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On the Link between E×B Sheared Flows and Rational Surfaces in Fusion Plasmas

On the Link between E×B Sheared Flows and Rational Surfaces in Fusion Plasmas

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ABSTRACT

Experimental evidence of flattening in plasma profiles has been observed in the edge region of the JET tokamak. This observation has been interpreted in terms of the influence of rational surfaces on plasma profiles. In the framework of this interpretation, significant ExB sheared flows linked to rational surfaces have been identified. These ExB sheared flows are close to the critical value to trigger the transition to improved confinement regimes. These results can explain the link between the magnetic topology and the generation of transport barriers reported in fusion devices

Recent progress in the control of plasma turbulence and transport has allowed the generation of edge and core transport barriers in magnetically confinement plasmas [1, 2]. Both edge and internal transport barriers are related with a large increase in the ExB flows with shear [3]. Transport barriers are linked to plasma regions with a unique plasma topology. In the plasma edge, the magnetic topology changes from a configuration with open field lines (Scrape off layer) to a region with nested magnetic surfaces. In the core plasma region, internal tranport barriers are though to be related with the presence of rational surfaces and with magnetic shear [4-9]. In particular, spontaneous generation of ITB near q=3 have been reported in the JT-60U tokamak [4]. In the JET tokamak, robust transport barriers are formed when the q=2 surface is located in the plasma core [8].

In stellarator plasmas, confinement properties are strongly linked with the magnetic topology of the magnetic trap. The presence of rational surfaces can cause the formation of island or magnetic ergodic regions, which, in some cases, can degrade the quality of confinement. On the other hand, experimental evidence of ExB sheared flows linked to rational surfaces has been observed in the TJ-II stellarator [9, 10] which have been interpreted in terms of Reynolds stress sheared driven flows [11]. Recent experiments have shown the possible influence of magnetic islands in the formation of edge transport barriers in stellarators [12]

In this paper we present experimental evidence of ExB sheared flows linked to rational surfaces in the plasma edge region of the JET tokamak.

Plasmas studied in this paper were produced in X-point configuration with toroidal magnetic fields $B_T = (1 – 2)$ T, plasma current $I_p = (1 – 2)$ MA, $P_{NBI} = 0 – 2$ MW and densities in the range $n = (2 – 3) \times 10^{19}$ m^{-3}. The position of the last closed flux surface (LCFS) was determined by the equilibrium code EFIT [13] and pressure balance analysis between target and reciprocating probes located in the top region of the device [14]. Plasma profiles and turbulence have been investigated in the JET plasma boundary region using a fast reciprocating Langmuir probe system located on the top of the device [15]. The experimental set-up is shown in fig.1. Nine Langmuir probes have been arranged in three groups of three. Two of them are at the same poloidal position, being separated 0.5 cm in the radial direction. This set-up allows investigation of the radial

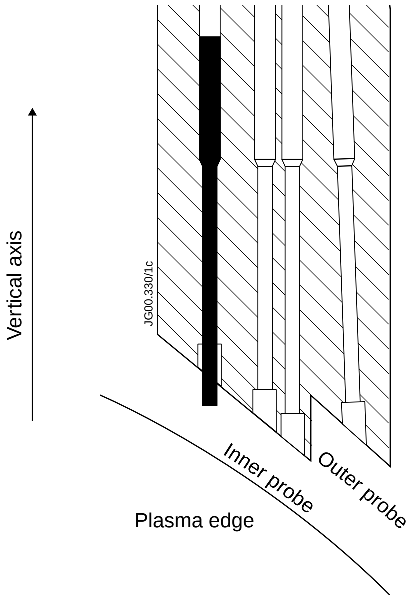

Fig.1: Schematic view of the probe head used for fluctuation studies in JET tokamak, showing the inner and outer probe tips in the vertical direction.

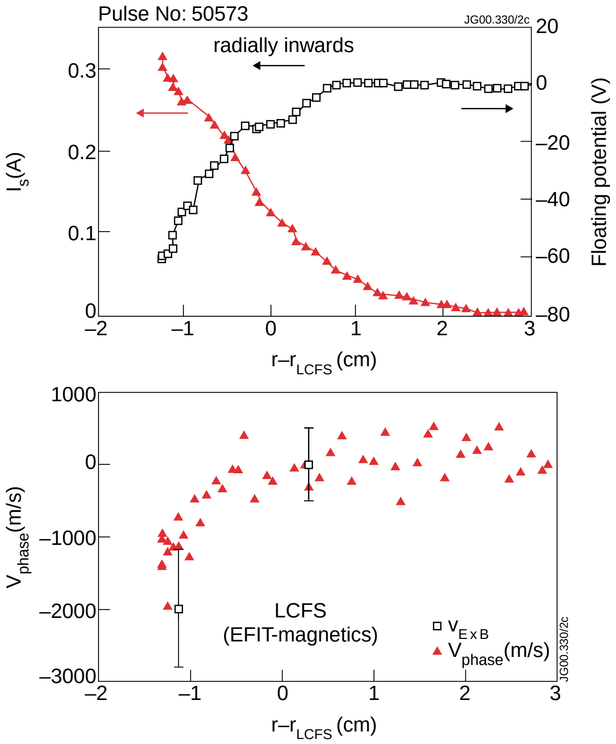

Fig.2: Ion saturation current, floating potential and poloidal phase velocity of fluctuations for the # 50673 (B_T = 2 T, I_p = 2 MA).

structure of fluctuations, using the inner and outer probes as shown in fig.1. Plasma fluctuations are investigated using standard signal processing techniques and 500 kHz digitizers. Plasma profiles are plotted against the distance from the LCFS mapped to the outer mid-plane.

Typically, ion saturation current (I_s) and floating potential (Φ_f) show a smooth increase as the probe moves radially inwards in the plasma edge. This behavior is shown in fig.2 for the shot 50573 (B_T = 2 T, I_p = 2 MA). Electron temperature has been measured using the swept probe method (0.1 kHz rate), showing values in the range 20 – 40 eV near the LCFS [16]. The mean velocity of fluctuations perpendicular to B_T has been computed as $v_{phase} = \Sigma\ S(k,\omega)\ (k/\ \omega)/\Sigma\ S\ (k,\ \omega)$ [17], with the two point correlation technique using floating probes separated 5 mm in the poloidal direction. A velocity shear layer has been observed near the location of the LCFS (as determined from magnetic measurements-EFIT). The poloidal phase velocity of fluctuations (v_{phase}) is small in the SOL region. In the plasma edge region, just inside the separatrix, v_{phase} increases in the electron drift direction up to 1000 m/s. This change can be explained in terms of ExB drifts.

On the other hand, experiments carried out in plasma configurations with B_T = 1 T, I_p = 1 MA and q_{95} = 3.3 have shown clear evidence of flattening in density and floating potential profiles with a radial extension of about 1 cm in the edge plasma boundary region (Fig.3 and 4). In this region, the cross correlation of fluctuations shows a quasi-coherent mode (Fig.5). It should be noted that in these shots there is a good agreement beween the location of the last closed flux

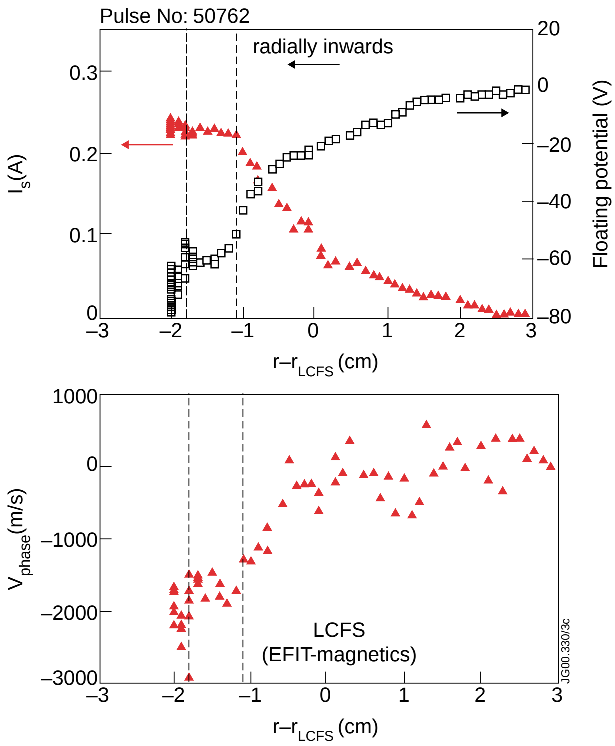

Fig.3: Ion saturation current, floating potential and poloidal phase velocity of fluctuations for the # 50762 (B_T = 1 T, I_p = 1 MA).

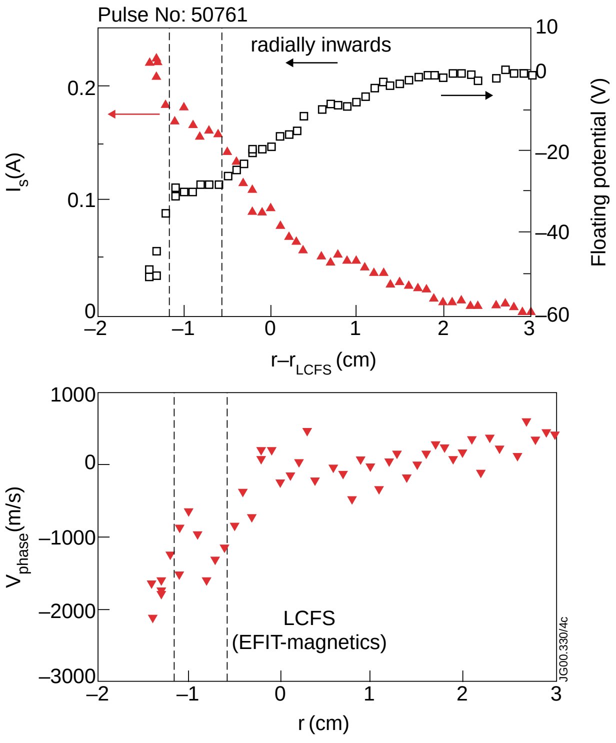

Fig.4: Ion saturation current, floating potential and poloidal phase velocity of fluctuations for the #50761 (B_T = 1 T, I_p = 1 MA).

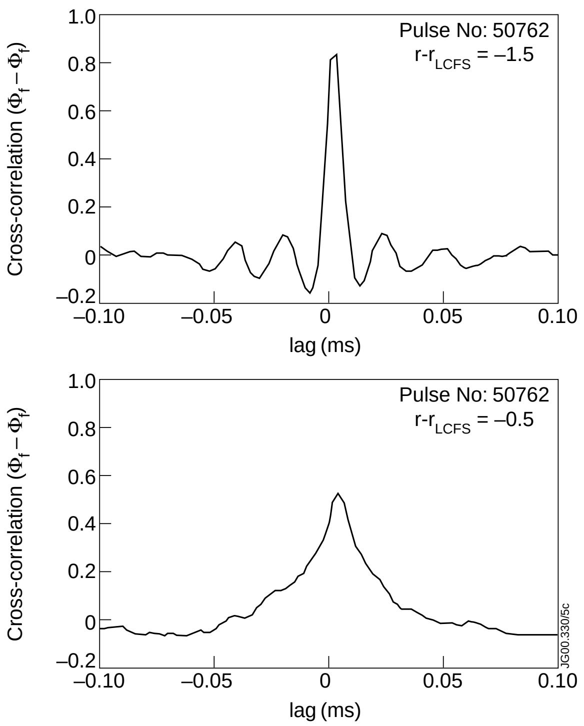

Fig.5: Cross-correlation of floating potential fluctuations near and out of the flattening region for the # 50762 (B_T = 1 T, I_p = 1 MA).

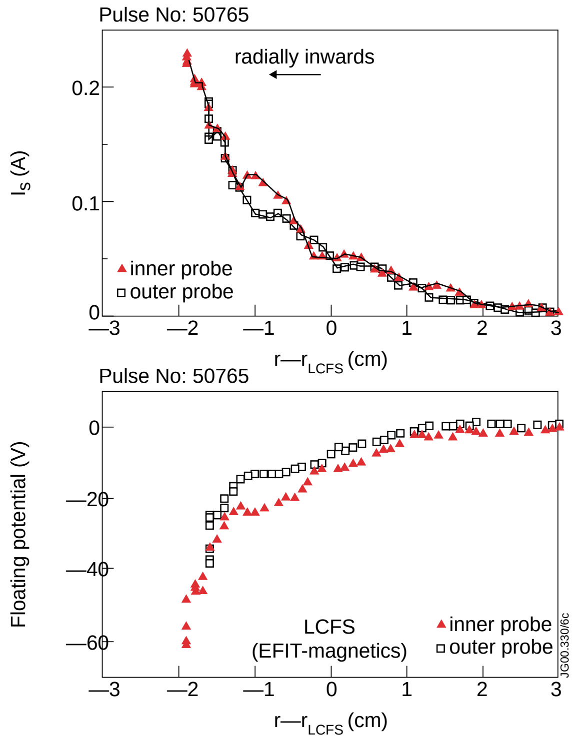

Fig.6: Radial profile of fluctuations using inner and outer probe arrays (# 50765).

surface using magnetic measurements and pressure balance analysis. This result clearly shows that reported flattening in plasma profiles is not a SOL phenomena, but is inside the LCFS.

Plasma profiles measured with the inner and outer probe arrays show very good agreement (i.e. there is no evidence of probe shadowing) except near the flattened region (Fig.6). This result suggests a modification in the plasma topology in the region where there is a flattening in both density and potential profiles. Regions with low pressure gradients, resembling a magnetic island (i.e. q = 3), have been also reported in the JET edge plasma region, using Li-beam emission spectroscopy [18]. Flattening in plasma profiles linked to rational surfaces have been also reported in stellarator plasmas [10].

The present observations have been interpreted in terms of the influence of rational surfaces (i.e. q=4) on plasma profiles in JET. In the absence of ExB sheared flows, fluctuations are expected to show maximum amplitude at the rational surface. As a consequence, turbulence should increase near rationals and plasma confinement would tend to deteriorate. At rational surfaces fieldlines any perturbation caused by the probe will be localised to a flux tube which maps back onto the probe itself. Hence the part of the probe body which is furthest in can cast a shadow on the probes further out, as can be seen in the JET data of fig.6.

Interestingly, significant sheared flows in the poloidal phase velocity of fluctuations are linked with the flattening of plasma profiles (Fig.3 and 4). The radial gradient in the poloidal phase velocity of fluctuations is in the range of 3×10^5 s^{-1} just at both sides of the flattening region, well below the L-H power threshold. If the ExB sheared flows reaches a critical value (i.e. the shearing rate is close to the growth rate of instabilities) a transport barrier will be formed linked to rationals**.**

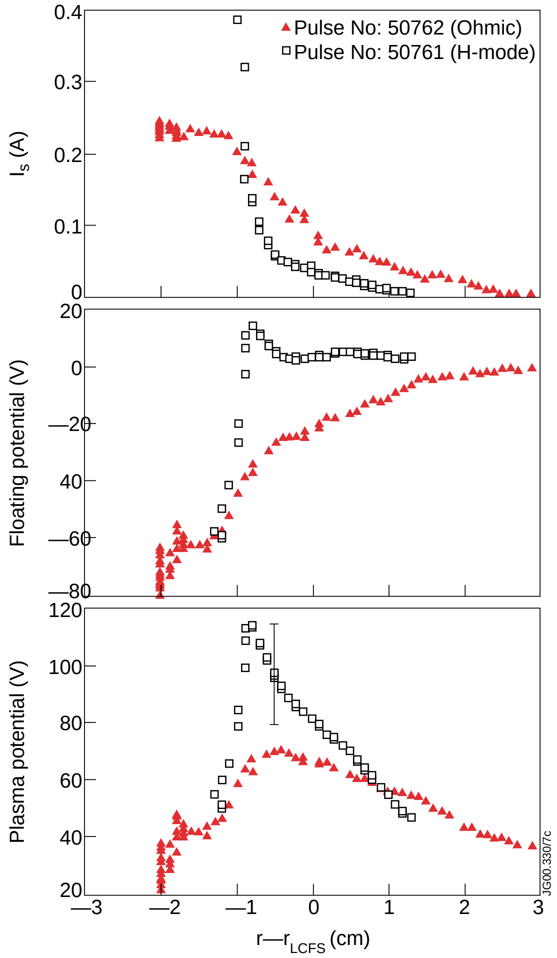

Fig.7: Radial profile of fluctuations in ohmic plasmas (50762; B_T = 1 T, I_p = 1 MA) and H mode regime (50761; B_T = 1 T, I_p = 1 MA, P_{NBI} = 2 MW)

Increasing the heating power above the power threshold produces a transition to the H mode regime. Figure 7 shows a comparative study of plasma profiles in ohmic (# 50762; B_T = 1 T, I_p = 1 MA) and H mode (# 50761; B_T = 1 T, I_p = 1 MA, P_{NBI} = 2 MW) regimes. Ion saturation current profiles become steeper and the floating potential becomes more negative in the H mode plasmas. Plasma potential (Φ_p) profiles, estimated from electron temperature and floating potential profiles using $\Phi_p = \Phi_f + 2.5\,T_e$, show an increase in the radial electric field in H mode plasmas. The resulting ExB sheared flow turns out to be in the range 6 x 10^5 s^{-1} which is comparable to those measured in the ohmic plasma regime. In the plasma region were the transport barrier is formed, the radial correlation of fluctuation is reduced, this reduction is more effective for low frequency fluctuations.

The existence of substantial sheared flows well below the L-H power threshold should be considered as an important ingredient of any transition modeling for the H-mode [3]. This result implies that there is not a continuous increase of the ExB flow shear when approaching the critical power threshold for the L-H transition. On the contrary, ExB sheared flows with decorrelation rates close to the critical value to reduce turbulence (i.e. $\omega_{ExB} \approx \gamma$, γ being the instability growth rate) are already developed well below the L-H power threshold.

JET results look very similar to previous experiments carried out in stellarator plasmas (TJ-II), which have shown flattening in plasma profiles and evidence of ExB sheared flows linked to rational surfaces (m=5/n=8, m=2/n=4) [9,10]. This similarity suggests that ExB flows are linked to the magnetic topology (rationals) both in tokamaks and stellarators. This might explain the interplay between transport barriers and magnetic topology previously reported in stellarator and tokamak plasmas.

Figure 8 shows the radial profile of normalized ion saturation current fluctuations and the root mean square (rms) value of floating potential fluctuations measured in the shots 50573 (B_T = 2 T, I_p = 2 MA) and 50762 (B_T = 1 T, I_p = 1 MA). The level of fluctuations increases as the toroidal magnetic field and plasma current decrease. Root mean square value of fluctuations in the floating potential of about 10 V and normalized ion saturation current of (10 - 20) % have been measured in the plasma edge side of the separatrix. There is a significant radial variation in the rms of fluctuations, suggesting Reynolds stress driven flows as a candidate to explain the generation of ExB sheared flows in the proximity of rationals [11] and in the plasma boundary region [19].

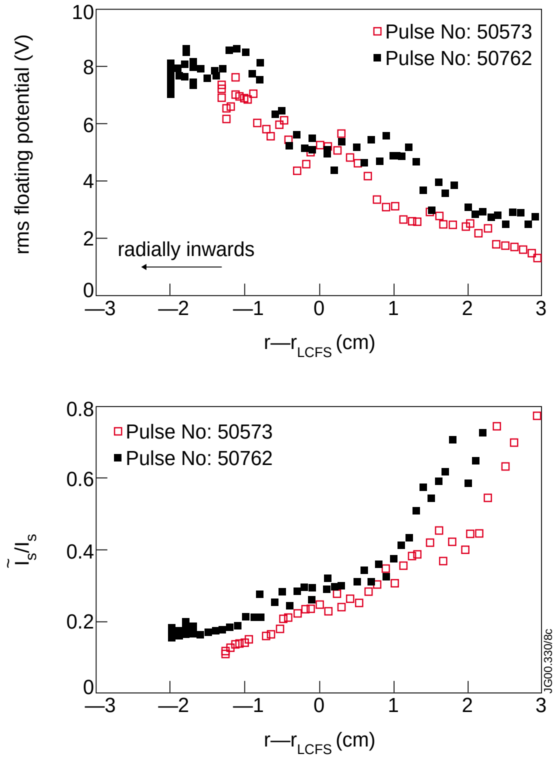

Fig.8: Radial profile of normalized ion saturation current and rms value of floating potential fluctuations in ohmic plasmas (# 50762, B_T = 1 T, I_p = 1 MA and # 50673, B_T = 2 T, I_p = 2 MA).

Reynolds stress measures the degree of anisotropy in the structure of turbulence. Radially varying Reynolds stress allows the turbulence to redistribute the poloidal momentum, generating sheared flows. This is a consequence of the generation of low frequency fluctuations in the plasma potential via nonlinear energy transfer from high frequency fluctuations [20]. In the frame work of ExB sheared flows driven by fluctuations the transport barrier power threshold may be understood as follows. When the level of fluctuations is large enough to drive a critical sheared flow the transition to improved confinement regimes takes place [21]. The level of fluctuations depends on the free energy source for fluctuations (i.e. gradients) and gradients are directly related with the input power.

In conclusion, experimental evidence of flattening in plasma profiles has been observed in the edge region of the JET tokamak. This observation has been interpreted in terms of the influence of rational surfaces on plasma profiles. Sheared flows in the range of ω_{ExB} critical have been observed linked to rationals, well below the L-H power threshold. When ExB sheared flows are below the critical value to decorrelate turbulence, rational surfaces would cause a deterioration in confinement. On the other hand, rational surfaces can be beneficial for confinement if the ExB sheared flows reach the critical value. These results can explain the strong interplay between the magnetic topology and the generation of transport barriers in fusion plasmas.

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