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

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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 $\partial_{\mathrm{r}}\langle\tilde{\mathrm{v}}_{\mathrm{r}}\tilde{\mathrm{v}}_{\theta}\rangle \neq 0$

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

C.J. McDevitt et al., 2010 POP

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

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

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

- The Reynolds stress can be expressed in the form:

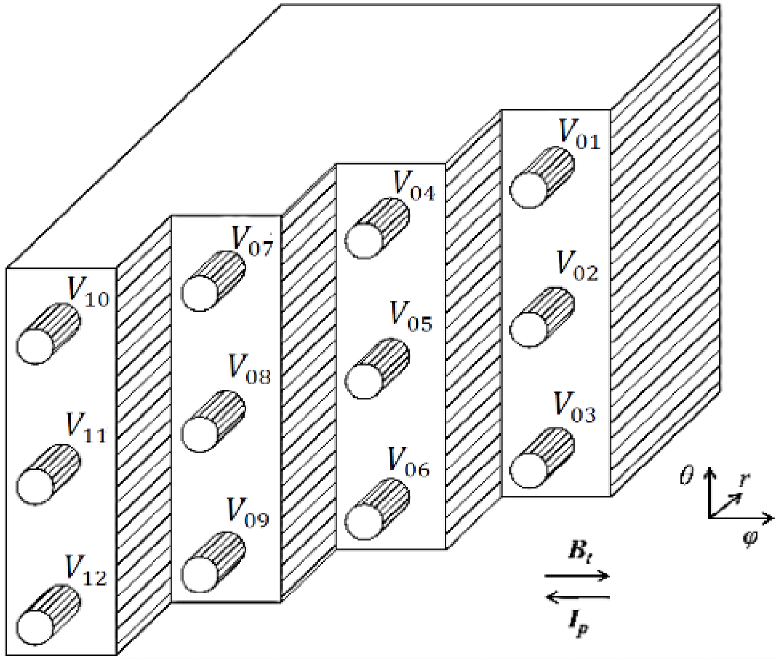
$$\langle\tilde{v}_r\tilde{v}_\theta\rangle = -\chi_\theta\frac{\partial\langle v_\theta\rangle}{\partial r} + v_r^{eff}\langle v_\theta\rangle + \Pi_{r\theta}^{Res}$$

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

$$\tilde{\phi}_f \sim \tilde{\phi}_p,\ \vec{E} = -\nabla \phi_p$$

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

$$T_e = (V_+ - V_f)/ln2$$

$$C_s = \sqrt{k T_e / m_i}$$

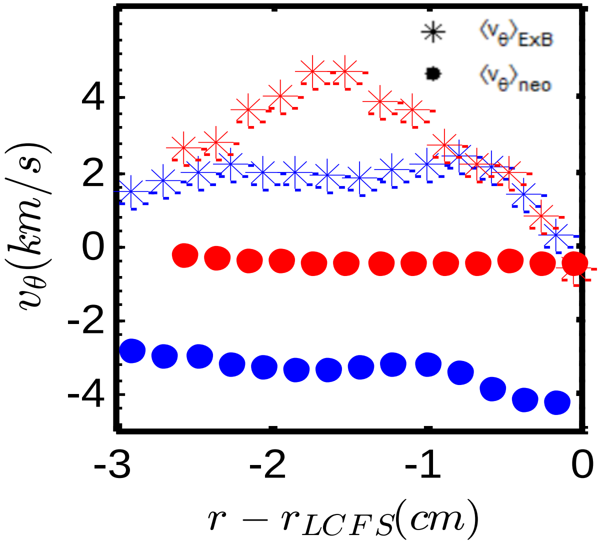
$$I_{sat} = (V_- - V_+)/R_s$$

$$n_e = I_{sat}/(0.61 e A_{eff} C_s)$$

Rotation and its deviation from neoclassical

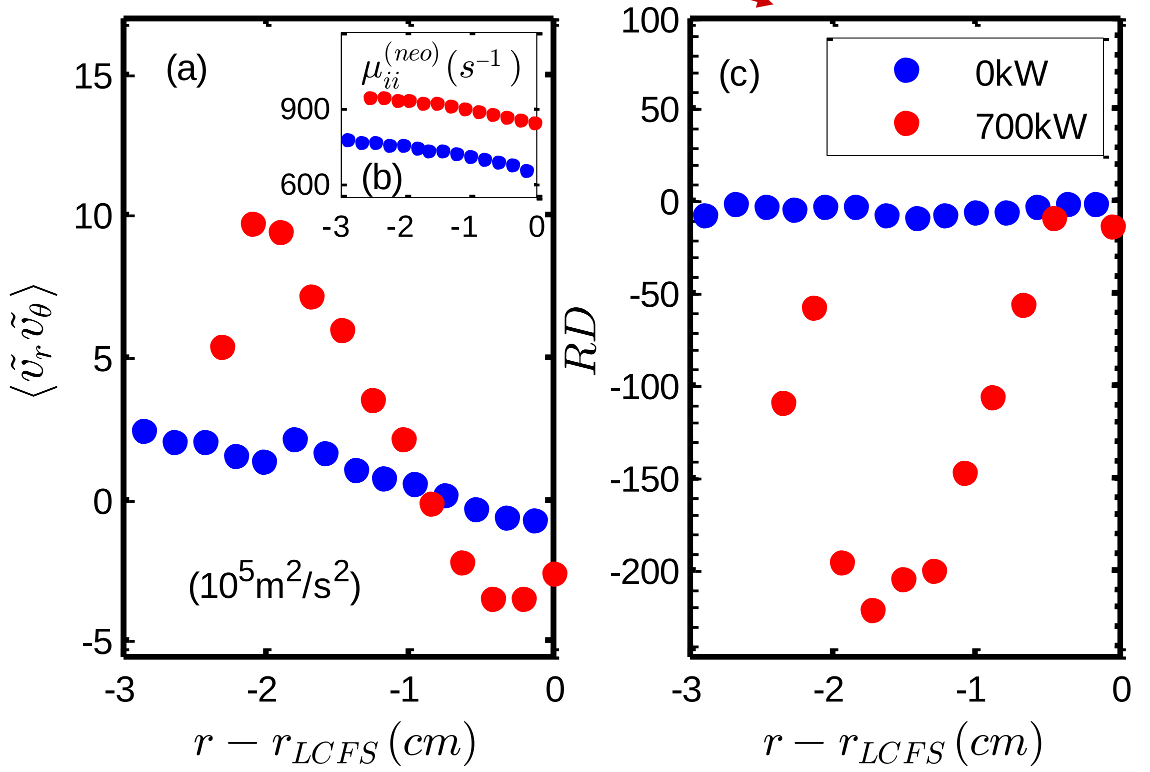
- **A significant deviation on Ohmic and ECRH heating power L mode.**
- With ECRH heating power, slope of Reynolds stress increases, **Relative Deviation** increases significantly.

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



plateau regime

$$\nu_i^* \equiv \nu_{ii} qR/(v_{thi}\varepsilon^{3/2}) \sim 1$$



Decomposition of Reynolds stress

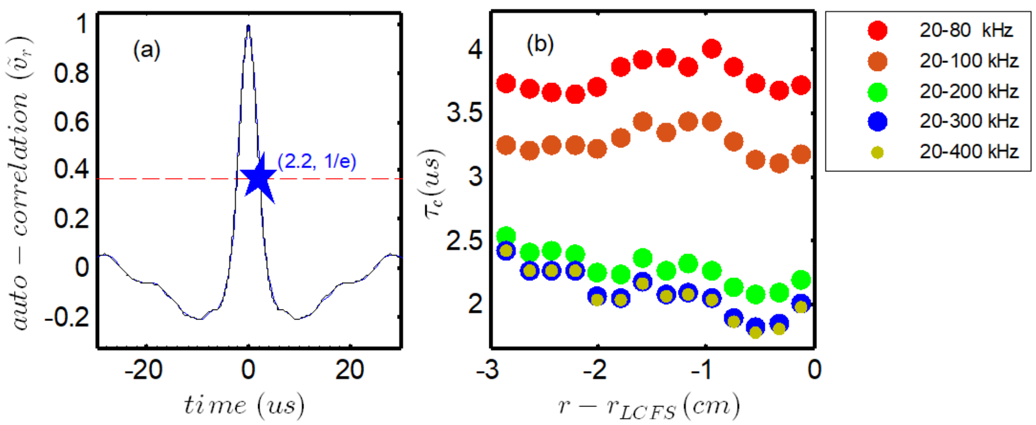
- **Contribution of these diffusive or non-diffusive stress to the turbulent generation of poloidal flows**

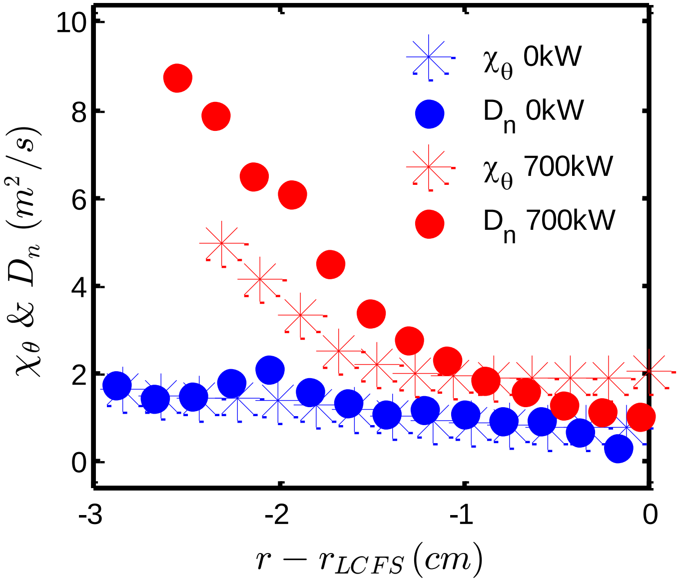
$$\underbrace{\langle\tilde{v}_r\tilde{v}_\theta\rangle}_{\text{Reynolds stress}} = \underbrace{-\chi_\theta\partial_r\langle v_\theta\rangle}_{\text{diffusive stress}} + \underbrace{\cancel{v_r^{eff}\langle v_\theta\rangle}}_{\text{convection stress}} + \underbrace{S_{r\theta}^{Res}}_{\text{residual stress}}$$

$v_r^{eff} \cong \chi_\theta/R$ A. G. Peeters et al., 2007 PRL

χ_θ and $D_n = -\frac{\langle\tilde{n}\tilde{v}_r\rangle}{\partial\langle n\rangle/\partial_r}$

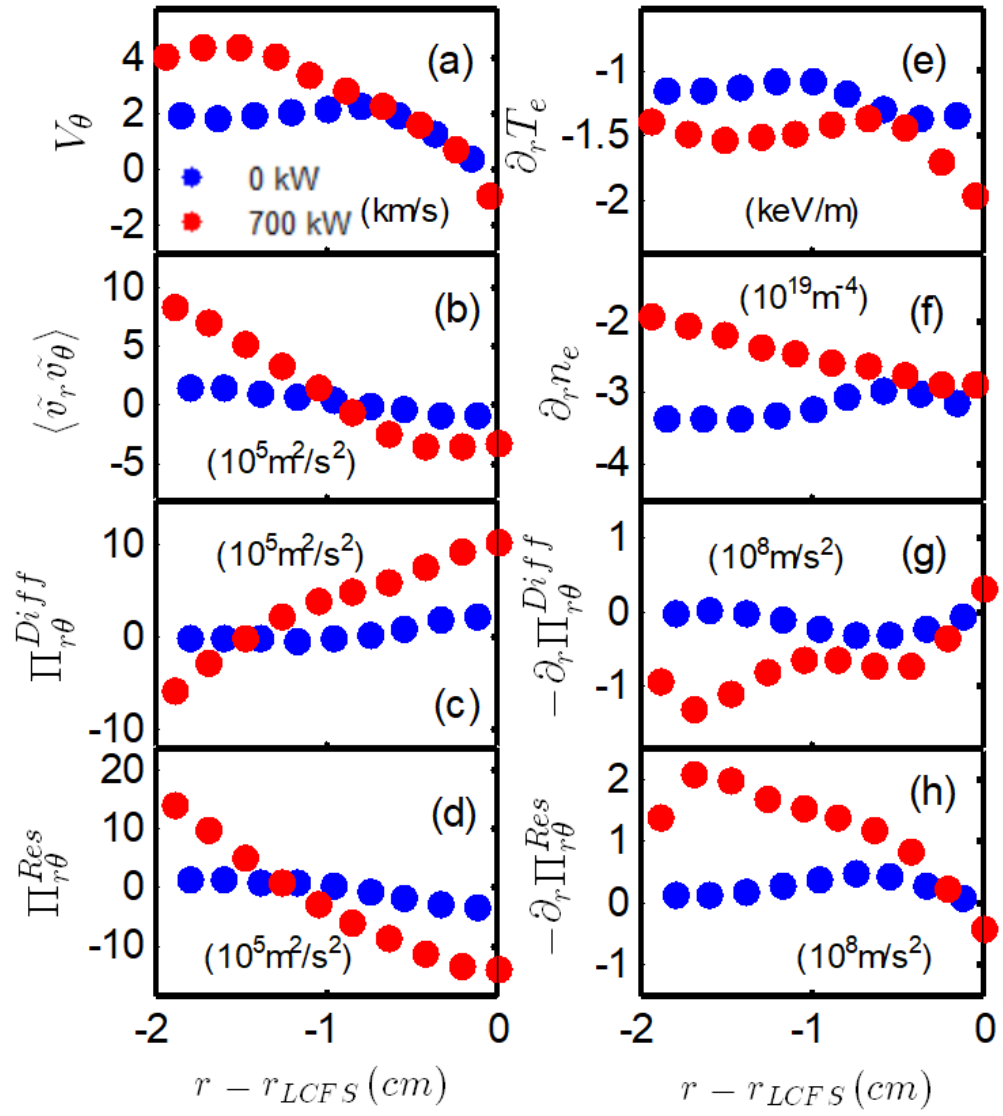
$\chi_\theta = \langle\tilde{v}_r^2\rangle\tau_{ac}$ Z. Yan et al., 2010 PRL





"Frequency saturation" in τ_{ac}

Decomposition of Reynolds stress



- Diffusive stress and residual stress are of the same order as Reynolds stress.
- The poloidal intrinsic torque, $-\partial_r(\Pi_{r\theta}^{Res})$ increases substantially with ECRH heating powers.
- Residual stress is a function of profiles of both density and **temperature**, which drive the turbulence.

Different from linear device:

$$\Pi^R = \frac{\Gamma}{n_0} - \chi_y v_d$$

$$v_d(x) = -d \ln n_0 / dx$$

A. Ashourvan et al., 2016 POP

Decomposition of Reynolds stress

- **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.**

P. H. Diamond et al., 2009 Nuclear Fusion

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

Gradients drive rotation via $\Pi_{r\theta}^{Res}$

heating power,
∇T drives the turbulence,
leading to profile relaxation
and the generation of flow
via turbulent stresses

analogy

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**

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

$|\omega|$ is the frequency of the Drift wave unstable mode

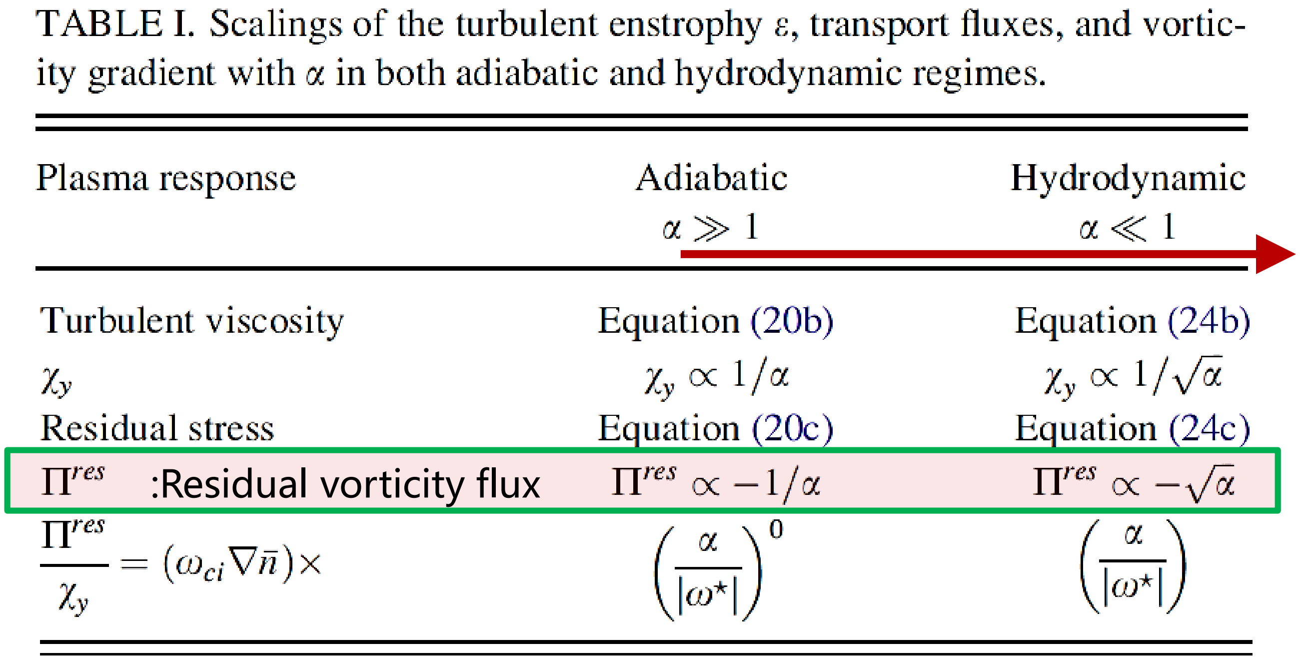


TABLE I. Scalings of the turbulent enstrophy ε, transport fluxes, and vorticity gradient with α in both adiabatic and hydrodynamic regimes.

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

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.

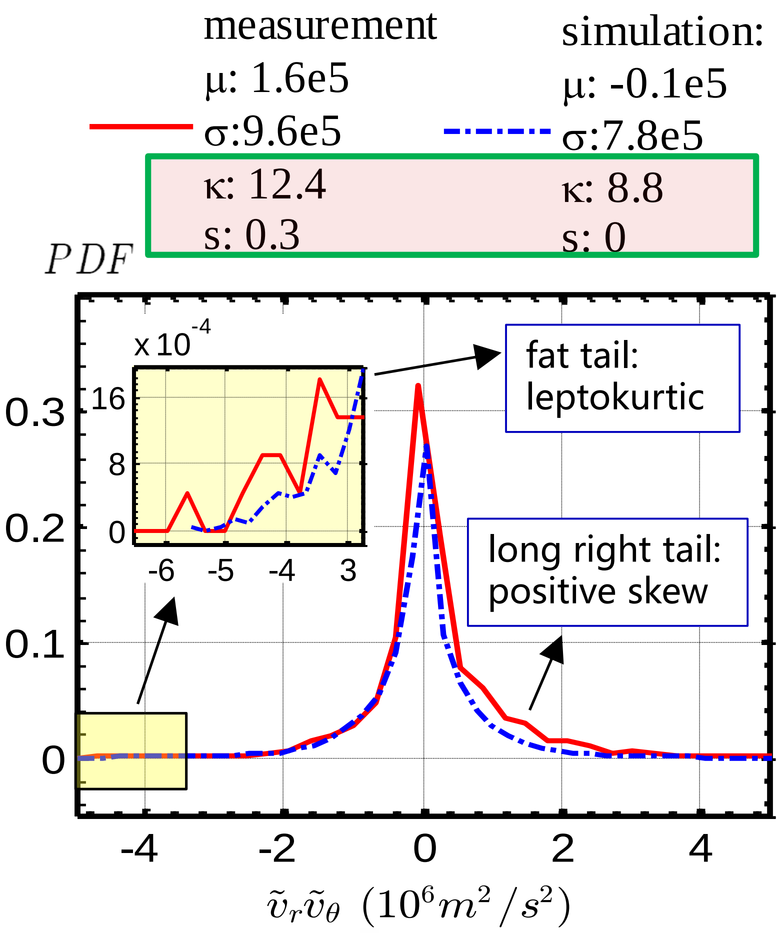
Skewness: asymmetry of the tail

Kurtosis: tail in general

$$s = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^3 / n}{\sigma^3} \qquad \kappa = \frac{\nu_4}{\sigma^4} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^4 / n}{\sigma^4}$$

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

ECRH (kW)	s	κ				
	$\tilde{v}_r\tilde{v}_\theta$	$\tilde{v}_r$	$\tilde{v}_\theta$	$\tilde{v}_r\tilde{v}_\theta$	$\frac{e\tilde{\phi}_f}{T_e}$	$\left\lvert\frac{e\tilde{\phi}_f}{T_e}\right\rvert^2$
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



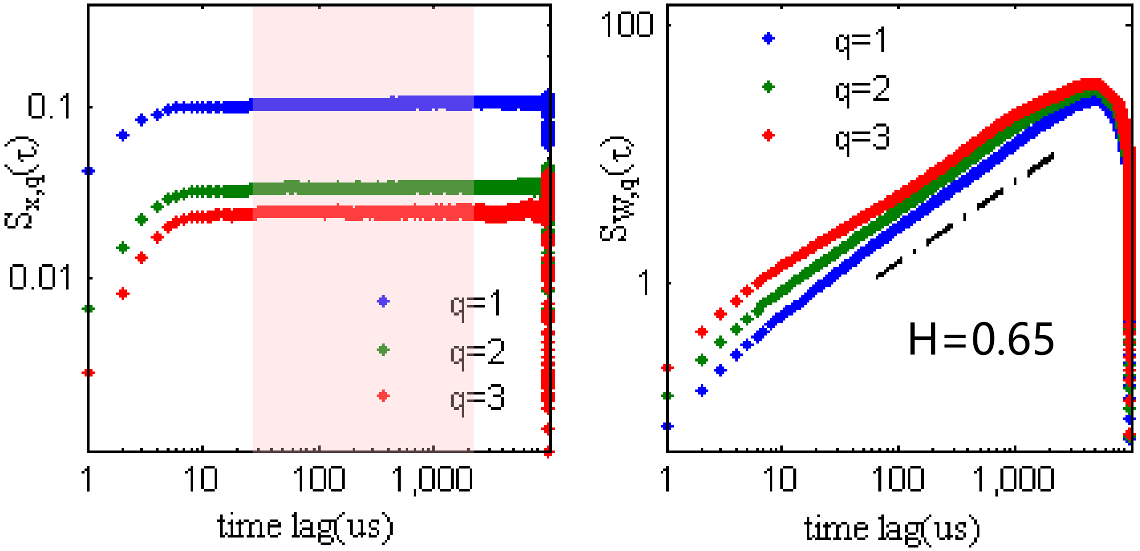
Strongly non-Gaussian dynamics regulate poloidal momentum transport. → Avalanches of poloidal momentum?

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



General (left) & cumulated(right) structure function method
Y. H. Xu et al., 2004 POP

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.

Discussion on cross phase and coherence

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

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

In frequency domain,

cross phase

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

coherence

$$= \frac{\langle \sum_\omega P_{\tilde{v}_r \tilde{v}_r}(\omega)^{1/2} P_{\tilde{v}_\theta \tilde{v}_\theta}(\omega)^{1/2} \cdot \gamma_{\tilde{v}_r \tilde{v}_\theta}(\omega) \cdot \cos\left(\varphi_{\tilde{v}_r \tilde{v}_\theta}(\omega)\right) \rangle}{\langle \sum_\omega P_{\tilde{v}_r \tilde{v}_r}(\omega) \rangle^{1/2} \cdot \langle \sum_\omega P_{\tilde{v}_\theta \tilde{v}_\theta}(\omega) \rangle^{1/2}}$$

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.

D. Guo et al., 2018 Nuclear Fusion

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

Summary

- 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!