Transport Physics of Density Limits

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Outline

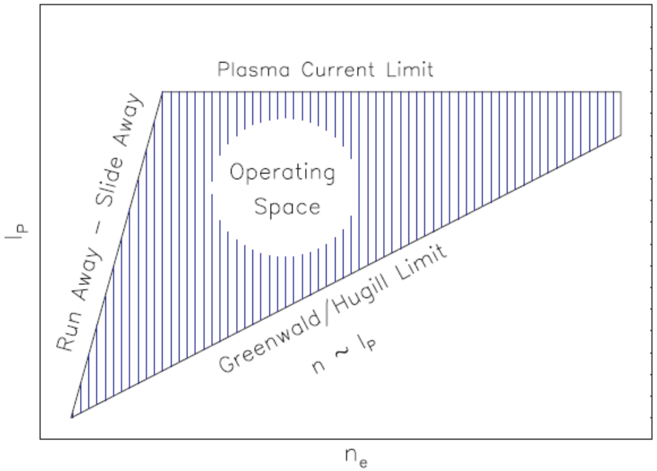
- Selected OV of density limit physics (L-mode)
  - Focus: role of particle transport
  - Emphasize: fluctuation studies ←→ role of edge shear layer
- Theory of shear layer collapse
  - Shear flow production and its decline
  - Key: electron adiabaticity
- Desperately seeking Greenwald
  - What of current scaling?
  - Tokamak vs. RFP vs. Stellarator
- Thoughts for experiments

A Look at Density Limit Phenomenology

Density Limits: Some Basic Aspects

- Not a review!
- Greenwald density limit:

$$\bar{n} = \bar{n}_g \sim \frac{I_p}{\pi a^2}$$

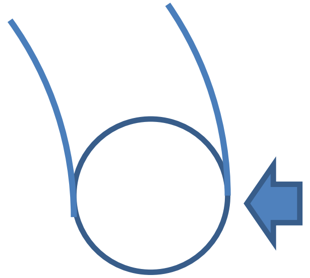


Constrains tokamak Operating Space

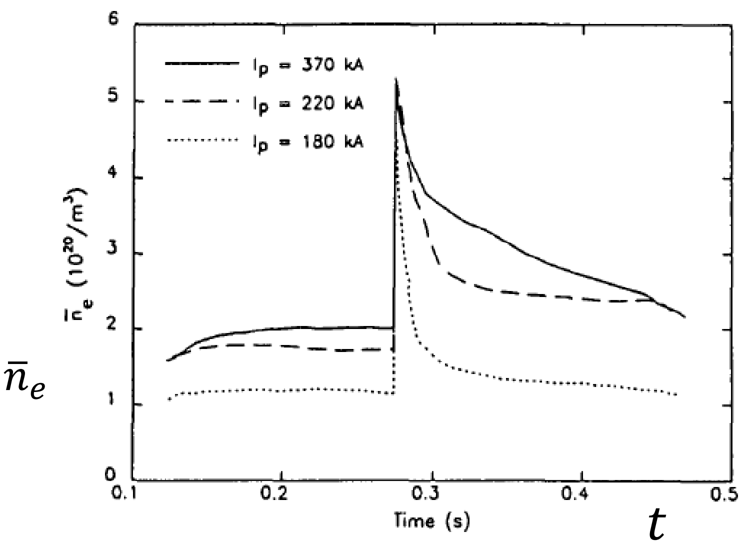
- Manifested on other devices
  - See especially RFP ($n \sim I_p$ scaling)

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

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



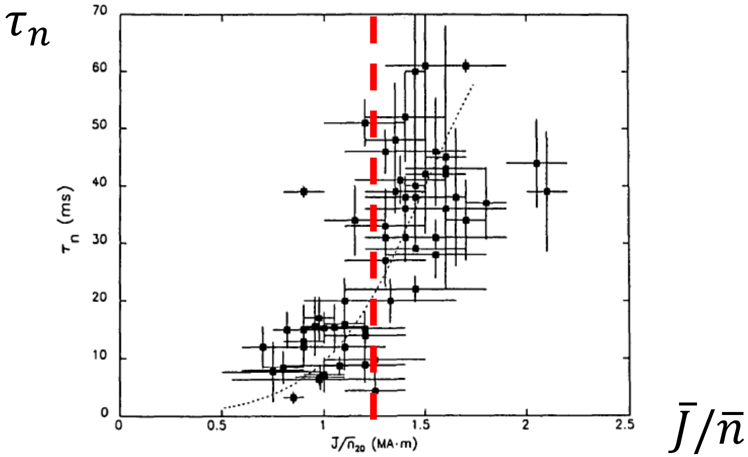
- Argue: Edge Particle Transport is crucial
  - ‘Disruptive’ scenarios secondary outcome, largely consequence of edge cooling, following fueling vs. increased particle transport
  - $\bar{n}_g$ reflects fundamental limit imposed by particle transport
- A Classic Experiment (Greenwald, et. al.)

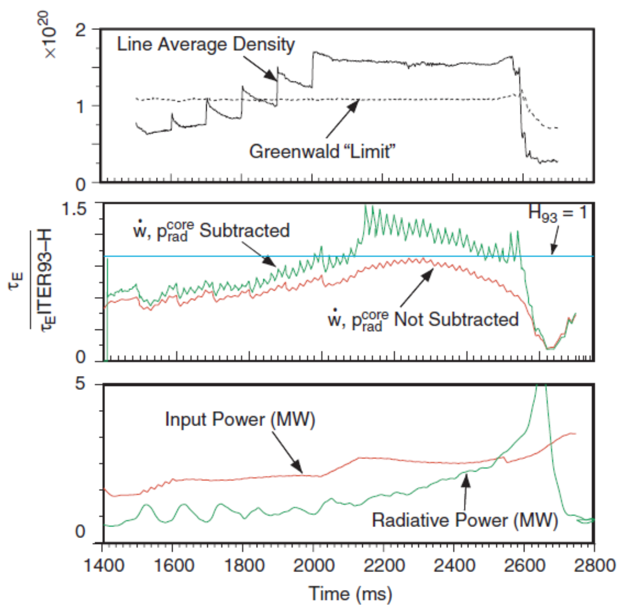


(Alcator C)

  - 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

- More Evidence for Role of Edge Transport



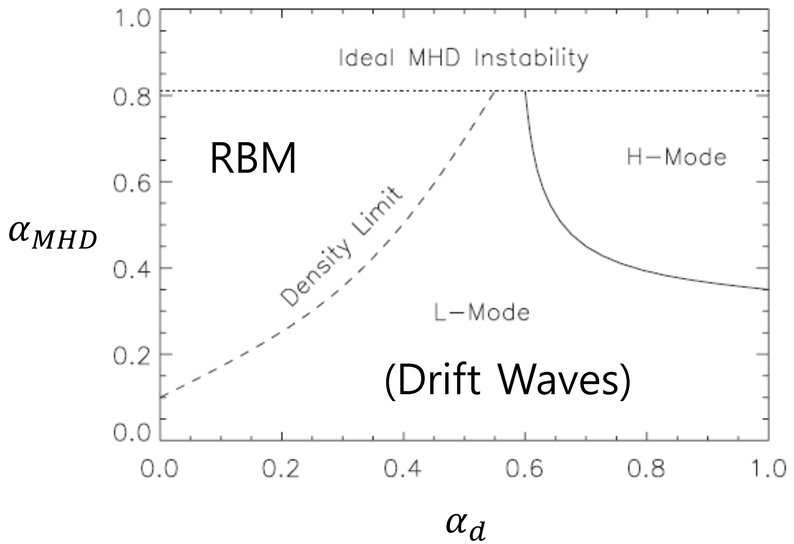


- Post-pellet density <u>decay time</u> vs $\bar{J}/\bar{n}$.
- Increase in relaxation time near (usual) limit: $\bar{J}/\bar{n} \sim 1+$
- Pellet in DIII-D beat $\bar{n}_g$
- Peaked profiles ←→ enhanced core particle confinement (ITG turbulence reduced?)
- Reduced particle transport ➔ impurity accumulation

(N.B. Deeper deposition)

Conventional Wisdom (Rogers + Drake '98, et seq.)

Reduced Fluid Simulation (no heat source)



$$\alpha_{MHD} = -Rq^2 d\beta/dr$$

←→ ∇P → ballooning drive

$$\alpha_d = \rho_S C_s t_0 / L_n L_0$$

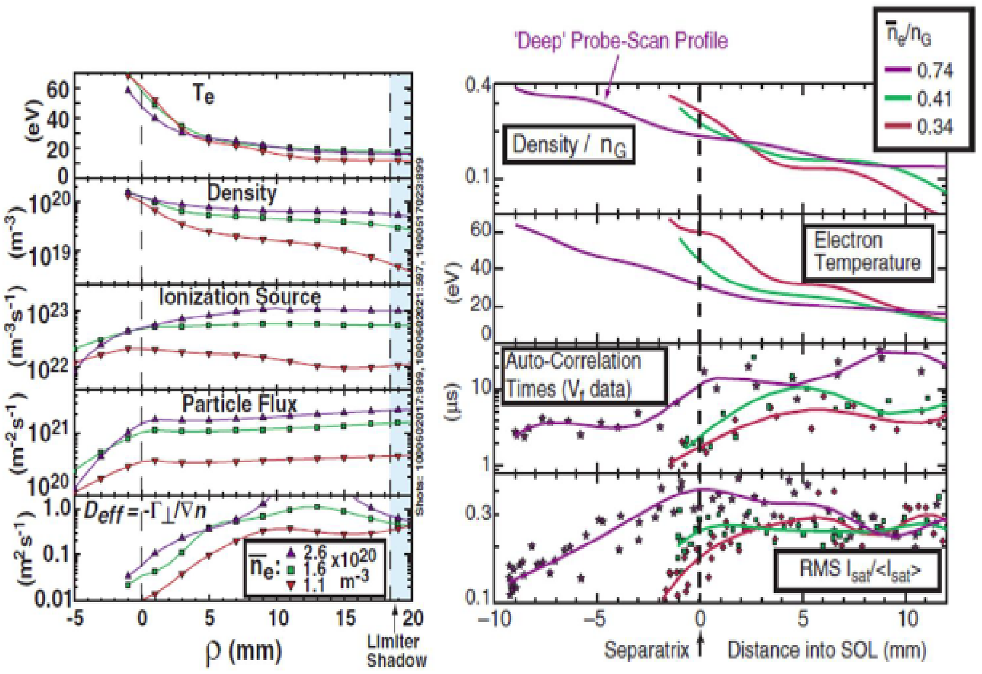
$$t_0 = \frac{(RL_n)^{\frac{1}{2}}}{c_S}$$

$$L_0 = 2\pi q \left(\frac{\nu_e R \rho_s}{2\Omega_e}\right)^{1/2}$$

→ Hybrid of drift frequency and collisionality

- D+R on n-limit physics:
  - State of high $\nabla P, \beta$, cool electrons
  - DWT → resistive ballooning turbulence
  - Issue: Density limit vs beta limit??

Density limit ←→ Fluctuation Structure

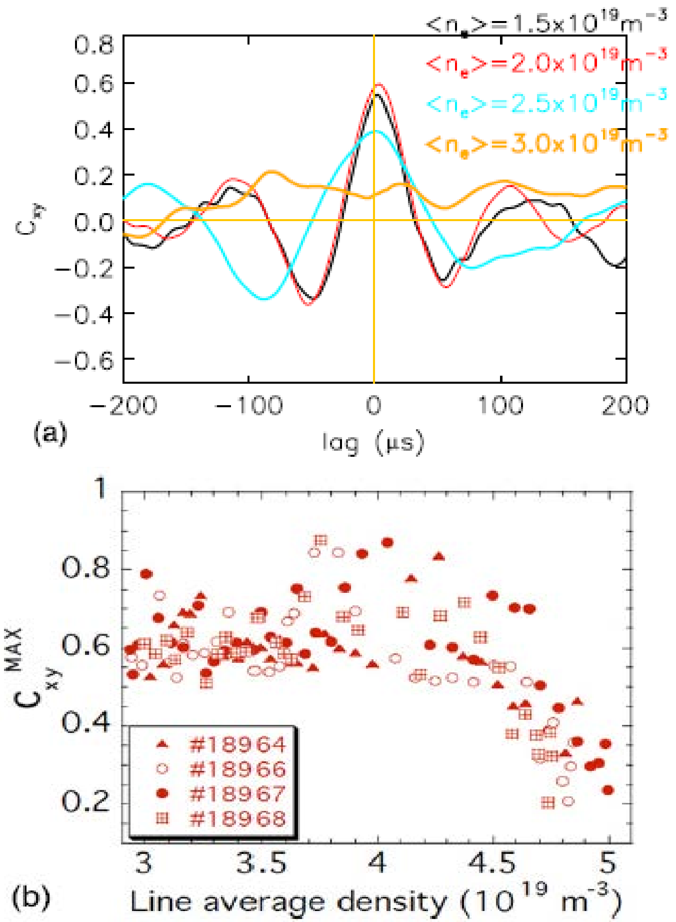


C-Mod profiles,
Greenwald et al, 2002, PoP

- 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 $n/n_G \to 1$.

Recent Experiments - 1

(Y. Xu et al., NF, 2011)



LRC vs $\bar{n}$

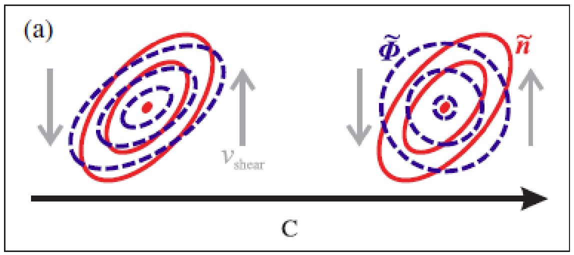
- Decrease in maximum correlation value of LRC (i.e. ZF strength) as line averaged density $\bar{n}$ increases at the edge (r/a=0.95) in both TEXTOR and TJ-II.
- At high density ($\langle n_e \rangle > 2 \times 10^{19}\ m^{-3}$), the LRC (also associated with GAMs) drops rapidly with increasing density.
- The reduction in LRC due to increasing density is also accompanied by a reduction in edge mean radial electric field (Relation to ZFs).

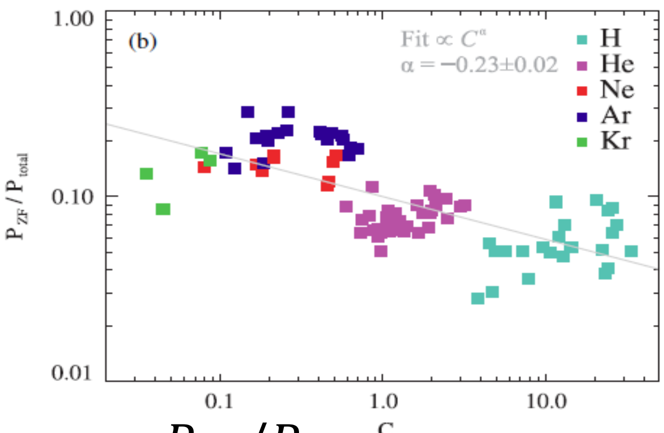
Is density limit related to edge shear decay?

Recent Experiments - 2

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

Eddy Tilt





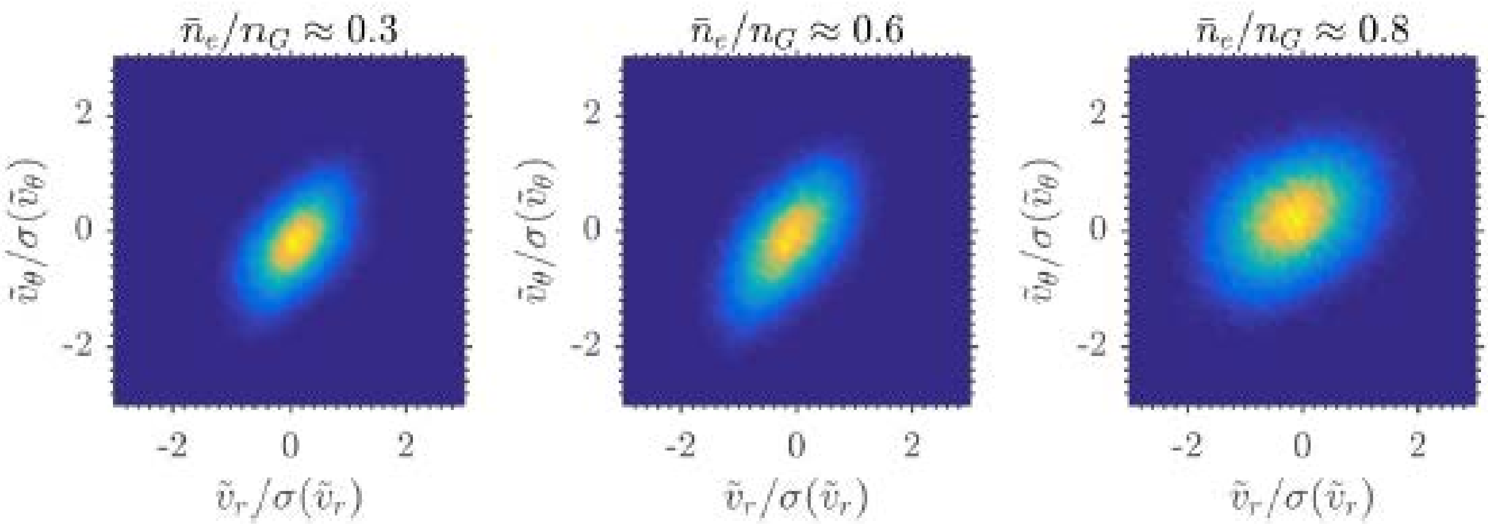
P_{ZF}/P_{tot}

- 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)

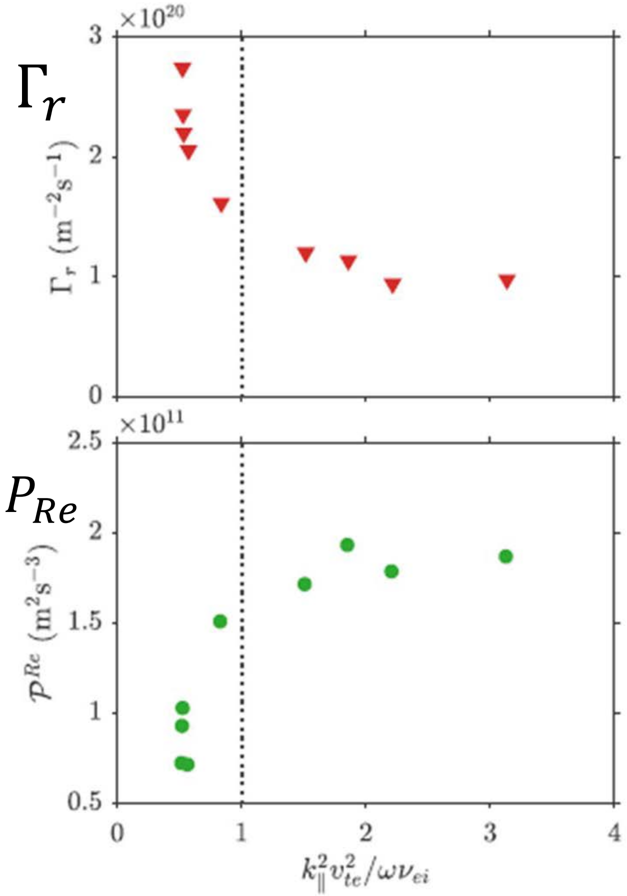
C ⇔ adiabaticity $k_{\parallel}^2 V_{th}^2/\omega\nu$

Recent Studies, Hong, et. al. (NF 2018)



- 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>
  - Consistent with drop in P_{Re}

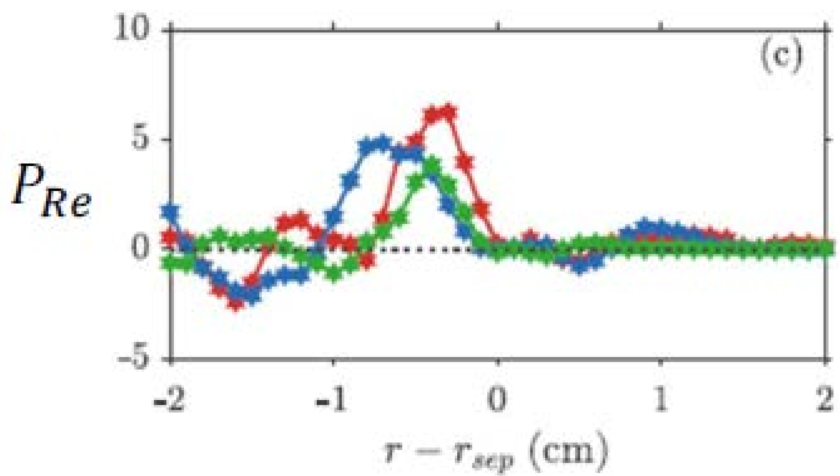
Key Parameter: Electron Adiabaticity



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 $\bar{n}$ 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.



N.B. Plasma beta remained very low

Synthesis of the Experiments

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

  → Key microphysics of density limit !?

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

  → Effect on production

- Degradation in particle confinement at density limit in L-mode is due to breakdown of self-regulation by zonal flow

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

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

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 : { shear layer → barrier
turbulence

Density Limit: strong turbulence ← { shear layer,
turbulence

➔ In particular, what is the fate of shear flow for hydrodynamic electrons: $k_{\|}^{2}V_{th}^{2}/\omega\nu < 1$?

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

  Ghatous and Gurcan ‘15

- 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 turbulence.

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

  dynamics of primary interest

A Theory of Shear Layer Collapse

A Simple, Generic Model

Hasegawa-Wakatani for Collisional DWT:

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

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

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

Fluctuation s

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

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

Mean Field s

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

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

For neoclassical mean field evolution

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

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

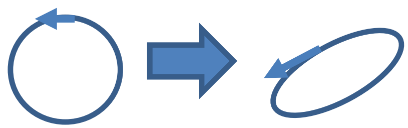
Step Back: Zonal Flows Ubiquitous! Why?

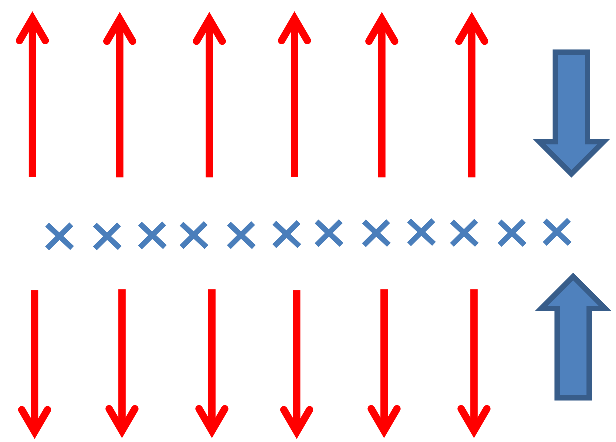
- Direct proportionality of wave group velocity and wave energy density flux

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

  Causality ←→ Eddy Tilting

i.e.



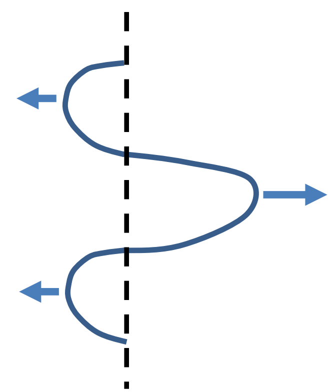


$\omega_k = -\beta\, k_x/k_\perp^2$: (Rossby)

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

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

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



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

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
- $V_{gr} = -\frac{2k_r \rho_s^2}{k_\perp^2 \rho_s^2}\,\omega_r$ ←??→ $\langle \tilde{V}_r \tilde{V}_\theta \rangle = -\langle k_r k_\theta \rangle$; 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

Reduced Model ⇔ Demonstrate Understanding

- Utilize models for real space structure to address shear layer

  e.g. { Balmforth, et. al. / Ashourvan, P.D. } ➔ Outgrowth of staircase studies

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

- 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

So

$\langle \tilde{q}^2 \rangle = \varepsilon$ – fluctuation potential enstrophy

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

Reduced Model, cont'd

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

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

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

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

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

- Fluxes:

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

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

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

Production and acceleration of flow by ∇n

Shear relaxation by turbulent viscosity

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

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

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

Clear dependence of D, χ_y, 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	$\Gamma_{adia} \sim \frac{1}{\alpha}$	$\Gamma_{hydro} \sim \frac{1}{\sqrt{\alpha}}$
Turbulent Viscosity χ	$\chi_{adia} \sim \frac{1}{\alpha}$	$\chi_{hydro} \sim \frac{1}{\sqrt{\alpha}}$
Residual stress Π^{res}	$\Pi^{res}{}_{adia} \sim -\frac{1}{\alpha}$	$\Pi^{res}{}_{hydro} \sim -\sqrt{\alpha}$
$\frac{\Pi^{res}}{\chi}$ = Vorticity Gradient	α^0	α^1

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

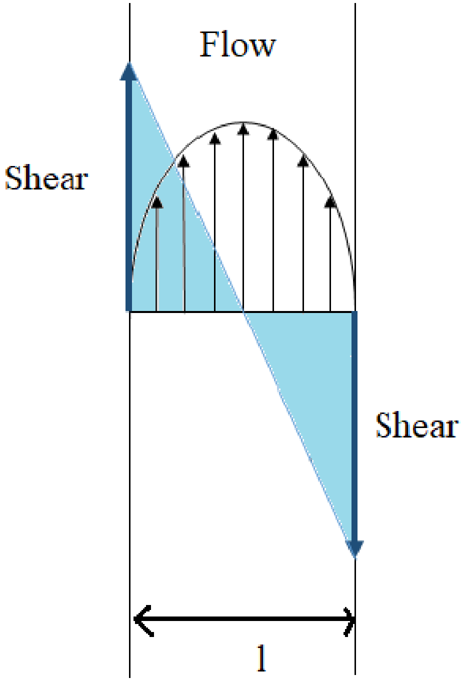
α <1 → weak flow production

- 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.

Some Theoretical Matters

Physics of Vorticity Gradient ?!

- ∇u, not flow shear, is natural flow order parameter
- [Jump in flow shear, over scale l] = [∇u, over scale l]
- Vorticity gradient prevents local alignment of eddy or mode with shear
- $\Pi = 0 \quad \rightarrow \quad \nabla u \ \sim \ \Pi^{res}/x_y$
- Standard interpretation: Enhanced 'drift wave elasticity' → ∇u converts turbulence to waves, so reducing mixing.



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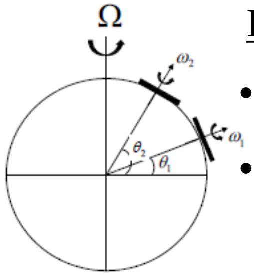
ZF Collapse ←→ PV Conservation and PV Mixing?

How reconcile?

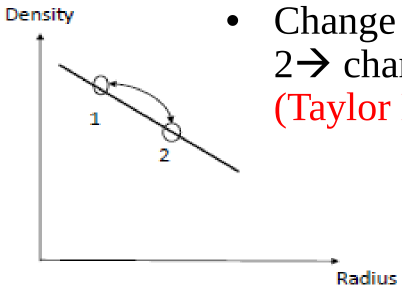


Rossby waves:

- $PV = \nabla^2\phi + \beta y$ 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 ω → Flow generation (Taylor's 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)



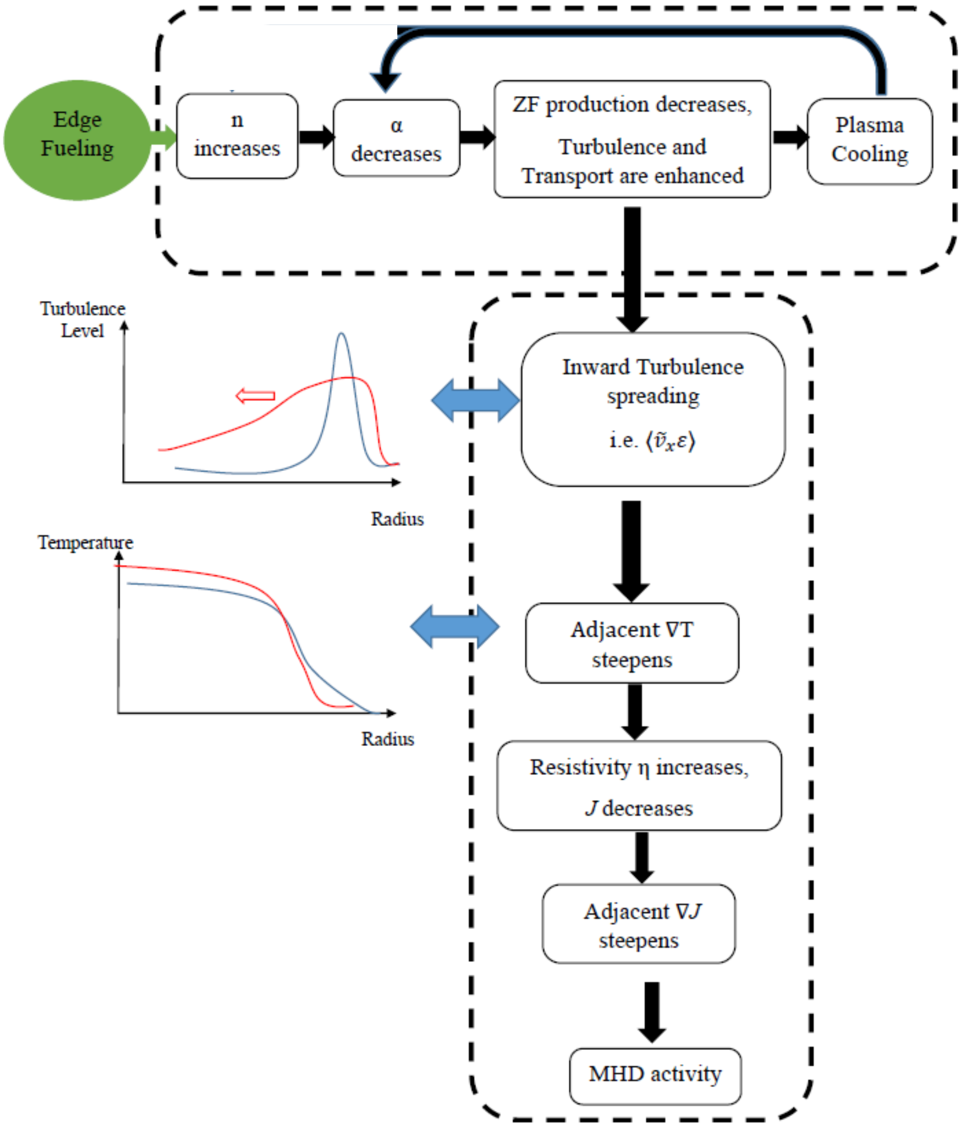
Quantitatively

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

- Branching ratio changes with α!

Some Pragmatic Matters

The Big Picture



Production ↓ → Cooling ↑ Feedback Loop

→ post-collapse intensity increase

→ inward spreading

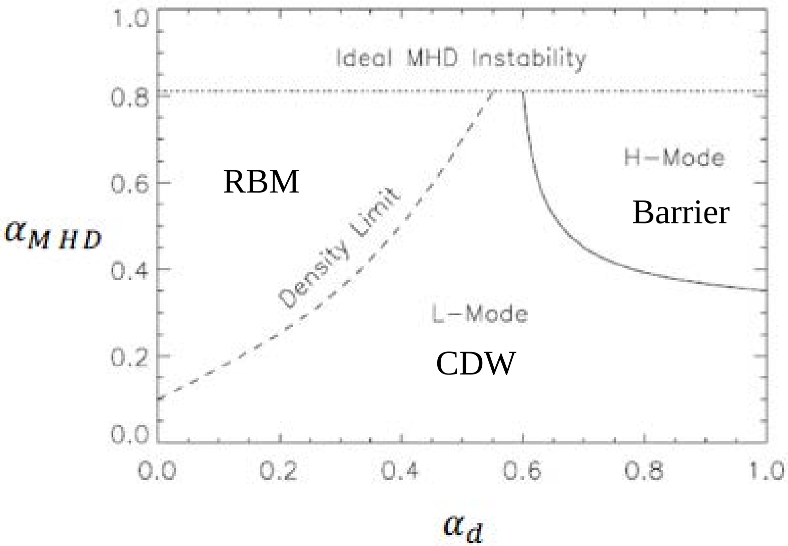
→ turbulence spreading 'transmits' edge cooling to low q resonance

Key: $[r_{sep} - r_q]$ vs $(D\tau_c)^{1/2}$

A Developing Story

From Linear Zoology to Self-Regulation and its Breakdown

(Drake and Rogers, PRL, 1998)



- $\alpha_{MHD} = -\frac{Rq^2 d\beta}{dr} \rightarrow \nabla$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 $\alpha > 1$	Secondary modes (ZFs and GAMs)
H-mode	Irrelevant	Mean ExB shear ∇Pi/n
Degraded particle confinement (Density Limit)	Hydrodynamic $\alpha < 1$	None - ZF collapse due weak production for $\alpha < 1$

Secondary modes and states of particle confinement

L-mode: Turbulence is *regulated* by shear flows, but not suppressed.
H-mode: *Mean ExB* shear $\leftrightarrow \nabla p_i$ suppresses turbulence and transport.
Approaching Density Limit: High levels of turbulence and particle transport, as shear flows collapse.

i.e. Shear Flow: Density Limit > | < L-mode > | < H-mode

Weak (none) | Modest | Strong Mean

Partial Conclusions (L-mode)

- ‘Density limit’ is consequence of particle transport dynamics, edge cooling, etc. secondary.
- Degraded particle confinement – shear layer collapse, breakdown of self-regulation; ‘Inverse’ of L→H transition
- Physics: Drop in shear flow production

  Key parameter: $k_{\parallel}^2 V_{The}^2/\omega\nu_e$ (adiabaticity)
- Penetration of turbulence spreading drives cooling front, related to MARFE etc.

Desperately Seeking Greenwald, and beyond…

- What of current scaling?
- Tokamaks, RFP, Stellarators?

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

Current Scaling, cont'd

- Shear flow drive:

emission from 'drift-mode' interaction

production

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

neoclassical response

  - Production ←→ beat drive
  - Response (neoclassical)

- Rosenbluth-Hinton '97 et seq

Increasing I_p decreases ρ_θ and off-sets weaker ZF drive

$$\left(\frac{e\hat{\phi}}{T}\right)_{ZF} \approx \frac{S_{k,q}}{\left(1 + 1.16\,\frac{(q(r))^2}{\epsilon^{1/2}}\right) q_r^2 \rho_i^2}$$

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 → $P \sim n^{-\alpha}$

- Higher current strengthens ZF shear, for fixed drive
- Can "prop-up" shear layer vs weaker production
- $\sim (1 + 2q^2)\rho_i^2$ for collisional regime

What of other Donuts? Pretzels?

- All devices exhibit edge shear layer in L-mode and many similar fluctuation properties (Carreras, Hidalgo et. al.)
- RFP ~ Cylinder ➔ 'neoclassical' effects ignorable

But:

- RFP exhibits Greenwald scaling $n \sim I_p$!
- Classical ZF response → ρ_i , but ρ_i set by current in RFP i.e. $\rho_i = \rho_{\theta i}$
- Stronger ZF shear at higher current, again

What of Stellarator? (Ackn T.-H. Watanabe, Carlos Hidalgo)

- Several attempts to ‘translate’ Greenwald scaling into stellarator (‘magnetic geometry thinking): $B_\theta \rightarrow$ iota, shear, ...
- Dubious outcomes...
- If ZF screening crucial, better ask: “What length scale appears in Z.F. response for stellarator?”
- Sugama-Watanabe: Principlal correction to classical screening is contribution from helically trapped particle (analysis for LHD).

What of Stellarator?, cont'd

- No obvious length scale emerges
- Need explore collisional regime

➔Begs: Will optimized stellarator have higher density limit due more robust edge shear layer?

➔Issue remains open

Thoughts for Experiment

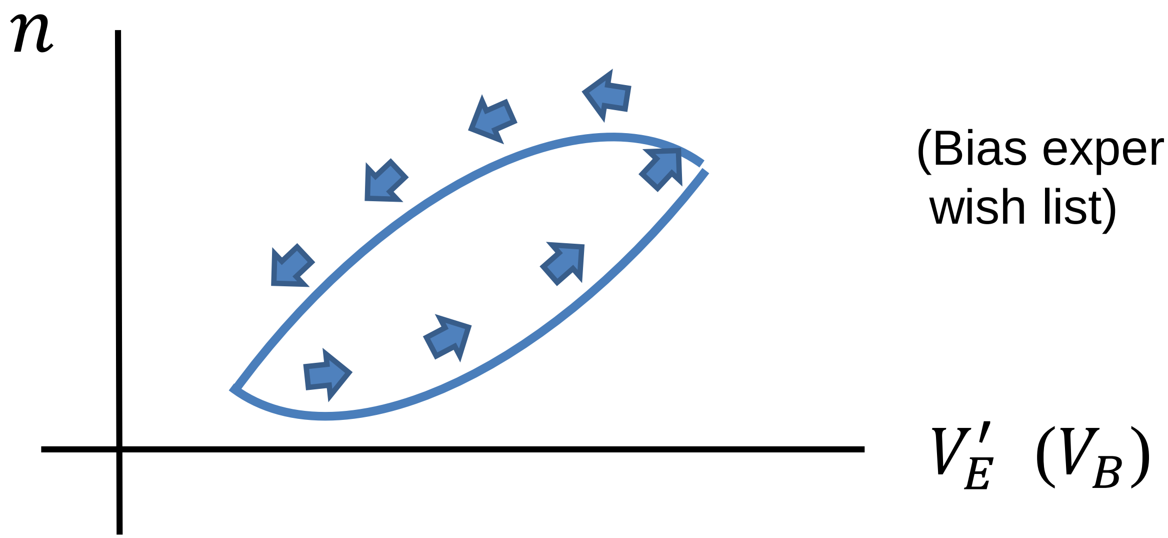
Suggestions for Experiment

- Criticality $k_{\parallel}^2 V_{The}^2/\omega\nu_e$ → T_e^2/n_e trade off
- Scale of shear layer collapse? - ρ_θ?
- Turbulence spreading penetration depth? – influence length
- Perturbative experiments: (J-TEXT, planned)
  - SMBI probe of relaxation (with fluctuations) → relaxation time
  - ExB flow drive (Bias) → enhance shear layer persistence beyond $\bar{n}_g$?
  - RMP → accelerate shear layer collapse?

N.B. Studies of turbulence and transport as $n \rightarrow n_g$, are part of (important) 'disruption question'.

In Particular:

- Can edge biasing (ala' driven L→H) sustain $\bar{n} > \bar{n}_g$ by driving shear layer?
- Is shear layer collapse hysteretic?



(Bias experiment,
wish list)

- Is shear layer collapse yet another case of a back-transition of transport bifurcation?

What of H-mode?

- H-mode density limit involves back-transition prior to $\bar{n}_g$, so key HDL problem is high density back-transition (H→L)
- I_{turb} in SOL can exceed that of pedestal

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- Is HDL due
  - Shear layer or well weakening? – How?
  - Invasion of pedestal from SOL turbulence
- Coupled pedestal-SOL model under consideration

General Conclusions

- Transport is fundamental to density limit. Cooling, etc. drive secondary phenomena.
- Shear layer collapse occurs as transport bifurcation from DW-ZF turbulence to convective cells, approaching density limit.
- Trends of Greenwald scaling follow from neoclassical zonal flow response.

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