# Experimental investigation of ExB sheared flow development in the TJ-II stellarator

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## 1.- Introduction

Experiments in the TJ-II stellarator have shown that the generation of spontaneous perpendicular sheared flow (i.e. naturally occurring shear layer) requires a minimum plasma density. Near this threshold density, the level of edge turbulent transport and the turbulent kinetic energy significantly increase in the plasma edge. Above this threshold value, the level of turbulence decreases with a concomitant development of ExB sheared flow that can be observed as a sharp change of the floating potential[1,2]. Recent experiments carried out in the LHD stellarator have shown that edge sheared flows are also affected by the magnitude of edge magnetic ripple: the threshold density to trigger edge sheared flows increases with magnetic ripple[3]. Those results have been interpreted as an evidence of the importance of neoclassical effect in the physics of ExB sheared flows.

## 2.- Experimental Set-up

Experiments were carried out in Electron Cyclotron Resonance Heated plasmas ($P_{ECRH}$= 200 - 400 kW, $B_T$ = 1 T, R = 1.5 m, <a> ≤ 0.22 m, ι(a)/2π ≈ 1.6 – 2.1) created in the TJ-II stellarator. Plasma density was in the range (0.35 – 1) x $10^{19}$ $m^{-3}$. Radial profiles were measured at the plasma edge region using Langmuir/Mach probes[4], reflectometry[5] and Heavy ion beam diagnostic (HIBP)[6]. A Princeton Scientific Instruments intensified camera with CCD sensor (PSI-5) with $H_\alpha$ filter, recording up to 250.000 frames per second, 64 by 64 pixels resolution and 1.2ms total recording time at maximum speed[7] was also used.

## 3.- Characterization of edge ExB sheared flow by multiple diagnostics in TJ/II

Radial plasma profiles and fluctuations studied by means of Lagmuir probes have previously shown that the existence of sheared edge flow in TJ-II requires a minimum plasma density (or plasma gradient) (Fig 1a). It has been also pointed out that there exists a link between the development of sheared flow and plasma edge turbulence in TJ-II[1,2].

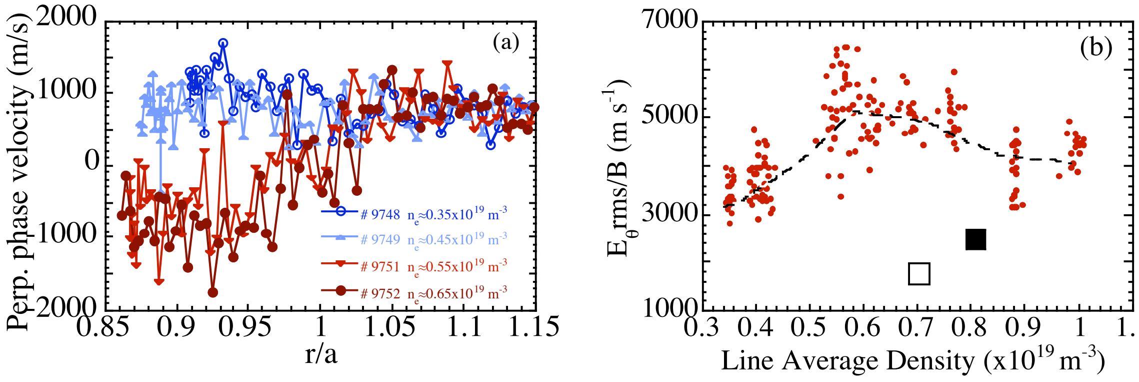


*Fig.1- (a) Radial profiles of the perpendicular phase velocity for different plasma density. (b) Behaviour of the perpendicular radial velocity as a function of the density. The open square corresponds to biasing experiment and closed one to naturally obtained improved confinement regime results (see section 4). Line is a guide for the eye.*

As density was increased in the range (0.35 – 1) x $10^{19}$ $m^{-3}$ ion saturation current increases and floating potential decreases. A sharp change in both magnitudes can be observed around the density threshold together with a maximum in the level of fluctuations of the ion saturation current and in the fluctuations of the perpendicular electric field, that means turbulent radial velocity ($\tilde{v}_r = \tilde{E}_\theta \,/\, B$) (Fig 1b). The local turbulent particle flux also shows an increase near the critical density[2]. In consistency with these results the perpendicular phase velocity reverses sign in the proximity of the Last Closed Flux Surface (LCFS). Shearing rate increases as density increases above the critical value (during sheared flow development) and remains constant for higher density values. It is remarkable that the observed shearing rates during improved confinement regimes are comparable to those observed associated to the naturally occurring shear layer[8].

The reversal in the ExB rotation has been recently 2-D visualized by means of Ultra Fast Speed cameras (Fig. 2). The view plane is in a near-poloidal cross-section with optimized B-field perpendicularity. Neutral recycling at the poloidal limiter is used to light up the outer plasma region (r/a≈ 0.8-1). Bright, long-living structures are frequently seen with a spatial extent of few centimetres. These "blobs" show predominant poloidal movements with typical speeds of $10^3$ - $10^4$ m $s^{-1}$ in agreement with the expected ExB drift rotation direction. In addition it has been shown that the degree of order (quantify as the root mean squared value in the orientation of turbulent blobs) increase once sheared flow is fully developed.

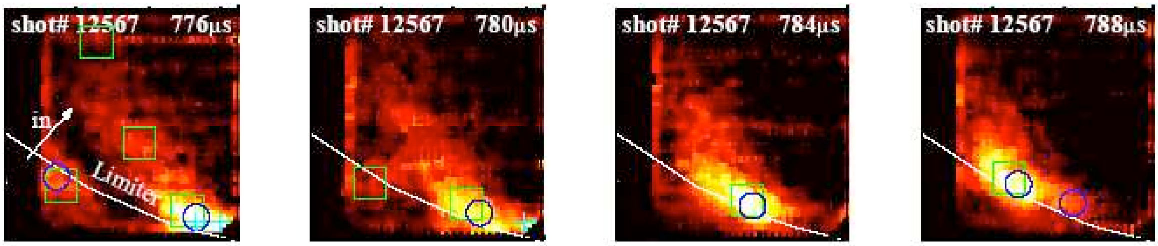


*Fig. 2.- Poloidal movement and position of located blobs (big scale-green squares, medium scale-blue circles, small scale-light blue pluses).*

HIBP measurements in ECR heating plasmas show that the plasma potential increases up to 1 kV near the magnetic axis (i.e. radial electric fields are radially outwards). In addition, the plasma potential shows a strong dependence on the plasma density. At plasma densities near the threshold value evidence of radially inwards edge radial electric fields has been observed, whereas in the plasma core the radial electric field remains positive. This result implies the simultaneous development of two sheared flows at the threshold density: one located in the proximity of the LCFS (r/a ≈ 1) and the other one near r/a ≈ 0.6 (Fig. 3a).

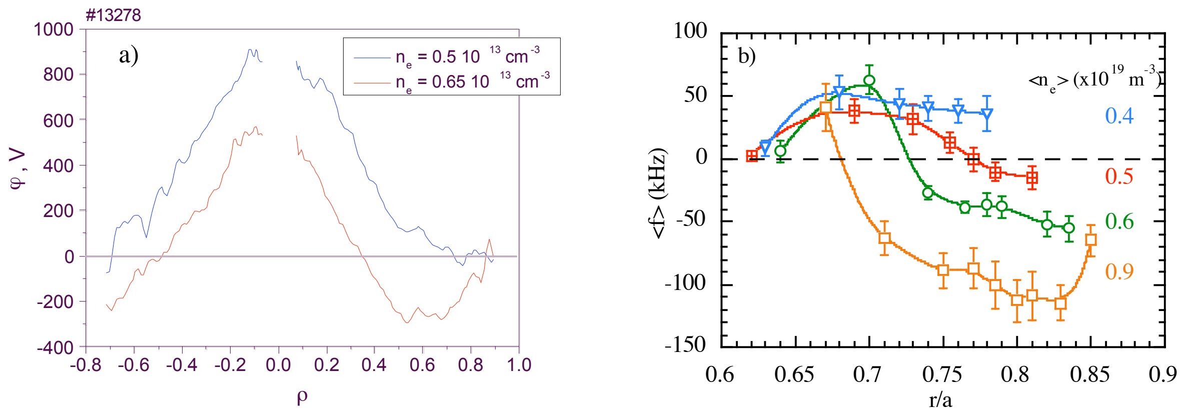


*Fig. 3.- a) Plasma potential measured by HIBP at two plasma density values. b) Mean frequency of the spectra vs. cut-off radius increasing density.*

The reversal in the perpendicular phase velocity is also seen in the reflectometer signals. Measurements also show that when the velocity shear layer develops at the plasma edge, simultaneously, a second velocity shear layer appears at $\rho = r/a \approx 0.8$ that moves to inner radial locations when the plasma density further increases (Fig. 3b).

**4.- Influence of the magnetic configuration**

The link between the development of sheared flows and plasma density in TJ-II has been observed in different magnetic configurations and plasma regimes. Preliminary results show that the threshold density value to develop the sheared flow increases with the plasma stability (iota) and also increases as edge ripple (plasma volume) decreases. This behaviour with ripple looks opposite to recent results from LHD stellarator (Fig. 4).

Recent experiments have shown that for some magnetic configurations with higher edge iota (ι/2π≥1.8) there is a sharp increase in the edge density gradient simultaneous to a strong reduction of fluctuations and transport and a slight increase of the shearing rate and perpendicular rotation (≥2 km/s) as density increases above the threshold. The measured level of fluctuations in these conditions is lower than the obtained for the biasing-induced improved confinement regime (see squared symbols in Fig. 1b). The role of the edge ripple and kinetic effects, the presence of rational surfaces, and properties of turbulent transport are considered as possible ingredients for this spontaneous trigger of the sheared flow-improved regime in the TJ-II stellarator.

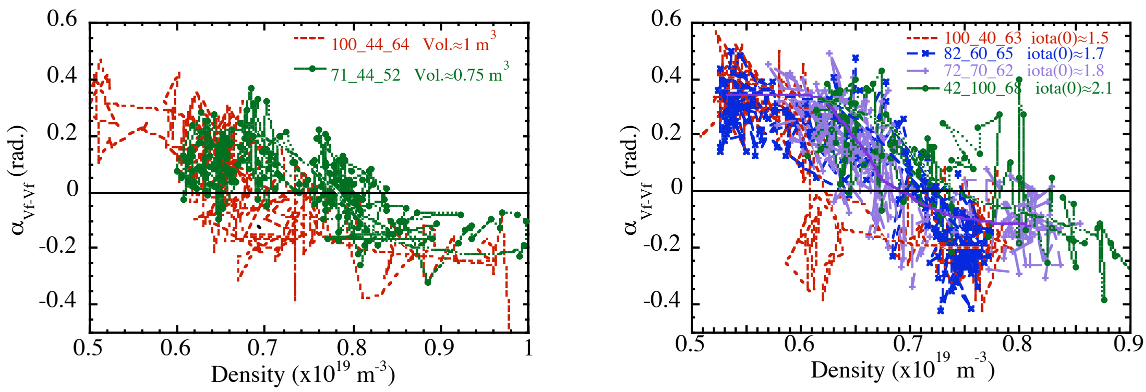


*Fig. 4.- Plasma volume and iota effects on the threshold density value. Figure shows the phase between two floating potential signals poloidally separated 0.3 cm for different plasma density values. Measurements were taken at the plasma edge (r/a≈0.85-1). Lines are guides for the eye.*

It seems that plasma is on the verge to jump to an improved confinement regime and a small change of the edge radial electric field, internal (via fluctuations) or externally driven could be enough to reach this state. Whether there is a common physics to explain the sensitivity of edge plasma potential and flows to plasma density in tokamak[9] and stellarator[10] (e.g. turbulent versus neoclassical mechanisms) remains as an open question.

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