ON THE INTERPLAY BETWEEN TURBULENCE AND POLOIDAL FLOWS IN PLASMAS

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Abstract

The radial profile of Reynolds stress has been measured in the plasma boundary region of tokamaks and stellarator plasmas. The electrostatic Reynolds stress (proportional to $<\tilde{E}_r \tilde{E}_\theta>$) shows a radial gradient close to the velocity shear layer location, showing that this mechanism can drive significant poloidal flows in the plasma boundary region of fusion plasmas. The generation of poloidal flows by Ion Bernstein Wave (IBW) is under investigation in toroidal plasmas. The radial gradient in the Reynolds stress increases with RF power and radial electric fields are modified at the RF resonance layer.

I. INTRODUCTION

Poloidal flows have been found to play an important role in the transition to improved confinement regimes in fusion plasmas [1]. Sheared poloidal flows can influence the turbulence by shear decorrelation mechanisms and, as a consequence, modify transport. Different mechanisms have been proposed to explain the generation of sheared poloidal flows in the plasma edge region. An important mechanism is the ion orbit loss caused by interaction with the limiter [2]. A complementary explanation is the generation of poloidal flows by plasma fluctuations via the Reynolds stress [3-4] and the poloidal spin-up of plasmas from poloidal asymmetry of particle and momentum sources [5]. More recently it has been argued that turbulence driven fluctuating zonal flows can reduce turbulent transport [6].

In the present paper we have studied the link between poloidal flows and fluctuations via the Reynolds stress in fusion (tokamaks and stellarators) and non-fusion plasmas. The experimental results will be compared with theoretical calculations of resistive interchange and ballooning turbulence induced poloidal flows. In addition, the generation of poloidal flows by Ion Bernstein Wave (IBW) is under investigation in toroidal plasmas.

II. REYNOLDS STRESS MEASUREMENTS IN TOKAMAKS AND STELLARATORS

The radial profile of the fluctuation driven flows via Reynolds stress is under investigation in the plasma boundary region of the TJ-IU torsatron (l=1, m=6, P_{ecrh} = 200 kW, f_{ecrh} = 37.5 GHz, iota (0) = 0.23, R = 0.6 m, a = 0.1 m, B_t = 0.67 T, $n_{line} \approx 0.5 \times 10^{13}$ cm^{-3}), ISTTOK (R

= 0.46 m, B ≈ 0.5 T, $I_p \approx 6$ kA) and JET (B = 2.6 T, Ip = 2 - 2.6 MA) tokamaks using multi-arrays of Langmuir probes.

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. The probes were oriented with respect to the magnetic field direction to avoid shadows between them. This experimental set-up provides a measurement of radial and poloidal electric field fluctuations in a plasma volume smaller than the typical correlation volume of fluctuations. The $<\tilde{v}_r \tilde{v}_\theta>$ term of the electrostatic Reynolds stress has been related to the ExB velocities, and experimentally computed as

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

$\tilde{E}_r$ 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 been computed neglecting the influence of electron temperature fluctuations.

Figure 1 shows the radial profile of the poloidal phase velocity of fluctuations, floating potential (ϕ), and the level of rms fluctuations in the floating potential in the boundary of the TJ-IU torsatron and ISTTOK tokamak. In both devices the floating potential becomes more negative and the ion saturation current increases as the probe is inserted into the plasma edge. The level of rms fluctuations in the floating potential fluctuations is in the range (4-12) V. Fluctuations are dominated by frequencies below 200 kHz. As observed in other devices, the radial electric field is sheared in the proximity of the velocity shear layer. From the S(k,ω) function, computed from the two-point correlation technique using two floating potential signals, the average poloidal phase velocity of fluctuations is defined as, $v_\theta = \Sigma_{\omega,k}(\omega/k)S(\omega/,k)/\Sigma_{\omega,k}S(\omega,k)$. In both devices, the poloidal phase velocity of fluctuations reverses from the ion drift direction in the SOL region to the electron drift direction in the plasma edge region. In the proximity of the velocity shear layer ($r = a_{shear}$) the electron density is about (0.5 - 1) x 10^{18} m^{-3} in both devices. In the plasma edge region ($r - a_{shear} \approx 1$ cm) the electron temperature increases up to 50 eV in ISTTOK and up to 30 eV in TJ-IU.

Figure 2 shows the radial profile of the Reynolds stress in the boundary of the TJ-IU torsatron and ISTTOK tokamak. The radial gradient in the Reynolds stress is maximum (dR/dr ≈ 10^8 ms^{-2}) in the proximity of the shear layer location. Preliminary experiments have shown dR/dr ≈ 10^7 ms^{-2} in the Scrape-Off Layer Side of the velocity shear layer location in JET tokamak plasmas. Work is underway to study the radial structure of the Reynolds stress at the L-H transition in the plasma boundary region in JET.

The importance of fluctuation induced flows in the evolution of the poloidal flow requires a comparison with the magnitude of the flows driven or damped by other mechanisms. The damping term due to magnetic pumping in the plasma edge region is $\gamma_{MP} v_{i\theta}$, where $v_{i\theta}$ is the ion poloidal velocity. For JET and ISTTOK edge plasma parameters, γ_{MP} is expected to be of the order $\nu_{ii} \approx 10^4$ s^{-1}. Assuming $v_{i\theta}$ of the order of the ExB poloidal velocity ($v_\theta \approx 10^3$ m s^{-1}), the contribution of magnetic pumping to the time evolution of the poloidal flow is comparable to the contribution of fluctuations via Reynolds stress. The damping of the poloidal rotation due to atomic physics (charge exchange) can be expressed as $\nu_{iCX} v_{i\theta}$, where ν_{iCX} is the momentum loss rate due to charge exchange mechanisms. For typical edge plasma conditions it follows that the contribution of atomic physics to the time evolution of the poloidal flow is in the range of 10^7 m s^{-2}. For the SOL region, an important influence of the radial electric field caused by the sheath conditions at the target plates is expected. These results suggest the importance of fluctuation induced flows in the plasma boundary region of fusion plasmas.

In contrast, the magnetic component of the Reynolds stress (proportional to $<\tilde{B}_r\ \tilde{B}_\theta>$) is negligible in the plasma boundary region of the TJ-IU torsatron, due to the relative phase (≈π/2) between poloidal and radial fluctuating components of the magnetic fields.

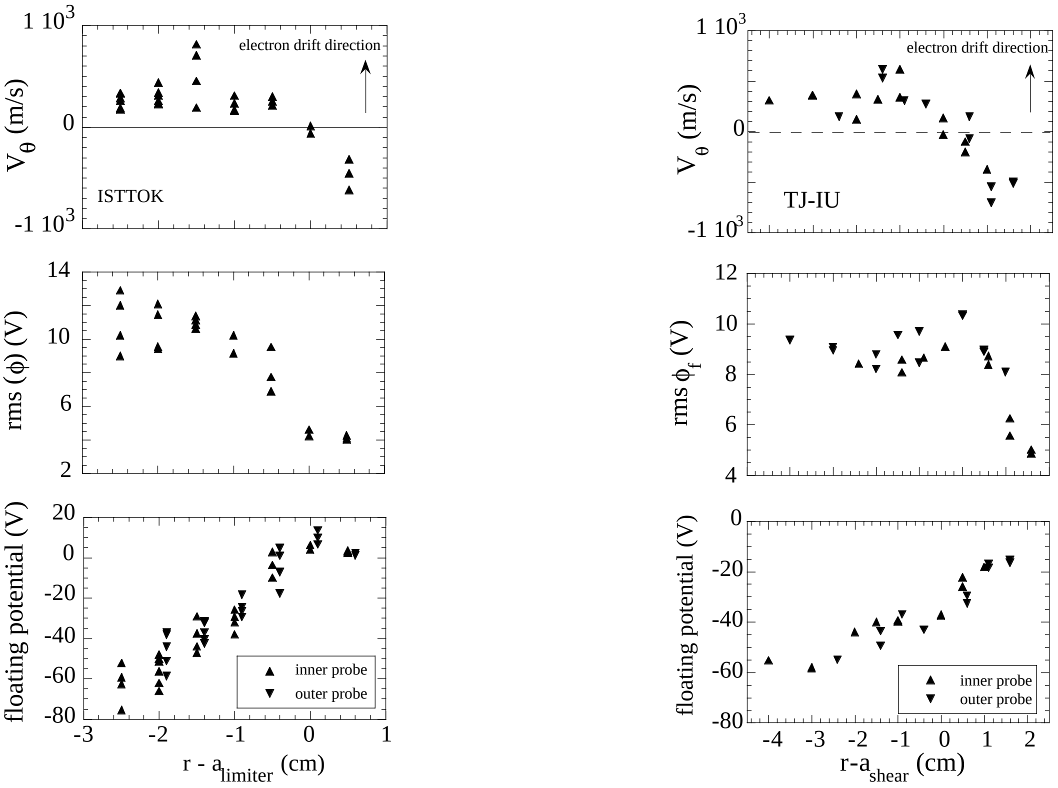

Fig. 1. Radial profile of phase velocity of fluctuations (v_θ), root mean squared (rms) value of floating potential fluctuations and floating potential in the plasma boundary region of TJ-IU torsatron and in the ISTTOK tokamak.

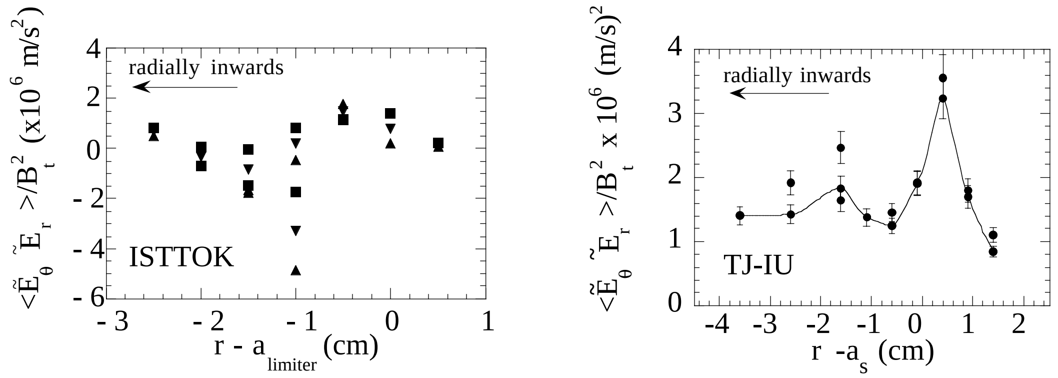

Fig. 2 Cross-correlation between poloidal and electric field fluctuations in the TJ-IU torsatron and in the ISTTOK tokamak.

The poloidal flow generation by different instabilities is under investigation. We have found that the Reynolds stress has two terms: one is proportional to the poloidal flow velocity, and leads to a dynamo instability and the generation of sheared flow. The second one is an effective turbulent viscosity and damps poloidal flow. For resistive interchange turbulence in stellarators, the Reynolds stress is dominated by the second term. Similar calculations are in progress for ballooning modes in tokamak geometry.

III. REYNOLDS STRESS AND ION BERNSTEIN WAVE HEATING

The generation of poloidal flows by Ion Bernstein Wave (IBW) is under investigation in Thorello device. 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 [7]. Typical plasma parameters are: plasma density 10^{11} cm^{-3} and electron temperature (3 - 5) eV. Ion Bernstein waves 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 Thorello device have shown fluctuation levels in density and potential up to 40% [8].

The radial profile of Reynolds stress has been measured with different ion Bernstein wave 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, 4th harmonic) (see figure 3). In consistency with these results, the radial electric field is modified at the RF resonance layer as RF power increases. Further experiments are underway in the Thorello device to study the influence of plasma conditions (neutrals, RF power) on the Reynolds stress, radial electric fields and poloidal flows. These experiments would explore, from the experimental point of view, the possibility of active suppression of turbulence, via Reynolds stress, by externally driven IBW.

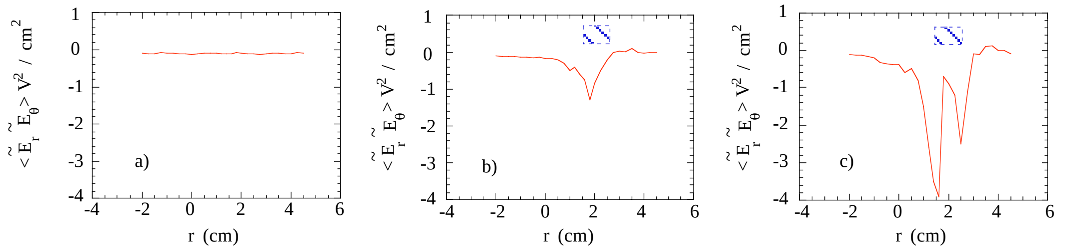

Fig. 3 Radial profile of the Reynolds stress in the Thorello device as RF power increases: $P_{RF} = 0$ W(a); $P_{RF} = 4$ W (b); $P_{RF} = 20$ W (c). The shaded area indicate the RF resonance region.

ACKNOWLEDGEMENTS

This research was sponsored in part by DGICYT (Dirección General de Investigaciones Científicas y Técnicas) of Spain under Project N° PB96-0112-C02-02.

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