In Search of Greenwald Scaling in Edge Shear Layer Collapse at High Density

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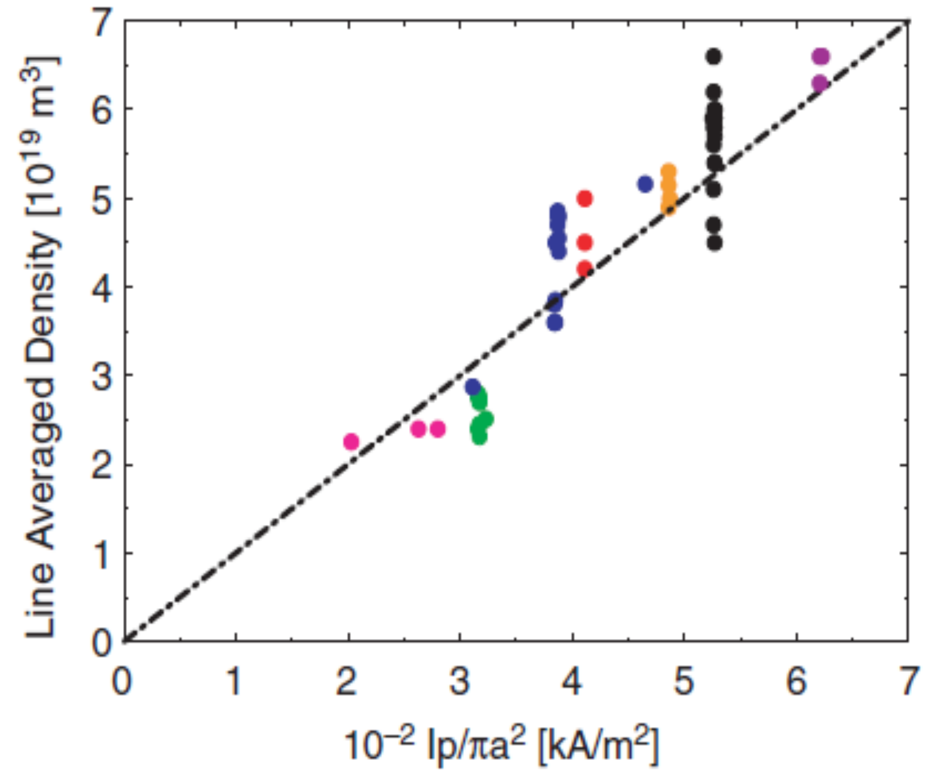
Density limit basics

- Discharge terminates when line integrated density exceeds a critical value $\bar{n}_g = \frac{I_p}{\pi a^2}$.
- Why care ? Fusion power $\propto n^2$.
- Not a dimensionless number
  ——more physics involved.



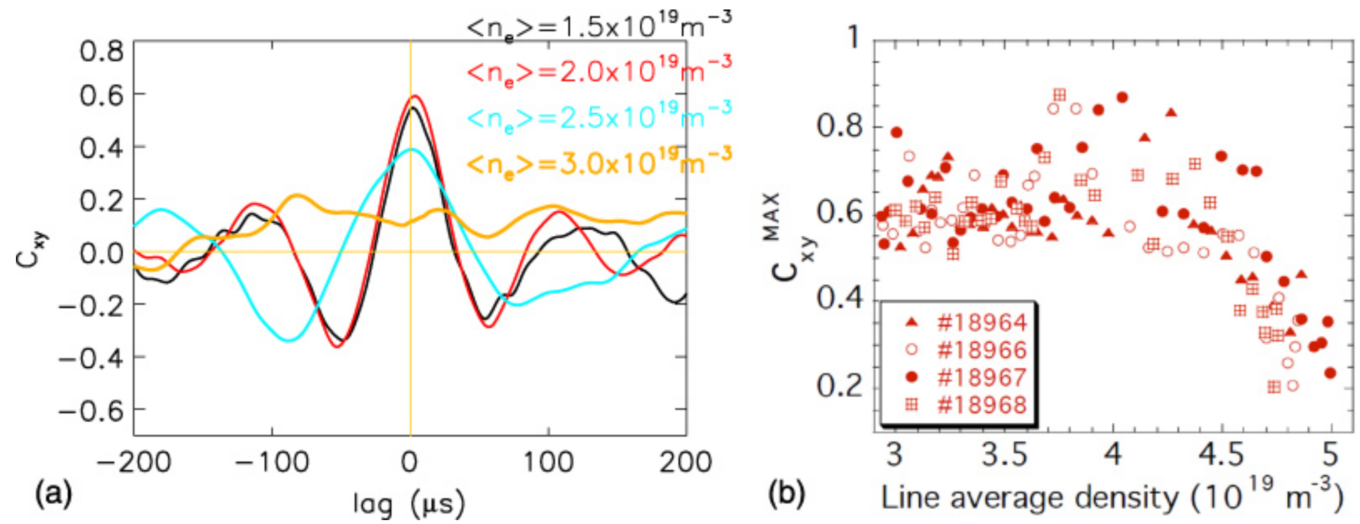
Greenwald PPCF 2002

- Still begging the origin of I_p scaling !?
- Recent experiments and theory suggest that density limit phenomenology emerge from the collapse of edge shear layer leading to increased turbulence, transport and edge cooling, et seq. [Hong etal NF 2018, Hajjar et al PoP 2018]

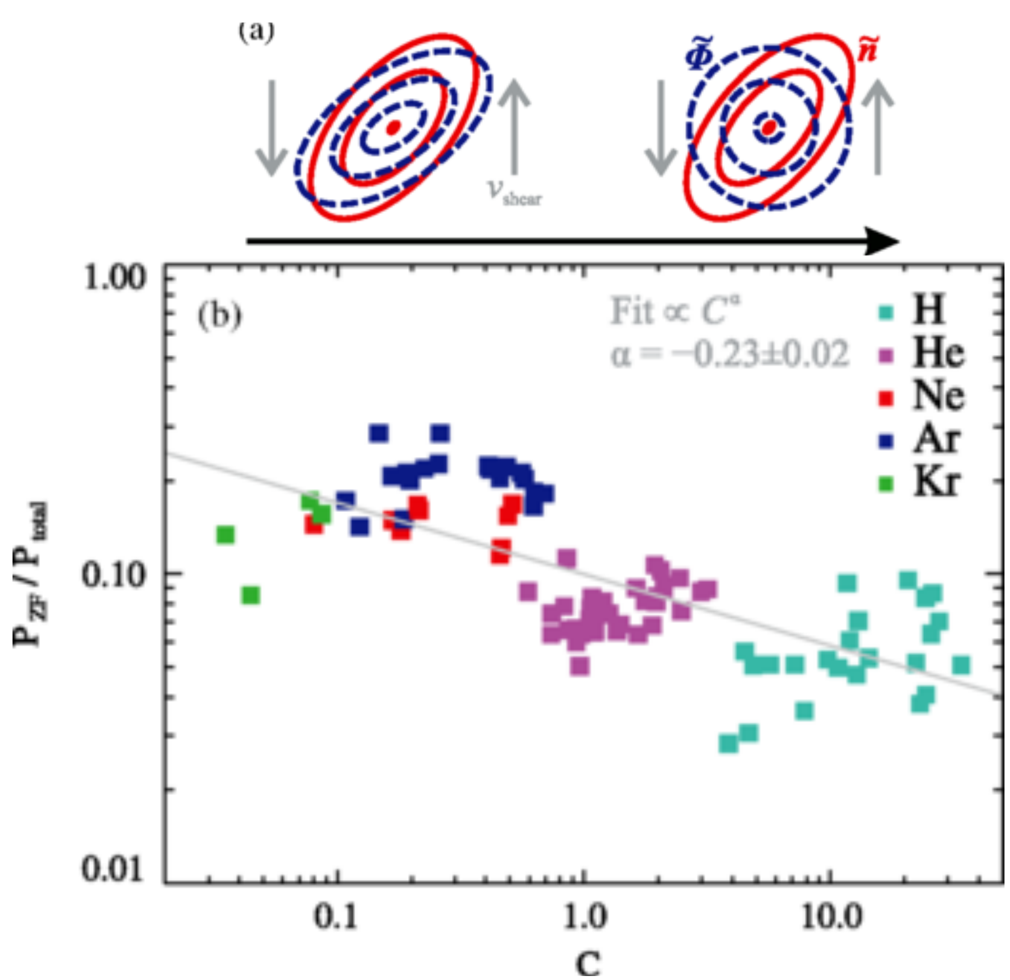
Recent experiments

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

- **Reduction in LRC is also accompanied reduction in edge mean radial electric field. (ZF related)**



Y. Xu *et al,* NF 2011



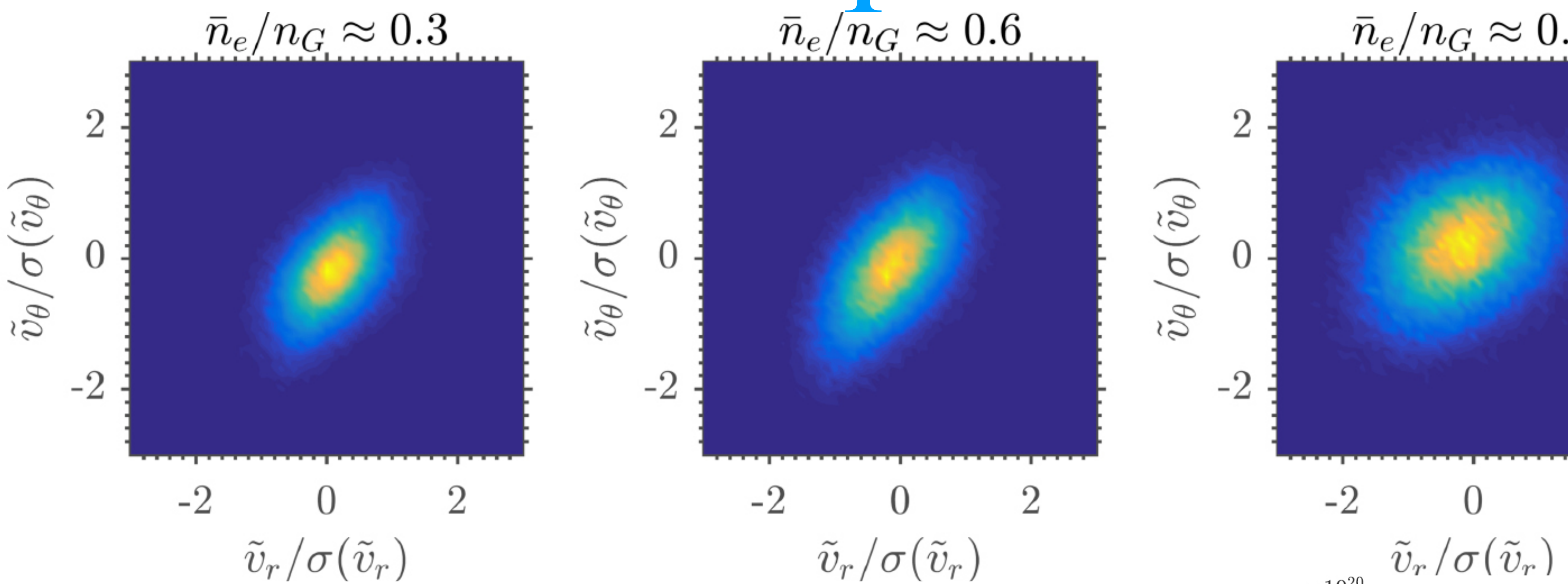
Schmid *et al* PRL 2017

- **Experimental verification of the importance of collisionality for large-scale structure formation in TJ-K.**

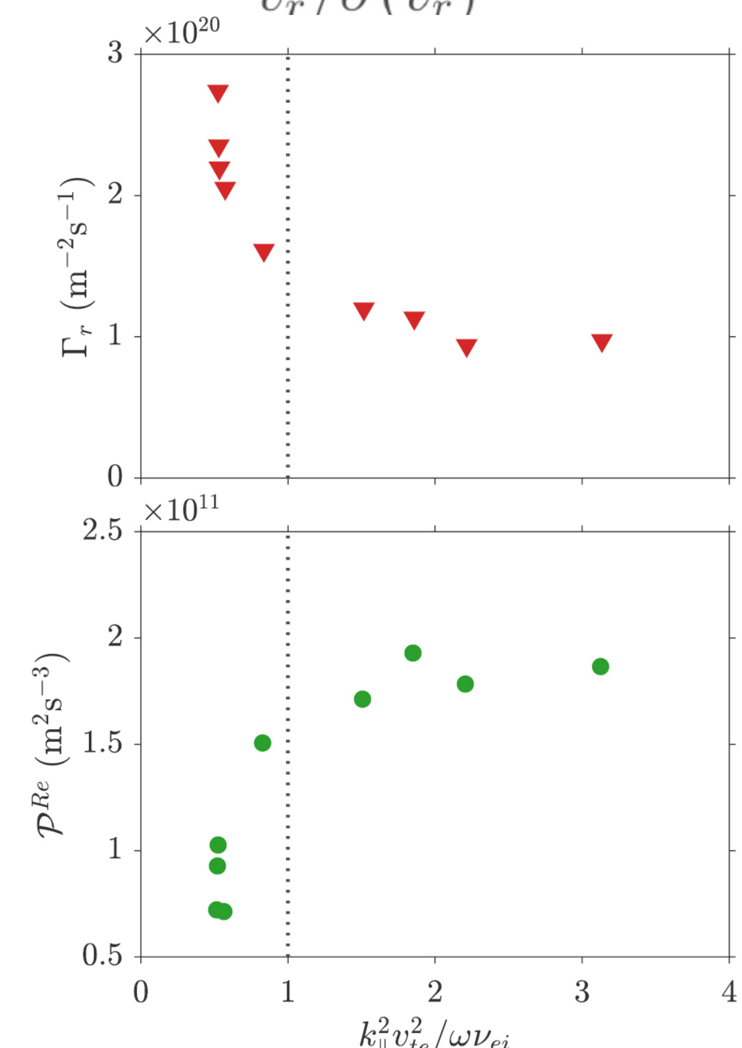
- **Coupling between density and potential decreases with increasing C → hinders zonal flow drive.**

- **Zonal flow contribution to the total turbulent spectrum P_{ZF}/P_{total} decreases with collisionality C.**

Recent experiments



Hong *et al* 2018



- **Joint pdf of $\tilde{v}_r$ and $\tilde{v}_\theta$ for 3 densities as $n \to n_g$ at $r - r_{sep} = -1$ cm**
- **Pdf becomes more symmetric as $n \to n_g$!**
- **$\tilde{v}_r$ and $\tilde{v}_\theta$ are less correlated when $n \to n_g$**
  $\Longrightarrow$**Reynolds stress weakens, Reynolds power drops !**
- **Key parameter: electron adiabaticity $\alpha = k_\parallel^2 v_{te}/\omega\nu_{ei}$**
- **Particle flux $\Gamma_r \uparrow$ and Reynolds power $P_{Re} = -\langle V_\theta \rangle \dfrac{\partial \langle \tilde{v}_r \tilde{v}_\theta \rangle}{\partial r} \downarrow$ as α drops below 1.**

Theory of shear layer collapse

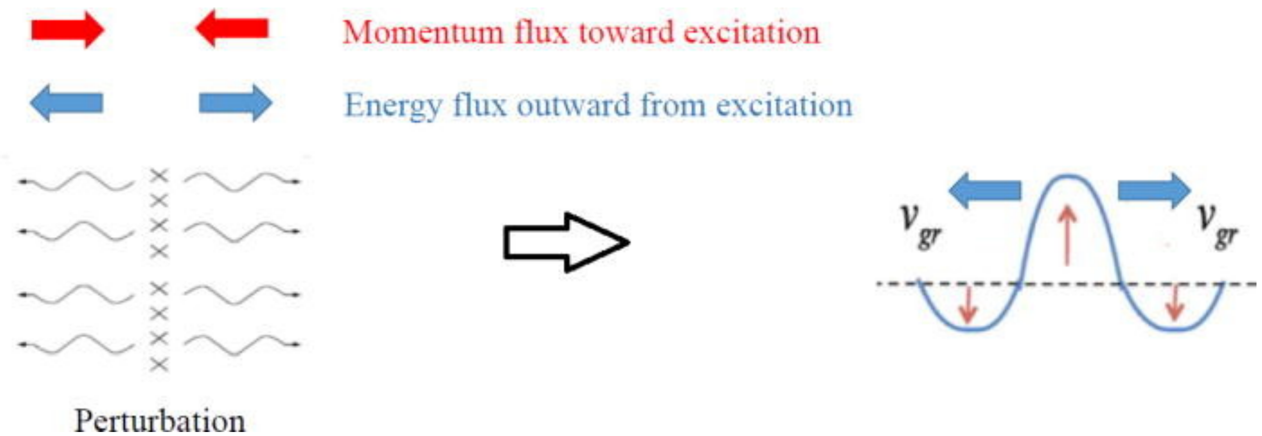
- Clearly, shear layer collapse, increased turbulence and transport as $n \to n_g$!

- Note that β in these experiments too small for conventional Resistive Ballooning Mode explanation [Drake and Rogers 1998].

- What physics governs the shear layer collapse as $n \to n_g$?

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

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



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 $\alpha \ll 1 \to$ weak regulation of turbulence and enhancement of particle transport and turbulence.

What about current scaling ?

- How does shear layer collapse scenario connect to Greenwald scaling $\bar{n}_g \sim I_p$?

- Key physics: zonal flow drive is "screened" by neoclassical dielectric [Rosenbluth - Hinton 1998].

  Emission from polarization interaction

  - $$\frac{\partial}{\partial t}\left\langle \left|\phi_k\right|^2 \right\rangle = \frac{2\tau_c \left\langle \left|S_k\right|^2 \right\rangle}{\left|\varepsilon(q)\right|^2}; \qquad \varepsilon = \varepsilon_{cl} + \varepsilon_{neo} = \frac{\omega_{pi}^2}{\omega_{ci}^2}\left\{1 + \frac{q^2}{\epsilon^2}\right\} k_r^2 \rho_i^2$$ banana regime

  Neoclassical response

  Zonal wave #

  - Poloidal gyro-radius ρ_θ emerges as screening length !

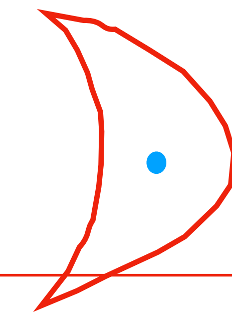
  - Effective ZF inertia ↓ as I_p ↑ →ZF strength increases with I_p

- But edge region is most likely in Plateau regime.[T Long et al NF 2019]

- Need revisit RH screening calculation !

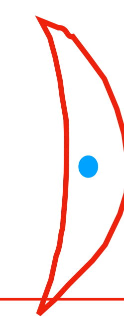
R-H response in different collisionality regimes

- **Banana** $\nu_{ii} \ll \omega_{bi} \ll \omega_{Ti}$ $\dfrac{\phi_k(\infty)}{\phi_k(0)} = \left(\dfrac{B_\theta}{B_T}\right)^2 \propto I_p^2$, screening length $\rho_{sc} = \sqrt{\rho_s^2 + \rho_\theta^2} \approx \rho_\theta$



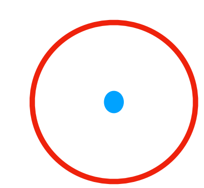
- **Plateau** $\omega_b \ll \nu_{ii} \ll \omega_T$ $\dfrac{\phi_k(\infty)}{\phi_k(0)} = \dfrac{1}{\mathscr{L}} \left(\dfrac{B_\theta}{B_T}\right)^2 \propto I_p^2$ where $\mathscr{L} = 1 - \dfrac{4}{3\pi}(2\epsilon)^{3/2} < 1$, screening length $\rho_{sc} = \sqrt{\rho_s^2 + \mathscr{L}\rho_\theta^2} \approx \mathscr{L}^{1/2}\rho_\theta$

  - Favorable I_p scaling persist in Plateau regime. Robust trend !



- **Pfirsch-Schluter** $\omega_{bi} \ll \omega_{Ti} \ll \nu_{ii}$ $\dfrac{\phi_k(\infty)}{\phi_k(0)} = 1$, screening length $\rho_{sc} = \rho_i$

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



  - The often quoted factor $\left(1+2q^2\right)$ applies to mass flow and NOT $E \times B$ flow.

Modulational growth and zonal noise increases with I_p

- Edge region is most likely in Plateau regime.

- Laplace transformed gyrokinetic quasi neutrality: $\varepsilon(p)\nabla^2\phi(p) = 4\pi\rho(p)$ yields zonal vorticity equation

$$\frac{d}{dt}\varepsilon\left\langle \nabla_\perp^2\phi\right\rangle = -\frac{\partial}{\partial x}\left\langle \delta v_{Er}\nabla_\perp^2\delta\phi\right\rangle + \mu_0\nabla_\perp^2\varepsilon\left\langle \nabla_\perp^2\phi\right\rangle \text{ where } \varepsilon = 1 + \frac{q^2}{\epsilon^2}\mathscr{L}$$

- Spectral closure calculations: Zonal intensity equation

Zonal Cross Corr.

$$\left(\frac{\partial}{\partial t} + 2\mu k_x^2\right)\left\langle\left|\phi_k\right|^2\right\rangle + 2\eta_{1k}^{zonal}\left\langle\left|\phi_k\right|^2\right\rangle + \Re\left[2\eta_{2k}^{zonal}\left\langle n_k\phi_k^\star\right\rangle\right] = F_{\phi k}^{zonal}$$

- NL damping -ve when $\frac{\partial I_q}{\partial q_x} < 0 \rightarrow$ Modulational growth $-\eta_{1k}^{zonal} \sim \frac{k_x^2}{\varepsilon} \sim k_x^2 I_p^2 \Longrightarrow$ Negative viscosity effect gets stronger with I_p.

- Modulational growth stronger in adiabatic regime than that in hydro regime.

- Cross transfer rate $\eta_{2k}^{zonal} \sim \frac{k_x^2}{\varepsilon} \sim k_x^2 I_p^2$, +ve.

More on ZCC and corrugations GO06.00011, Tuesday meeting

- Zonal noise $F_k^{zonal} = \frac{4}{\epsilon^2}\sum_q \Pi_q^2\Theta_{k,-q,q}^{(r)} \sim I_p^4$; Spectral Reynolds stress $\Pi_q = q_x q_y I_q$

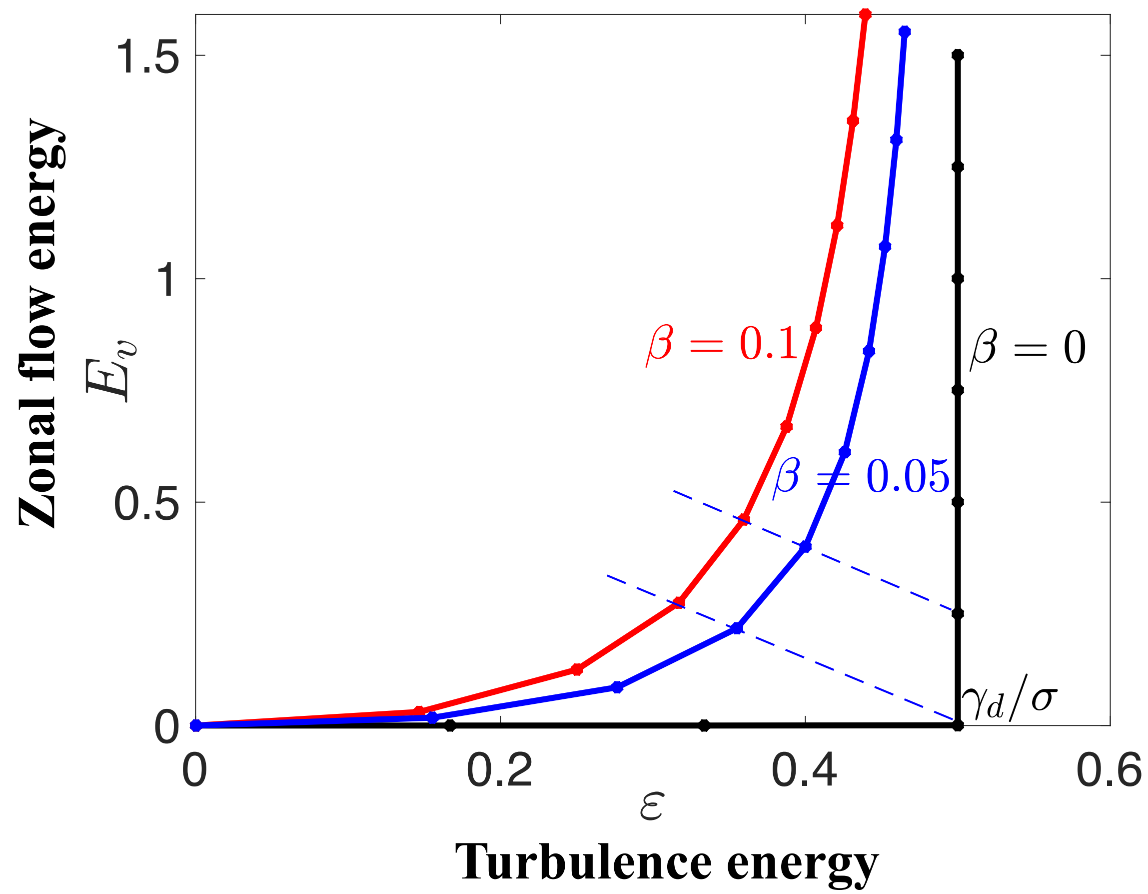
- Stronger zonal flow seeding with increasing current !

Zonal noise crucial to feedback

I_p jacks up zonal noise

→ stronger feedback

on turbulence.



With noise:

- Both zonal 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 $E_v = \beta\varepsilon^2/\left(\gamma_d - \sigma\varepsilon\right) \uparrow$ with I_p.
- Turbulence energy never hits the modulational instability threshold, absent noise!
- Turbulence energy ↓ and zonal flow energy ↑:- Noise feeds energy into zonal flow!

Vorticity gradient increases with I_p

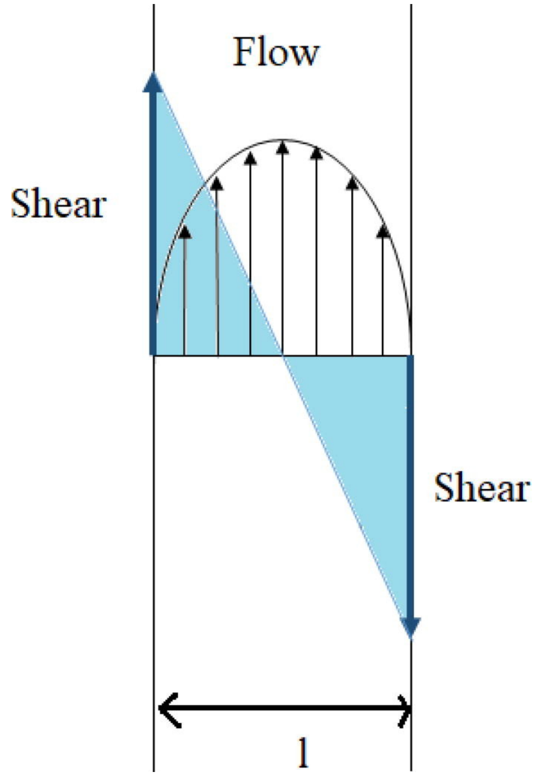
- Vorticity gradient reduces growth rate and has strong feedback on turbulence. [Heinonen & Diamond 2020]

- Vorticity flux: $\left\langle \tilde{v}_{Er} \nabla_\perp^2 \tilde{\phi} \right\rangle = -\chi_y \varepsilon \dfrac{d\left\langle \nabla^2 \phi \right\rangle}{dx} + \Pi^{res}$

- In absence of external source/sink, steady state vorticity gradient:

$$\frac{d\left\langle \nabla^2 \phi \right\rangle}{dx} = \frac{\Pi^{res}}{\chi_y \varepsilon} \approxeq \frac{1}{\mathscr{L}} \left(\frac{B_p}{B_T} \right)^2 \frac{\Pi^{res}}{\chi_y} \sim I_p^2$$

  - Stronger vorticity gradient with increasing current !



Jump in shear

- Particle flux Γ_n remains independent of neoclassical polarization.

  - yet a current dependence through $k_\parallel \sim \dfrac{1}{q} \sim I_p$ possible, $\Gamma_n \sim \dfrac{1}{I_p^2}$.

➡Particle flux ↓ and zonal shear ↑ when I_p ↑.

➡This is a favorable trend for Greenwald scaling .

Conclusions

- Neoclassical zonal flow screening, with polarization $\varepsilon(p) = \frac{\omega_{pi}^2}{\omega_{ci}^2}\frac{q^2}{\epsilon^2}\mathscr{L}$ and screening length $\rho_{sc} = \sqrt{\rho_s^2 + \mathscr{L}\rho_\theta^2} \approx \mathscr{L}^{1/2}\rho_\theta$, is a natural mechanism for emergence of I_p scaling of Greenwald density limit. The current scaling due to neoclassical screening survives in the ion plateau regime, characteristics of edge plasmas. $\mathscr{L} = 1$ for Banana, $\mathscr{L} < 1$ for Plateau and $\mathscr{L} = 0$ for P-S regime.

- Modulational growth $\sim I_p^2$ and zonal noise $\sim I_p^4$. Stronger flow seeding with increasing current.

- Mean vorticity gradient $\sim I_p^2$. Vorticity gradient regulates turbulence.

- Large I_p favors stronger zonal flow production and stronger feedback on turbulence.

- Finally, a 1d transport modeling including zonal intensity, turbulence intensity and particle transport with explicit I_p is needed to nail down emergence of Greenwald scaling in shear layer collapse. [Future work]