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On the link between edge sheared flows and turbulence in fusion plasmas

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Abstract

The development of new diagnostic and analysis tools is spawning a new era in fusion plasma research to unravel the global picture connecting transport and flows. Properties of turbulent transport in fusion plasmas can not be understood without considering the coupling with sheared flows. The link between edge sheared flows and turbulence has been investigated in the plasma edge region of stellarator (TJ-II) and tokamak (JET) plasmas. The fact that different quadratic terms in fluctuating velocities ($<\tilde{v}_\parallel \tilde{v}_r>$ and $<\tilde{v}_\perp \tilde{v}_r>$) change during edge sheared flow generation means that shear flow physics involves 3-D physics phenomena in which both perpendicular and parallel dynamics are involved. A new strategy has been recently applied to plasma physics to quantify the local energy transfer between flows and turbulence by computing the production term. Experimental results show that turbulence can act as an energy sink and energy source for the mean flow near the shear layer.

I. Introduction

The heat and particle transport in fusion plasmas is generally due, in part, to turbulent process associated with small-scale instabilities driven by the in-homogeneity of density and temperature profiles in the direction normal to the magnetic surfaces. The magnitude of turbulent transport is probably the dominant parameter affecting the global confinement properties and hence the economical performance of a fusion reactor. Understanding the physics of anomalous transport in fusion devices remains one of the key issues in magnetic fusion research.

Heat and particles are transported from the plasma core to the plasma boundary. At least two areas with different magnetic topology can be distinguished around the plasma boundary of fusion plasmas: the plasma region located inwards from the Last Closed Flux Surface (LCFS), and the so called scrape-off layer (SOL) region, in which the field lines intersect material surfaces. Near the Last Closed Flux Surface (LCFS), sheared flows develop in all magnetic confinement devices, thus providing a convenient point of reference in the plasma boundary region of fusion devices. The influence of sheared flows on turbulence and transport has been a very active area of investigation in nuclear fusion research [1].

Characterizing fluctuation driven particle and energy fluxes requires experimental techniques for measuring the variations in parameters such as density, temperature, and magnetic and electric fields with good temporal and spatial resolution. Until recently, this kind of measurement was mostly limited to the plasma edge where material probes can be applied. The use of probes arrays and more recently 2-D beam emission spectroscopy and fast visible cameras [2] has permitted a transition from mostly single point measurements to 2-D visualization. This improvement in plasma diagnostics is providing a route to a better understanding of edge turbulence and momentum physics.

Plasma flows play a crucial role on transport in magnetically confined plasmas [3]. It is well known the importance of flow shear in the development of transport barriers; both edge and core transport barriers are related to a large increase in the ExB sheared flow [4]. Thus momentum is expected to play a key role to control both energy and particle confinement.

This paper deals with the physics of generation of edge sheared flows and their self-consistency with plasma turbulence.

II. The concept of negative viscosity and development of sheared flows

The resistance of fluids to shearing motion is a well known observation. The tendency of sheared motion to be reduced with the passage of time, if no other forces are at work to maintain it, leads to the concept of (positive) coefficient of viscosity, the constant of proportionality relating the stress to the shear. In a turbulent flow, when the momentum flux perpendicular to the mean flow direction is directed from regions of larger values toward regions of smaller values of mean flow, it is said that a turbulent (eddy) viscosity is present.

The concept of a reverse effect (e.g. negative viscosity) is something which appears to be against common sense [5]. However, for certain kind of flows (e.g. planet´s atmosphere [5], plasmas [6]) evidence of negative viscosity effects have been reported. In this case the mean flow can gain kinetic energy from the turbulence with direct impact in the development of sheared flows.

Some conditions must be fulfilled in the system to show negative viscosity behaviour in steady state plasmas. First eddies, which transport the momentum contrary to the gradient of mean flow, must have a supply of turbulent kinetic energy (otherwise they will die out). Second, the mean flow should experience some form of braking (e.g. positive viscosity) so that its value does not increase without limit. However, this braking should be low enough to allow the generation of differential rotation. Third, some kind of turbulent irregularity must be present. This ingredient is illustrated in figure 1, showing a flow with some hypothetical pattern producing a convergence of momentum into the mid-channel [5]. The essential features are the elliptical circulation and the systematic tilts of their major axes, which can be expressed as gradients in quadratic terms of fluctuating velocities ($\partial < \tilde{v}_i \tilde{v}_j > / \partial r \neq 0$).

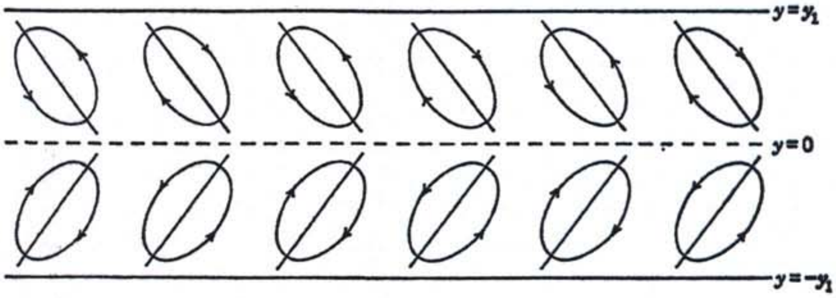

Fig. 1 Flow with some hypothetical pattern producing a convergence of momentum into the mid-channel [5].

III. Transport intermittency, radial electric fields and sheared flows

Sheared poloidal flows can influence the turbulence via shear decorrelation mechanisms and, as a consequence, modify the induced transport. A strong radial gradient in the radial electric field (E_r) produces strong shear in the particle ($E_r \times B$) drift velocity (B being the toroidal magnetic field). This tears apart the coherent cellular pattern of the unstable modes. This effect can be expressed by a decorrelation time which is proportional to the inverse of the radial gradient of the radial electric field, $\tau_c \approx B^{-1}(d E_r / d r)^{-1}$. On the other hand, the decorrelation time due to background diffusion is estimated by $\tau_b \approx L_c^2 / D$, where L_c is the radial scale length of fluctuations and D is the diffusion coefficient. When τ_c is smaller than τ_b, the sheared flow reduces the radial scale (correlation) length of the fluctuations, and consequently the level of anomalous transport (Fig. 2). Historically, this mechanism for reducing turbulent transport was proposed for the explanation of the transition to the High Confinement mode (H-mode), which is now obtained routinely at the plasma edge and corresponds to the formation of a local transport barrier.

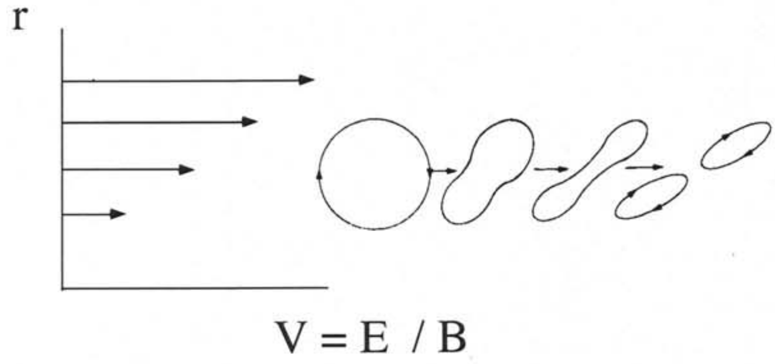

Fig. 2. Influence of sheared flows on turbulent pattern. When the shearing rate reaches a critical value, the correlation length of fluctuations is reduced.

Sheared flows (electric fields) can damp the turbulence level, and the resulting transport can influence the gradients (the free energy source) themselves – giving rise to a feedback loop (Fig. 3). The discovery of the stabilizing effect of sheared flows on plasma turbulence brought on a new era in nuclear fusion research. Recently, the best fusion performance to date has been obtained in plasma conditions where turbulent transport reduction by shear decorrelation is taking place. For the first time, it has been possible to reduce the rate of ion thermal transport to the minimum level set by particle collisions (neoclassical transport) over the whole plasma. These results represent a revolutionary step forward in the control of plasma turbulence and transport.

Although understanding the physics underlying the generation of flows is a key issue in the plasma physics fusion community, the interplay between sheared flows, intermittent transport events and turbulence still remains an active area of research. Visualizing the predicted tilt of convective cells once the shear flows reach the critical value ($\tau_b \approx \tau_c$) has been recently achieved using e.g. 2-D imaging techniques [7]. On the other hand, turbulent events (blobs) may also provide an additional mechanism for flow generation via Reynolds stress (e.g. eddy tilting and negative viscosity effects). Quantifying the importance of such mechanisms requires the measurement of the energy transfer between flows and turbulence.

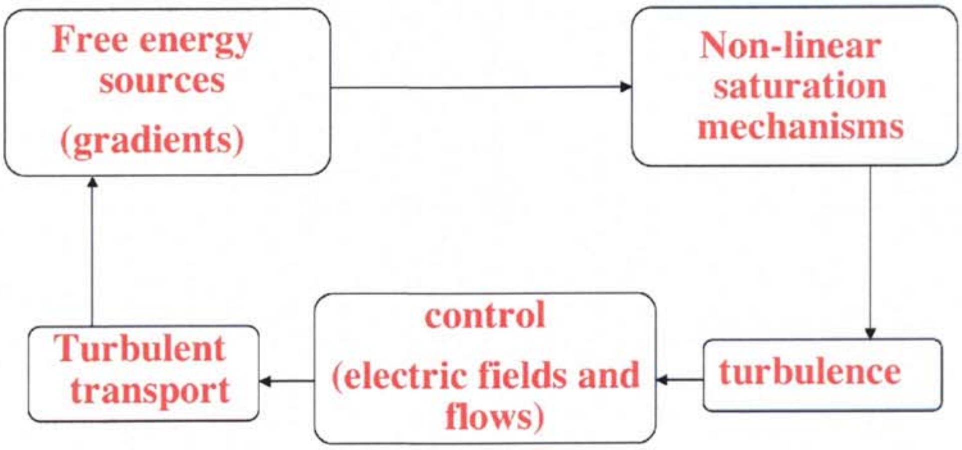

Fig. 3 Sheared flows (electric fields) can damp the turbulence level, and the resulting transport can influence the gradients (the free energy source) themselves – giving rise to a feedback loop.

IV. Energy transfer between turbulence and flows

The measure of the energy transfer between turbulence and flows is an appropriate strategy to quantify its degree of coupling coupling. The energy transfer can be computed by means of the turbulence production term following classical works to derive equations for the mean flow (E) and turbulence (k) kinetic energy evolution [8]. The equations for E and k can be written as [8]

$$\frac{dk}{dt} + \nabla T' = P - \varepsilon$$

$$\frac{dE}{dt} + \nabla \overline{T} = -P - \overline{\varepsilon}$$

$$P \equiv - < v_i v_j > \frac{\partial < V_i >}{\partial x_j}$$

where the quantity P is called the production of turbulent kinetic energy.

There are four terms in the k equation: the mean flow convection (dk/dt), the turbulent transport ($\nabla T'$), the dissipation (ε) and the production (P) [8]. It should be noted that the production term (P) appears with different sign both in the mean-kinetic-energy equation and turbulent-kinetic-energy equation. It combines fluctuating velocity cross-correlations with mean velocity gradients and gives a measure of the amount of energy per unit mass and unit time that is transferred locally between mean flow and fluctuations.

The strategy of quantifying the energy transfer between flows and turbulence by means of the production term (P) is a different point of view with respect to previous works [9 and references therein]. In those works a flux surface averaging was implicit in the momentum balance equation relating radial gradient in Reynolds stress and perpendicular plasma rotation, while in the energy approach discussed in this paper all averaged quantities are time-averaged and flux surface-averaging is not supposed. Thus, the quantity P should be considered as a local estimate of the turbulent kinetic energy production. Considering that with the present state of art in plasma diagnostics local (instead of flux averaged) measurements of fluctuating velocities are available, this local character in P strongly simplifies the interpretation of measurements. On the contrary, care should be taken in trying to extrapolate from these local measurements the influence in the whole plasma.

V. Properties of spontaneous sheared flows in TJ-II

Experiments carried in the TJ-II stellarator have shown that the generation of spontaneous perpendicular sheared flows (which self-organize, via fluctuations, to a value close to marginal stability) requires a minimum plasma density. Near this critical density, the level of turbulent edge transport and the turbulent kinetic energy increases significantly in the plasma edge [10]. The development of edge sheared flows, first reported by means of Langmuir probe measurements (Fig. 4), has been recently visualized in 2-D by means of Ultra Fast Speed cameras, reflectometry and HIBP measurements.

Bright, long-living structures are frequently seen with a spatial extent of few centimetres. Those structures, previously referred to as "blobs", show predominant poloidal movement with typical speeds in the range of 10^3 - 10^4 m s^{-1}, in agreement with the expected ExB drift rotation direction. In addition, the plasma potential measured by HIBP shows a strong dependence on the plasma density. At plasma densities near the threshold value, evidence of inward radial electric fields has been observed at the plasma edge, whereas in the plasma core the radial electric field (as measured by the HIBP system) remains positive. This result implies the simultaneous development of two sheared flows at the threshold density: one

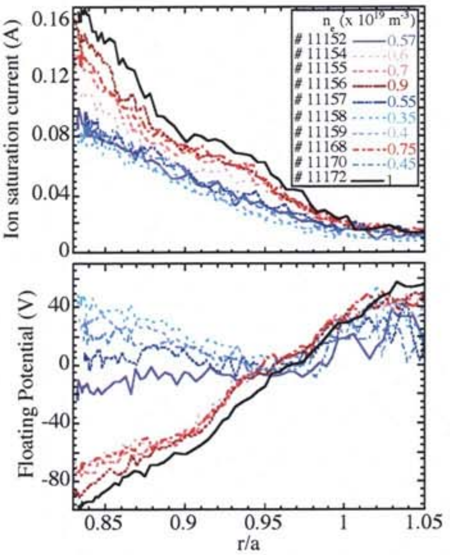

Fig. 4 Edge profiles of ion saturation current and floating potential measured at different plasma densities in the TJ-II stellarator. When plasma density reaches a threshold value (0.55 x 10^{19} m^{-3}) the edge ion saturation current gradient increases, and the floating potential becomes more negative in the plasma edge. Because the edge temperature profile (in the range of 20–40 eV) is rather flat in the TJ-II plasma periphery, the radial variation in the floating potential signals directly reflects changes in the radial electric field [10].

located in the proximity of the LCFS (r/a ≈ 1) (the one investigated by means of probe measurements and fast cameras) and the other one near r/a ≈ 0.7. Reflectometry measurements show that the inner shear layer moves inwards as density increases above the threshold. A wavelet-based method was used to characterize turbulent structures geometry and polarity in different poloidal velocity shear regimes [7]. As sheared flows develop, turbulence structures become stretched which can be interpreted as a modification in the perpendicular degree of turbulence anisotropy. This result is consistent with a basic prediction of the shear decorrelation model (put forward more than 15 years ago).

Recently, it has been shown that experimental results concerning the emergence of the plasma edge shear flow layer in TJ-II can be explained using a simple model for a second order transition based on shear flow amplification by Reynolds stress and turbulence suppression by shearing. In the dynamics of the model, the resistive interchange instability was used. This model predicts a power dependence on density gradients before and after the transition, consistent with experiment [11]. In the framework of this interpretation, the observed spontaneous transitions to improved confinement, triggered by edge sheared flows which organize themselves near marginal stability, could be interpreted as the first step (second order phase transition) leading to an H mode transition.

IV. Flows near marginal stability and energy transfer between flows and turbulence

It has been shown that the magnitude of the spontaneous developed sheared flow (quantified as the radial derivate of the perpendicular phase velocity) is comparable to that measured during biasing-induced improved confinement regimes in the TJ-II stellarator [].This result suggests that in the TJ-II stellarator the spontaneous ExB flows and fluctuations organized themselves close to marginal stability (i.e. the shearing rate is close to the critical value to modify plasma turbulence).

It should be noted that TJ-II results are consistent with previous observations in tokamaks [12] and reversed field pinches [13]. From this perspective, an important question is to identify which mechanism allows fluctuations and sheared flows to organize themselves to be close to marginal stability. Whereas this property is consistent with turbulent driven DC flows [14], it is difficult to understand in which way other mechanisms, like neoclassical mechanisms, can allow sheared flows and fluctuations to reach marginal stability. It is easy to understand why turbulent driven flows (e.g. via Reynolds stress) allow sheared flows and fluctuations to reach marginal stability condition. The Reynolds stress tensor (whose components can be quantified as the cross-correlation of fluctuating velocity components $<\tilde{v}_i\tilde{v}_j>$) allow the interchange of energy (and momentum) between mean flows and fluctuations. Once the Reynolds stress driven sheared flows reach the critical value to modify fluctuations a negative feedback mechanism will be established which will keep the plasma near the marginal stability condition.

Following this argument the degree of anisotropy of fluctuations (quantified as $<\tilde{v}_\perp \tilde{v}_r>$) should be modified during the development of spontaneous sheared flows in the TJ-II stellarator. Experiments using fast cameras in the TJ-II device support this view [7]. Interestingly, gradients in $<\tilde{v}_\perp \tilde{v}_r>$ have been reported near the edge shear region in other devices like JET [9 and references therein].

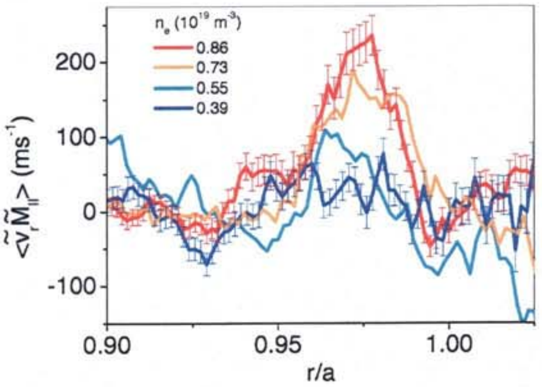

Fig. 5 Radial-parallel Reynolds stress component in the TJ-II plasma boundary region at different densities. Parallel velocity is quantified by the adimensional parallel Mach number.

Recent experiments [15] in the TJ-II stellarator have investigated the evolution of turbulence during edge shear development by quantifying the quadratic term of fluctuating radial and parallel velocities and results are shown in figure 5. Radial variations in $<\tilde{v}_\parallel \ \tilde{v}_r>$are clearly developed in the proximity of the threshold density ($n \approx 0.6 \times 10^{19}$ m^{-3}). The fact that different quadratic terms in fluctuating velocities ($<\tilde{v}_\parallel \ \tilde{v}_r>$ and $<\tilde{v}_\perp \tilde{v}_r>$) changes during edge sheared flow development has an important consequence: shear flow physics involves 3-D physics phenomena in which both perpendicular and parallel dynamics are involved.

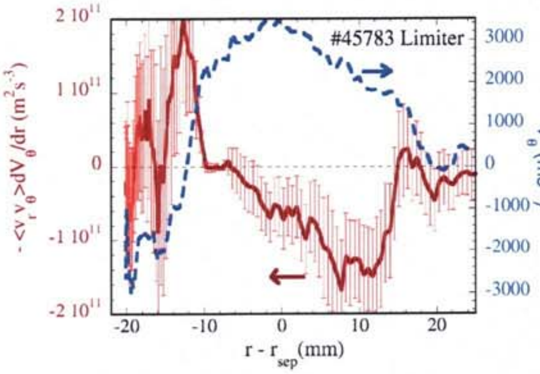

Fig. 6 Radial –perpendicular Reynolds stress component in the plasma boundary region in the JET tokamak.

The radial –perpendicular component of the production term has been investigated in the LCFS vicinity in the JET tokamak [9]. It has been found that the energy transfer from DC flows to turbulence, directly related with the momentum flux (e.g. $<\tilde{v}_\perp \tilde{v}_r>$) and the radial gradient in the perpendicular flow, can be both positive and negative in the proximity of sheared flows (Fig. 6). Furthermore, the energy transfer rate is comparable with the mean flow kinetic energy normalized to the correlation time of turbulence, implying that this energy transfer is significant]. These results show that turbulence can act as an energy sink and energy source for the mean flow near the shear layer, emphasizing the important role of turbulence to understand perpendicular dynamics in the plasma boundary region of fusion plasmas.

More recently experiments in the TJ-II stellarator have investigated the radial-parallel component of the production term, showing the existence of significant parallel turbulent forces at plasma densities above the threshold value to trigger edge sheared flows [15]. This finding provides the first experimental evidence of the role of parallel turbulence forces on edge momentum redistribution in fusion devices.

V. Conclusions

There have been significant changes in the understanding of mechanisms underlying momentum transport in the boundary of fusion plasmas devices, driven partly by diagnostic development and partly by the exploration of novel concepts for transport. It is now clear that intermittent transport cannot be understood without considering the coupling with plasma (sheared) flows.

The link between edge sheared flows and turbulence was investigated in the plasma edge region of stellarator (TJ-II) and tokamak (JET) plasmas. The fact that different quadratic terms in fluctuating velocities ($<\tilde{v}_{\parallel}\,\tilde{v}_r>$ and $<\tilde{v}_{\perp}\,\tilde{v}_r>$) change during edge sheared flow generation means that shear flow physics involves 3-D physics phenomena in which both perpendicular and parallel dynamics are involved.

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