How the Birth and DEATH of Shear Layers Determines Confinement Transitions in Tokamak (and Stellarators)
➔ Especially Transport Physics of Density Limits

P.H. Diamond

U.C. San Diego, USA and SWIP, Chengdu

Festival de Theorie 2021 (virtual)

This research was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, under Award Number DEFG02-04ER54738.

Collaborators:

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

(NF 2021, PPCF 2021, PoP 2018)

Experiments: Ting Long, Rui Ke and J-TEXT and SWIP Teams

(in preparation → APTWG '21)

R. Hong, G. Tynan and HL-2A Teams (NF '18)

SOL Width → HDL: Xu Chu, University CAS

(in preparation → APTWG '21)

Acknowledge:

M. Greenwald, J. Rice, C. Hidalgo, T.S. Hahm, S. Cappello

Background Material:

Physics 218c – 2021, Spring UCSD Physics Site

→ includes student write-ups. (basic fusion theory)

KITP: Staircase 21 (more theoretical)

Outline

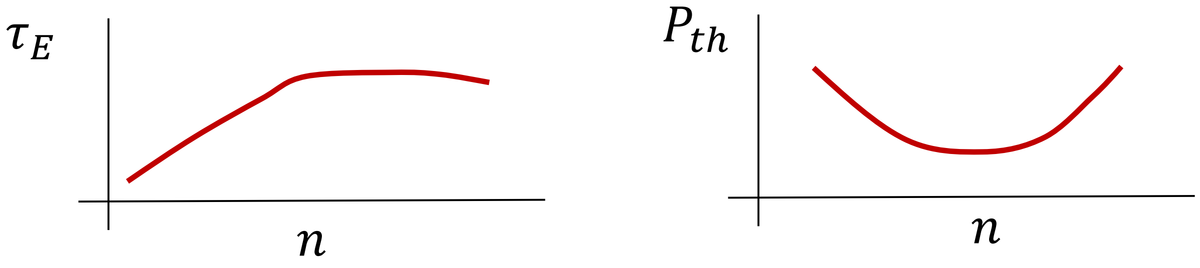
- Things in Common – especially shear layers
- OV of Greenwald Limit Physics (L-mode)
  - Basics, History
  - Emphasis - Role of particle transport
    - Fluctuation studies ↔ shear layers
- Theory of shear layer collapse
  - Shear production and electron adiabaticity
  - Noise, neoclassical screening and predator-prey
  - Current Scaling? – Dimensionless parameters

Outline, cont'd

- Sneak Previews
  - J-TEXT Experiments (T. Long)
    - Shear Layer Collapse
    - Turbulence Spreading and Transport Events
    - Comment – Bias Experiment
- What of HDL? (Xu Chu)
  - Broadening the SOL by turbulence spreading
- Discussion

Things in Common

- There are no "good" tokamaks… But all tokamaks do have certain things in common. And each tokamak is diabolical in its own unique way -- apologies to Lev Tolstoy
- Things in common: Ohmic Phenomenology (Rice 2020)
  1. LOC→SOC transition (mitigated by pellet injection; Greenwald '84)
  2. Intrinsic rotation reversals
  3. L→H P_{th} minimum vs n
  4. Density Limit



- Items $1 \sim 4$ (previous) unified by scaling:

$$n_{crit}\, q\, R \ = B_T$$

➔ $n/n_G = const$ (various const)

$\left\{ \right.$ $n_G \sim I_p$ is unifying scaling for Ohmic Phenomenology

➔ suggests Greenwald density limit is fundamental

- Something else → Edge Shear Layer
- Evident shear layer near last closed flux surface in most tokamak operating regimes
- Discovered by Ch.P. Ritz, TEXT ‘84

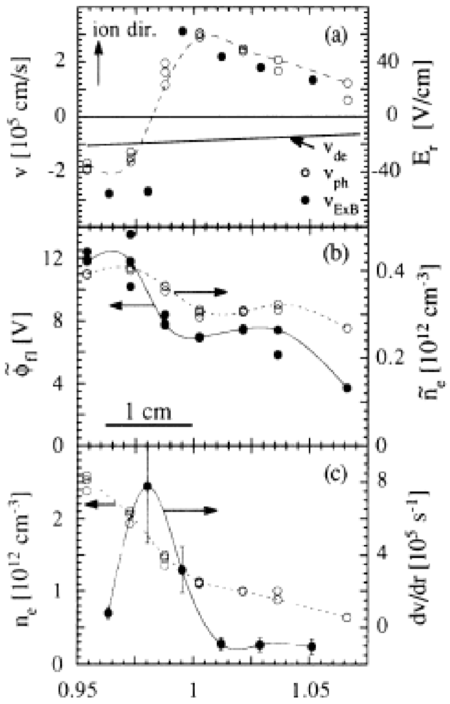
- Shear layer impacts/regulates edge turbulence even in Ohmic/L-mode, enhanced in H-mode

- Ritz, et. al. 1990

v_{ph} - closed

v_{pl} - open

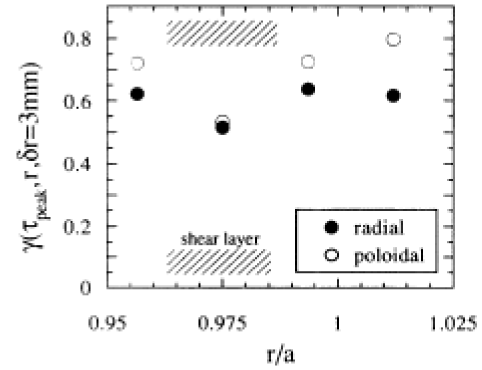
density



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

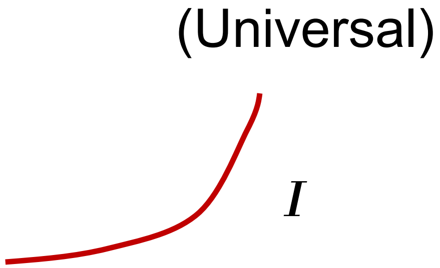
FIG. 3. Peak values of the normalized two-point correlation function for poloidally and radially separated probes with fixed separations of $\delta r = 3$ mm.

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

n.b. <u>not</u> H-mode!

Why an Edge Shear Layer?

$-\partial_r \langle \tilde{V}_r \tilde{V}_\theta \rangle$



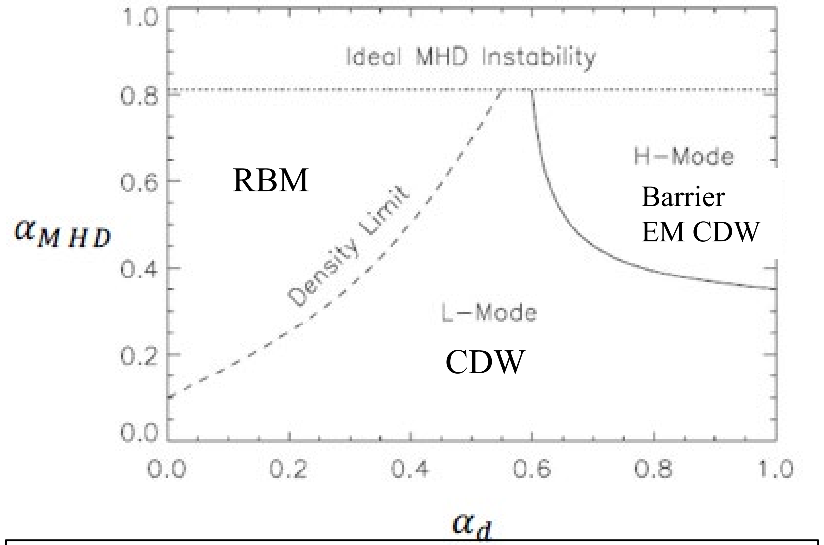
- Fluctuation intensity profile → Reynolds Force
- Transition to sheath etc. beyond last closed flux surface
- Also in Stellarators → c.f. Hidalgo…
- The Point: Without shear layer, L-mode confinement would be <u>worse</u>…

Preview: A Developing Story

From Linear Zoology to Self-Regulation and its Breakdown

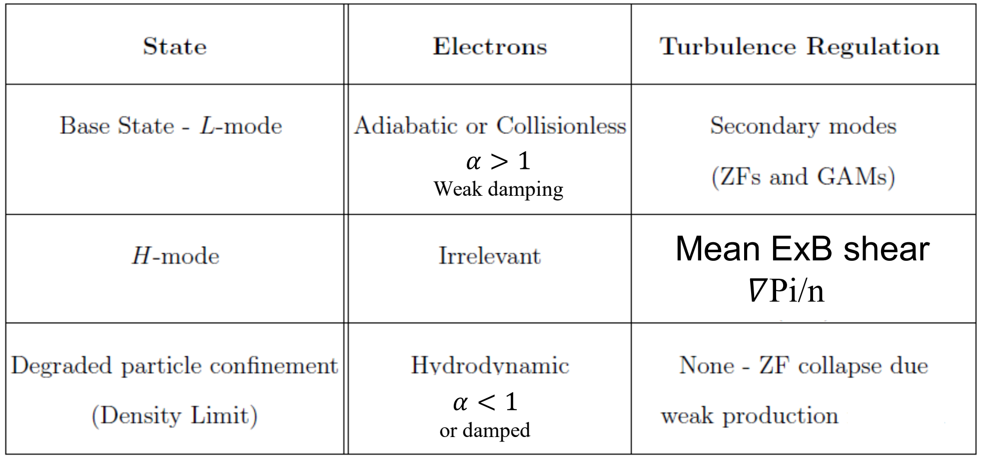
1-mode per regime

(Drake and Rogers, PRL, 1998)



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

(Hajjar et al., PoP, 2018)

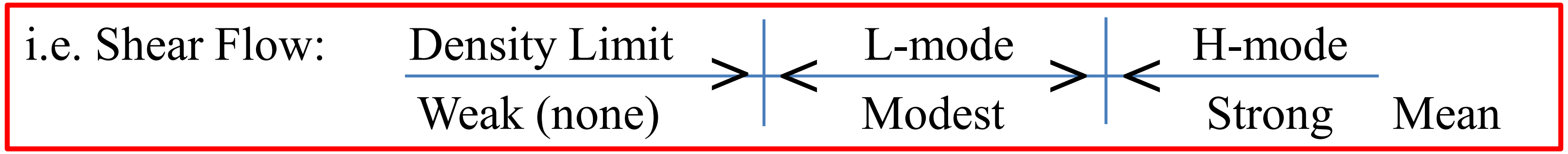


State	Electrons	Turbulence Regulation
Base State - *L*-mode	Adiabatic or Collisionless $\alpha > 1$ Weak damping	Secondary modes (ZFs and GAMs)
H-mode	Irrelevant	Mean ExB shear ∇Pi/n
Degraded particle confinement (Density Limit)	Hydrodynamic $\alpha < 1$ or damped	None - ZF collapse due weak production

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.
Approaching 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

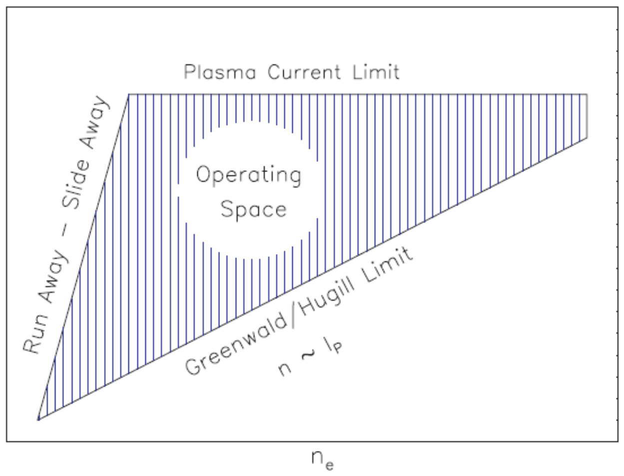
A Look at Density Limit Phenomenology

→ Greenwald Limit

Density Limits: Some Basic Aspects

- Not a review!
- Greenwald density limit:

(Dimensions!) $\bar{n} = \bar{n}_g \sim \dfrac{I_p}{\pi a^2}$



→ Constrains tokamak Operating Space

- Manifested on other devices
  - See especially RFP ($n \sim I_p$ scaling)

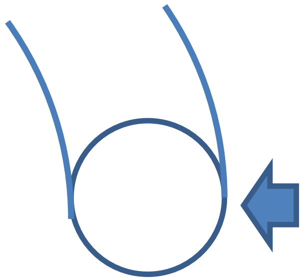
N.B.: density attractive
$n\,\tau\,T$; β etc

- Line averaged limit
- (Too) simple dependence!?
- Begs origin of I_p scaling?!

Stellarators? – T.B.C.

- Most fueling via edge → edge transport critical to $\bar{n}$ limits

Pinch



→ Pinch: $\Gamma_n = Vn \; - D\nabla n$

A Brief History of Density Limits

- Old story, Many Density Limits…
- Recall: Murakami, Callen et. al., Hugill …
- Most → evolutionary dead ends…

➔ Survivor: (c.f. Greenwald PoP, “20 yrs of Alcator C-Mod”)

- Greenwald, emerged late ’80s
- Where from? - discharge termination studies Alcator-C

  - n tracked I_p, consistently
- Regression plots followed…

A Brief History of Density Limits
→ Conventional Wisdom

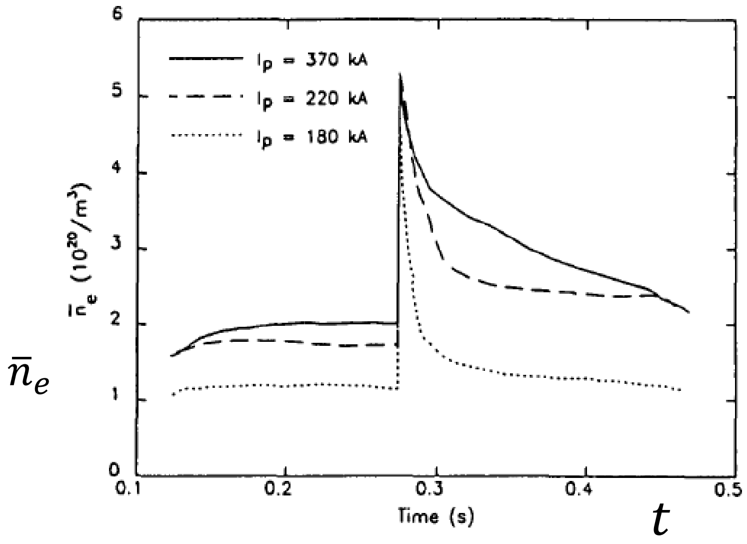
- High density → edge cooling (transport?!)
- Cooling edge → MARFE (Multi-faceted Axisymmetric Radiation from the Edge) by Earl Marmar and Steve Wolfe

  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 secondary outcome, largely consequence of edge cooling, following fueling vs. increased particle transport
  - $\bar{n}_g$ reflects fundamental limit imposed by particle transport
- An Important Experiment (Greenwald, et. al. ‘88)

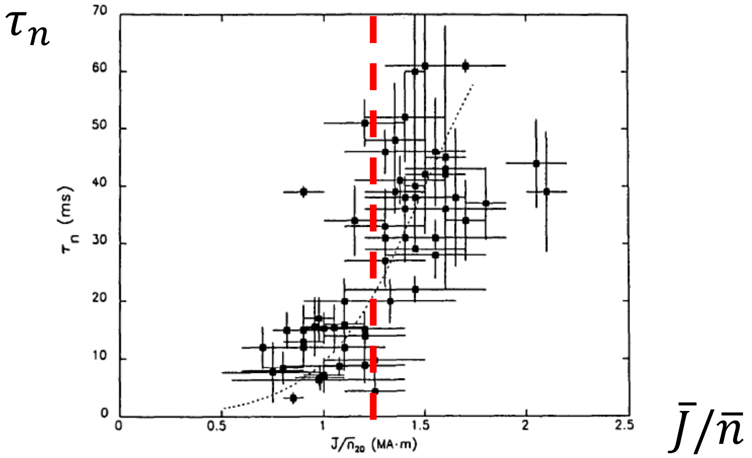


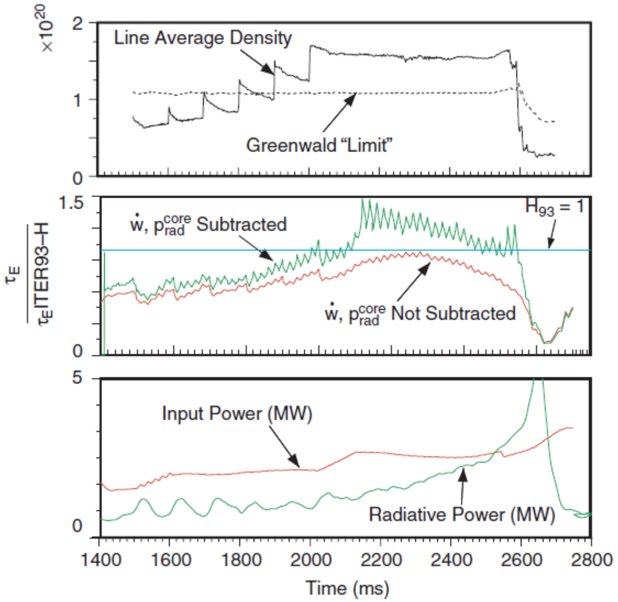
(Alcator C)

- 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?

• More Evidence for Role of Edge Transport

(Alcator C)

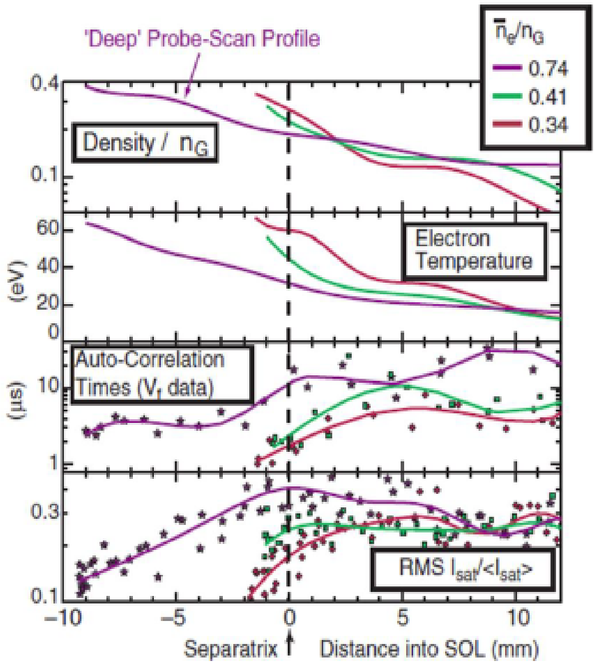




- Post-pellet density <u>decay time</u> vs $\bar{J}/\bar{n}$.
- Increase in relaxation time near (usual) limit: $\bar{J}/\bar{n} \sim 1+$
- Large Pellets in DIII-D beat $\bar{n}_g$
- Peaked profiles ←→ enhanced core particle confinement (ITG turbulence reduced?)
- Reduced particle transport ➔ impurity accumulation!

(N.B. Deeper deposition here)

Density limit ←→ Fluctuation Structure

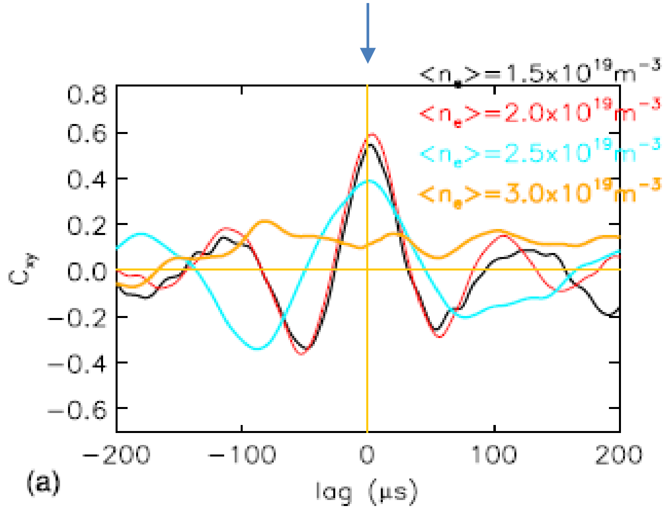


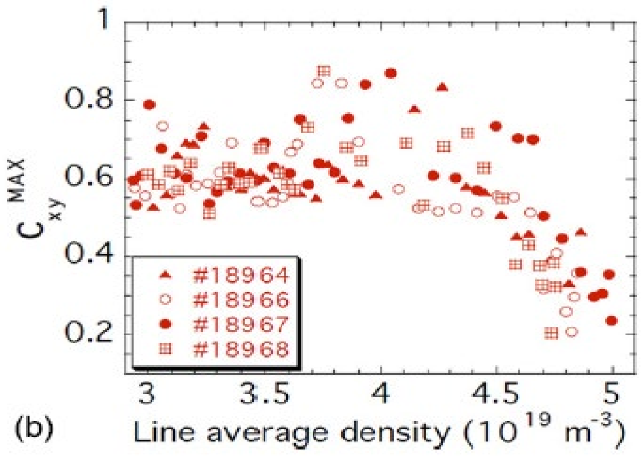
C-Mod profiles,
Greenwald et al, 2002, PoP

- Average plasma density increases as a result of edge fueling → edge transport crucial to density limit.
- As *n* increases, high ⊥ transport region extends inward and fluctuation activity increases.
- Turbulence levels increase and perpendicular particle transport increases as $n/n_G \rightarrow 1$.

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.
- At high density ($\langle n_e \rangle > 2 \times 10^{19}\ m^{-3}$), the LRC (also associated with GAMs) drops rapidly with increasing density.
- The reduction in LRC due to increasing density is also accompanied by a reduction in edge mean radial electric field (Relation to ZFs).

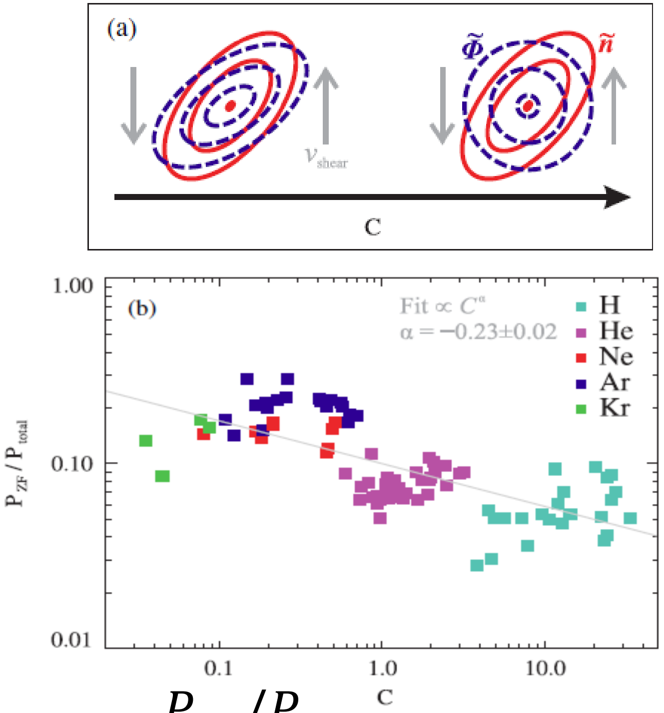
Is density limit related to edge shear decay?!

Recent Experiments - 2

(Schmid, Manz et al., PRL, 2017) – stellarator experiment

– explored collisionality, not n/n_G

Eddy Tilt



P_{ZF}/P_{tot}

- Experimental verification of the importance of collisionality for large-scale structure formation in TJ-K.
- Analysis of the Reynolds stress shows a decrease in coupling between density and potential for increasing collisionality → hinders zonal flow drive (Bispectral study)
- Decrease of the zonal flow contribution to the total turbulent spectrum with collisionality *C*.

a) Increase in decoupling between density (red) and potential (blue) coupling with collisionality C.
b) Increase in ZF contribution to the spectrum in the adiabatic limit (C→0)

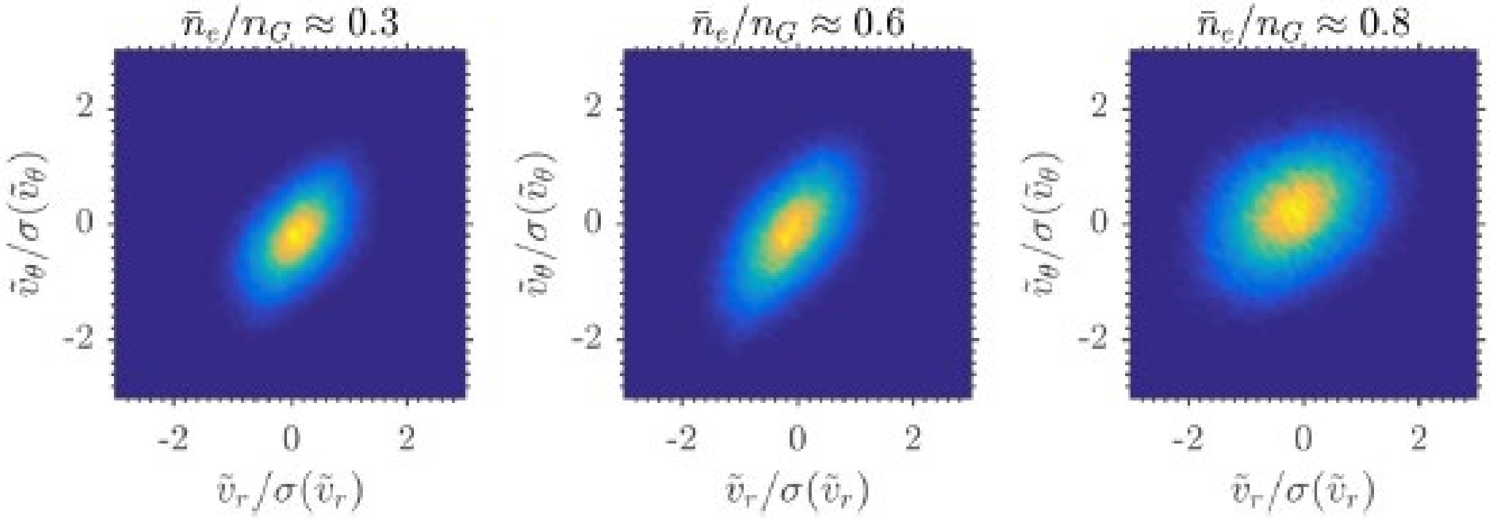
C ⇔ adiabaticity $k_\parallel^2 V_{th}^2/\omega\nu$ ← density via collisionality

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

Distribution

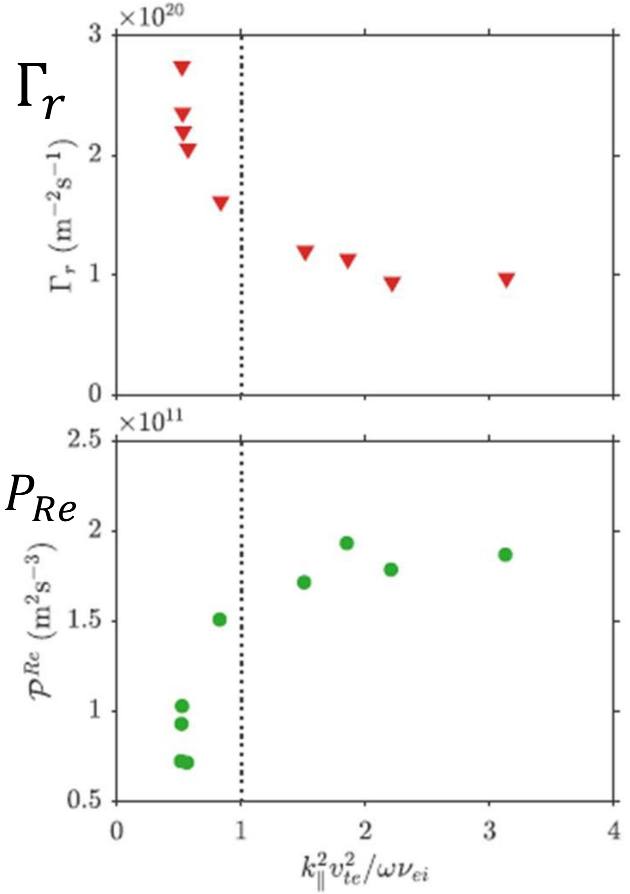
Fluctuating

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 $\bar{n} \to \bar{n}_g$ ➔ <u>Weakened shear flow production by Reynolds stress</u> as $n \to n_g$
  - Consistent with drop in P_{Re} observed

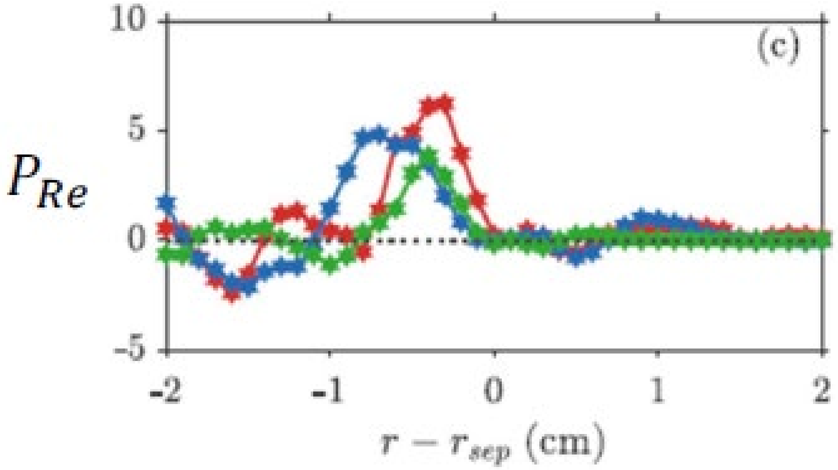
Key Parameter: Electron Adiabaticity



adiabaticity

- Electron adiabaticity $\alpha = \frac{k_{||}^2 v_{th}^2}{|\omega| \nu_{ei}}$ emerges as interesting local parameter. $\alpha \sim 3 \rightarrow 0.5$ during $\bar{n}/n_G$ scan

- Particle flux ↑ and Reynolds power $P_{Re} = -\langle V_\theta \rangle \partial_r \langle \tilde{V}_r \tilde{V}_\theta \rangle$ ↓ as α drops below unity
  ➔ shear layer collapse. Particle flux rises



Red 0.3 n_G
Blue 0.6 n_G
Green 0.8 n_G

N.B. Plasma beta remained very low → cannot be explained by appeal to RBM

Synthesis of the Experiments

- Shear layer collapse and turbulence and D (particle transport) rise as $\frac{\bar{n}}{\bar{n}_G} \rightarrow 1.$

  → Key "microphysics" of density limit !? can trigger cooling, et. seq.

- ZF collapse as $\alpha = \frac{k_{||}^2 v_{th}^2}{|\omega| \nu_e}$ drops from $\alpha > 1$ to $\alpha < 1.$

  → Effect on production → Reynolds power drop

- Degradation in particle confinement at density limit in L-mode is due to breakdown of self-regulation by zonal flow. Back to Predator-Prey, now focusing on collapse/back transition

- Note that β in these experiments is too small for the simplistic Resistive Ballooning Modes (RBM) explanation.

➡ How reconcile all these with our understanding of drift wave-zonal flow physics?

→ Familiar Themes, New Direction

The Key Questions

- What physics governs shear layer collapse (or maintanance) at high density?

⇔ 'Inverse process' of familar L→H transition !?

i.e. L→H : $\begin{cases} \text{shear layer} \rightarrow \text{barrier} \\ \text{turbulence} \end{cases}$

Density Limit: $\begin{matrix} \text{strong} \\ \text{turbulence} \end{matrix} \Leftarrow \begin{cases} \text{shear layer,} \\ \text{turbulence} \end{cases}$

➔ What is the fate of shear flow for

hydrodynamic electrons: $k_{\parallel}^2 V_{th}^2/\omega\nu < 1$? Why?

➔ What of high density, with $k_{\parallel}^2 V_{th}^2/\omega\nu > 1$?

➔ P_{aux}

A Theory of Shear Layer Collapse

A Simple, Generic Model

$\left\{ \begin{array}{l} \text{1 generic model in multiple limits} \\ \text{vs} \\ \text{1 mode-per-regime} \end{array} \right.$?

Hasegawa-Wakatani for Collisional DWT:

$$\frac{dn}{dt} = -\boxed{\frac{v_{th}^2}{\nu_{ei}} \nabla_{\|}^2} (\phi - n) + D_0 \nabla^2 n$$

$$\frac{d\nabla^2\phi}{dt} = -\boxed{\frac{v_{th}^2}{\nu_{ei}} \nabla_{\|}^2} (\phi - n) + \mu_0 \nabla^2 (\nabla^2 \phi)$$

$$\boldsymbol{\alpha = \frac{k_{\|}^2 v_{th}^2}{|\omega| \nu_{ei}}}$$

Fluctuations

$$\partial_t \tilde{n} + \tilde{v}_x . \nabla \bar{n} = -\boxed{\frac{v_{th}^2}{\nu_{ei}} \nabla_{\|}^2} (\tilde{\phi} - \tilde{n}) - \{\tilde{\phi}, \tilde{n}\} + D_0 \nabla^2 \tilde{n}$$

$$\partial_t \nabla^2 \tilde{\phi} + \tilde{v}_x . \nabla \overline{\nabla^2 \phi} = -\boxed{\frac{v_{th}^2}{\nu_{ei}} \nabla_{\|}^2} (\tilde{\phi} - \tilde{n}) - \{\tilde{\phi}, \nabla^2 \tilde{\phi}\} + \mu_0 \nabla^2 (\nabla^2 \tilde{\phi})$$

Mean Fields (Zonal)

$$\partial_t \bar{n} = -\partial_x \langle \tilde{V}_x \tilde{n} \rangle + D_0 \bar{\nabla}_x^2 \bar{n}$$

$$\partial_t \overline{\nabla_x^2 \phi} = -\partial_x \langle \tilde{V}_x \nabla^2 \tilde{\phi} \rangle + \mu_0 \nabla_x^2 \overline{\nabla_x^2 \phi}$$

Reynolds Stress (GIT)

For neoclassical mean field evolution

$\rho_i^2 \rightarrow \rho_{eff}^2 \approx \rho_{\theta i}^2$

Dispersion Relation for $\alpha < 1$ and $\alpha > 1$

Dispersion relation:

$$\omega = \frac{1}{2}\left(- i\frac{\hat{\alpha}(1+k_\perp^2\rho_s^2)}{k_\perp^2\rho_s^2} + \sqrt{\frac{4i\omega^\star\hat{\alpha}}{k_\perp^2\rho_s^2} - \left(\frac{\hat{\alpha}(1+k_\perp^2\rho_s^2)}{k_\perp^2\rho_s^2}\right)^2}\right)$$

$$\hat{\alpha} = -\frac{v_{th}^2}{\nu_{ei}}\nabla_\parallel^2$$

$$\alpha = \frac{k_{||}^2 V_{the}^2}{\nu_{ei}|\omega|}$$

Adiabatic Limit:

($\alpha \gg 1$ and $\hat{\alpha} \gg |\omega|$)

$$\omega_{adiabatic} = \frac{\omega^\star}{1+k_\perp^2\rho_s^2} + i\frac{\omega^{\star 2}k_\perp^2\rho_s^2}{\hat{\alpha}}$$

Wave + inverse dispersion

(Classic Drift Wave)

Hydro Limit:

($\alpha \ll 1$ and $\hat{\alpha} \ll |\omega|$)

$$\omega_{hydrodynamic} \simeq \sqrt{\frac{\omega^\star\hat{\alpha}}{2k_\perp^2\rho_s^2}}(1+i)$$

~ Convective Cell

key: $\alpha < 1$ → drift wave converts to convective cell

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

- Physics of collapse left un-addressed, as adiabatic regime $(k_{\parallel}^2 V_{the}^2\omega/\nu > 1)$

  dynamics of primary interest - ZFs

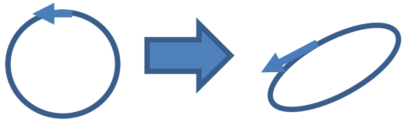
Step Back: Zonal Flows Ubiquitous! Why?

- 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.



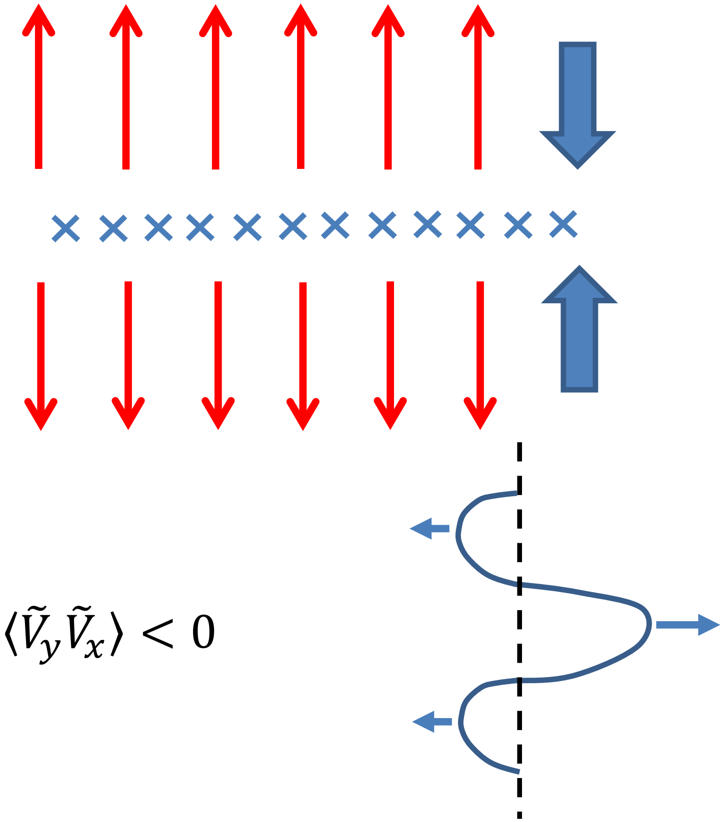
  $\omega_k = -\beta\, k_x / k_\perp^2$: (Rossby)

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

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

  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 flow convergence! ➔ Shear layer spin-up

But NOT for hydro convective cells:

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

↓

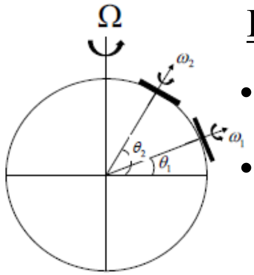
→ Eddy tilting ($\langle k_r k_\theta\rangle$) does not arise as direct consequence of causality

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

➔ Physical picture of shear flow collapse emerges

ZF Collapse ←→ PV Conservation and PV Mixing?

How reconcile?

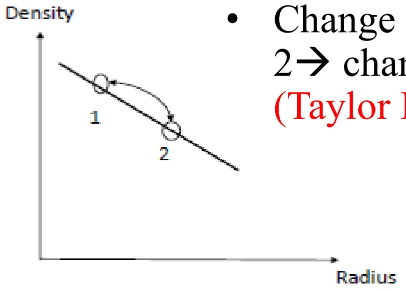


Rossby waves:

- $PV = \nabla^2\phi + \beta y$ is conserved from θ_1 to θ_2.
- Total vorticity $2\vec{\Omega} + \vec{\omega}$ frozen in→ Change in mean vorticity Ω leads to change in local vorticity $\omega \rightarrow$ Flow generation (Taylor ID)

Drift waves:

- In HW, $q = \ln n - \nabla^2\phi = \ln n_0 + h + \tilde{\phi} - \nabla^2\phi$ conserved along the line of density gradient.
- Change in density from position 1 to position 2→ change in vorticity → Flow generation (Taylor ID)



h critical

Quantitatively

- Total PV flux $\Gamma_q = \underset{\uparrow}{\langle \tilde{v}_x h \rangle} - \rho_s^2 \underset{\uparrow}{\langle \tilde{v}_x \nabla^2\phi \rangle}$
- Adiabatic limit $\alpha \gg 1$:
  +Particle flux and vorticity flux are tightly coupled (both prop. to $1/\alpha$)
- Hydrodynamic limit $\alpha \ll 1$:
  - Particle and vorticity flux decouple
  Γ_n → ZF generation
- PV mixing still possible without ZF formation → Particles carry PV flux

- Branching ratio changes with α!

Some Theoretical Matters

Reduced Model ⇔ BLY Reloaded

- Utilize models for real space structure to address shear layer

e.g. $\left\{ \begin{array}{l} \text{BLY ('98)} \\ \text{Ashourvan, P.D. (2016)} \end{array} \right.$ ➔ Outgrowth of staircase studies

See also: J. Li, P.D. '2018 (PoP) – Zonal flow saturation for friction → 0 ⇦

– Wave-flow resonance

- Exploit PV conservation: (PV ←→ Potential Vorticity)
  - $q = \ln n - \nabla^2 \phi$ → conserved PV ←→ equivalent to phase space density
  - $\tilde{q} = \tilde{n} - \nabla^2 \tilde{\phi}$

$\langle n \rangle$ - mean density
$\langle \nabla^2 \phi \rangle$ - mean vorticity
} define mean PV
$\langle \tilde{q}^2 \rangle = \varepsilon$ – fluctuation potential enstrophy

So

- Natural description: $\langle n \rangle, \langle \nabla^2 \phi \rangle, \langle \tilde{q}^2 \rangle = \varepsilon$

ε = fluctuation P.E.

Reduced Model, cont'd

$$l_{mix} = \frac{l_0}{\left(1+\frac{(l_0 \nabla u)^2}{\varepsilon}\right)^{\delta}} \to l_0$$

$$\partial_t n = -\partial_x \Gamma_n + D_0 \nabla_x^2 n$$

$$\partial_t u = -\partial_x \Pi + \mu_0 \, \nabla_x^2 u$$

N.B.: Encompasses 'predator-prey' model

$$\partial_t \varepsilon + \partial_x \Gamma_\varepsilon = -(\Gamma_n - \Pi)(\partial_x n - \partial_x u) - \varepsilon^{\frac{3}{2}} + P$$

- Fluxes:

{ can encompass 2 length scales;
not critical here

Γ_n → Particle flux $\langle \tilde{V}_x \tilde{n} \rangle$

Π → Vorticity flux $\langle \tilde{V}_x \nabla^2 \tilde{\phi} \rangle = -\partial_x \langle \tilde{V}_x \tilde{V}_y \rangle$ (Taylor, 1915)

↕

Reynolds Force

Γ_ε → turbulence spreading, $\langle \tilde{V}_x \tilde{\varepsilon} \rangle$ → triad interactions

Expression for Transport Fluxes:

$\rightarrow \Gamma_n = -D\, \partial_x n = -\frac{(\hat{\alpha} + |\gamma_m|)}{|\omega + i\hat{\alpha}|^2} \frac{d \ln n}{dx} \langle \delta v_x^2 \rangle$ → Diffusive Flux

$\rightarrow \Pi = -\chi\, \partial_x u + \Pi^{res}$

(Physics of vorticity gradient t.b.d.)

Production and acceleration of flow by ∇n

Shear relaxation by turbulent viscosity

$$\chi = \frac{|\gamma_m| \langle \delta v_x^2 \rangle}{|\omega|^2}$$

$$\Pi^{res} = \frac{k_\theta \rho_s c_s \omega_{ci} \hat{\alpha} \left[(\omega^r)^2 (\omega^\star - \omega^r) - |\gamma_m|^2 (\omega^r + \omega^\star) - \omega^\star \hat{\alpha} |\gamma_m| \right]}{|\omega|^2 \times |\omega + i\hat{\alpha}|^2} \langle \tilde{\phi}^2 \rangle$$

$\rightarrow \Gamma_\varepsilon = -l_{mix}^2 \sqrt{\varepsilon}\, \partial_x \varepsilon$ → Turbulence Spreading

Clear dependence of D, χ, Π^{res} on $|\omega|$ and $\hat{\alpha}$

Scaling of transport fluxes with α (adiabaticity parameter)

Plasma Response	Adiabatic (α >>1)	Hydrodynamic (α <<1)
Particle Flux Γ	$\Gamma_{\text{adia}} \sim \frac{1}{\alpha}$	$\Gamma_{hydro} \sim \frac{1}{\sqrt{\alpha}}$
Turbulent Viscosity χ	$\chi_{adia} \sim \frac{1}{\alpha}$	$\chi_{hydro} \sim \frac{1}{\sqrt{\alpha}}$
Residual stress Π^{res}	$\Pi^{res}{}_{\text{adia}} \sim -\frac{1}{\alpha}$	$\Pi^{res}{}_{\text{hydro}} \sim -\sqrt{\alpha}$
$\frac{\Pi^{\text{res}}}{\chi}$ = Vorticity Gradient	α^0	α^1

$\Gamma_n, \chi \uparrow$ and $\Pi^{\text{res}} \downarrow$ as the electron response passes from adiabatic (α >1) to hydrodynamic (α <1)

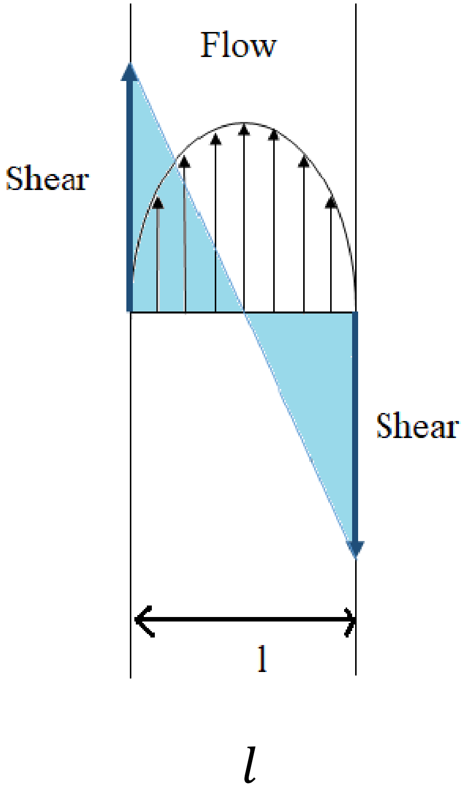
α <1 → <u>weak flow production</u>

- Mean vorticity gradient ∇u (i.e. ZF strength) proportional to $\alpha \ll 1$ for convective cells.
- Weak ZF formation for $\alpha \ll 1$ → weak regulation of turbulence and enhancement of particle transport and turbulence.

Physics of Vorticity Gradient ?!

- Beyond shear … see also: R. Heinonen, PD 2020

- ∇u vs. flow shear, is stronger flow order parameter
- [Jump in flow shear, over scale l] = [∇u]
- Vorticity gradient prevents global alignment of eddy or modes with uniform shear
- $\Pi = 0 \quad \rightarrow \quad \nabla u \ \sim \ \Pi^{res}/x_T$
- Standard interpretation: Enhanced ‘drift wave elasticity’ → enhanced ∇u converts turbulence to waves, so reducing mixing. (after McIntyre)



Desperately Seeking Greenwald

- **What of current scaling?**
- **What of $\alpha > 1$ – Collapse Mechanism?**
- **Dimensionless Parameter !?**

See: R. Singh, PD; NF 2021

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:

emission from 'drift-mode' interaction

production

incoherent
emission

S → polarization NL

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

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

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

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)

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

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

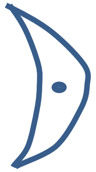
- Favorable I_p scaling of time asymptotic RH response persists in plateau regime. Robust trend.
- Compare to Banana ($L = 1$);

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

Current scaling but smaller ratio

Summary re Collisionality

- Banana(RH) $\nu_{ii} < \omega_{bi} < \omega_{Ti}$ $\frac{\phi_k(\infty)}{\phi_k(0)} = \left(\frac{B_\theta}{B_T}\right)^2 \sim I_p^2$



- Plateau $\omega_{bi} < \nu_{ii} < \omega_{Ti}$ $\frac{\phi_k(\infty)}{\phi_k(0)} = \left(\frac{B_\theta}{B_T}\right)^2 \frac{1}{L}$ $L < 1$

{ Scaling persists
weaker factor

- Pfirsch-Schluter $\omega_{bi} < \omega_{Ti} < \nu_{ii}$ $\frac{\phi_k(\infty)}{\phi_k(0)} = 1$ $\rho_{sc} = \rho_i$

➔ GAM can still manifest favorable trend with I_p in P.-S.

Revisiting Feedback (c.f. Singh, P.D. PPCF ‘21)

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

<u>Zero D</u>: $\underline{(\alpha > 1)}$

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 et. seq.

Revisiting Shear Layer Collapse

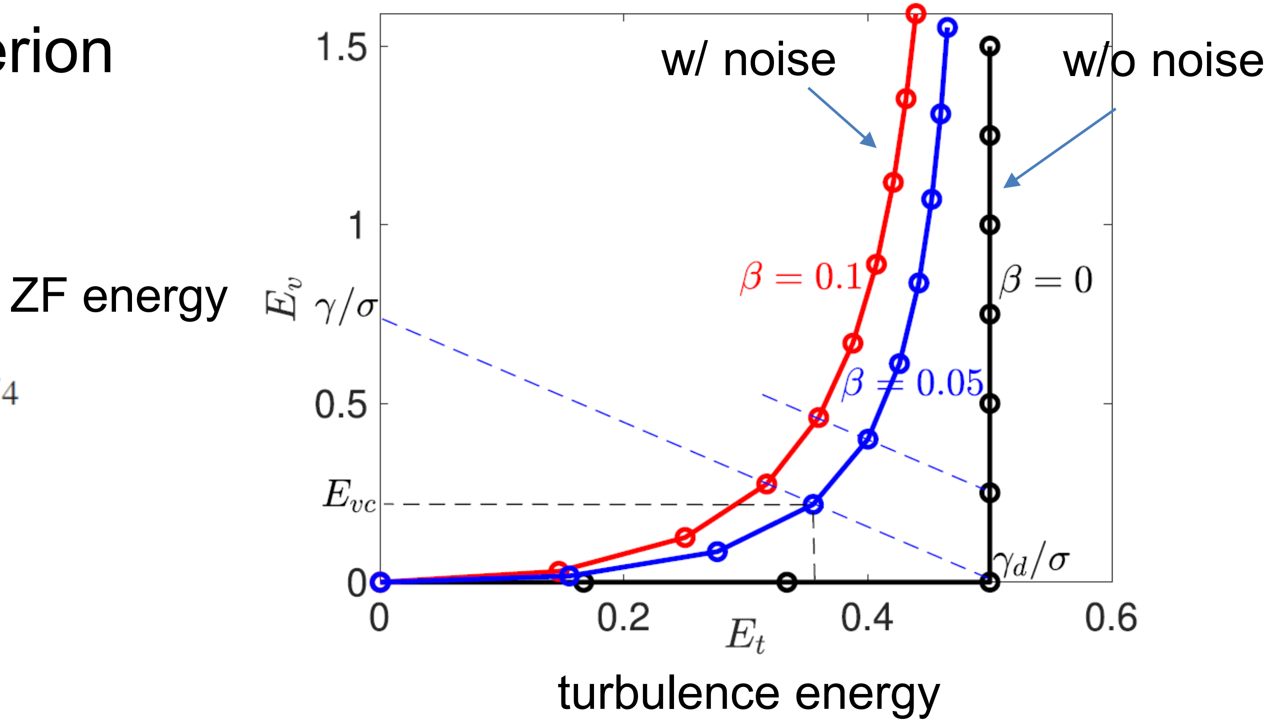
- For collapse limit, criterion without noise is good approximation to with noise

- Derive shear layer persistence criterion

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

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

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



Larger B_θ enhances persistence of ZF

Collapse Criteria, Cont'd

- Can determine critical particle source strength triggering collapse

$$\left(\frac{S}{nc_S}\right) > \ (crit.) \quad \text{(fuel strength limit)} \qquad crit. \sim \rho_\theta^3/\rho_i^3$$

- Then convert to <u>local limit</u> on <u>edge density</u>:

$$n \ < \frac{\rho_S}{\rho_\theta}\left(\frac{S}{c_S}\right)^{\frac{1}{3}}(crit') \ \approx \ I_p$$

- Variations for charge exchange friction…

➔ Density limit by shear layer collapse scenario seems viable for $\alpha > 1$.

Neoclassical screening is key.

More to say, but better to revisit reality…

Experimental study of edge shear layer evolution near the density limit of J-TEXT tokamak

T. Long (龙婷)[1], P. H. Diamond[2], R. Ke (柯锐)[1],

M. Xu (许敏)[1] and J-TEXT team[3]

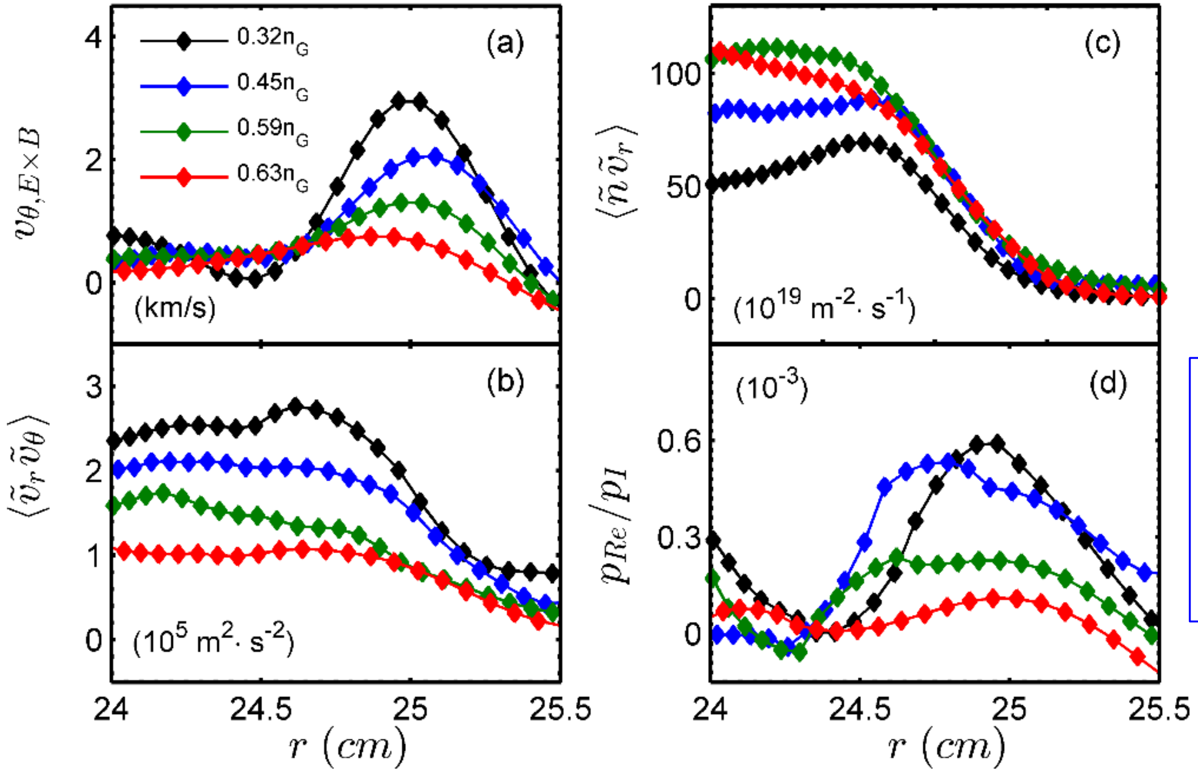
1 Southwestern Institute of Physics (核工业西南物理研究院), Chengdu, China

2 CASS and Department of Physics, University of California, San Diego, CA, USA

3 College of Electrical and Electronic Engineering, Huazhong University of Science and Technology (华中科技大学), Wuhan, China

Edge shear layer collapse as n approaches n_G

- As line-averaged density approaches Greenwald density, edge shear layer collapses.
- The ratio of Reynolds power $\mathcal{P}_{Re}$ to production power $\mathcal{P}_I$ decreases dramatically.

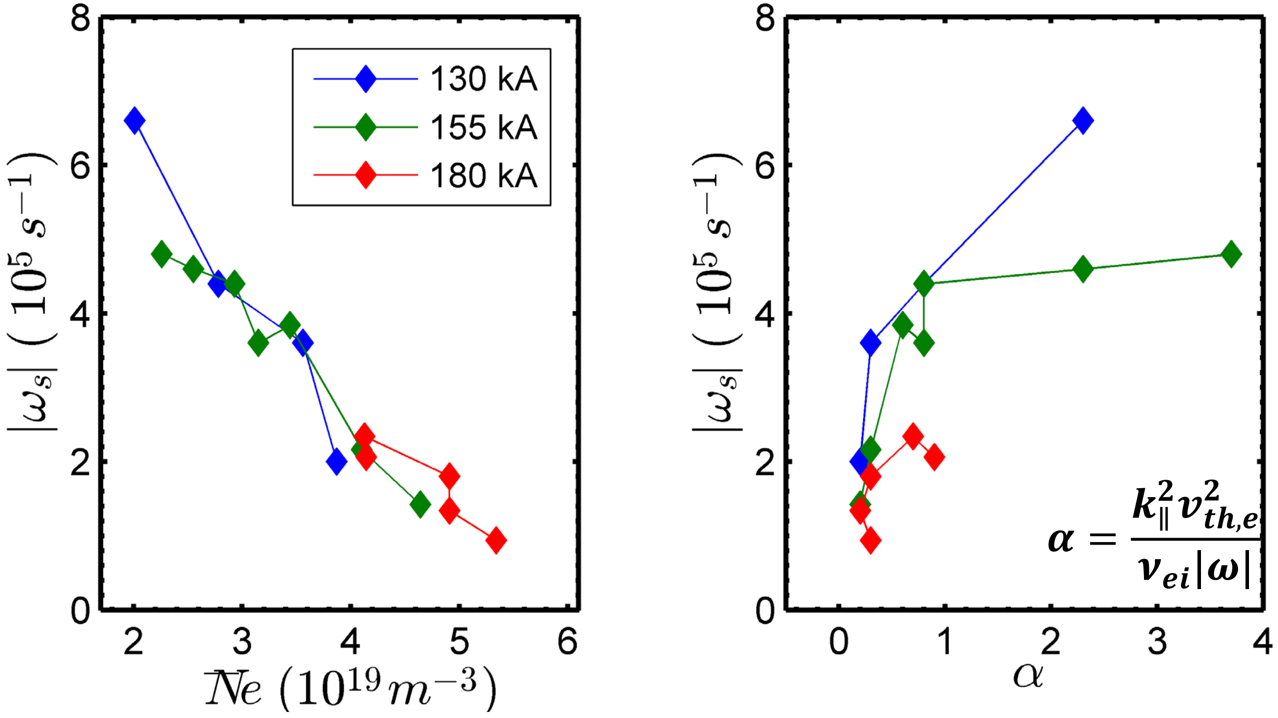


$$\frac{\mathcal{P}_{Re}}{\mathcal{P}_I} = \frac{-\langle v_\theta \rangle \partial_r \langle \tilde{v}_r \tilde{v}_\theta \rangle}{-c_s^2 \langle n \rangle \partial_r \langle \tilde{v}_r \tilde{n} \rangle / \langle n \rangle^2}$$

LCFS: $r = 25.5$ cm

Edge shear layer collapse as n approaches n_G

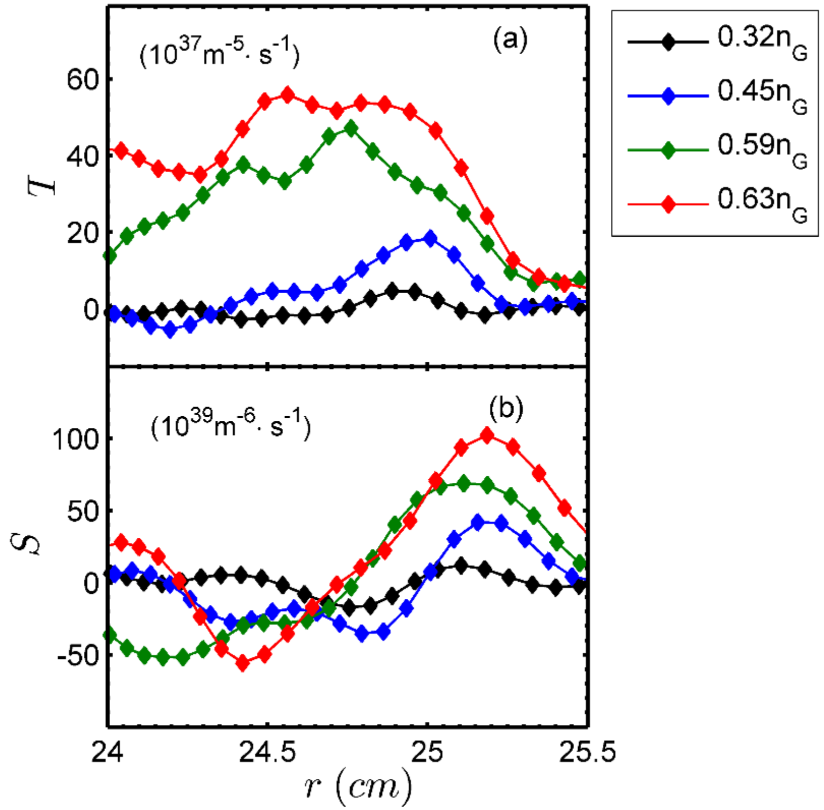
- Edge shearing rate $|\omega_s| = |\partial_r \langle v_{\theta,E\times B} \rangle|$ decreases as line-average d density increases.
- Edge shearing rate decreases sharply as electron adiabaticity $\alpha < 1$.



Both $\mathcal{P}_{Re}/\mathcal{P}_I$ and $|\omega_s|$ drop as $\alpha < 1$

Turbulence spreading behavior

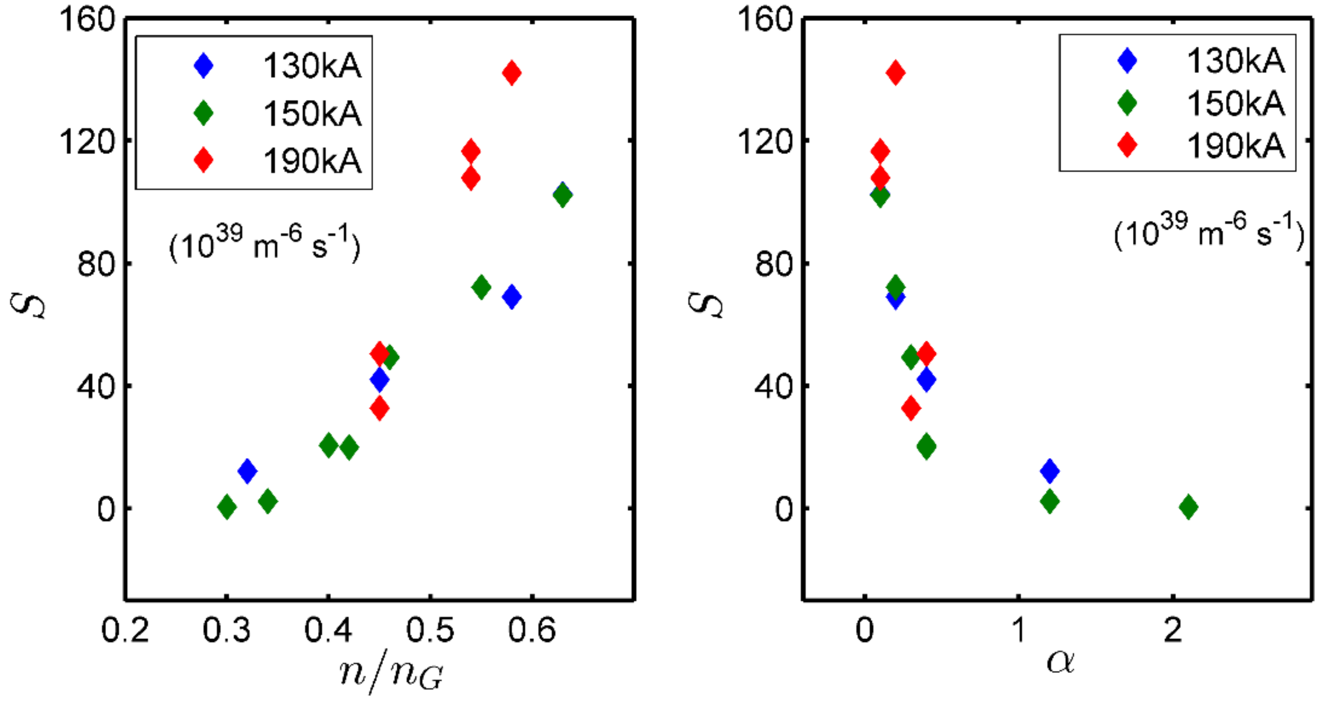
- Turbulent fluctuation energy transport $T = \langle \tilde{v}_r \tilde{n}^2 \rangle / 2$ and turbulent spreading rate $S = -\nabla \langle \tilde{v}_r \tilde{n}^2 \rangle / 2$ increase as n approaches n_G.



Collapse of shear layer → enhanced turbulence spreading

Turbulence spreading behavior

- Turbulence spreading increases as n/n_G increases.
- Turbulence spreading increases as α decreases, sharply for $\alpha < 1$.

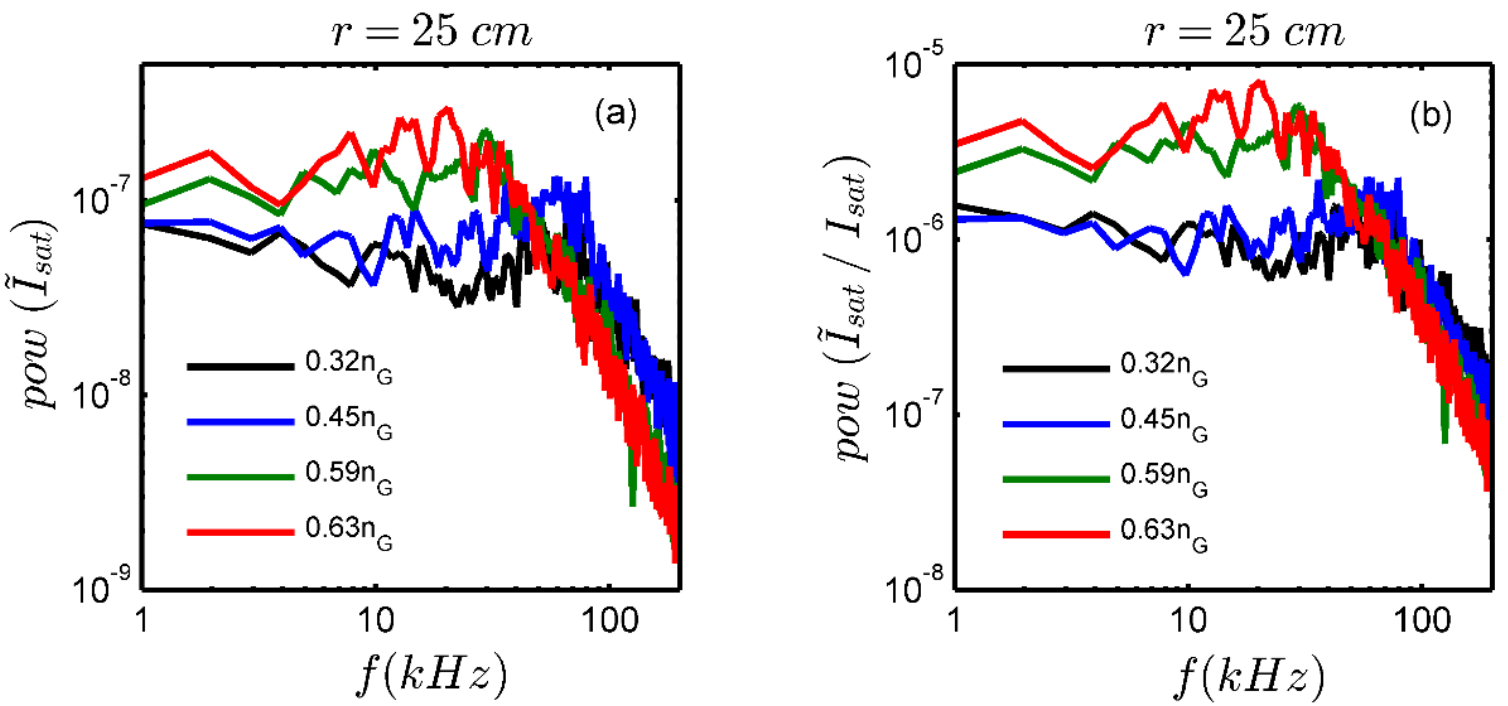


Collapse of shear layer releases turbulence propagation event.
Hereafter “transport event”.

Low frequency "transport event"

- As n approaches n_G, the low-frequency components (<50 kHz) of ion saturation current fluctuations increase drastically.

$\tilde{I}_{sat}/I_{sat} \cong \tilde{n}/n$

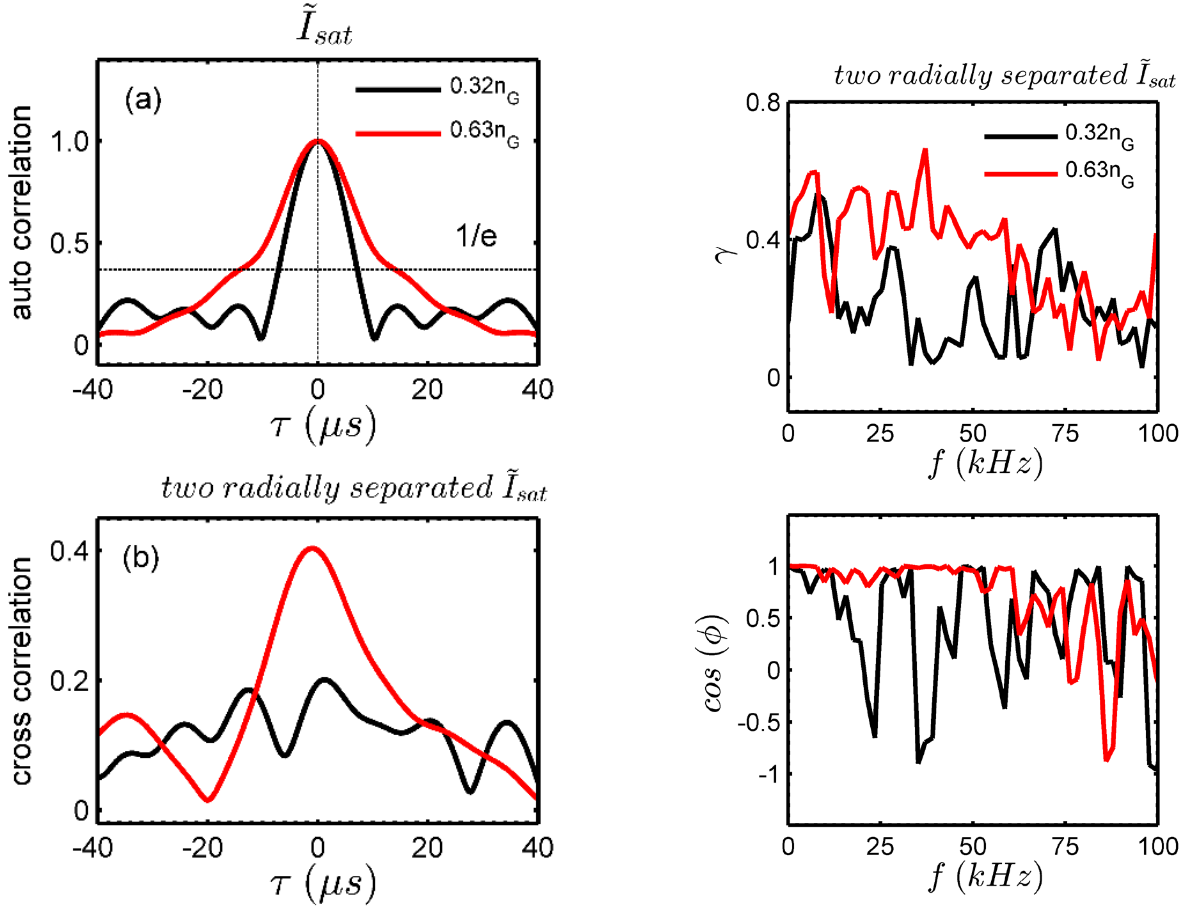


Large low-frequency fluctuation as $n \to n_G$.

(Hurst parameter TBD)

Low frequency "transport event"

- As line-averaged density increases:
  - auto correlation time τ_{ac} for $\tilde{I}_{sat}$ increases
  - cross correlation of radially separated $\tilde{I}_{sat}$ increases

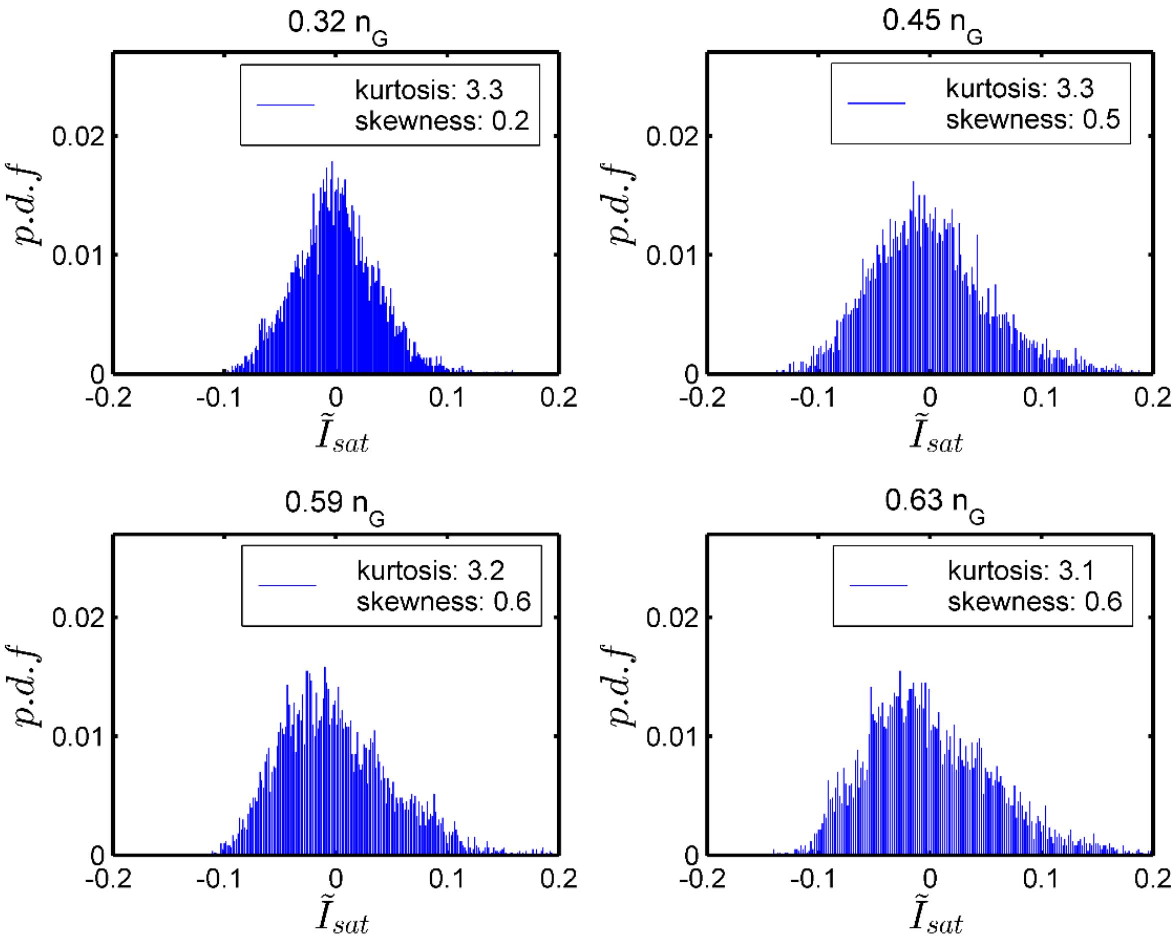


As density increases:

- coherence in low-frequency range (2-50 kHz) increases;
- cross phase is close to 1 in 2-50 kHz.

Low frequency "transport event"

- PDF of $\tilde{I}_{sat}$:
  - ➢ increasing skewness as n/n_G increases due to more positively biased tail.



Conclusions

- Shear layer collapses as $n \rightarrow n_G$, resulting in enhanced transport
- Both $\mathcal{P}_{Re}/\mathcal{P}_I$ and $|\omega_s|$ decline
- Increased turbulence spreading as $n \rightarrow n_G$
- $\alpha < 1$ emerges as "trigger criterion " here
- Collapse $\Rightarrow$ "quasi-coherent" overturning event, "slug" emission

Physics of the SOL Heat Load Scale Stability and Turbulence Spreading

[1]Xu Chu, [2]P. H. Diamond

[1] University of Chinese Academy of Sciences

[2] University of California, San Diego

中国科学院大学
University of Chinese Academy of Sciences

Motivation

- Goldston, et. al. heuristic drift scaling [1] works well for present day discharges.
  Based on neoclassical transport: $\lambda \sim v_D \tau_{\parallel} \sim \epsilon \rho_\theta$
- Goldston, et. al. [2], pointed out the importance of the competition of $E \times B$ shear and the interchange mode in the SOL.
  - $\gamma \sim c_s/(R\lambda)^{1/2} - \phi/\lambda^2$

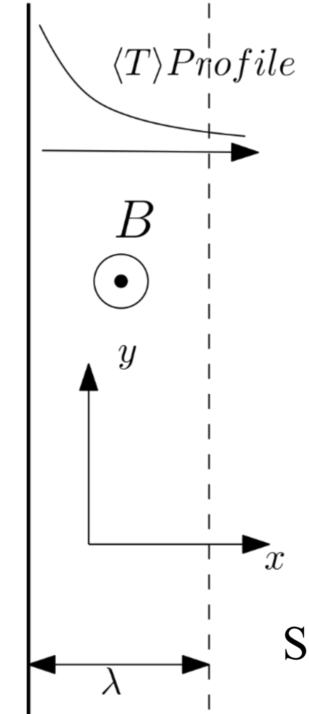
- Objectives:
  - Studying the SOL stability with combined effects of $E \times B$ shear, sheath resistivity and interchange mode, and the possibility of broadening the SOL with locally generated turbulence.
  - Study the influence of turbulent spreading from pedestal on the SOL width

[1] R. J. Goldston, Nuclear Fusion 52, 013009 (2012).
[2] R. J. Goldston, A. Brown, Bulletin of the American Physical Society, 2020

Linear Analysis: SOL Stability

Model: (Linear Perturbation of the model by Myra. et. al. 2002 [3]):

$$\begin{cases} \partial_t \Delta\delta\phi + \lambda_T \omega_s e^{-x/\lambda_T} \partial_y \Delta\delta\phi - e^{-x/\lambda_T} \beta \partial_y \delta n \\ \qquad = \alpha e^{x/2\lambda_T} \delta\phi + \nu \Delta^2 \delta\phi \\ \partial_t \delta n + \lambda_T \omega_s e^{-x/\lambda_T} \partial_y \delta n + \partial_y \delta\phi \partial_x ln n_0 \\ \qquad = D\Delta\delta n/n + 2D\partial_x ln n_0 \partial_x \delta n \end{cases}$$

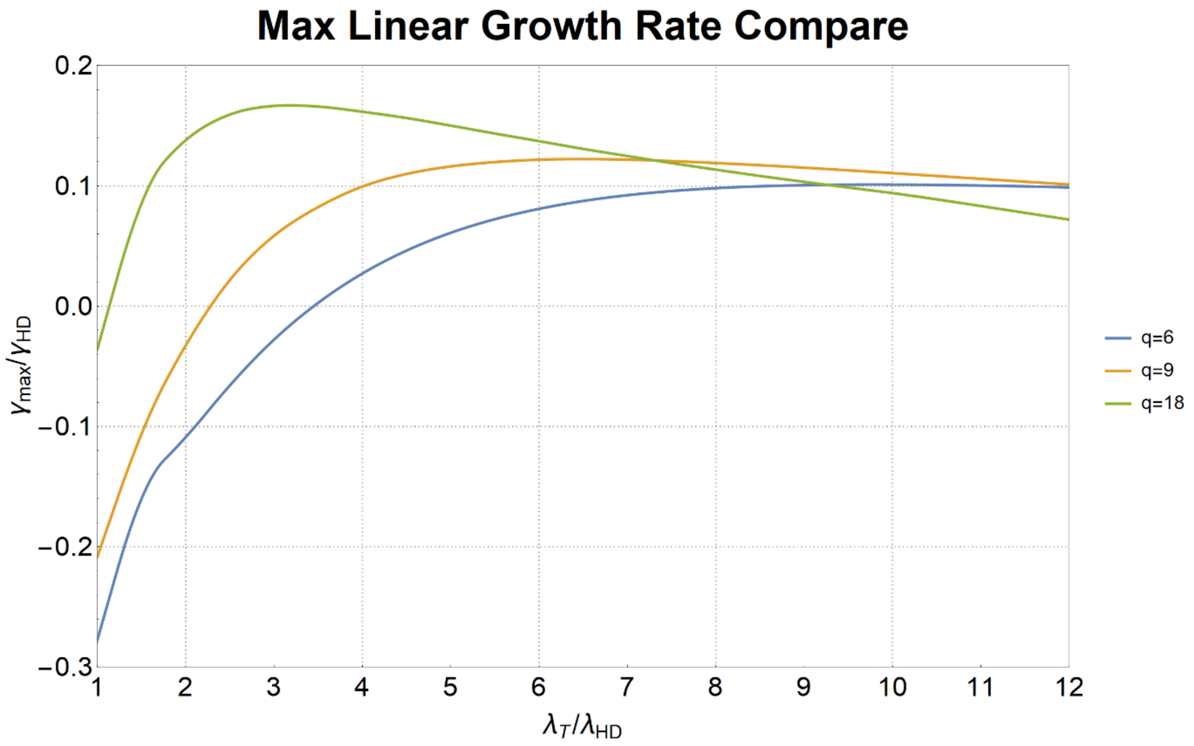


Note: $\beta = 2\rho/R$
Usual: denoted by β_t

Shearing Rate:
$\omega_s = 3/\lambda_T^2$

Small Heat Load Width

Linear growth rate with neoclassical diffusion.



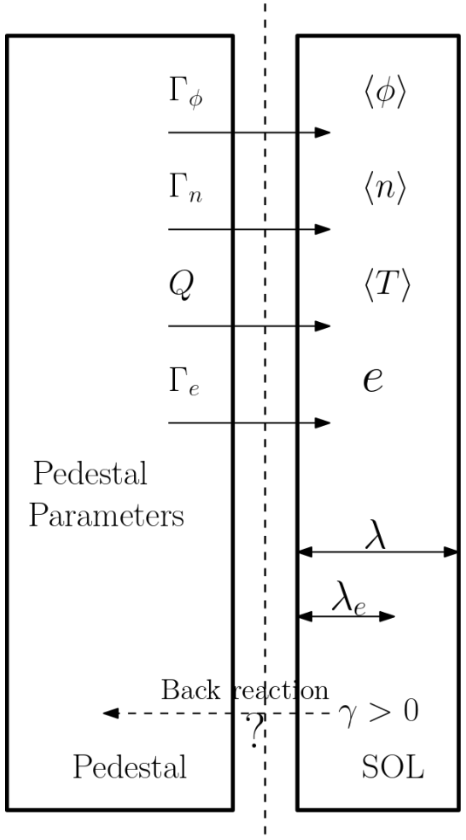
Interchange mode is stabilized by the combination of shear, sheath resistivity and neoclassical diffusion.

Spreading: Pedestal → SOL

Pedestal Intensity Flux: Ongoing

- Drift Wave:
  - $\Gamma \sim \tau_c K \partial_x K$
    - K: turbulent kinetic energy
  - $\tau_c v_* = \rho$
  - $\Gamma \sim a\frac{L_n}{\Omega\rho}K\partial_x K$, a of $O(1)$
- Ballooning Mode:
  - $\tilde{v} \sim \gamma\Delta_r = L_p\omega_A\left(\frac{L_{pc}}{L_p}-1\right)^{0.5}\frac{\Delta_r}{L_p}$
    - L_p is the pedestal width
  - $\Gamma \sim \tilde{v}^3 \sim \tilde{v}\tilde{p}^2$

Analogue: Spreading of a turbulent spot



SOL Model with Intensity Flux

- $\boldsymbol{\partial_t e = \gamma e - \sigma e^{1+\kappa} - \partial_x \Gamma_e}$
- Turbulent Energy Balance:
  - $\boldsymbol{\Gamma_0 = \lambda_e|\gamma|e + \sigma e^{1+\kappa}\lambda_e}$
  - Γ_0: intensity flux from pedestal
- Linear Damping:
  - $\gamma = \gamma_0 - 3/\lambda_T^2 \approx -3/\lambda_T^2$
- Nonlinear Damping: (One possibility)
  - Inverse Cascade: $\kappa = 1/3,\ \sigma = \alpha^{1/3}$
- $\lambda_e = \tau\sqrt{e}$
- Heat flux Q determines $\langle T\rangle_{sep}$ and enters the model from c_s in γ_0
- SOL as a BL with 2 drives

中国科学院大学
University of Chinese Academy of Sciences

Spreading: Γ_{min}

- What's the minimal pedestal fluctuation needed to broaden the SOL?
- The criterion: $\lambda_e = \lambda_{HD}$, or equivalently $\tilde{v} = v_D$ when $\tau = \tau_\parallel$.($\lambda_e = \tau e^{0.5}$)

CDW

1. Balance Linear Damping:
   - $\Gamma_0 = |\gamma| \lambda_{HD}^3 \tau_\parallel^{-2}$

   Balancing with the estimation in the pedestal
   - $\frac{|\delta v|}{c_s} \sim \left(\frac{3L_e}{aL_n}\right)^{0.25} \lambda_e^{0.25} q^{-0.5} \rho^{-0.25}$
2. Balance Nonlinear Damping:

   $\Gamma_0 = \alpha^3 \lambda_e^9$

   Balancing with the estimation in the pedestal

   $\frac{|\delta v|}{c_s} \sim \left(\frac{L_e}{aL_n}\right)^{0.25} \lambda_e^{2.25} q^{-0.75} \rho^{-1.5} R^{-0.75}$

Ballooning

1. Balance Linear Damping:
   - $\Gamma_0 \sim |\gamma| \lambda_{HD} v_D^2$
   - $\left(\frac{\Delta_r}{L_p}\right)\left(\frac{L_{pc}}{L_p} - 1\right)^{0.5} \sim (q\rho)^{2/3} \frac{R^{1/3}}{L_p} \sqrt{\beta_t}$
2. Balance Nonlinear Damping:
   - $\Gamma_0 \sim \alpha^3 \lambda_{HD}^9$
   - $\left(\frac{\Delta_r}{L_p}\right)\left(\frac{L_{pc}}{L_p} - 1\right)^{0.5} \sim \frac{\rho q^3}{L_p} \sqrt{\beta_t}$

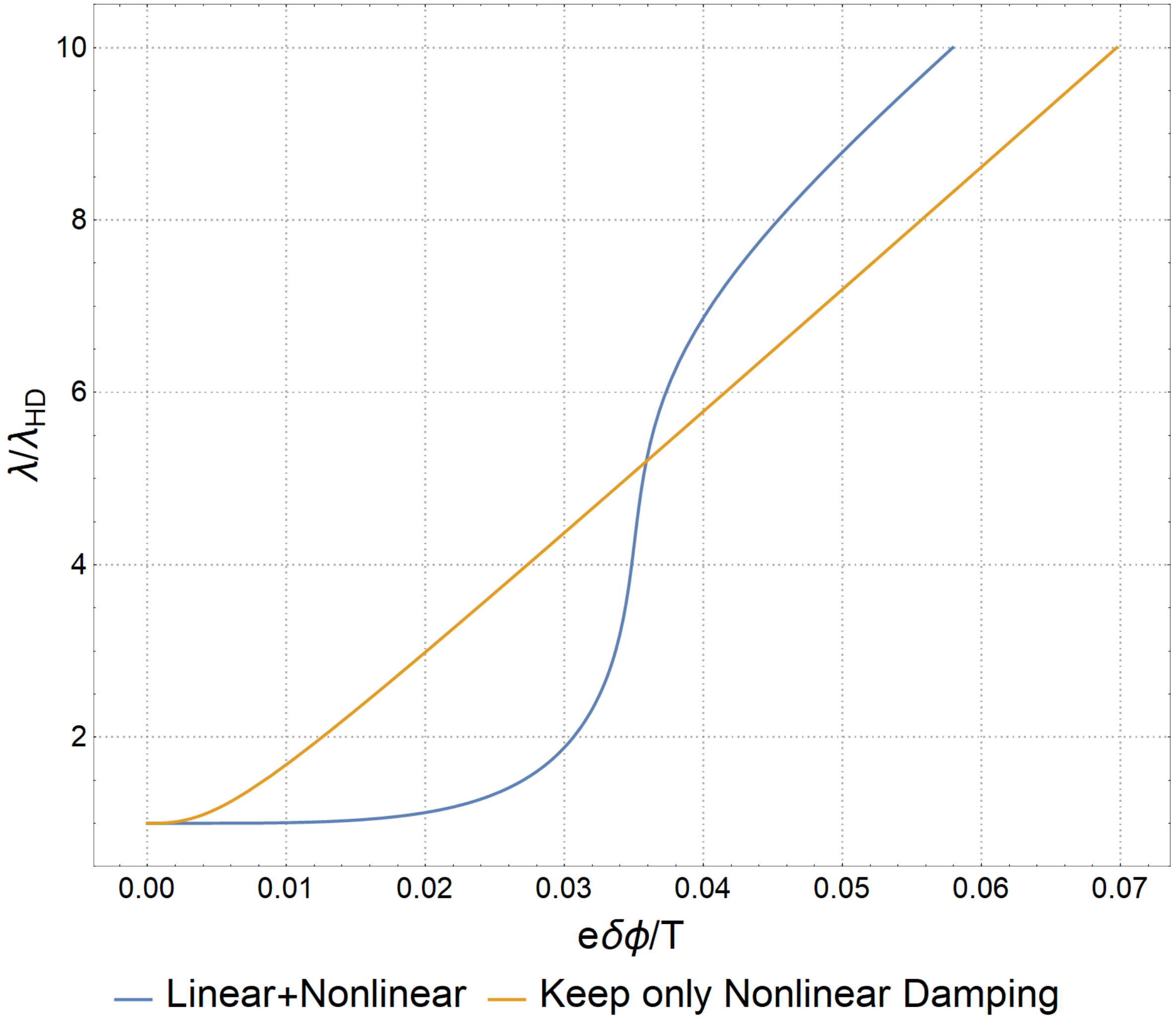
The Question:
Is the turbulence level in pedestal to broaden the layer compatible with good confinement?

University of Chinese Academy of Sciences

SOL Layer Width – Unified Estimation

- $\lambda_e = \lambda = \sqrt{\lambda_{HD}^2 + \tau_\parallel^2 e}$
- $\Gamma_e = \left(\sqrt{\beta/\lambda} - 3/\lambda^2\right)e\lambda + \sigma e^{1+\kappa}\lambda$
- $\sigma = 0.6, \kappa = 0.5$
- The fluctuation level is converted from intensity flux using DW estimation

- Effective critical fluctuation level is required.

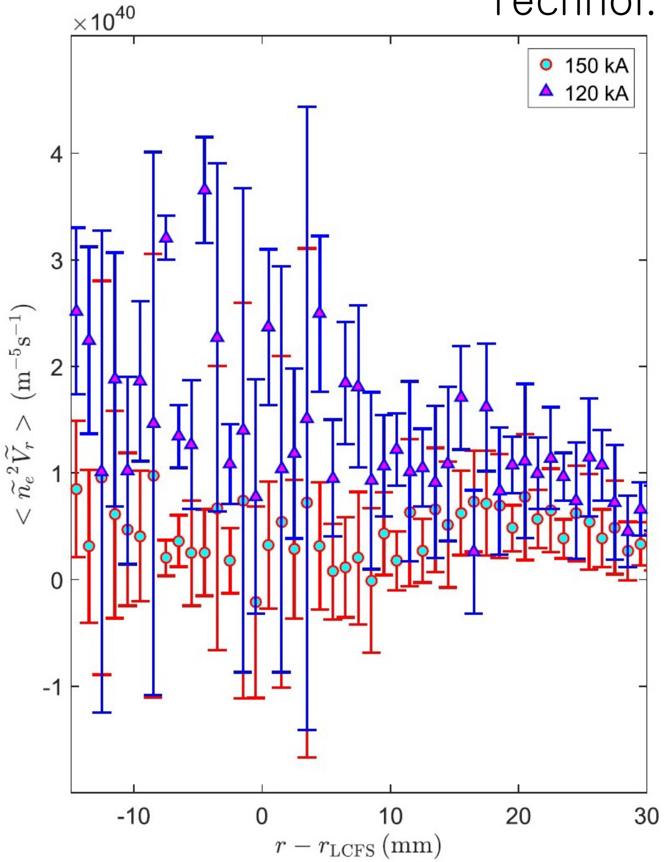


University of Chinese Academy of Sciences

Inside→Outside Separatrix Connection

L mode: HL-2A

Wu Ting, et. al. Plasma Sci. Technol.



Turbulence spreading reduced at larger current

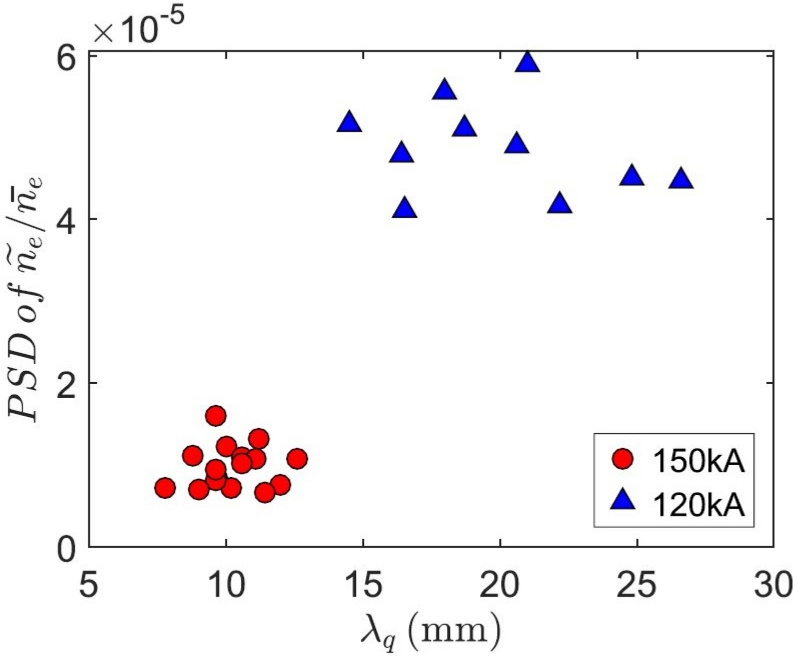


Figure 7. The power of relative density fluctuation level at $r - r_{\mathrm{LCFS}} \approx -15$ to -10 mm versus SOL width with different plasma currents.

PSD of near (inside) separatrix $\tilde{n}/n$ vs. SOL width

SOL widths larger for stronger edge turbulence levels at lower current.

Suggests Inside turbulence→SOL width influence due to spreading.

Conclusions

- SOL is linearly stable due to large $E \times B$ shear and sheath resistivity
- Turbulent spreading from the pedestal can broaden the layer and should be considered
- SOL width is related to intensity flux across the separatrix which is in turn determined by pedestal parameters
- Intensity flux balances linear and nonlinear damping in the SOL
- There exist a minimal intensity flux for spreading such that $\lambda > \lambda_{HD}$
- Future research:
    - HDL: Strong layer broadening weakens shear stabilization and makes SOL interchange unstable.
    - Does SOL turbulence invade pedestal, cause H→L, defining HDL?
    - Two levels: onset and invasion, Gap?

Discussion and Conclusions

- Density limit macroscopics rooted in microphysics of particle transport, edge turbulence and shear layer
- Shear layer collapse as $n \rightarrow n_G$ is origin of enhanced particle transport
- Electron adiabaticity, neoclassical screening, incoherent emission, zonal flow damping all enter dynamics of ZF collapse
- Predator-Prey model is unifying structure

- $\rho_s/(\rho_\theta L_n)^{1/2}$ > crit. is zonal flow persistence criterion. ID's dimensionless parameter characteristic of Greenwald limit
- 'Second Wave' of fluctuation experiments identifies production ratio, enhanced spreading, $\alpha > 1 \rightarrow \alpha < 1$, 'quasi-coherent' phenomena
- Turbulence spreading across ~~DMZ~~ separatrix may mitigate Goldston heat load pessimism but strong broadening ➔ HDL

Looking Ahead (Experiments)

- Support the shear layer ↔ bias (ongoing)
- L-mode with P_{aux} → collapse? Stress T^2/n
- Revisit perturbation experiments
- Dog → Tail vs Tail → Dog and HDL

  ➔ Role of SOL→Core spreading
- Negative Triangularity !?

Supported by U.S. Dept. of Energy under Award Number DE-FG02-04ER54738