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Generation of sheared poloidal flows via Reynolds stress and transport barrier physics

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Abstract. A view of the latest experimental results and progress in the understanding of the role of poloidal flows driven by fluctuations via Reynolds stress is given. Reynolds stress shows a radial gradient close to the velocity shear layer location in tokamaks and stellarators, indicating that this mechanism may drive significant poloidal flows in the plasma boundary. Observation of the generation of $E \times B$ sheared flows via Reynolds stress at the ion Bernstein resonance layer has been noticed in toroidal magnetized plasmas. The experimental evidence of sheared $E \times B$ flows linked to the location of rational surfaces in stellarator plasmas might be interpreted in terms of Reynolds stress sheared driven flows. These results show that $E \times B$ sheared flows driven by fluctuations can play an important role in the generation of transport barriers.

1. Introduction

Recent progress in the control of plasma turbulence and transport in magnetically confined plasmas has opened a new era in plasma transport physics research [1, 2]. In addition to the generation of edge transport barriers [3], internal transport barriers have allowed the reduction of transport coefficients to a transport rate of collisional processes [4–7]. Both edge and core transport barriers are related with a large increase in $E \times B$ flows with shear [8]. Sheared poloidal flows can influence turbulence by shear decorrelation mechanisms.

Numerous mechanisms on edge and core transport barrier transition physics have been proposed, including ion orbit losses [9], Stringer spin-up [10], critical gradients [11], Reynolds stress [12, 13], magnetic shear [14, 15], and atomic physics [16]. In particular, it has been suggested that Reynolds stress may play a role as a trigger of edge and core transport barriers [17].

In the present paper we study the link between poloidal flows and fluctuations via the Reynolds stress in fusion (tokamaks and stellarators) and non-fusion plasmas.

2. Reynolds stress measurements in tokamaks and stellarators

The phenomenology of the generation of internal and edge transport barriers may suggest that a common physics is involved [2]. Interestingly, these plasma regions show some similarities from the point of view of fluctuations.

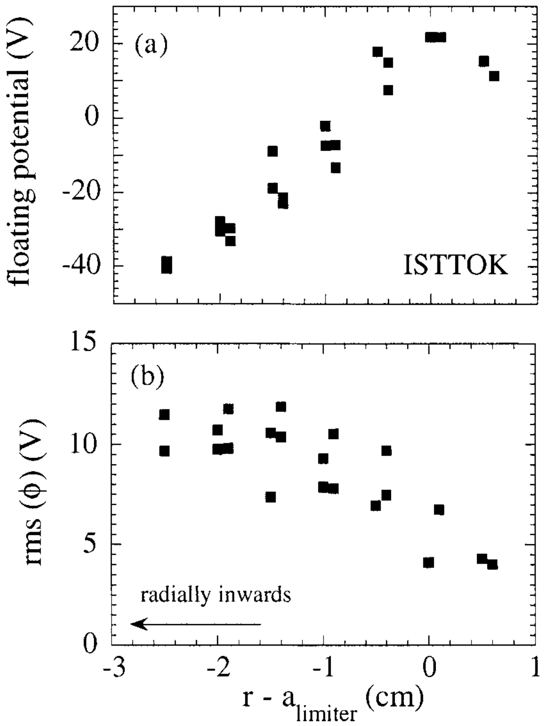

Figure 1. The radial profile of the floating potential and rms value of the fluctuations in the plasma boundary region of the ISTTOK tokamak.

The Reynolds stress measures the degree of anisotropy in the structure of the fluctuations. Radially varying Reynolds stress allows the turbulence to redistribute the poloidal momentum, generating sheared poloidal flows. This is a consequence of the generation of low-frequency fluctuations in the plasma potential via nonlinear energy transfer from high-frequency fluctuations [18].

Significant gradients in the level of fluctuations in the boundary region of magnetically confined plasmas have been reported [19]. Figure 1 shows the radial profile of floating potential and the corresponding root mean square (rms) fluctuations in the edge region of the ISTTOK tokamak [20]. The floating potential becomes more negative and the rms fluctuation level increases in the plasma edge region. The poloidal phase velocity shows a change in the propagation direction of fluctuations from the ion drift direction in the outer edge of the plasma to the electron drift direction in the plasma edge [20]. This result can be interpreted in terms of a change in the sign of the radial electric field. The large gradients in the level of fluctuations can contribute to the radial–poloidal non-isotropy of the turbulence (i.e. $\mathrm{d}\langle\tilde{v}_r\tilde{v}_\theta\rangle/\mathrm{d}r$ is not zero) [12, 13]. In the plasma core region, a modification in the degree of anisotropy in the radial–poloidal structure of fluctuations might occur near rational surfaces, where fluctuations are expected to show maximum amplitude [21, 22]. This common feature may suggest a similar basic mechanism of the edge and core transport barriers. The mechanism of Reynolds stress driven flows may also explain the initial role of poloidal flows in the change of the radial electric field in edge and core transport barrier formation followed by the dominance of a pressure gradient contribution in the radial electric field [2]. However, there are some barriers where the toroidal rotation shear is the dominant effect [8].

Recent experimental work has been carried out to quantify the importance of the Reynolds stress driven flows in tokamaks and stellarators using multiarrays of Langmuir probes [20, 23–25]. The experimental set-up consists of two arrays of three Langmuir probes, radially separated to measure the radial electric field. Two tips of each set of probes, aligned perpendicular to the magnetic field and poloidally separated, were used to measure the poloidal electric field. This experimental set-up can provide measurement of the radial and poloidal electric field fluctuations in a plasma volume smaller than the typical correlation volume of fluctuations. The $\langle \tilde{v}_r \tilde{v}_\theta \rangle$ term of the electrostatic Reynolds stress can be related to the $E \times B$ velocities, and experimentally computed as

$$R = \langle \tilde{v}_r \tilde{v}_\theta \rangle = \langle \tilde{E}_r \tilde{E}_\theta \rangle / B^2$$

$\tilde{E}_r$ and $\tilde{E}_\theta$ being the radial and poloidal components of the fluctuating electric field and B is the toroidal magnetic field.

The electrostatic component of the Reynolds stress has computed, neglecting the influence of electron temperature, in the plasma boundary region of the ISTTOK tokamak and TJ-IU stellarator [20, 24]. Electron temperature fluctuations could modify the absolute value of the measured electrostatic Reynolds stress. However, considering that the radial profile of the floating potential fluctuations is closely correlated with the level of the plasma potential fluctuations [26], the radial gradient in Reynolds stress is not expected to be significantly modified by T_e fluctuation effects.

In both devices, the electrostatic Reynolds stress shows radial gradients in the proximity of the velocity shear layer (figure 2). A quantitative estimation of the fluctuation-driven flows with the magnitude of poloidal flow damping mechanisms (magnetic pumping and charge exchange) shows that these mechanisms can play a significant role in explaining the physics of poloidal flows [20]. In particular, the damping term due to magnetic pumping in the plasma edge region can be expressed as $\gamma_{\mathrm{mp}} v_{\mathrm{i}\theta}$, where $v_{\mathrm{i}\theta}$ is the ion poloidal velocity. For ISTTOK edge plasma parameters, γ_{mp} is expected to be in the range 10^4 s^{-1}. Assuming $v_{\mathrm{i}\theta}$ of the order of the $E \times B$ poloidal velocity ($v_\theta \approx 10^3$ m s^{-1}), the contribution of the magnetic pumping to the time evolution of the poloidal flow is about 10^7 m s^{-2}. The present experiments show that the radial gradient of $\langle \tilde{v}_r \tilde{v}_\theta \rangle$ (i.e. $\mathrm{d}R/\mathrm{d}r$) is of the order of 10^7–10^8 m s^{-2} in the proximity of the velocity shear layer. This suggests the importance of fluctuation-induced flows in the plasma edge region of the ISTTOK tokamak. Work is underway to study the role of Reynolds stress during the L–H transition in tokamak and stellarator devices.

The transport barrier formation is generally characterized by a power threshold. The scaling properties of the transport barrier thresholds have been investigated in different devices [27]. The role of collisionality, ion orbit losses, atomic physics and turbulence has been considered to explain the driving and damping mechanisms of $E \times B$ sheared flows during the transition. In the framework of $E \times B$ flows driven by fluctuations this power threshold may be understood as follows [17]. When the level of the fluctuations is large enough to drive a critical sheared flow, the transition to an improved confinement regime takes place. The level of fluctuations depends on the free energy source for fluctuations (i.e. gradients) and gradients are directly related with the power input. In this way, this mechanism implies a power threshold for transport barrier formation.

3. Rational surfaces and $E \times B$ sheared flows

The operational flexibility and the control of the magnetic topology in stellarator devices make them unique tools to investigate the role of rational surfaces on transport. In the TJ-II stellarator this flexibility is provided by the central conductors, which consist of circular and helical coils

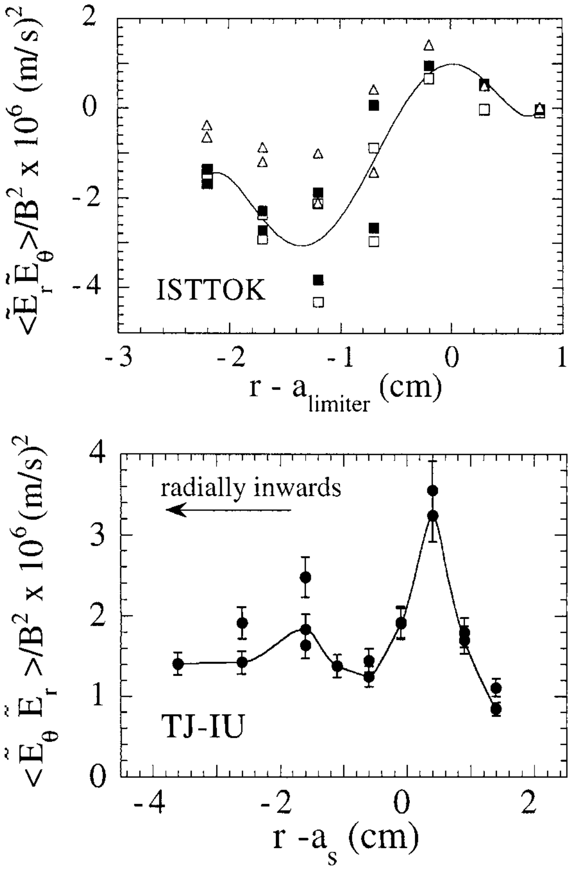

Figure 2. The radial profile of the electrostatic Reynolds stress in the TJ-IU torsatron and the ISTTOK tokamak in the proximity of the velocity shear layer (a_s) and limiter radius (a_{limiter}).

[28]. TJ-II is a low magnetic shear stellarator of the heliac type, with an average major radius of 1.5 m and an average minor radius less than 0.22 m. The existence of closed and nested magnetic surfaces is in good agreement with the calculated surfaces as has been demonstrated by magnetic surface measurements [29]. Experiments reported in this paper were carried out in ECRH plasmas ($f = 53.2$ GHz, $P_{\mathrm{ECRH}} \approx 300$ kW) [28].

To study the effect of the rational surfaces on the radial electric field we have chosen the plasma configuration with iota (a) ≈ 1.6 and focused in the $n = 8/m = 5$ resonance which is located near the last closed flux surface. In this plasma region, Langmuir probes can be used to investigate the structure of plasma profiles and electric fields with good spatial resolution [30]. The location of the natural 8/5 resonance, as predicted by field line vacuum calculations, coincides with a flattening in the edge plasma profiles (figure 3) [31]. There is a significant variation in the floating and plasma potential just outside the flattening region. These results can be interpreted as an increase of the sheared $E \times B$ flow linked to the radial location of the 8/5 rational surface with a resulting a radial gradient $(\mathrm{d}E_r/\mathrm{d}r)B^{-1}$ of about 10^5 s^{-1}. This value turns out to be comparable to the inverse of the decorrelation time of fluctuations usually measured [32]. These experimental results illustrate the impact of the rational surfaces on the $E \times B$ sheared flows, which could explain the spontaneous formation of transport barriers near the rational surfaces.

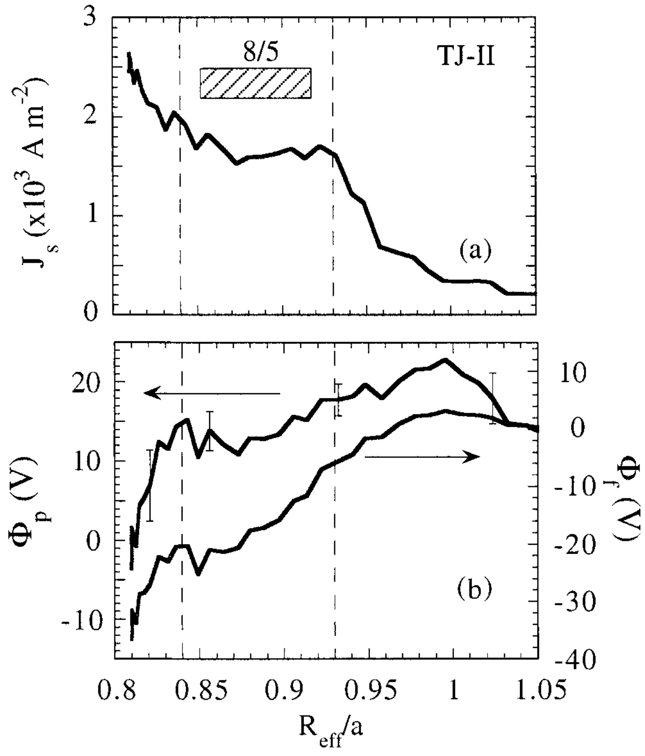

Figure 3. The radial profile of the ion saturation density current (J_s), floating and plasma potential in a plasma configuration with a low-order resonance (8/5) located near the plasma boundary in the TJ-II stellarator.

Understanding the mechanisms which drive the $E \times B$ sheared flows linked to rational surfaces is an important physics issue in tokamaks and in shearless stellarator devices. At least two mechanisms should be considered for the generation of $E \times B$ flows at resonant surfaces: the $E \times B$ flows driven by the ion–electron flux difference created in the vicinity of rational surfaces [33] and the $E \times B$ sheared flows driven by fluctuations via Reynolds stress [34].

4. Reynolds stress measurements and ion Bernstein wave heating

The generation of poloidal flows by ion Bernstein waves (IBW) has been investigated in the Thorello device [35]. The main goal of the Thorello toroidal magnetized plasma ($R = 0.40$ m, $B \approx 0.2$ T) is to study basic plasma–wave interaction phenomena. Typical plasma parameters are: plasma density 10^{11} cm^{-3} and electron temperature 3–5 eV. IBW are launched by means of a slow-wave antenna system composed of four blades in the plasma edge region. Previous measurements of plasma fluctuations in the Thorello device have shown fluctuation levels in density and potential up to 40% [36].

The radial profile of Reynolds stress has been measured with different IBW heating powers in the proximity of the resonance layer, using the multi-arrays of Langmuir probes. The gradient in the Reynolds stress increases at the resonance layer with RF power ($f = 13.3$ MHz, fourth harmonic) (figure 4). Consistent with these results, the radial electric field and the poloidal phase velocity of fluctuations are modified at the RF resonance layer as to RF power increases

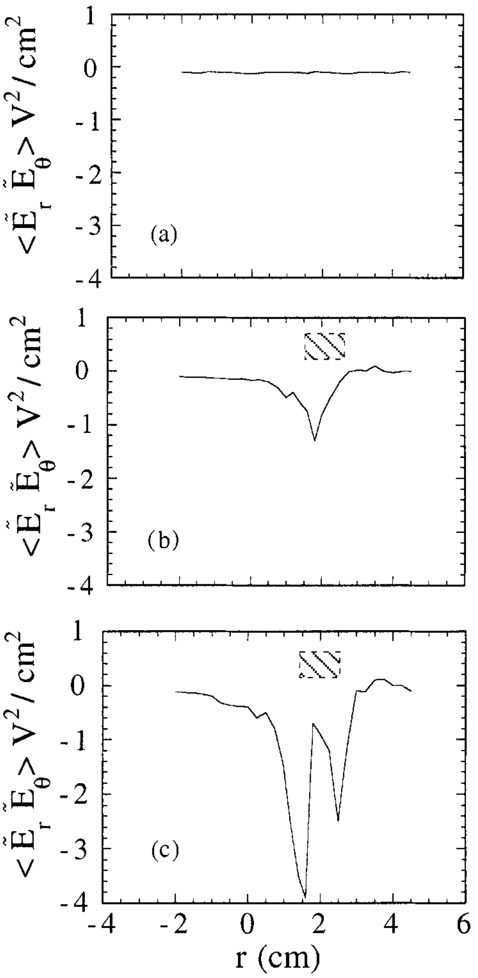

Figure 4. Radial profile of the Reynolds stress in the Thorello device as the RF power increases: (a) $P_{\mathrm{RF}} = 0$ W, (b) $P_{\mathrm{RF}} = 5$ W and (c) $P_{\mathrm{RF}} = 10$ W. The shaded area indicates the RF resonance region.

[35]. These experimental results have provided experimental evidence for the generation of poloidal flows driven by fluctuations via Reynolds stress [37].

5. Conclusions

The important role of the magnetic topology in the generation of transport barriers may be understood in terms of the generation of $E \times B$ flows linked to rational surfaces and to the proximity to the last closed flux surface. Flows driven by fluctuations can play an important role as a trigger of transport barrier formation.

The radial profile of Reynolds stress has been measured in the plasma boundary region of tokamaks and stellarator plasmas. The electrostatic Reynolds stress shows a radial gradient close to the velocity shear layer location, showing that this mechanism can play a significant role in explaining the physics of poloidal flows in the plasma boundary.

Observation of the $E \times B$ sheared flows via Reynolds stress at the IBW resonance layer has opened up a new bridge between experimental measurements and theoretical models to understand the underlying physics of improved confinement regimes using rf heating in magnetically confined plasmas.

The possible role of rational surfaces in accessing high-confinement regimes in fusion plasmas should be considered. The resulting $E \times B$ sheared flows associated with rational surfaces would depend on the competition between the driving flow mechanisms and the damping flow process (i.e. magnetic viscosity). When the $E \times B$ sheared flow reaches a critical value a spontaneous transport barrier may be formed in the proximity of the rational surfaces.

Further investigation on the scaling of Reynolds stress and poloidal flows with plasma parameters (i.e. heating power) are needed to quantify the importance of the Reynolds stress as compared with other mechanisms (i.e. ion orbit losses in the plasma edge). The experimental investigation of Reynolds stress should consider the measurement of the degree of poloidal–radial anisotropy in the structure of fluctuations and the study of the nonlinear energy transfer from high- to low-frequency fluctuations [38]. The application of nonlinear analysis tools to detect the phase coherence between high- and low-frequency fluctuations might provide more insight into the physics of poloidal flows driven by fluctuations.

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