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Plasma edge cross-field transport: experiment and theory

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Abstract

In recent years, the basic physics picture of plasma transport in the scrape-off layers of tokamaks and stellarators has changed. This basic picture was based on slow diffusive cross-field transport competing with fast parallel transport. However, the idea of a local diffusive cross-field transport picture is not compatible with some of the experimental findings. Cross-field particle fluxes have an intermittent character. Large transport events can be responsible for a large portion of the total integrated flux. Those measurements also show the existence of long-range correlations in time and space. These correlations break down a possible separation of scales that was the base in deriving the macroscopic transport models. Structures are not limited to density fluctuations; they also appear on edge flows. The interaction between fluctuations and flows becomes one of the most important issues in the plasma edge dynamics.

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1. Introduction

Understanding transport in magnetically confined plasmas seems to be an elusive goal when we focus on the target of achieving a predictive model. However, it becomes a less daunting task when we look back and assess the progress being made. Fifteen years ago, when the Transport Task Force started its activities, a set of papers [1] reviewing the status of the transport studies was published. One of them was on edge plasma transport [2]. It is interesting to look back at this time in order to gain a perspective on the progress made in plasma-edge-fluctuation and transport studies.

Progress in those studies has been the result of improvements in several areas. One is the continuous improvement of edge plasma diagnostics. New diagnostics have allowed us to go from single point measurements to a visualization of structures at the plasma edge. Another improvement, an increase in data-handling capacity, has given us at least a tenfold increase in statistics, which has been critical in gain understanding of plasma edge fluctuation properties. The modeling tools have also improved considerably, allowing us to gain a better insight into edge plasma transport.

Here, I will review some aspects of the progress made. I will focus on the fluctuations and cross-field transport in the scrape-off layer (SOL). In a strict sense, the SOL begins in the region of open field lines. However, a shear flow layer in general mediates the transition from the confinement region to the open field line region. In this layer, the strong shear flow decorrelates fluctuations and modifies the transport properties. To avoid repeated caveats about these effects, I will refer to the SOL as the region outside the shear flow layer.

A new understanding of the SOL transport has emerged from the new information obtained on edge

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plasma fluctuations and the improvements on modeling those plasmas. In the last 14 years, the overall picture of fluctuations and transport in the SOL has changed. This change is probably due more to the accessibility of the SOL than to its intrinsic nature. From a quasi-Gaussian diffusive cross-field transport model we have changed to an intermittent transport model dominated by large transport events. Different authors [3–6] have given different names to these transport events. 'Blob', the first name used [3], is attractive because of its ambiguity. It does not suggest any specific mechanism or even a unique origin for those events. For these reasons, I will refer to the large transport events as blobs.

2. Plasma fluctuations in the SOL

From the first plasma edge measurements, it is known that fluctuations in the SOL are large, about 10% or higher. There is a significant correlation between potential and density fluctuations. Therefore, the turbulence-induced particle flux is probably the dominant component in the total cross-field flux in the SOL. Reviews of the research on fluctuations and fluctuation-induced transport in plasmas can be found in Refs. [1,2,7–9]. An important first step in understanding cross-field transport is to understand fluctuations.

The most common fluctuation diagnostics techniques used in the SOL are based on electrostatic Langmuir probes. They are used in measuring ion saturation current fluctuations (proportional to density fluctuations), floating potential fluctuations (from which one may derive the plasma potential [10]), parallel velocity fluctuations, and less frequently, electron temperature fluctuations. A local particle flux is often calculated from these measurements by assuming that the floating potential fluctuations are really the plasma potential fluctuations. Nowadays, the large statistical samples that can be obtained from these measurements allow detailed statistical analysis of the measurements.

An important result from the analysis of these measurements is the intermittent and non-Gaussian character of the fluctuations. In particular, the probability distribution function (pdf) of the ion saturation current fluctuations is clearly non-symmetric, having tails that are consistent with exponential decay of the probability with the fluctuation amplitude [11–23]. This result is based on data from tokamaks, stellarators, and linear machines.

The use of probe arrays [3,13,23–26], 2-D beam emission spectroscopy [6], and gas puff imaging diagnostics [27–29] has confirmed the existence of poloidally localized and toroidally extended density structures. They were first detected in the Caltech tokamak and were called 'blobs' [3]. The existence of blobs is consistent with the non-Gaussian character of the density fluctuations. However, their existence is not necessarily the only reason for the non-Gaussianity.

The increase in the time series length of the fluctuations measurements has allowed more-detailed studies of their statistical properties. In order to understand the basic properties of the fluctuations and to compare measurements under different plasma conditions, it is useful to find the best variables to represent the results. One interesting way is by normalizing the fluctuations to their standard deviation. Let us consider a fluctuating quantity, X. The corresponding probability distribution function is $P(X)$. It is easy to construct the function

$$F_X(Y) = \sigma_X P(X) \quad \text{with } Y = (X - \langle X\rangle)/\sigma_X, \tag{1}$$

where σ_X is the standard deviation and $\langle X\rangle$ is the mean of the variable X. When the function F_Γ is plotted for the time series of fluxes, $\{\Gamma_t;\ t = 1,\ldots,N\}$, measured in the SOL under different conditions, all sets of points tend to fall on the same curve. Furthermore, one obtains similar results from the time series taken from different experimental devices [14,15]. The same happens for density fluctuations in the SOL [5]. The corresponding F_n seems to be independent of plasma conditions and confinement devices.

We can ask how accurate the similarity of the pdfs is. There is some dispersion of the points at the tails of the pdfs. There are several potential reasons for that dispersion. Some of the reasons that can be invoked, such as poor statistics or contamination effects, are not relevant to the dynamics of the plasma. However, we cannot discard the possibility that the dispersion is caused by the dynamics. More systematic comparisons to sort out these issues would be desirable.

The exact self-similarity of the function F_X under the transformation Eq. (1) implies that the skeweness and other higher moments of the distribution function of the fluctuations do not depend on plasma conditions. This property suggests a universal behavior of the fluctuation in the SOL [5,30–32].

In the case of a time sequence of measured fluxes, we can also construct time records with a temporal resolution m, $\left\{\Gamma_\tau^{(m)};\ \tau = 1,\ldots,N/m\right\}$, by averaging over non-overlapping blocks of m elements from the original series. That is, we define the following averaged fluxes:

$$\Gamma_t^{(m)} = \frac{1}{m}\sum_{i=1}^{m}\Gamma_{mt-m+i}. \tag{2}$$

For these sequences of fluxes, we can construct the correspondent function $F_\Gamma^{(m)}$ [see Eq. (1)]. For a broad range of scales, the function $F_\Gamma^{(m)}$ is independent of m [33]. This independence from the time scale shows that the fluxes are self-similar over a range of time scales.

Furthermore, $F_\Gamma^{(m)} \approx F_n \approx P_{\mathrm{BHP}}$ [32], where P_{BHP} is the Bramwell–Holdsword–Pinton probability distribution function [34]. Bramwell et al. [34] have suggested that the pdf of a measure in a large class of highly correlated systems has the same functional form. It is difficult to determine whether the similarity between the BHP probability distribution and the plasma edge fluctuation pdfs is a coincidence or an indication that the SOL belongs to the universal class of systems of Bramwell et al. [34].

The non-Gaussian structure of the pdfs is an indication of the possible existence of correlations in the SOL dynamics. We will discuss the issue of correlations in Section 3.

The similarity between the turbulent flux and density fluctuation distribution may also suggest that the blobs essentially produce the tails of the pdf and that they are the dominant contributors to the cross-field transport.

Most of the information on the pdf of the fluctuations comes from measurements in the outward region of the torus. The very few measurements of fluctuations in the inward region of the torus [28] indicate that the fluctuation levels are considerably lower there than in the outward region. This is consistent with the ballooning character of the fluctuations, but there is no systematic information on changes in their statistical properties.

3. Correlations

From the perspective of one-point measurements, the existence of blobs implies the presence of correlations in the density fluctuations over a time of the order δ_b/V_b, where δ_b is the cross-field scale length and V_b is the velocity of the blob. This is a short time scale of the order of tens of microseconds.

Beyond these well-defined correlations, we are interested in possible correlations between blobs. These correlations can provide information on blob dynamics and its impact on macroscopic transport. The correlations between blobs are difficult to measure because they are correlations between intermittent events over long time scales. There are several types of possible correlations [35]: (1) correlations between small events that either precede or follow large events (precursors and aftershocks), (2) correlated groups of medium-size or large events, and (3) anticorrelation between very large events.

There is not a priori any reason why all these correlations should be present in SOL dynamics. However, if they are, there will be a mixture of the different types of correlations that can be present. Therefore, techniques based on interpreting correlations as single-valued functions [30] of size and waiting time, for instance, do not work as a detection technique. They do not even work for simple model-generated sequences.

There are several techniques to explore the existence of long-range correlations. One method is the rescaled adjusted range (R/S) statistics proposed in Ref. [30] and based on the analysis by Hurst [36]. This method was first applied to the plasma edge fluctuations within the confinement region [37] in order to detect signatures of self-organized criticality (SOC) [38]. Long-range correlations were detected, but they tend to disappear in crossing the shear layer due to the effect of the shear flow correlation over turbulent fluctuations. In the SOL, a dynamical mechanism like SOC does not make any sense. Therefore, correlations induced by the core dynamics are expected to be weak if they exist at all. However, long-range correlations have been observed in a variety of devices. They have been shown to exist over a range of time scales from fluctuation time scale to the order of confinement time. In particular, in Alcator C-mod it was found that those correlations exist and are a function of the density [39]. They increase as the plasma density increases. The results suggest that the density limit plays a role in the increased correlation and, as a consequence, in the dynamics of the blobs [40].

Another possible way to find out about long-range correlations is by considering the distribution of the quiet time between events. The quiet-time statistics is an extension of the traditional waiting-time statistics with two main differences: First, it is important to measure quiet times instead of waiting times [41,42] if we intend to separate the correlations induced by the trigger of the events from those induced by the dynamics. Second, the distribution of the quiet times between all transport events in the system essentially reflects the statistics of the triggers [43]. However, correlations between transport events can be made apparent by constructing the pdf of the quiet times between transport events whose duration (or size) must be greater than a threshold value. In this situation, and when correlations exist, the pdf suffers a strong distortion that takes the form of a power law [43,44]. This technique confirms the results obtained with the R/S analysis of increased correlations when approaching the density limit.

4. Blobs

Blobs have been studied experimentally from different perspectives. The conditional averaging technique [45] has proven to be a very useful tool in analyzing these structures [20–25,46] from information taken from multiple probes. An alternative way of studying these structures has been by direct visualization of the blobs [6,26–28]. From these studies, one may conclude that blobs are extended structures along the field lines; they look like filaments but are rather localized in the perpendicular direction with a cross-field size of the order of 1 cm. There is no uniform pattern of motion for the blobs. In tokamaks they may move poloidally and/or radially, but sometimes they form and fade away without clear motion [28]. Radial velocities were measured in DIII-D in the range of 500–2500 m/s [25], about 500 m/s in Alcator C-mod [27], and about 1000 m/s in NSTX [29]. The double vortex structure associated with the density fluctuation event [24] is typical of structures observed in resistive interchange turbulence or similar magnetohydrodynamics (MHD) instabilities. In some of the movies on blobs [47], one can distinguish some with the characteristic mushroom structure; however, that is not the most common case.

In the W7-AS, it was found [24] that the motion of the blobs is mostly poloidal with small radial velocity. There is not enough systematic information to be sure that this difference is intrinsic to the stellarator or that it is a consequence of different operational regimes. Blobs in different experiments 'look' similar, but this similarity maybe misleading. These structures may not have the same dynamical origin or even be related.

In any case, even if blobs have a common origin in tokamaks and stellarators, there are possible reasons for their different behavior. The magnetic structure of the SOL is different in tokamaks and stellarators, and that difference may play a role in the observed differences. Also, as indicated before, it may be a connection between blob dynamics and the density limit. Tokamaks and stellarators have very different behavior close to this limit. Therefore, the explanation for the observed differences in blob dynamics may lie on the nature of the density limit.

There are several alternative approaches to explaining the blob dynamics. On the basis of the SOL model of Ref. [48], Krasheninnikov [4] has put forward a qualitative picture of the blobs as entities that are convected radially outwards. The ∇B drift in a tokamak magnetic field results in plasma polarization and the corresponding $E \times B$ flow. This $E \times B$ flow is reinforced in the SOL by the effective sheath resistivity. This qualitative picture has been supported with numerical modeling of propagating structures [49,50]. Coupling the neutrals plays an interesting role in such an evolution. Fast-moving blobs produce strong wall recycling, and the neutrals created near the wall feed the incoming blobs. This process leads to strong positive feedback [51].

Another approach to understanding SOL transport is through a 2-D fluid turbulence model based on interchange instability [48,52]. This model is flux-driven instead of having a prescribed density gradient. The flux driven character of this model is very important because it allows the interaction of long time scales related to changes in equilibrium with the fluctuations on short time scales [53,54]. This model is very attractive for both its simplicity and its ability to reproduce many features of the data. In this model, poloidally localized 'fingers' develop. They propagate in the radial direction and change shape and direction as they move. These structures are more like an avalanche process than the radial displacement of a fixed-shape blob. The pdfs of the fluctuations have the type of exponential tails seen in experiments.

There is a great deal of information that could be gathered from such a model. One important point is the existence or non-existence of long-range correlations between the avalanches. For example, it could be determined whether the model dynamics contain the correlations or whether some slower dynamics are needed. Also, the model is driven by a constant flux from the core. It would be interesting to test how correlations change with increasing flux. In a tokamak, the flux from the core is intermittent. One question is whether such intermittent flux can be used in driving the model. If it were possible, it would be interesting to explore whether the creation of avalanches is correlated with the incoming flux.

These two descriptions give a different view of the propagation process of the blobs, although they have its propagating character in common. The basic question raised by these two interpretations is whether the propagation velocity of the event and the velocity of the mass transport are the same. This is a critical issue in defining a macroscopic operator that describes the transport induced by blobs. Models based on steady-state streamers do not seem to fit the description of the experiment.

More detailed models of the plasma edge exist. An example is the 3-D fluid turbulence model of the edge, including the geometry of the *X*-point implemented in the BOUT code [55,56]. It is based on pressure driven resistive instabilities and has been used in combination with the UEDGE transport code. Such a model is probably more difficult to use for statistical studies but is a powerful tool for detailed comparisons with experiments [57,58].

5. Flows in the SOL

In recent years, information on SOL flows has increased considerably. The use of Mach probes [59,60] in several positions has contributed to some characterization of flow patterns. This information has been complemented by the use of spectroscopic measurements and other new diagnostics [61,62]. Understanding is being gained by detailed comparisons of measurements with theoretical models.

In the SOL, there is a complicated superposition of mechanisms responsible for driving flows. Parallel flow patterns develop that depend on the magnetic geometry of the SOL [57,63–68]. Particles flow along field lines toward the divertor. However, there is a reversal point [69–72] for the velocity along the field line. This point is located in the outer region of the SOL. The poloidal angle where the flow reverses is not the same on all the magnetic field lines. Measurements of the parallel velocity in the outer SOL indicate that it decreases with increased averaged line density [67,71].

The next-order flow mechanism is the ∇B drift. To better detect its effect, one can look near the flow reversal point. The reversal region changes when the ∇B direction is changed [56]. This is possibly the dominant mechanism for the asymmetry of flows when the field is reversed. However, other higher-order mechanisms can be in operation and can break the exact asymmetry. At that level, detailed comparisons with models are needed to extract more information on the flow mechanisms [57,63,66,73,74]. Of course, for a proper comparison between experiment and theory, the numerical models should include all drifts as well as flow generated by turbulence.

For a divertor configuration with a single null and in the inner SOL region, particles from the outer SOL stream through at high speed toward the divertor. For a double null divertor configuration, the flow at the midplane in the inner SOL is weak. In this inner region, the measured particle flux is very low. This is consistent with the ballooning character of the fluctuations [28,75], and it has been suggested that the poloidal gradients induced by this flux in the outer SOL are drivers for flows [67]. A correlation has also been found between the cross-field turbulent fluxes and the speed of the parallel flow [76].

The existence of blobs and their associated convective cells opens another source for SOL flows. The generation of sheared flows by convective cells in the presence of drifts is a common phenomenon in neutral fluids [77] and plasmas [78,79]. Flow is generated through Reynolds stress. Such a picture has been shown to be consistent with SOL dynamics, and zonal flow generation mechanisms have been identified [57].

As is well known, sheared flows decorrelate and even quench turbulence [80]. Therefore, a consistent picture of the SOL dynamics can only be achieved by a self-consistent treatment of turbulence and flows. Because magnetic geometry is so important for SOL flows, the self-consistent treatment requires a full 3-D geometry with all its implications. However, simplified models may still be very useful in developing an understanding of some of the dynamical components of the SOL puzzle.

6. Cross-field transport in the SOL

The classical picture of transport in the SOL [81] was simpler than with the present view. It was based on a competition between cross-field transport, which was assumed to be normal diffusion, and parallel transport. The balance between the two gives the width of the SOL. Because parallel transport was the dominant transport component, and because SOL widths are narrow, most particle recycling must be done at the divertor. An initial problem found with this interpretation is that the predicted SOL width does not agree with the measurements. Experiments always found that the SOL width was significantly wider than expected.

Large diffusion coefficients were needed to explain the change of the density slope in the outer SOL [82–86]. At the same time, modeling of particle transport was not always able to account for the full particle balance [87–89]. These contradictions stimulated a great deal of research. The accumulated information in the previous sections confirms that the picture of SOL transport has radically changed.

If we think in terms of a particle transport equation, practically all terms in the equation must change. When blobs are present, the transport operator cannot be just the second-order derivative in space motivated by normal diffusion. The source may also change. The source of neutrals is not necessarily the divertor. Fast-moving blobs can interact with the walls. Therefore, the recycling from the walls can be significant [86]. Because emergence of blobs is not poloidally uniform, the distribution of the neutral particle source can be quite complicated. Also, flows must be included in the model. They have complex patterns, and an important component may be generated by the same turbulence.

If blobs are well-defined entities that move as a solid body, a pure convection term in addition to the normal diffusion term could be a good representation of macroscopic transport. The flatter density profiles in the far SOL [82,84,90–93] and the need for diffusion coefficients that increase with the distance [83–85] to the last closed surface are strong indications of global convective effects. However, it may be more complicated to find an operator that describes this process if blobs are avalanche-like events that propagate and cause some mass transport. Particle tracer calculations for interchange turbulence in close field line systems [94,95] have shown that diffusion is anomalous and cannot be macroscopically described by a second-order derivative operator. The mechanism in that situation is neither pure convection nor normal diffusion. Combinations of normal diffusion and convection can be used to explain the data; however, such combinations will not give the right scaling with system size and, therefore, will have little predictive capability. It would be interesting to find out the properties of particle tracers in dynamical models of SOL in the flux-driven regime. To do so would provide a better sense of the macroscopic transport mechanism.

Experimentally, the dependence of the effective diffusivities on plasma parameters has been studied by measuring the scaling of the gradient scale length of the density and temperature profiles [89–93]. The connection of these scale lengths to the diffusivities is based on transport models that are not consistent with the present picture of cross-field transport; however, the models still provide information on the level of cross-field transport.

Another source of information on the level of transport is obtained from the modeling of discharges [82–86,88].

Collisionality seems to play a role in SOL cross-field transport. As collisionality increases, the effective diffusivities increase [96,97]. This increase in the transport losses may be connected to the proximity to the density limit [98] or vice versa. As suggested in Ref. [98], the increase in density leads to an increase in flow damping causing at the density limit the collapse of the plasma edge sheared flow. As the flow decorrelation effects decrease, one can expect to see an increase in the correlations of the turbulence fluctuations. We have already discussed the increase of short-range and long-range correlations in fluctuations as the density limit is approached. All these results point to strong connection between transport in the SOL and the density limit. As collisionality increases, it may be a change in the character of resistive pressure-gradient-driven turbulence. We can expect changes in the instability [99] and changes in the associated flows.

7. Conclusions

There have been significant changes in the understanding of cross-field transport in the SOL. From a basically diffusive mechanism, it has evolved to a transport mechanism dominated by intermittent events. Systematic studies are still needed of fluctuations in different confinement devices for different confinement parameters and at several poloidal positions.

Flows can be strongly coupled to transport events and to turbulence fluctuations in general. They are also strongly influenced by the geometry of the system. The dynamics of the transport events is probably connected to the density limit. Therefore, the overall picture of the SOL transport can only be fully unraveled by the self-consistent treatment of all these elements.

However, we can still learn a great deal from simplified models with reduced geometry if they keep the coupling between the different time and space scales and the self-consistent treatment of flows.

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