Tracing the Pathway from Drift-Wave Turbulence with Broken Symmetry to the Onset of Sheared Axial Flow

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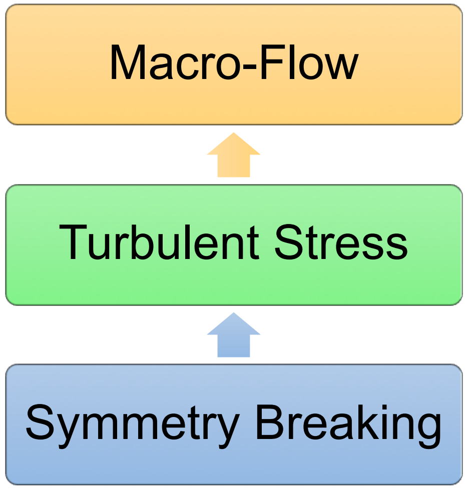
Outline

- Motivation: Connect Formation of Intrinsic Flow to Microscopic Mechanism
- Experimental Setup in a Linear Device—CSDX
- Axial Flow Driven by Turbulent Stress
- Density Gradient $\Longrightarrow$ Residual Stress
- Residual Stress $\Longleftrightarrow$ Spectral Symmetry Breaking
- Dynamical Symmetry Breaking Model
- Conclusion



Intrinsic parallel flow driven by residual stress

- Intrinsic flow (toroidal rotation) improves stability and confinement in magnetized plasmas

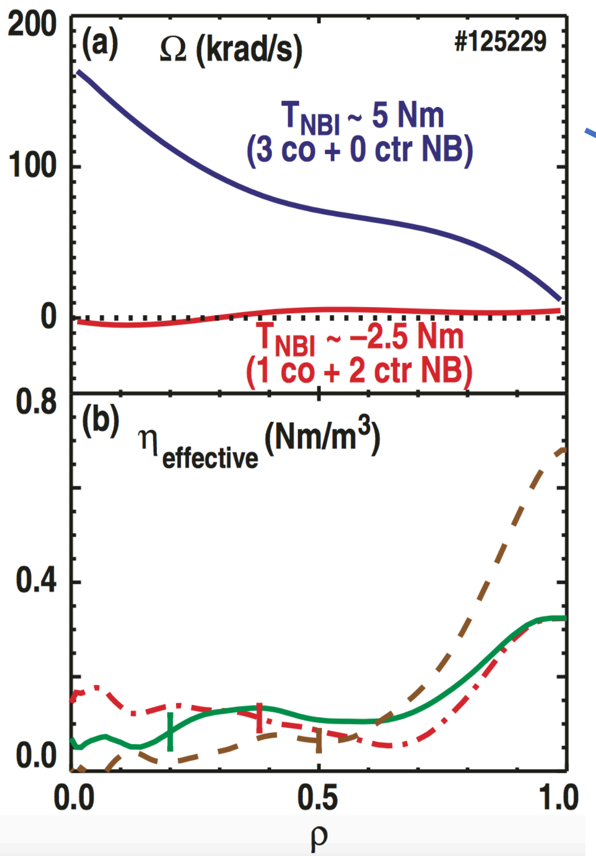
- Intrinsic flow can arise from a non-diffusive, residual stress

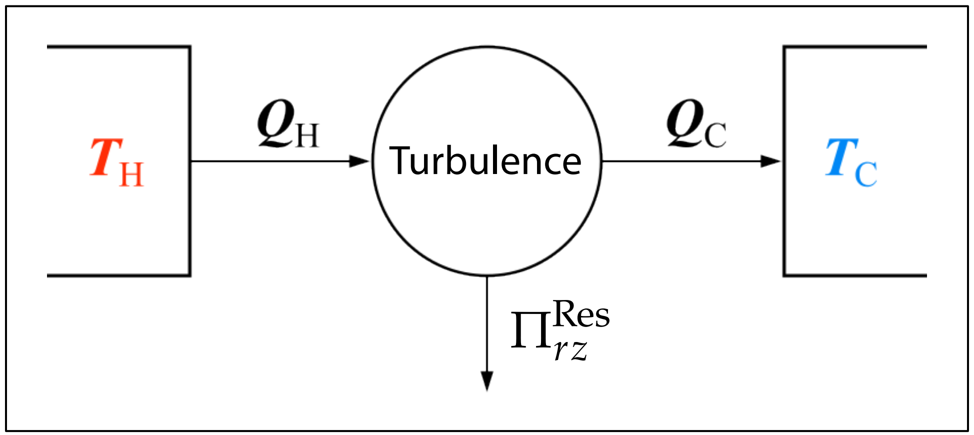
$$\langle \tilde{v}_\phi \tilde{v}_r \rangle = -\chi_\phi \partial_r V_\phi + V_{\mathrm{p}} V_\phi + \Pi_{r\phi}^{\mathrm{Res}}$$

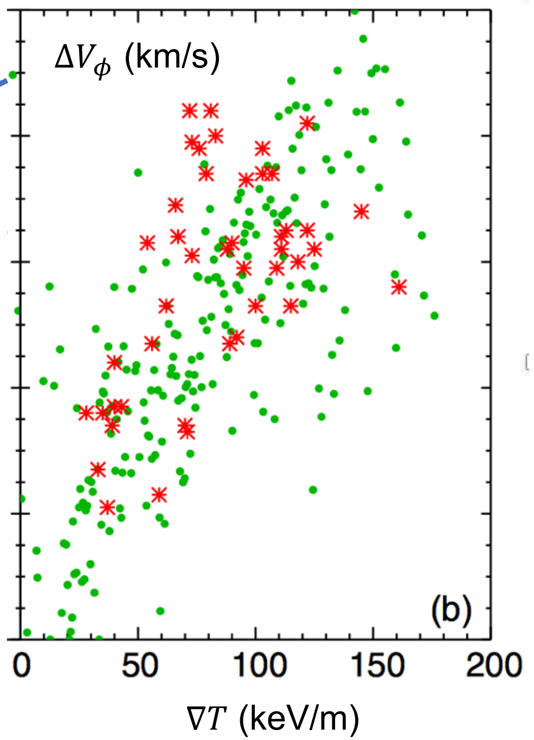
Diffusion Pinch

- Momentum diffusion and pinch cannot serve as a momentum source
- $\nabla \cdot \Pi_{r\phi}^{Res}$ constitutes intrinsic force driving parallel flow
- $\Pi_{r\phi}^{Res}$ depends on turbulence, so $\Pi_{r\phi}^{Res} \propto$ free energy source

Evidence for residual stress driven flow: Macroscopic







'Cancellation' experiments in DIII-D show substantial intrinsic torque at edge

[Solomon, NF 2009]

Heat engine model:

Heating $\Rightarrow \nabla T \Rightarrow \Pi_{r\phi}^{Res} \Rightarrow V_\phi'$

[Kosuga, PoP 2010]

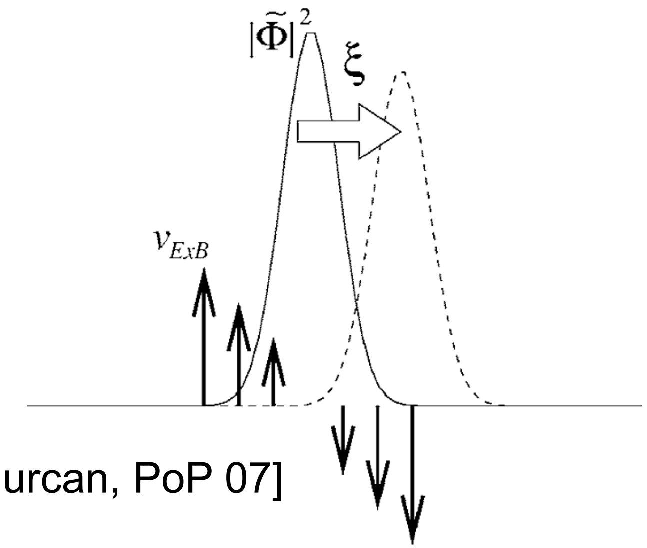
In C-Mod, $\Delta V_\phi \propto \nabla T_i$ in H-and I-mode plasmas

[Rice, PRL 2011]

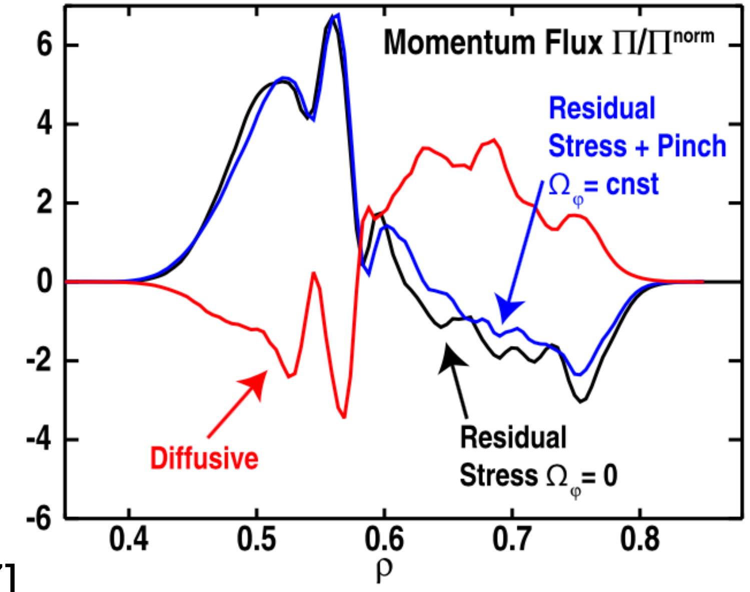
Evidence for residual stress: Micro-turbulence

- Finite $\Pi_{r\phi}^{Res}$ requires symmetry breaking $\langle k_\theta k_\phi \rangle \neq 0$
- $\langle k_\theta k_\phi \rangle \neq 0$ can be induced by E_r'
- TJ-II: parallel turbulent force, $-\nabla_r \langle \tilde{v}_r \tilde{v}_\phi \rangle$, increases w/ density [Goncalves PRL 06]
- TEXTOR: significant $\Pi_{r\phi}^{Res}$; E_r' threshold for triggering $\Pi_{r\phi}^{Res}$ [Xu, NF 13]
- GK simulations predicts dipolar structure of $\Pi_{r\phi}^{Res}$ consistent w/ measured rotation profile in DIII-D

Macro V_ϕ' $\overset{?}{\longleftrightarrow}$ Micro $\Pi_{r\phi}^{Res}$ $\overset{?}{\longleftrightarrow}$ $\langle k_\theta k_\phi \rangle \neq 0$



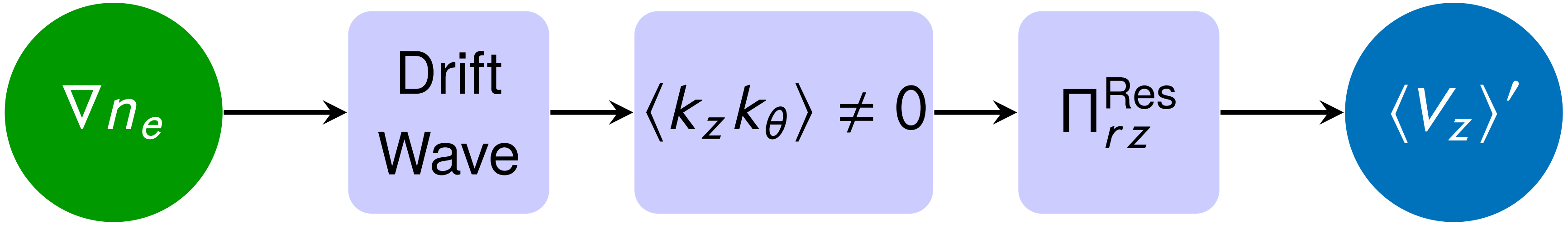
[Gurcan, PoP 07]



[Wang, PoP 17]

Tracing the Micro → Macro connection

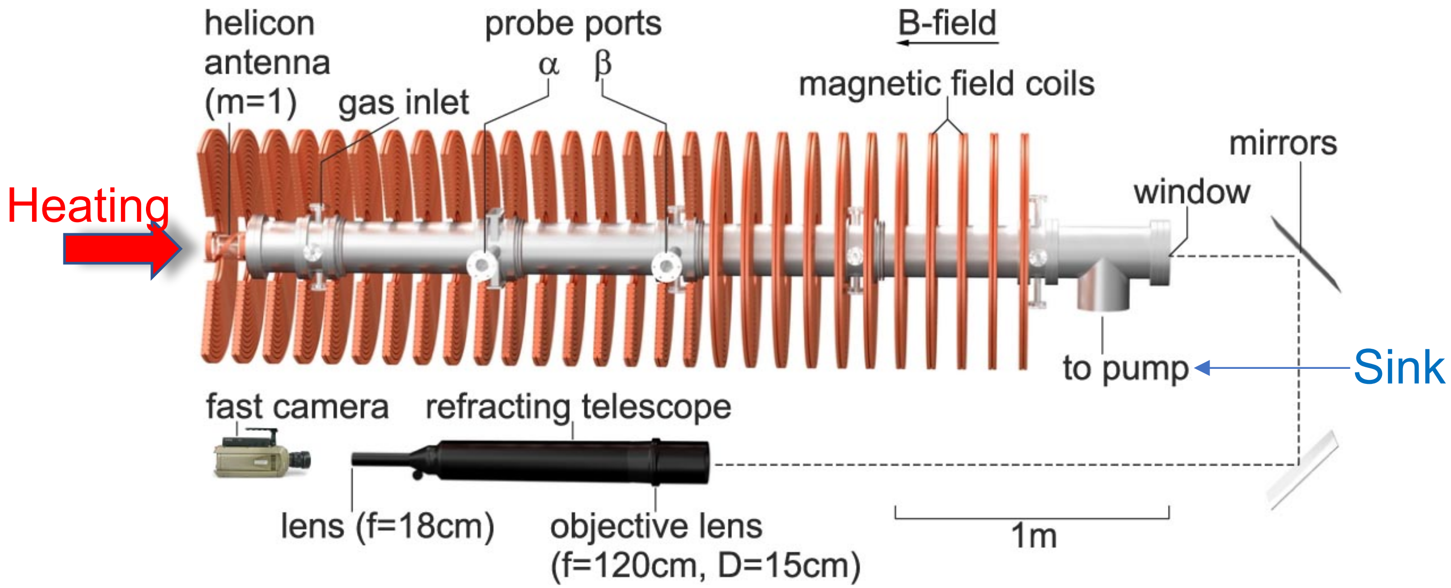
- Trace the pathway from **symmetry breaking** to **development of residual stress** and thus **onset of sheared parallel mean flow**



- Fundamental issues of intrinsic flow study in linear plasma devices
  - Does turbulence drive parallel flow in a linear plasma device?
  - Connection between free energy source and turbulent drive?
  - Is there direct evidence linking symmetry breaking to finite residual stress?

Experimental Setup—CSDX

- Straight, uniform magnetic field in axial direction
- Argon plasma produced by RF helicon source, P_{rf}=1.8 kW with 2 mtorr
- *Insulating* endplate avoid strong sheath current
- Diagnostics: Combined Mach and Langmuir probe array



CSDX: Promising testbed for drift-wave physics

Parameters	Tokamak Boundary	CSDX
$\rho_* = \rho_s/L_n$	~ 0.1	~ 0.3
$k_\parallel^2 v_{te}^2/\omega\nu_e$	$\sim 0.5 - 5$	$1 - 3$
λ_{ei}/L_{conn}	$\lesssim 1$	$\sim 0.1 - 0.3$
l_{cor}/ρ_s	$\lesssim 1$	~ 1

- Some dimensionless parameters show similarity between linear device and Tokamak SOL region
- CSDX can serve as a testbed for studying drift-wave-driven residual stress and intrinsic axial flow

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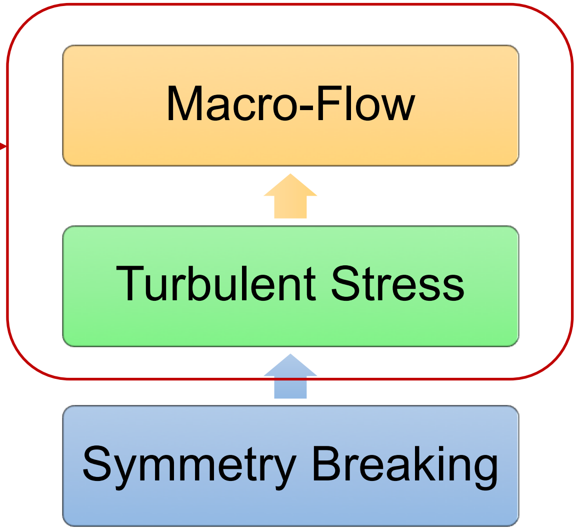
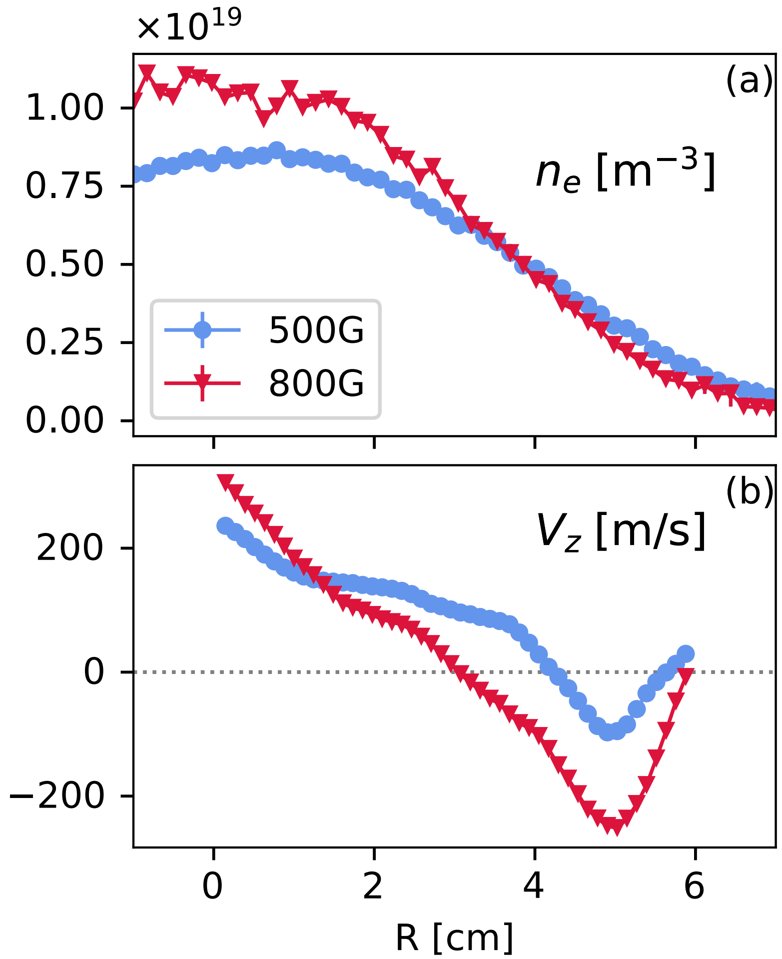
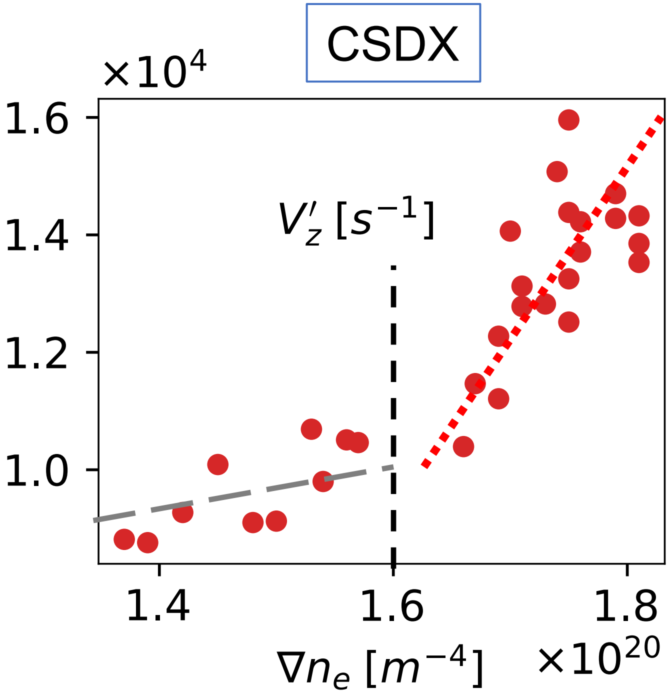


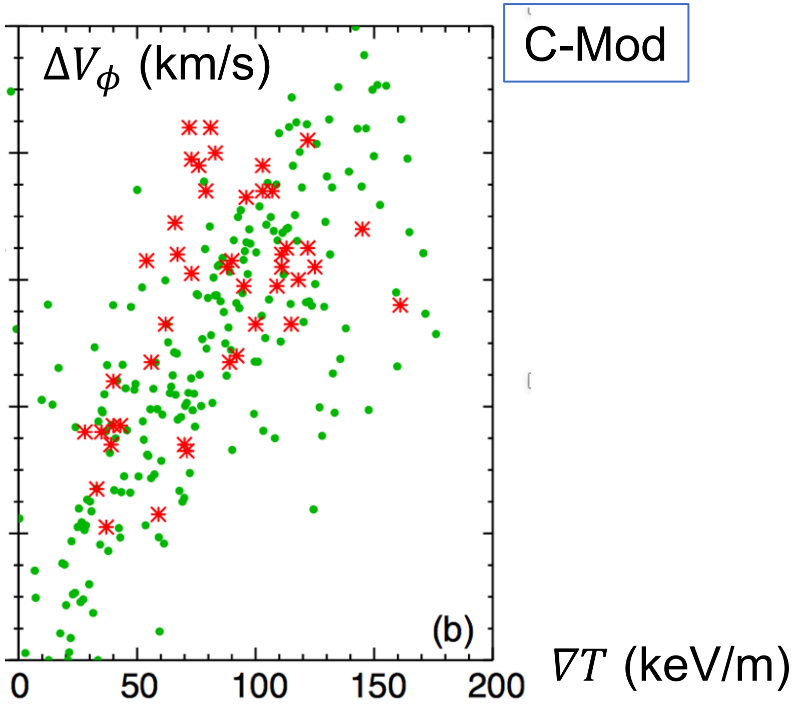
Axial flow shear scales w/ ∇n—free energy source

- Obtain different profiles by varying B field strength
- Steepened density gradient with higher B
- V_z shear increases with increasing ∇n as B is raised
- $L_n^{-1} \gg L_{T_e}^{-1} \Rightarrow \nabla n$ is primary free energy source
- *Question:* Connection between ∇n and V_z'? *(Rice scaling)*



Axial flow shear tracks ∇n—free energy source





- Existence of ∇n threshold at $\sim 1.6\times10^{20}$ m^{-4}
- V_z' increases sharply with ∇n after the threshold
- Reproduce a Rice-like scaling—Intrinsic flow ∝ free energy source
- *Question*: Connection to turbulence?

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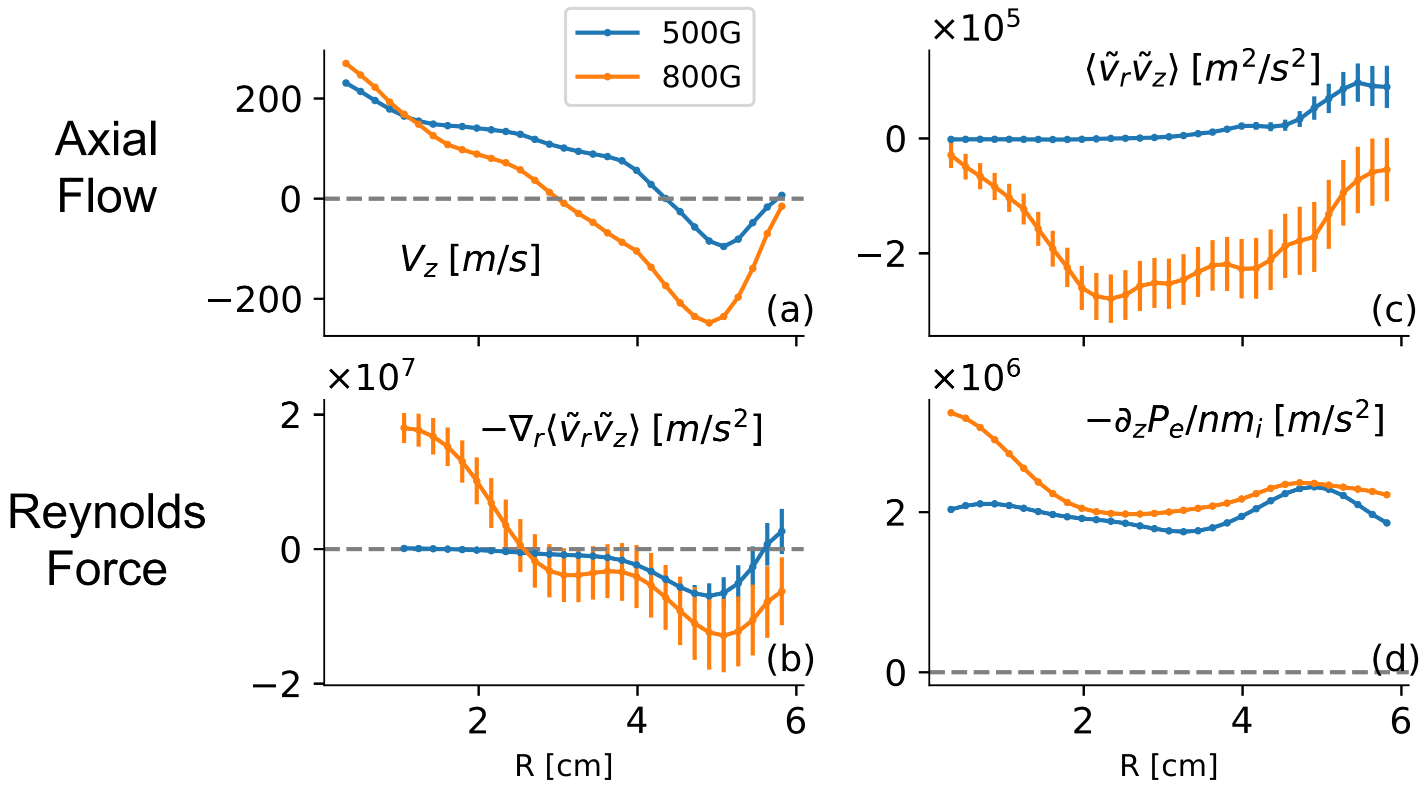
Axial flow is driven by turbulent force



- V_z shear increases and *reverses* at edge
- $\langle\tilde{v}_r\tilde{v}_z\rangle$ shows strong inward momentum flux at higher B and ∇n
- Reynolds force $F_z^{Re} = -\nabla_r\langle\tilde{v}_r\tilde{v}_z\rangle$ increases and reverses V_z at edge
- $-\nabla_r\langle\tilde{v}_r\tilde{v}_z\rangle$ is about ×5 larger than force due to axial pressure drop

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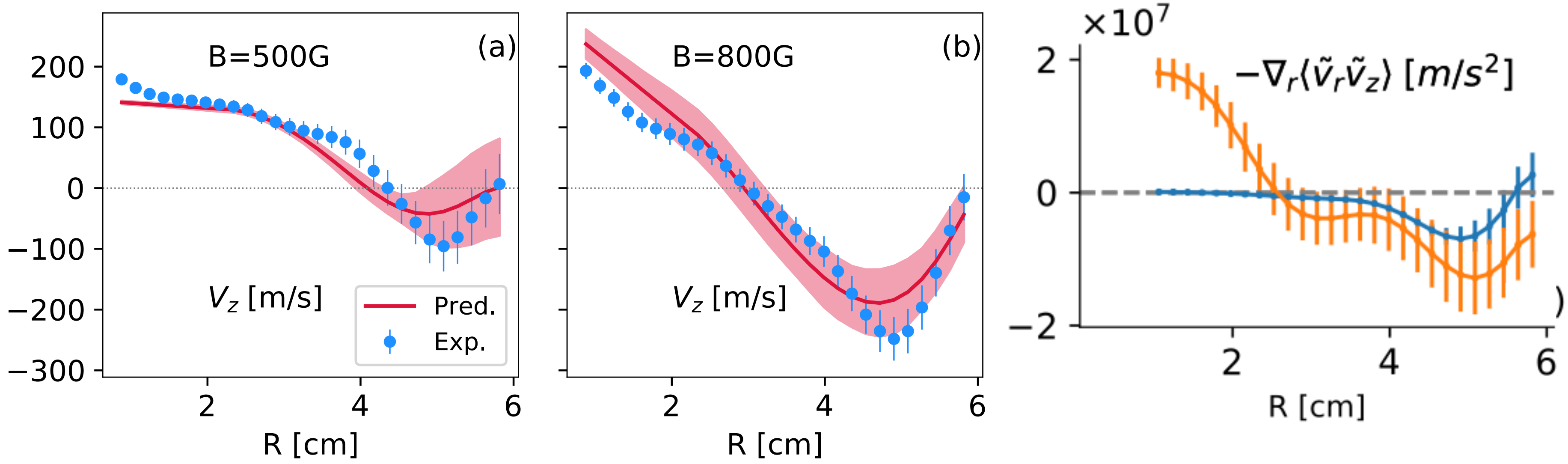
Reynolds force + Collisional damping ⇒ V_z profile



$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\langle\tilde{v}_z\tilde{v}_r\rangle\right) = -\frac{1}{m_i\langle n\rangle}\frac{\partial P_e}{\partial z} - \nu_{in}V_z + \frac{1}{r}\frac{\partial}{\partial r}\left(\mu_{ii} r\frac{\partial V_z}{\partial r}\right)$$

- Ion momentum equation used to calculate V_z profile w/ no-slip b.c.
- Calculated V_z profiles agree with measured ones
- $\nu_{in} = n_{gas}v_{ti}\sigma_{in} \sim 3 - 6\times10^3$ s^{-1} and $\mu_{ii} = \frac{6}{5}\rho_i^2\nu_{ii} \sim 3 - 5$ m^2/s
- Coefficients may have small spatial variations: $\nu_{in} \propto T_i^{-1/2}$ and $\mu_{ii} \propto nT_i^{-1/2}$

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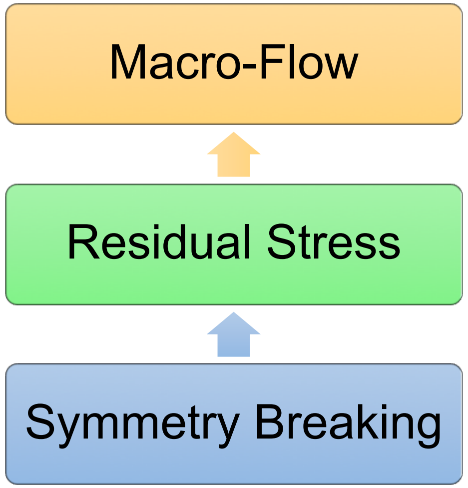


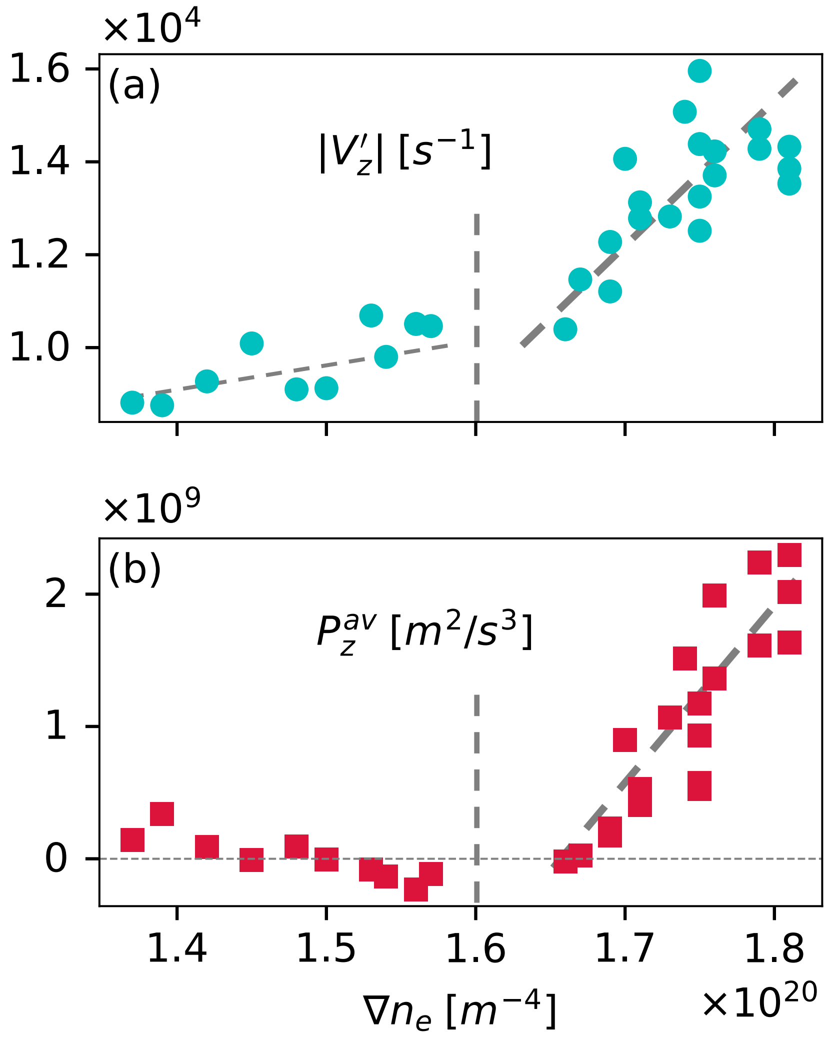
Axial Reynolds power tracks ∇n

- Reynolds power $P_z^{Re} = -V_z \nabla_r \langle \tilde{v}_r \tilde{v}_z \rangle$ measures nonlinear energy transfer into shear flow
- When P_z^{Re} is negligible, V_z' is driven by axial pressure drop

- P_z^{Re} *tracks* ∇n after threshold exceeded
- Axial flow shear V_z' also increases with ∇n

Free energy ⇒ Turbulence ⇒ Intrinsic flow

$\nabla n \Rightarrow P_z^{Re} \Rightarrow V_z'$



Synthesize residual stress

- Reynolds stress is written as

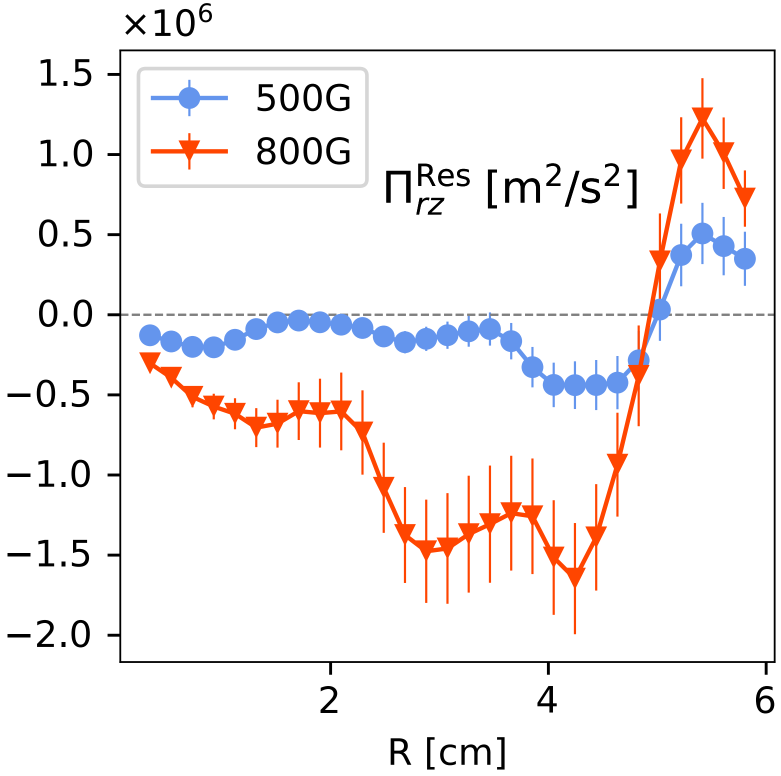
$$\langle \tilde{v}_r \tilde{v}_z \rangle = -\chi_z V_z' + V_p V_z + \Pi_{rz}^{Res}$$

- Pinch ($V_p V_z$) arises from toroidal effects, irrelevant in linear machine

- Synthesize residual stress

$$\Pi_{rz}^{Res} = \langle \tilde{v}_r \tilde{v}_z \rangle + \langle \tilde{v}_r^2 \rangle \, \tau_c \, V_z'$$

- Larger residual stress at higher B field
- *Question:* Link Π_{rz}^{Res} to ∇n?



Link residual stress to ∇n: A simple model

- Parallel velocity fluctuation written as

$$\frac{\partial \tilde{v}_z}{\partial t} = -c_s^2 \nabla_z \left(\frac{e\tilde{\phi}}{T} + \frac{\tilde{P}}{P_0} \right) - \tilde{v}_r \frac{\partial V_z}{\partial r}$$

- With adiabatic electrons, $\frac{e\tilde{\phi}}{T} \sim \frac{\tilde{n}}{n_0}$ and $\frac{\tilde{P}}{P_0} \sim \frac{\tilde{n}}{n_0}$, one obtains

$$\tilde{v}_z \approx -\sigma_{vT} \tau_c \frac{c_s^2}{L_z} \frac{\tilde{n}}{n_0} - \tilde{v}_r \tau_c \frac{\partial V_z}{\partial r}$$

- Using mixing length theory, $\tilde{n} \sim l_c |\nabla_r n_0|$, where $l_c \sim \tilde{v}_r \tau_c$

$l_c \sim \rho_s$ in CSDX

$$\tilde{v}_z \approx -\sigma_{vT} \tau_c \frac{c_s^2}{L_z} \frac{l_c}{n_0} |\nabla_r n_0| - \tilde{v}_r \tau_c \frac{\partial V_z}{\partial r}$$

- Reynolds stress becomes

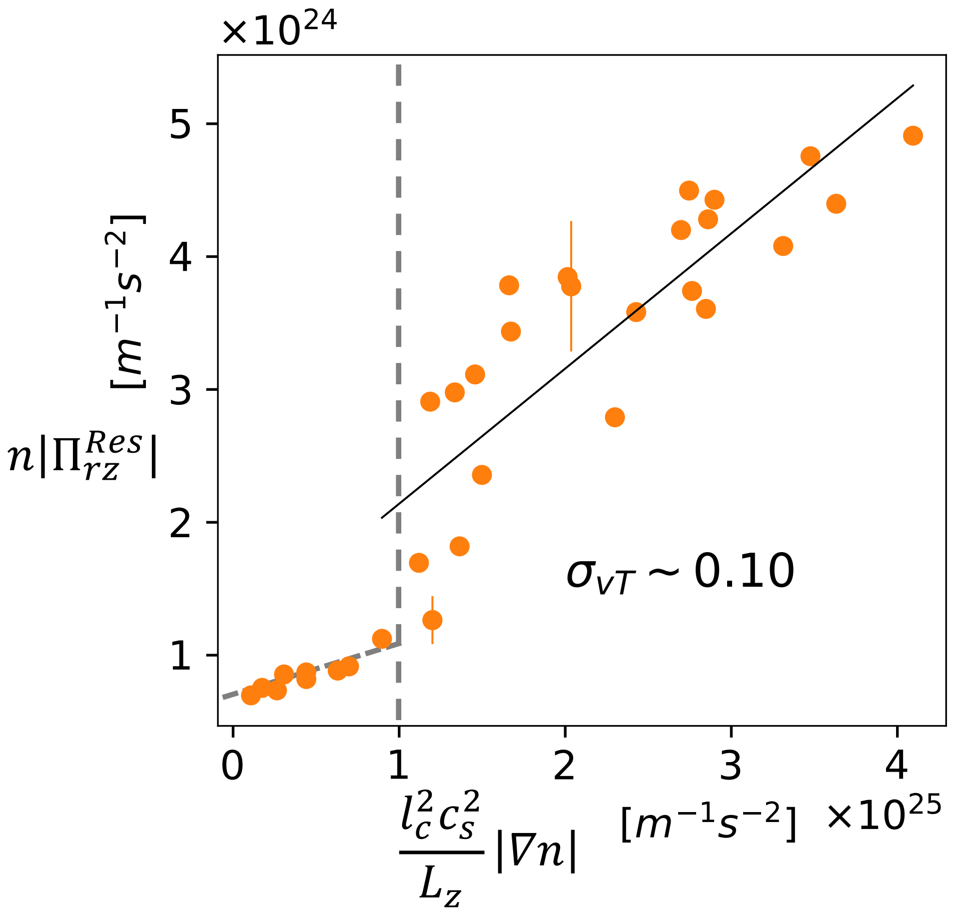
$$\langle \tilde{v}_r \tilde{v}_z \rangle \approx -\sigma_{vT} \frac{c_s^2}{L_z} \frac{l_c^2}{n_0} |\nabla_r n_0| - \langle \tilde{v}_r^2 \rangle \tau_c \frac{\partial V_z}{\partial r}$$

Residual Stress — Diffusive term

σ_{vT} quantifies degree of symmetry breaking

Residual stress scales with ∇n

- Use synthesized residual stress
$$\Pi_{rz}^{Res} = \langle \tilde{v}_r \tilde{v}_z \rangle + \langle \tilde{v}_r^2 \rangle \, \tau_c \, V_z'$$
- At lower ∇n, Π_{rz}^{Res} independent of ∇n (i.e. $\sigma_{vT} \to 0$)
- At higher ∇n, Π_{rz}^{Res} increases with ∇n
- Least-square fit gives $\sigma_{vT} \sim 0.1$ at larger ∇n
- Π_{rz}^{Res} is determined by density gradient



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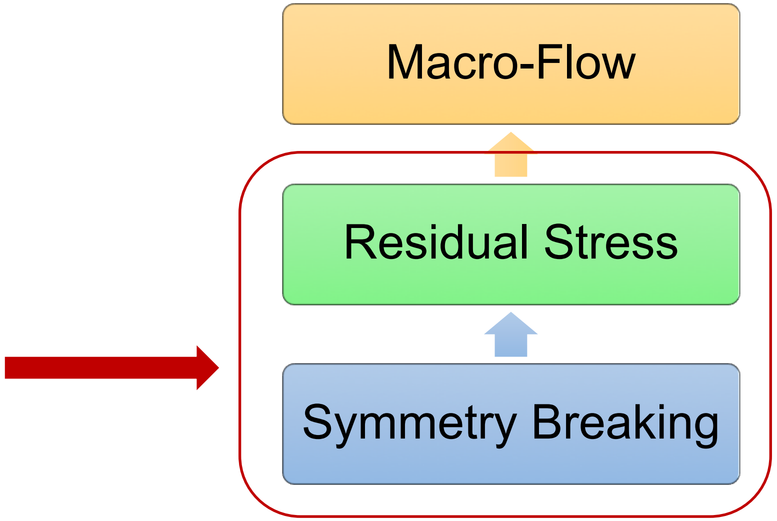
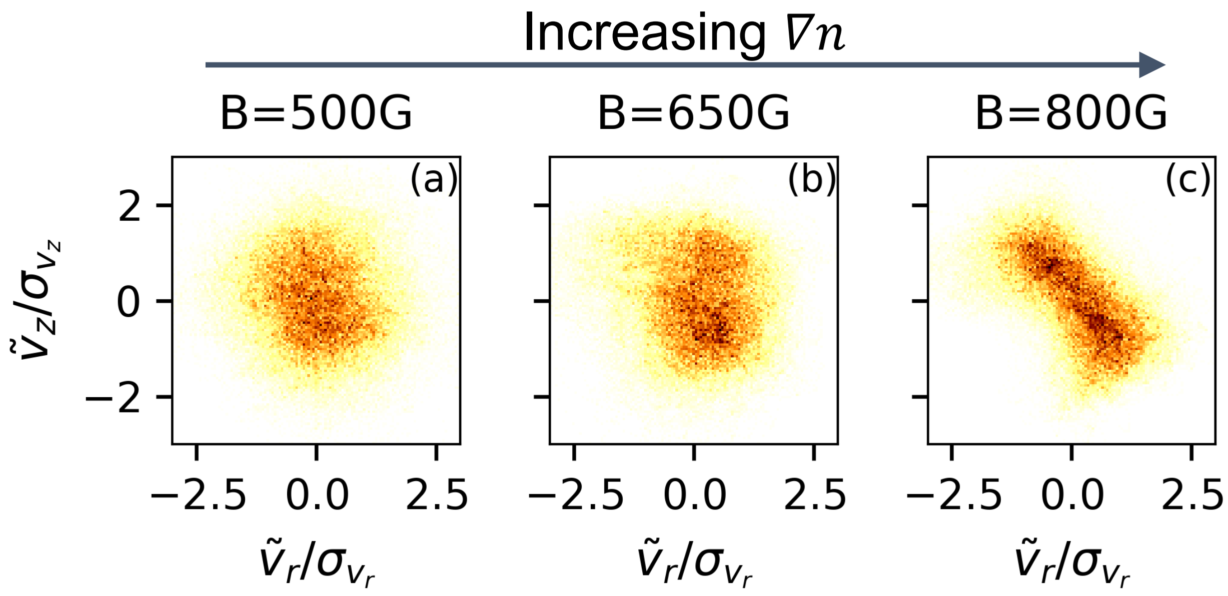


Demonstrate spectral asymmetry



- Joint PDF $P(\tilde{v}_r, \tilde{v}_z)$ empirically represents spectral correlator $\langle k_\theta k_z \rangle$
  - $\tilde{v}_r \sim k_\theta \tilde{\phi}$ and $\tilde{v}_z \sim k_z \tilde{P} \sim k_z \tilde{\phi}$ for adiabatic plasma
- $P(\tilde{v}_r, \tilde{v}_z)$ is isotropic at lower ∇n; anisotropic and elongated at higher ∇n
- Evidence for symmetry breaking $\langle k_\theta k_z \rangle \neq 0$ which implies a finite residual stress

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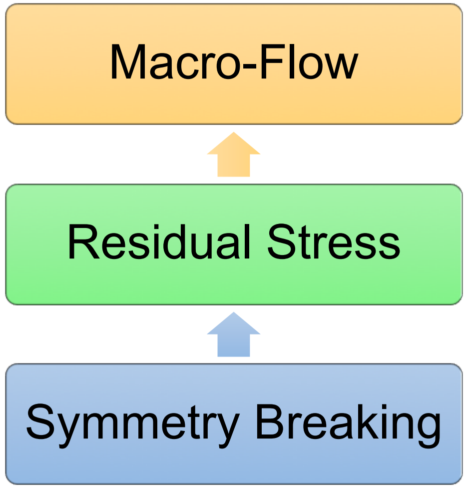


Towards a theory of symmetry breaking

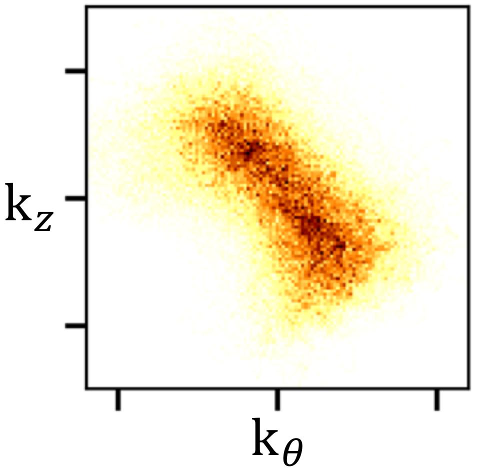
- General theory of intrinsic flow: analogy to heat engine [Kosuga PoP 10]
  - Heating $\Rightarrow \nabla T \Rightarrow \Pi_{rz}^{Res} \Rightarrow V_z'$
  - Finite Π_{rz}^{Res} needs symmetry breaking $\langle k_\theta k_z \rangle \neq 0$
- In tokamaks, symmetry breaking relies on magnetic shear
  - $k_z \sim \frac{k_\theta x}{L_s} \Rightarrow \langle k_\theta k_z \rangle \rightarrow k_\theta^2 \langle x \rangle / L_s$
- In CSDX, uniform axial B field and *no* magnetic shear
- Dynamical symmetry breaking model [Li et al, PoP 16]
  - No requirement for magnetic shear
  - Analogy to zonal flow generation via modulational instability

Dynamical symmetry breaking

- DW growth rate and frequency shift:

$$\omega_k \cong \frac{\omega_*}{1+k_\perp^2\rho_s^2} - \frac{k_\theta k_z \rho_s c_s \langle v_z\rangle'}{\omega_*}$$

$$\gamma_k \cong \frac{\nu_{ei}}{k_z^2 v_{The}^2}\frac{\omega_*^2}{(1+k_\perp^2\rho_s^2)^2}\left(\frac{k_\perp^2\rho_s^2}{1+k_\perp^2\rho_s^2} + \frac{k_\theta k_z \rho_s c_s \langle v_z\rangle'}{\omega_*^2}\right)$$



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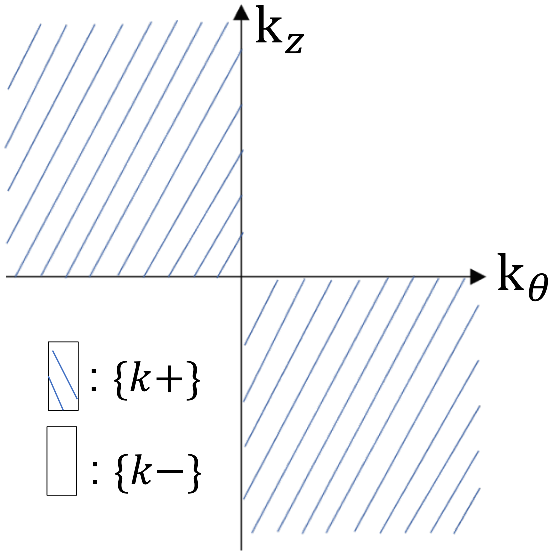


modes in shaded domains grow faster

- Spectral imbalance:

Infinitesimal test axial flow shear, e.g. $\delta\langle v_z\rangle' < 0$

Modes with $k_\theta k_z < 0$ grow faster than other modes,

$\gamma_k|_{k_\theta k_z<0} > \gamma_k|_{k_\theta k_z>0}$

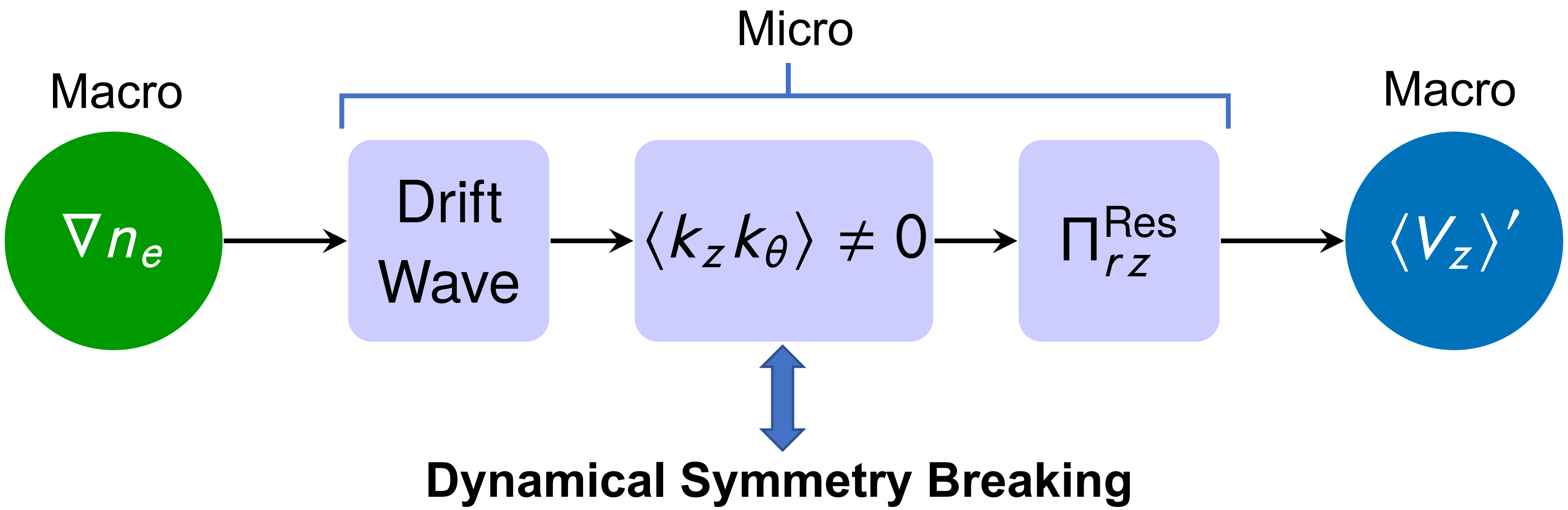
Spectral imbalance in $k_\theta k_z$ space

$\langle k_\theta k_z\rangle < 0 \rightarrow \Pi_{rz}^{Res} \neq 0$

[Li et al, PoP 16]

Conclusion: Macro-Micro connection

- Axial flow is driven by turbulent stress
- Both axial flow shear and Reynolds power tracks ∇n
- Residual stress Π_{rz}^{Res} scales with ∇n
- Demonstrate direct link between symmetry breaking and residual stress
- Finite Π_{rz}^{Res} at zero magnetic shear emerges from dynamical symmetry breaking

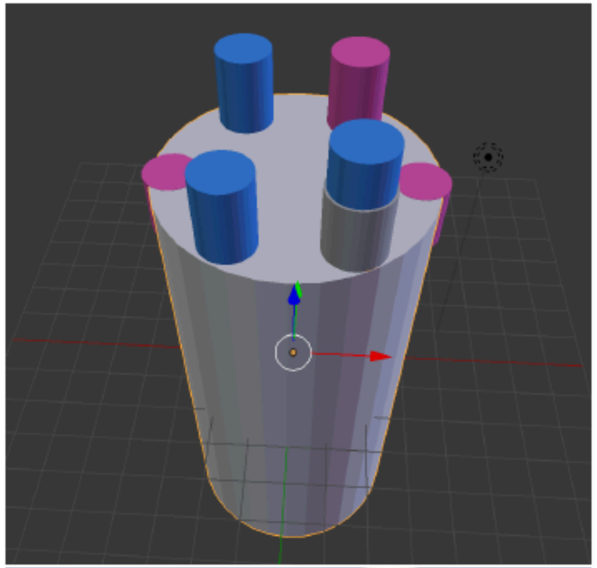


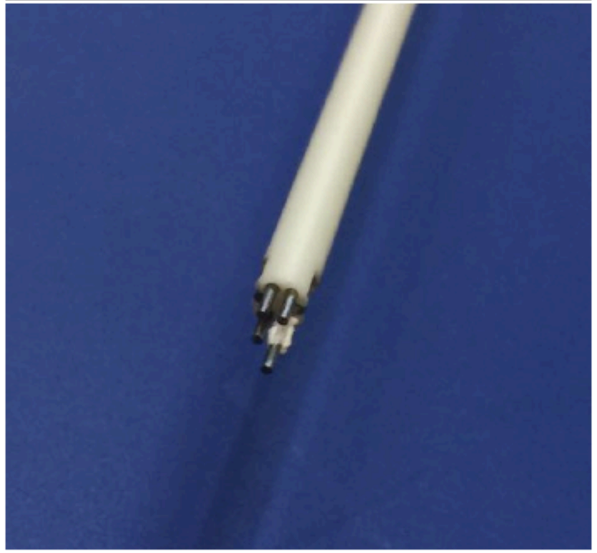
Thank You

Probe configuration

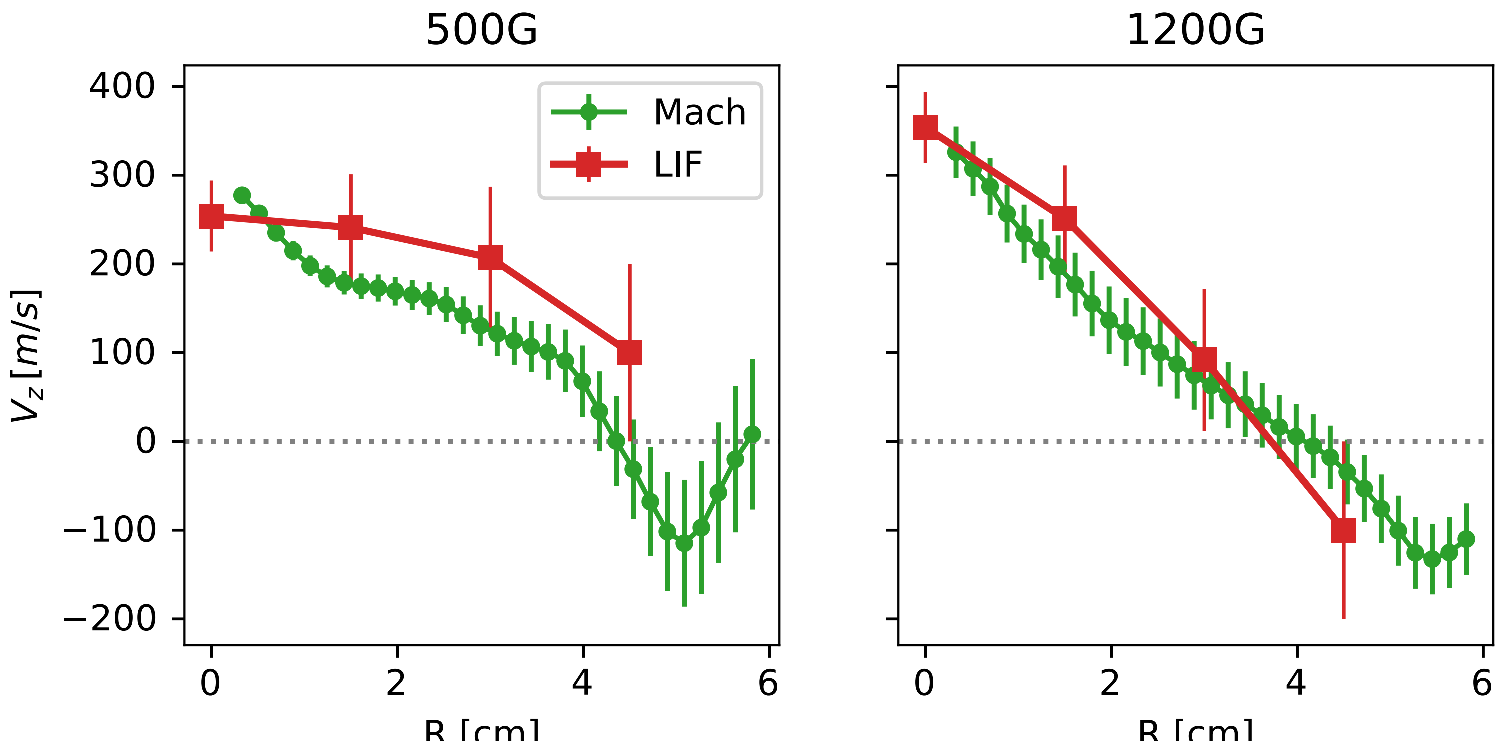
Combined Mach and Langmuir probe array

- $I_{s,i}$ (pink) and ϕ_{fl} (blue)
- $v_z = 0.45 c_s \ln \dfrac{\Gamma_{\mathrm{up}}}{\Gamma_{\mathrm{dn}}}$
- $\tilde{v}_r = -\dfrac{1}{B}\dfrac{\Delta\tilde{\phi}_{\mathrm{fl}}}{dy}$ and $\tilde{v}_\theta = \dfrac{1}{B}\dfrac{\Delta\tilde{\phi}_{\mathrm{fl}}}{dx}$
- $n_e = \dfrac{I_{\mathrm{is}}}{0.5 e c_s A}$
- Measure $\langle \tilde{v}_z \tilde{v}_r \rangle$ and $\langle \tilde{v}_\theta \tilde{v}_r \rangle$ profiles simultaneously

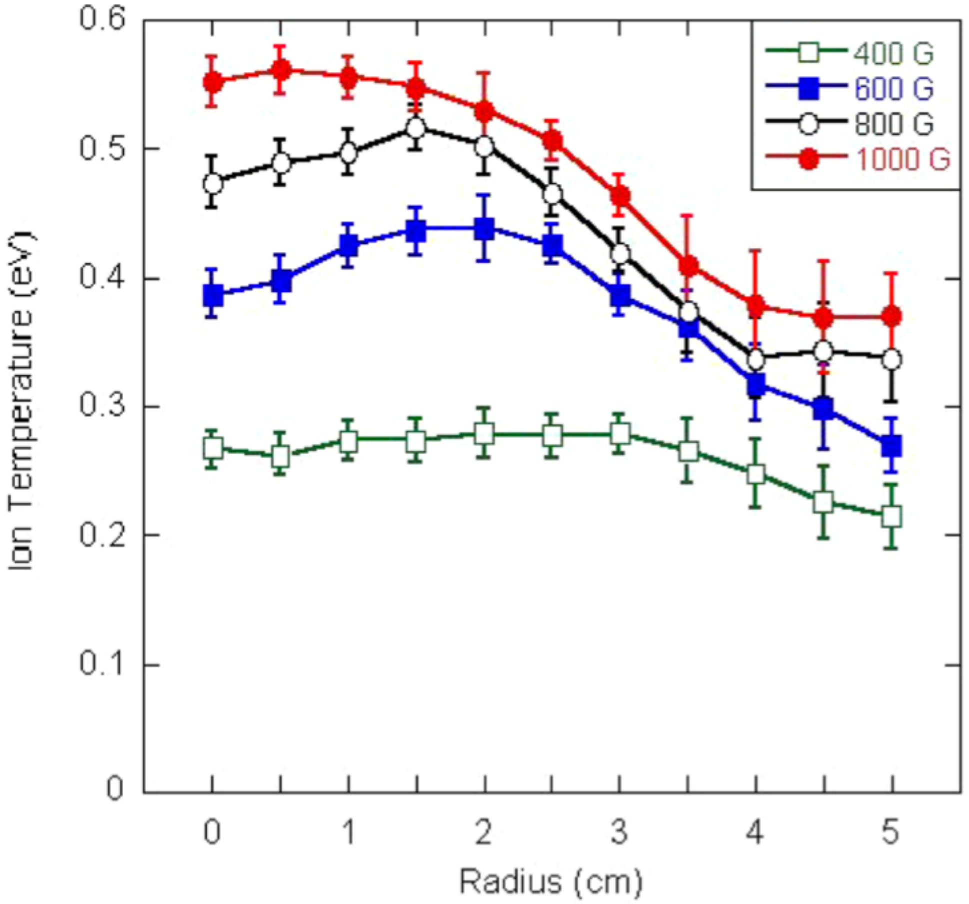




LIF vs Mach probe measurement



Ion temperature profile



Residual stress profiles