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Influence of long-scale length radial electric field components on zonal flow-like structures in the TJ-II stellarator

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Abstract. The interplay between long and short radial scale structures in radial electric fields and their role on the radial correlation length of the turbulence have been investigated in the edge plasma of the TJ-II stellarator by using two electrical rake-probes. The results presented here show an empirical correlation between the properties of long-range correlations with zonal flow-like structure and the magnitude of radial (neoclassical) electric fields in TJ-II Neutral Beam Heated plasmas. These experimental findings show that the radial electric field enhances the magnitude of long-range correlations, considered as a proxy of Zonal flows while the radial correlation length of the turbulence was found to decrease in about a 30-40 %. A strong coupling between the magnitude of long and short radial scale structures in the electric field was found. The calculation of the shearing rate in the radial electric field show that, along short scale lengths the radial electric field can reach enough magnitude for acting upon the radial turbulence as a transport barrier (through $\boldsymbol{E_r} \times \boldsymbol{B}$ **velocity**).

1. Introduction

Various experiments have shown the detection of long range correlations consistent with the theory of "zonal flows", i. e., stable modes that are driven by turbulence and regulate turbulent transport [1 and references there in]. The amplification of zonal flows by externally imposed radial electric fields has been observed both in tokamaks and stellarator devices [2, 3]. The coupling between long range correlations in floating potential and the radial turbulent transport was already studied in TJ-II edge plasmas [4, 5] and the drive and damping mechanisms for the $E_r \times B$ velocity associated to zonal flows were discussed [6]. At present, the investigation of the interplay between zonal flows and transport barrier development is an active area of research to identify the trigger mechanism of the transition to improved confinement regimes [7].

Radial electric fields play a key role in explaining transport in fusion plasmas. It is known that in quasi-axisymmetric or quasi-helically symmetric magnetic configurations the collisional plasma transport is intrinsically ambipolar. In a non-quasi-axysimmetric magnetic field configurations, parallel viscosity and neoclassical non-ambipolar fluxes determine the radial electric field (long scale length) and plasma rotation [8]. On the other hand, recent simulation results in tokamak plasmas have shown the development of multiple radial scale lengths for the electric field and plasma pressure together with spontaneously formed long-lived pattern of $E_r \times B$ flows [9].

Simulations have shown that the interplay between turbulent driven transport and 3-D drift-optimized configurations could be explained on the basis of the reduction of turbulent transport by zonal flow generation [10]. The amplification of low frequency ZF-structures in plasma scenarios with reduced neoclassical viscosity has been observed in TJ-II [11]. In addition, gyrokinetic simulations have shown the influence of radial electric fields in the zonal flow residual level in stellarators [12, 13].

The paper is organized as follows. In section 2 the experimental set up is described. In the following section are shown the approximations that were taken for the calculation of radial electric field and long range correlations as well as the related experimental results obtained. Section 4 contains experimental results coming from the study if the radial correlation length of the turbulence. The study of the radial electric field and its shear at different spatial scale length is included in section 5. Finally, some conclusions are shown in the last section.

2. Experimental set-up and plasma conditions

Experiments have been carried out in ion root (negative electric fields) plasmas, pure NBI heated (two NBI systems, two beams with up to 700 kW of port-through power at 33kV were injected) plasmas in the TJ-II stellarator (magnetic field $B \sim 1T$, plasma minor radius $a \sim 0.20\ m$).

The results reported here were obtained by the use of a detection system which consists in two Langmuir probe arrays, known as Probe 1 and Probe 2, located at two different toroidal/poloidal ports, as seen in figure 1. The use of multi-Langmuir probes at different locations allows measuring different plasma parameters simultaneously and make global as well as local study of these parameters. The rake probe 1 is installed on a fast reciprocating drive at the top of the plasma. This probe consists of twuelve Langmuir probe tips (measuring floating potential) radially separated 3 mm together with three polidally separated tips at the rake probe front measuring the floating potential (V_f)and the ion saturation current (I_{sat}). The second probe (probe 2) is also installed on a fast reciprocating drive and is located in a bottom port entering the plasma through a higher flux compression region than probe 1. This probe consists of eight probes separated 1.7 mm together with three poloidally separated tips at the top of the probe head. The sampling rate of the floating potential signals is 2 MHz. The two probe systems placed at different poloidal/toroidal positions were used for the study of the temporal and spatial evolution of floating potential profiles, radial correlation length of floating potential fluctuations and long range correlations in the hydrogen plasma edge.

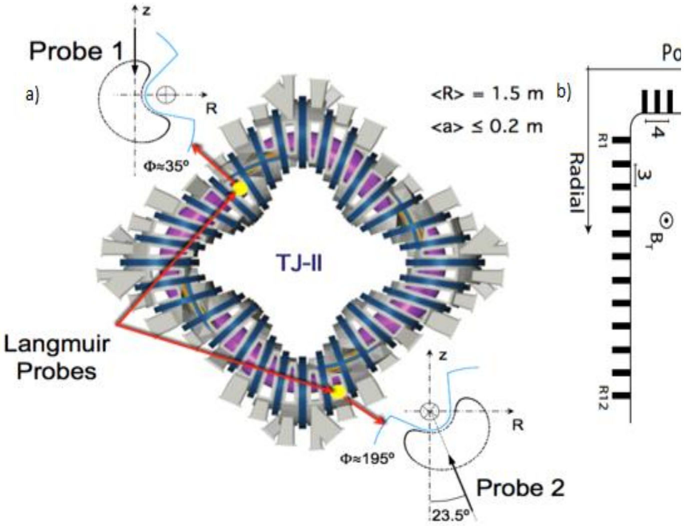

Figure 1. a) Schematic view of the location of the two Langmuir probe arrays (160º toroidally and 155º poloidally separated and b) a sketch of rake probe 1 (C Silva et al. 2011 *Nucl. Fusion* **51** 063025).

Figure 2 shows the time evolution of line-averaged plasma density and edge fluctuations, as well as the edge floating potential profiles. The density is scanned in the range (1-7) x 10^{19} m^{-3}. The level of edge fluctuations increases and edge plasma potential profiles become steeper as plasma density increases.

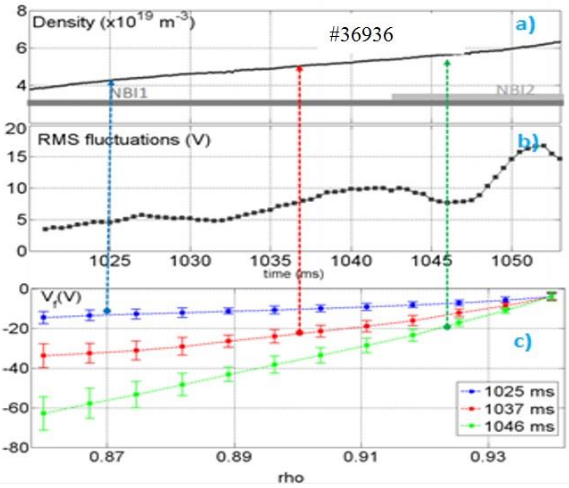

Figure 2. a) Temporal evolution during a given discharge of the line averaged density b) and the fluctuations of the floating potential. c) The slope of the radial profile of V_f evolves during the plasma discharge and increases with the density.

3. Long scale length radial electric fields and Long Range Correlations

The mean velocity of fluctuations perpendicular to the magnetic field ($v_\perp$) has been previously measured with a two-point correlation technique in the plasma edge of tokamaks [14] and stellarators [15]. Experiments have shown that, close to the outermost closed flux surface, the perpendicular velocity of the fluctuations ($v_\perp$) is dominated by the $E_r \times B$ velocity [14].

The mean velocity of fluctuations perpendicular to B and along the magnetic flux surface has been computed with the two point correlation technique in the laboratory frame of reference using floating potential signals from probes poloidally separated 3 mm in the edge of the TJ-II stellarator. In the plasma edge region $v_\perp$ increases in the electron drift direction up to few km/s. In the present TJ-II plasma conditions, strong correlation was found between the E_r deduced from the gradient in floating potential and the perpendicular velocity of fluctuations, as seen in figure 3. Thus, gradients in floating potential have been used as a proxy for radial electric fields.

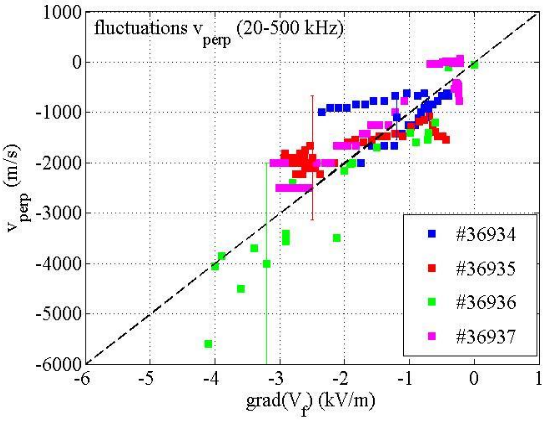

Figure 3. Perpendicular velocity of the fluctuations plotted versus the calculated gradient of floating potential.

The equilibrium radial electric fields have been measured from a linear fit of the radial profile of the floating potential calculated along a distance in the order of tens of ion Larmor radius. As shown in figure 2, floating potential profiles are strongly dependent on plasma density. The deduced E_r magnitude reaches values up to 3kV/m, which is in quantitative agreement with neoclassical calculations in the TJ-II stellarator [16].

Zonal flows are global low-frequency fluctuations ($k_{poloidal} = k_{toroidal} = 0$) with finite radial scale length ($k_r \neq 0$) [17]. Thus, the fingerprint of ZF is the development of Long Range Correlated (LRC) structures with phase shift close to zero and finite radial scale length.

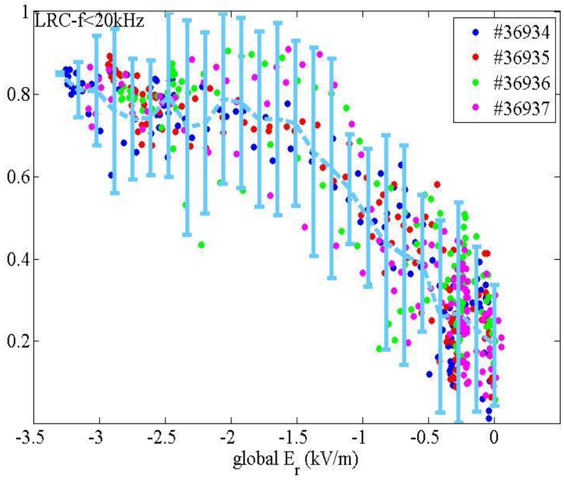

Figure 4. Long range correlation (LRC) increases with equilibrium radial electric field (NC) and reaches saturation once the radial electric field has values larger than about 2 kV/m.

Experimental results described in this report have shown an empirical correlation between the amplitude of LRC (proxy of zonal flows) and the radial gradients of floating potential (proxy of radial electric fields) in NBI plasmas (L-mode regime). As shown in figure 4, the amplitude of LRC strongly increases with increasing radial electric field, reaching saturation for E_r values in the order of 1 kV/m. In other words, there is an empirical coupling between neoclassical radial electric fields and the amplitude of zonal flow-like structures.

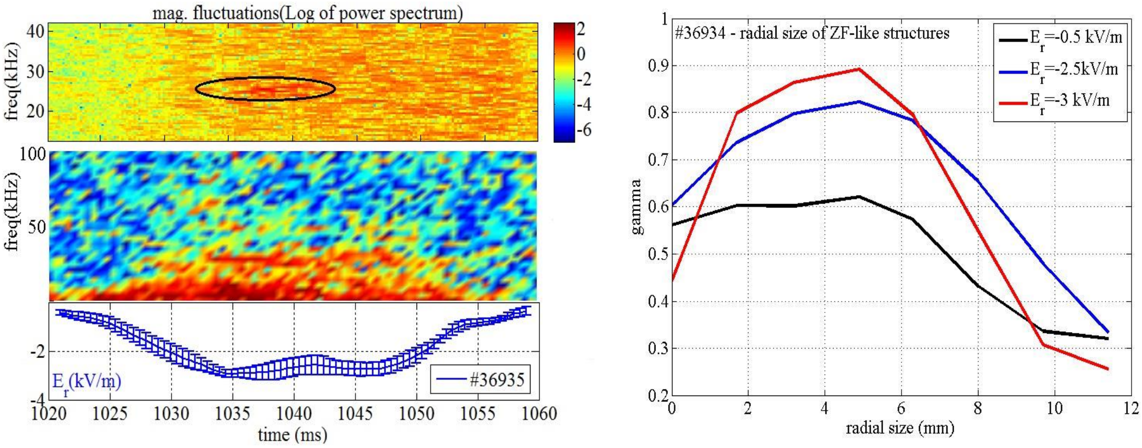

Figure 5. a) Temporal evolution of the radial electric fields, LRC and magnetic fluctuations. When the radial electric field increases, the cross-coherence expands to higher frequencies. It is necessary to distinguish ZF-like structures and the coherent mode that appears at about 30 kHz corresponding, to a MHD event, as shown in the figure above. b) The radial size of the LRC increases with its amplitude.

Long range correlations are dominated by frequencies below 20 kHz. Interestingly, the high toroidal cross-coherence appears also for higher frequencies as the radial electric field increases, that is to say that zonal flows become more stationary (dominated by frequencies below 5 kHz) in plasma regimes with small E_r and more fluctuating (dominated by frequencies below 20 kHz) as E_r reaches values of above 1 kV/m, as shown in figure 5.

The influence of E_r on the radial size of the zonal flow-like structures has also been investigated. As shown in figure 5.b, the radial size of LRC structures decreases with increasing E_r.

4. Long scale length radial electric fields and radial correlation length of plasma fluctuations

The radial correlation length of plasma fluctuations (L_r) has been calculated using the twelve floating potential signals radialy separated 3 mm of probe 1 array. This gives a spatial resolution of 3mm and allows a maximum radial scale of 36 mm to measure L_r. The radial correlation length of the turbulence is defined as the distance in which the cross-correlation coefficient (1) calculated between two signals X and Y decays below e^{-1}.

$$c_{XY} = \frac{\langle [x(t)-\bar{x}][y(t+\tau)-\bar{y}]\rangle}{\sqrt{\langle [x(t)-\bar{x}]^2\rangle\langle [y(t)-\bar{y}]^2\rangle}}, \quad (1)$$

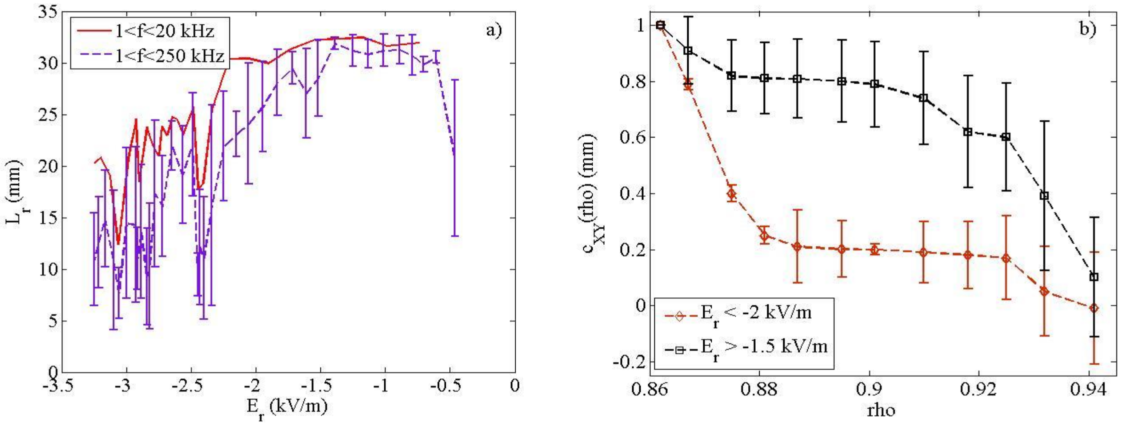

Figure 6. a) Mean L_r from four four discharges. Dashed line means L_r for four shots (#36934, 35, 36, 37) and for all frequency spectra. Blue line represents the mean L_r for the four discharges and low frequencies (1 – 20 kHz). b) Cross-correlation coefficient (for the same four shots) as a function of the radial separation between probes and its dependence on the value of the neoclassical radial electric field.

Radial cross-correlation was calculated for the different frequency bands. It was found to be clearly dominated by low frequencies (≤ 20 kHz). Experimental results shows that the magnitude of the radial correlation length decreases in about 30 – 40 % when the radial electric field (neoclassical) increases, as seen in figure 6.a. The clear decrease of the radial correlation length is motivated by the decrease of the cross-correlation function in function of radial distance, as shown in figure 6.b.

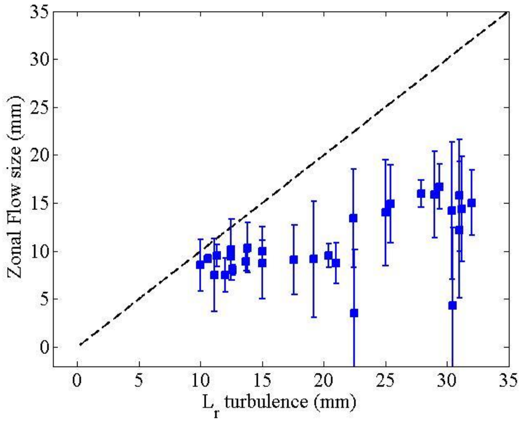

Figure 7. When the radial electric field reaches highest values, cross-correlation coefficient decays radially. This figure shows the decrease of radial size of ZF-like structures in front of the calculated decrease of the size of radial turbulence. It can be appreciated that, the lowest values of L_r are close to the lowest values of the size of the ZF-like structures.

However, for the highest values of E_r, the high radial cross-correlation for low frequencies ($1 \leq f \leq 20$ kHz) is mainly due to the size of the zonal flow-like structures (already shown in figure 5.b) instead of the radial correlation length of the turbulence.

5. Shearing rate of the radial electric fields

The shearing rate of radial electric fields has been computed along two different radial scale lengths for frequencies below 20 kHz: a) global or long-scale length (in the range of tens of ion Larmor radius) shearing rate, which represents the shearing rate of the neoclassical E_r and b) short-scale length (in the range of some ion Larmor radius) shearing rate.

2.1. Calculation of the shearing rate

The $E_r \times B$ shearing rate has been calculated as the second derivative of the floating potential measured by the twelve radially disposed electric probes (dividing by the distance between probes, 3 mm). In principle, for the local calculation of the short scale length shearing rate of E_r three probes radially disposed are enough. However, in this case, the objective was to study the influence of the spatial scale length on the magnitude. Then, the radial distance along which the second derivative is calculated is modulated by the use of a discrete Gaussian Kernel.

The shearing rate was calculated at $\rho \approx 0.9$. During these experiments, the rake probe 1 was radially fixed and $\rho \approx 0.9$ corresponds approximately to the innermost sixth probe of the rake probe. By modifying the value of the scale parameter, t, of the Gaussian Kernel, the radial distance along which the second derivative of the floating potential is calculated is modulated, as shown in figure 8 a.

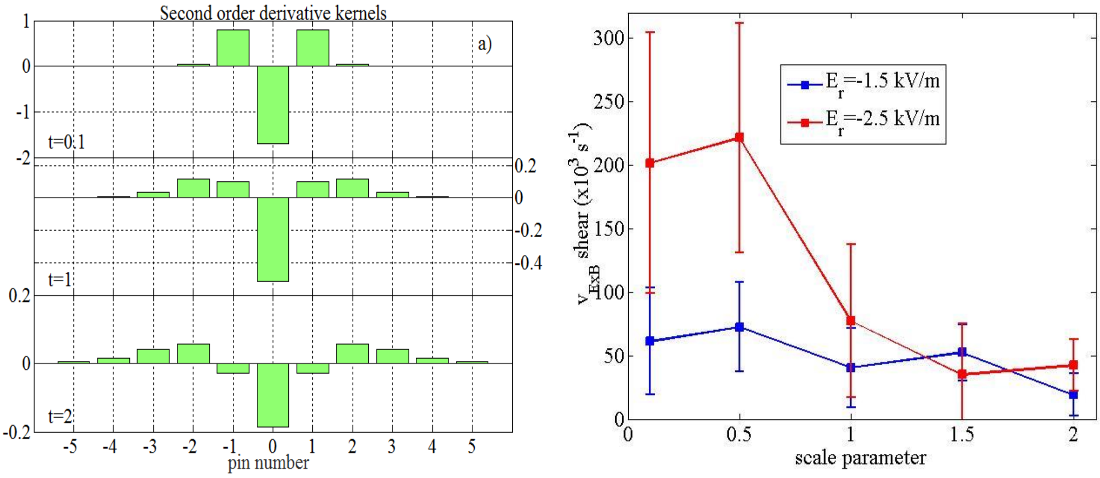

Figure 8. a) The profile of the second order derivative kernel depends on the scale parameter, can be seen that as the scale parameter decreases, the second derivative is weighted more locally. b) The magnitude of the sharing rate of the radial electric field depends (for high values of E_r) on the distance along which it is calculated. For high neoclassical electric field, short scale E_r shearing rate is enhanced.

2.2. Results: shearing rate magnitude depends on the spatial scale length

Figure 8 b shows how the magnitude of the shearing rate of E_r depends on the spatial scale along which is calculated, that is modulated by the scale parameter of the kernel. The results show that for values of E_r (neoclassical) smaller than about 2 kV/m the modulation in the distance does not have an influence in the value of the shearing rate of the radial electric field. On the other hand, when E_r reaches higher values, the magnitude of the second derivative of the floating potential strongly depends on the scale parameter of the Gaussian Kernel, in other words: the shearing rate of the short scale length radial electric field increases when the neoclassical E_r increases.

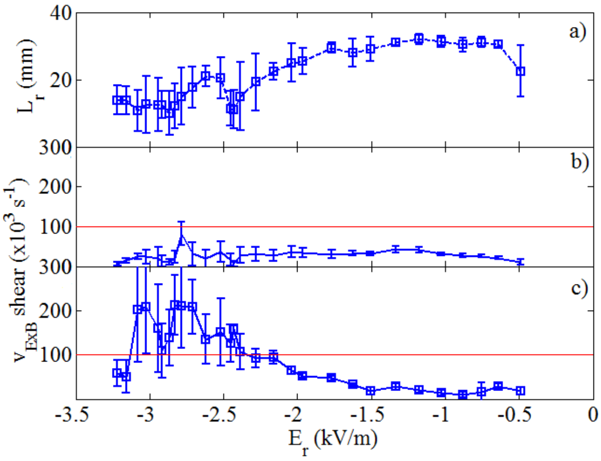

Figure 9. a) The radial correlation length of turbulence is reduced with E_r, b) shearing rate of the poloidal velocity due to the long scale length E_r and c) shearing rate due to the short scale length E_r.

Figure 9 shows the evolution of the radial correlation length of the turbulence as well as local and global $E_r \times B$ shearing rates versus the magnitude of the neoclassical (long scale length) E_r. In addition, the turbulence de-correlation rate is directly estimated as $\frac{1}{\tau_c}$, where τ_c denotes the auto-correlation time of the potential fluctuations, which is in the order of $10^5 s^{-1}$ [18, 19]. Interestingly, the global shear rate is always well below $10^5 s^{-1}$, whereas the local shearing values are above $10^5 s^{-1}$ concomitant with the reduction in the radial correlation length of the turbulence. These findings point out the importance of different radial scale lengths in the radial electric field, including both neoclassical (long radial scales) and turbulent (short radial scales) mechanisms, to control the radial correlation length of fluctuations.

6. Conclusions

The influence of long scale length radial electric fields on zonal flow-like structures has been investigated in the TJ-II stellarator with the following conclusions:

The amplitude of LRC strongly increases with increasing radial electric field reaching saturation for $E_r$values in the order of 1kV/m. The frequencies involved in ZF-like structures increase with increasing the neoclassical E_r. There is an empirical coupling between neoclassical radial fields and the properties of zonal flow-like structures.

There was found a clear decrease of L_r for high values of the radial electric field(neoclassical).The radial correlation length of plasma fluctuations is determined both by edge plasma turbulence and zonal flows. This observation is particularly relevant to unravel the dependence of the characteristic size of turbulent structures with plasma gyro-radius and the isotope physics [20]. In particular, once L_r is fully controlled by zonal flows, an increase in L_r does not imply a deleterious effect on transport.

Neoclassical and turbulent radial scales should be considered to deal with the influence of $E_r \times B$ sheared flow in the radial correlation length of fluctuations and transport.

These findings are consistent with previous experiments showing that the amplitude of LRC is amplified by external radial electric fields [4] and in the proximity of the L-H transition [21] as well as with GK simulations showing the influence of radial electric fields in the zonal flow residual level [5,6]. The observed interplay between neoclassical $E_r \times B$ shear flows and the development of low frequency zonal flow-like structures could be explained considering the role of electric fields as a turbulence symmetry-breaking mechanism [22, 23, 24] or/and the influence of radial electric fields on particle orbits [25, 26,27]. This is something that is under study at the moment.

The Neoclassical radial electric field [28,29] arises in 3D magnetic configurations to satisfy the ambipolarity condition. At high density, this electric field (that shows a negative value) satisfies the ion-root solution for ambipolar particle fluxes and it was measured in different stellarator-heliotron devices [30].

The amplification of ZFs structures in plasma scenarios with reduced neoclassical viscosity [31], its coupling with neoclassical radial electric field reported in this paper in the TJ-II stellarator and scaling with the ion Larmor radius [32] are of special relevance for stellarators with reduced neoclassical transport, in as much as the shearing caused by those structures can determine the saturation level of turbulent transport.

Acknowledgements

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