Spatio-temporal structure of turbulent Reynolds stress zonal flow drive in 3D magnetic configuration

B Schmid¹, P Manz²,¹, M Ramisch¹ and U Stroth²,³

¹ IGVP, Universität Stuttgart, D-70569 Stuttgart, Germany
² Max-Planck-Institut für Plasmaphysik, D-85748 Garching, Germany
³ Physik-Department E28, Technische Universität München, D-85747 Garching, Germany

E-mail: Bernhard.Schmid@igvp.uni-stuttgart.de

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Abstract

The poloidal dependence of the zonal flow drive and the underlying Reynolds stress structure are studied at the stellarator experiment TJ-K by means of a poloidal Langmuir-probe array. This gives the unique possibility to study the locality of the Reynolds stress in a complex toroidal magnetic geometry. It is found that the Reynolds stress is not homogeneously distributed along the flux surface but has a strong poloidal asymmetry where it is concentrated on the outboard side with a maximum above the midplane. The average tilt of the turbulent structures is thereby reflected in the anisotropy of the bivariant velocity distribution. Using a conditional averaging technique the temporal dynamics reveal that the zonal flow drive is also maximal in this particular region. The results suggest an influence of the magnetic field line curvature, which controls the underlying plasma turbulence. The findings are a basis for further comparison with turbulence simulations in 3D geometry and demonstrate the need for a global characterisation of plasma turbulence.

1. Introduction

Turbulence self-generated zonal flows can play an important role in the spontaneous transition to a high confinement regime in fusion devices [1–8]. With a homogeneous potential structure (i.e. poloidal and toroidal wavenumber \( k_p = k_r = 0 \)) and a finite radial extent \( k_r \neq 0 \) they are intrinsically connected to a zonal shear flow [9]. Because of their symmetry these mesoscale turbulent structures do not contribute to turbulent cross-field transport and can suppress radial transport by shearing off drift-wave eddies. Like in a self-organisation process, the zonal flow is generated by the ambient turbulence itself with a vortex-thinning mechanism [10, 11]. Drift-wave eddies are tilted and drive the shear flow, which leads to a self-amplification of the zonal flow [4, 12–15]. For tilted vortices the so-called Reynolds stress \( \mathcal{R} = \left\langle \overline{\upsilon \upsilon_i} \right\rangle \) is unequal zero and the radial gradient of this flux surface averaged quantity, as indicated by the brackets, drives the zonal flow. However, this does not imply that the Reynolds stress and the resulting gradients are homogeneously distributed on a flux surface, especially since the underlying plasma turbulence depends strongly on the poloidal angle. In stellarators, with their complex 3D geometry, even a toroidal dependency has to be considered. So the understanding of the Reynolds stress dependence on local magnetic field parameters is of great importance for a further optimisation of magnetic configurations with respect to easy access to improved confinement.

To study the local Reynolds stress dependence, measurements with a poloidal probe array have been performed at the stellarator experiment TJ-K. With 128 Langmuir probes, the Reynolds stress can be calculated for 32 poloidal positions on two neighbouring flux surfaces. Thus a direct estimate of the local and flux surface averaged radial Reynolds stress gradient is possible. It is found that the local Reynolds stress and the resulting zonal flow drive are concentrated on the outboard side, where the normal curvature is negative. These measurements go beyond previously published results [16, 17] and motivate complementary turbulence simulations in 3D geometry in order to quantitatively address the magnetic field dependence of microscopic (drift-wave turbulence) and macroscopic (zonal flow) dynamics.
This paper is organised as follows. The measurement principle of the turbulent Reynolds stress with different probe configurations is introduced in section 2. In section 3 the mean Reynolds stress dependence and the connection to the velocity distribution is presented in detail. Turbulent fluctuations of the Reynolds stress and the localised Reynolds stress drive of the zonal flow are studied in the subsequent part. In section 6 the results are discussed with regard to possible consequences for local measurements and the conclusion is presented.

2. Global Reynolds stress measurement

The experiments were carried out in the low-temperature plasmas of the stellarator TJ-K. As a $l = 1$, $m = 6$ torstaron, the magnetic field exhibits a sixfold symmetry, in which the measurements were conducted in the triangular cross section with tokamak like geometry. At a magnetic field of $B = 72$ mT on axis, the plasma is heated with $3$ kW by microwaves with a frequency of $2.45$ GHz [18]. The reached electron temperature in the helium plasma is around $T_e \approx 9$ eV, measured with a swept Langmuir probe, at a line-averaged density of $n_e \approx 1.2 \times 10^{17}$ m$^{-3}$, latter determined from a microwave interferometer. The ions, on the other hand, can be considered cold ($T_i \leq 1$ eV) [19]. Although the plasma parameters are comparatively low, it has been shown that normalised quantities are similar to those in fusion edge plasmas [20, 21]. Furthermore, many studies demonstrated the drift-wave nature of the plasma turbulence in the TJ-K device with a density-potential cross phase close to zero and finite parallel wavelength [22–25]. Especially for small ion masses the $\beta_i$ scaling was found to be close to predictions for drift-wave turbulence [26].

The low temperatures allow the use of Langmuir probes in the entire confinement region. Therefore, ion saturation current ($I_{sat}$) and floating potential ($\phi_f$) can be acquired with high spatial and temporal resolution at the same time. Because temperature fluctuations are negligible in TJ-K [27], fluctuations in the ion saturation current can be associated with density fluctuations ($I_{sat} \propto \bar{n}$) and floating potential fluctuations ($\phi_f \approx \phi_f^0$), respectively. With a data acquisition at $1$ MHz with up to $2^{20}$ samples, a detailed study of turbulent dynamics is possible.

In principle the flow velocity can be determined using two neighbouring probes ($i$ and $i + 1$) at a distance $\Delta x$, where the floating potential is measured, and the perpendicular $E \times B$ drift velocity is given by $\bar{v}^E \times B \approx (\phi_f^{i+1} - \phi_f^i) / (B \Delta x)$. Measuring both velocity components in the poloidal cross section, the local turbulent Reynolds stress $R$ is then given as the product of fluctuations in radial $\bar{v}_r$ and poloidal $\bar{v}_\phi$ velocity,

$$R = \bar{v}_r \bar{v}_\phi \approx \frac{(\phi_f^{\theta_{i+1}} - \phi_f^\theta)(\nu_{\theta_{i+1}} - \nu_\theta)}{\Delta \theta \Delta r \bar{B}^2}. \quad (1)$$

Due to the 3D structure of the magnetic field, these components are not identical to the normal and perpendicular velocities $\bar{v}_n$ and $\bar{v}_p$, with respect to the magnetic field line. Compared to the normal-perpendicular Reynolds stress $\bar{v}_n \bar{v}_p$, the radial-poloidal Reynolds stress $\bar{v}_r \bar{v}_\phi$ is approximately $10\%$ lower on the outboard side. In figure 1(b) the 2D-movable probe is shown consisting of five probe tips in a cross like configuration. With such a probe Reynolds stress can then be directly measured point wise in the midplane. For the zonal flow drive the radial gradient of the zonally (poloidally) averaged Reynolds stress is important, so the Reynolds stress has to be measured on different flux surfaces. Therefore, a poloidal probe array was used consisting of 128 Langmuir probes with 32 probes on each of four neighbouring magnetic flux surfaces (figure 1(a)). It is designed for the triangular cross section and placed in the confined region just inside the separatrix (dashed white line), where the pressure gradient is steepest. The average poloidal probe spacing is $\Delta \theta = 1.4$, $1.5$, $1.6$, and $1.7$ cm on the four different flux surfaces at relative radius $R - R_0 = 9.5$, $10.0$, $10.5$, and $11.0$ cm. Also, with a spatial uncertainty of $2$ mm, the distances are still below the typical structure size of $3$–$5$ cm [25, 28, 29]. The array makes it possible to measure the flux surface averaged Reynolds stress (indicated by $\langle \bar{\nu}_n \rangle$) on two different flux surfaces (i.e. FS 2 and FS 3, counted from inside), giving the possibility to get a direct estimate of the zonal flow drive.

Figures 1(b) and (c) show typical probability distribution functions (PDF) of the velocity components $\nu_{r,\theta}$, the resulting local Reynolds stress $R$, and the flux surface averaged Reynolds stress $\langle R \rangle_f$, skewness $S$ and kurtosis $K$ of each distribution are given in the respective figure. The comparison with the reference Gaussian distribution (grey long dashed line) shows that both radial and poloidal velocities exhibit a near Gaussian statistics. Due to the nonlinearity, the local Reynolds stress, calculated with equation (1), has a very high kurtosis and is positively skewed. A positive skewness implies that, on average, events with outward-going transport and positive poloidal velocity, or inward-going negative velocity events, dominate the Reynolds stress at this position. Further, the moments of the PDF are an indication of an intermittent or bursty momentum transport, which was found in other experiments as well [30]. Also after the flux surface average has been taken the Reynolds stress distribution is distinctly non-Gaussian with a skewness of $S = 0.537$ and a kurtosis of $K = 1.874$. 
3. Poloidal dependence of background Reynolds stress

Starting with the poloidal momentum balance for divergence free two-dimensional flows, the governing equation of the poloidal mean flow can be derived [31]. Using the Reynolds decomposition for the velocity field \( \mathbf{v} = \langle \mathbf{v} \rangle + \mathbf{v}' \) and a subsequent average results in

\[
\frac{\partial}{\partial t} \langle \mathbf{v}_0 \rangle = -\nabla \cdot \langle \mathbf{v}_0 \mathbf{v}_0 \rangle + \mu_d \frac{\partial^2}{\partial r^2} \langle \mathbf{v}_0 \rangle - \nu_{10} \langle \mathbf{v}_0 \rangle.
\]  
(2)

The left-hand side is the acceleration of the poloidal flow, which is driven by the Reynolds stress \(-\nabla \cdot \langle \mathbf{v}_0 \mathbf{v}_0 \rangle\) and damped by ion viscosity \(\mu_d\) and ion-neutral friction \(\nu_{10}\). For the measurement parameters used herein, viscous damping dominates over damping due to friction. The average can be taken zonally \(\langle \mathbf{v}_0 \rangle\) along a flux surface, or over time \(\langle \mathbf{v}_0 \rangle\), where a local dive is connected to a mean flow in time. For now, only the temporal mean \(\mathbf{R}(\mathbf{r}, t) = \langle \mathbf{R}(\mathbf{r}, t) \rangle\) of the local Reynolds stress at the position \(\mathbf{r}\),

\[
\mathbf{R}(\mathbf{r}, t) = \mathbf{R}(\mathbf{r}) + \mathbf{R}(\mathbf{r}, t),
\]

is considered. In this section the spatial distribution of the mean Reynolds stress is studied in detail. Since plasma conditions are stationary, the temporal average is taken over about 1 s, which corresponds to 220 samples.

With the 5-pin probe the radial potential and Reynolds stress profile has been measured in the midplane from the plasma centre to the scrape-off layer (figure 2(a)). The floating potential \(\phi_f\) (blue open circles) has a minimum in the edge region and is zero at the separatrix (dotted vertical line). A similar structure is found for the mean Reynolds stress \(\mathbf{R}(\mathbf{r} - \mathbf{R}_0)\) (red filled circles) which is here always negative with a sharp minimum at \(\mathbf{r} - \mathbf{R}_0 = 11.5\) cm. It should be stressed that the values are not calculated from the mean values of the potentials but rather from the temporal mean taken of the product of the velocity fluctuations calculated according to equation (1). Similar experiments in a linear plasma device (CSDX) showed that the divergence of the radial mean Reynolds stress drives an azimuthally symmetric flow [32, 33]. However, in our experiment a poloidally symmetric Reynolds stress profile cannot be assumed and the angular dependence is studied in the following.

The poloidal probe array covers the extreme regions of the Reynolds stress profile and its radial position is marked with a grey box in the figure. As mentioned before, the flux surfaces at this toroidal position have similar geometrical properties as the field lines in a tokamak. For the radial location of the array (FS 3), the poloidal dependencies of the field line curvature components are shown in figure 2(c). The poloidal angle \(\theta \in [-\pi, \pi]\) is counted from the inboard midplane counterclockwise and is zero at the outboard midplane (see figure 1(a)). On the inboard side the normal curvature \(\kappa_n\) (blue solid line) is positive and gets negative on the outboard side. The geodesic curvature \(\kappa_g\) (green dashed line) changes sign at the midplane and has a sinusoidal form with minimum and maximum at bottom and top, i.e. \(\theta \approx \pm \pi/2\), respectively. In the top right of figure 2 the poloidal mean

\[
\begin{align*}
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\]
Reynolds stress profile $\mathcal{R}(\theta)$ for both flux surfaces is shown. Non-zero values of the mean Reynolds stress arise relatively localised in regions of negative normal (‘bad’) curvature $\kappa_n$. The poloidal dependence is similar for both flux surfaces, whereas differences, marked as coloured region in the figure, measure the radial Reynolds stress gradient. They indicate flow drive and are only found on the outboard side. A pronounced maximum is visible above the midplane ($\theta \approx 0.4\pi$) falling into the shaded area. In this region the normal curvature is still negative whereas the geodesic curvature is positive. A similar behaviour has been found for the radial cross-field transport $\Gamma = \langle \tilde{\chi} \tilde{n} \rangle$ [25, 34]. These investigations have shown that the turbulent transport is peaked in regions with the above mentioned combination of curvature parameters ($\kappa_n < 0, \kappa_g > 0$). This is in line with theoretical studies which predict a ballooning of fluctuation amplitudes for $\kappa_n < 0$ [35, 36] and it shows an additional influence by the geodesic curvature. Since the Reynolds stress $\mathcal{R} = \langle \tilde{\chi} \tilde{v}_r \rangle$ can be seen as radial transport of poloidal momentum and it also directly depends on the underlying drift-wave turbulence, a comparable influence of the curvature terms can be assumed. Not only normal and geodesic curvature are suspected to influence the Reynolds stress, but also the local magnetic shear (not shown). As the local magnetic shear is up-down symmetric at this toroidal position, it can not explain the asymmetry in the poloidal Reynolds stress profile.

Like in the case of turbulent particle transport $\Gamma$ where a positive correlation of radial velocity $\tilde{\chi}$ and density fluctuation $\tilde{n}$ result in an outward cross-field transport, a correlation of radial and poloidal velocity leads to non-zero Reynolds stress. With the Wiener–Khinchin theorem the correlation can be connected to the cross power spectrum $S_{\chi v_r}^{\phi}(f)$, consisting of the cross coherence $\gamma_{v_r v_r}^{\phi}(f)$ between the fluctuations, the respective auto power spectra $S_{v_r}^{\phi}(f)$ and $S_{v_r}^{\phi}(f)$, and the cross phase spectrum $\alpha_{v_r v_r}^{\phi}(f)$:

$$\mathcal{R}(\theta) = \sum_{\theta} \gamma_{v_r v_r}^{\phi}(\theta, f) \sqrt{S_{v_r}^{\phi}(\theta, f)S_{v_r}^{\phi}(\theta, f)} \cos(\alpha_{v_r v_r}^{\phi}(\theta, f)).$$

A high coherence implies a linear dependence of the two signals, indicating a constant phase relation. The values of the coherence are restricted to the interval $[0, 1]$ and the cross phase to $[-\pi, \pi]$, where a zero phase results in a positive correlation and $|\alpha| \approx \pi$ in an anticorrelation. In figure 3(b) the coherence spectrum of the velocity components is shown for the poloidal circumference of a flux surface. For comparison the spectrum of the potential fluctuations $S_{\phi}^{\phi}(\theta, f)$ is shown in (a). The spectrum of the potential is broad for the whole poloidal circumference, whereas the coherence spectrum of the velocity components shows a comparable structure as the poloidal mean Reynolds stress profile (figure 2 (b)). In the region of the pronounced poloidal Reynolds stress maximum ($\theta \approx 0.4\pi$) high coherence can be found for frequencies above 10 kHz, which are associated with the dominant drift wave structures. But also on the inboard side (e.g. $\theta = -0.9\pi$) considerable coherence is present.
whereas the mean Reynolds stress is zero. This illustrates that for the actual mean Reynolds stress both coherence and phase of the fluctuating velocity components have to be considered.

For a further investigation the relation between the velocity components is compared at three distinct poloidal positions (figure 4). The bivariant probability distribution function (2D-PDF) as well as the coherence and the phase spectra are shown at the inboard side (a), (b), (c) the bivariant probability distribution functions can be seen. The $1/e$ level of the reference Gauss is drawn as solid white line. The $1/e$ level of the reference Gauss is plotted as white circle. On the inboard side ($\phi_\text{p} \approx -\pi$) the velocity distribution is isotropic, which results in a Reynolds stress value near zero. For the before mentioned midrange frequencies the coherence is significant, but the corresponding phase changes between $0.2\pi$ and $0.6\pi$ which in total leaves no strong mean contribution. The situation changes when the positions on the outboard side are considered. The 2D-PDFs are strongly anisotropic pointing to a high resulting mean Reynolds stress and explain the values of skewness and kurtosis found before (figure 1 (d) for $\phi_\text{p} \approx 0.4\pi$). For the angle $\phi_\text{p} \approx 0.4\pi$ the absolute value of the phase is near $\pi$ for frequencies with high coherence, which constitutes the negative correlation of the velocity components. In contrast a positive Reynolds stress, as for $\phi_\text{p} \approx 0.4\pi$, is reflected by zero phase shift (figure 4(f)).

Figure 4. Connection between radial and poloidal velocity components for three different poloidal locations. In the upper row (a), (b), (c) the bivariant probability distribution functions can be seen. The $1/e$ level of the reference Gauss is drawn as solid white line. The $1/e$ level of the reference Gauss is plotted as white circle. On the inboard side ($\phi_\text{p} \approx -\pi$) the velocity distribution is isotropic, which results in a Reynolds stress value near zero. For the before mentioned midrange frequencies the coherence is significant, but the corresponding phase changes between $0.2\pi$ and $0.6\pi$ which in total leaves no strong mean contribution. The situation changes when the positions on the outboard side are considered. The 2D-PDFs are strongly anisotropic pointing to a high resulting mean Reynolds stress and explain the values of skewness and kurtosis found before (figure 1 (d) for $\phi_\text{p} \approx 0.4\pi$). For the angle $\phi_\text{p} \approx 0.4\pi$ the absolute value of the phase is near $\pi$ for frequencies with high coherence, which constitutes the negative correlation of the velocity components. In contrast a positive Reynolds stress, as for $\phi_\text{p} \approx 0.4\pi$, is reflected by zero phase shift (figure 4(f)).
4. Turbulent Reynolds stress distribution

So far, the temporal mean Reynolds stress \( R(\bar{r}, t) \) has been investigated in detail, as for now, the fluctuating part will be considered,

\[
R(\bar{r}, t) = \bar{R}(\bar{r}, t). \tag{5}
\]

This means that either the mean Reynolds stress is not shown (i.e. \( f = 0 \)) or that it is explicitly subtracted for the analysis (i.e. \( \langle R(\bar{r}, t) \rangle \)). Similar to the previous section, the spatial distribution of the Reynolds stress signal power will be shown first, and then in section 5 the connection to the zonal flow will be made.

Figure 5(a) shows the poloidally resolved auto power frequency spectrum of the Reynolds stress \( S_R(\theta, f) \), which in total is proportional to the standard deviation \( \sigma \propto \sum_{f=0}^{\infty} S_R(\theta, f) \). In comparison to the poloidal profile of the potential spectrum (figure 3(a)), the Reynolds stress fluctuations exhibit a very strong inboard-outboard asymmetry, and again the maximal amplitudes can be found above the midplane. In addition this asymmetry is reflected in the frequency range that contributes most to the Reynolds stress. The poloidal structure resembles the poloidal profile of the mean Reynolds stress (figure 2(b)), but in contrast to the mean, the standard deviation is more continuous, especially visible for the outboard side. In addition to the magnetic curvature, also the local magnetic shear could influence the Reynolds stress [39]. The local magnetic shear is a measure for the shearing of radially adjacent field lines and at the two poloidal positions \( \theta \approx \pm 0.62 \pi \) the local magnetic shear has maximal absolute values [34]. There are noticeable values in the Reynolds stress spectrum at these positions (marked on the abscissa in figure 5(a)) and, therefore, a hidden shear influence, albeit weak, could be possible.

For a comparison of turbulent structure sizes, the poloidal wavenumber spectra (normalised with the drift scale \( \rho_f \)) of potential \( \phi_R \), Reynolds stress \( R \), and local radial Reynolds stress gradient \( \partial_r R \) are shown in figure 5 (b). The radial gradient of the Reynolds stress is calculated at each time step from the Reynolds stress fluctuations on the two neighbouring flux surfaces for 32 poloidal positions. Since the measurement positions of both Reynolds stress profiles do not exactly match in poloidal angle \( \theta \), the values on one of the flux surfaces have to be interpolated in order to calculate the radial gradient. The poloidal wavenumber spectrum of the potential shows the characteristic form of 2D turbulence and quickly decays with higher wavenumbers, whereas the Reynolds stress and especially the local Reynolds stress gradient are strong for smaller scales \( k_\rho \approx 1 \). This is reminiscent of an earlier study on TJ-K [10], supported by computational results [40], where it was shown that the zonal flow is predominantly driven by the smaller scales.

5. Zonal flow drive

If a zonal average is used, equation (2) states that a radial gradient in the averaged turbulent Reynolds stress is the driving force of a poloidal flow,

\[
\partial_t \left\langle m \right\rangle_\theta = -\partial_r \left\langle \bar{v} \bar{w} \right\rangle_\theta = -\partial_r \langle \bar{R}(\theta, t) \rangle_\theta. \tag{6}
\]

The damping of the zonal flow by the ion viscosity as well as other damping mechanisms (e.g. the Kelvin–Helmholtz instability [41], geodesic transfer effects [40, 42, 43]) are not further considered in the present investigation.

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Figure 5. The auto power frequency spectrum of the Reynolds stress is shown in figure (a). The Reynolds stress is strongest on the outboard side and asymmetric to the upper half. For a comparison of the different length scales, the wavenumber spectra of floating potential (black solid), Reynolds stress (blue dash–dot), and Reynolds stress gradient (red dashed) are plotted in figure (b). The y-axis is rescaled for comparison. Smaller scales dominate the radial Reynolds stress gradient.
After averaging along a flux surface the temporal dependence of the fluctuating quantities still remains. Since we are interested in the interplay between Reynolds stress and poloidal flow during the zonal flow occurrence, a conditional averaging technique\cite{14, 44} is used to create an ensemble average. The zonal flow, regarded as poloidal shear flow, is interconnected with a potential fluctuation on the complete flux surface ($\theta = \theta_0$). Hence the zonal potential $\tilde{\phi}_k$ approximated as poloidally averaged signal from the floating potential of the probes on the 3rd flux surface is used as trigger signal with the condition $s + 2$, triggering on the rising edge. Subwindows with a time span of $256 \mu s$ are extracted around the trigger time points and centred on the respective maximum, so that $t = 0$ marks the position of the maximal zonal potential. In total 896 realisations are used for the ensemble average. All together, the result reflects the averaged dynamics around the zonal event.

In figure 6(a) the spatially resolved Reynolds stress evolution $\tilde{R} (\theta, \tau)$ on the poloidal circumference is shown as coloured contour plot. The connected local radial gradient of the Reynolds stress $\partial_r \tilde{R} (\theta, \tau)$ is overlaid as contour lines, where continuous and dashed lines show negative and positive gradients, respectively. As seen from equation (6), a negative Reynolds stress gradient drives a flow in positive direction (here positive values). Although the fluctuations in both quantities are small in scale, it is clear that strong contributions of turbulent Reynolds stress and its local gradient are restricted to the outboard side of the plasma. Beyond that the up down asymmetry, already revealed by the spectra (see figure 5 (a)), can be detected for the whole time evolution around the zonal flow. Large contributions to the drive are found where also the mean Reynolds stress amplitudes are large. Shortly before the trigger condition is reached ($\tau = 0$), the Reynolds stress gradient shows contributions also on the lower side ($\theta \approx -0.4 \pi$).

The zonally averaged terms of the drive equation are shown in the lower part of figure 6 for the same time scale. In red with a solid line the time evolution of the Reynolds stress drive $-\partial_r \langle \tilde{\psi} \tilde{\psi} \rangle_{\theta_0}$ is displayed, whereas the acceleration of the poloidal flow $\partial_t \langle \tilde{\psi} \rangle_{\theta_0}$ is drawn in dashed black. Similar to the poloidally resolved picture, the Reynolds stress drive fluctuates fast as compared to the poloidal flow. Shortly before the flow gets maximal the Reynolds stress drive is strong and reaches comparable absolute values. Both pictures together, spatially resolved and flux surface averaged, show that the zonal flow is driven by the Reynolds stress, but this drive turns out to be poloidally localised.

Figure 6. Conditional averaged dynamics of Reynolds stress drive and zonal flow response. For the time evolution around the trigger time point the Reynolds stress $\tilde{R} (\theta, \tau)$ (filled contour) and the local Reynolds stress gradient $\partial_r \tilde{R} (\theta, \tau)$ (contour lines) are plotted in (a). Both Reynolds stress and Reynolds stress gradient are strong on the outboard side. For the same timescale the radial gradient of the flux surface averaged Reynolds stress $-\partial_r \langle \tilde{\psi} \tilde{\psi} \rangle_{\theta_0}$ (red solid) and the acceleration of the poloidal flow $\partial_t \langle \tilde{\psi} \rangle_{\theta_0}$ (black dashed) are shown below (b).
6. Discussion and conclusion

The objective of this work was to study the structure of the Reynolds stress and its connection to zonal flows with high resolution in space and time. To this end, Langmuir-probe measurements in low-temperature plasmas at the stellarator TJ-K were carried out in the triangular cross section of the experiment. The geometric properties at the measurement location in TJ-K resemble those of a tokamak. With specially designed probe configurations, the Reynolds stress could directly be calculated from the acquired floating potential fluctuations. A movable Langmuir probe allowed measuring the radial Reynolds stress profile and a sophisticated poloidal probe array, consisting of 128 probes, gave the poloidally resolved contributions to the Reynolds stress. Since the probe array covers multiple flux surfaces, an estimate of the radial gradient of the Reynolds stress could also be measured, which is of major interest because it is the driving force of the zonal flow [31].

In the first place, the spatial structure of the time-averaged Reynolds stress was investigated. Radial and poloidal profiles clearly show a strong spatial variation of the local contribution to the global Reynolds stress in the confined region of the plasma. The time-averaged Reynolds stress is high in regions where the pressure gradient is steep and poloidally localised where the normal magnetic curvature $\kappa_n$ is negative. In spite of the up-down symmetry of the flux surfaces the Reynolds stress maximum is shifted to the region where the geodesic curvature $\kappa_g$ is positive, i.e. above the midplane. A similar dependency was previously found for the turbulent cross-field transport $\Gamma$ on the same experiment [34], which is plausible by reason of similar conceptual form of both quantities. Often the poloidal momentum balance is evaluated using measurements of Reynolds stress and poloidal flow velocity localised to a small area on a magnetic flux surface [32, 33]. For cylindrical linear magnetic field configurations this is acceptable, but for toroidal configurations the assumption of an azimuthally symmetric Reynolds stress profile may not be valid. Further, the findings suggest that a 3D redistribution of turbulent and mean kinetic energy has to be considered in general, which underlines the nonlocality of the background shear flow formation [45].

Using a conditional averaging technique, the evolution of both poloidally resolved and flux surface averaged Reynolds stress was analysed in a time window around a zonal flow occurrence. A direct comparison of the driving term and the poloidal flow illustrates the Reynolds stress drive of the zonal flow. But also here the poloidally resolved measurements show that the important contributions are restricted to the outboard side with an additional up-down asymmetry. The spatial structure is similar to that of the mean Reynolds stress suggesting an analogue influence of the background magnetic field. This has implications for local Reynolds stress measurements since the locality of the Reynolds stress can corrupt causality studies between Reynolds stress drive and zonal flow [46]. The magnetic field dependence of the Reynolds stress drive has consequences for zonal flows in advanced stellarators such as Wendelstein 7-X. The neoclassical optimisation leads to low values of $\kappa_n$, which in return would result in low Reynolds stress values reducing zonal flow drive. But on the other hand, since optimisation also results in minimised $\kappa_n$, zonal flow damping is also reduced.

In conclusion, the local contributions to the Reynolds stress and radial Reynolds stress gradient are not homogeneously distributed along a flux surface in the stellarator experiment TJ-K. The measurements show the complex structure of both quantities, where the main contributions are concentrated on the outboard side with a maximum above the midplane. Especially for the zonal flow drive, the locality of the Reynolds stress implies that a connection between local Reynolds stress measurements and mesoscopic turbulent flows cannot always be made. On the other hand, the localisation of the Reynolds stress in the bad curvature region makes local measurements on the low field side of tokamaks relevant for studies of the global behaviour. This study demonstrates the importance of global measurements when comparisons with turbulent simulations are carried out.

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