Long-Range Correlations and Edge Transport Bifurcation in Fusion Plasmas

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Abstract. It is well-known that the E×B sheared flows play a key role in regulating turbulent transport and consequently lead to edge plasma transport bifurcations to improved confinement regimes. Recently, a European transport project has been carried out among several fusion devices for studying the possible link between the mean radial electric field (E_r), long-range correlation (LRC) and edge bifurcations in fusion plasmas. The main results reported in this paper are: (i) the discovery of low-frequency LRCs in potential fluctuations which are amplified during the development of edge mean E_r using electrode biasing and during the spontaneous development of edge sheared flows in stellarators and tokamaks. Evidence of nonlocal energy transfer has also been observed. The observed LRCs are consistent with the theory of zonal flows described by a "predator-prey" model. The results point to a significant link between the LRC and transport bifurcation. (ii) Comparative studies in tokamaks, stellarators and reversed field pinches have revealed significant differences in the level of the LRC. Whereas the LRCs are clearly observed in tokamaks and stellarators, no clear signature of LRCs was seen in the RFX-mod reversed field pinch experiments. These results suggest the possible influence of magnetic perturbations on the LRC, in agreement with recent observations in the Resonant Magnetic Perturbations experiments in tokamaks. (iii) The degree of the LRCs is strongly reduced as approaching the plasma density limit in tokamaks and stellarators, suggesting the possible role of collisionality or/and the impact of mean E_r×B flow shear on zonal flows.

1. Introduction

Transport barriers are a key element for enhancing the confinement properties in magnetic confinement devices and therefore are of great importance for the development of magnetic fusion as an alternative energy source. At present, there exists robust evidence on the importance of the radial electric field (E_r) to control edge plasma turbulence and during the development of edge plasma bifurcations. However, the mechanism governing the development of this bifurcation is still one of the main scientific conundrums facing the magnetic fusion community. In parallel, various experiments [1−4] have detected long-range correlations (LRCs) consistent with the theory of "zonal flows" described by a predator-prey model, i. e., modes that are driven by zonal flow-turbulence interaction and with the potential to regulate turbulent transport [5, 6].

A European transport project has been recently executed in several machines for surveying the possible link between the mean E_r, LRC and edge transport bifurcation in fusion plasmas. Common features are shown on the results obtained in various devices, e. g., tokamaks, stellarators and reversed field pinch. In this article, we will present the LRCs measured in these different machines. The influence of the Resonant Magnetic Perturbations

(RMP) and plasma density on the LRC will also be reported.

2. Experimental set-up

The measurements were performed in several devices for comparative studies. The experimental conditions are as follows: In the ***TJ-II stellarator*** in electron cyclotron resonance heated plasmas [$P_{ECRH} \leq 400$ kW, magnetic field $B_T = 1$ T, major radius <R> = 1.5m, minor radius <*a*>= 0.22 m, rotational transform $\iota(\alpha)/2\pi \approx 1.5$-1.9, line-averaged density $<n_{e0}> = (0.35\text{-}1.0)\times10^{19}$ m^{-3}]. The floating potential (V_{fl}) and ion saturation current (I_s) fluctuations were detected simultaneously by two reciprocating Langmuir probe arrays, separated about 160° torodidally and 150° poloidally (~ 5 m away) [7]. At the ***TEXTOR tokamak*** in ohmically heated plasmas [$I_p = (200\text{-}250)$ kA, $B_T = (1.9\text{-}2.25)$ T, R = 1.75 m, $a \approx$ 0.48 m, $<n_{e0}> = (1.0\text{-}3.0)\times10^{19}$ m^{-3}]. The V_{fl} and I_s fluctuations were simultaneously measured by two Langmuir probe arrays (one is stationary and the other is reciprocating), both installed at the outer midplane of the torus (~ 7 m away) [8]. In the ***TJ-K stellarator*** in microwave-generated plasmas [P= 1.8 kW, B= 72mT, $<n_{e0}>=10^{17}$ m^{-3}, R_0=0.6 m, *a*=0.1m]. The V_{fl} and I_s fluctuations were simultaneously measured by poloidal multi-array probes, consisting of 128 pins on 4 adjacent flux surfaces [9]. In the ***ISTTOK tokamak*** in ohmically heated plasmas [$B_T = 0.5$ T, R =0.46m, $a \approx 0.085$m, $<n_{e0}>=(0.5\text{-}1)\times10^{18}$ m^{-3}]. The V_{fl} and I_s fluctuations were simultaneously detected by two Langmuir probe arrays, separated 120° torodidally and 90° poloidally (~1 m away) [10]. In the ***RFX-mod reversed field pinch*** device in ohmically heated plasmas [I_p= 300 kA, $B_T \approx 0.13$ T, R = 2 m, $a = 0.459$ m, $<n_{e0}> \approx 1\times10^{19}$ m^{-3}]. The V_{fl} and its fluctuations were collected using two different probes inserted in the equatorial plane, 15° toroidally separated. It is worth remembering that the main magnetic field at the edge of an RFP is in the poloidal direction and that the configuration operates at a low value of the safety factor $q(a) \approx -0.01$, and thus, the probes are 15 m away along the flux tube. At these values of current, RFX-mod operates in the so-called Multiple Helicity regime, characterized by a stochastic core due to a large spectrum of resonating tearing modes. The topology of the external region is further complicated by the presence of a chain of poloidally symmetric and toroidally localized magnetic islands, dubbed m = 0 islands, due to the resonance of the m=0 modes at the surface where the toroidal field reverses (around r/a ~ 0.9) and to the beating of m = 1 modes [11].

In the edge biasing experiments in TJ-II [7], TEXTOR [8], TJ-K [9] and ISTTOK [12], the biasing-induced improved confinement was realized using an biasing electrode inserted several *cm* inside the last closed flux surface (LCFS) and several hundred *volts* biased onto the limiter or vacuum vessel. In the TJ-II stellarator, a spontaneous L-H transition occurred with Neutral Beam Injection (NBI) heating ($P_{NBI} \approx 450$kW) on the ECRH target plasmas [13]. In all devices, the toroidal (or poloidal) LRCs between the fluctuation signals *x* and *y*, measured on the distant probes, were estimated by computing their cross-correlation $C_{xy}(\tau) = \langle[x(t)-\bar{x}]\cdot[y(t+\tau)-\bar{y}]\rangle / \sqrt{\langle[(x(t)-\bar{x})^2]\rangle\langle[(y(t)-\bar{y})^2]\rangle}$, where τ is the time lag.

3. Experimental results and discussion

3.1 LRCs in electrode-biasing and spontaneous H-mode experiments

Figure 1 plots the time evolution of the toroidal LRC of I_s and V_{fl} fluctuations measured by two toroidally separated probes during a biasing experiment in the TJ-II stellarator. The top panel shows a rise of the line-averaged density during the biasing-induced improved confinement phase. In Fig. 2, the time histories of the fast probe (the stationary probe stays at a fixed radial position) and the toroidal LRC on I_s and V_{fl} fluctuations detected in a biasing experiment at TEXTOR tokamak are depicted. The results in the two machines show very similar features: (i) in the discharge phase without biasing there is a small cross correlation exhibited on the V_{fl} signals when the two toroidally separated probes are localized around the same radial position; (ii) during the biasing phase the LRCs in V_{fl} fluctuations are substantially enhanced; (iii) both before and during the biasing, no cross correlation is seen in the I_s signals. Similar amplification of the toroidal LRC on V_{fl} signals has also been observed in the ISTTOK tokamak during biasing-induced improved confinement [12]. In the low temperature plasma regime at the TJ-K stellarator, the poloidal LRCs on V_{fl} and I_s ($\propto$ density) fluctuations both exist prior to the biasing with an m=4 mode [9]. During biasing, the LRCs are both amplified and the poloidal modes of the LRC in V_{fl} and I_s fluctuations change into m=0 and 3, respectively, as shown in figure 3. In addition to biasing-induced improved confinement, an increase of the LRC has also been observed during a spontaneous L-H transition in the NBI heated plasmas in the TJ-II stellarator [13]. Figure 4 plots the maximum value of the toroidal LRC in V_{fl} fluctuations along with $1/H_a$ signals across a spontaneous L-H transition. One can see that the LRC increases signify-

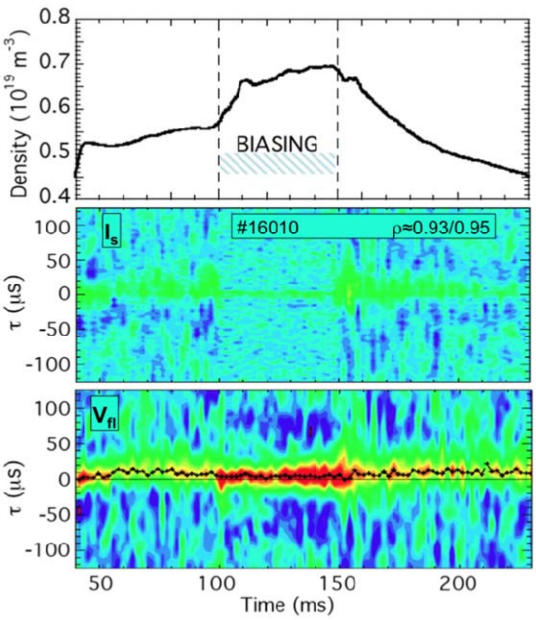

FIG. 1 Increase of the LRC on V_{fl} signals during the biasing experiment in the TJ-II stellarator [7]. (a) Time trace of line-averaged density. Contour plot of cross-correlation in (b) I_s and (c) V_{fl} fluctuations as a function of time measured toroidally apart by two probe arrays, which are located at about the same radial position (r/a=0.93 and 0.95) in the plasma edge.

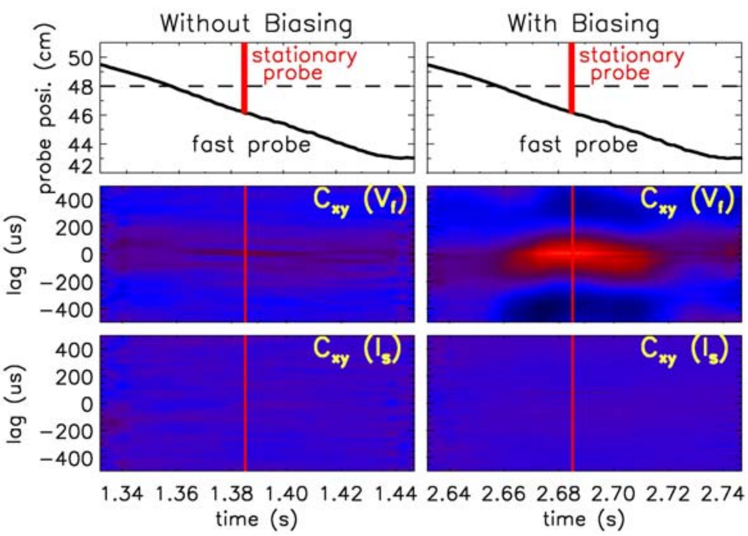

FIG. 2. Increase of the LRC on V_{fl} signals during the biasing experiment at the TEXTOR tokamak [8]. Time history of fast/stationary probes and the contour plot of cross-correlation on V_{fl} (middle panels) and I_s (bottom panels) fluctuations measured before (left column) and during (right column) the biasing phase (No.108288). The dashed lines on top panels denote limiter locus. The vertical red lines in contour plots indicate the time when the two probes are at the same radial location.

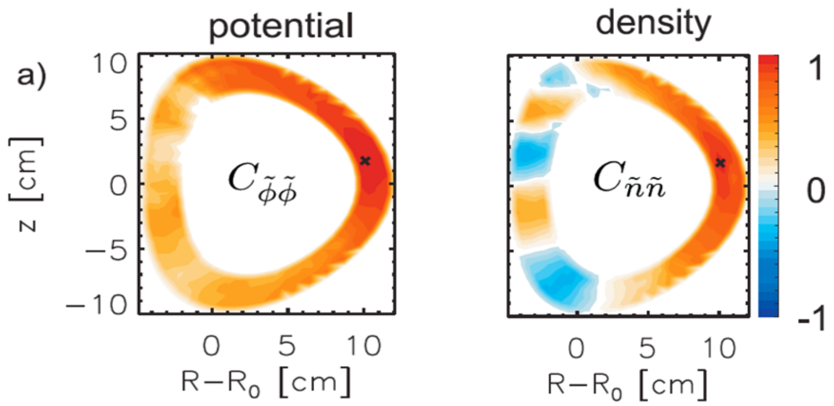

FIG. 3. Increase of the LRC on both (a) potential (m=0) and (b) density fluctuations (m=3) during the biasing experiment in the TJ-K stellarator [9]. The cross-correlations are measured between the reference probe (**x**) and other poloidally separated probes at zero delay time.

cantly at the transition time when H_α drops abruptly. In all above cases, the observed long-range correlations with toroidal mode n≈0 are dominated by low-frequency fluctuations (<10 kHz) and hence are associated with zonal flows [7-10, 12, 13].

Moreover, evidence of nonlocal energy transfer between the drift-wave turbulence and zonal flows has been observed in the TJ-K stellarator, where the energetic interaction between ambient turbulence and zonal flows has been investigated in a 2D wave-number space using extensive poloidally-spaced multi-array probes [14]. The results are illustrated in Fig. 5. In the figure the T^V_{tot} represents the total transfer function and the curve is a projection of the 2D data on the $k_\theta=k_{\theta 1}+k_{\theta 2}$ axis. One can see that the energy transfer to zonal flows (k_θ=0), shown by red positive values along the $k_{\theta 1} = - k_{\theta 2}$ line in the plot, arises mainly from smaller scales ($k_{\theta 1}\geq 1$). Note that k_θ here is normalized to the drift scale ρ_s. The results reveal a nonlocal energy cascading from drift-wave turbulence to zonal flows. Besides, in the ISTTOK tokamak the coupling between the GAM-related LRC and local turbulent transport has been observed [10]. Plotted in Figs. 6(a) and (b) are the time evolution of the toroidal LRC (at τ=0) and local turbulence-driven particle flux. The vertical dashed and solid lines show that the amplitudes of the LRC (related to GAM) and turbulent flux vary oppositely with time, as verified further in Fig. 6(c), where the averaged flux decreases with increasing covariance (defined as correlation without normalization) in V_{fl} fluctuations. This result implies a GAM modulation on local turbulent transport.

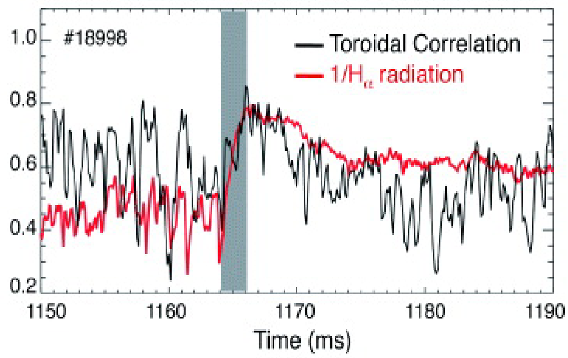

FIG. 4. Time evolution of the maximum value of the LRC in V_{fl} fluctuations and the $1/H_\alpha$ signal measured in the TJ-II stellarator [13]. The shadow area indicates the L-H transition time.

The common feature of the above biasing-/spontaneous H-mode experiments is the development of edge mean E_r during the H-mode regime. Thus, the amplification of the LRC and zonal flows is closely linked to the development of edge E_r and $E_r\times B$ sheared flows. The development of the LRC (zonal flows) driven by turbulence requires a mechanism for transferring the turbulent energy to large scales, such as Reynolds stress, e. g., via the eddy tilting mechanism. The impact of sheared flows on edge turbulent structures show results that are consistent with the picture of the shear stretching blobs as well as ordering, thus providing a possible explanation for the experimentally observed link between mean sheared flows and the development of LRCs [15]. The results are also in accordance with the theory of "zonal flows" described by a predator-prey model, i. e., modes that are driven by zonal flow-turbulence interaction and with the potential to regulate turbulent transport [5, 6, 16].

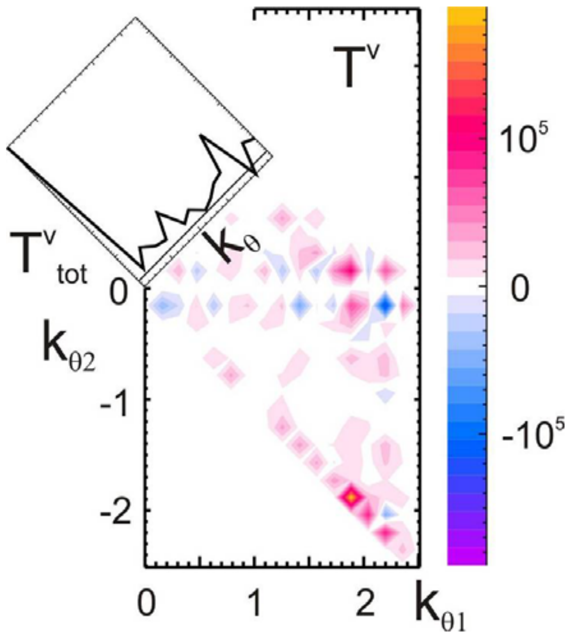

FIG. 5. Nonlinear fluid kinetic energy transfer observed in the TJ-K stellarator [14].

The LRCs have been also investigated in plasma regimes with reduced level of plasma fluctuations (H-mode). Experiments at the TJ-II stellarator [13] have shown that once the transition to an improved confinement regime is completed, the level of LRCs decreases, as can be seen in Fig. 4. Experiments in AUG have shown that LRCs due to GAMs also strongly decrease in the H-mode [17]. Similar results have been observed in JFT-2M tokamak [18].

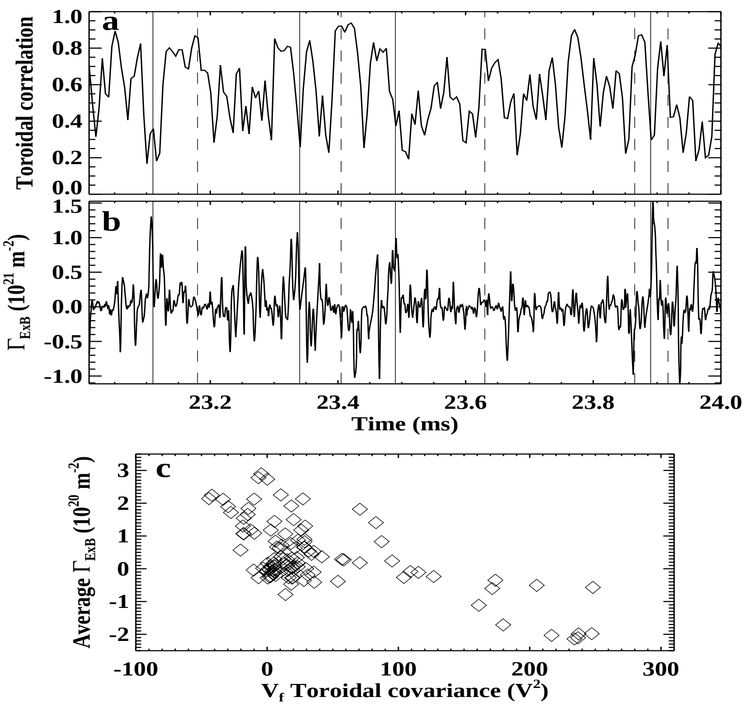

FIG. 6. Time evolution of (a) the value of LRC (τ=0) on V_{fl} fluctuations and (b) fluctuation-induced particle flux. (c) Average particle flux against the V_{fl} covariance (τ=0) measured in the ISTTOK tokamak [10].

3.2 Impact of Resonant Magnetic Perturbation (RMP) on the LRC

Comparative studies in tokamaks, stellarators and reversed field pinches have revealed significant differences in the properties of the LRC measured in the plasma edge. Whereas LRCs are clearly observed in the plasma regions in tokamaks and stellarators with significant mean E_r and flow shear, no clear signature of the LRC was observed in the RFX-mod reversed field pinch experiments despite the highly sheared E_r observed [19]. The lack of long-range correlations in V_{fl} fluctuations in RFX-mod may result from the high level of magnetic fluctuations observed in low-current RFP discharges: these fluctuations may induce a certain degree of stochasticity. Furthermore the topology is complicated by the presence of m=0 islands. These islands are found to modulate the plasma wall interaction, field line connection length and also contribute in the formation of the radial electric field in the extreme periphery, modifying ion and electron diffusion processes and the resulting ambipolar electric field [11]. The series of islands modify the external region creating regions of high degree of stochasticity (X-point) and region of better confinement (O-point) thus limiting the formation of zonal flow structures. In figure 7 an example of the LRC in V_{fl} fluctuations between two distant tips (at about the same radial position) is shown as a function of time and time lag. The average value in the time interval chosen is shown in panel (b) where it is clearer that no correlation is present. In the bottom panel the time evolution of the maximum of the absolute value of the LRC with the corresponding sign is shown, in order to emphasize that the cross-correlation values do not exceed 0.25. At lower values of $q(a)$ sporadic bursty increasing of the LRC is observed. This is most likely due to reconnection events associated

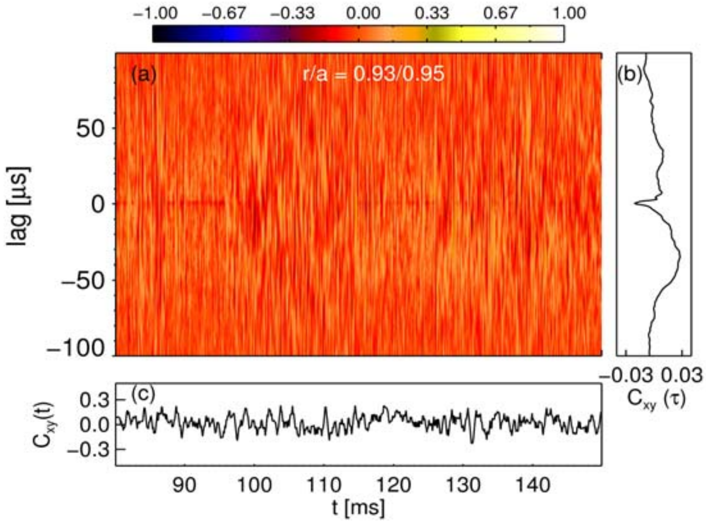

FIG. 7. Absence of the LRCs in the RFX-mode. (a) Cross correlation between two floating potential tips (15m away) as a function of time and time lag when the two probe tips are at about the same radial position (r/a=0.93 and 0.95) in the plasma edge; (b) average cross-correlation and (c) time traces of the signed maximum of the absolute value of the cross-correlation.

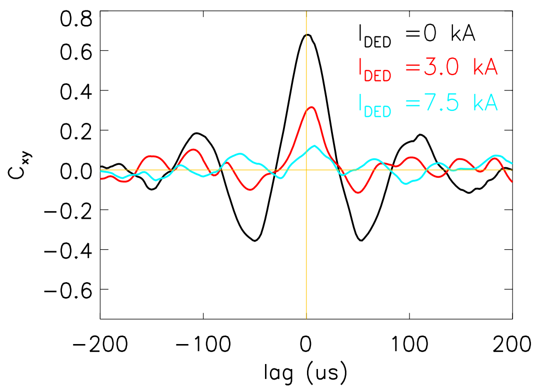

FIG. 8. Maximum values of the toroidal LRCs measured under different DED currents (I_{DED}=0, 3.0, 7.5 kA) in a m/n=6/2 DED configuration at TEXTOR tokamak [$q(a)$=5.0].

to a poloidally symmetric current sheets which propagates in the toroidally direction with velocity of the order of 40-60 km/s [20].

The above results are consistent with recent observations in the Resonant Magnetic Perturbation (RMP) experiments at TEXTOR. In TEXTOR the Dynamic Ergodic Divertor (DED) system can ergodize the edge magnetic field lines and hence create a stochastic magnetic topology via the RMP with various perturbation base modes (m/n=12/4, 6/2 and 3/1) [21]. With increasing DED current the ergodization is expected to be stronger. In Fig. 8 the maximum values of the toroidal cross-correlation C_{xy} (when two probes are at the same radial location) are shown for three different DED currents (I_{DED} = 0, 3.0 and 7.5 kA) in an m/n=6/2 DED configuration. One can clearly see that the LRCs on V_{fl} fluctuations are reduced with increasing DED current. Similar results have also been seen in other DED configurations. As a consequence, these results reveal the impact of the RMP on LRCs and related zonal flows, and hence on plasma transport, as reported in Ref. [22].

3.3 LRCs in density-limit experiments

The LRC has also been investigated in the proximity of the density-limit in the TEXTOR tokamak and the TJ-II stellarator. Shown in Fig. 9(a) are the maximum values of the toroidal LRC on V_{fl} fluctuations detected in different density discharges at TEXTOR. At low densities ($\langle n_e \rangle \leq 2.0\times10^{19}$ m^{-3}) the LRCs are quite large and change little with increasing density. However in higher density cases the LRC reduces rapidly with increasing plasma density when approaching the density-limit. Similar results have also been observed in the TJ-II stellarator (see Fig. 9(b)), where the degree of the toroidal LRCs drops drastically with increasing density toward operational limits. In the density-limit discharges the increase of plasma density usually induces a reduction of edge temperature and consequently a change in collisionality. In both machines, it is interesting to find that the reduction of the LRC due to increasing density is always accompanied by a reduction of edge mean radial electric field. Therefore, the results suggest the possible role of collisionality and the impact of mean $E_r\times B$ flow shear as well on the long-range correlation and zonal flows.

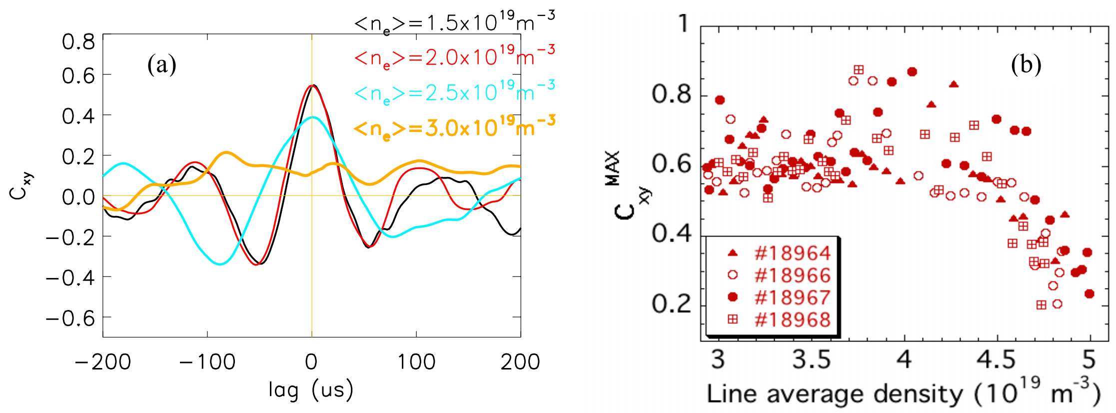

FIG. 9. Reduction of the LRCs with increasing plasma density toward density-limit in TEXTOR tokamak and TJ-II stellarator. (a) Maximum correlation value of the toroidal LRCs measured in different density plasmas at TEXTOR [q(a)=5.9]; (b) Maximum correlation value of the toroidal LRC as a function of plasma density in TJ-II stellarator.

4. Conclusion

A European transport project has been carried out among several fusion devices for investigating the possible link between the radial electric field, long-range correlations and edge bifurcations in fusion plasmas. Similar results have been observed in various devices, including tokamaks, stellarators and a reversed field pinch: (i) the discovery of low-frequency LRCs in potential fluctuations that are amplified during the development of edge mean E_r using electrode biasing in TJ-II/TJ-K stellarators and TEXTOR/ISTTOK tokamaks and during the spontaneous development of edge sheared flows in TJ-II stellarator. Evidence of nonlocal energy transfer has been observed in the TJ-K stellarator. The observed LRCs are consistent with the theory of zonal flows described by a "predator-prey" model. The results point to a significant link between the $E_r\times B$ sheared flows, LRCs and transport bifurcations. (ii) Comparative studies in tokamaks, stellarators and reversed field pinches have revealed significant differences in the level of the LRC. The absence of the LRC in the RFX-mod reversed field pinch suggests a damping effect of magnetic perturbations on the LRCs, in agreement with observations in the RMP experiments in TEXTOR tokamak. (iii) The degree of the LRCs is strongly reduced as approaching the plasma density limit in TEXTOR tokamak and TJ-II stellarator, implying the possible role of collisionality or/and the impact of mean $E_r\times B$ flow shear on zonal flows.

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