Edge Shear Flows and Particle Transport near the Greenwald Limit of the HL-2A Tokamak

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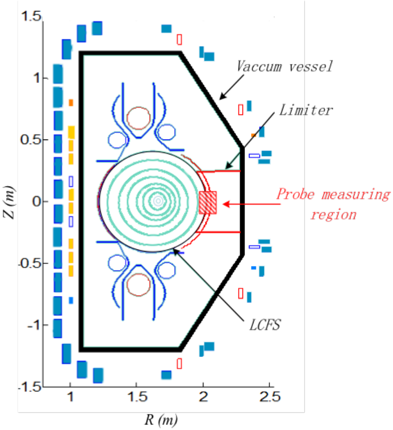
Motivation and Background

- High density is desirable, but usually limited by $n_G = \dfrac{I_p}{\pi a^2}$
- Conventionally, n_G is explained by radiation models
  - Radiation power balanced with heating power $\Rightarrow n_{\text{lim}}$
  - Presume shrinkage of current profile ∇J_p due to edge cooling
- Edge cooling can be triggered by enhanced edge transport
- Enhanced particle flux at high density[1]
  - Driven by collisionality dependent instabilities
  - ? Destruction of edge shear layer — reverse of *L-H* transition
- We seek to measure the evolution of edge shear flows when n_G is approached

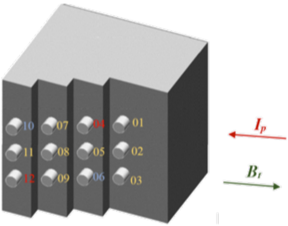
[1] LaBombard '05 NF

Experimental Setup on HL-2A



- Midplane probe array measures n_e, T_e and $\phi_{\rm fl}$
- $\tilde{v}_E = -\nabla\tilde{\phi}_{\rm fl}/B \Rightarrow \langle\tilde{v}_\theta\tilde{v}_r\rangle$, $\langle\tilde{n}_e\tilde{v}_r\rangle$

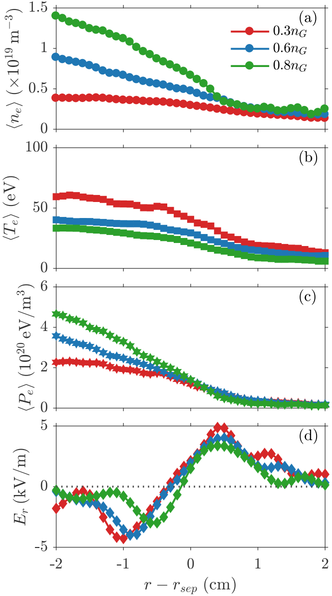
- Density scanning experiment, $\bar{n}_e = 0.8$ to $3.0 \times 10^{19}\,\mathrm{m}^{-3}$, i.e. $0.3 - 0.9\,n_G$
- Ohmic heated in LSN geometry with $I_p = 150\,\mathrm{kA}$ and $B_T = 1.3\,\mathrm{T}$



Equilibrium Profiles

As line-averaged density, $\bar{n}_e$, is raised from 0.3 to 0.8 n_G

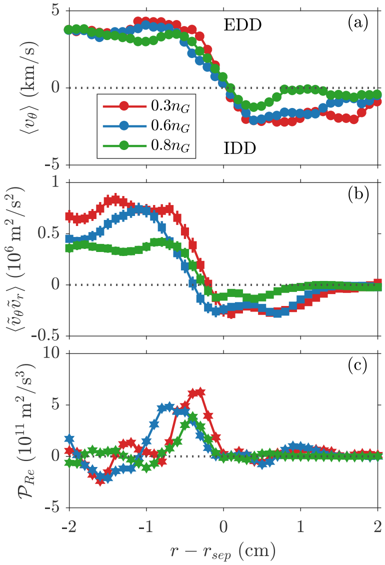
- Density gradient increases
- Electron temperature flattens
- Pressure gradient increases
- Peak value of E_r decreases, where $E_r = -\partial_r(\phi_{\mathrm{fl}} + 2.8T_e)$ $\Rightarrow$ Collapsed $E_r \times B$ shear flows



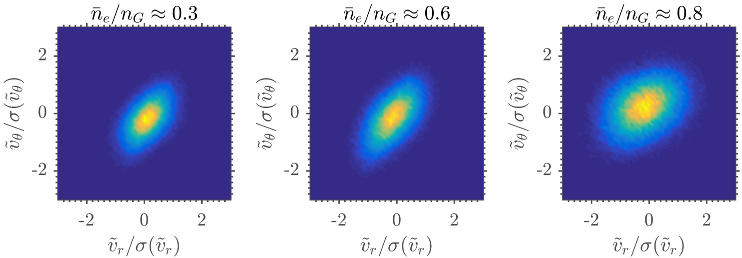
Energy Transfer from Turbulence to Shear Flow

As line-averaged density is raised

- Edge phase velocity decreases
- Turbulent Reynolds stress drops
- Reynolds power, $\mathcal{P}_{Re} = -\langle v_\theta \rangle \partial_r \langle \tilde{v}_\theta \tilde{v}_r \rangle$, collapses
- Indicating mean flow (zonal flow) gains less kinetic energy from turbulence



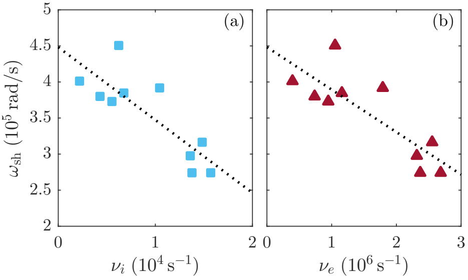
Inhibition of Eddy-Tilting Process

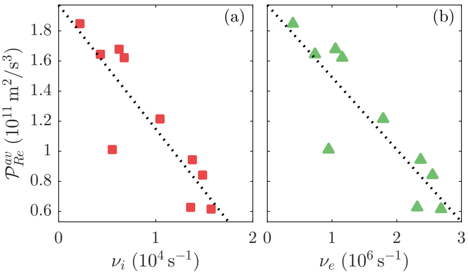


- Joint PDF of radial and poloidal velocities $\mathbb{P}(\tilde{v}_r, \tilde{v}_\theta)$ was measured inside separatrix
- Tilting angle (anisotropy) of eddies decreases as $\bar{n}_e/n_G$ is raised
- Shear decorrelation is inhibited at high density

Collisional Damping Effects

- Mean flow shearing rate, $\omega_{\text{sh}} = |\partial_r V_\theta|$, is averaged over $-1 < r - r_{\text{sep}} < 1$ cm
- Lower ω_{sh} associated with higher collision rates



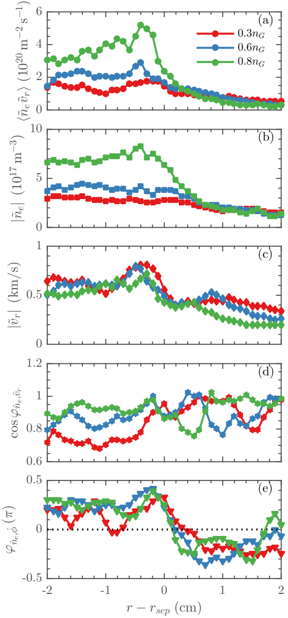


- Reynolds power $\mathcal{P}_{Re}$ averaged over the same region
- $\mathcal{P}_{Re}^{av}$ decreases as collision rate increases

Enhanced Turbulent Particle Flux

As $\bar{n}_e$ is raised from 0.3 to 0.8 n_G

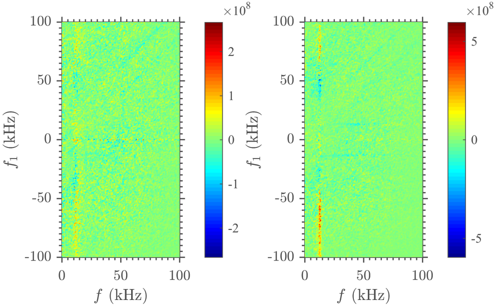
- Particle flux increases substantially
- Amplitude of density fluctuations increases
- No obvious change in $|\tilde{v}_r|$
- Cross-correlation between density and velocity increases
- $k_\parallel^2 v_{te}^2/\omega\nu_e$ drops from about 2 to 0.3 $\Rightarrow$ non-adiabatic electron response

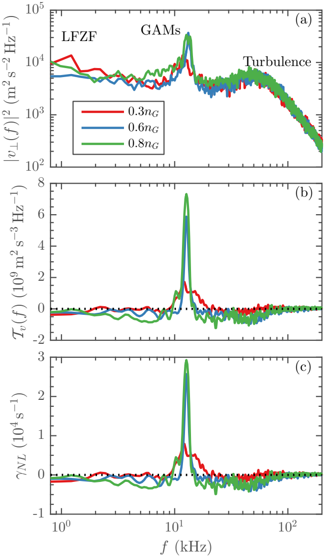


GAMs Increase at Higher Density

As $\bar{n}_e/n_G$ is raised

- GAMs' amplitude increases
- GAMs gain more energy from ambient turbulence ($40 < f < 100$ kHz)
- $\mathcal{T}_v(f, f_1) = -\mathrm{Re}\left\langle \mathbf{v}^*_{\perp,f} \cdot \left(\mathbf{v}_{\perp,f-f_1} \cdot \nabla_\perp \mathbf{v}_{\perp,f_1}\right)\right\rangle$



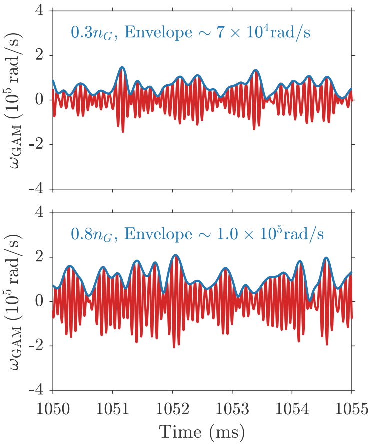


Shearing Rate of GAMs Less than Mean Flow

Why GAMs do *not* mitigate turbulent transport?

- Eddy turnover rate $\omega_{\text{eddy}} \sim 0.4 - 1.2 \times 10^5\ \text{s}^{-1}$
- Mean flow shearing rate $\omega_{\text{sh}} \sim 3 - 5 \times 10^5\ \text{s}^{-1}$
- GAMs shearing rate $\omega_{\text{GAM}} \sim 0.7 - 1 \times 10^5\ \text{s}^{-1}$
- $\omega_{\text{GAM}} \lesssim 0.3 \times \omega_{\text{sh}}$

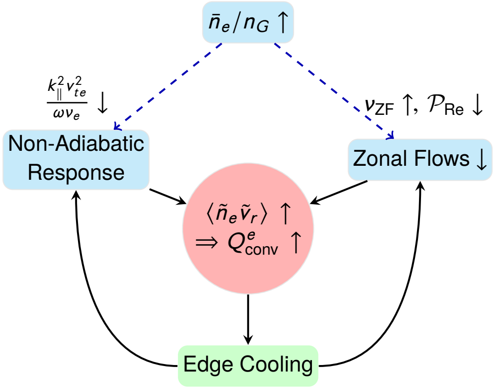
Mean flow plays leading role in shear decorrelation



$\omega_{\text{GAM}} = \frac{V_1^{\text{GAM}} - V_2^{\text{GAM}}}{\Delta_{12}}$, where $V_{1,2}^{\text{GAM}}$ is at different probe steps

Feedback Loop to Edge Cooling

- $\bar{n}_e/n_G \uparrow$ triggers non-adiabatic electron response and damping of zonal flows
- Both effects increase particle and heat fluxes, which reduce T_e and lead to edge cooling
- Edge cooling then triggers MHD activities and even disruptions

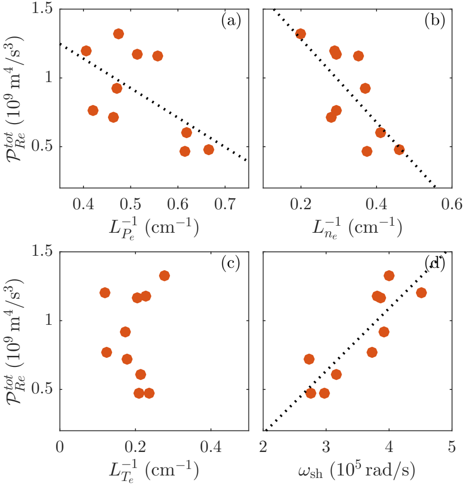


Future Plan

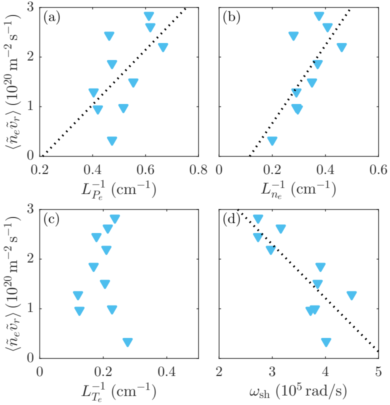
- Effect of magnetic stress $\langle \tilde{B}_\theta \tilde{B}_r \rangle$ should be included at larger α_{MHD}
  - The signs of magnetic stress and Reynolds stress are opposite for drift-Alfven waves, i.e. $\partial_t V_\theta = -\nabla_r \left[\langle \tilde{v}_\theta \tilde{v}_r \rangle - \langle \tilde{B}_\theta \tilde{B}_r \rangle / (4\pi n_i m_i) \right]$
- Perturbative experiments are required to clarify which is affected by collisionality first
  - Collisional damping of shear flows, V'_θ
  - Collapse of turbulent drive, $\langle \tilde{\varpi} \tilde{v}_r \rangle$
- In addition to poloidal sheared flows, toroidal rotation can also regulate turbulent transport
  - Both V_θ and V_φ can be driven by turbulence, coupling between them deserves further studies
  - Simultaneous measurements of poloidal and toroidal Reynolds stress are ongoing

Thank You

Reynolds Work Scaling

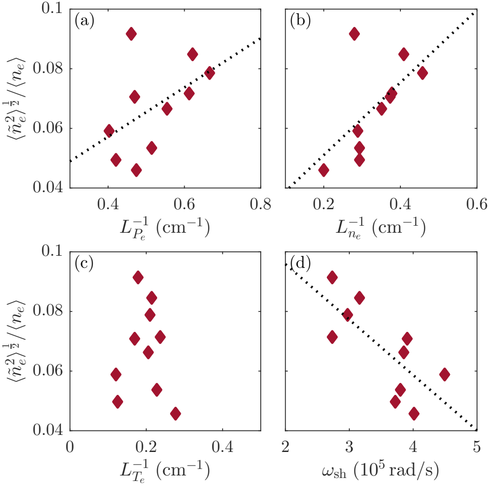


Particle Flux Scaling

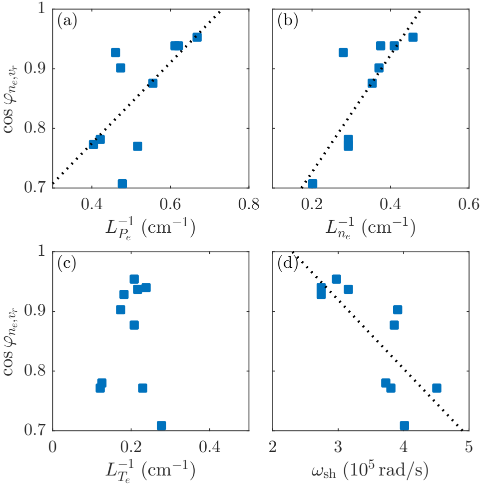


- Turbulent particle flux increases with density gradient
- It drops when shearing rate increases

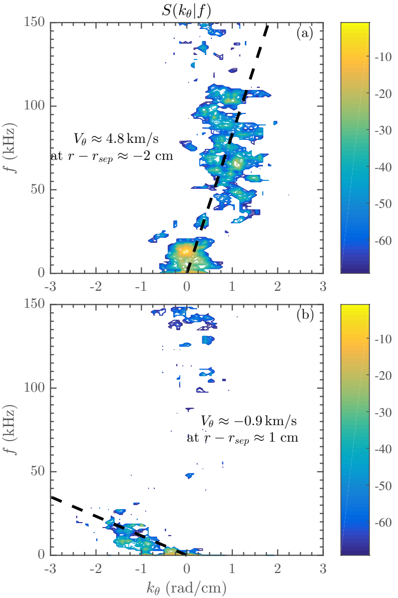
Density Fluctuation Scaling



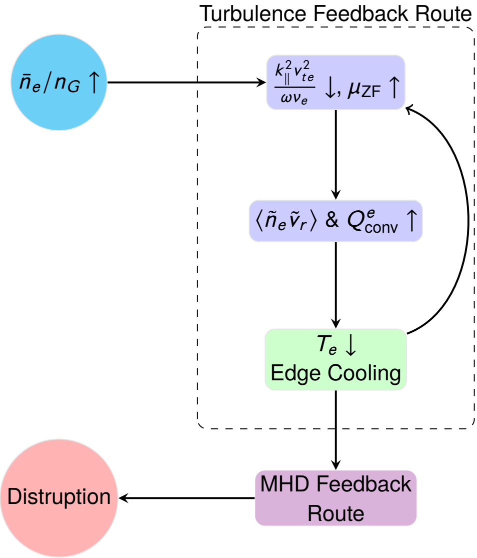
Cross-Correlation Scaling



Dispersion Relation



Link to Radiation Models



Predator-Prey Model for Shear Flow and Turbulence

Power balance between the turbulence and zonal flows

$$\partial_t \bar{K} = -\partial_r \bar{T} + \mathcal{P} - \nu \bar{K} \quad (1)$$

$$\partial_t \tilde{K} = -\partial_r \tilde{T} - \mathcal{P} + (\gamma_{\text{eff}} - \gamma_{\text{decor}})\tilde{K} \quad (2)$$

- $\bar{K} = \frac{1}{2} \langle v_\theta \rangle^2$ and $\tilde{K} = \frac{1}{2} \left\langle \tilde{v}_\theta^2 \right\rangle$
- Shear flow production term $\mathcal{P} = \langle \tilde{v}_r \tilde{v}_\theta \rangle \, \partial_r \langle v_\theta \rangle$
- $\bar{T} = \langle \tilde{v}_r \tilde{v}_\theta \rangle \langle v_\theta \rangle$ and $\tilde{T} = \left\langle \tilde{v}_r \tilde{v}_\theta^2 \right\rangle$
- Reynolds power $\mathcal{P}_{Re} = -\partial_r \bar{T} + \mathcal{P} = -\langle v_\theta \rangle \, \partial_r \langle \tilde{v}_r \tilde{v}_\theta \rangle$

Bispectral Energy Transfer

The study of the nonlinear energy transfer from turbulence to the shear flows utilizes the bispectral analysis

$$\mathcal{T}_v(f, f_1) = -\operatorname{Re}\left\langle \mathbf{v}_\perp^*(f) \cdot \left(\mathbf{v}_\perp(f - f_1) \cdot \nabla_\perp \mathbf{v}_\perp(f_1)\right)\right\rangle$$

- $\mathcal{T}_v(f, f_1)$ measures the transfer of energy between velocity fluctuations at frequency f and their gradient fluctuations at f_1 at a specific location
- A positive $\mathcal{T}_v(f, f_1)$ indicates $v(f)$ gains energy from $\nabla_\perp v(f_1)$
- Total nonlinear energy transfer $\mathcal{T}_v(f) = \sum_{f_1} \mathcal{T}_v(f, f_1)$