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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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1. Introduction

Mass flows are important in plasma stability and confinement. Experimental and theoretical efforts have been made to improve the understanding of the momentum transport mechanisms that determine the observed plasma rotation profiles. In stellarators, with non-axisymmetric magnetic fields, the neoclassical non-ambipolar fluxes dominate the equilibrium radial electric field [1]. Fluctuating, flux surface-constant zonal flows are thought to be instrumental in turbulent transport control and to be a natural state of turbulent plasmas. Different magnetic configurations can host zonal-flow structures. For stellarators, it has been found that neoclassical optimization could lead to reduced zonal flow (ZF) damping and, as a consequence, to turbulent transport optimization [2].

Previous experiments performed in the TJ-II stellarator have shown that long-range toroidal correlations (LRC) in potential fluctuations are amplified by externally imposed radial electric fields [3], near the L-H confinement edge transition [4] and in plasma regimes with reduced neoclassical viscosity. Gyro-kinetic linear simulations of collisionless ZF relaxation with the global code EUTERPE [5] have been carried out in the TJ-II geometry. Both the ZF oscillation frequencies and the ZF residual level have been studied under different plasma conditions. In particular, an increase of the residual both with the radial ZF wavelength and the electric field strength is found in the simulations, in agreement with previous works [6]. The residual level increases with the external electric field strength until reaching saturation for intense fields.

Recent results in tokamak plasmas have shown the development of multiple radial scales with spontaneously formed long-lived pattern of $E \times B$ flows together with long-lived pressure corrugations and interspersed with regions of turbulent avalanching [7].

This contribution focuses on the interplay between multi-scale physics mechanisms and long-scale length (neoclassical) radial electric field in the TJ-II stellarator.

2. Experimental set-up

Experiments were carried out in the four-period, flexible, low-shear stellarator TJ-II (B = 1 T, edge rotational transform $\iota/2\pi(a) = 1.65$, $\langle R \rangle = 1.5$ m and $\langle a \rangle \leq 0.22$ m). This report is focused on pure (ion root) NBI heated hydrogen plasma discharges ($P_{NBI\,1} \approx 610$ KW, $P_{NBI\,2} \approx 460$ KW). The results reported here were made possible by the use of a unique detection system: two Langmuir probe arrays, named Probe 1 and Probe 2, installed on fast reciprocating drives located at two different toroidal ($\Delta\phi$) / poloidal ($\Delta\theta$) locations, approximately $\Delta\phi = 160º$ toroidally apart and poloidally separated $\Delta\theta = 155º$. Probe 1 consists of 12 tips in the radial direction spaced 3 mm apart plus 3 tips in inner position spaced 3 mm apart in the poloidal direction. Probe 2 has a similar configuration with 8 tips spaced about 2 mm and 3 mm in the radial and poloidal directions respectively. This set-up permitted the simultaneous investigation of short-range (i.e. plasma radial profiles with spatial resolution in the range of millimeters) and long-range fluctuation scales (i.e. plasma structures at scales of about 10 m) in the plasma boundary region [Fig. 1].

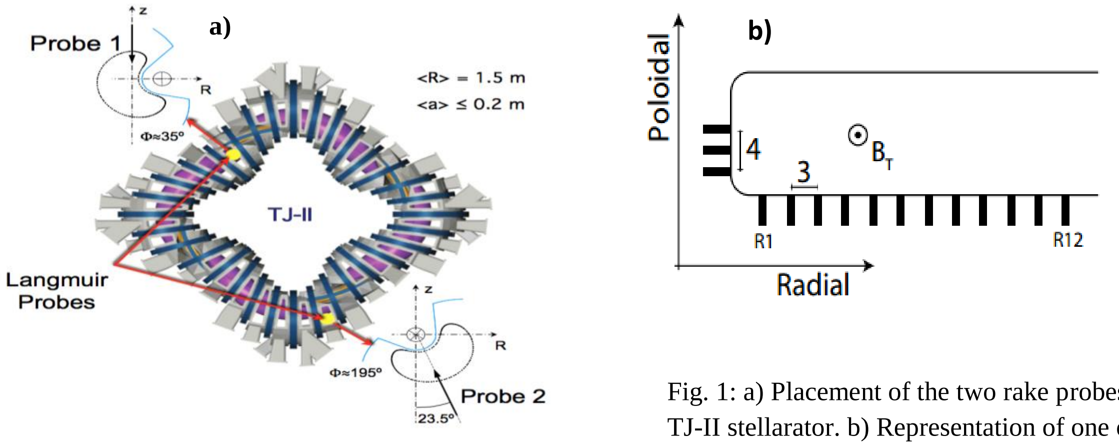

Fig. 1: a) Placement of the two rake probes in the TJ-II stellarator. b) Representation of one of the rake probes (probe 1)

3. Experimental results

3.1. Long and short scale radial electric fields

The mean velocity of fluctuations perpendicular to B_T and along the magnetic flux surface ($v_\perp$) is computed with the two point correlation technique using floating potential probes poloidally separated 3 mm. In the plasma edge region, just inside the LCFS, $v_\perp$ increases in the electron drift direction up to few km/s. Previous experiments have shown that $v_\perp$ is dominated by the ExB velocity and, in some conditions, by the diamagnetic drift velocity [8, 9]. High correlation was found between the E_r deduced from the gradient in floating potential and the perpendicular phase velocity of fluctuations. Thus, in the present plasma conditions, gradients in floating potential have been used as a proxy for radial electric fields. The long-wave length (~ 20 ion Larmor radius) radial electric fields have been measured from a linear fit of the radial profile of the floating potential; E_r values are strongly dependent on plasma density reaching values up to 3 kV/m. Short scale (~ 5 ion

Larmor radius) radial electric fields are measured by using Langmuir probes measurements along the radial direction with spatial separation is of 3 mm and time averaging in the range of 1 ms. Its magnitude varies along radial direction, exhibiting an oscillating-like behavior about the mean E_r. The amplitude of this oscillation has been determined and is called "corrugation" in E_r. This oscillation increases radially inwards and is also bigger for higher values of the global long-scale length radial electric field. This result shows coupling between long and short scale length components of E_r, with the level of corrugation increasing with the neoclassical radial electric field.

3.2. Long Range Correlation

The experimental set-up is ideal for measuring long range correlations. The long-range spectrum is dominated by frequencies below 20 kHz. An increase of the amplitude of Long Range Correlations (LCR) with the long scale radial electric field strength is found reaching saturation for E_r values in the order of 1 kV/m [Fig. 2]. These results are qualitatively consistent with GK simulations showing the influence of radial electric fields in the zonal flow residual level. The interplay between neoclassical ExB 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 (i.e. amplifying Reynolds stress driven flows) or/and the influence of radial electric fields on particle orbits (neoclassical damping).

3.3. Radial correlation length measurements

The radial correlation (L_r) of floating potential fluctuation was characterized using 12 radially spaced (3 mm apart) tips of Probe 1. L_r is defined as the distance in which the correlation between two signals decays below 1/e of the maximum of the correlation function. L_r was calculated using two different approaches, cross-correlation function and cross-coherence coefficient showing very similar results. Radial correlation frequency spectra are dominated by low frequencies (<20 KHz). We observe that L_r decreases as E_r increases [Fig. 3.a].

3.4. Shear in the electric field

The E_r shearing rate has been calculated at different radial scale lengths. For calculating the short scale shearing rate three Langmuir probes, placed at the middle region of the rake probe, measuring floating potential along the radial direction have been used. In order to obtain the global (long wave length) shear, a kernel function is applied to modulate the number of tips which are used for calculating the second derivative. Experimental results show that the local shear in the electric field is larger than the global one [Fig. 3] reaching values in the order of $10^5 s^{-1}$.

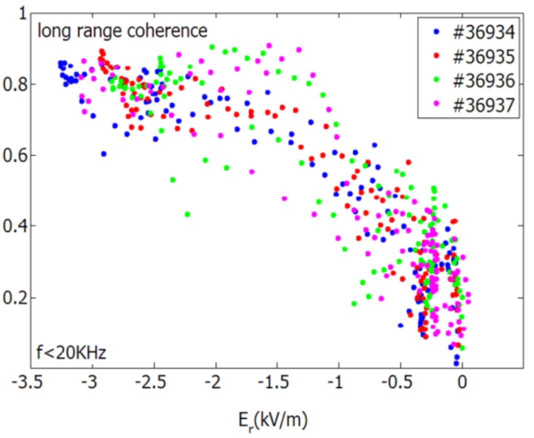

Fig. 2: Amplitude Long Range Correlations versus the long scale radial electric field for low frequencies (f < 20 kHz).

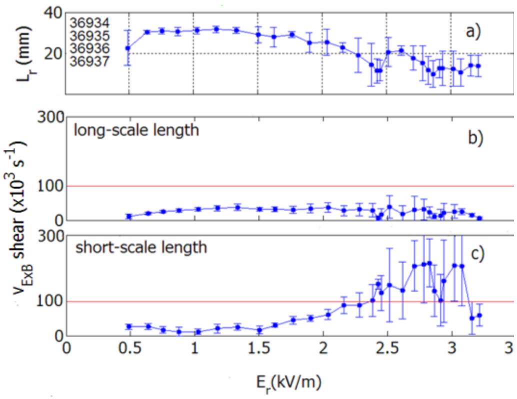

Fig. 3: a) Radial correlation, long (b) and local (c) E_r shearing rates versus the long scale radial electric field.

4. Conclusions

Long-scale length radial electric field (Er) was found to play a role in controlling the amplitude of LRC with zonal flow-like structures, in consistency with gyrokinetic (GK) simulations. At the same time, the radial correlation length of turbulence decreases. Long and short scale length components of the radial electric field are coupled and the level of corrugation increases with the neoclassical radial electric field. Experimental results show that the local shear in the electric field is larger than the global one reaching values in the order of $10^5 \mathrm{s}^{-1}$.

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