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

[Rameswar Singh and P H Diamond, NF **61**(2021) 076009; PPCF **63**(2021) 035015]

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Summary

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

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

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

- Neoclassical screening + drift wave - zonal flow dynamics → 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.*

Particle source S		Local edge density n	Zonal flow damping
$\rho_s/\sqrt{\rho_{sc}L_n} < crit \rightarrow S < S_c \sim B_\theta^{-3}$	↗	$n > n_c \sim B_\theta$	**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 limits: Basic Aspects

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

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

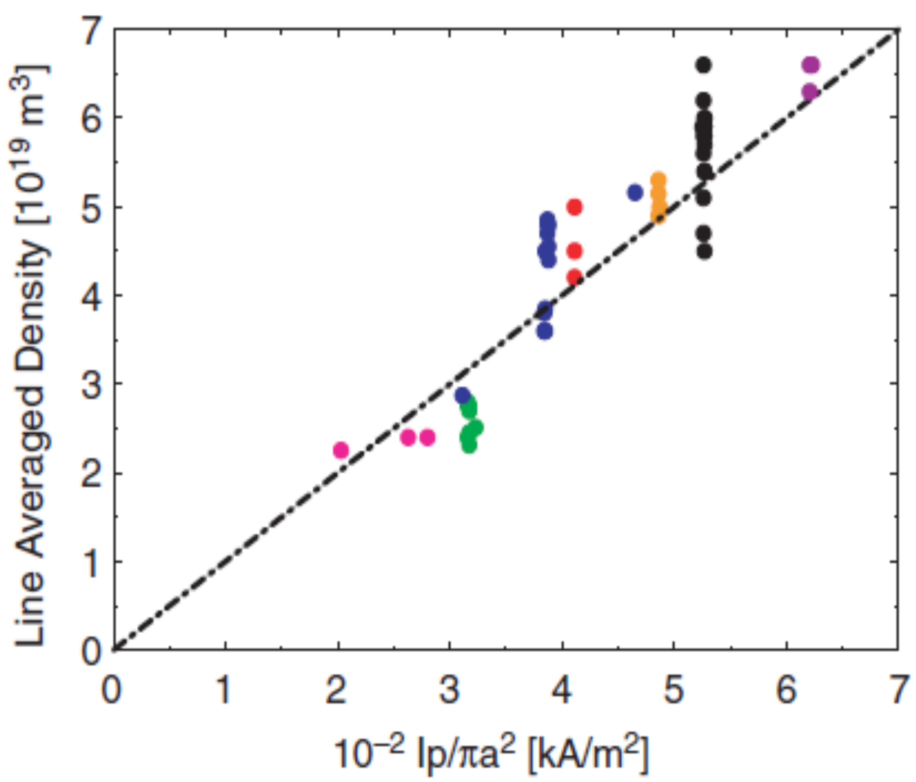
- A fundamental limit on performance.

- 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 the microscopic physics?

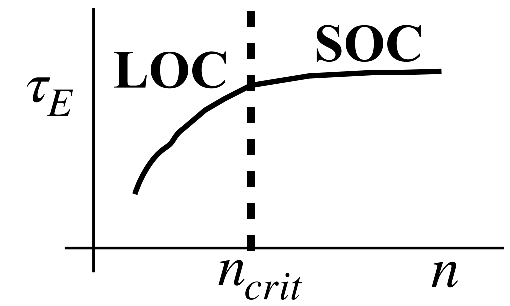
Connecting Greenwald with Ohmic confinement phenomenology and L-H threshold power minimum

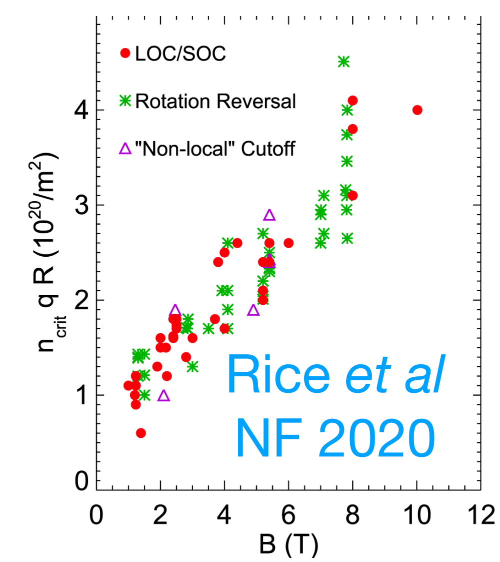
- LOC-SOC transition (mitigated by pellet injection, Greenwald' 84)
- Intrinsic rotation reversal
- L→H transition threshold power P_{th} minimum vs n.
- Greenwald density limit

n_{crit} **low**
Less violent

↓

n_{crit} **high**
More violent



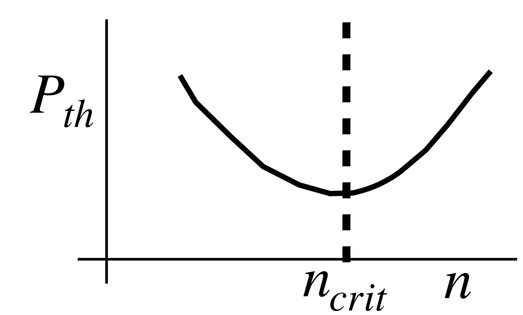


- All the above can be unified by scaling $n_{crit}qR \sim B_T$

➡ $n/n_G = various \quad constants \leq 1$

➡ Greenwald density limit is fundamental

- <u>P_{th} minimum</u>: 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,$\Longrightarrow P_{th} \uparrow$ with n.

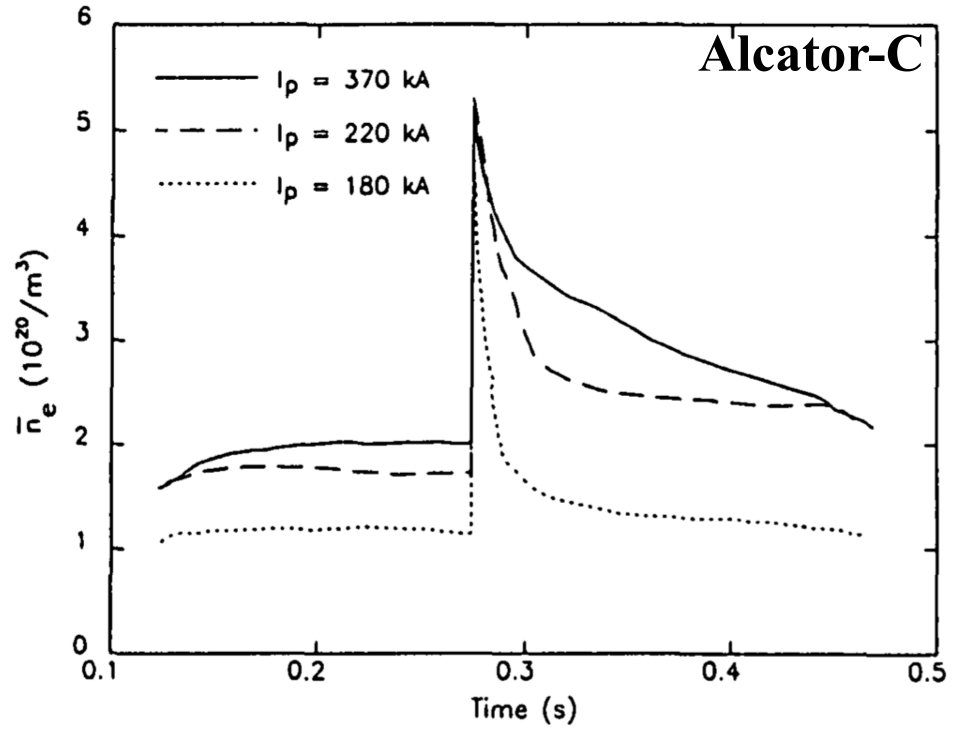


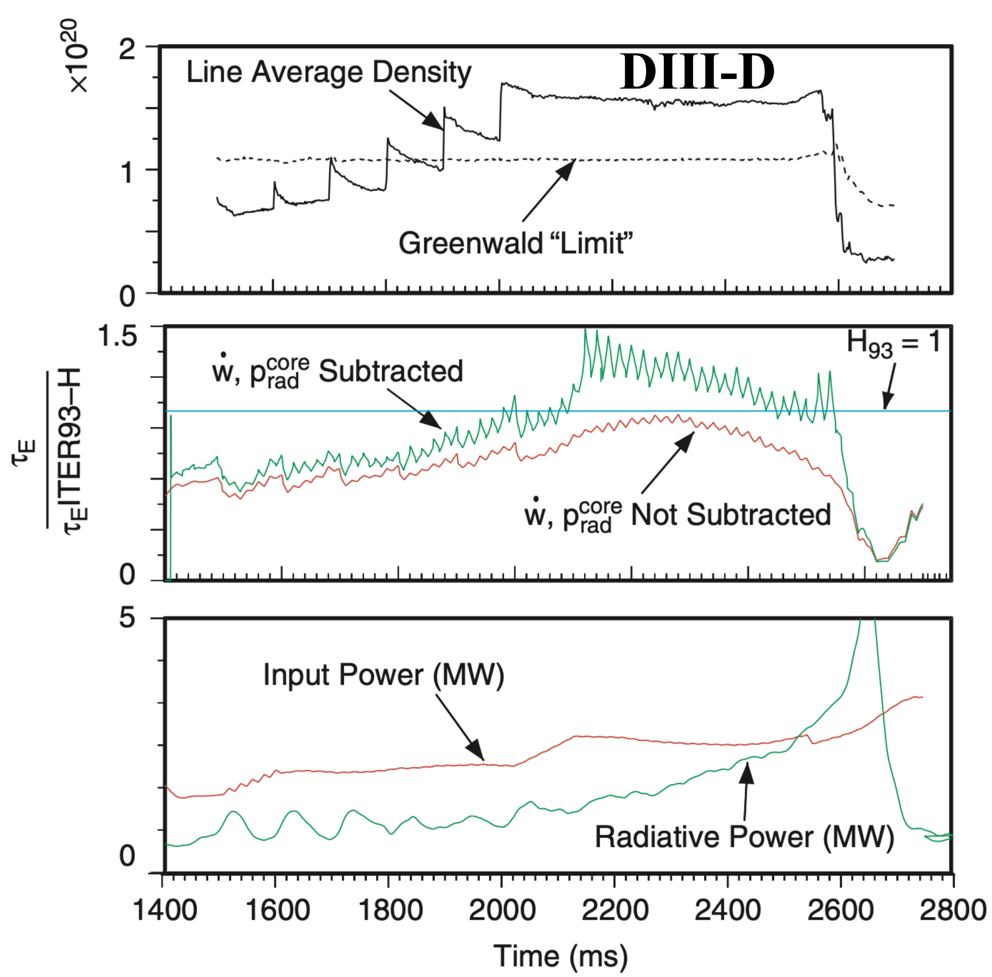
Connections with transport physics

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!



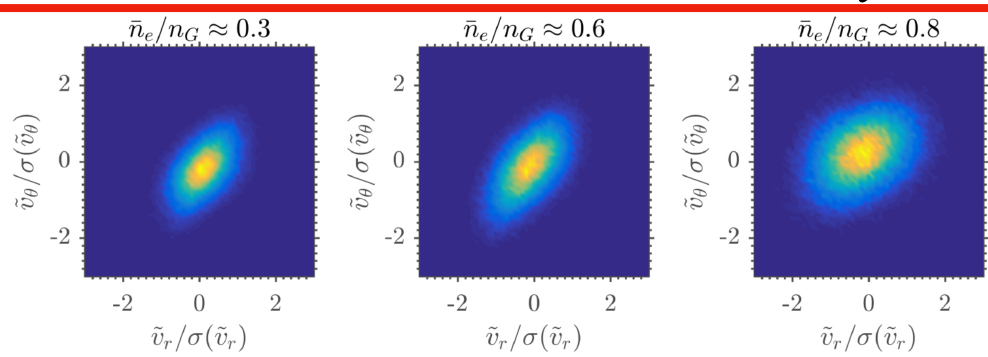


- Pellet in DIII-D beat n_g by peaked density profiles ⟷ enhanced core confinement. Accumulation of impurities ⟶ increase in radiation ⟶disruption.[Mahdavi *et al* 1997]

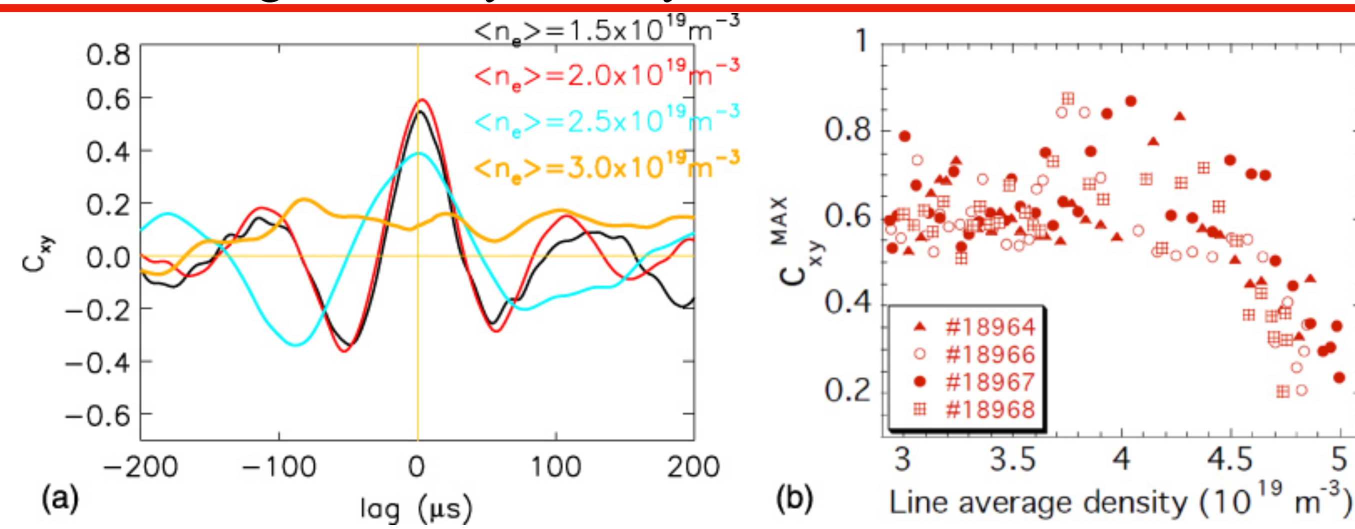
- Disruption ensuing as a <u>secondary</u> consequence of strong edge cooling due to gas fueling/ radiative cooling.

Recent experiments

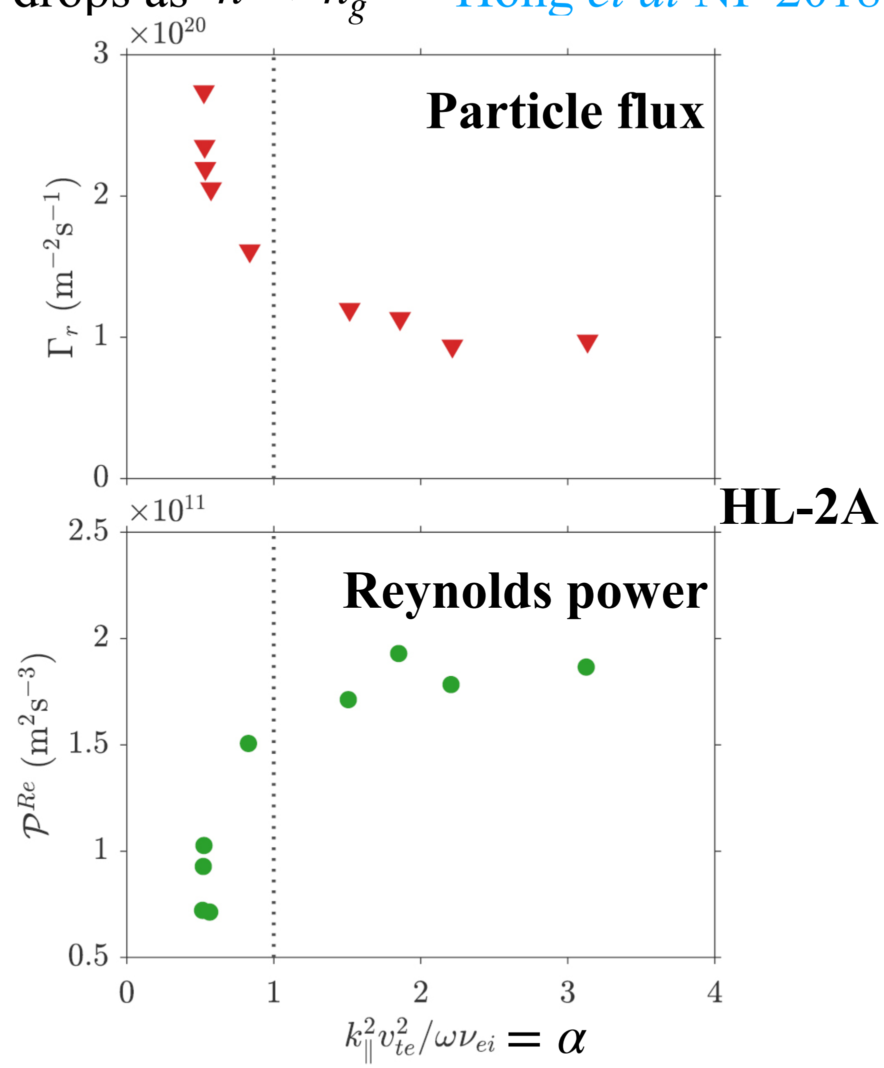
Is the density limit related to edge shear layer decay?



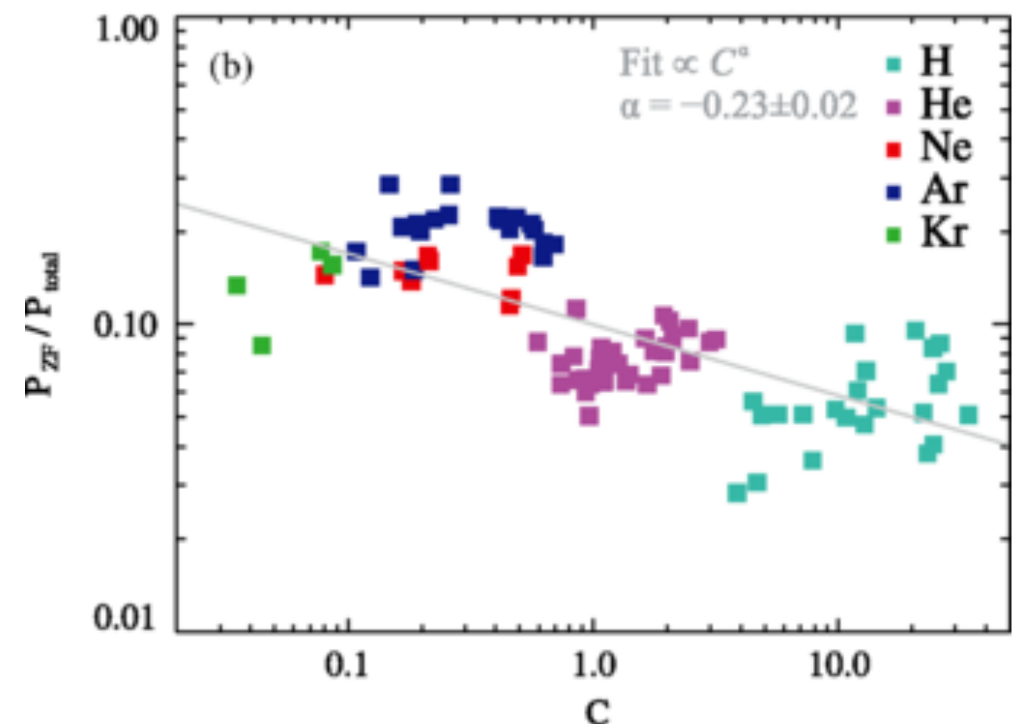
Radial and poloidal velocity correlations drops as $n \rightarrow n_g$ Hong *et al* NF 2018



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



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

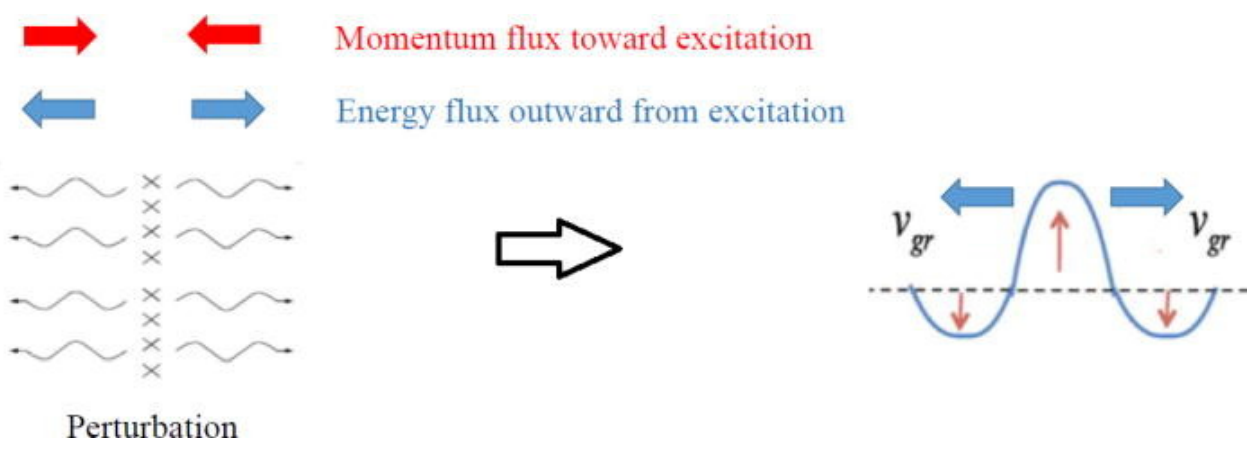
…and the most recent experiments by T Long et al @ J-TEXT (this meeting)

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

- Clearly, shear layer collapse ⟶ increased turbulence and transport as $\bar{n} \rightarrow n_g$! <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 $\alpha \ll 1 \rightarrow$ 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]. $\frac{\partial}{\partial t}\left\langle\left|\phi_k\right|^2\right\rangle = \frac{2\tau_c\left\langle\left|S_k\right|^2\right\rangle}{\left|\varepsilon(q)\right|^2}$; $\varepsilon = \varepsilon_{cl} + \varepsilon_{neo} = \frac{\omega_{pi}^2}{\omega_{ci}^2}\left\{1 + \frac{q^2}{\epsilon^2}\right\} k_r^2 \rho_i^2$ banana regime

  Emission from polarization interaction

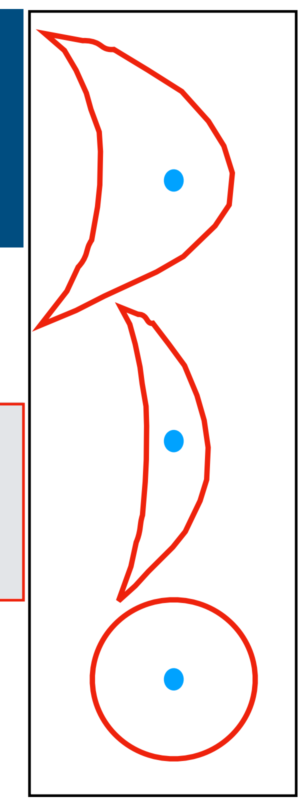
  Neoclassical response

  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

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

Induced diffusion ($\sigma E_v E_t$)

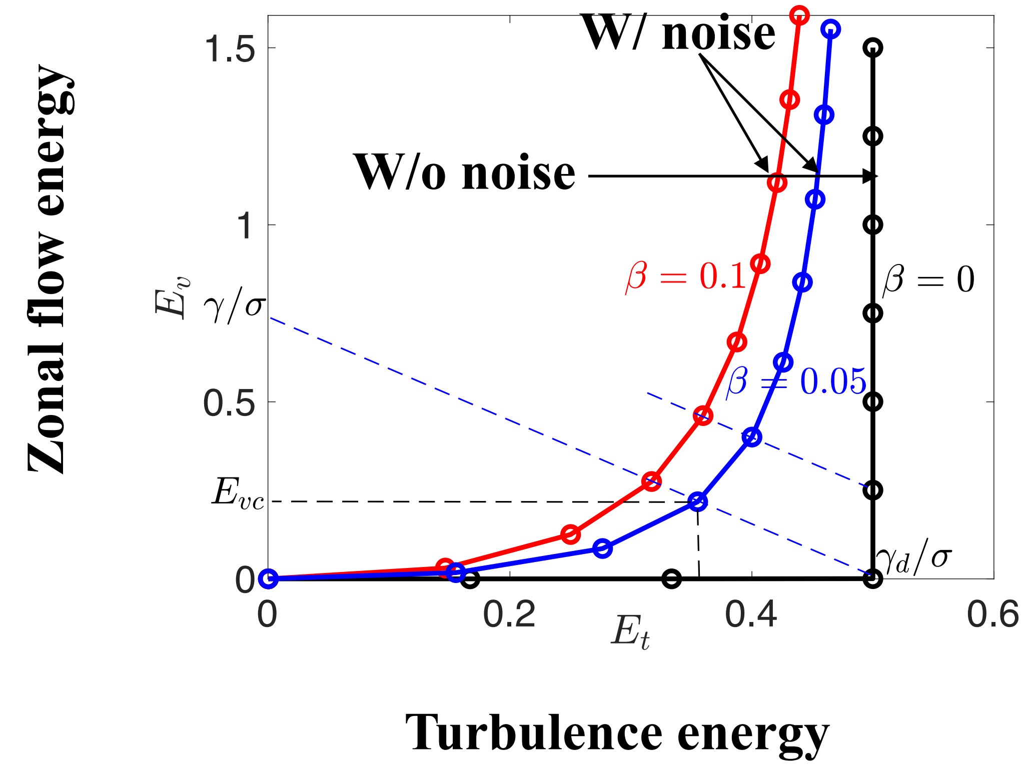
Nonlinear damping (ηE_t^2)

Zonal flow energy E_v evolves as

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

Modulational growth ($\sigma E_t E_v$)

Zonal noise (βE_t^2)



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:

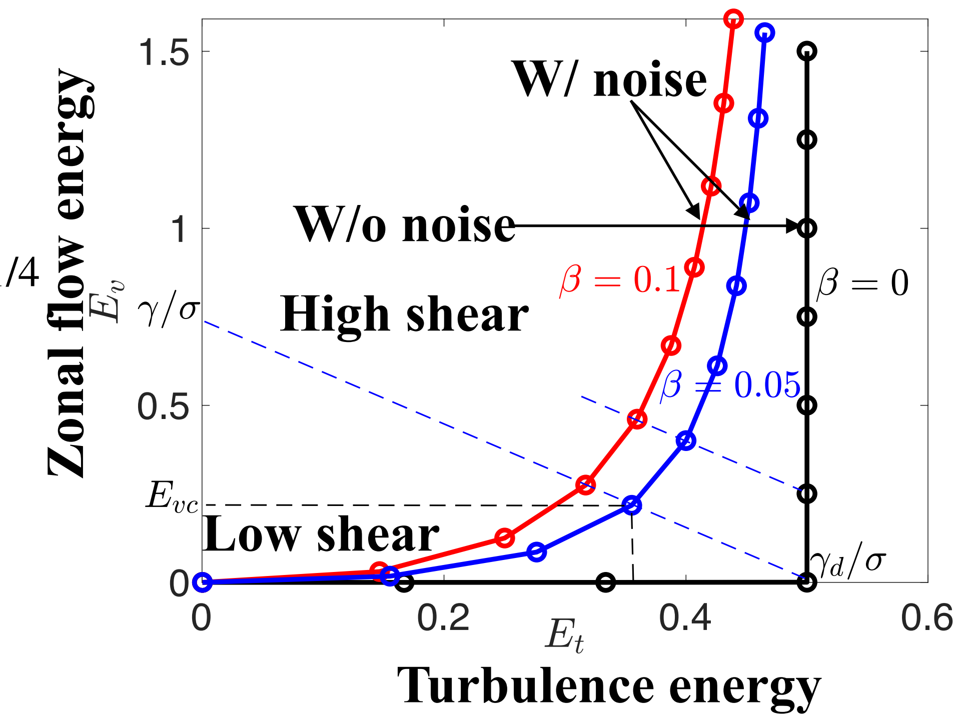
- Both zonal flow and turbulence co-exist at any growth rate: - No threshold in growth rate for zonal flow excitation.
- Zonal flow energy is related to turbulence energy as $E_v = \beta E_t^2 / (\gamma_d - \sigma E_t) \uparrow$ with I_p.
- Turbulence energy never hits the 'old' modulational instability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

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

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



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

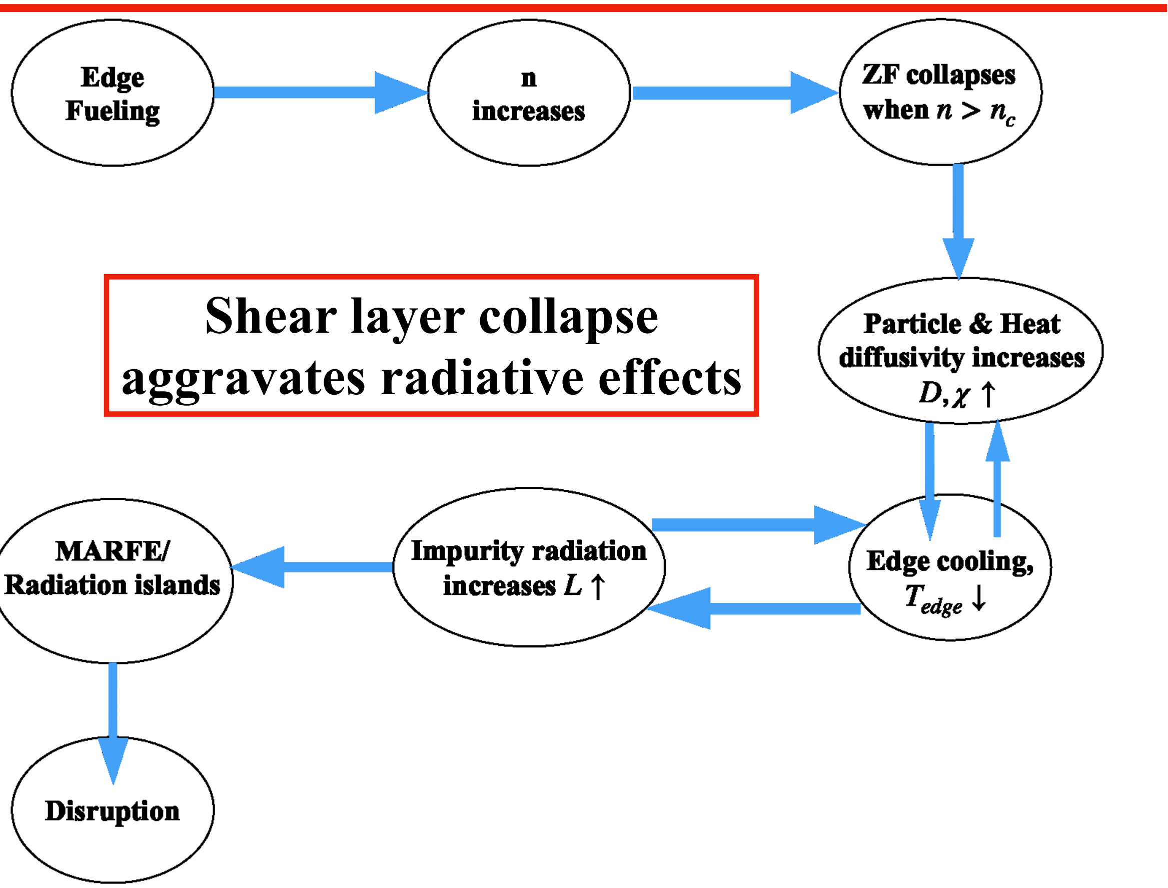
- In the charge exchange friction dominated regime, $n_{crit} \sim \rho_s^2/\rho_{sc}^2 \sim B_\theta^2 \sim I_p^2$ (NB: stronger I_p dependence!)

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.



- $\rho_s/\sqrt{\rho_{sc}L_n}$ 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.

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 $n > n_g$?