Transport Physics of the Density Limit

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TTF 2019

This research was supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, under Award Number DE-FG02-04ER54738.

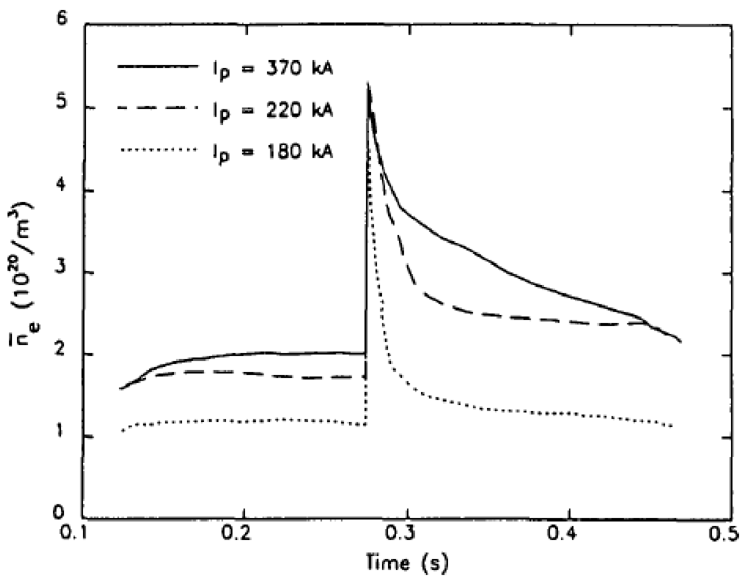
Outline

- Density limit ($\bar{n}/\bar{n}_G \rightarrow 1$) as a transport phenomenon (mostly L-mode)
- Recent experimental studies of the density limit ➔ <u>shear layer collapse</u>
- Theory of shear layer collapse

Thesis: For hydrodynamic electrons, drift wave turbulence cannot self-regulate via flows

- Physics of current dependence
- Possible Experiments

- Density Limit: Edge Transport is Key
  - ‘Disruptive’ scenarios secondary outcome, largely consequence of edge cooling
  - $\bar{n}_g$ reflects fundamental limit imposed by particle transport (c.f. Greenwald)
- Indication



(Alcator C)

  - Density decays non-disruptively after pellet injection
  - $\bar{n}$ asymptote scales with I_p
  - Density limit enforced by transport-induced relaxation.

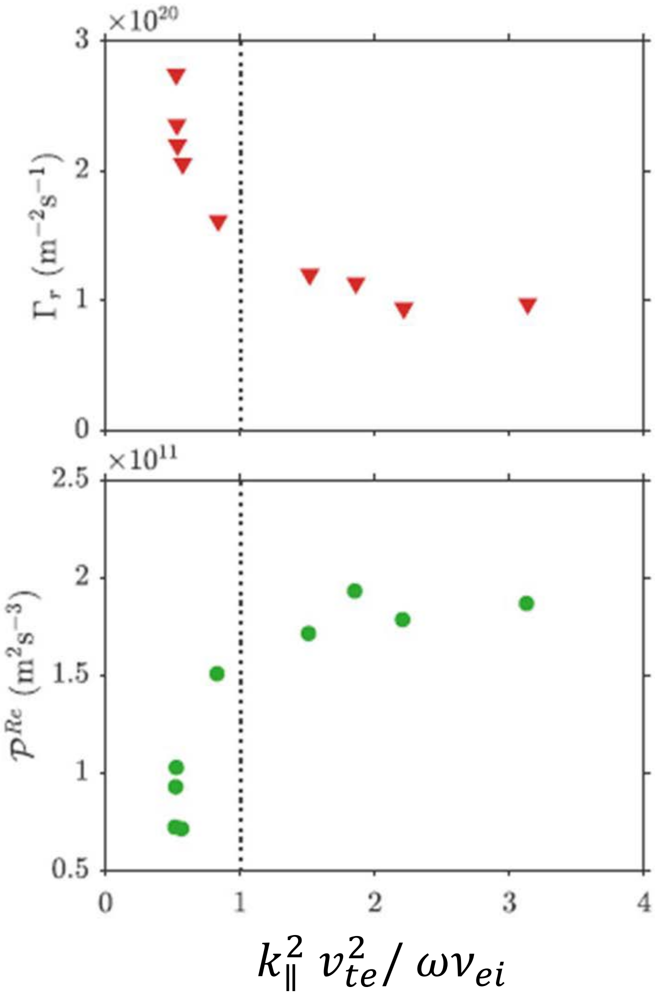
Synthesis of the Fluctuation Experiments

- Shear layer collapse and turbulence and D (particle transport) rise as $\frac{\bar{n}}{\bar{n}_G} \rightarrow 1$.
- ZF collapse as $\alpha = \frac{k_{||}^2 v_{th}^2}{|\omega| \nu_e}$ drops from $\alpha > 1$ to $\alpha < 1$.
- Degradation in particle confinement at density limit in L-mode is due to breakdown of self-regulation by Z.F.
- 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?

See: Y. Xu, et al. NF 2011
Schmidt, Manz, et al. PRL 2017
Hong, et al. NF 2018

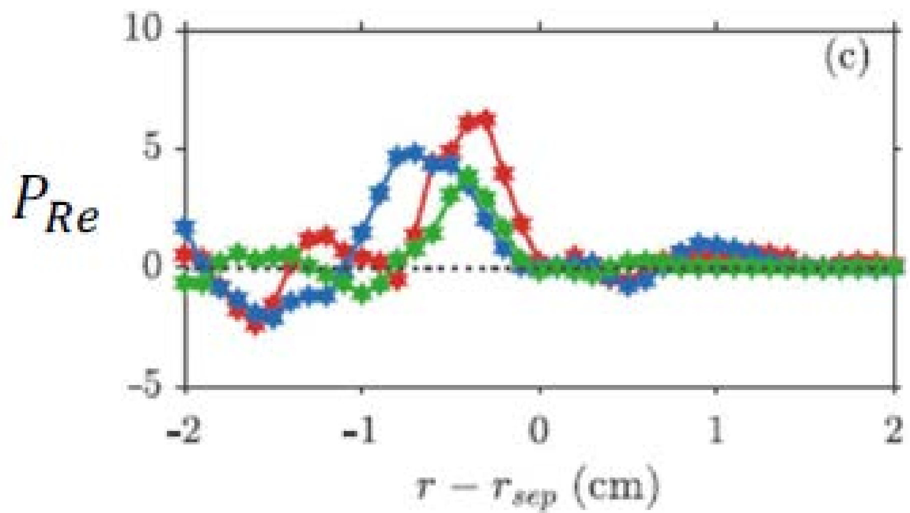
} all present consistent picture

Key Parameter: Electron Adiabaticity



- Electron adiabaticity $\alpha = \frac{k_{\parallel}^2 v_{th}^2}{|\omega|\nu_{ei}}$ emerges as an 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.



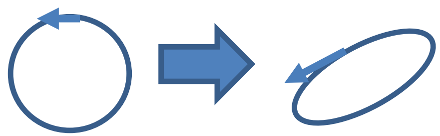
Hong, et al. NF 2018

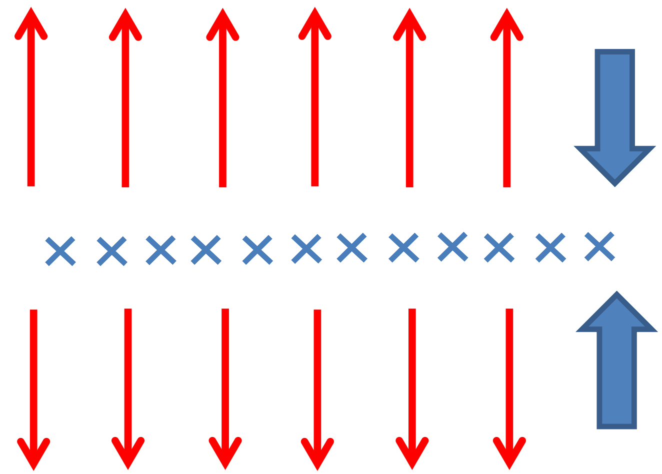
Step Back: Why Zonal Flows Ubiquitous?

- 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. 

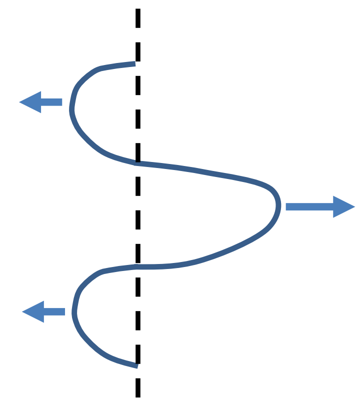


$\omega_k = -\beta\, k_x / k_\perp^2$: (Rossby)

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

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

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



- Outgoing waves generate a flow convergence! ➔ Shear layer spin-up

But NOT for hydro limit:

- $\omega_r = \left[\frac{|\omega_{*e}|\hat{\alpha}}{2k_\perp^2\rho_s^2}\right]^{1/2}$ → for hydro regime of H-W

- $V_{gr} = -\frac{2k_r\rho_s^2}{k_\perp^2\rho_s^2}\,\omega_r$ $\overset{?}{\longleftrightarrow}$ $\langle\tilde{V}_r\tilde{V}_\theta\rangle = -\langle k_r k_\theta\rangle$ direct link broken

→ Energy, momentum flux no longer directly proportional

↓

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

➔ ZF generation <u>not</u> ‘natural’ outcome in hydro regime!

Scaling of transport fluxes with α

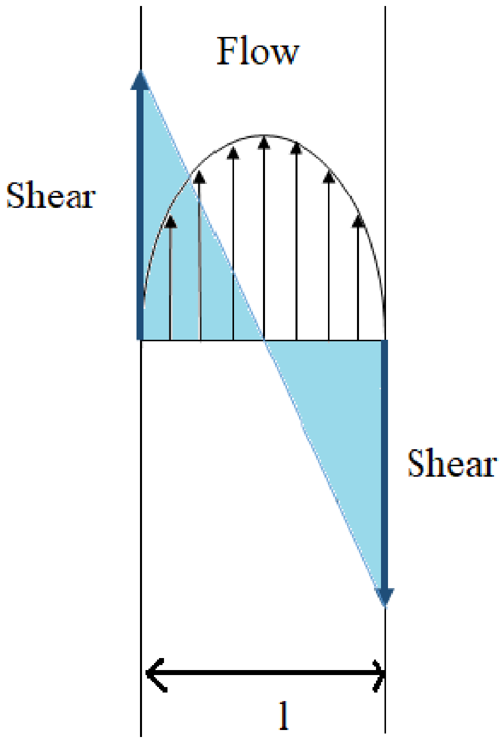
Plasma Response	Adiabatic ($\alpha >> 1$)	Hydrodynamic ($\alpha << 1$)
Particle Flux Γ	$\Gamma_{\text{adia}} \sim \frac{1}{\alpha}$	$\Gamma_{hydro} \sim \frac{1}{\sqrt{\alpha}}$
Turbulent Viscosity χ	$\chi_{adia} \sim \frac{1}{\alpha}$	$\chi_{hydro} \sim \frac{1}{\sqrt{\alpha}}$
Residual stress Π^{res}	$\Pi^{res}{}_{\text{adia}} \sim -\frac{1}{\alpha}$	$\Pi^{res}{}_{\text{hydro}} \sim -\sqrt{\alpha}$
$\frac{\Pi^{\text{res}}}{\chi} = (\omega_{\text{ci}} \nabla n) \times$	$\left(\frac{\alpha}{\lvert\omega \star\rvert}\right)^0$	$\left(\frac{\alpha}{\lvert\omega \star\rvert}\right)^1$

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

- Mean vorticity gradient ∇u (i.e. ZF strength) becomes proportional to $\alpha \ll 1$ in the hydrodynamic limit.
- Weak ZF formation for $\alpha \ll 1 \rightarrow$ weak regulation of turbulence and enhancement of particle transport and turbulence.

Hajjar, Diamond, Malkov, PoP 2018

Also: Physics of Vorticity Gradient



- Vorticity gradient emerges as natural measure of shear flow strength, shear stabilization
- $\Pi = 0 \rightarrow \nabla u = \Pi^{res}/\chi_y$
- i.e. production vs. turbulent mixing
- What is physics of vorticity gradient?

  i.e. "Rossby wave elasticity" inhibits wave breaking

➔ A jump in the flow shear over a scale length *l* is equivalent to a vorticity gradient over that scale length

➔ Vorticity gradient precludes local alignment with shear

Physics of current scaling?
– Desperately seeking Greenwald...

- Obvious? : How does shear layer collapse scenario connect to

  Greenwald scaling, $\bar{n} \sim I_p$?

- Consideration

  – RFP exhibits $\bar{n} \sim I_p$ scaling!

  – Stellarator different

- Scenario: Neoclassical dielectric ←→ ρ_θ as screening length

  i.e. $\epsilon_{neo} = 1 + 4\pi\rho c^2/B_\theta^2$

  Screening/'effective inertia' of ZF weaker for higher I_p

Current scaling, cont'd

- For ZF driven by turbulence beats

$$\frac{e\hat{\phi}_z}{T} = \frac{beats(\vec{k},\vec{k}+\vec{q})}{\left(1+1.6\frac{q^2}{\varepsilon^{1/2}}\right) q_r^2 \rho_i^2}$$

classical   neo   zonal wave #

Increasing I_p decreaes ρ_θ and offsets weaker ZF drive at high I_p (Rosenbluth, Hinton '97)

$$\sim \ \alpha^P \left|\frac{c\hat{\phi}}{T}\right|^2 / \rho_\theta^2 \qquad (\alpha < 1)$$

$$\sim \left(B_\theta^2/n^p\right) \left|\frac{c\hat{\phi}}{T}\right|^2$$

- In RFP, neoclassical contribution absent, but $\rho = \rho_\theta$

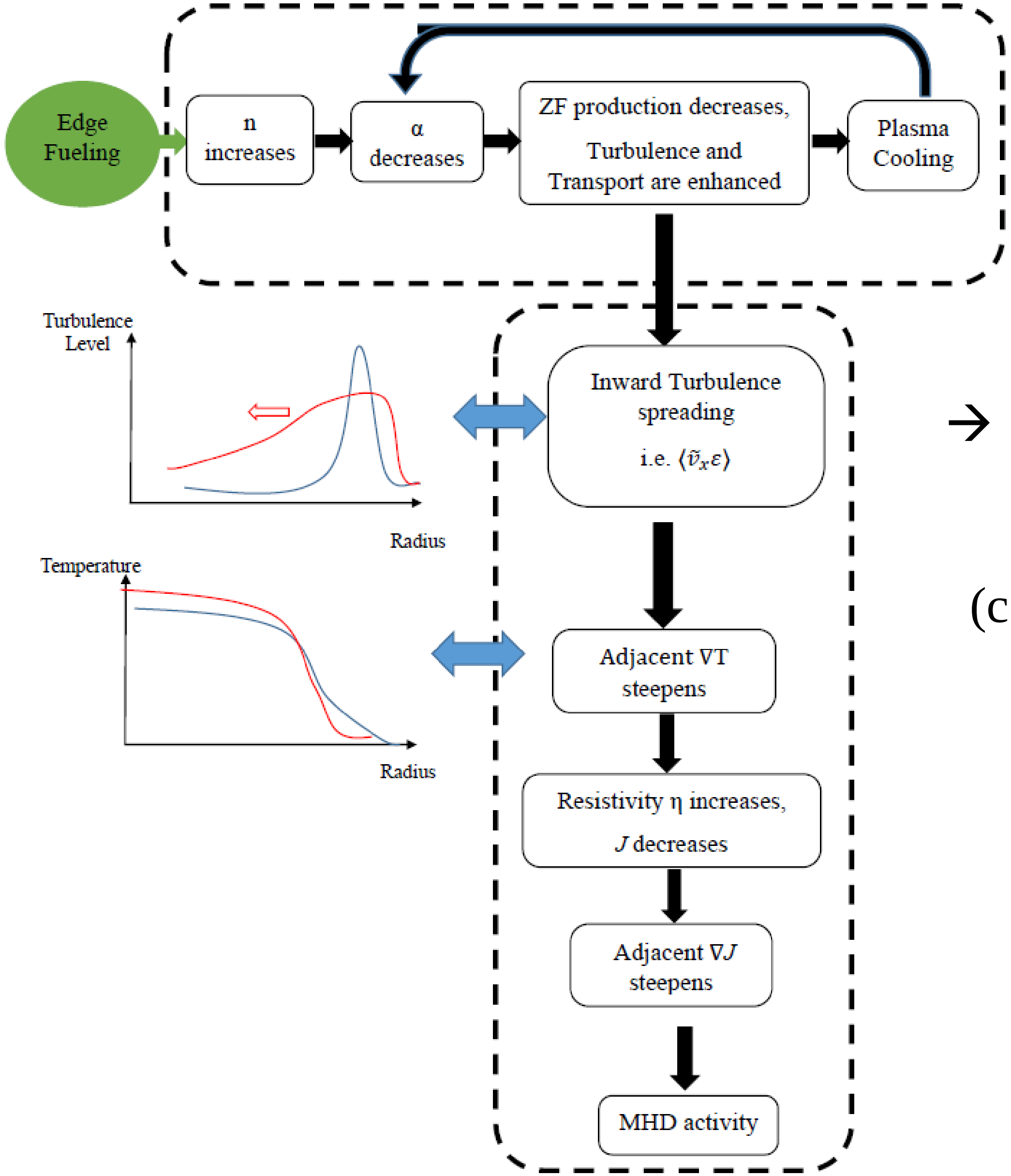
  (i.e. B_θ sets gyro-radius)

Current scaling, cont'd

- Neoclassical response connects shear layer collapse physics to Greenwald scaling
- Need explore both modulation and beat drive, but trend is generic

➔ Does stellarator density limit scaling correlate with zonal flow screening scaling for that configuration?

Feedback loop for edge cooling



→ post-collapse intensity peak

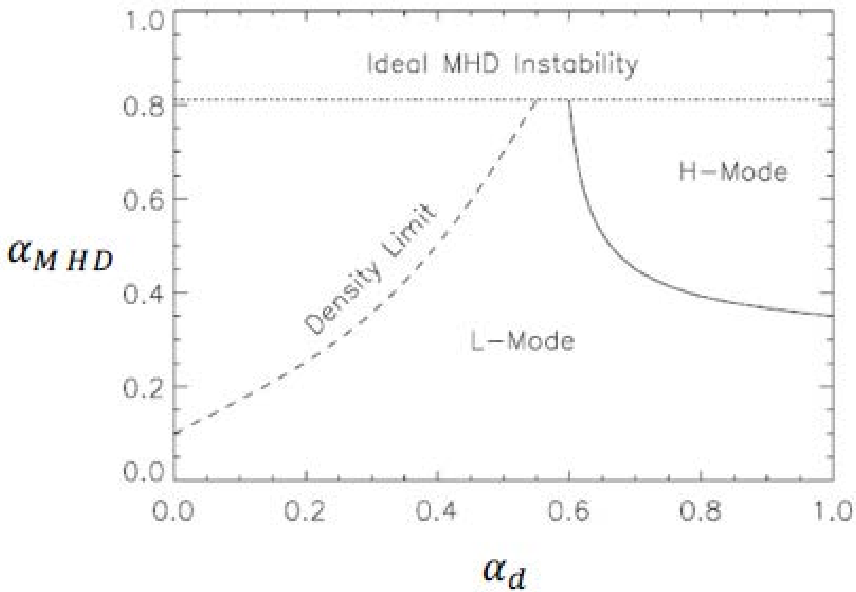
➔ inward spreading

(c.f. R. Singh, this meeting)

The Old Story / A Better Story

Modes, Glorious Modes / Self-Regulation and its Breakdown

(Drake and Rogers, PRL, 1998)



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

(Hajjar et al., PoP, 2018)

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

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

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
- Physics: Drop in shear flow production

  Key parameter: $k_{\|}^2 V_{The}^2 / \omega \nu_e$ (adiabaticity)
- Penetration of turbulence spreading → cooling front, MARFE etc.
- $\bar{n} \sim I_p$ scaling ←→ Zonal Flow screening response !?

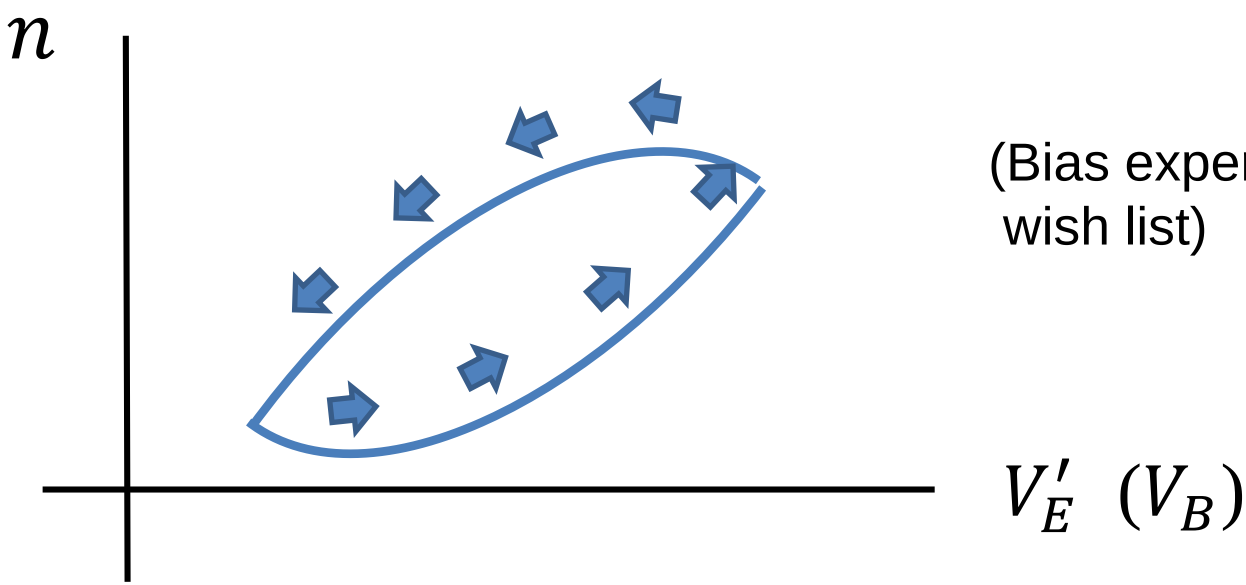
  Analogue for stellarator?

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)
  - ExB flow drive (Bias) → enhance shear layer persistence beyond $\bar{n}_g$?
  - RMP → accelerate shear layer collapse?

N.B. Turbulence/transport part of 'disruption studies'!

- 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 $\bar{n}_g$
- Key HDL problem is high density back-transition
- I_{turb} in SOL exceeds that of pedestal

∴

- Is HDL due
  - Shear layer weakening
  - Invasion of pedestal from SOL
- Coupled pedestal-SOL model in progress

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.
- Greenwald scaling can result from neoclassical polarization.

Support by U.S. Department of Energy under

Award Number DE-FG02-04ER54738