

# Experimental study of the relation between neoclassical and turbulent mechanisms in stellarators

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## 1. Introduction

The interplay between long (neoclassical) and short (turbulent) radial scale structures in radial electric fields and their role on the radial correlation length of the turbulence have been investigated in the plasma edge of the TJ-II stellarator [1]. Experimental findings show an empirical correlation between the properties of Long Range Correlations (LRC) with Zonal Flow-like structure and the magnitude of radial (neoclassical) electric fields. The radial electric field was found to enhance the magnitude of the LRC while the radial correlation length of the turbulence decreases in about a 30-40%. In addition, a strong coupling between the magnitude of long and short radial scales in the electric field was measured and the shearing rate in the radial electric field along short scale lengths can reach magnitudes in the order of the correlation time of the turbulence.

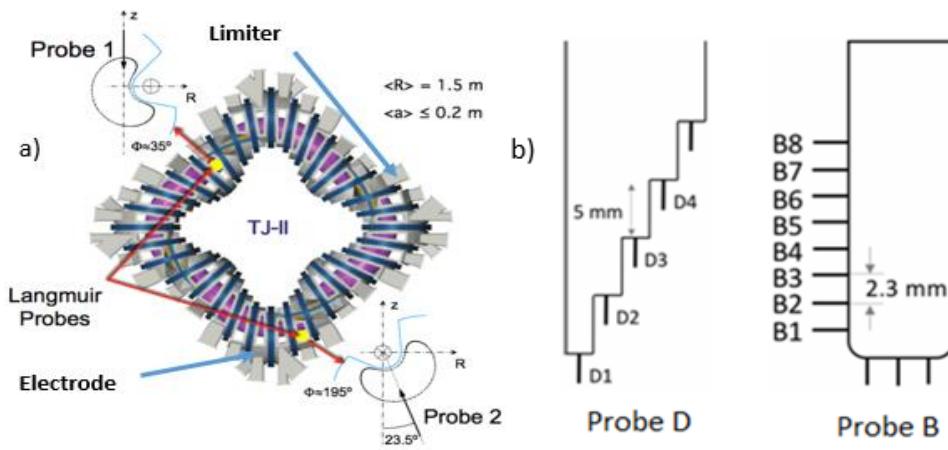
The mechanisms underlying the observed interplay between neoclassical radial electric fields and the amplification of low frequency zonal flow-like structures are at present under investigation, considering a) that sheared electric fields are efficient turbulence symmetry-breaking mechanism, amplifying the Reynolds stress drive of zonal flows, b) that radial electric fields give rise to  $E_r \times B$  drifts that prevent locally trapped particle orbits from drifting radially, reducing the effective damping of zonal flows. Actually, the amplification of low frequency ZF structures in plasmas with reduced viscosity has been confirmed by experimental observations in TJ-II [2].

Considering these two concepts, the Reynolds stress (as a mechanism of zonal flow (ZF) generation from turbulence) and the influence of radial electric fields in the damping times of ZF events are under investigation in the TJ-II stellarator plasmas. Simulation studies (MHD and gyro-kinetic) also are being done with this end.

Data from two types of discharges have been used for these studies: a) discharges characterized by a plasma density ramp with evolving neoclassical radial electric field and b) plasma pulses where edge radial electric field were externally modified by electrode biasing while the plasma density kept constant during the discharge.

## 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 two sets of plasma discharges. First, pure (ion root) NBI heated hydrogen plasma discharges ( $P_{NBI1} \approx 610$  kW,  $P_{NBI2} \approx 460$  kW). On the other hand, ECRH+NBI heated pulses ( $P_{ECRH} \approx 240$  kW,  $P_{NBI1} \approx 500$  kW,  $P_{NBI2} \approx 340$  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  $\Delta\phi = 160^\circ$  toroidally apart and poloidally separated  $\Delta\theta = 155^\circ$ . While performing the first set of discharges, one probe (considered Probe 1) consisted 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 was installed in sector D of TJ-II. Probe 2 has a similar configuration with 8 tips spaced about 2 mm and 3 mm in the radial and poloidal directions respectively and is installed on sector B [already described in the reference 1]. On the other hand, a second set of analyzed discharges corresponding to experiments in which a graphite electrode was biased (with AC functions) with respect to a radially removable lithium limiter



**Figure 1.** a) Scheme view of the TJ-II stellarator and the location of the two Langmuir probe, electrode, and Lithium limiter arrays on it. b) Sketch of the two types of Langmuir probe arrays used (the 2-dimensional probe on the left hand side)

with an AC voltage. Here, a two-dimensional probe array consisting of 4x4 pins radially spaced 5 mm and poloidally spaced 3 mm was installed in the place of Probe 1 [Figure 1].

### 3. Procedure and results:

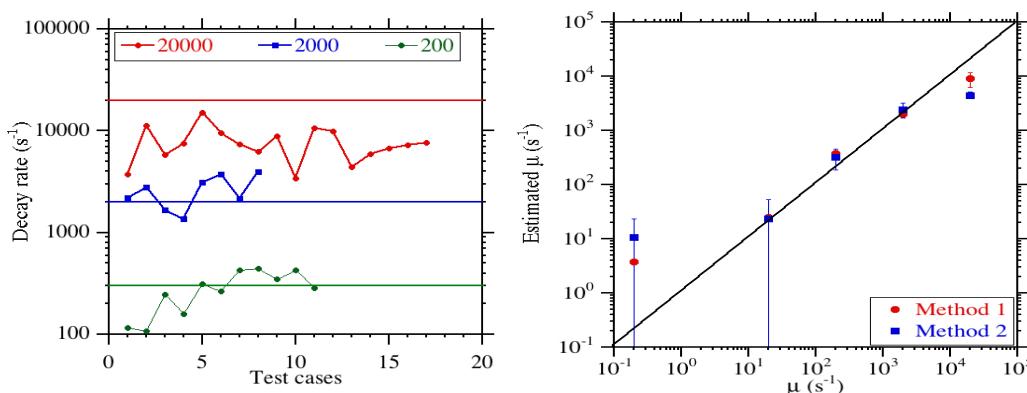
Plasma viscosity can be estimated from measurements of the decay of the velocity of zonal flows and plasma turbulence fluctuations. To this end, we are using results from numerical simulations of plasma turbulence based on resistive MHD equations that have been done for several values of viscosity. Details on these type of calculations can be found in [3]. In determining the decay of the velocity two different approaches have been explored:

One approach consist on the selection of several velocity oscillations and measuring the characteristic time scale of the exponential decay by fitting and exponential function. This method has been applied to the calculated evolution of the turbulence for five values of viscosity:  $2 \times 10^4$ ,  $2 \times 10^3$ ,  $2 \times 10^2$ , 20 and 0.2 in units of  $s^{-1}$ . A example of the results is shown in [Fig. 2.a]. The estimation by this method has some limitations. In the case of high viscosity is difficult to separate the fast decay from oscillations of the turbulence. In the case of very low viscosity the fluctuations do not decay and the method cannot be applied.

Another method is based on the simplified Lotka-Volterra equation, which describes the ZF velocity ( $V$ ) in function of Reynolds stress (driving) and viscosity (damping) as shown in (eq. 1), where  $V$  is the perpendicular velocity,  $\langle \Phi^2 \rangle$  is equivalent to the Reynolds stress, and  $\mu$  is the plasma viscosity.

$$\frac{1}{V} \frac{dV}{dt} = \alpha \langle \Phi^2 \rangle - \mu$$

Based on this equation we can calculate from the data the left-hand side term,  $(1/V)(dV/dt)$  and plot it as a function of the estimated value of the square of the fluctuation level. Then these data is fitted by a straight line and the value of the viscosity can be determined by the intersection of the line with the zero fluctuations. We have done this calculation for the five values of the

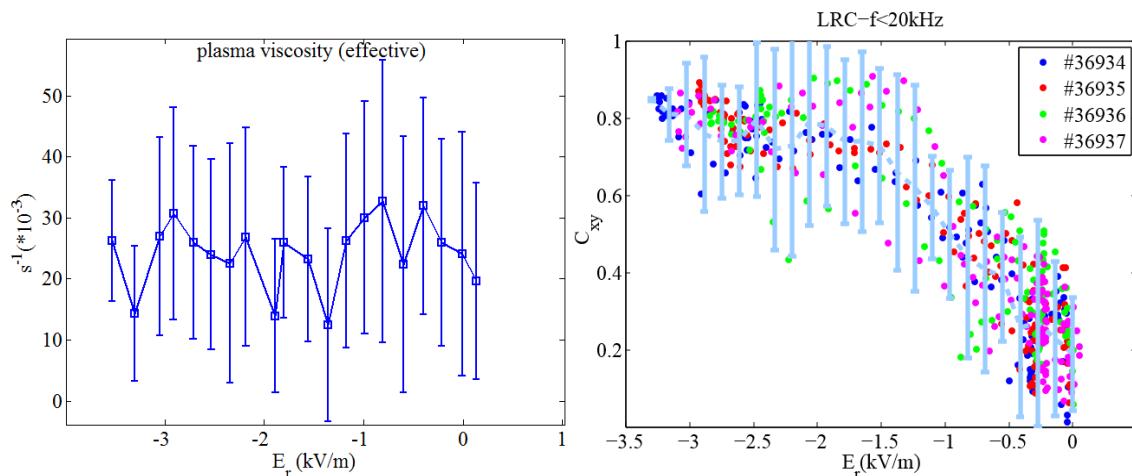


**Figure 2.** Simulations. On the left, values of the decay time of the oscillations of the Zonal Flow obtained from several oscillations velocity and for different values of viscosity. The right hand side figure shows the estimated viscosity determined after the plot of velocity as a function of fluctuation level.

viscosity, and the results are shown [Fig. 2.b]. This method does not work for the lowest values of the viscosity but it shows good results for the larger values. One of the problems with this method is the evaluation of the  $(1/V)(dV/dt)$ . Where we have high noise, either numerical or by the same turbulence, the evaluation of the derivative is not very reliable.

### Experiments:

The methods explained before are being applied to experimental data from TJ-II discharges. Two sets of plasma discharges where the radial electric field was modulated by the plasma itself and by electrode biasing respectively were selected. Effective viscosity is calculated as discussed in the previous section, by identifying oscillation decays and fitting by an exponential [Fig. 3.a]. First results give viscosity values in the order of  $10^4 s^{-1}$  but (within the error bars) no variation with  $E_r$  was detected in spite of the strong dependence of LRC with  $E_r$  [Fig 3.b].



**Figure 3.** a) The influence of the neoclassical radial electric field on the effective viscosity was studied, first results does not show dependence within the error bars in spite of the evidence of the modulation on the LRC levels for low frequencies

### Conclusions and future work:

Plasma effective viscosity was determined for TJ-II plasmas for MHD simulations and for experimental data. The magnitude of the obtained effective viscosity is in the order of  $10^{-4} s^{-1}$ , in agreement with previous works in TJ-II stellarator [4]. The influence of the neoclassical radial electric field on the magnitude of the viscosity is under study now in TJ-II.

### Acknowledgements

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