

Scaling of radial turbulent structure velocities in the tokamak SOL

O. Grulke¹, J. L. Terry², S. J. Zweben³

¹ *Max-Planck Institute for Plasma Physics, EURATOM Association, Greifswald, Germany*

² *PSFC, Massachusetts Institute of Technology, Cambridge, USA*

³ *Princeton Plasma Physics Laboratory, Princeton, USA*

It is a well known feature of turbulence that it displays intermittency, i.e. large-amplitude fluctuation events, which are ascribed to the formation of turbulent spatiotemporal patterns. This structure formation is of particular importance for magnetically confined plasmas due to the associated transport processes. In the last few years advanced diagnostics of tokamak scrape-off layers (SOLs) revealed that turbulent structures propagate coherently across the magnetic field over distances larger than the structure size [1, 2]. The structures form close to the separatrix and propagate into the far SOL, thereby impacting key reactor issues like helium 'ash' pumping, first wall sputtering of impurities, and first wall recycling. Several models have been proposed to address the radial propagation of turbulent structures in tokamak SOL. They commonly rely on the curvature of the magnetic field, either due to polarization of density structures and contact to material surfaces [3, 4] or due to interchange mode drive [5, 6]. Although those model approaches differ fundamentally, they are in rather good agreement with experimental results. Furthermore, the models make predictions of the radial structure speed, based on characteristic structure feature like relative fluctuation amplitude and spatial size, and configurational parameters like the magnetic field strength and curvature and connection length to material boundaries. However, the predicted scalings differ significantly and are sometimes contradictory.

In the present paper we address the scaling properties of turbulent structures in the SOL of the NSTX and Alcator C-Mod tokamak. The basic configuration of the considered situations is a lower single null Ohmic discharge in Alcator C-Mod and an inner wall limited discharge in NSTX. It has been shown that radially propagating structures can be observed in both devices [7, 8]. The SOL plasma, however, differs strongly in collisionality and the magnetic field strength, which are important quantities for scaling considerations in the models. For the discharges considered here the magnetic field was 5.4 T for Alcator C-Mod and 0.4 T for NSTX. The SOL plasma pressure fluctuations are observed with gas puff imaging diagnostics [9]. The D_α emission intensity of a localized gas puff is observed at the outer midplane with a fast framing camera. The camera view is tangentially along the local magnetic field, such that a radial-poloidal cross-section is imaged. The spatial area imaged is for C-Mod $(\Delta r, \Delta z) = (6,6)$ cm and is larger for NSTX with $(\Delta r, \Delta z) = (23,23)$ cm. The camera frame rate for the present experiments

was 250 kHz, which is sufficient to resolve the power spectrum of turbulent fluctuations, and 300 camera frames are stored. This corresponds to a total of 1.2 ms recording time. The individual frames are post-processed to separate the D_α intensity fluctuations from the time-averaged emission by high-pass filtering the time series of the individual camera pixels. Additionally, to avoid strong pixel-to-pixel noise-induced variations median filtering is applied, which limits the spatial resolution to $\approx 1 \text{ cm} = 5 \rho_s$ for NSTX and $\approx 3 \text{ mm} = 15 \rho_s$ for C-Mod, where ρ_s denotes the drift scale.

An example measurement of fluctuations in the Alcator C-Mod SOL for four time instants is shown in Fig. 1. The camera field of view is indicated by the diamond-shaped white boundary. The time instants are chosen to show the evolution of an individual fluctuation event. At t_0 the formation of the structure close to the separatrix is observed. During its evolution the amplitude increases, which is primarily related to an increased density of the gas puff, which is located approx. 1 cm behind the limiter edge indicated by the dashed gray line. The structure propagates poloidally in the direction of the background $E \times B$ drift, which is in parallel to the ion diamagnetic drift directed downward in this representation. However, the predominant propagation in the mid- and far-SOL is radially outward into the limiter shadow, where the structure decays.

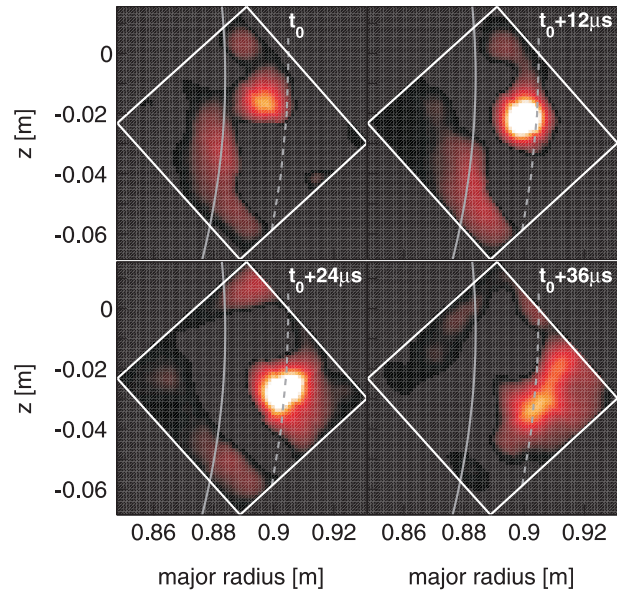


Figure 1: Camera imaging of D_α intensity fluctuations in a radial-poloidal cross-section of the outer midplane SOL of Alcator C-Mod. The separatrix is indicated by the solid gray line, the dashed gray line indicates the edge of a poloidal limiter.

To reveal the dependency of the radial propagation speed on the relative fluctuation amplitude and size of structure we separate structures in the camera images by applying thresholds [10]. First, the D_α intensity fluctuations of each pixel time series is normalized to standard deviation σ . We then apply a threshold to the fluctuation amplitude to decompose the images into events of different relative fluctuation levels. Additionally, only fluctuation structures are considered, which exceed a certain spatial size to only consider the large-scale fluctuation events. The minimum size considered for NSTX is 1 cm and for C-Mod 6 mm. We

apply three different amplitude conditions to the peak amplitude A of fluctuation structures: (1) large-amplitude events having $A > 3\sigma$, (2) moderate fluctuation amplitudes having $2\sigma < A < 3\sigma$, and (3) small amplitude fluctuation events with $1\sigma < A < 2\sigma$. As it is expected we find that an increased amplitude of the structures corresponds also to an increased spatial size of structures, such that we not only decompose into different amplitude scales but also into different spatial scales. We track the detected events through the camera field of view by detecting their center of mass position, which consequently yields their radial velocities. Since the velocities are distributed the characterization is done by calculation of their probability distribution function (PDF). The result of this procedure is depicted in Fig. 2. Shown are the PDF's for the three different amplitude threshold conditions for an Alcator C-Mod and NSTX discharge, respectively. The velocities are scaled to the ion sound speed. In general the PDFs are shifted to positive velocities, which corresponds to outward propagation of structures. The distributions are relatively broad with maximum structure velocities reaching $5\%c_s$, where c_s is the ion sound speed and for the discharges under consideration is in the SOL ≈ 35 km/s for NSTX and ≈ 50 km/s for C-Mod. It is generally the tendency observed that the widths of the distributions become slightly larger for smaller peak fluctuation amplitudes.

The mean velocities, i.e. the center of the distributions, is found at a few $\%c_s$ in both situations, C-Mod and NSTX. Based on these results no strong dependency on the magnetic field strength is observed. Furthermore, the radial velocity changes only little with structure size and amplitude. In the case of NSTX the mean velocity is roughly constant at $\approx 1\%c_s$. In the case of C-Mod the tendency to larger velocities with increased structure amplitude is visible. Comparing the low amplitude structures with $1\sigma < A < 2\sigma$ with the largest having $A > 3\sigma$ the mean radial velocity essentially doubles from $1\%c_s$ to $2\%c_s$. This behavior is in rough agreement with the interchange mode scaling [11], but is opposite to the sheath connected model for structure propagation [3].

In summary we investigated the radial velocity of large-amplitude fluctuation structures in

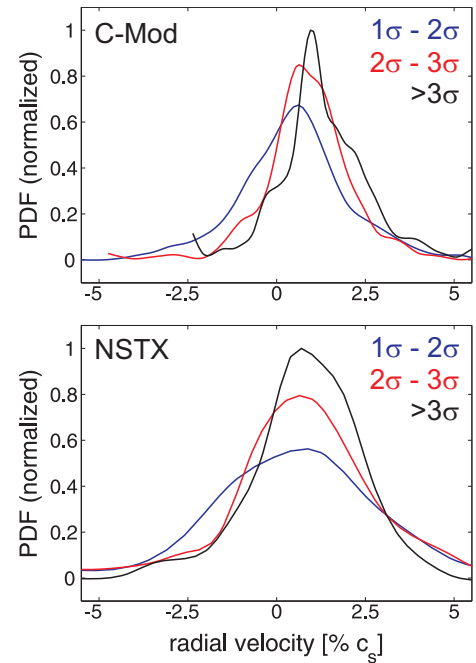


Figure 2: Probability distribution function of the radial velocities for Alcator C-Mod and NSTX for three different amplitude threshold conditions. The radial velocity is scaled to the ion sound speed c_s .

the SOL of the Alcator C-Mod and the NSTX tokamak. The analysis yields similar velocities in both devices and no clear dependency of the magnetic field is observed. For Alcator C-Mod an increased radial velocity is found for increased fluctuation amplitudes, which is along the line of the dissipationless interchange mode scaling, but stands in contrast to sheath connected models, which are generally not expected to apply for the C-Mod SOL due to its high collisionality. The results strongly suggest that the radial structure velocity is affected by additional mechanisms as considered in the model approaches. Especially the complex dynamics along the magnetic field and the interaction with the magnetic field topology, material surfaces etc is expected to strongly influence the structure dynamics and is generally not considered in simplified models.

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