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On the origin of “intermittency” in the scrape-off layer of linear magnetic confinement devices

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The goal of this article is to show that the “intermittent” convective transport in the scrape-off layer (SOL) of linear magnetic confinement plasmas actually takes place *periodically*. This is reflected in several features that are unveiled in this article. It is found that the distribution of the time between high-amplitude bursts, selected above a given threshold, has a central frequency in the SOL. Moreover, this distribution is found similar to the one taken inside the main plasma column as the threshold is reduced, suggesting links between the SOL and the main plasma column. The power spectrum of the radial flux is determined, indicating the presence of a coherent peak that accounts for about 50% of the transport. Using two probes that are poloidally and radially separated, it is shown that a burst in the SOL is correlated to a wave packet inside the main plasma column. The relation between the two distant regions is thus assured by avaloids that are nonlocal structures in nature as they have velocities much higher than the background. © 2003 American Institute of Physics. [DOI: 10.1063/1.1599855]

I. INTRODUCTION

Intermittency in the scrape-off layer (SOL) was observed in nearly all magnetically confined plasmas.^{1–4} A recent investigation indicates that intermittent events have large scales, greater or about the macro-scale of turbulence, and high radial velocities as high as 1/10th of the sound speed.⁵ These structures were named avaloids, and they transport about 50% of matter outside the main plasma. Because of their properties, avaloids alter the concept of the scrape-off layer (SOL) where hot and dense plasma is no longer limited to a region near the last closed flux surface but can be found far from it with intensity as high as at the plasma edge.^{5,6} Avaloids density and temperature do not decay exponentially, leading to the observed flat profiles in tokamaks and linear plasma devices⁷ that cannot be described by a purely diffusive approach. They can explain the enhanced erosion and the high impurity levels recorded on different tokamaks.⁸ For devices like ITER (International Thermonuclear Experimental Reactor),⁹ they could lead to a high level of erosion of the first wall. Furthermore, recent results suggest that there may exist a relation between the fast convective transport and the density limit.¹⁰ Other area where avaloids may play a crucial role is the Bohm versus gyro-Bohm scaling. The identification of large-scale events with high radial velocity can in fact explain the gyro-Bohm scaling.⁹ Taking into account the new experimental findings, high radial velocity was included in the widely used UEDGE code model, leading to an accurate description of the plasma parameters in the DIII-D tokamak.¹¹

The goal of this article is to show that, even though avaloids are encountered intermittently, they are generated periodically by an instability occurring at the plasma edge. The results of this article are obtained in the PISCES linear plasma device. We believe, however, that they are relevant to

toroidal fusion devices, as we have shown in detail that the statistical properties of turbulence in the scrape-off layer of linear and toroidal devices are identical.⁶ This was obtained using different types of data analyses, and in spite of the different magnetic configurations and Langmuir probe architectures.

II. THE PISCES SETUP

The results presented here are obtained on the PISCES linear device.^{12,5,6} Figure 1 illustrates a schematic of PISCES. A baffle tube, acting like a circular limiter, reduces the radial extension of the plasma to 2.5 cm in radius while the chamber walls have a radius of $r=10$ cm. The axial magnetic field is $B=0.12$ T. The electron density and temperature are shown in Figs. 2(a) and 2(b), respectively. The plasma density shape can be approximated by a Gaussian in contrary to the temperature profile, where the gradient at the plasma edge is steeper. The plasma recorded farther than 2.5 cm is caused by radial transport, as it is the only plasma source present in this region. We call SOL in PISCES the region $10 \geq r \geq 2.5$. Langmuir probes are used with three cylindrical tips having a length of 0.5 mm and a diameter of 0.2 mm. Two tips are floating and one is biased to the ion saturation current (I_{sat}). The acquisition frequency is set to 2 MHz with 2×10^6 points recorded.

III. EXPERIMENTAL RESULTS

A. Conditional averaging threshold variation

The conditional averaging technique consists in selecting maxima of I_{sat} above a certain threshold (I_{th}), here equal to three times the standard deviation (σ). Figure 3(a) shows that the probability distribution function (PDF) of the time between bursts (ΔT) peaks around 5 kHz in the SOL of

FIG. 1. Schematic of the PISCES-A linear plasma device.

PISCES.⁵ It is hard, however, to conclude whether the generation process is periodic or intermittent because of the long tail toward longer waiting times. We should emphasize that the same distribution is recorded in the SOL of the Tore Supra, Alcator C-MOD and Mega-Ampère Spherical Tokamak (MAST) tokamaks, as exposed in Ref. 6. Figure 3(a) indicates that $\text{PDF}(\Delta T)$ changes shape as the main column plasma is probed. It seems more spread not having a definite central frequency. But this is merely a consequence of the lack of events selected above the threshold. Figure 3(b) shows the number of spikes decreasing dramatically when the probe is moved inside the main plasma column. This is caused by the change in the signal properties from intermittent ($r > 2.5$) to Gaussian ($r < 2.5$), as was shown in Ref. 5.

FIG. 2. (a), (b), and (c) show the radial dependence of electron density and temperature and the plasma space potential in PISCES in dots. In (a) and (c), the thick solid lines reflect a Gaussian fit of the experimental data. In (b), the thick solid line reflects the filtered data.

In order to have more information about the nature of the fluctuations inside the main plasma column, the number of bursts, N_b , is determined as function of I_{th} . The result is plotted in Fig. 4(a) for different radial positions of the probe. For $r > 2.5$, N_b decreases rather slowly according to $I_{th}^{-0.5}$, in agreement with the results found on the Tore Supra tokamak.¹³ This is reflective of intermittency and in contrast to a random Gaussian signal, where $N_b \sim I_{th}^{-1}$. Inside the main plasma column, Fig. 4(a) shows that N_b decreases sharply just after $I_{th} = 2\sigma$, and the number of spikes nearly goes to zero. This behavior is expected for signals where the amplitude is bounded, such as waves. The threshold position in this case plays a critical role: when it is below the amplitude of the oscillation all the events are enumerated; otherwise, no events are selected and N_b tends rapidly to zero. Furthermore, for $I_{th} \sim 1.8\sigma$ the distribution of the waiting times in the SOL and inside the plasma are now similar, as shown in Fig. 4(b). This strongly suggests a relationship between the average waiting time between two bursts in the SOL and the dynamics inside the main plasma column.

B. The power spectrum

The coherent oscillation, suggested by changing the threshold of the conditional averaging, is reflected more clearly in the power spectra plotted in Fig. 5(a). The frequency spectra of the density ($|n(f)|^2$), radial velocity ($|V_r(f)|^2$) and radial flux ($\Re(n(f)V_r^*(f))$) inside the plasma contain a coherent peak at a frequency $f \approx 80$ kHz. According to Fig. 5(a), about 50% of the particles that are ejected radially outside the main plasma column is taking place at this frequency.

The complete characterization of what type of instability is out of the scope of this paper. It requires numerical simulations, taking into account, for example, the plasma rotation, the fixed boundary caused by the baffle tube presence, the finite Larmor radius effects ($\rho_i \approx 3$ mm) and the presence of a high-intensity turbulent fluctuations. However, some insight on the nature of the low-frequency mode observed on PISCES can be gained using simple arguments.

Experimentally, two typical frequencies reflecting coherent oscillations are detected. First is the low-frequency oscillation about 5 kHz. It is reflected in the filtered I_{sat} signal for $r < 2.5$ cm, plotted in Fig. 5(b), as well as in distribution between high-intensity events in the SOL. Second is the 80 kHz oscillation reflected in the raw signal of I_{sat} and thus in the power spectrum. The difference between the two typical frequencies can be accounted for by considering the $\vec{E} \times \vec{B}$ and the diamagnetic drifts. This is because the time between two bursts does not depend on the Doppler shift as does the power spectrum. Figure 2 shows the profiles of the electron density and temperature as well as the plasma space potential as function of r . One can deduce the length scale of density and temperature gradients to be about 1 cm. From Fig. 2(c), the radial electric field is about 3 V/cm. Accordingly, the frequencies associated to the $\vec{E} \times \vec{B}$ and the diamagnetic drifts are about 17 and 50 kHz, respectively. Adding them up yields an average Doppler frequency of about 67 kHz.

FIG. 3. (a) The PDF of ΔT at $r=4, 5$, and 6 cm, and the solid edge bars are for $r=2$ cm. The PDF's are not normalized so the y axis reflects the number of counts. (b) The number of bursts recorded on I_{sat} for $I_{\text{th}}=3\sigma$ as a function of r for four plunges to demonstrate the reproducibility of the result. At the main plasma column edge, the signals are nonstationary leading to the fast modulation of N_b where there is overestimation followed by underestimation of N_b as r increases.

A 1 cm scale of the density and temperature gradient leads to a drift-wave instability frequency about $50m$ kHz, m being the azimuthal mode number. Even for $m=1$, this type of instability cannot explain either of the two frequencies detected experimentally as it yields values too high with respect to what is being observed (around 50 kHz for the low frequency and 120 kHz when the Doppler shift frequency is added). However, this instability could well be behind the high level of incoherent turbulent fluctuations observed in PISCES and reflected in the broadband component of the spectrum that accounts for about 50% of the radial transport.

The type of instabilities leading to the coherent low-frequency oscillation could well be of Rayleigh–Taylor type.¹⁴ The theoretical investigation of the centrifugal flute-mode instability in bounded plasmas with high rotation was investigated in Ref. 15. Accordingly, and for the plasma conditions of PISCES, one finds that the mode frequency is about the diamagnetic drift velocity for the ions. The ion temperature in PISCES being about 1 eV leads to a mode frequency about $5m$ kHz. For $m=1$, this mode frequency is close to the one observed experimentally from the time between two bursts. Moreover, adding the $\vec{E} \times \vec{B}$ and the diamagnetic drift frequencies leads a value in agreement with the position of the power spectrum coherent peak, that is, about 80 kHz. Should we mention that previous attempts in the Columbia linear device to identify the instability behind an 80 kHz mode has led to the same conclusion.¹⁶

By inducing a high level of fluctuations, drift-wave turbulence could trigger other instabilities, such as Rayleigh–Taylor, that initially would have been stable for low levels of fluctuations. So, even if the instability might be of the Rayleigh–Taylor type, one should take into account the in-

terplay with drift-wave turbulence that could supply the high level of fluctuations needed to destabilize the flow.

C. Cross-correlating inside and outside the main plasma column

We aim now at showing that the fluctuations in the SOL, dominated by avaloids, and the fluctuations inside the main plasma column, dominated by the mode at 80 kHz, are actually correlated. We make use of two identical Langmuir probes positioned horizontally and vertically in PISCES to relate the density fluctuations deduced from the two ion saturation currents. The horizontal probe is fixed, and its position (r_F) is altered after each plunge of the vertical reciprocating probe. The data acquisition on the two probes is triggered at the same time and for each r_F , two million points are recorded. Figure 5(b) shows two I_{sat} signals recorded at the same time where the vertical probe is inside the plasma and the horizontal probe is at $r_F=7$ cm. The vertical probe signal was filtered around 80 kHz. Inside the plasma, Fig. 5(b) indicates that the peak at 80 kHz is actually formed of a wave that grows, saturates, loses intensity, and then grows again. At the same time, far into the SOL, the signal contains high-intensity bursts on top of a small background turbulent level. One can see that the time interval between wave packets is about the same as the time between bursts, leading to the similarity of PDF(ΔT) in the SOL and inside the plasma reported in Fig. 4.

The two I_{sat} signals recorded on the vertical and horizontal probes are divided into a number, N , of nonoverlapping regions. After calculating the cross-correlation coefficient C_{RF} for the $N \times N$ matrix, it is found that C_{RF} is above the

FIG. 4. (a) The number of bursts N_b plotted against I_{th}/σ for $r=2.5$ and 6 cm in thick solid lines; the thin solid lines represent intermediate values of r . (b) The PDF of ΔT at $r=2$ and 6 cm for $I_{\text{th}}=1.8\sigma$, showing the strong similarities in shape. The PDF's are not normalized so the y axis reflects the number of counts.

FIG. 5. (a) The power spectra of the density (n), radial velocity (V_r), and radial flux (Γ_r) in arbitrary units at $r \approx 2$ cm normalized to maximum intensity. (b) The thick solid line represents I_{sat} from the fixed probe at $r_F \approx 7$ cm. At the same time, the solid curve is I_{sat} from the reciprocating probe filtered around 80 kHz at $r_R \approx 2$ cm. Both I_{sat} signals are in arbitrary units.

noise level only for time series starting at the same time on the two probes. This is shown in Fig. 6(a) for $r_F \approx 2$ cm using the quantity $\max(C_{RF}) - \min(C_{RF})$.

On the other hand, the amplitude of $\max(C_{RF}) - \min(C_{RF})$, shown in Fig. 6(b), varies with r . It is about 0.6 when the two probes are inside the plasma. The cross-correlation amplitude then decreases with increasing r . When the reciprocating probe is in the SOL at $r \sim 8$ cm, and even though they are poloidally separated by an angle of 90 deg, an amplitude of about 0.8 is recorded. Figure 6 clearly indicates the correlation between fluctuations in the main plasma and the SOL.

However, one might argue that this correlation may be caused by the background turbulence and not by avaloids.

So, because we are interested in what happens to avaloids in particular, we performed cross-conditional averaging (CA_{RF}) between the signals on the two probes. Maxima above 3σ are selected on one probe (reciprocating probe) and the averaging over N_b of the $N_b \times 201$ matrix is made on the fixed probe. The number of points around each maximum is 201. The result is shown in Fig. 7(a) for $r_F = 8$ cm.

Figure 7 shows that for $r_R > 10$ cm, the wall position, the signal is essentially white noise and no correlation exists between the signals recorded on the two probes. As the reciprocating probe moves in the SOL, the amplitude of CA_{RF} increases, indicating the correlation between bursts on the two probes. The shape of CA_{RF} is similar to the result of the auto-conditional averaging shown in Fig. 8(a), indicating that

FIG. 6. (a) and (b) Top and side views of a 3-D plot showing the maximum subtracted from the minimum of the cross-correlation coefficient C_{RF} . The two I_{sat} signals recorded on the horizontal and vertical probes were used. The plots are function of the reciprocating probe position r_R , and time on the fixed probe. The thick vertical solid line in the two subplots indicates the position of the fixed probe where $r_F \approx 2$ cm. The number of points used in each segment is 50 000. In (a), the diagonal black line indicates that correlation is detected only when the two probes are sampled at the same time.

FIG. 7. (a) The cross-conditional average CA_{RF} as a function of time and r_R for $r_F = 8$ cm. The two I_{sat} signals on the horizontal and vertical probes used to compute CA_{RF} and thus to produce the graph were normalized to their standard deviations. (b) CA_{RF} for $r_F = 8$ cm and $r_R = 7$ (solid), 2 (dashed), and 11 (dash-dotted).

the amplitude of an average burst increases sharply and decays slowly. Moreover, only positive fluctuations are recorded. The amplitude of CA_{RF} decreases toward 0 as the probe approaches the plasma. When the probe reaches inside the plasma, CA_{RF} increases to ± 0.2 . This is another clear indication that the high-amplitude fluctuations in the SOL are correlated to inside the main plasma column, and is in agreement with the cross-correlation behavior of Fig. 6. Most importantly, the temporal behavior of CA_{RF} indicates that an avaloid in the SOL is correlated to a *wave-packet* occurring inside the main plasma column. The shift in time of CA_{RF} is hard to interpret because it includes the phase of the wave, the time when an avaloid is emitted, and the poloidal and radial velocities.

The region where the high cross-correlation between the SOL and inside the plasma is observed depends on the ava-

loid's propagation in the poloidal plane, and thus on their radial and poloidal velocities, as well as on the two probe locations. Accordingly, the high amplitude of cross-correlation depicted in Fig. 7 reflects the fact the avaloids that are emitted at $\theta = 0$ and $r \approx 2.5$ reach $\theta = \pi/2$ at $r \approx 8$ cm. Using the same reasoning, one is led to deduce that the region at $r \sim 5$ cm should be correlated to a region that has a poloidal angle different from 0. This explains the low level of cross-correlation observed in Fig. 7 for $r_R \sim 5$.

D. Other supporting evidence

Avaloids typical shape is shown in Fig. 8(a), where the amplitude increases sharply and decreases slowly (see also Ref. 6 for other tokamaks). A similar shape is observed for edge localized modes or events generated by sawteeth relaxation inside tokamak plasmas (see, e.g., Refs. 17, 18). This similarity supports the main result of this article that avaloids are caused by some nonlinear instability saturation. Furthermore, in neutral fluids intermittency is associated with coherent vorticity structures occurring rarely in a nondeterministic fashion.¹⁹ Coherent structures led to vortices with symmetric shape and, because of the conservation of mass, high-intensity spikes are usually accompanied with negative density fluctuations. Both of these properties are not met for avaloids as Fig. 8(a) shows, indicating that they are not coherent structures as described in fluid turbulence.¹³

More support to the main results of this article comes from Fig. 8(b), where no dependence is recorded between the amplitude of the bursts and the waiting time ΔT . This behavior was also observed in the Tore Supra, Alcator C-MOD, and MAST tokamaks and is a clear indication that the process is *not* driven by self-organized criticality²⁰ or any type of process that links the amplitude to the time between events. The analysis above, showing that avaloids are generated periodically, is in agreement with the results of Fig. 8(b), where the periodic nature of the process does not force a correlation between the amplitude of the bursts and the waiting time.

IV. CONCLUSION AND DISCUSSION

In this article, the use of several data analyses allowed us to unveil the origin of convective transport by avaloids. They are emitted into the scrape-off layer *periodically* due to a

FIG. 8. (a) The auto-conditional average of I_{sat} , CA_{RR} , for r between 7 and 9 cm from the plasma center. The signal is normalized to its standard deviation, so an amplitude equal to 6 means that the spikes on the average are 6 times the standard deviation of the overall signal. It is clear that the auto-conditional average shape is reproducible and the error is small. (b) The density fluctuation amplitude plotted against the waiting time (+) for maxima above 3σ in the SOL of PISCES.

nonlinear saturation of instability inside the main plasma column. This conclusion explains the experimental results presented here, namely, the following.

- (1) The periodic process of generation of avaloids explains why the probability distribution function of ΔT possesses a typical frequency. The average frequency is about 5 kHz and seems independent of the magnetic fusion device as reported in Ref. 6.
- (2) Because avaloids in the far SOL reflect the instability inside the main plasma explains the reason behind the similarity of PDF(ΔT) determined inside and outside the main plasma column once the threshold is decreased.
- (3) The dependence of the number of bursts on the threshold inside the plasma clearly indicates that the high-intensity amplitudes are bounded. It is worth mentioning that unlike intermittent or Gaussian fluctuations, coherent oscillations lead to bounded signals.
- (4) Avaloids in the SOL being correlated to oscillations in the core explains why the estimated contribution of convective transport is the same when using (1) the power spectrum inside the plasma and (2) the radial flux in the SOL.⁵ It is about half of the total radial transport.
- (5) The shape of the bursts with a sharp front and slow decay supports the saturation mechanism as the latter leads to similar perturbations observed in edge-localized modes (ELMs) and sawteeth.
- (6) The fact that avaloids are emitted periodically explains why no relation exists between the amplitude and the waiting time.

Most importantly, the correlation between inside and outside the main plasma column demonstrates beyond doubt that, even though they are far apart, the two regions are still correlated by nonlocal transport events. The time dependence of this cross-correlation clearly indicates that a *burst in the SOL is correlated to a wave packet in the plasma*.

Several reasons can lead to aperiodic detection even though avaloids are periodically generated, giving rise to the intermittent aspect of the fluctuation signals. One reason is the nonlinear character of the saturation phenomena and the existence of strong turbulent fluctuations inside the plasma. Another reason is their propagation in ambient turbulent plasma leading to different trajectories in the SOL and thus to aperiodic detection at a given point in space.

Applying the same type of analyses to tokamak plasmas is very difficult for two major factors. First is the strong perturbation of the signals recorded by probes as they approach the plasma edge. The second major difficulty is re-

lated to the complex topology of the magnetic field in tokamaks that leads to poloidal and toroidal asymmetries. This fact makes the second analyses exposed here above by cross-correlating the SOL and the plasma edge extremely hard. However, in our previous publication⁶ we used different types of data analyses (up to 8), to show that the statistical properties of the scrape-off layer fluctuations in the PISCES linear device and in toroidal devices such as Tore Supra, Alcator C-MOD, and MAST are *identical*.⁶ Therefore, we strongly believe that the conclusion that avaloids are emitted *periodically* from the main plasma column as a result of instability saturation applies to toroidal devices.

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