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Authors
Long, T
Diamond, P
Xu, M
et al.

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Studies of Reynolds Stress and the Turbulent Generation of Edge Poloidal Flows on the HL-2A Tokamak

T. Long\textsuperscript{1}, P.H. Diamond\textsuperscript{1,2}, M. Xu\textsuperscript{1}, R. Ke\textsuperscript{1}, L. Nie\textsuperscript{1} and HL-2A team

\textsuperscript{1} Southwestern Institute of Physics, Chengdu, China
\textsuperscript{2} University of California, San Diego, California, USA

E-mail: longt@swip.ac.cn
Outline

Motivation

Experimental set up

Poloidal rotation and Reynolds Stress
  Rotation and its deviation from neoclassical
  Decomposition of Reynolds stress
  Discussion on residual stress vs adiabatic parameter

Beyond the quasi-gaussian Ansatz
  PDF statistics of Reynolds stress
  Discussion on cross phase and coherence

Summary
Motivation

The theory of turbulence effects on poloidal flow via turbulent flux of momentum—Reynolds stress--has been studied and widely validated in the fusion community, since it was first proposed.

P. H. Diamond et al., 1991 Physics of Fluids B

- Poloidal flow can shift relatively to its neoclassical value, if $\partial_r \langle \tilde{v}_r \tilde{v}_\theta \rangle \neq 0$

$$\mu_{ii}^{(\text{neo})} (\langle v_\theta \rangle - \langle v_\theta \rangle_{\text{neo}}) = -\partial_r \langle \tilde{v}_r \tilde{v}_\theta \rangle$$

C.J. McDevitt et al., 2010 POP

- $\langle v_\theta \rangle_{\text{neo}}$ by KDG model & viscous damping rate

$$v_{\theta i,\text{neo}} = \frac{B_\phi K^i T_i L_{T_i}^{-1}}{Z_i e_i B^2} \quad \mu_{ii}^{(\text{neo})} \equiv \frac{1}{\tau_{ii}} \frac{\langle B^2 \rangle}{B^2} \mu_{00}$$

Y.B. Kim et al., 1991 Physics of Fluids B

- The Reynolds stress can be expressed in the form:

$$\langle \tilde{v}_r \tilde{v}_\theta \rangle = -\chi_\theta \frac{\partial \langle v_\theta \rangle}{\partial r} + v_{r,\text{eff}}^\text{eff} \langle v_\theta \rangle + \Pi_{r\theta}^{\text{Res}}$$

Ö. D. Gürcan et al., 2007 POP
Experimental set up

- A specially designed **Langmuir probe** array on the outer mid-plane of HL-2A tokamak was used to do the main experimental measurement—

**Study Reynolds stress & turbulent generation of edge poloidal flows**

Potential and electric field

\[ \tilde{\phi}_f \sim \tilde{\phi}_p, \quad \vec{E} = -\nabla \phi_p \]

**ExB velocity**

\[ \tilde{v}_\theta = (\tilde{V}_{f,5} - \tilde{V}_{f,11})/2 \, d_r B_t \]
\[ \tilde{v}_r = (\tilde{V}_{f,09} - \tilde{V}_{f,07})/2 \, d_\theta B_t \]

**Electron temperature & density**

\[ T_e = (V_+ - V_f)/l \, n2 \]
\[ C_s = \sqrt{k \, T_e / m_i} \]
\[ I_{sat} = (V_- - V_+)/R_s \]
\[ n_e = I_{sat} / (0.61eA_{eff}C_s) \]
Rotation and its deviation from neoclassical

- A significant deviation on Ohmic and ECRH heating power L mode.
- With ECRH heating power, slope of Reynolds stress increases, **Relative Deviation** increases significantly.

\[
RD = - \frac{\partial_r \langle \tilde{v}_r \tilde{v}_\theta \rangle}{\mu_{ii}^{(\text{neo})} \langle v_\theta \rangle_{\text{neo}}} \sim \frac{\langle v_\theta \rangle - \langle v_\theta \rangle_{\text{neo}}}{\langle v_\theta \rangle_{\text{neo}}}
\]

- With ECRH heating power, slope of Reynolds stress increases, **Relative Deviation** increases significantly.

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**plateau regime**

\[ v_i^* \equiv \nu_{ii} q R / (v_{thi} \varepsilon^{3/2}) \sim 1 \]
Decomposition of Reynolds stress

- Contribution of these diffusive or non-diffusive stress to the turbulent generation of poloidal flows

\[
\langle \tilde{v}_r \tilde{v}_\theta \rangle = -\chi_\theta \partial_r \langle v_\theta \rangle + v_r^{\text{eff}} \langle v_\theta \rangle + S_{r\theta}^{\text{Res}}
\]

Reynolds stress \hspace{2cm} diffusive stress \hspace{2cm} convection stress \hspace{2cm} residual stress

\[v_r^{\text{eff}} \approx \frac{\chi_\theta}{R}\]  
A. G. Peeters et al., 2007 PRL

\[\chi_\theta = \langle \tilde{v}_r^2 \rangle \tau_{ac}\]  
Z. Yan et al., 2010 PRL

\[\chi_\theta \text{ and } D_n = -\frac{\langle \tilde{n} \tilde{v}_r \rangle}{\partial \langle n \rangle / \partial r}\]

"Frequency saturation" in \(\tau_{ac}\)
Diffusive stress and residual stress are of the same order as Reynolds stress.

- The poloidal intrinsic torque, \(-\partial_r(\Pi_{r\theta}^{\text{Res}})\), increases substantially with ECRH heating powers.
- Residual stress is a function of profiles of both density and temperature, which drive the turbulence.

\[
\Pi^R = \frac{\Gamma}{n_0} - \kappa_y v_d \\
v_d(x) = -d \ln n_0 / dx
\]

A. Ashourvan et al., 2016 POP
As a consequence of wave-flow momentum exchange, the residual stress drives an off-diagonal turbulent momentum flux and its divergence defines an intrinsic poloidal torque.

\[ \Pi_{r\theta}^{Res} = \Pi_{r\theta}^{Res} (\nabla T, \nabla n) \quad \text{torque} = - \partial_r (\Pi_{r\theta}^{Res}) \]

Gradients drive rotation via \( \Pi_{r\theta}^{Res} \)
- heating power, \( \nabla T \) drives the turbulence, leading to profile relaxation and the generation of flow via turbulent stresses

A car engine burns fuel, converts thermal energy liberated into kinetic energy of a rotating wheel.

Y. Kosuga et al. 2010 POP
Discussion on residual stress vs adiabatic parameter

- **Adiabatic parameter —— (non-) adiabatic electron response**

\[ \alpha = \frac{k_{\parallel}^2 \nu_{th}^2}{v_{ei} |\omega|} \]

| \( |\omega| \) is the frequency of the Drift wave unstable mode |

**TABLE I.** Scalings of the turbulent enstrophy \( \epsilon \), transport fluxes, and vorticity gradient with \( \alpha \) in both adiabatic and hydrodynamic regimes.

| Plasma response | Adiabatic \( \alpha \gg 1 \) | Hydrodynamic \( \alpha \ll 1 \) |
|-----------------|-----------------|-----------------|
| Turbulent viscosity | Equation (20b) | Equation (24b) |
| \( \chi_y \) | \( \chi_y \propto 1/\alpha \) | \( \chi_y \propto 1/\sqrt{\alpha} \) |
| Residual stress | Equation (20c) | Equation (24c) |
| \( \Pi^{res} \): Residual vorticity flux | \( \Pi^{res} \propto -1/\alpha \) | \( \Pi^{res} \propto -\sqrt{\alpha} \) |
| \( \frac{\Pi^{res}}{\chi_y} = (\omega_{ci} \nabla \tilde{n}) \times \) | \( \left( \frac{\alpha}{|\omega^*|} \right)^0 \) | \( \left( \frac{\alpha}{|\omega^*|} \right) \) |

The dominant modes may switch from adiabatic drift waves to non-adiabatic resistive driven modes.

R. J. Hajjar et al., 2018 POP

Experimental study and validation in near future.
Beyond the quasi-gaussian Ansatz

- Virtually all models of turbulent momentum transport are based on quasi-gaussian (quasilinear models), we explore statistics of edge Reynolds stress.

Skewness: asymmetry of the tail
Kurtosis: tail in general

\[ s = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^3}{\sigma^3} \quad \kappa = \frac{\nu_4}{\sigma^4} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^4}{\sigma^4} \]

Table 1  Skewness and kurtosis with/out ECRH heating at 1.5 cm inside LCFS

| ECRH (kW) | \( \bar{\nu}_r \bar{\nu}_\theta \) | \( \bar{\nu}_r \) | \( \bar{\nu}_\theta \) | \( \bar{\nu}_r \bar{\nu}_\theta \) | \( \frac{e\phi_f}{T_e} \) | \( \left( \frac{e\phi_f}{T_e} \right)^2 \) |
|-----------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0         | 0.3              | 3.4             | 3.3             | 12.4            | 3.2             | 9.9             |
| 700       | 0.9              | 3.1             | 3.3             | 14.8            | 3.1             | 9.4             |

Strongly non-Gaussian dynamics regulate poloidal momentum transport. → Avalanches of poloidal momentum?
Beyond the quasi-gaussian Ansatz

- Deviation from Gaussian suggests the consideration of:
  - Validity of quasilinear models of edge turbulence transport
  - Coherence and phase dynamics between $\tilde{v}_r$ and $\tilde{v}_\theta$

Hurst exponent of "coherence cross phase" $\frac{\tilde{v}_r \tilde{v}_\theta}{|\tilde{v}_r| |\tilde{v}_\theta|}$

Hurst exponent of potential perturbation is ~0.85

$H=1/2$, random walk, occurs in Brownian motion;
$0<H<1/2$, the dynamics exhibit rapid switching between high and low values, temporal anticorrelation
$1/2<H<1$, the dynamics manifest a sustained memory, and positive correlation in time, long-term persistence.

General (left) & cumulated(right) structure function method
Y. H. Xu et al., 2004 POP
Discussion on cross phase and coherence

➢ Coherence and phase dynamics between $\tilde{v}_r$ and $\tilde{v}_\theta$

$$\langle \tilde{v}_r \tilde{v}_\theta \rangle = \langle |\tilde{v}_r|^2 \rangle^{1/2} \cdot \langle |\tilde{v}_\theta|^2 \rangle^{1/2} \cdot X_{factor}$$

In frequency domain,

$$X_{factor} \equiv \gamma_{\tilde{v}_r \tilde{v}_\theta} \cos \varphi_{\tilde{v}_r \tilde{v}_\theta}$$

Strong shear layer, cross phase is randomly scattered—“incoherent phase slips”. Reynolds stress is determined by cross phase dynamics. Weak shear region, cross phase stays in a coherent state—“phase locked state”, turbulence fluctuation and coherence are more important.

Our next step:
Study the coherence and cross phase in frequency domain
Compare with the results in time domain

D. Guo et al., 2018 Nuclear Fusion
• Significant deviation of mean poloidal flow from the neoclassical value is deduced.
• The deviation increases with heating power.
• Both diffusive and non-diffusive stresses contribute to the deviation.
• The turbulent poloidal viscous flux and residual stress are synthesized using fluctuation data.
• The turbulent poloidal viscosity is comparable to the turbulent particle diffusivity.
• The residual stress increases with heating power and exhibits a sharper gradient for higher powers.
• The PDFs of both Reynolds stress exhibit fat tails and large kurtosis, suggesting non-Gaussian processes control momentum transport.
• It’s significant that Reynolds stress has non-Gaussian features, despite the fact that momentum transport is a secondary process.

• Experimental study of scaling of residual stress with adiabatic parameter will be conducted soon.
• Further study of coherence and phase dynamics via Hurst parameter and in frequency domain has been planned.
Thanks for your attention!