On How Edge Shear Layer Collapse Defines Greenwald Limit $n_g \sim I_p$

[Rameswar Singh and P H Diamond, Nucl. Fusion **61**(2021) 076009]

Rameswar Singh and P H Diamond

CASS, University of California San Diego

APTWG Zoom Meeting, July 7, 2021

Acknowledgement: 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.

Summary

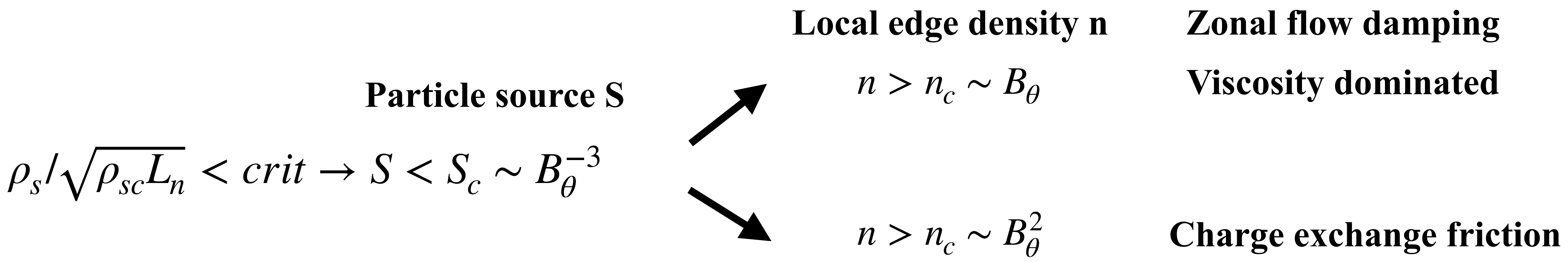
- Edge shear layer collapse triggers the sequence of events leading to Greenwald density limit phenomenology.

- A theory of edge shear layer collapse for $n \to n_g$ in the adiabatic regime.

- Neoclassical zonal flow screening is key to the origin of current scaling.

- Neoclassical screening + drift wave - zonal flow dynamics $\longrightarrow$ a novel predator - prey model.

- *The threshold condition for edge shear layer collapse* $\rho_s/\sqrt{\rho_{sc}L_n} < crit$. Here, ρ_s is ion sound radius, ρ_{sc} is screening length and L_n is density scale length. *Smaller* ρ_{sc} *i.e., higher* B_θ *expands the regime of zonal flow persistence.*



Local edge density n **Zonal flow damping**

Particle source S

$\rho_s/\sqrt{\rho_{sc}L_n} < crit \to S < S_c \sim B_\theta^{-3}$

$n > n_c \sim B_\theta$ **Viscosity dominated**

$n > n_c \sim B_\theta^2$ **Charge exchange friction**

- Shear layer collapse aggravates radiative cooling effects! Radiative cooling is secondary (i.e., a consequence of) to the transport bifurcation.

Density limit basics

- Discharge terminates when line integrated density exceeds a critical value $\bar{n}_g = I_p/\pi a^2$.

- Why care? Fusion power $\propto n^2$.

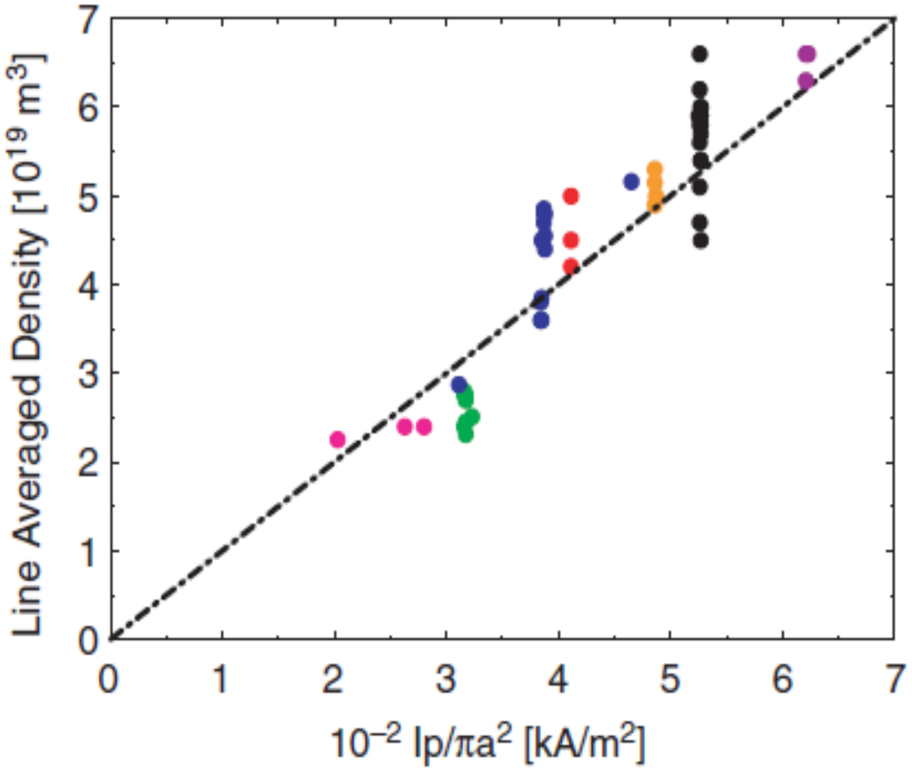
- A fundamental limit on performance.

- Not a dimensionless number
  ➤ more physics involved.

- Still begging the origin of current I_p scaling!?

- Also manifested in RFPs.

- What about Stellarators?



From discharge termination studies in Alcator-C, Greenwald PPCF 2002

<u>Often associated with macroscopic phenomena</u>

- Global thermal collapse, Radiative condensation / MARFEs.

- Poloidal detachment, Divertor detachment, MHD activity -radiation driven islands.

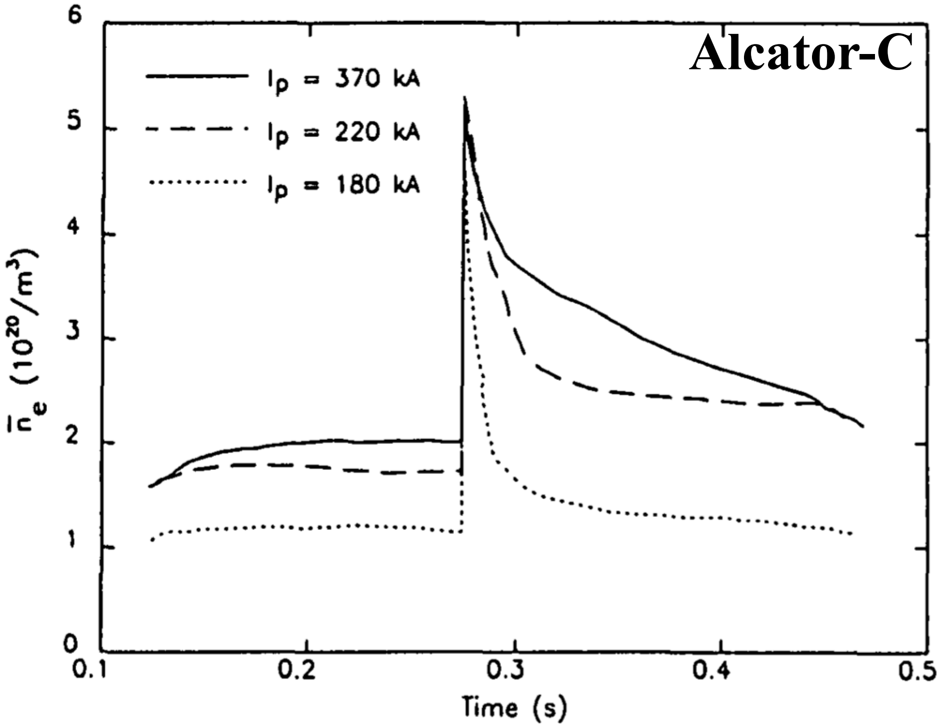
What's beyond macroscopic ?

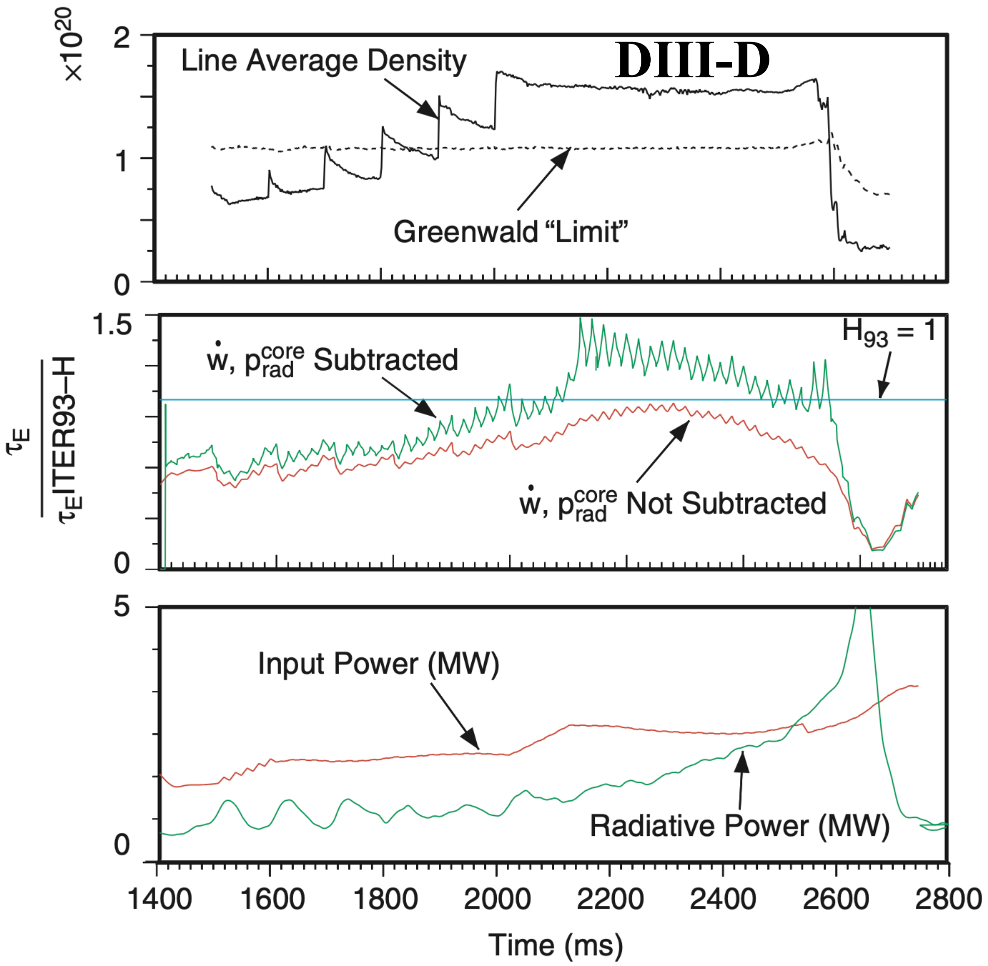
Connections with transport physics

Role of particle transport?

- A SOFT limit: Shallow pellet injection in plasma with $\bar{n} = n_g$ triggered transient particle increased relaxation to n_g by transport rather than by disruption! [Greenwald NF 1988]

- Shallow pellet injection avoids excessive edge cooling— No MARFEs, disruptions!



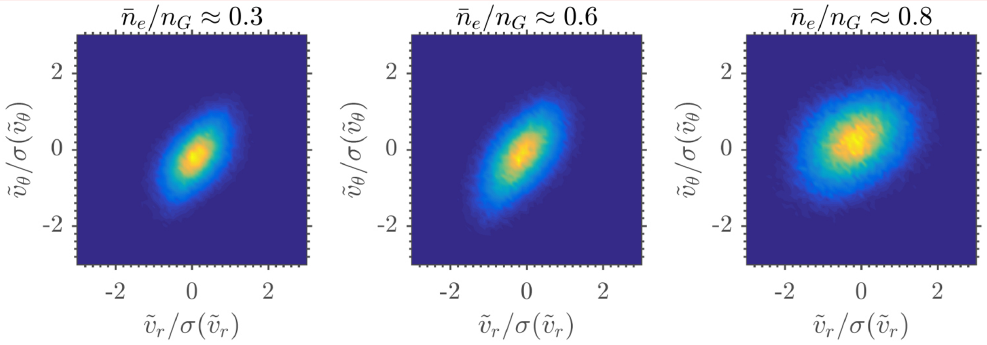


- Pellet in DIII-D beat n_g by peaked density profiles $\longleftrightarrow$ enhanced core confinement. Accumulation of impurities $\longrightarrow$ increase in radiation $\longrightarrow$disruption.[Mahdavi *et al* 1997]

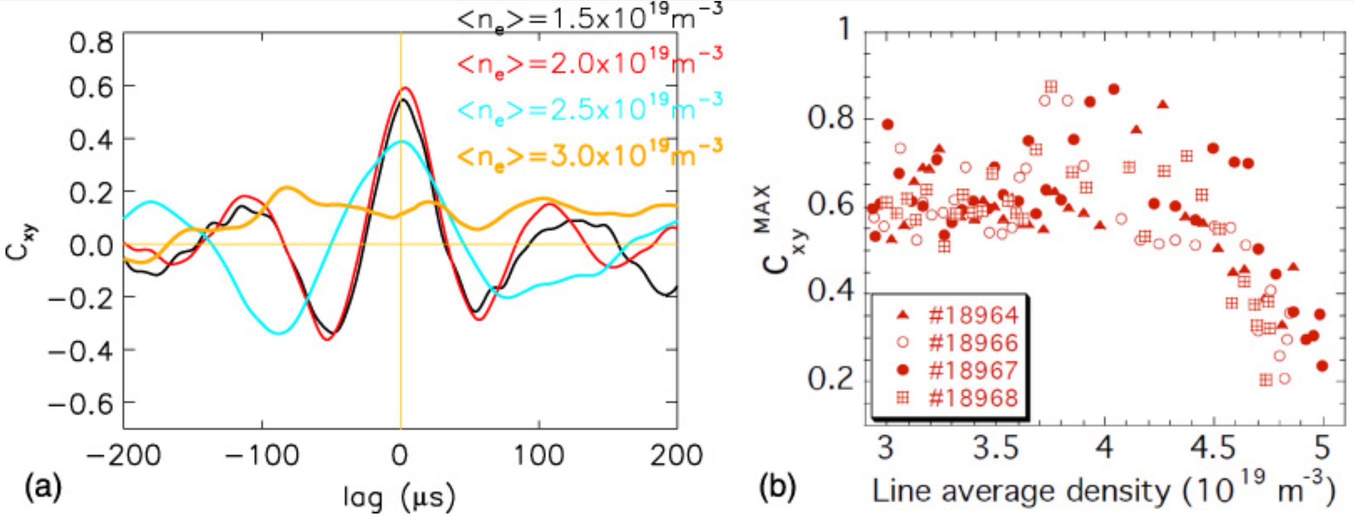
- Disruption ensuing as a secondary consequence of strong edge cooling due to gas fueling/ radiative cooling.

Recent experiments

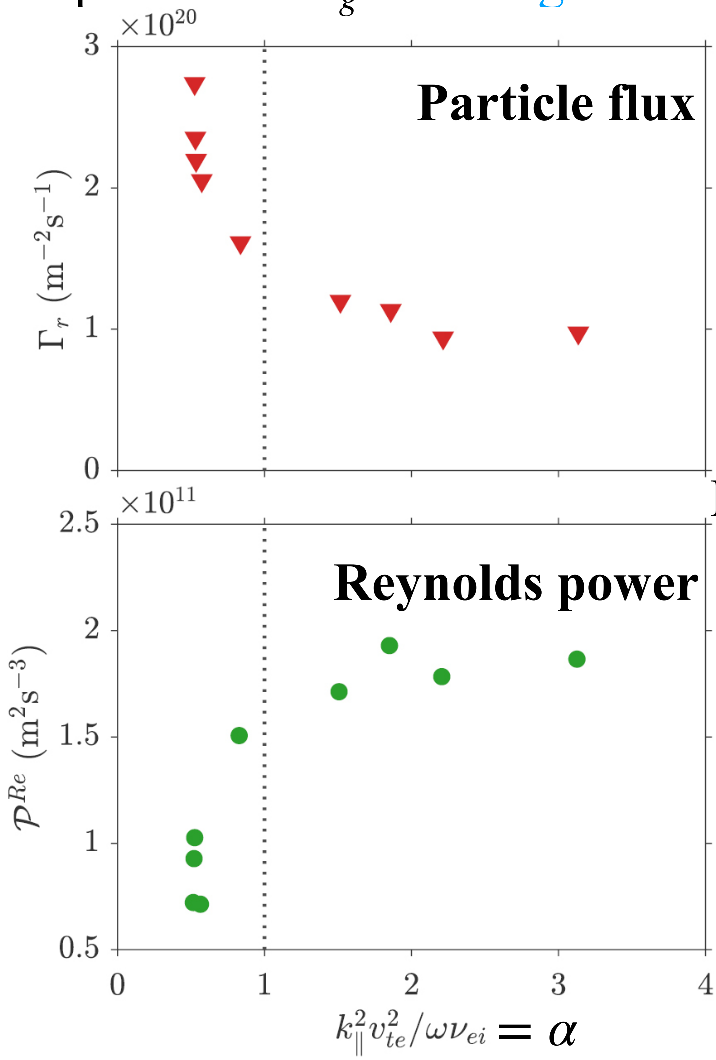
Is the density limit related to edge shear layer decay?



Radial and poloidal velocity correlations drops as $n \to n_g$ Hong *et al* NF 2018

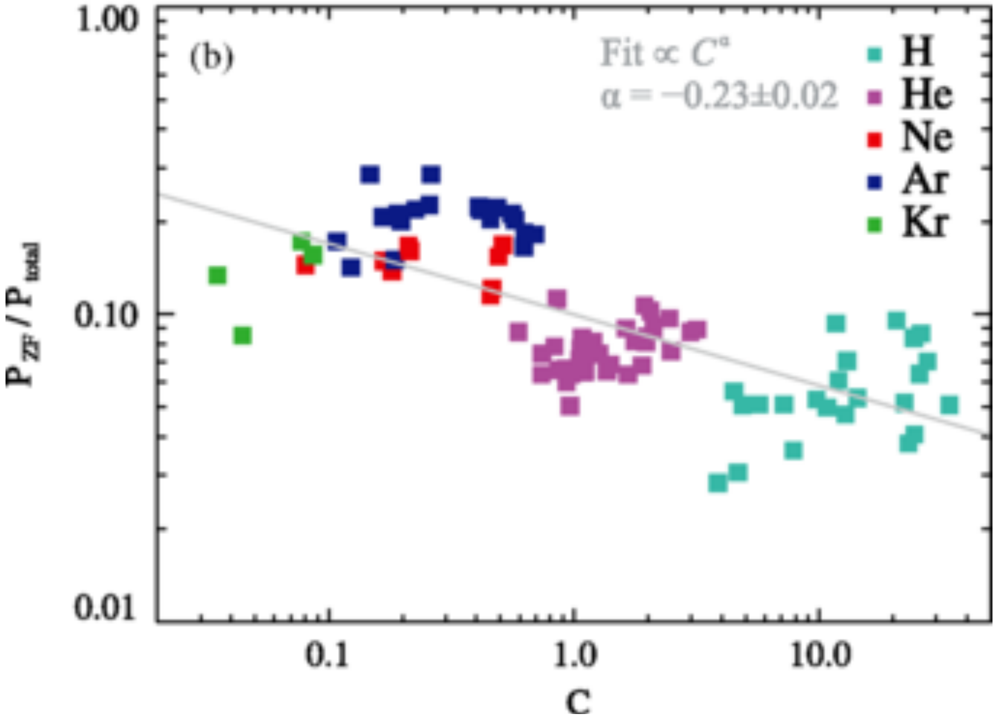


Long range correlations (LRC) decrease as the line averaged density increases in both TEXTOR and TJ-II. LRC ↔ ZF strength Y. Xu *et al* NF 2011



HL-2A

Reynolds power $P_{Re} = -\langle v_\theta \rangle \partial_r \langle \tilde{v}_r \tilde{v}_\theta \rangle$↓and particle flux↑as α drops below 1.



TJ-K

Zonal flow contribution to the total turbulent spectrum decreases with collisionality. Schmid *et al* PRL 2017

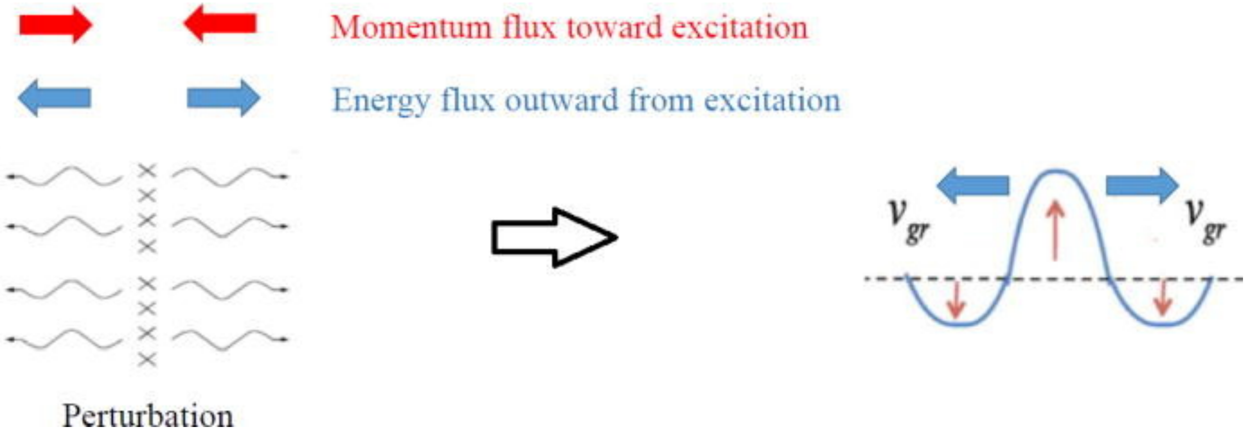
…and the most recent experiments by T Long et al @ J-TEXT (this meeting)

Shear layer collapse with hydrodynamic electrons: HDM theory and its limitations

- Clearly, shear layer collapse $\longrightarrow$ increased turbulence and transport as $\bar{n} \to n_g$! <u>Edge shear layer exist in all devices tokamaks, RFPs, Stellarators</u>.

- Plasma response for Hasegawa - Wakatani :- HDM Theory[Hajjar, Diamond, Malkov 2018]

Response	Adiabatic	Hydro
Particle flux Γ_n	$\sim \alpha^{-1}$	$\sim \alpha^{-1/2}$
Turbulent viscosity χ_y	$\sim \alpha^{-1}$	$\sim \alpha^{-1/2}$
Residual vorticity flux Π^{res}	$\sim \alpha^{-1}$	$\sim \alpha^{1/2}$
Vorticity gradient $\nabla_r^3 \bar{\phi} = \dfrac{\Pi^{res}}{\chi}$	$\sim \alpha^{0}$	$\sim \alpha^{1}$



In hydro-regime the link of wave energy flux to Reynolds stress is broken !

- $\Gamma_n, \chi \uparrow$ and Π^{res}, $\nabla_\perp^2 \bar{\phi} \downarrow$ as the electron response passes from adiabatic to hydrodynamic regime.

- Weak zonal flow production for $\alpha \ll 1$ → weak regulation of turbulence and enhancement of particle transport and turbulence.

<u>Limitations (Key Questions)</u>

- Connection of shear layer collapse scenario with Greenwald scaling $\bar{n}_g \sim I_p$?

- Shear layer collapse in hydro regime only. Not relevant for **hot** tokamaks. What of collapse in adiabatic ($\alpha > 1$) regime?

- Dimensionless parameter ?

Origin of current scaling

- Key physics: zonal flow drive is "screened" by neoclassical dielectric [Rosenbluth - Hinton 1998]. $\frac{\partial}{\partial t}\left\langle|\phi_k|^2\right\rangle = \frac{2\tau_c\left\langle|S_k|^2\right\rangle}{|\varepsilon(q)|^2}$; $\varepsilon = \varepsilon_{cl} + \varepsilon_{neo} = \frac{\omega_{pi}^2}{\omega_{ci}^2}\left\{1 + \frac{q^2}{\epsilon^2}\right\} k_r^2\rho_i^2$

Emission from polarization interaction

banana regime

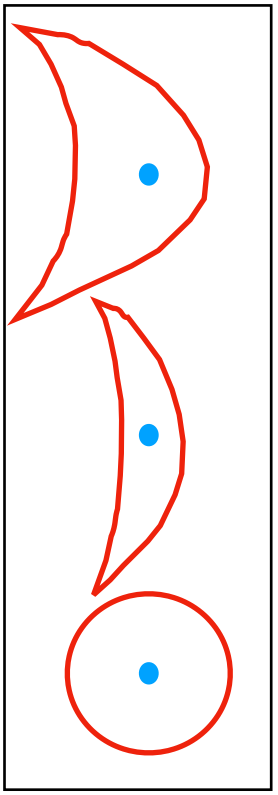
Neoclassical response

Zonal wave #

- Poloidal gyro-radius ρ_θ emerges as screening length! Effective ZF inertia ↓ as I_p ↑ →ZF strength increases with I_p, for fixed drive.

- But edge region is most likely in Plateau regime.[T Long *et al* NF 2019]→Need revisit R-H screening calculations.

Collisionality regimes	**Screening length** ρ_{sc}	**Residual level** $\frac{\phi_k(\infty)}{\phi_k(0)}$	B_θ**-dependence**
Banana	$= \sqrt{\rho_s^2 + \rho_\theta^2} \approx \rho_\theta$	$\approx \left(\frac{B_\theta}{B_T}\right)^2$	Favorable
Plateau	$= \sqrt{\rho_s^2 + \mathscr{L}\rho_\theta^2} \approx \mathscr{L}^{1/2}\rho_\theta$	$\approx \frac{1}{\mathscr{L}}\left(\frac{B_\theta}{B_T}\right)^2$	Favorable
P-S	$= \rho_s$	$= 1$	None



Here $\mathscr{L} = 1 - \frac{4}{3\pi}(2\epsilon)^{3/2} < 1$. Favorable I_p scaling persist in plateau regime. Robust trend!

No I_p scaling in P-S regime. Effective inertia minimum in P-S

Feedback loop with nonlinear zonal noise

Neoclassical screening + drift wave - zonal flow dynamics ⟶ a novel predator - prey model.

Turbulence energy E_t evolves as

Induced diffusion

$$\frac{\partial E_t}{\partial t} = \gamma E_t - \sigma E_v E_t - \eta E_t^2$$

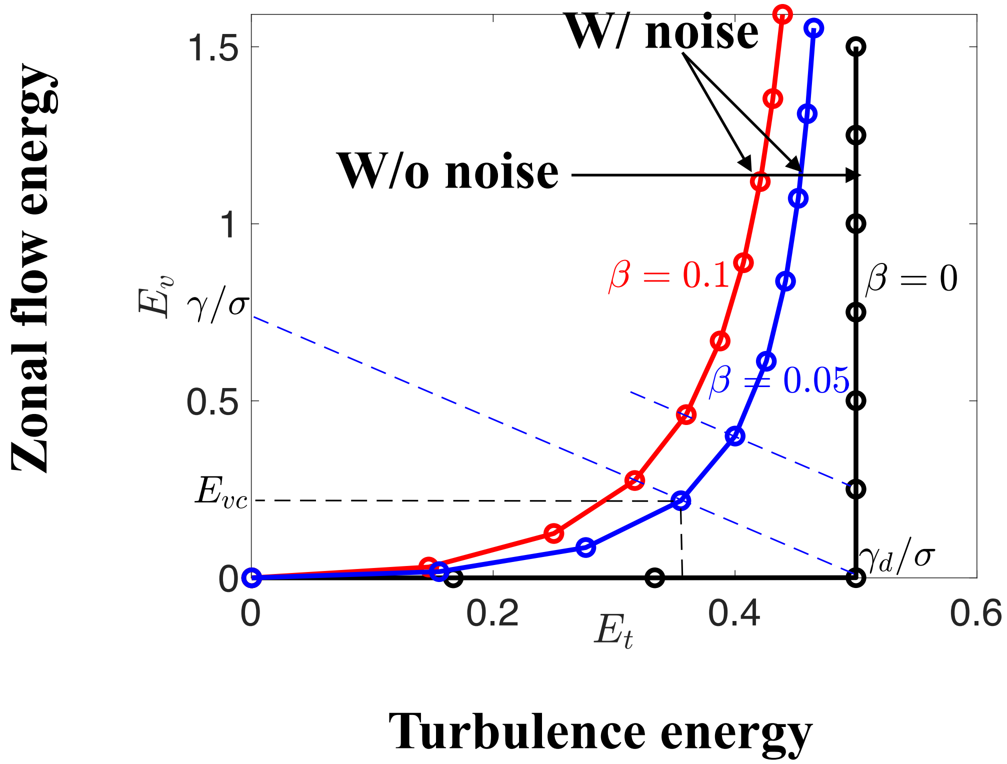
Nonlinear damping

Zonal flow energy E_v evolves as

Modulational growth

$$\frac{\partial E_v}{\partial t} = \sigma E_t E_v - \gamma_d E_v + \beta E_t^2$$

Zonal noise



Notice, $\sigma \sim \varepsilon^{-1} \sim B_\theta^2 \sim I_p^2$ and $\beta \sim \varepsilon^{-2} \sim B_\theta^4 \sim I_p^4$

$\Longrightarrow I_p$ jacks up modulational growth and zonal noise → stronger feedback on turbulence.

[Singh and Diamond PPCF 2021]

With noise:

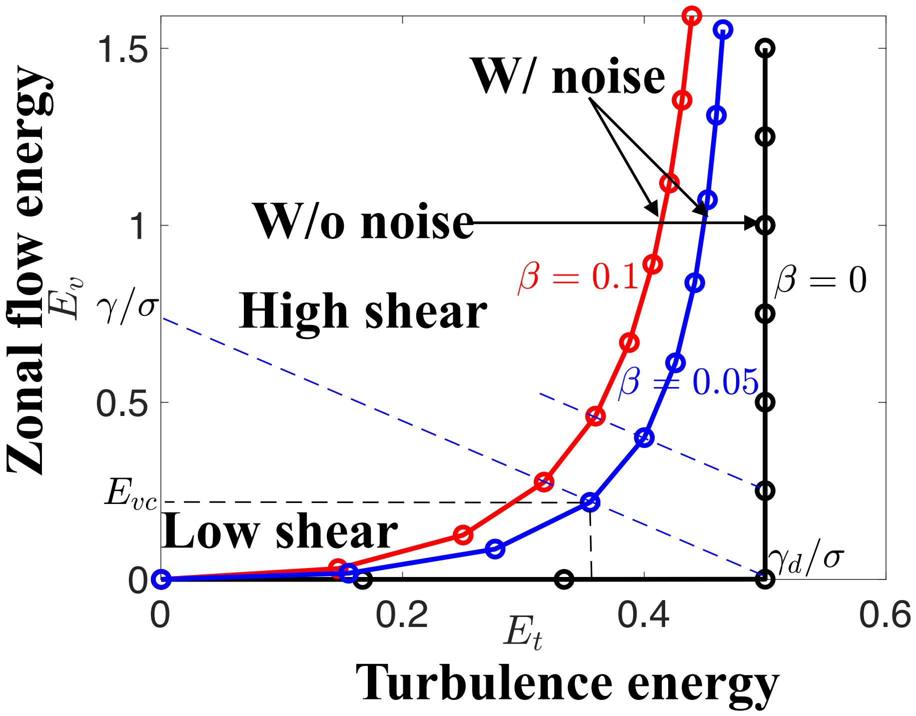
- Both zonal flow and turbulence co-exist at any growth rate: - No threshold in growth rate for zonal flow excitation.
- Zonal flow energy is related to turbulence energy as $E_v = \beta E_t^2 / (\gamma_d - \sigma E_t) \uparrow$ with I_p.
- Turbulence energy never hits the ‘old’ modulational instability threshold!
- Turbulence energy ↓ and zonal flow energy ↑:- Noise feeds energy into zonal flow!

Shear layer collapse in adiabatic regime

- Criterion for zonal flow collapse with noise tracks that for collapse of zonal flow without noise i.e.,

$$E_v < E_{vc} \rightarrow E_{v0} < 0 \implies \gamma < \eta \frac{\gamma_d}{\sigma}$$

$$\implies \boxed{\frac{\rho_s}{\sqrt{\rho_{sc} L_n}}} < \left[\frac{\eta}{\Omega_i} \frac{\gamma_d}{2k_x^2 \rho_s^2 \Theta \Omega_i^2} \frac{\hat{\alpha}}{q_\perp^2 \rho_s^2} \frac{\left(1 + q_\perp^2 \rho_s^2\right)^3}{q_y^2 \rho_s^2} \right]^{1/4}$$



- Note that smaller ρ_{sc} i.e., higher B_θ enlarges the regime of zonal flow persistence.

- Particle diffusivity $D \sim \rho_{sc}^2/\rho_s^2 \sim B_\theta^{-2} \sim I_p^{-2}$. [Consistent with T Long's expt.(this meeting)]

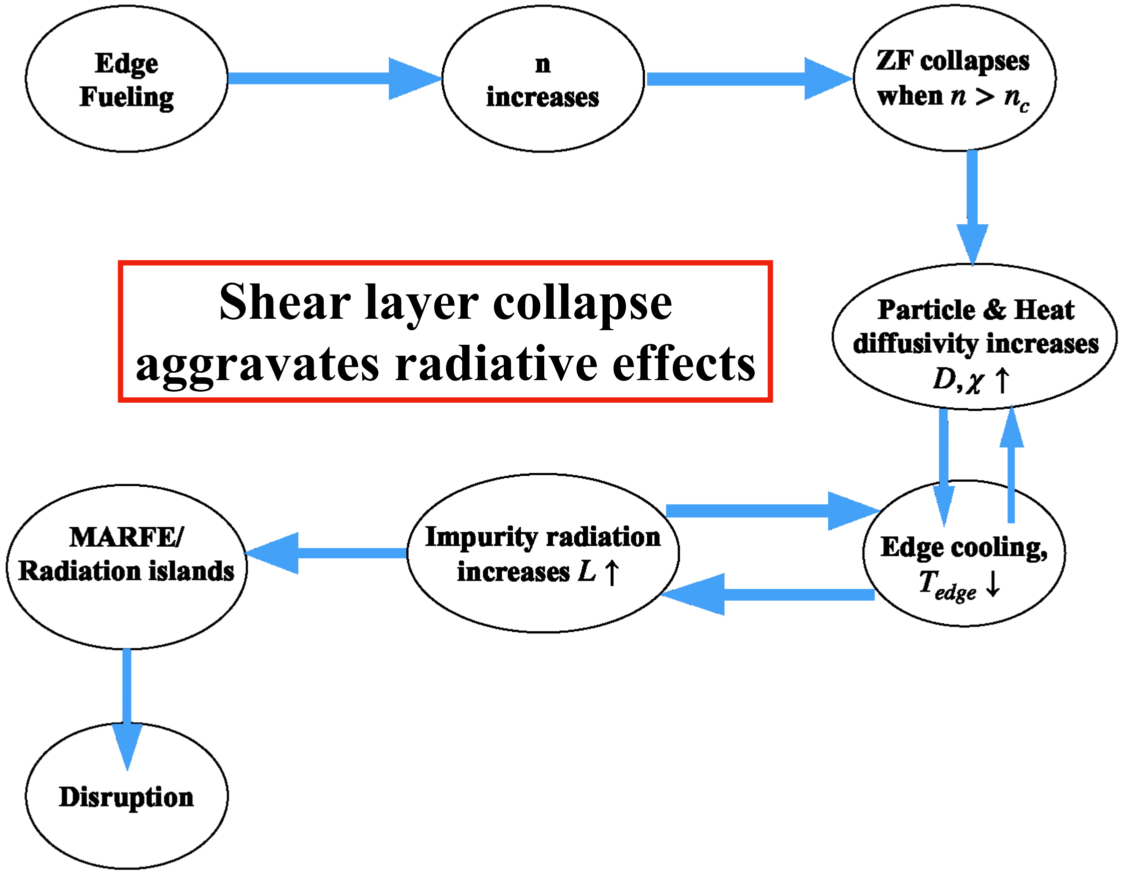
- Zonal flow collapse criterion in terms of particle source S: $S < S_{crit} \sim \rho_{sc}^3/\rho_s^3 \sim B_\theta^{-3} \sim I_p^{-3}$. Critical particle source required to hold shear layer decreases with plasma current.

- In the <u>viscosity dominated regime</u>, zonal flows collapse when the local density $n > n_{crit} \sim \rho_s/\rho_{sc} \sim B_\theta \sim I_p$.

- In the <u>charge exchange friction dominated regime</u>, $n_{crit} \sim \rho_s^2/\rho_{sc}^2 \sim B_\theta^2 \sim I_p^2$ (NB: stronger I_p dependence!)

Conclusions

- Density limit is linked to shear layer collapse which is (in part) controlled by neoclassical screening response.
- Neoclassical zonal flow screening is key to the emergence of the current scaling $n_g \sim I_p$.
- Radiative cooling is secondary (i.e., a consequence of) to the transport bifurcation.



Edge Fueling

n increases

ZF collapses when $n > n_c$

Particle & Heat diffusivity increases $D, \chi \uparrow$

Edge cooling, $T_{edge} \downarrow$

Impurity radiation increases $L \uparrow$

MARFE/ Radiation islands

Disruption

Shear layer collapse aggravates radiative effects

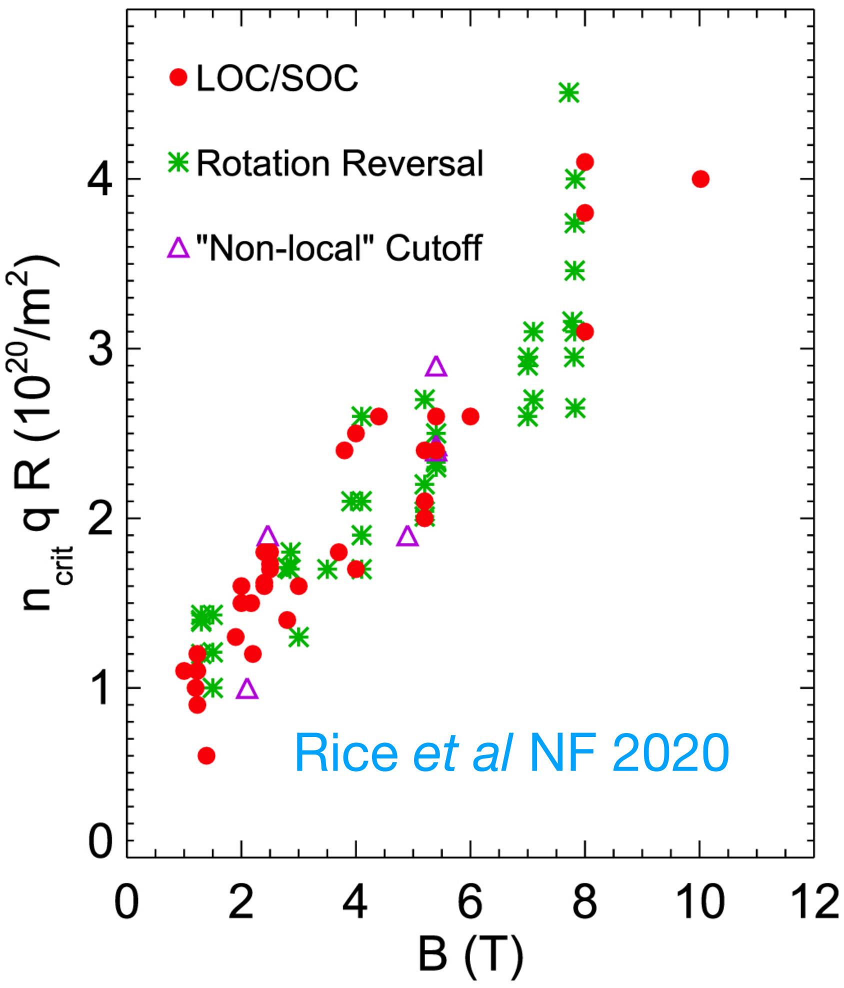
- $\rho_s/\sqrt{\rho_{sc}L_n}$ emerges as the key dimensionless ratio which underpins the density limit. Zonal flows collapse when $\rho_s/\sqrt{\rho_{sc}L_n} < crit$. Smaller screening length ρ_{sc} i.e., higher B_θ expands the regime of zonal flow persistence.
- Using particle balance, the zonal flows collapse when the particle source $S < S_{crit} \sim B_\theta^{-3} \sim I_p^{-3}$. $\Longrightarrow$ Particle source required to hold the shear layer decreases with increasing current.
- In terms of local edge density, zonal flows collapse when $n > n_{crit}$. In a <u>viscosity dominated regime</u> $n_{crit} \sim B_\theta \sim I_p$ and in charge exchange friction dominated regime $n_{crit} \sim B_\theta^2 \sim I_p^2$.

Implications for other devices

- Density limit is linked to shear layer collapse which is (in part) controlled by neoclassical screening response.
- In stellarators, the principal correction to classical screening is due to helically trapped particles.
- This has no obvious length scale other than ρ_i the zonal flow screening is classical. Thus the "effective inertia" for zonal flows in stellarators is lower than that for tokamaks.

Connection with Ohmic confinement phenomenology and L-H threshold power minimum

- Ohmic phenomenology (i.e., LOC-SOC, rotation reversal etc.) may be unified by the scaling relation $n_{crit}qR = B_T$. This is equivalent to $n/n_G = \mathcal{O}(1/2)$.
- Greenwald limit phenomenology-i.e., radiative cooling, Marfes, disruption etc., - set in for $n/n_G = \mathcal{O}(1)$
- Why the similarity to the Greenwald scalings, but for phenomena which occur at lower density?
- These occur for $n/n_G < 1$———>a precursor to the more violent phenomena associated with the density limit.



Rice *et al* NF 2020

- $n_{crit}qR = B_T$ appears to be related to the minimum in the power threshold for L→ H transition.
- This may be due to the onset of pre-transition shear layer decay for $n/n_G < 1$.
- This in turn weakens the 'seed' shear which initiates the L→ H transition, and thus necessitates an increase in the power required for the transition.

Suggestions for experiments

- Shear layer collapse study in L mode with P_{aux}. (Note $\alpha \sim T^2/n$)
- Scale of shear layer collapse and its relation with screening length.
- Pellet/SMBI experiment of Greenwald with relevant fluctuations measurements. Relate the density relaxation time to the predictions based on transport dynamics.
- Is the critical edge density with RMP lower than without? Is this because zonal shears are already weekend by the RMP?
- Can edge biasing sustain $n > n_g$ by driving the edge shear layer, externally?
- Is the shear layer collapse transport bifurcation hysteretic or not?

Future directions in theory

- Interplay of B_θ scaling via ρ_{sc} with B_θ scaling from $k_{||} = 1/qR$ (i.e., from Landau damping!?)
- H-mode density limit: H-L back transition by mean ExB shear collapse? Mechanism of mean shear collapse at high density?
- How flux surface shaping effects the shear layer collapse criterion? Can negative triangularity sustain $n > n_g$?