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Plasma transport in the Scrape-off-Layer of magnetically confined plasma and the plasma exhaust

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An overview of the plasma dynamics in the Scrape-off-Layer (SOL) of magnetically confined plasma is presented. The SOL is the exhaust channel of the warm plasma from the core, and the understanding of the SOL plasma dynamics is one of the key issues in contemporary fusion research. It is essential for operation of fusion experiments and ultimately fusion power plants. Recent results clearly demonstrate that the plasma transport through the SOL is dominated by turbulent intermittent fluctuations organized into filamentary structures convecting particles, energy, and momentum through the SOL region. Thus, the transport cannot be described and parametrized by simple diffusive type models. The transport leads to strong localized power loads on the first wall and the plasma facing components, which have serious lasting influence.

1. Introduction

The so-called Scrape-off Layer – SOL – is the transition layer from the hot plasma in the core to the cold material surfaces. In a toroidal, magnetically confined plasma, e.g., a Tokamak configuration, the SOL [1,2] has open magnetic field lines that connect to material surfaces and surround the hot core plasma confined by closed field lines. The last closed magnetic flux surface – LCFS - separates the SOL from the edge plasma. The poloidal cross section of a toroidal plasma configuration – a Tokamak - is sketched in Figure 1, for the case of a so-called divertor configuration, where the open magnetic field lines are diverted to target plates far away from the core plasma. The plasma that enters the SOL should be guided along the field lines down to the divertor plates, which would take most of the power load to protect the first wall and the plasma facing components (PFC) from excessive power loads. The divertor target can be actively cooled and is designed to take care of the heat load - for ITER conditions this will amount to about 10 MW/m² [3,4], which is at the upper limit of technical cooling capabilities.

The SOL together with the edge plasma acts as a dynamical boundary condition for the core plasma. The conditions of the SOL and the coupling of the SOL with the edge plasma over the LCFS is of crucial importance and dictates the plasma behaviour – all plasma has to go through the edge

and into the SOL, where it is connecting to the material walls and plasma facing components. The SOL is acting as the exhaust channel for the hot plasma. Thus, the understanding of the SOL plasma is one of the key topics in contemporary fusion research. A detailed understanding is demanded for predictive modelling of the SOL dynamics, which will be mandatory for the design and operation of present and future fusion experiments – and of future fusion power plants.

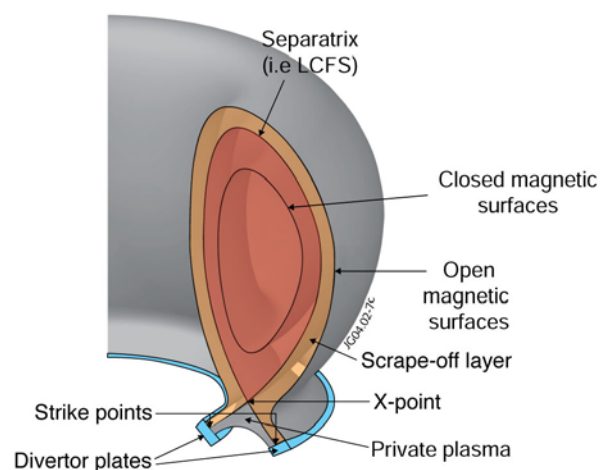


Figure 1. Sketch of a divertor configuration with definitions, see text. (Courtesy EFDA/JET) <https://www.euro-fusion.org/jet/>

2. Characteristics of the SOL plasma

The SOL plasma [1] is considerably colder than the core - and edge plasma - with electron and ion temperatures of up to few tens of eV (for major present day experiments), compared to keV temperatures in the core plasma. Contrary to the core the SOL plasma is not fully ionized. The SOL region involves particularly plasma interaction with solid materials (plasma material interaction PMI) - the first wall, plasma facing components (PFC), the divertor plates etc. - and interaction with neutral particles. This involves complex atomic physics including ionization and excitation of neutrals, which may appear as single atoms or molecules. These issues play an important role in the SOL plasma, which exhibits a complexity exceeding the complex behaviour found in the core plasma.

We should mention the strong contribution to the investigations of SOL plasma dynamics -- with emphasis on PMI -- from non-fusion devices such as linear devices for basic PMI studies at parameters and conditions resembling SOL conditions in Tokamaks, like PISCES-B [5] and others [6].

The significant amount of neutrals in the SOL has different sources: i) The plasma wall interaction and recycling creates impurity particles, which might also appear as larger dust like particles. It is unwanted to get these impurities into the core plasma, where they will be ionized and pollute the fuel. Particularly, heavy, highly charged ions are significant energy sinks through radiation losses via bremsstrahlung. ii) Neutral gases are deliberately puffed into the SOL for several purposes: a) neutral gases mediate radiation losses cooling the plasma before encountering the material surfaces; b) gas puffing is a standard way of fuelling the plasma – the neutrals penetrate towards the LCFS where they get ionized and provide the plasma particle source. When the SOL plasma gets sufficiently hot and dense the neutrals will be completely ionized in the SOL, with the effect that the gas puff fuelling efficiency decreases significantly and other methods have to be applied for fuelling, like pellet injection. This appears to be the case for the ITER plasma, where fuelling is challenging.

3. Plasma transport in the SOL

It is well established that turbulence is the dominating mechanism for transporting particles, energy and momentum in hot magnetized plasma. This is also the case in the edge and SOL of toroidal plasmas. The fluctuations in the SOL are found to be strongly intermittent with amplitude probability density functions (PDF) far from Gaussian

distributions and having a significant excess kurtosis and skewness. This behaviour appears to be universal and is found in basically all toroidal confinement devices, e.g., [7-14] in addition to non-fusion simple tori, e.g., [15,16] and even in linear basic devices, e.g., Q-machines [17]. A typical example is illustrated in Figure 2, which shows the density fluctuations in the edge and SOL of the JET tokamak [11]. It should be noted that the relative fluctuation level in the SOL is often significantly exceeding one.

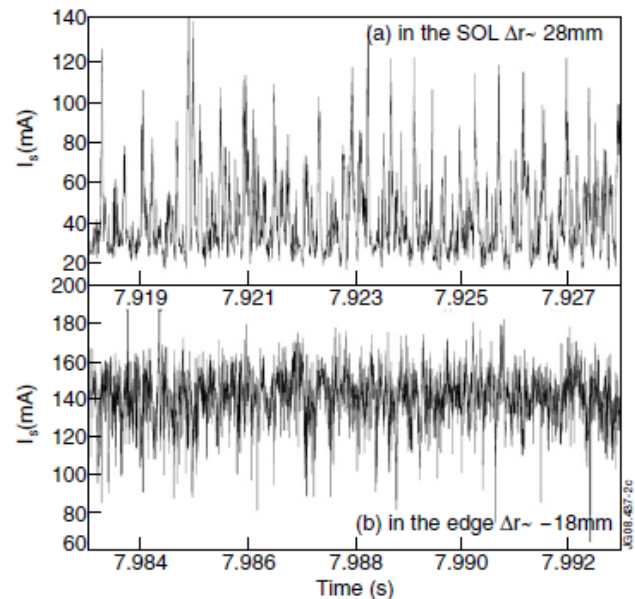


Figure 2. Measurements of ion saturation current, I_s , fluctuations to a probe in the SOL (a) and edge (b) of the JET device. The I_s fluctuations are taken as proxy for the density fluctuations. Δr is the distance to the LCFS. Adapted from Ref. [11].

The transport in the SOL is strongly dominated by the intermittent large outbreaks of hot plasma. These bursts – often termed plasma blobs - appear as filamentary structures aligned along the magnetic field. They are formed near the last closed flux surface (LCFS) and propagate far into the SOL. They set the density and temperature profiles [10,13,14] as well as determine the power load onto plasma facing components. The structures appear in both Low and High confinement regimes, in the latter case they are related with the so-called Edge-Localized-Modes, ELMs [12,18]. The hot filamentary structures contribute significantly (> 50%) to the particle density flux and the flux PDFs also have a strong excess kurtosis and skewness. From this it is obvious that the transport in the SOL cannot be described/parametrized by simple Fickian

diffusion combined with a convection term [7,10], and predictions of the flux need to account for the full PDF. Mean field transport models will not be able to provide predictive capabilities. It is necessary to account for the full dynamical evolution treating the profile evolution on the same footing as the fluctuations. Recent analysis and modelling have confirmed the universal characteristics of the SOL fluctuations and demonstrate the convergence towards PDFs closely related to Gamma distribution functions, see [19,20] and references therein.

The main features of the SOL turbulence and transport dynamics have been modelled by the ESEL model (Edge-Sol-Electrostatic) [21,10,13]. The model is a three-field drift-fluid model including vorticity, density, and electron pressure equations, using the Braginskii closure for collisions. The model is solved on a 2D domain representing the out-board mid-plane of a Tokamak including both the SOL and edge region. The parallel dynamics is parameterized in the SOL accounting consistently for the parallel losses along magnetic field lines to the divertor plates.

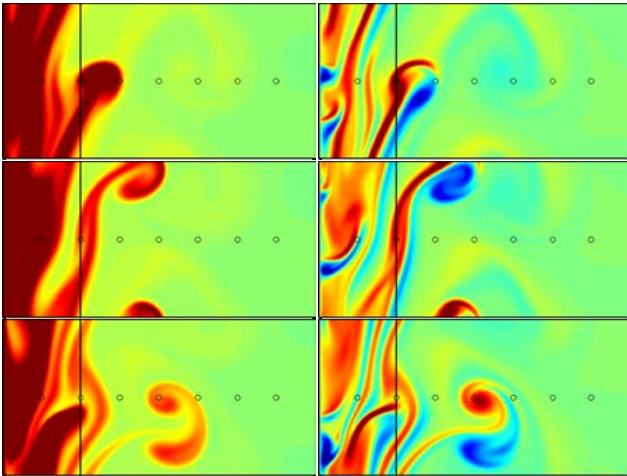


Figure 3. Typical blob evolution from ESEL simulations. Left column: density evolution, Right column: vorticity evolution. Blue colors designate negative values, while red are positive values. The vertical thin line shows the position of the LCFS.

Figure 3 shows a typical evolution of density blob structures in the ESEL simulations. The density blobs pinch off near the LCFS and propagate radially out into the SOL. The density blob induces a dipolar structure in the vorticity according to the driving interchange mechanism, which drives the propagation. The PDF of the particle density flux is shown in Figure 4, where experimental results from

the TCV tokamak are compared with ESEL simulations performed at same parameters [10].

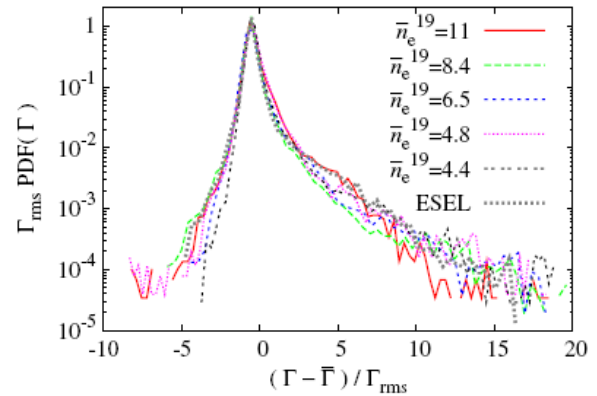


Figure 4. The PDF of the particle density flux for different densities in the TCV device compared with ESEL results. Adapted from [10] (Nucl. Fusion 47 (2007) 667)

4. Summary

In this contribution we present an overview of the dynamics of the SOL plasma as described above. Particularly, we discuss recent experimental investigations performed by means of advanced probe heads (see, e.g. [22]) and the comparison with the modelling based on ESEL-like codes. The ESEL models do not account for the full complexity of the SOL – for example no neutral particle interactions are included, the dynamics in the edge plasma region is incomplete, and the plasma materials interaction is parametrized. The codes may provide estimates of the power deposition on the divertor targets, but back reaction to the plasma is not considered. Recently, investigations of the plasma neutral interactions in the dynamically evolving SOL plasma have been initiated. Preliminary results demonstrate that the neutral-plasma interaction can have significant influence on the SOL dynamics. In that connection gas puff fuelling in dynamically evolving SOL plasmas may be addressed.

Acknowledgement

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