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Universality of Intermittent Convective Transport in the Scrape-off Layer of Magnetically Confined Devices

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This article describes briefly recent results on the universality of intermittent convective transport reported in the scrape-off layer. We show that the statistical properties of turbulence are identical for four different magnetic fusion devices. The four devices are the PISCES linear plasma device, the Tore Supra tokamak with limiter configuration, the Alcator C-MOD with divertor configuration and high magnetic field, and the MAST spherical tokamak where the walls are far from the last closed flux surface (LCFS). These four devices do not only have different magnetic configurations but also have four different probes designs. Nine different types of statistical analyses are used, here we present just a few.

1 Introduction

Anomalous transport in fusion plasmas is extensively studied in order to control and enhance the performance of fusion devices. Even after several decades, the nature of such transport is still a subject of intensive research. In the scrape-off layer (SOL), experimental measurements revealed spiky aspect of plasma transport not in agreement with a random diffusive process. Recent experimental studies showed that intermittency in the SOL of magnetic fusion devices is caused by avaloids (also called blobs) [1]. Avaloids are defined as large-scale plasma structures with high radial velocity encountered intermittently in the SOL. In the PISCES linear plasma device and far from the main plasma column Fig. 1 clearly shows that avaloids have large scales (1 cm in comparison to 2.5 cm for the plasma radius) and large radial velocities (about 1/10th of the sound speed). Intermittent convective transport leads to hot plasma in contact with the chamber first wall even when the latter is far from the last closed flux surface (LCFS). Exponential, or nearly-exponential, density decay often exists near the LCFS, but in the far SOL, the fast intermittent convective transport tends to flatten the profile. Consequently, the SOL is a region extending up to the vacuum vessel walls of open field lines where turbulence dynamics are still complex and highly intermittent. We focus here on showing the universality of this phenomenon in other fusion devices with toroidal geometries. The full details of this work was published in Ref. [3].

2 The Four Different Devices

The plasma density and temperature inside the PISCES linear plasma device main column is similar to tokamak edge plasmas. The radius of the plasma is 2.5 cm set by the axial magnetic field and a baffle tube that acts like a circular limiter. The chamber walls are at 10 cm from the center leaving with lot of space to study and characterize intermittency. The probe tips and protecting cylinders can be very small about 0.1 mm and 1 mm respectively. The Alcotor C-MOD tokamak plasmas are limited by a divertor configuration. The walls are close to the plasma just few centimeters away. It has a high magnetic field about 5.3 Tesla. See Ref. [2] for more information about the tokamak and the type of probe used. The Tore Supra tokamak plasmas are limited by a limiter. For more information see Ref. [5]. The probe on Tore Supra is rather perturbative as it consists of a protecting cylinder making about 5 cm in diameter with holes drilled through it. Behind the holes is installed six tips, the diameter

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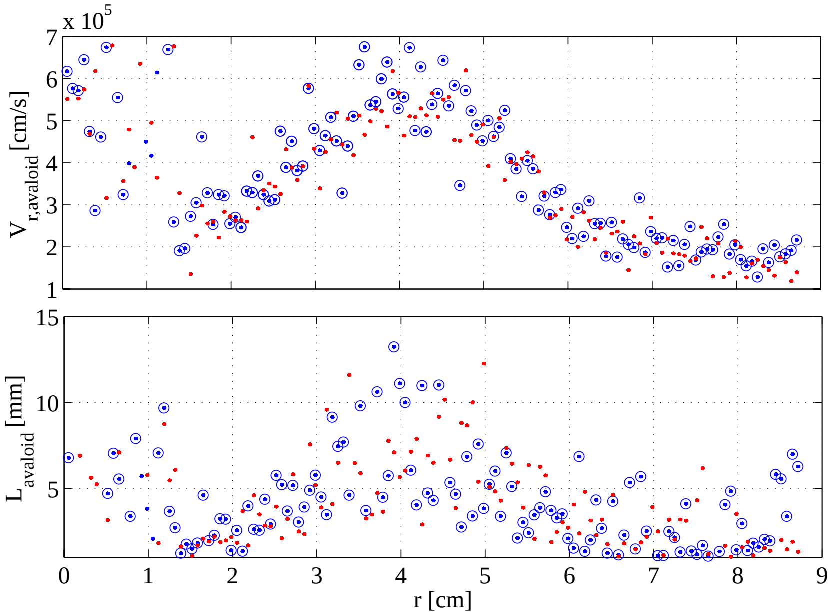

Fig. 1 (a) represents the radial $E \times B$ velocity of avaloids deduced from two floating probe tips. Knowing avaloids life-time from the auto-conditional averaging function, when can deduce their radial scales. This is plotted in (b) as function of the distance to the center of the main plasma column. In PISCES the plasma radius is 2.5 cm. The two symbols . and o represent two plunges of the Langmuir multi-tip probe.

of the holes is few millimeters defining the collection area. The MAST spherical tokamak is a low aspect ratio device with first wall far from the last closed flux surface. It is divertor device for more information see Ref. [6]. Except PISCES, on all the other devices the acquisition frequency of the data was set to 1 MHz.

3 The Comparison

This section presents some of the comparisons that were exposed in a detailed manner in Ref. [3]. Fig. 2 shows the raw ion saturation signals as function of the distance to the plasma edge in PISCES and MAST. Plasma is detected as far as 30 cm away from the LCFS in MAST. In consequence, one can show that the average profile is flat for distances between 7 and 30 cm away from the LCFS. It is worth noting here that avaloids radial scales reported in MAST and PISCES are respectively 1.1 and 5 cm, the radial velocities being 1.5 and 1 km/s.

The probability distribution function of the four devices are plotted in Fig. 3. It is clear that the four PDFs are similar where they all possess a parabolic shape for the negative fluctuations, and a rather linear (exponential) decrease for the positive fluctuations. One can deduce that the intermittent bursts perturb only the positive fluctuations leaving the negative fluctuations Gaussian.

In Fig. 4 is shown the power spectra of the four devices. They have one scaling region only with a scaling exponent close to -1.6. One can notice that high frequency fluctuations are almost absent reflecting the fact that avaloids are large-scale structures. The scaling exponent is a measurement of the average of the rise and decay time scales of avaloids as they dominate the signal properties. Note that there is no $1/f$ scaling region.

Conditional averaging is used to study the high intensity bursts independently of the background. After selecting the maxima above a certain threshold here equal to three times the standard deviation, averaging over the number of events is done with a width around each maximum. The result is shown in Fig. 5. The plots show the average shape of an avaloid in time as it passes across a probe. Note that the shape does not conserve mass in the sense that avaloids have positive densities only. Note also the asymmetric shape with fast rise time and slow decay time. This shape could indicate that vorticity is not an important parameter in the formation of avaloids as vorticity tends to make the structures symmetric and tends to accumulate density in the core while rarifying in other spatial locations. This rarefaction leads to negative density fluctuations not observed here.

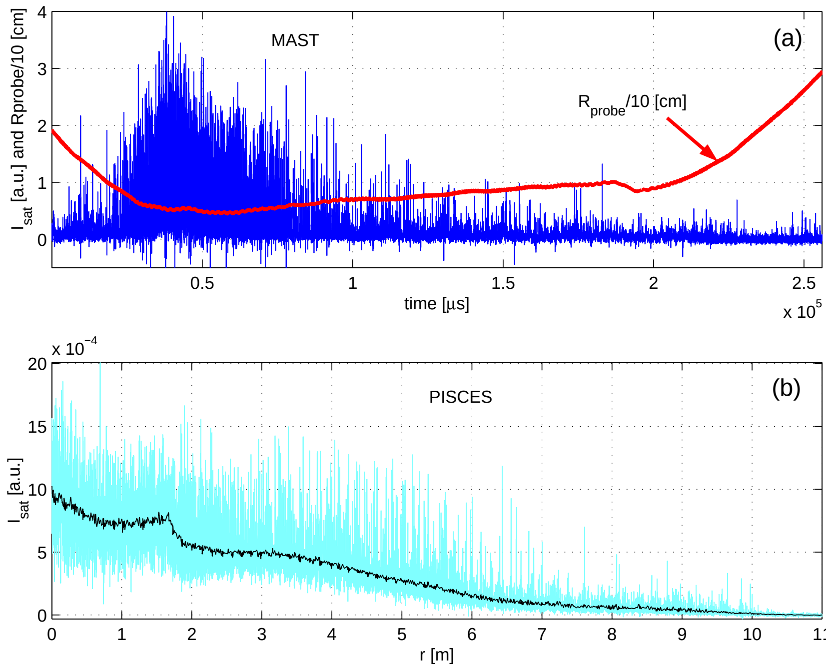

Fig. 2 (a) and (b) the ion saturation current with respect to r in MAST and PISCES. The solid line in (b) represents the average profile. Note that (1) plasma in both devices is recorded far from the edge. (2) plasma far from the edge exists in the form of intermittent bursts; the contribution of diffusive turbulence can be neglected. Inside the main plasma turbulence is different with fluctuations close to Gaussian.

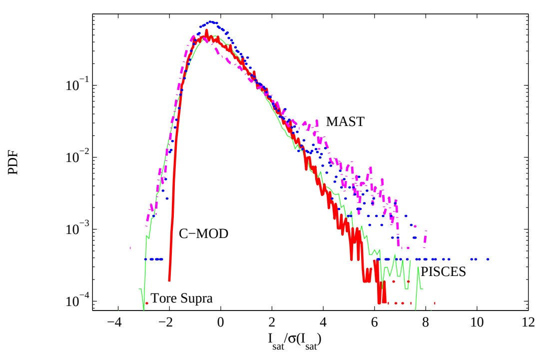

Fig. 3: A semi-logarithmic plot of the PDF of the ion saturation current in the Tore Supra (solid line), Alcator C-Mod (thick solid line), MAST (dash-dotted line) and PISCES (dots). The ion saturation current was normalized to the standard deviation and the integral of the four PDF is set equal to 1.

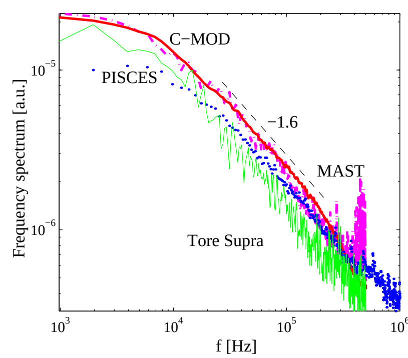

Fig. 4: A log-log plot of the power spectrum of the ion saturation current fluctuations in Tore Supra (solid line), Alcator C-Mod (thick solid line), MAST (dash-dotted line) and PISCES (dots). The ion saturation currents, taken in the SOL, were normalized to the standard deviations.

4 Conclusion and Discussion

In summary, we presented Langmuir probe measurements showing that plasma is detected in the PISCES linear device and the MAST spherical tokamak far from the core plasma column, that is, at four times the plasma radius due to avaloids. The universality of convective turbulence in the scrape-off layer of magnetically confined plasmas was demonstrated using four devices, the MAST spherical tokamak, the Alcator C-Mod conventional

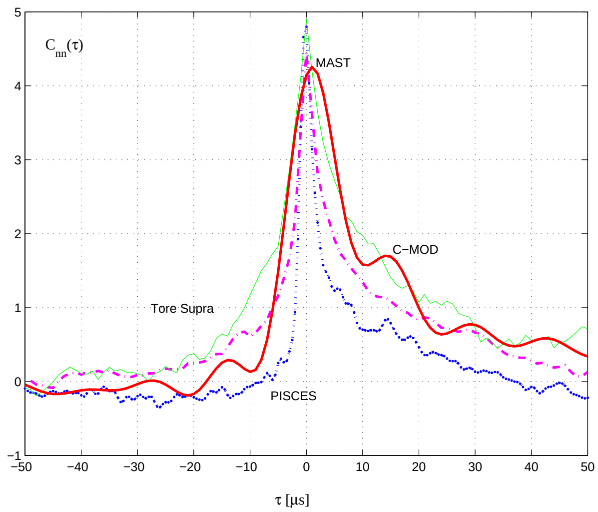

Fig. 5: The auto-conditional average C_{nn} in Tore Supra (solid line), Alcator C-Mod (thick solid line), MAST (dash-dotted line) and PISCES (dots).

high-field tokamak, the Tore Supra tokamak and the PISCES linear plasma device. The comparison among the different turbulent signals was performed using different statistical analyses. The reason behind using several signal processing schemes is to show that the signals are identical in many different ways. In complex media such as fusion devices, the use of different statistical analyses to compare the properties of different devices or when a comparison between theory and experiment is made is crucial and essential. One has to keep in mind that very different processes can lead to the same power spectra or the same probability distribution functions. So, the more the number of statistical analyses that are used the more we will be sure that the similarity put forward reflects reality.

The present comparison was made not only on different magnetic confinement devices but also using different probe designs. The dimensions of the probe scan from rather big in Tore Supra to very small in PISCES. The present investigation shows that the probe perturbation is not responsible for the bursts generation and does not alter significantly turbulence properties in the scrape-off layer. The main reason behind that is that it is found that avaloids have scales that are larger than the probes. Hence, the perturbation of the probe, which affects mainly scales of the same order or smaller than its size, is not important at large scales.

The detailed study presented in this article showed that intermittent convective transport by intermittent large-scale high-velocity events, called avaloids, is universal in the sense that it is encountered in most toroidal as well as linear plasma devices leading to identical properties of turbulent fluctuations in the scrape-off layer.

I believe that the use of the term avaloids will certainly help making the discussion more precise. It was found that avaloids are not coherent structures in the fluid sense where coherent vorticity plays the essential role [4]. Avaloids are large scales as it was shown using several data analyses [4, 1, 3]. One can show that avaloids scales is set by the instability at the plasma edge that generates them and there is no hierarchy of scales as it was proposed in models such as self-organized criticality [7]. Moreover, if their scales are of the order of the 'normal' turbulence scales, they would be mixed with the background in an efficient manner famous for turbulence mixing. The fact that avaloids have large radial velocity is a crucial element. Not any 'blobby' structure seen or measured near the LCFS is an avaloid. One has to show that the radial velocity is large; this would be a main mean to distinguish between normal turbulent structures and avaloids. Often turbulence intensity due to diffusion decays rather rapidly in the SOL, so avaloids are more clearly observed in the far SOL, say more than twice the decay length of the SOL using the diffusion component alone.

One interesting comparison can be made between intermittency found in fusion devices and the one found in neutral fluid. In three-dimensional turbulence in neutral fluids, intermittency is at small scales reflecting the inherent property of the turbulent structures to occupy smaller and smaller space with decreasing scales. [8] In fusion plasmas, intermittency has a different origin as it is due to large-scale structures. As it was argued above in discussing the shape of the auto-conditional averaging function, avaloids do not result from an organization of turbulence. Consequently, one can describe intermittency in 3D fluid turbulence as *local* because its properties depend on the local turbulent fields; whereas intermittency in fusion devices is *non-local* with properties that depend on the onset of some instabilities at the plasma edge far from the SOL where they are recorded.

Fig. 6 illustrates the major change in our understanding of the scrape-off layer. It is no longer formed of a simple exponentially decaying layer close to the last closed flux surface. Hot and dense plasma is present intermittently far from the LCFS mainly because of the high radial velocities of avaloids that allow them to compete with the parallel transport and thus survive far from the production region. The region near the target plates were left unaffected by avaloids because there are preliminary results on MAST that indicate that avaloids are not poloidally symmetric. The effect of magnetic shear should be taken into account as a stabilizing force against the instability that leads to avaloids generation.

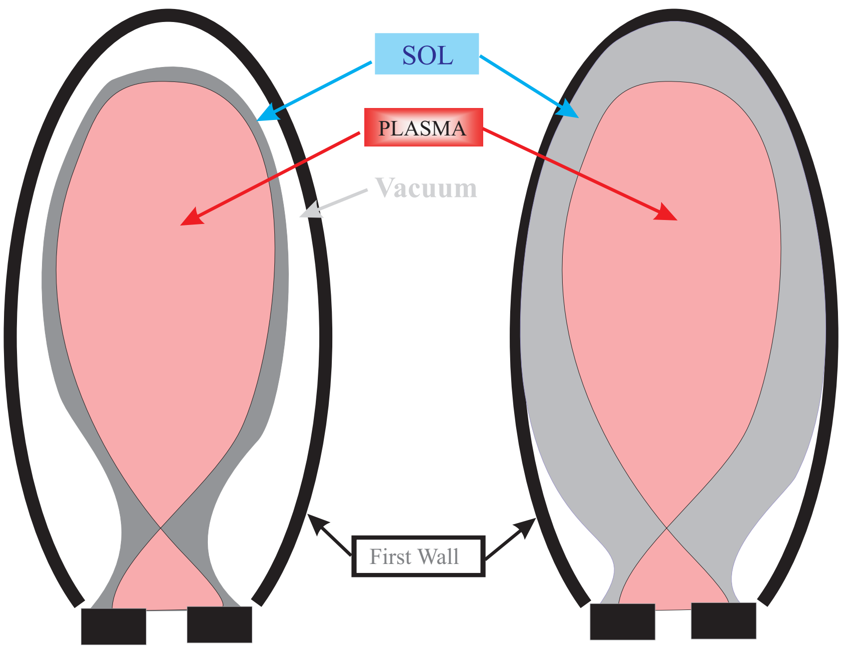

Fig. 6: Illustration of the general picture that one ends up to after the recent progress in understanding the SOL turbulence. The major change is that hot and dense plasma is no longer retained close to the last closed flux surface with intensity decaying exponentially. Hot and dense plasma can be found far from the LCFS in an intermittent fashion. Hence, the concept of a vacuum region in tokamaks no longer exists.

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