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INSTABILITY THRESHOLDS, RATIONAL SURFACES AND FLUCTUATIONS IN THE TJ-II STELLARATOR

C. Hidalgo, M.A. Pedrosa, T. Estrada, J.A. Jiménez, A.L. Fraguas, B. Van Milligen, and E. Sánchez

Laboratorio Nacional de Fusión por Confinamiento Magnético
Asociación Euratom-Ciemat, 28040 Madrid, Spain

B. Gonçalves
Euratom-IST, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

E-mail: Carlos.Hidalgo@ciemat.es

Abstract

A view of recent experimental results and progress in the characterization of plasma turbulence in the TJ-II stellarator device is given. An empirical similarity in the scaling properties of the probability distribution function (PDF) of turbulent transport has been observed in the plasma edge region. This result supports the view that turbulent transport displays universality in fusion plasmas and emphasizes the importance of the statistical description of transport processes in fusion plasmas. Comparative studies in different magnetic confined plasmas show that fluctuations and sheared poloidal flows organize themselves to be close to marginal stability. This property should be considered as a critical test for improved confinement transition models. Magnetic configuration scan experiments in stellarator devices have shown a complex interplay between transport and sheared radial electric fields in the proximity of rational surfaces.

I. Introduction

Although the dominant free energy source driving fluctuations have not been identified, one of the important achievements of the fusion community has been the development of techniques to control plasma fluctuations based in the ExB stabilizing mechanism [1]. The best performance of existing fusion plasma devices has been obtained in plasma conditions where ExB shear stabilization mechanisms are likely playing a key role [2]. These results emphasize the importance of clarifying the driven mechanisms of sheared flows in fusion plasmas.

Comparative studies of the structure of plasma turbulence carried out in different magnetic confinement devices have led to insights furthering the understanding of turbulent transport in fusion plasmas [3]. The overall similarity in the structure in the statistical properties of fluctuations has led to conclude that plasma turbulence in magnetically confined plasmas, as many other dynamical systems, display universal characteristics [4].

This paper reports recent results in the characterization of the statistical properties of turbulence and the physics of ExB sheared flows in the TJ-II stellarator.

II. Statistical properties of turbulent transport

Due to the flexibility of the TJ-II configuration, the magnetic well depth may be modified over a broad range of values, i.e. from 0% to 6 %, while the radial extent of the magnetic well can also be strongly modified. Recent experiments[5] have shown that, as expected from the theoretical point of view, the level of edge fluctuations and the degree of intermittency show a significant increase when magnetic well is reduced in the TJ-II stellarator. Fluctuation-induced E×B particle transport has been computed in the edge of plasmas in different magnetic configurations changing the magnetic well depth. Results show that the turbulent flux decreases as the well is increased. Electron density profiles measured by reflectometry during the magnetic well scan show a widening of profiles and an increase of the gradient as the magnetic well increases.

In the TJ-II stellarator, as in other devices, the probability density function (PDF) of the turbulent transport shows significant non-gaussian features. The Probability Density Functions (PDFs) of the local ExB turbulent flux are modified when decreasing magnetic well (Figure 1): these changes are mainly an increase on the probability of large amplitude flux transport events. The PDF of ExB turbulent fluxes can be rescaled using a finite-size scaling law[6] ,

$$\mathrm{PDF}\ (\Gamma_{ExB}) = L^{-1}\ g(\Gamma_{ExB}/L)$$

where Γ_{ExB} is the turbulent ExB flux and L is an scaling factor (Figure 1).

In order to identify the relation of the scaling parameter with plasma parameters it is important to keep plasmas with similar properties (magnetic topology, colisionality, etc.) but with different magnetic well (i.e. different level of fluctuations). This study has shown that the scaling parameter L is directly related with the level of fluctuations. Similar dependence has been recently observed in the JET tokamak[7]. The empirical similarity in turbulent fluxes suggests that edge plasma turbulent transport evolves into a state in which the PDFs of transport exhibit the same behaviour over the entire amplitude range of transport events.

III. Sheared poloidal flows and transport near marginal stability

From the wave number and frequency spectra S(k,ω), computed from the two points correlation technique[8], we define the poloidal phase velocity of fluctuations as,

$$v_{phase} = \sum S(k,\omega)\,(\omega / k) / \sum S(k,\omega)$$

A reversal in the phase velocity of fluctuations (shear layer) has been observed in the proximity of the last closed flux surface (LCFS) in magnetic fusion devices. Experiments carried out in the TJ-II stellarator show that the resulting radial gradient dv_{phase}/dr is in the range of $10^5\ s^{-1}$, which turns out to be comparable to the inverse of the correlation time of fluctuations, in the range of 10 μ s (Fig. 2). These changes in the poloidal phase velocity of fluctuations can be explained, or at least are consistent, in terms of ExB drifts. This result suggests that ExB flows and fluctuations organized themselves closed to marginal stability (i.e. the shearing rate is close to the critical value to modify plasma turbulence).

It is interesting to compare the results obtained in the TJ-II stellarator with those previously reported in other devices. In stellarator plasmas such as ATF[9] a reversal in the phase velocity of fluctuations have been observed. The position of the shear depends on the magnetic configuration and the resulting radial gradient dv_{phase}/dr was in the range of $10^5\ s^{-1}$, like in the TJ-II stellarator. It is remarkable that similar results have been obtained in tokamak plasmas. In particular, experiments carried out in JET[10] show that the resulting shearing rate in the poloidal phase velocity of fluctuations is also in the range of $10^5\ s^{-1}$. Similar results were found in the plasma edge of TEXT tokamak[11]. Large ExB sheared flows have also been reported in reversed field pinches[12].

These findings show that the presence of sheared flows with shearing rates close to the critical value modify plasma turbulence in the plasma boundary of magnetically confined plasmas. This result implies that there is not a continuous increase of the ExB flow shear when approaching the critical power threshold for the transition to improved confinement regimes (i.e. L-H transition)[2]. On the contrary, sheared flows with decorrelation rates close to the critical value to reduce turbulence are already developed well below the L-H power threshold. This property should be considered as an important ingredient in the modeling of the L-H transition. Recent numerical simulations have shown that turbulent driven fluctuating radial electric field via Reynolds stress has the property to get ω_{ExB} critical[13]. On the contrary, it is less obvious to understand in which way other mechanisms, like those based on the role of ion orbit losses, can allow the sheared poloidal flows and fluctuations to self-organize to reach the condition ω_{ExB} critical.

IV. Rational surfaces, radial electric fields and transport

The operational flexibility and the control of the magnetic topology in stellarator devices make them useful tools to investigate the role of rational surfaces on transport [14]. The presence of natural resonances has clearly been observed as a flattening in the edge plasma profiles in the TJ-II stellarator and in the LHD stellarator. Structures in plasma profiles have been observed in the case of low-order rational surfaces (n=8 / m = 5, n= 4 / m = 2) in the TJ-II stellarator. Both in TJ-II[14] and LHD[15] devices there is a significant variation in plasma potential just outside the flattening region. These results have been interpreted as an increase of the sheared ExB flow linked to the radial location of rational surfaces. The resulting radial gradient $(dE_r/dr)B^{-1}$ can reach values of about 10^5 s^{-1} and this value turns out to be comparable to the inverse of the decorrelation time of fluctuations usually measured.

These experimental results illustrate the impact of rational surfaces in the generation of ExB sheared flows. These results look very similar to recent experiments carried out in JET tokamak, which have shown flattening in plasma profiles and evidence of ExB sheared flows linked to rational surfaces[16]. This similarity suggests that ExB sheared flows are connected to the magnetic topology (rationals) both in tokamaks and stellarators. A possible explanation of the flow structure near rational surfaces is the coupling of flow generation and turbulence[13] (i.e. sheared flows driven by fluctuations via Reynolds stress). This mechanism can provide sheared poloidal flows linked to the location of rational surfaces. As pointed out in section II this mechanism is consistent with the magnitude of the observed shearing rates (close to the critical value to reduce fluctuations) in the vicinity of the magnetic island.

Recent experiments in TJ-II stellarator have shown that the local ExB fluctuation induced fluxes are significantly modified in the proximity of rational surfaces[17]. In the case of measurements taken in the proximity of the n = 4/m = 2 resonant surface, located near the plasma boundary, the local ExB fluctuation particle flux shows a reverse direction (from outwards to inwards). This modification is due to a change in the phase relation between density and electric field fluctuations. The absolute value of the measured local ExB transport is similar in both cases with (inward transport) and without (outward transport) the presence of the n=4/m=2 rational surface (Fig. 3).

Although the mechanism responsible of the observed inward transport has not been identified, it may be related with the presence of convective cells linked to rational surfaces. The fact that no significant differences were found in the global confinement, strongly suggests a local nature of the measured turbulent transport. Simultaneous measurements at different poloidal and toroidal locations are needed to clarify this question.

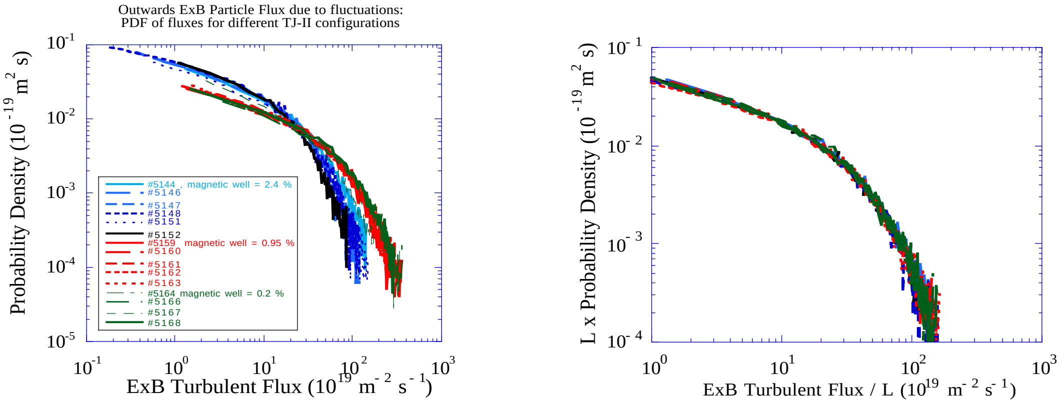

Fig. 1. PDFs of turbulent transport measured in plasmas with different magnetic wells (a), rescaled PDFs (b) in the TJ-II stellarator.

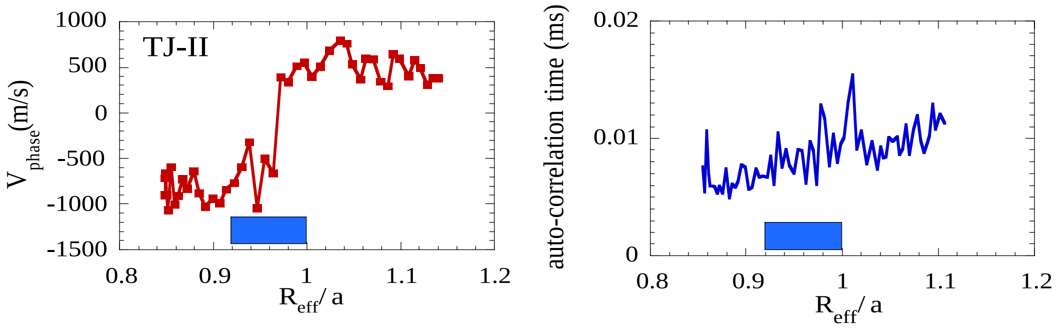

Fig. 2 Radial profile of the phase velocity and auto-correlation time of fluctuations in the proximity of the LCFS in the TJ-II stellarator. Dashed area indicates the location of the velocity shear layer.

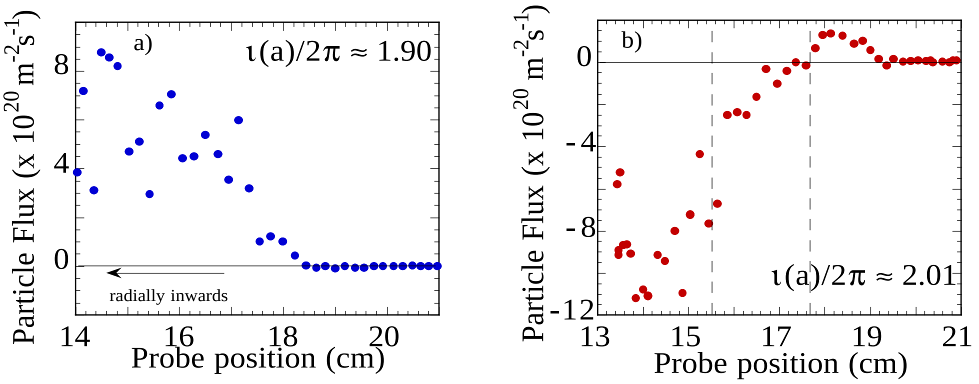

Fig. 3. Radial profile of the turbulent particle flux measured in a configuration free of low order rational surfaces (a) and with a low order resonance (4/2) located near the plasma boundary (b) in the TJ-II stellarator.

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