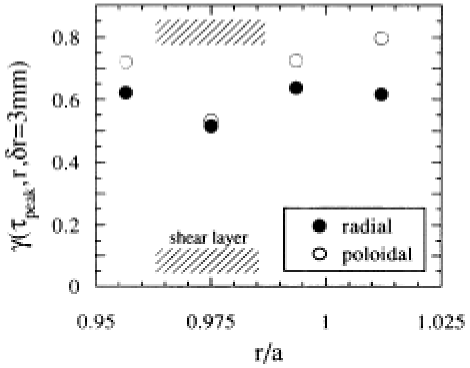
density



V'

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

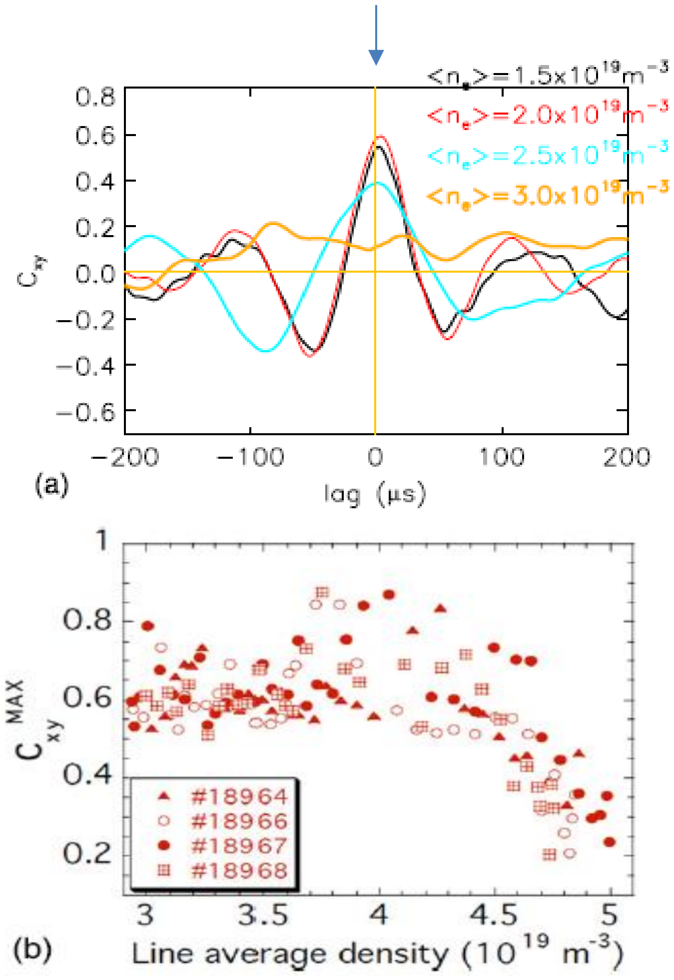
Title: “Evidence for Confinement Improvement by Velocity Shear Suppression of Edge Turbulence”

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 !

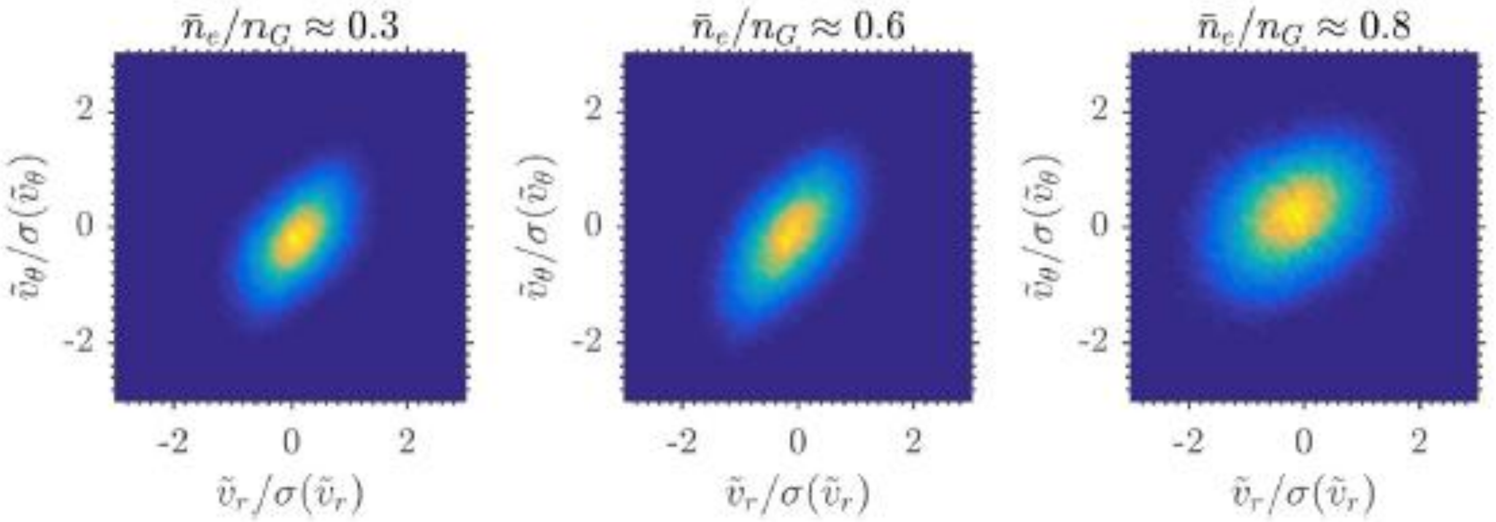
Reynolds work (Flow production) drops as $n \rightarrow n_G$ (Hong+ '18)

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

Reynolds Power (Flow Production)

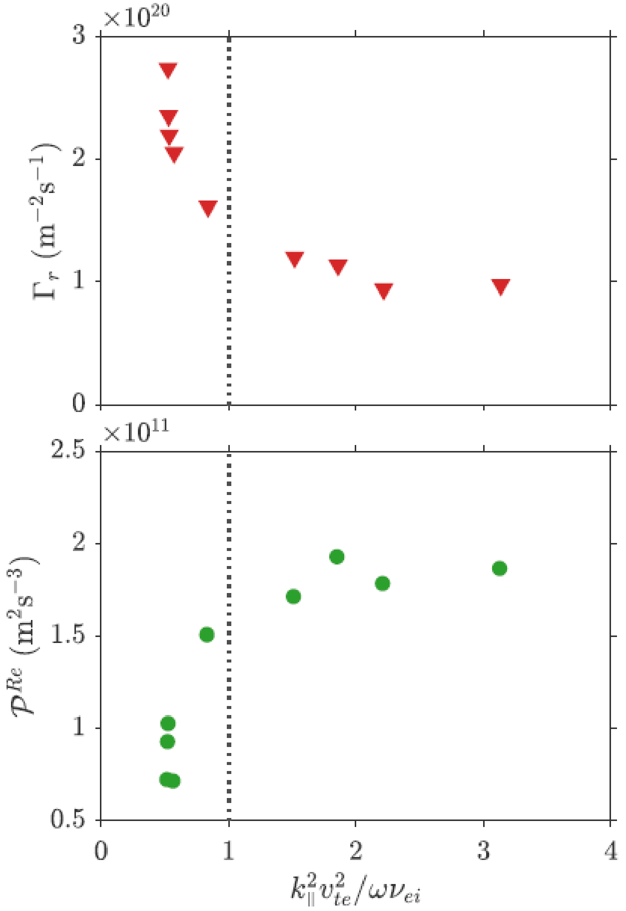
- Studies of $P_{Re} = -\langle \tilde{v}_r \tilde{v}_\theta \rangle \, \partial \langle V_E \rangle / \partial r$ vs n/n_G

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

adiabaticity

$\alpha \ll 1$ → celluar, hydro turbulence ~ 2D

$\alpha \gg 1$ → drift wave turbulence



Particle flux surges for $\alpha > 1$

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

→ Is DL evolution linked to degradation of edge shear layer ?

→ Adiabaticity as key parameter

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

See also: PD + Phil Trans 2024, T. Long, P.D.+, NF 2024

N.B. These experiments were “theoretically motivated”

J-TEXT – Ohmic

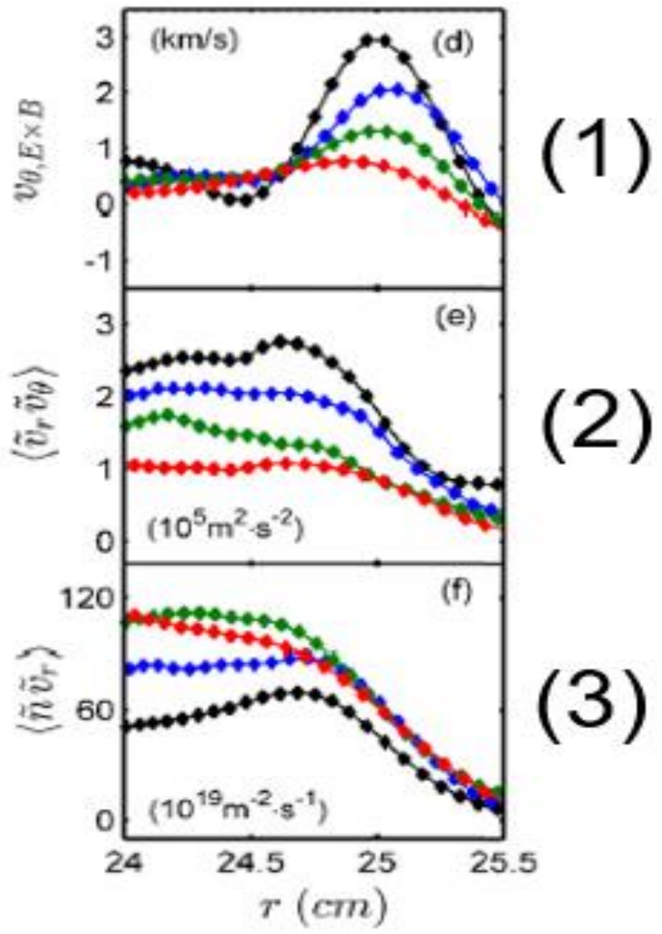
Black - $0.3n_G$

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 collapses 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

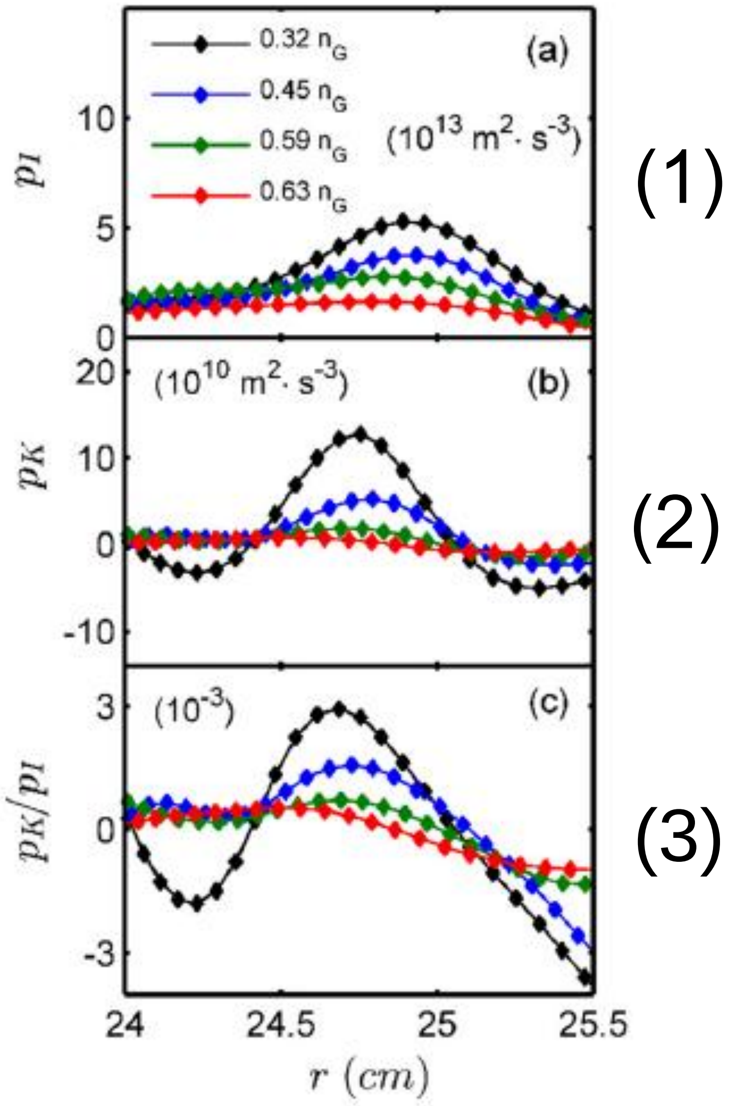
$$P_k = -\langle \tilde{V}_r \tilde{V}_\theta \rangle \langle V_E \rangle'$$

– 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

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

Triplet → $\langle v_r \varepsilon \rangle$; Production → P_I; Spreading → $\frac{\partial}{\partial r}\langle v_r \varepsilon \rangle$

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

- Then P_S → Power coupled to fluctuation energy flux → Turbulence spreading

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

→ Turbulence Spreading Power

- Turbulence Spreading encompasses "Blob" and "Void" propagation

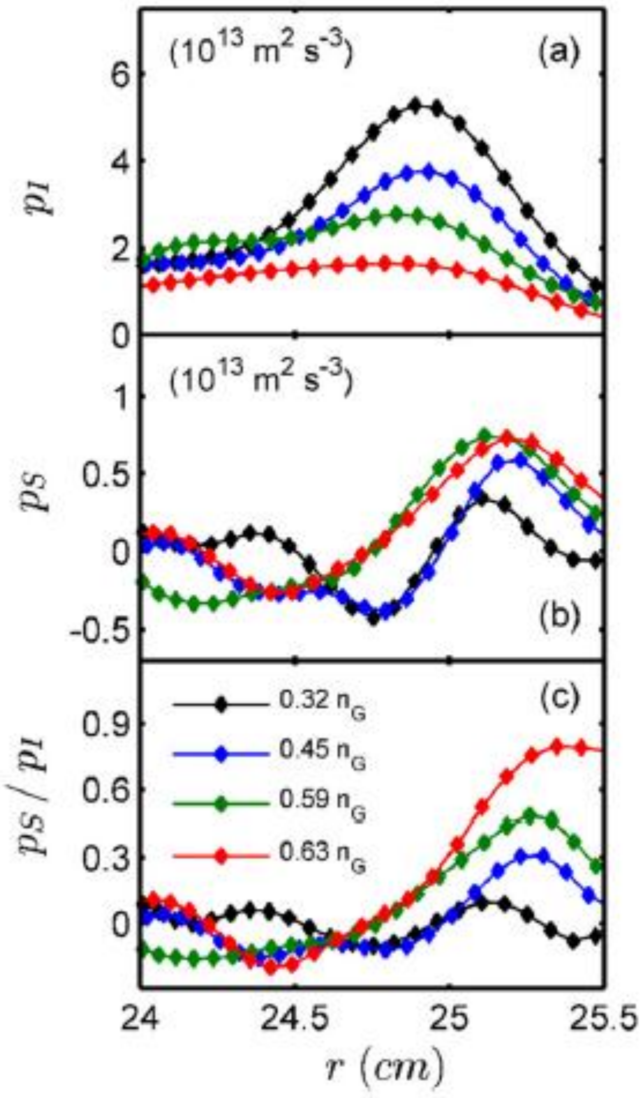
Fate of the Energy, Cont'd

- Turbulence Spreading !
  - Reynolds power drops
  - P_s <u>increases</u>; 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

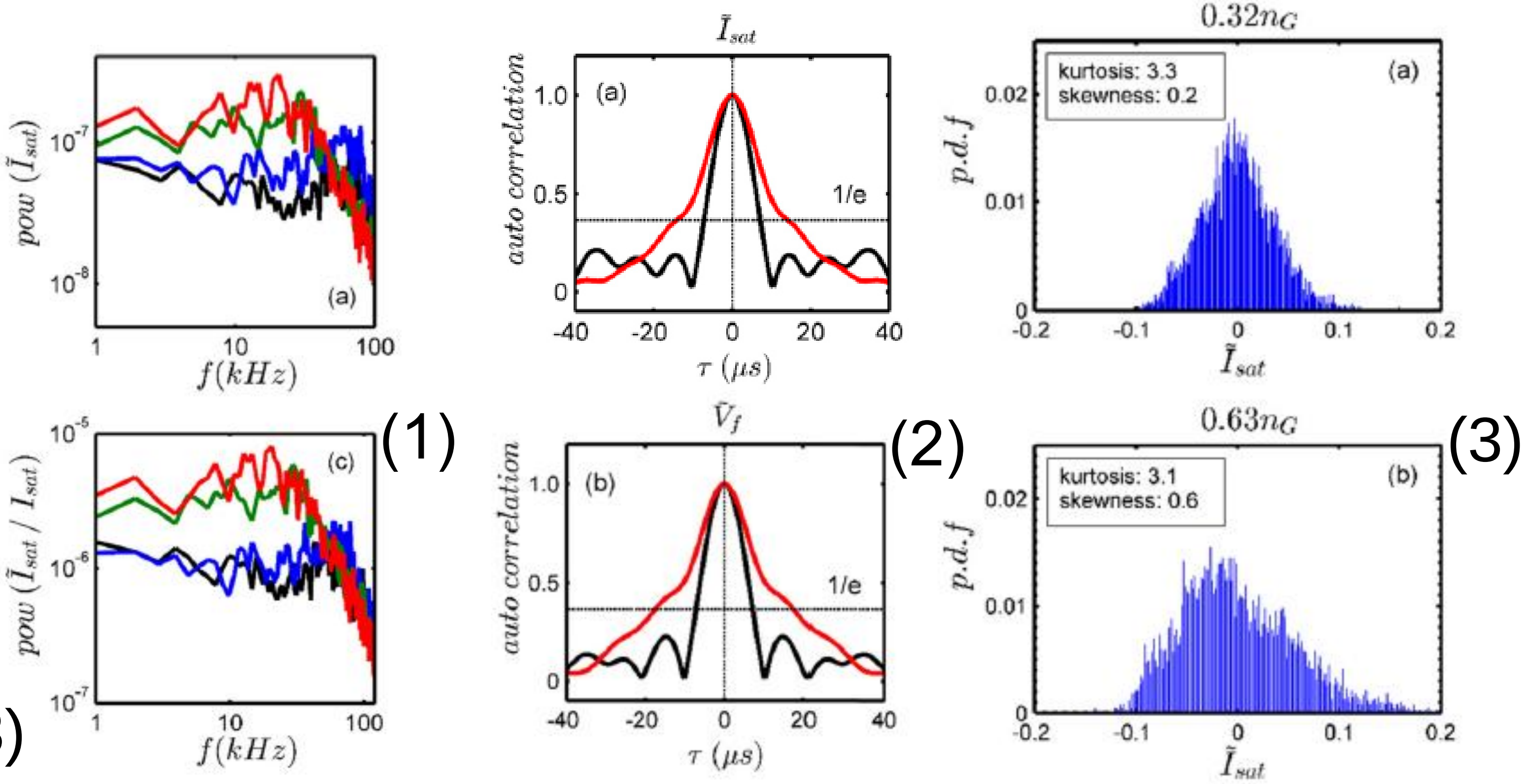


- N.B. Recent result (Long + 2024, N.F.): δ(spreading flux) is more robust indicator of DL then δ(particle flux)

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)



See also T. Long, P.D. NF 2024 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 $\alpha\uparrow$

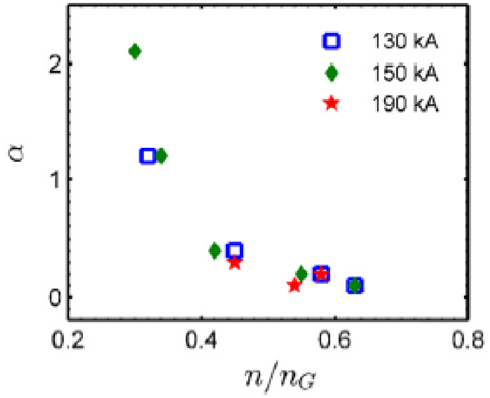
  $\sigma(\tilde{I})/I$ decreases with $\alpha\uparrow$

  P_s/P_I decreases with $\alpha\uparrow$

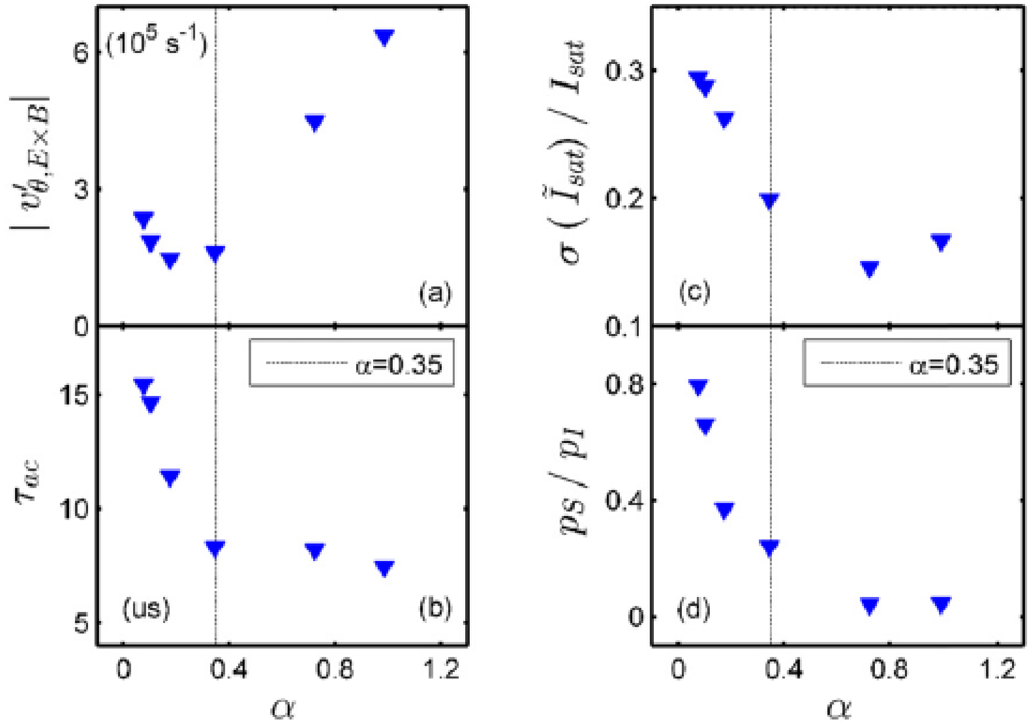
re: Adiabaticity

$\alpha > 1$ → drift waves

$\alpha < 1$ → convective cells



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

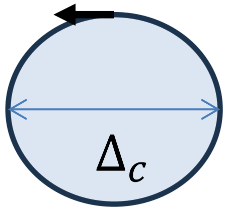


Microphysics of Edge Turbulence vs n/n_G

(with J. (Peter) Sheng, T. Long, T. Wu)

➔ How the Turbulence Evolves vs $n/n_G, I_p$ etc.

Microphysics of Edge Turbulence: A Tale of Two Numbers



$\tau_{flight} \sim \Delta_c/\tilde{V}$

- Kubo Number
  - Also Strouhal Number
  - Ku ~ $\tilde{V}\,\tau_{ac}/\Delta_c \sim \tau_{ac}\,/\,\tau_{flight}$ R. Kubo 1963
  - Auto correlation time vs time to advect over scale ~ "time of flight"
  - Derived from statistical theory of stochastic differential equations

Kubo #, continued

i.e. $\frac{\partial f}{\partial t} + \tilde{v} \cdot \nabla f + \ ... = 0$ Liouville, stochastic

$\rightarrow f = \exp\left[-\int \tilde{v} \cdot \nabla dt\right] f_0$

$\langle f \rangle = \langle \exp\left[-\int \tilde{v} \cdot \nabla dt\right] \rangle f_0$ Statistics, τ_{ac} crucial

$\rightarrow \langle f(1) f(2) \rangle = \left\langle \exp\left[-\int_{t_1}^{t_2} v \cdot \nabla dt\right] \right\rangle f_0(1) f_0(2)$

- Ku < 1 (short τ_{ac}) → many kicks in Δ_c scale

  → suggestive of diffusion, QL

- Ku > 1 (long τ_{ac}) → long auto-correlation time vs time of flight

  → coherency over many scatters

  → trapping, percolation … ? (~ frozen scatters)

Kubo # and MFE

- Reduced turbulence/transport models are unavoidable
- Virtually <u>all</u> reduced models are variations on the theme of quasilinear theory …

  $\tau_{ac} < \tau_{TR}, \tau_{ev}$

- Quasilinear theory ←→ Ku < 1

and/but:

- Ku ~ 1 is often said to be characteristic of plasma turbulence (simulations)

  $\tau_{ac} \sim \tau_{flight}$

  ←→ "Mixing Length Estimates" - $\tau_c \sim \tau_{flight}$

- What of Ku > 1 ?

"Contamination" vs Local Relaxation ←→ Turbulence Spreading, Avalanching, Blobs

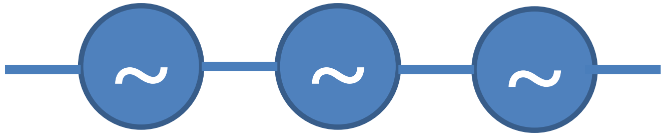
- Reduced models invariably posit local flux-gradient relation

yet:

- Intense consideration of turbulence spreading, avalanching etc. (cast of thousands)

←→ "Contamination Processes" – c.f. Y. Pomeau 1986

Re: Oscillator array



"… each oscillator if in a turbulent state may either relax spontaneously towards its quiescent state or contaminate its neighbors (if they are already turbulent, this interaction changes nothing)."

i.e. neighbor coupling ←→ drive

"Contamination" vs Local Relaxation, cont'd

∴

- Must incorporate contamination processes – spreading, etc. → intensity fronts, etc
- Spreading = 'contamination of stable region by unstable region' is for too limiting a definition

∴

- Need measure of drive via contamination vs production by local relaxation

➔ Production Ratio

(Pomeau Number ?!)

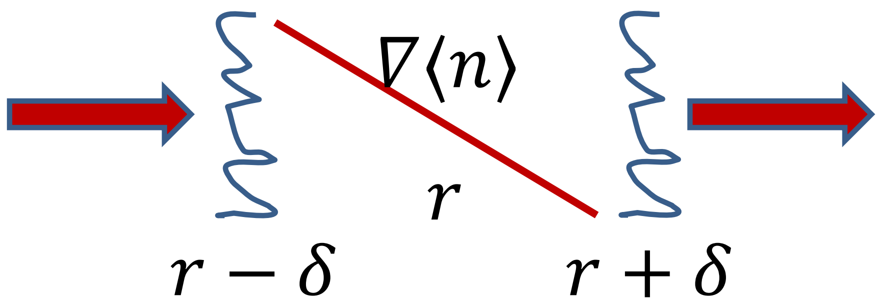
Production Ratio

(c.f. Manz; Wu, P.D.)

$$R_p\,(r,\delta) = \left[\Delta\langle \tilde{v}_r \tilde{n}^2\rangle \Big/ \left(-\int_{r-\delta}^{r+\delta} \langle \tilde{v}_r \tilde{n}\rangle \frac{\partial\langle n\rangle}{\partial r}\right)\right]$$

$$\Delta\langle \tilde{v}_r \tilde{n}^2\rangle = \langle \tilde{v}_r \tilde{n}^2\rangle\Big|_{r+\delta}^{r-\delta} \qquad \delta > \Delta_c$$

- Ratio of net spreading / contamination drive to net local production in interval



- $R_p > 1$ → turbulence intensity front driven region → contamination dominated

- Ku ←→ R_p ?!

Production Ratio

- Many versions of P_R possible, depending on quantity of interest
- For kinetic energy:

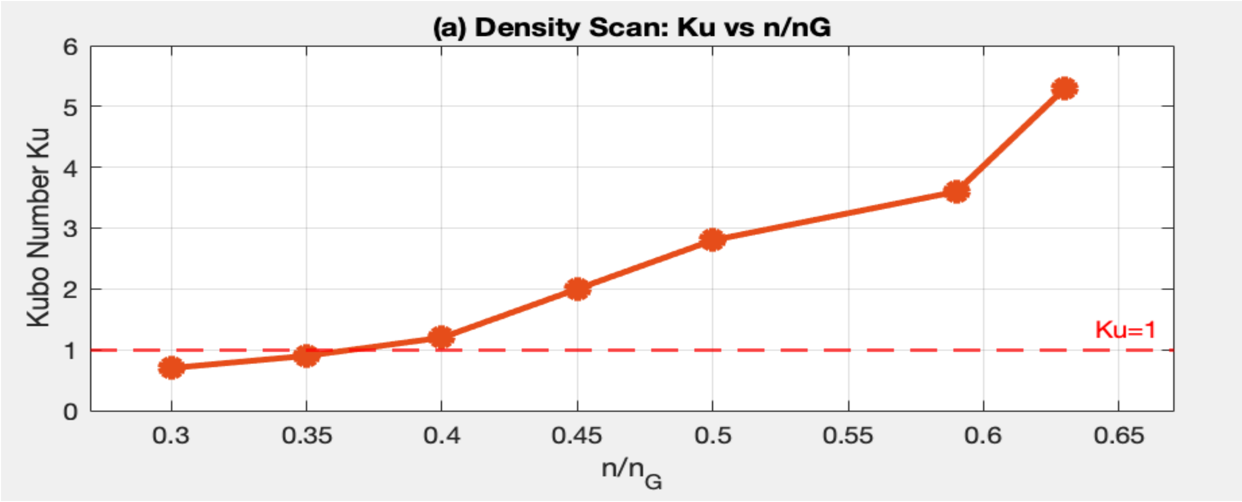
$$P_R = \Delta\langle\tilde{v}_r\tilde{v}^2\rangle \Big/ \int_1^2 dr \left[\frac{c_s^2}{R}\left\langle\frac{\tilde{v}_r\tilde{n}}{n_0}\right\rangle - \langle\tilde{v}_r\tilde{v}_\perp\rangle\frac{\partial}{\partial r}\langle v_\perp\rangle\right]$$

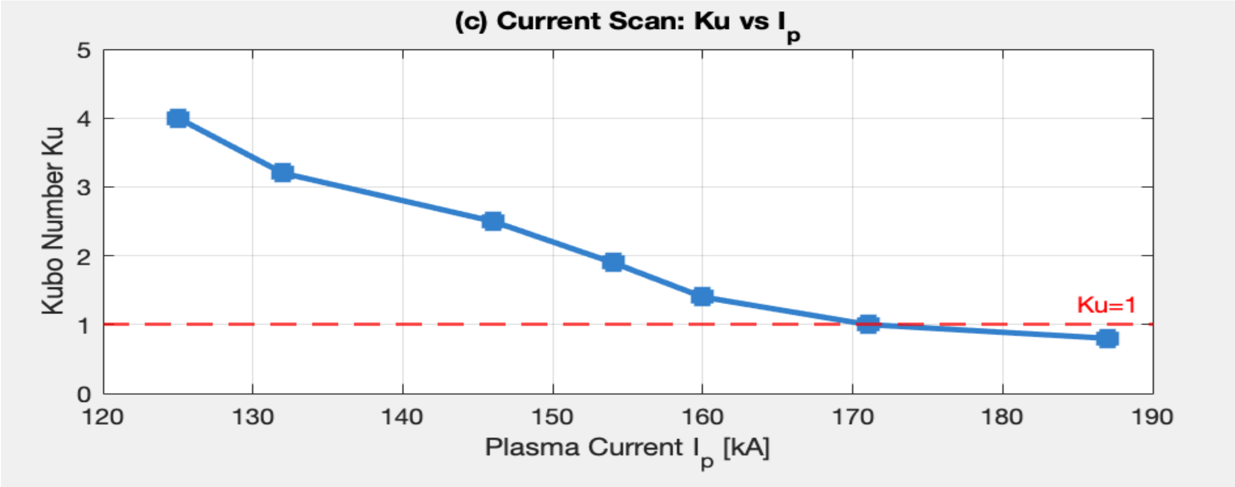
The Data

- T. Long+, NF`22, `23, `24 – J-TEXT n/n_G study

  T. Wu+, NF`23 – HL-2A
- Edge turbulence in OH
- Emphasis on n/n_G scan, but not only
- Langmuir Probes – full characterization (BES velocimetry → $\tilde{v}_r$, spreading)
- Also – Electrode bias data on J-TEXT
  – Control of shearing ←→ Fate of Ku, P_r

Results

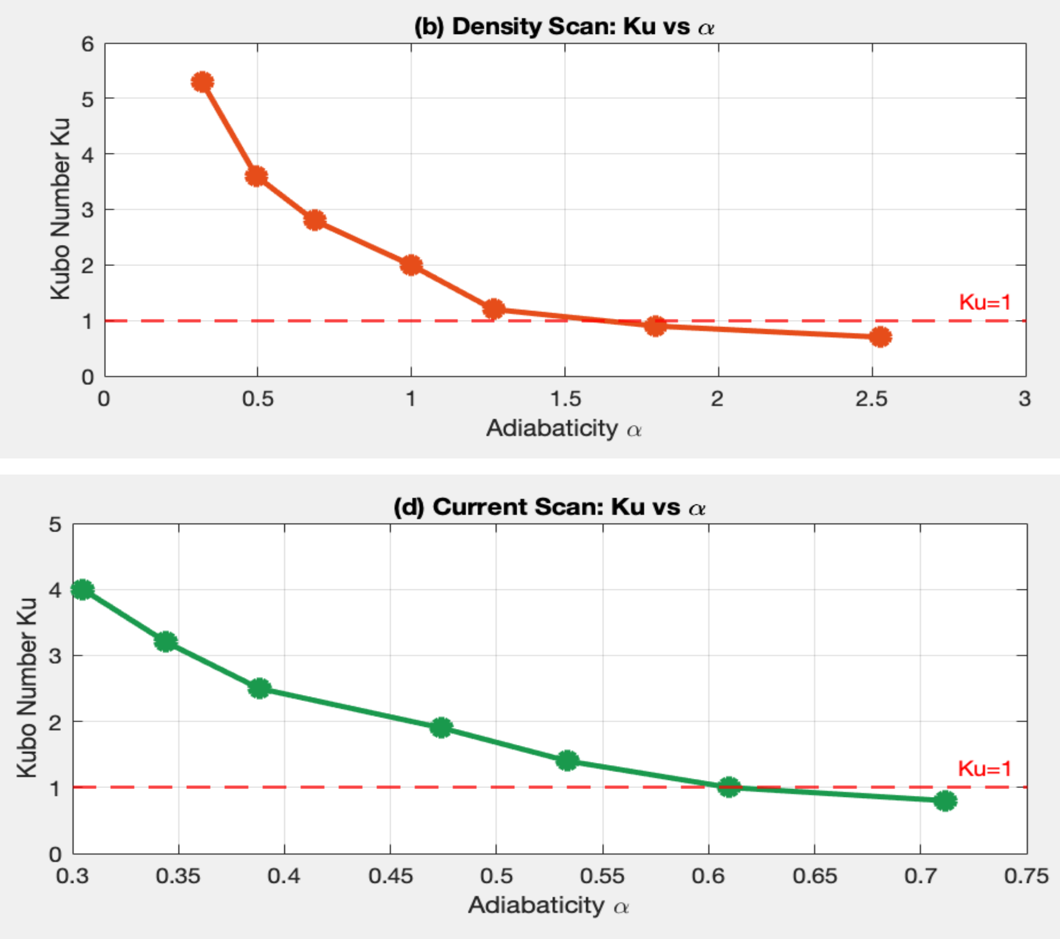




→ Ku >> 1 at 'large' Greenwald fraction !

Results, cont'd

- Physics parameter adiabaticity $\alpha = k_{\parallel}^2 V_{th}^2 / \omega \nu$



- Ku >> 1 in hydrodynamic regime → coherent cells

Results, cont'd

- What is the anomalous physics at Ku >> 1 ?

➔

- Blobs … (see previous)

- Interesting to define Ku_{Blob}

$$Ku_B \sim u_b \tau_{L,b} / \Delta_b$$

u_b ~ blob speed

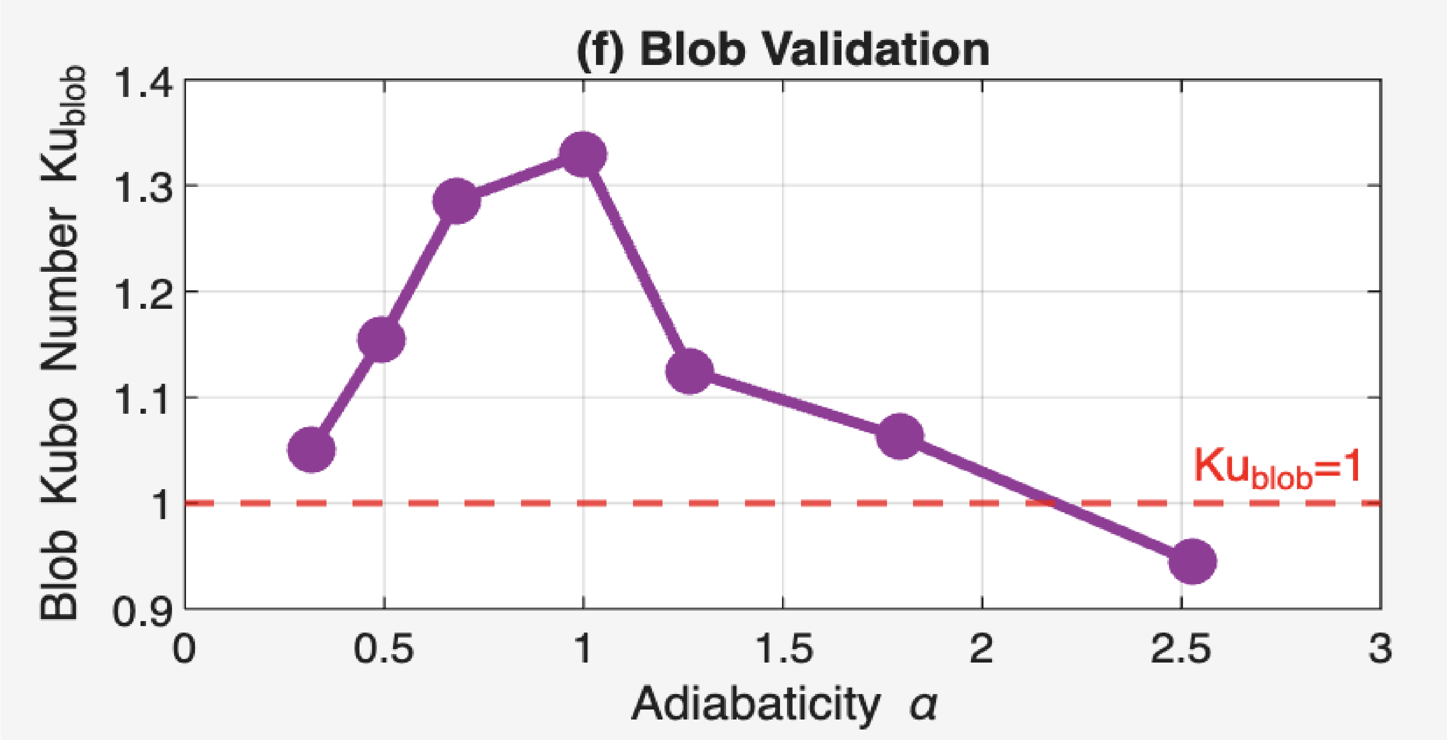
$\tau_{L,b}$ ~ blob life time

Δ_b ~ blob scale

~ analogous to Knudsen #

- If turbulence → ensemble of blobs, expect $Ku_B \rightarrow 1$

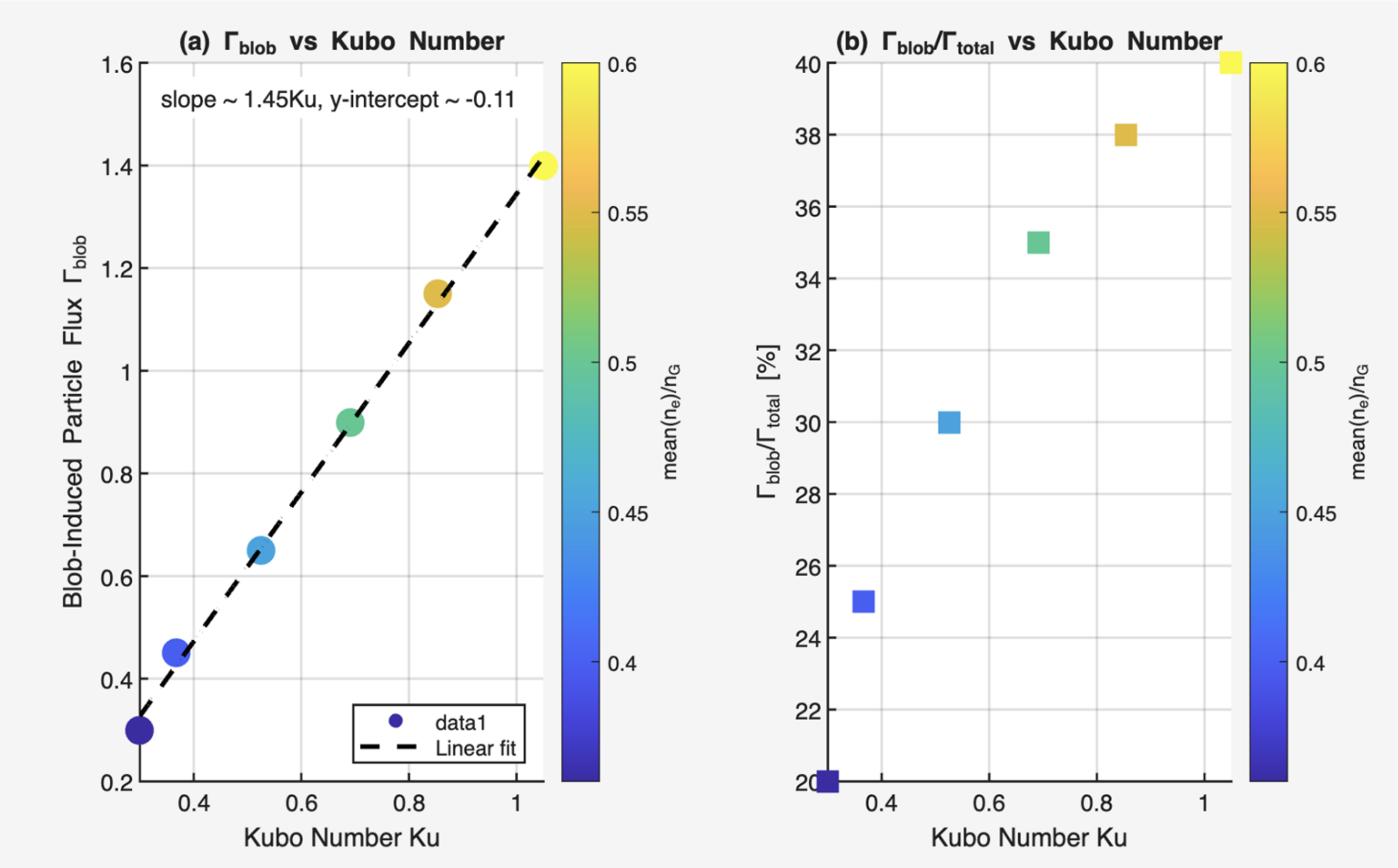
Results, cont'd



$$Ku_{blob} \sim 1$$

- At high nn_G, turbulence best modeled as a gas of blobs
- Message for edge modellers in relevant BP regimes.

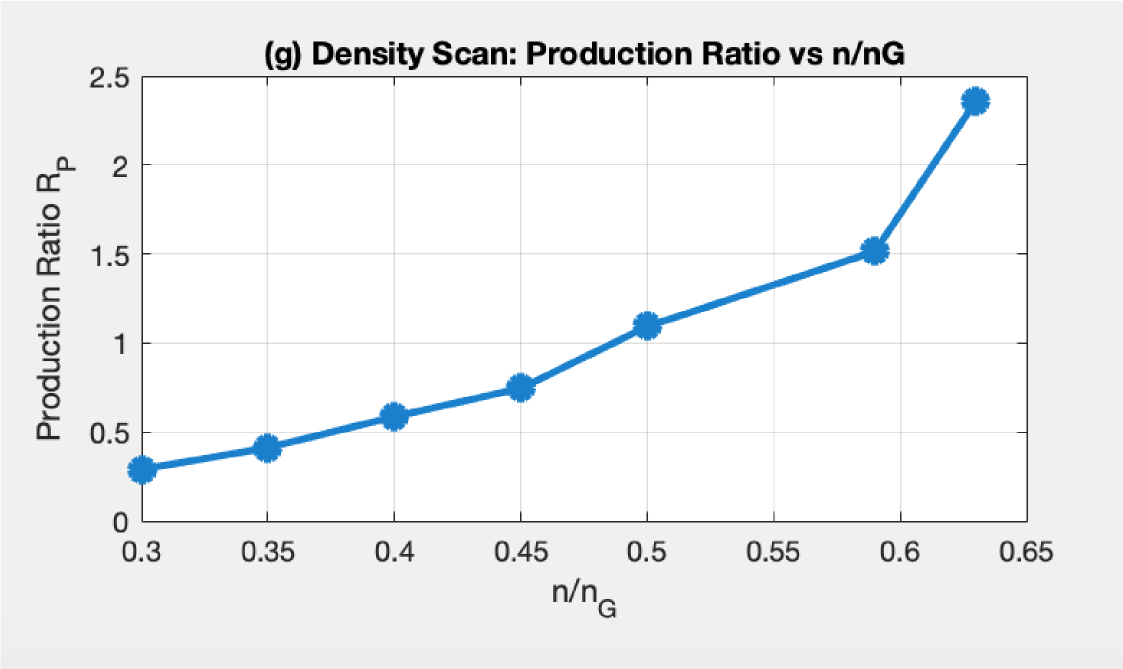
Results, cont'd



- Fraction of particle flux carried by blobs increases with Ku
- $\Gamma_{blob} \equiv$ particle flux windowed for blob contribution → conditional average

Results, cont'd

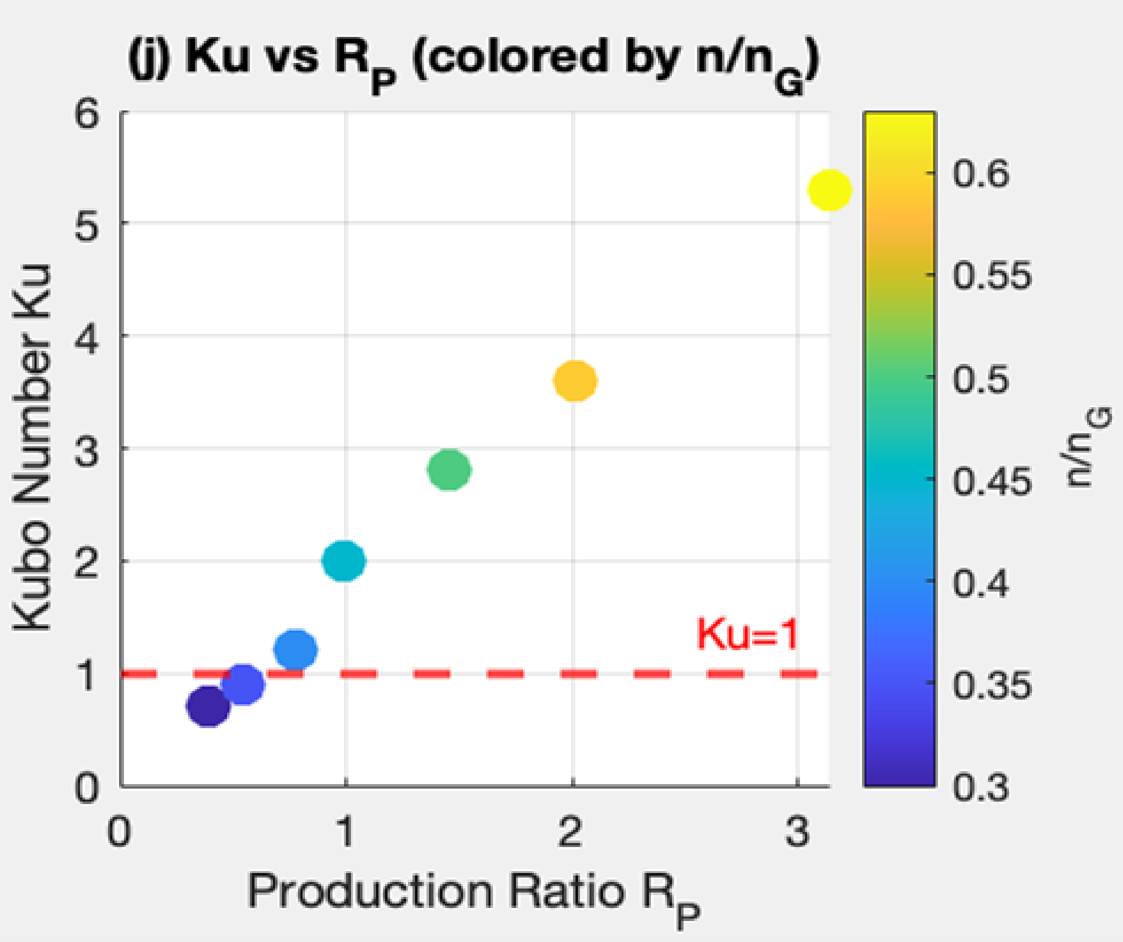
- What are consequences for relaxation?



- Production ratio R_p exceeds unity for large n/n_G

→ Blob turbulence pulse 'contamination' controls drive

Results, cont'd



- Ku closely tracks R_p
- $R_p > 1$ → Ku > 1

Long τ_{ac} phenomena linked to (generalized) turbulence spreading pulse

Results – General Lessons

- Ku > 1 happens in relevant, macroscopically stable edge regimes – i.e. DL

- Ku ~ P_R ➔ Spreading, contamination – due blobs – underlies Ku > 1 phenomena

- General question: Long τ_{ac} phenomena ←→ contamination connection (DIII-D upcoming – Kin, P.D., Zeyu Li)

Results – General Lessons

- Ku > 1 regimes – mode ensemble description is <u>pointless</u>

- Better: inhomogeneous turbulence closure model

  Output: $\langle \tilde{n}^2 \rangle, \langle \tilde{v}^2 \rangle$ etc.

Results – next

- “But what of gyrokinetics ?”
- Diagnosing/quantifying turbulence spreading is challenging in GK

  → local relaxation rarely vanishes…
- Kinetic Production Ratio (ITG)

$$P_R = d \int d^3v \, \langle \tilde{v}_\perp \tilde{g} \tilde{g} \rangle / R$$

$$R = \int_{r-\delta}^{r+\delta} dr \int d^3v \frac{|e|\langle f \rangle}{T} \left[\langle \frac{\partial \phi}{\partial t} \tilde{g} \rangle + V(E) \langle \frac{\partial \phi}{\partial y} \tilde{g} \rangle \right]$$

$$d(F) = F(r+\delta) - F(r-\delta)$$

- Extensions possible… P_R for moments, i.e. $\langle \tilde{v}_r \tilde{T} \tilde{T} \rangle$
- Formulate from 2pt theory $\langle \tilde{g}(1) \tilde{g}(2) \rangle$

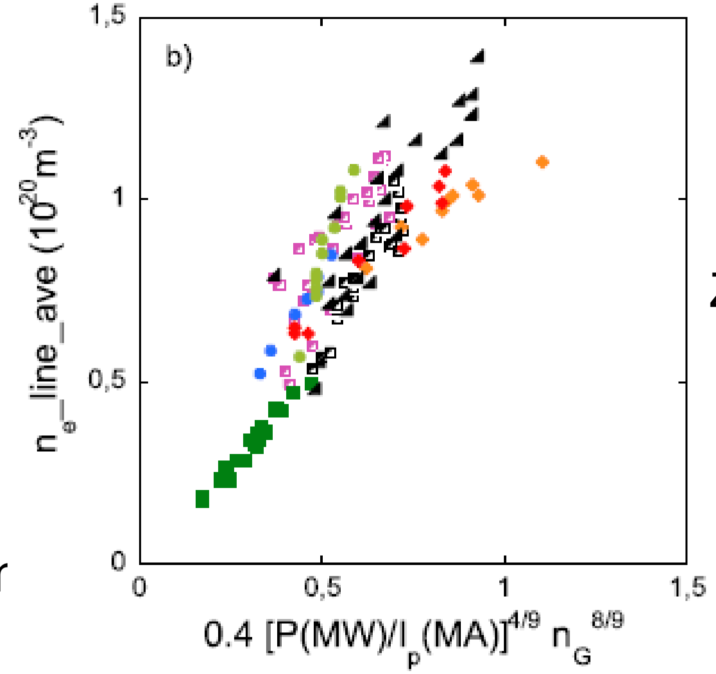
Density Limits beyond Greenwald …

➔ Power (Heat Flux) Scaling

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 ➔ $\bar{n} \sim P^{1/4}$
- Giacomin+: Simulations recover power scaling
- Observe: $Q_i|_{\mathrm{bndry}}$ will drive shear layer → LH mechanism
- So: $P_{\mathrm{scaling}} \leftrightarrow$ shear layer physics: a natural connection

  also support vs radiation
- $Q_i,\ Q_e$ at boundary as physical quantities



Zanca +

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

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

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

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

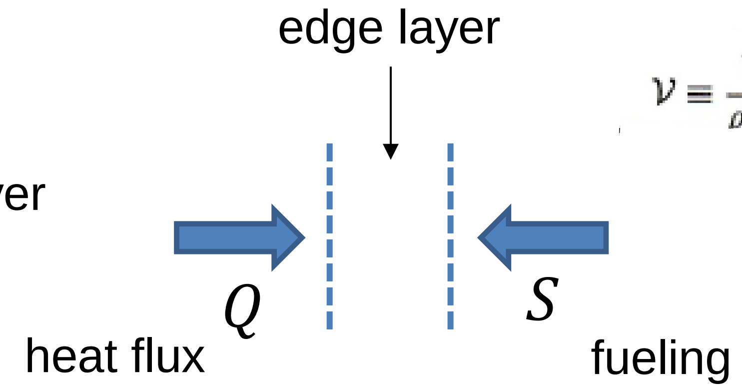
{ n, S → fueling

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

Shear (mean)

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

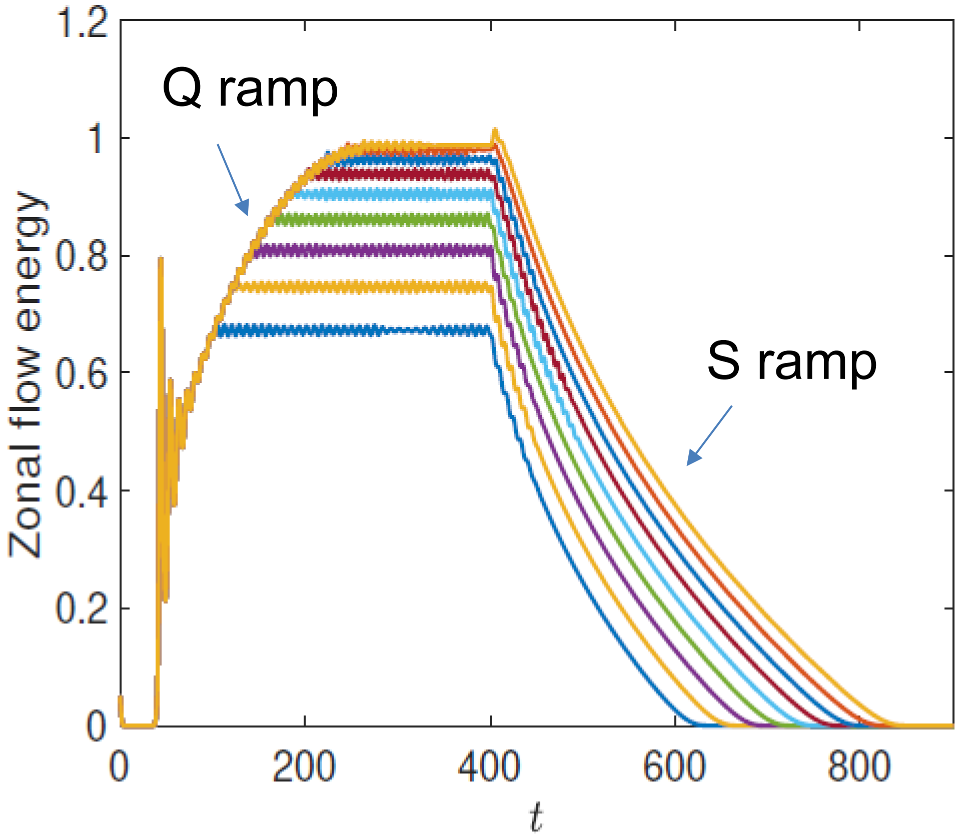
N.B. i) ZeroD → interpret as edge layer
ii) Does not determine profiles
iii) Coeffs for ITG



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

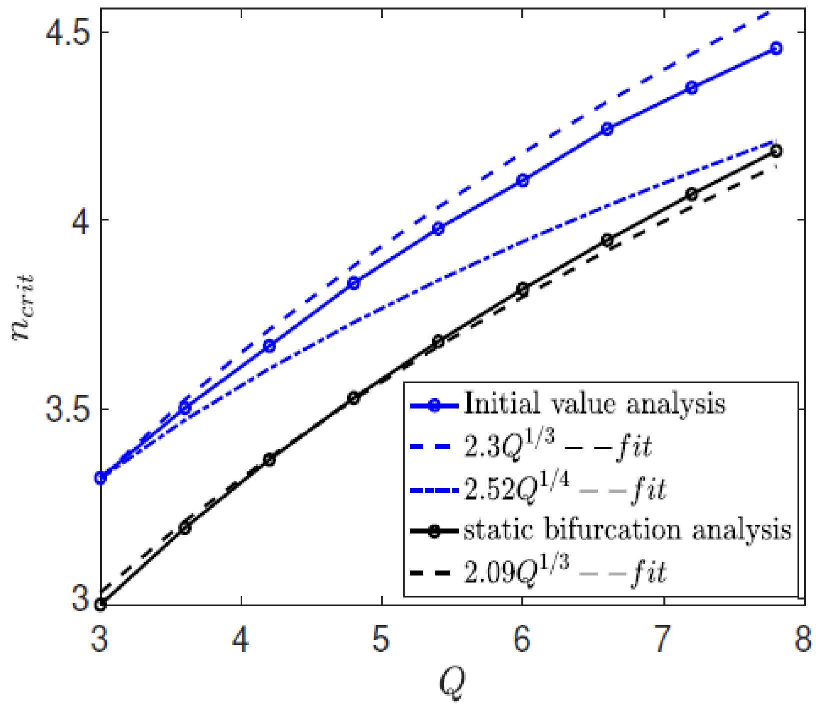
- Look for shear layer collapse
- Q ramp-up to L-mode, followed by S ramp-up
- Oscillations → predator-prey cycles
- n for ZF collapse increases with Q

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

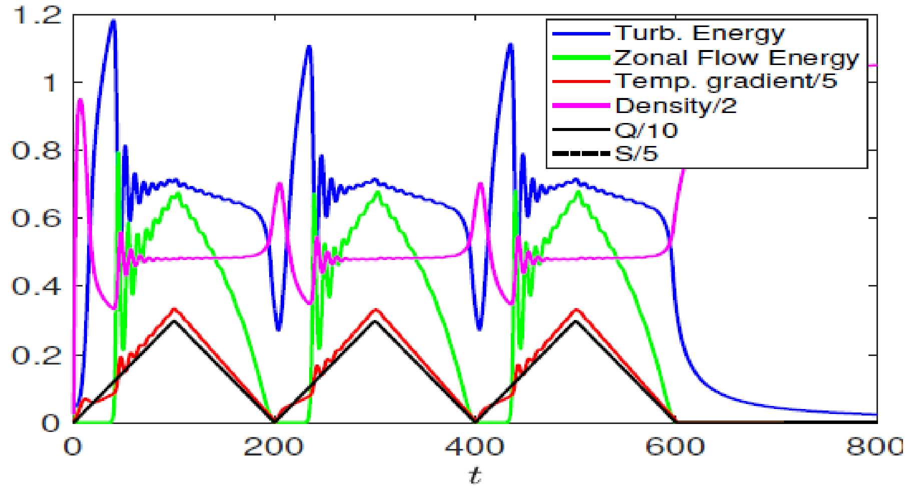
"If it Flux Like a Duck… (M.N. Rosenbluth, after F. Wagner)"

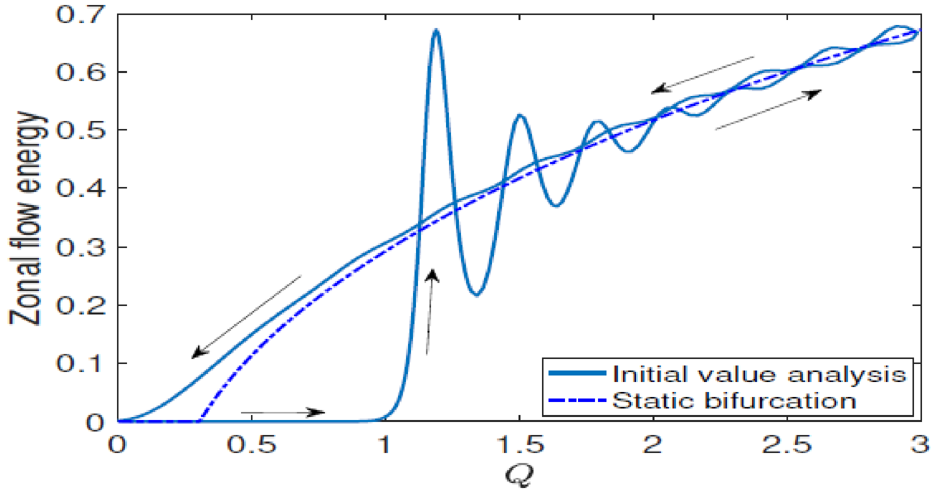
- Hysteresis ! in ε_{ZF} vs Q → Critical slowing down effect
- Expected, given 2 states transport
- Not familiar bistability !
- Physics prediction… beyond scaling

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





Partial Conclusions: V_E' as Ubiquitous 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
- Back Transition is in state of edge plasma.

Recent L-DL Experiments in DIII-D with NT

R. Hong, P.D., O. Sauter + → NF 2026

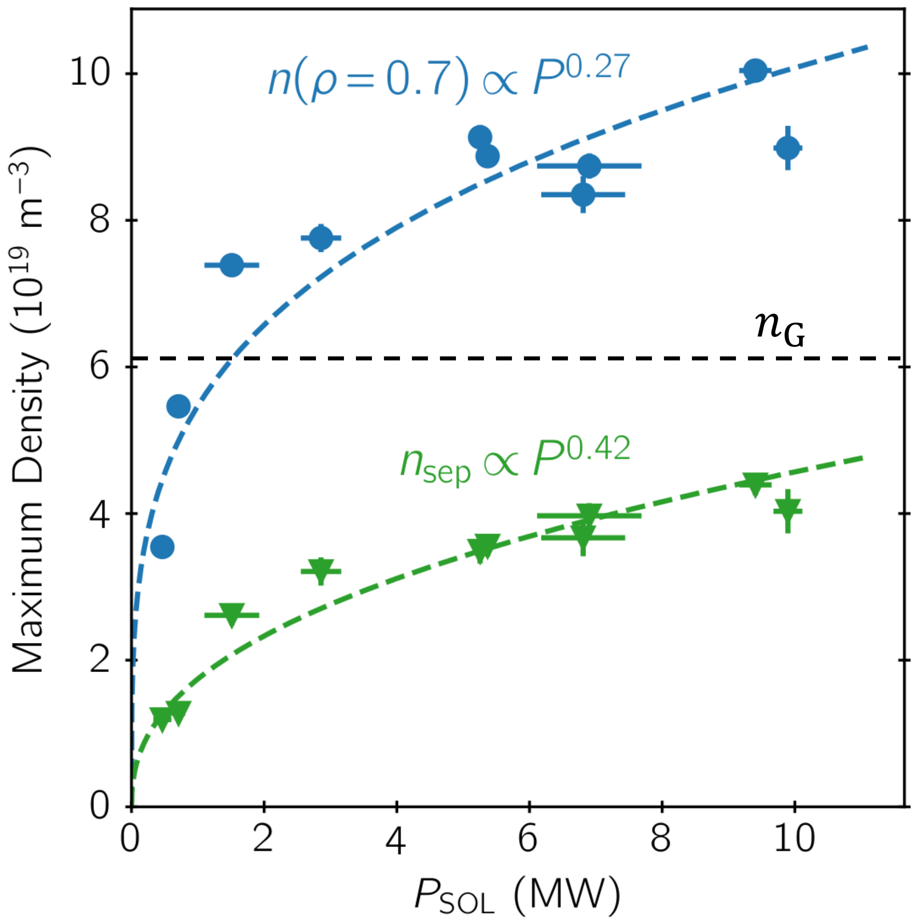
O. Sauter, R. Hong + → N.F. 2025

N.B. : - NT suppresses L→H transition, even at high power

- Extends dynamic range of P for L-DL studies

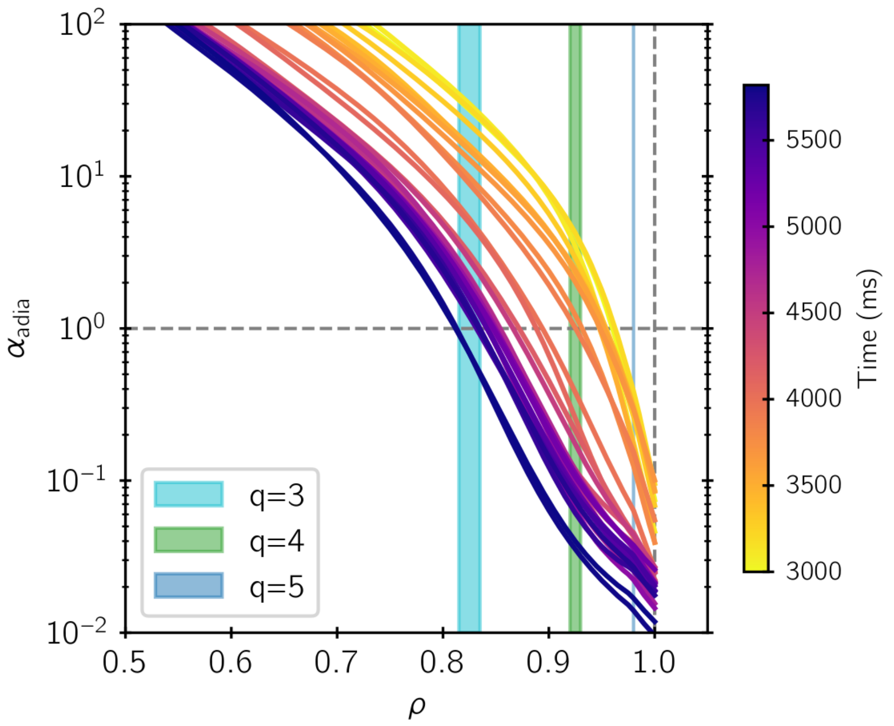
Power Scalings

- Distinct power scalings of sep. and core density, over wide range
- No unique "Density Limit"
- $n_{sep} < n_G$ but steadily increasing with power
- Most cases don't terminate in disruption
- Radial departure from conventional wisdom



Adiabaticity vs Time

- $\alpha = k_{\parallel}^2 V_{th}^2/\omega\nu$ drops, with low values penetraing inward with cooling
- Broad range of hydrodynamic turbulence develops after radiation

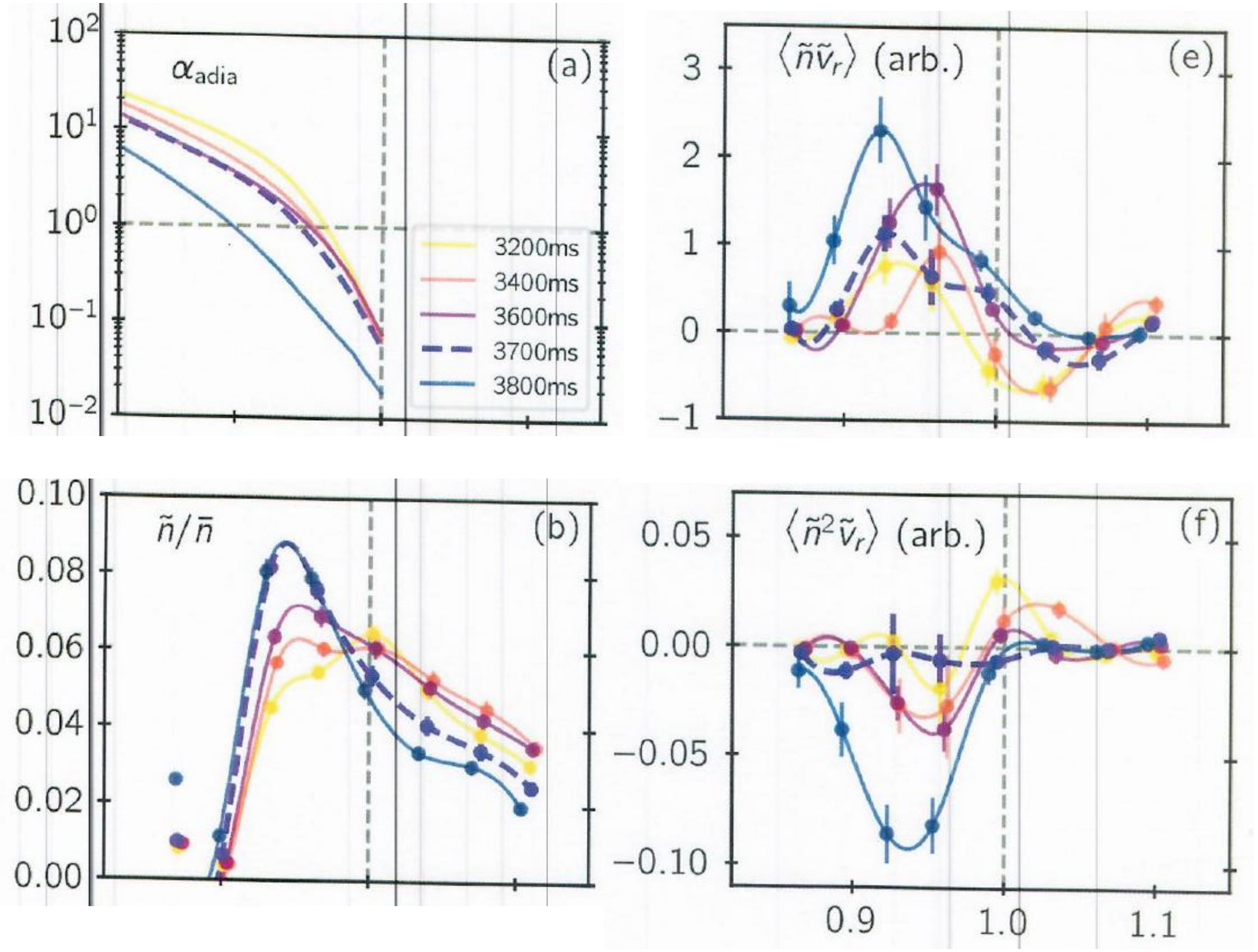


- $\alpha \leq 1$ at low q linked to disruption

→ proximity q_{res} to q_{95} relevant

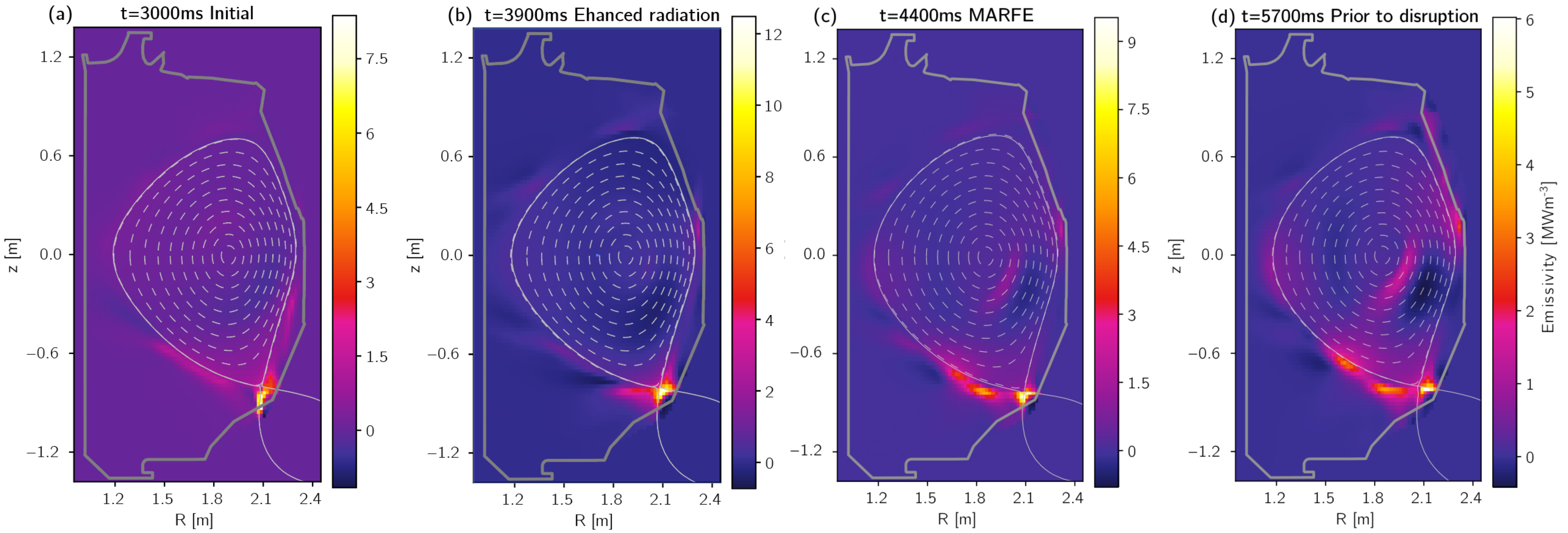
α, Transport and Spreading

- With strong radiation:
  - α drops
  - $\tilde{n}/n$ increases
  - $\langle \tilde{v}_r \tilde{n} \rangle$ increases
  - spreading flux $\langle \tilde{v}_r \tilde{n}^2 \rangle$ increases, spreading inward



- Suggests DL as Radiation ←→ Condensation ←→ Turbulent Transport Synergy

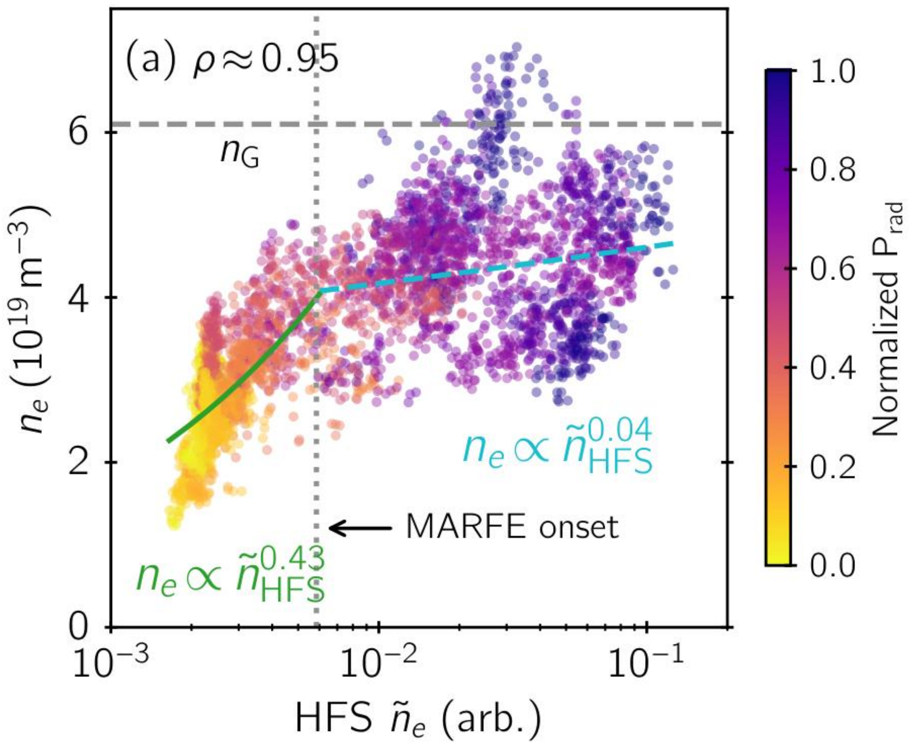
Evolution of Radiation and MARFE



- Edge density limit linked to radiation
- Disruption follows strong MARFE

Fluctuations and Density

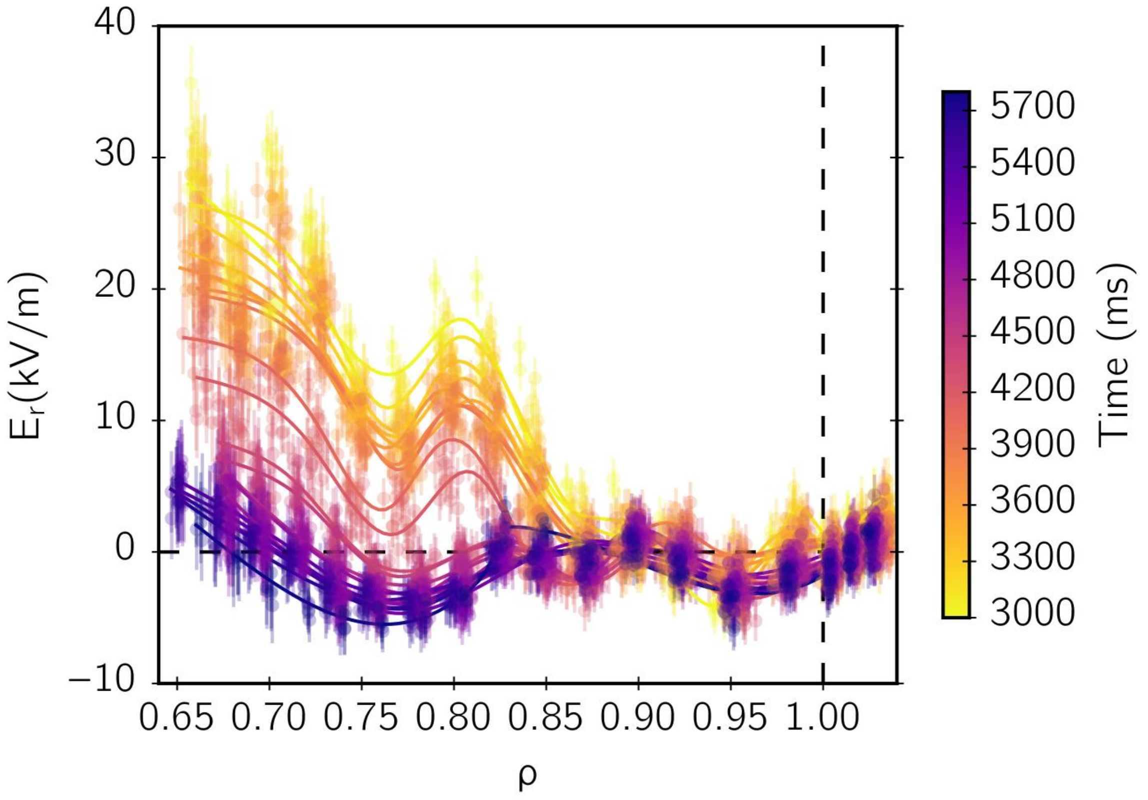
- Edge density rises with $\tilde{n}_{HFS}$ pre-MARFE
- Post MARFE edge density ~ "clamps", manifesting a 'limit', as $\tilde{n}_{HFS}$ increases.
- Broad ragne edge n_e, some exceeding n_G.
- Larger fluctuations and density saturation follow radiation onset.



Electric Field Shear Decays

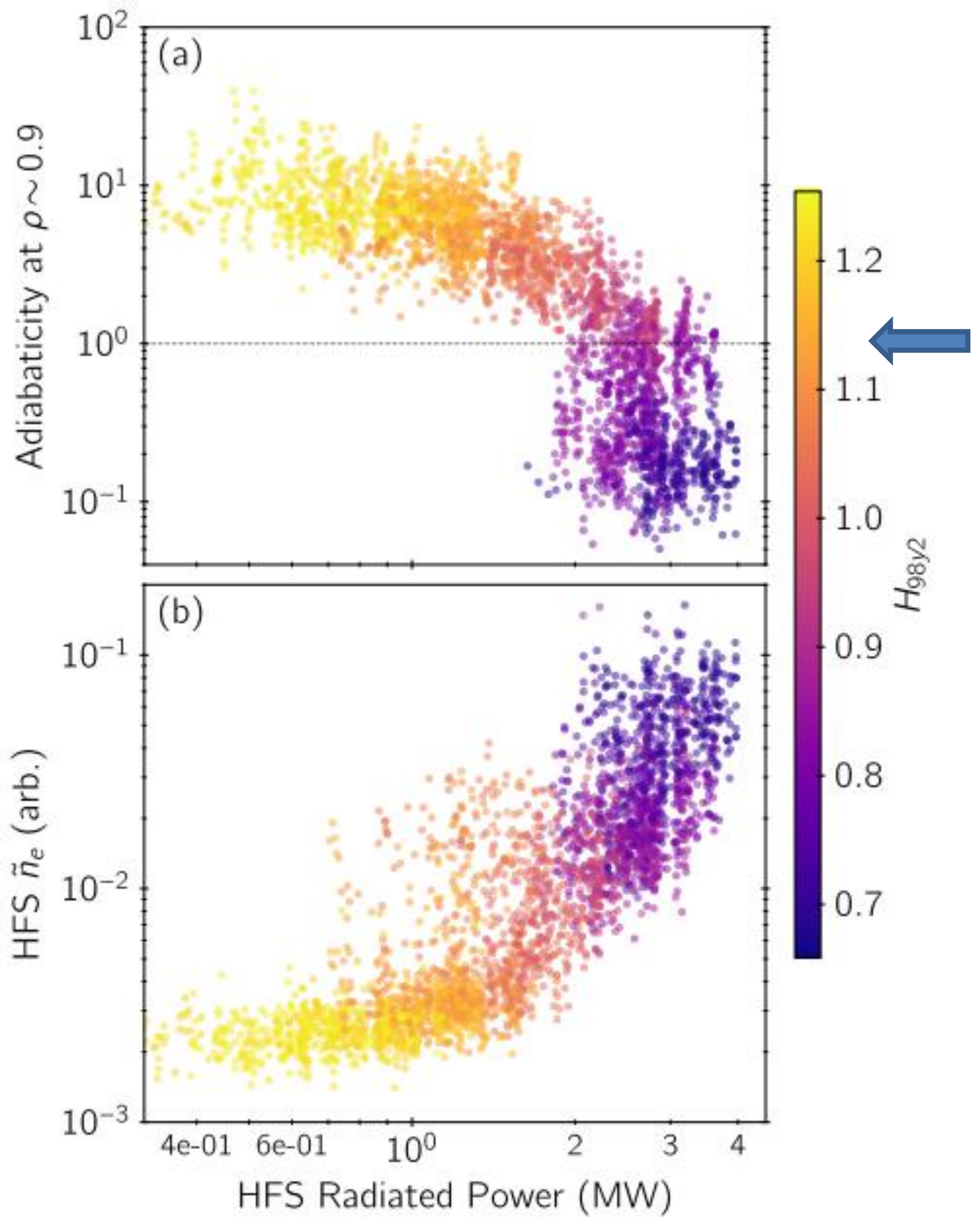
Electric field shear for $\rho > 0.85$

decays with time



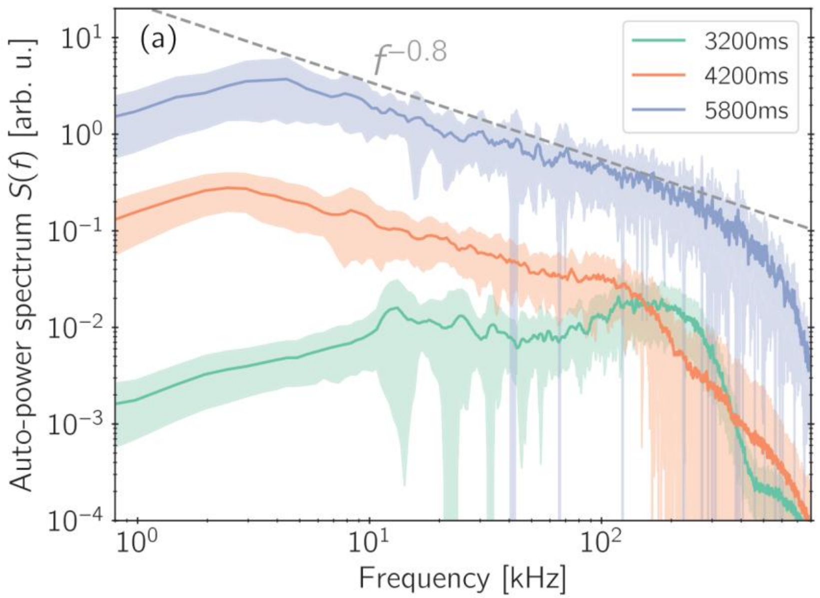
α and turbulence level versus radiated power

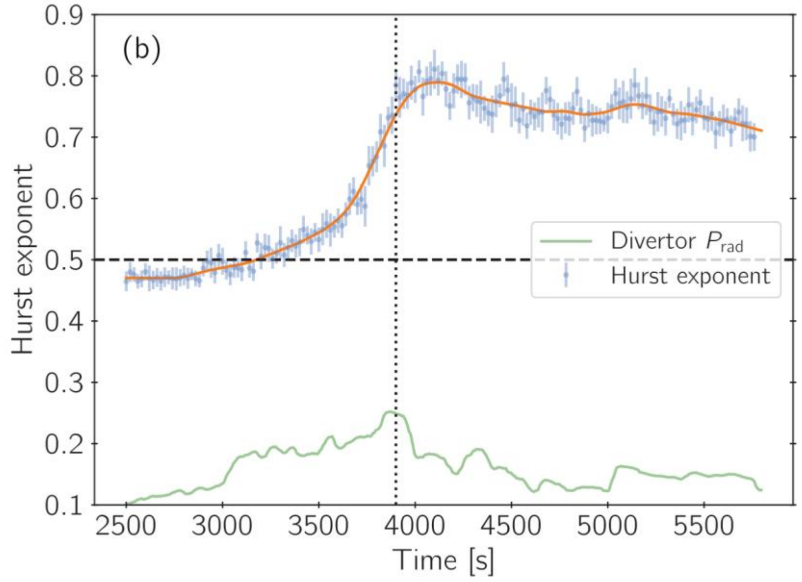
- Rise in fluctuations tracks drop in $\alpha < 1$ as HFS P_{rad} increases
- Radiation induces drop in adiabaticity to hydrodynamic regime: $\omega\tau > 1$



Core Fluctuations

- Recall ~ independent core density limit
  - as n rises, $S(f) \sim f^{-0.8}$
  - P_{rad} Hurst exponent → ~ 0.7
  - Core DL ←→ Avalanching ?!

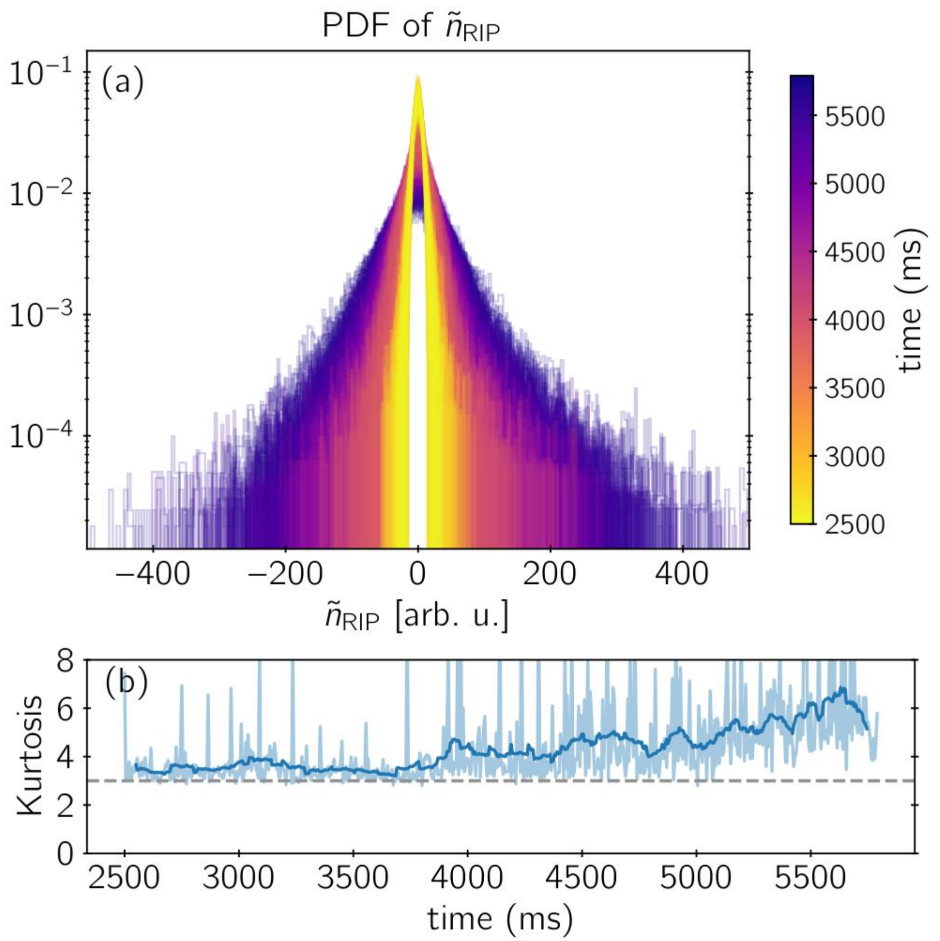




Fluctuation PDF

- PDF of $\tilde{n}$ exhibits 'fat tails' at longer time
- Kurtosis rises

➔ Core density limit enforced by density avalanching ?!



What have we learned?

- No single "DENSITY LIMIT", but rather an edge and core n saturation, with different mechanisms
- Power dependence unambiguous
- Soft limit → most plasmas don't disrupt
- Suggests evolution:

Radiative condensation MARFE → edge cooling → $\alpha < 1$ hydro-regime → enhanced transport with shear layer collapse → DL via particle outflow

i.e. Radiative cooling releases strong particle transport → 'density clamp'

More Theory

- A Work in Progress

What is Needed?

- Model of radiative condensation/MARFE in turbulent medium
- Radiative condensation: Thermal (cooling) instability s/t $\omega < k_{\parallel} c_s$ so $\delta P = 0$

$$\gamma = \frac{2}{5n}\left(\frac{2L}{T} - \frac{\partial L}{\partial T}\right) - \chi_{\perp} k_{\perp}^2 - \chi_{\parallel} k_{\parallel}^2 \qquad L \sim n\, n_Z\, f(\tau_c)$$

- c.f. G. Field .. 1965 → Drake 1987 (linear theory in cylinder)

  ↓

  infinity of papers on ISM c.f. Balbus, 1995 for tutorial

- R.C. plus turbulence intensively studied in ISM cf Max Gronke+ MNRAS 2021

Strategy

- Incorporate radiative cooling into reduced model
- Defining competition for power scaling will be Heat Flux vs Turbulent Transport + Cooling
  - α sets branching ratio
  - Coupling: cooling ↑ → α ↓ → transport ↑

    Ratio [R.C. / Transport] of interest
- Minimal Model:
  - Fluctuation energy
  - Zonal energy
  - T_e → high n, $T_e \sim T_i$; $D \sim \chi_e$ for electrostatics

Proto-Model

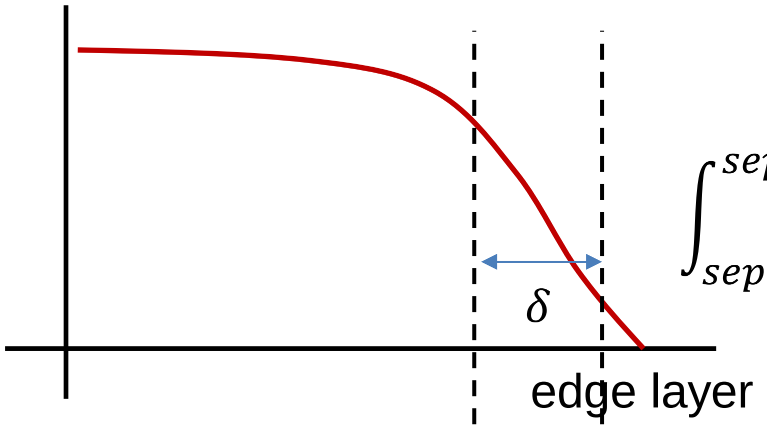
- Temperature Equation – Mean field, $k_{\parallel} = 0$

$$n\frac{\partial T}{\partial t} = \nabla_r \, n\chi(\varepsilon)\nabla_r T - L$$

radiative loss ($L > 0$)
$L = L(n, T) \approx n^2\Lambda$

turbulent transport
$\chi(\varepsilon)$ - fluctuation dependent

- So



$$\int_{sep-\delta}^{sep}$$

$$\langle n\frac{\partial T}{\partial t}\rangle = n\chi(\varepsilon)\nabla_r T\Big|_{sep} - n\chi(\varepsilon)\nabla_r T\Big|_{sep-\delta} - \int_{sep-\delta}^{sep} L$$

Proto-Model, cont'd

- But: $-n\,\chi(\varepsilon)\nabla_r T|_{sep-\delta} \;= Q$ → heat flux from core

So for edge layer:

transport loss at sep. $\nabla_r T < 0$

$$\langle n\frac{\partial T}{\partial t}\rangle = Q_{core} - (\delta)L \;+\; n\,\chi(\varepsilon)\nabla_r T\,\Big|_{sep}$$

radiative losses

and can simplify to:

$$\frac{\partial T}{\partial t} = -\frac{\chi(\varepsilon)T}{\Delta^2} + q - \frac{L(n,T)}{n}$$

becomes a simple mean field temperature equation $\Delta \equiv$ layer width

Key Ratio

- Physics of Power Scaling of Great Interest

- From T eqn, radiation and transport compete for q, so

$$\frac{L/n}{\chi(\varepsilon)T/\Delta^2} \sim \frac{\gamma_{RC}}{\chi(\varepsilon)/\Delta^2} \sim D_{a,R}\,(Q, n, \ldots)$$

Radiative Damkohler # (after Gronke)

$D_a \sim \tau_{turb}/\tau_{react}$ → Damkohler #, from combustion

$D_a \gg 1$ → reaction time short → flame sheets

$D_a \ll 1$ → mixing time short → pre-mixed flame

- Expect $D_{a,R}$ first
  - rises to ≥ 1 as R.C. grows
  - drops to ≤ 1 as edge plasma cools

  ∴ time history of interest → drop $D_{a,R}$ → density clamp

  Is $D_{a,R} \sim 1$ indicative of edge turbulence levels at high density ?

Minimal Model → ala' Singh + P.D.

$$\frac{\partial T}{\partial t} = -\frac{\chi \varepsilon T}{\Delta^2} + q - \frac{L(n,T)}{n}$$ → temp

$$\frac{\partial \varepsilon}{\partial t} = a_1\,\gamma(n,T)\varepsilon - a_4\,V_Z^2 \varepsilon f(\alpha) - a_2 \varepsilon^2$$ → fluctuation energy

$$\frac{\partial V_Z^2}{\partial t} = a_4\,V_Z^2\,\varepsilon\,f(\alpha) - b_3 n V_Z^2$$ → zonal flow

→ $f(\alpha) \equiv$ adiabaticity "switch" - T evolves, α follows

$\alpha \sim k_\parallel^2\,v_{th}^2/\,\omega\nu\ \sim T^2$ accounts for Z.F. decay,

↔ production drop

$f(\alpha) \sim 1, \alpha > 1$

$f(\alpha) \ll 1, \alpha \ll 1$

$f(\alpha) \ll 1$ → Z.F. collapse

Next Steps

- Exercise Model → Prediction!

Edge DL defined by $\gamma_{rad}(n)$ sufficient to induce $\alpha < 1$!?

n limit to induce strong particle transport

- 1D version → cooling fronts !?

➔ cooling + transport fronts ?!

- Profile structure, magnetic geometry?

N.B. $\chi_{\parallel} k_{\parallel}^2 \sim (D_T \chi_{\parallel})^{1/2} k_\theta / L_s$ ➔ higher m modes damped by conduction + turbulence interaction

$D_r/\Delta^2 \sim \chi_{\parallel} {k'_{\parallel}}^2 \Delta^2$

➔ supports mean field theory approach

- Can radiative condensation couple to turbulence dynamics directly??

Partial Conclusion

- "Causality" counter-intuitive

  Radiation/MARFE → cooling → strong transport

  $$\alpha > 1 \rightarrow \alpha < 1$$

  Opposite to conventional wisdom!

- Non-disruptive termination

- Two channels for power scaling, strongly coupled. $D_{a,R}$ is useful → experimental analysis !?

$$D_{a,R} \sim \gamma_{rad} / \frac{\chi(\varepsilon)}{\Delta^2}$$

- Model extended to encompass radiative condensation

From then to now of DL

- Greenwald (1988) scaling → Incomplete → Power Scaling, Multiple Limits

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

- Sudo (1990) Scaling (stellarator) → entering mainstream → G + S unification

  $\bar{n} \sim P^{1/2}$ Transport Physics Central

- DL as MHD + Disruption phenomenon → frequently, even usually, not the case

  Rebut, Gates, White ?? (revision needed)

- DL as a 'Back-Transition' → from heresy to convention
- Radiation triggers MHD → Rad. triggers transport...
- Better Density 'Saturation' than 'Limit' !

Remaining Issue: "Causality"

- Demonstrated link: Radiation ←→ Transport
- Which is trigger?
- RI mode – reanimated for SPARC (via Temasek fund)

How avoid MARFE's → shift plasma off inner wall

∴

$n \leq n_{DL}$ and shift plasma toward inner wall

- ➔ induce MARFE and increased particle transport, i.e. hit DL?

Back-Up

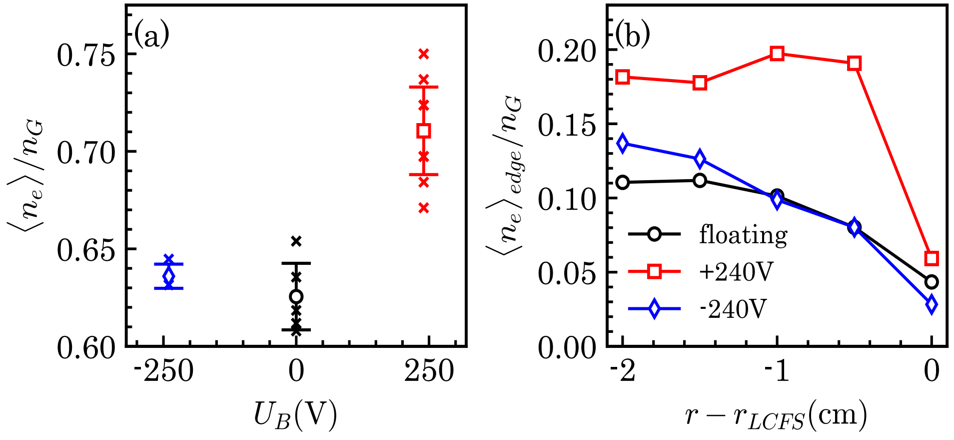
The Obvious Question

- 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 → $J_r \to V_\theta \to V_E'$ etc.
- New Here?
  - High Density
  - Gas Puffing → push on DL
  - Analysis

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

The Answer – Looks Promising!

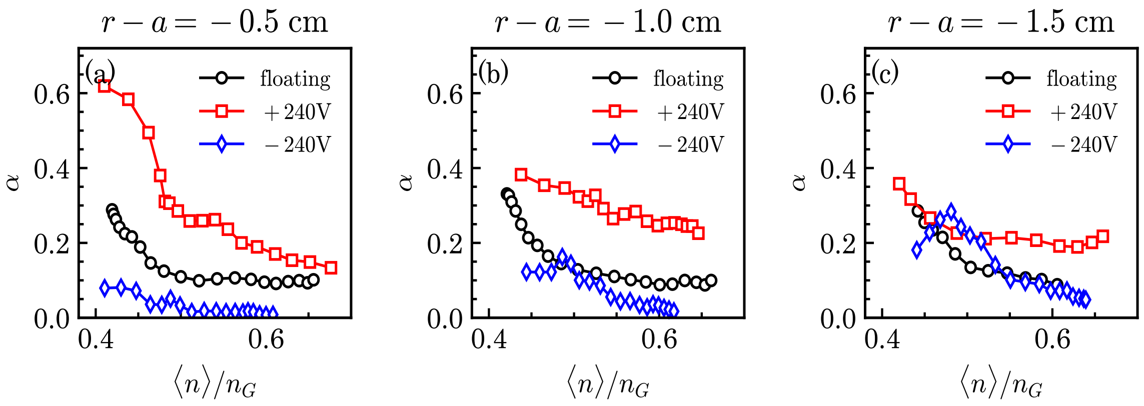
- Edge density doubled for +240V bias



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

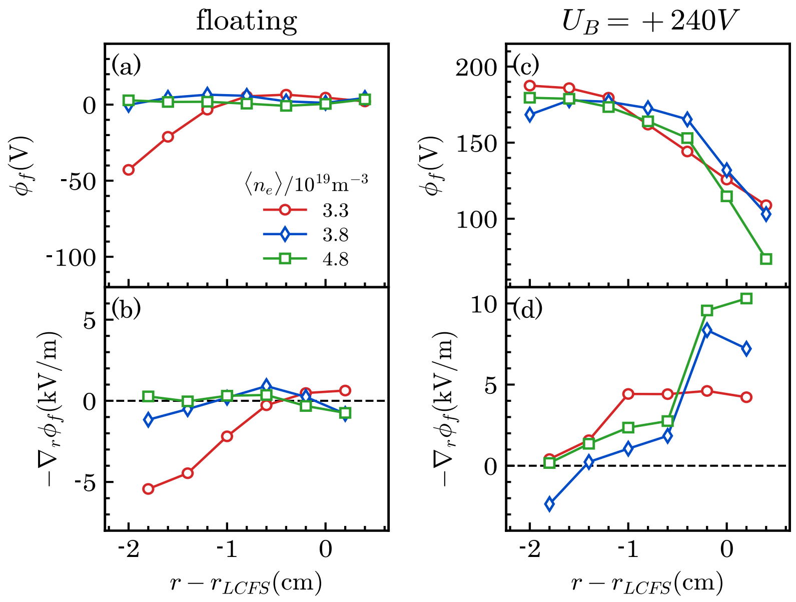


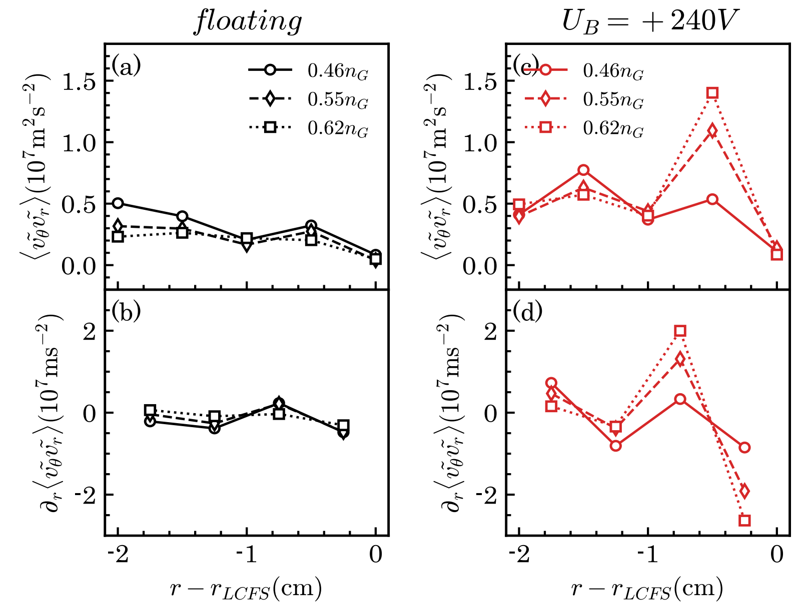
- Turbulence spreading quenched by positive bias

The Physics

- Edge Shear Layer produced for +bias

N.B. Not an E_r well





- Reynolds stress, force increase for +bias

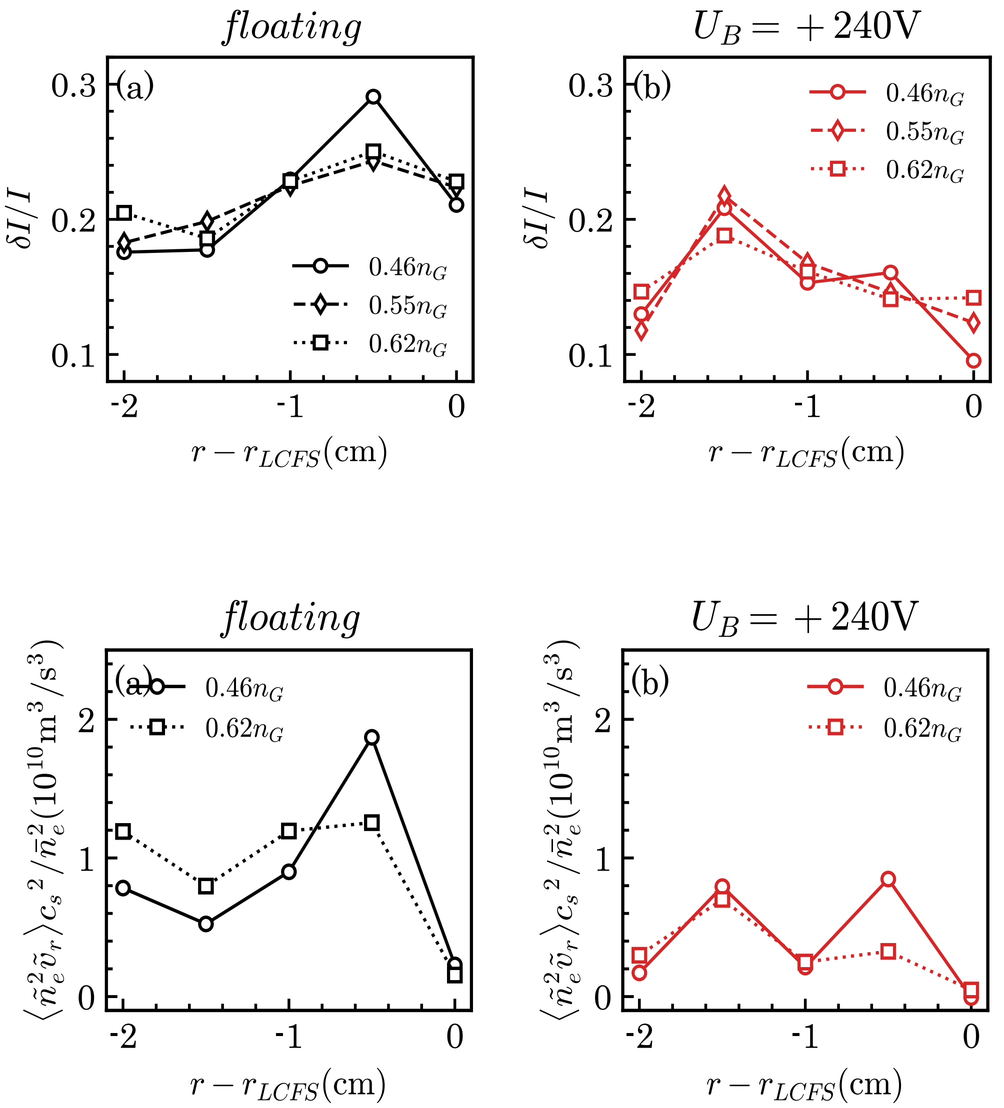
←→ bias effect on eddy alignment

"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

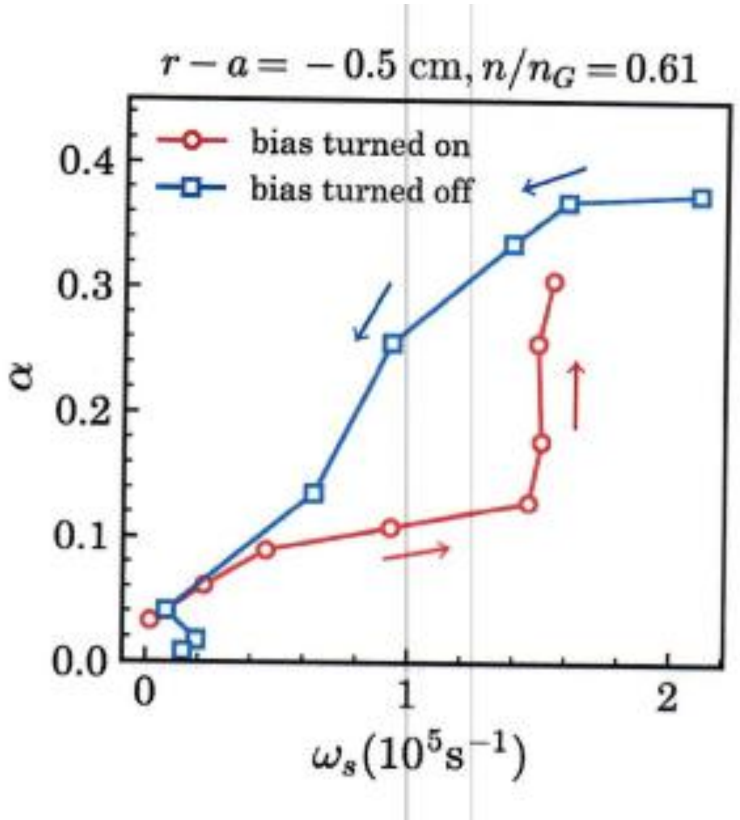


Key Parameter vs Control Parameters

- 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, N.F.):

  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
  – No apparent correlation of spreading and particle flux

Thank You !

Supported by U.S. D.O.E.