EUROFUSION WPMST1-CP(16) 15185

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Preprint of Paper to be submitted for publication in
Proceedings of 26th IAEA Fusion Energy Conference

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Scrape Off Layer and Divertor Physics Advances in MAST

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Abstract. The physics of the plasma exhaust is a central research area for MAST. In the last two years, significant progress was made in understanding experimental observations, in developing the capability to simulate the Scrape Off Layer (SOL) plasma with first principles codes and in developing theoretical models to rigorously interpret empirical data. In this paper, several aspects of SOL midplane and target physics are discussed, with particular attention to the interplay between mean profiles of thermodynamic quantities and filaments. The latter, observed in all experimental regimes, are shown to be responsible for a number of SOL phenomena, such as the non-exponential nature of the midplane profiles, and are therefore thoroughly characterized from both an experimental and theoretical point of view. Collecting all empirical and modelling evidence, it is shown that filaments can travel as coherent structures while maintaining at the wall a significant fraction of their original ion energy. Their parallel dynamics is likely to be affected by the interaction with neutral deuterium which can lead to the longer cross field scale lengths for the density in the SOL. It is also shown that filaments are responsible for the heat deposition in the far SOL at the target, where the deposition occurs in spiral patterns. Heat flux profiles collected in double null discharges are shown to agree with larger cross machine databases, although additional parameters might be required to improve the fitting. Finally, the modelling of alternative divertor configurations is discussed, in preparation for the Super-X divertor in MAST-Upgrade. Predictions of detachment at lower line averaged density and heat load reduction at the target are discussed and are suggestive of the beneficial effects of the new magnetic configuration.

1. Introduction

This work reviews the recent MAST exhaust programme, with particular emphasis on the basic mechanisms responsible for setting plasma profiles in the Scrape Off Layer (SOL) and their interplay with intermittent fluctuations (filaments), and on the physics of advanced divertors. In the last two years, the MAST team produced a wealth of experimental and theoretical results that cover issues related to operations and performance in ITER as well as the design of the first wall and of the divertor in DEMO.

To optimise its fusion gain, ITER must operate at large plasma densities and high plasma current, while at the same time controlling the interaction with the plasma facing components and, in particular, ensuring robustness against transients. To extrapolate present day results to DEMO with sufficient confidence, adequate predictive capability, based on first principles insight, must be obtained through both development and validation of theoretical models. A conventional divertor might yet not be able to handle the power exhaust in DEMO conditions, hence understanding solutions based on advanced magnetic configurations, such as the Super-X divertor implemented in MAST-U, represents an indispensable risk mitigation strategy.

2. Midplane profiles

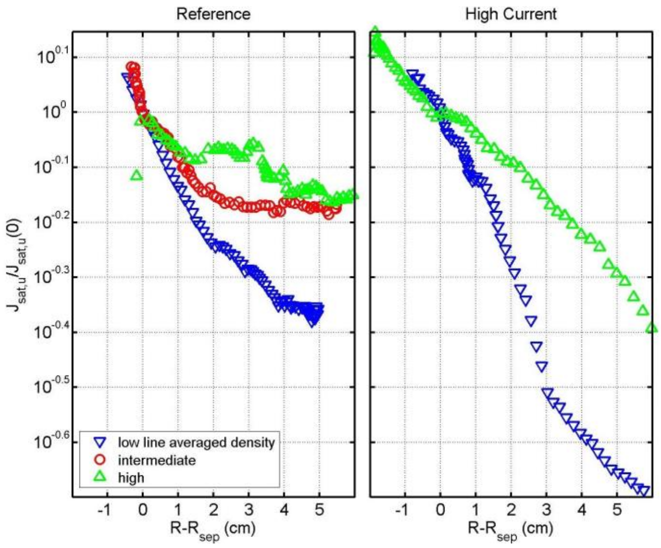

Fig. 1. (left) broadening of SOL density profiles (represented by the ion saturation current) as the core density increases. (right) Lack of broadening for same experimental conditions but with higher I_p

In L-mode and in the inter ELM phase of the H-mode, it is commonly observed that the midplane density decay length increases moving out from the separatrix [1-4]. This situation worsens as the line averaged density is increased, thus raising concerns about the wall interactions and the fuelling efficiency for ITER and especially for DEMO. Recent MAST data [4], see Fig.1, robustly demonstrate for the first time that this density broadening can occur in the absence of detachment and independently from ionisation sources in the SOL, two phenomena widely used to interpret the broadening in literature. Specifically, a higher line averaged density induced broader far SOL density profiles, but also a systematic increase of the ion flux at the target and a decrease in the D_γ/D_α emission, which are signs of an attached divertor. Furthermore, ionisation profiles depended on line averaged density but not on plasma current, while the broadening was affected by both. Importantly, at comparable density levels, discharges with higher current did not show broadening, possibly due to the reduction in the connection length and implying that parallel as well as cross field transport regulate the SOL decay lengths.

At the midplane, measurements using Ball-pen (BP) and Retarding Field Energy Analyser (RFEA) probes and High Resolution Thomson Scattering (HRTS) were systematically performed. The potential profile measured by the BPP significantly differs from the floating potential both in polarity and profile shape. From this profile, the radial electric field can be calculated, and it is shown to be sheared, peaked at ~1kV/m and increasing with plasma current [5]. The RFEA data showed that the background ion temperature in the SOL is systematically 2-4 times higher than the electron temperature at low line averaged density [6]. Similar ion and electron temperatures were measured at higher density, as inter species collisional energy exchange becomes more important. Precise measurements of the density and electron temperature were also made available by a new binning technique of the HRTS data. Mean profiles showed near SOL decay lengths decreasing with plasma current and increasing with fuelling levels. A good correlation was found between decay lengths and the D_α emission, suggesting a role for the neutral particles in setting the profiles.

3. Target profiles

Double null configurations might be needed for reactor relevant machines to alleviate target power loads on the inboard side. In MAST, a database of double null inter-ELM heat flux profiles at the target was generated and their fall off length, λ_q, was extracted for a range of plasma parameters [7]. The MAST data shows good agreement with multi-machine scaling laws [8]: the fall off length has the strongest dependence on the plasma current. The best scaling found, i.e. the one with the smallest χ^2 error, utilizes the plasma current and the power crossing the SOL in the relation $\lambda_q=4.57(\pm0.54)I_p^{-0.64(\pm0.15)}P_{SOL}^{0.22(\pm0.08)}$ with $R^2=0.55$. The moderate quality of fit suggests that additional parameters are required to accurately reproduce the observed variation. No correlation is seen between the fall off length and the radial separation between primary and secondary separatrix.

4. Comparison between midplane and target profiles

To shed light on the transport between upstream and downstream regions of the SOL in L-mode, outer target ion saturation current, measured with wall mounted Langmuir probes, and heat flux decay lengths, obtained with IR thermography, were compared with midplane data collected with a reciprocating probe and HRTS [4].

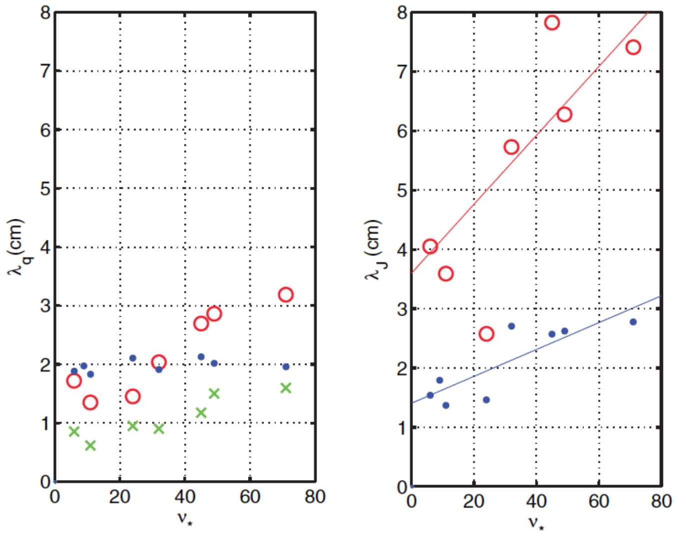

Fig. 2. Parallel heat flux (left panel) and ion saturation current (right panel) decay lengths in the near SOL as a function of the electron collisionality. The symbol (•) represents the upstream projection of the target measurements, (O) the upstream measurements (with convective assumption for the heat flux) and (×) the upstream measurements with conductive assumption for the heat flux. The solid curves on the right panel show the linear fit of the upstream and target projected data

For the saturation current, the upstream projections of the target values, based on diffusive models [8], did not match the midplane measurements, neither in amplitude nor in trend, see Fig. 2. However, agreement was found for the heat fluxes, suggesting a different perpendicular transport mechanism for the two channels. Furthermore, the value of the target heat flux decay length was quite insensitive to changes in the thermodynamic conditions, in agreement with recent scaling laws [8] and the results discussed in Section 3.

5. Transient events

Transient events play a central role in determining the SOL profiles as plasma filaments form the building blocks of anomalous transport. At the target, L-mode filaments form spiral patterns that produce bands of increased heat flux, which was measured using infrared thermography [9], see Fig. 3. These results showed that filaments can account for the full divertor target heat flux in the far SOL.

Ion and electron temperature in L-mode filaments were measured in MAST an RFEA probe at the midplane and at the target, showing that in low collisionality discharges the ion temperature, T_i, in large filaments was 2 to 3 times larger than the background plasma, while the electron temperature, T_e, was around 3 to 7 times smaller than T_i [6]. These measurements demonstrate that the filaments carry the energy of the ions to large distances, which has negative implications for first wall erosion.

A fast framing camera operating at 100kHz was used to track the motion of filaments in MAST across a range of plasma scenarios and geometries, thus allowing a statistical analysis of the filaments' characteristics. Both the radial size (~2 cm) and radial velocity (~1 km/s) of the filaments are found to decrease as the plasma current is increased at constant density and input power [10]. This suggests a relation between mean profiles and fluctuations as the former steepen at low current, see Section 2, which is compatible with the reduction of the cross field motion of the plasma filaments. In particular, going from 400 kA to 900 kA, the radial size of the filament decreases by 16%, while their radial velocity decreases by 56% which is well matched to the 50-60% reduction in the midplane density decay length.

6. Theory and modelling of boundary plasmas

The experimental programme in MAST was supported by the development of numerical and analytical tools that allow interpretative and predictive capability.

Detailed measurements of the motion, shape and amplitude of individual filaments identified in high speed movies were compared to large scale 3D two-fluid simulations conducted in the STORM module of BOUT++ [11]. Seeded filament simulations were performed and were able to reproduce the dynamics observed in experiments with accuracy up to the experimental error bar levels. Synthetic diagnostics reproducing the D_α emission from the filament were developed to have a fair comparison between simulated and experimental data, see Fig. 4. In addition, the numerical results showed that filaments characterised by similar size and light emission intensity can have quite different dynamics if the pressure perturbation is distributed differently between density and temperature components.

The validated code was also used to perform systematic theoretical studies. An analytical model, supported by 2D and 3D simulations, was developed to assess the effect of the observed ellipticity of the filaments in the drift plane [12]. The velocity of small filaments electrically disconnected from the target was found to depend on their radial size, while for larger connected ones it depended on their binormal size (i.e. normal to the magnetic field and to the radial

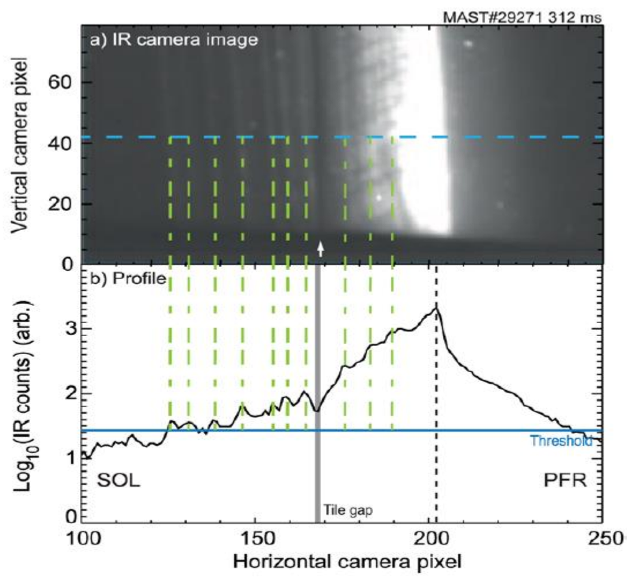

Fig. 3. (a) Raw IR camera counts, background subtracted and plotted on a log scale showing filaments at the divertor. The horizontal camera pixel corresponds to the radial direction across the divertor and the vertical camera pixel corresponds to the toroidal direction. (b) The IR camera counts profiles along the blue dashed line in panel (a). The solid blue line corresponds to a signal to noise of one. The grey vertical bar is the location of the tile gap. The radius increases to the left due to the orientation of the camera.

direction). The balance between temperature and density contributions to the filament pressure is difficult to determine experimentally. Numerical studies revealed that when the pressure is dominated by the temperature perturbation the radial motion of the filament is slowed down and its poloidal rotation is increased [13]. This is due to the monopolar component of the electrostatic potential associated with the filament, which is caused by the temperature non-uniformity at the target due to the fluctuations. The effect of low divertor temperature, as expected in high recycling or detached conditions, was simulated by increasing the resistivity close to the target [14]. It was found that the electrical disconnection of the filaments, which results in faster cross field motion, starts to play a role only for temperatures below 1eV. In addition, the increase of the filament's velocity is continuous (i.e. there is no transition) and only modest: less than a factor 2 for filaments in the inertial regime (small perpendicular size) and less than a factor 10 in the extreme sheath regime (i.e. very large perpendicular size). This suggests that for typical filament sizes, increases in collisionality of several orders of magnitude would be required to see a visible change of the radial motion of the filament as a consequence of the electrical disconnection from the target. These simulations confirm and extend to a full 3D geometry the conclusions of the two region model elaborated in [15].

Linking the transient events to the midplane profiles, a theoretical framework was developed to interpret the experimental features of the density and temperature profiles in the SOL on the basis of simple properties of the filaments, such as their radial motion and their draining towards the divertor [16,17]. The framework describes L-mode and inter-ELM filaments as a Poisson process in which each event is independent and modelled with a wave function with (initial) amplitude and width statistically distributed according to experimental observations and dynamically evolving according to proper reductions of fluid equations. The framework can be used to rigorously understand the mechanisms that lead to the non-exponential nature of the radial SOL profiles as well as the increase of the relative fluctuation amplitude in the far SOL. Several models for the dynamics of the filaments, which can be applied to the framework, were derived for the purpose of identifying how different assumptions lead to the emergence of features in the profiles. Multiple alternative models can explain the observations, thus motivating more stringent and focused experimental analysis. In particular, radially accelerating filaments, less efficient parallel exhaust and also a statistical distribution of the velocity of the filaments can all contribute to induce flatter profiles in the far SOL. A quite general result is the resiliency of the non-exponential nature of the profiles. At the same time, alternative models can capture the increase of the relative fluctuation amplitude observed in the far SOL. Several scenarios are compatible with the broadening of the SOL at high fuelling levels, which could be caused by interactions with neutral particles in the divertor or by a significant radial acceleration of the

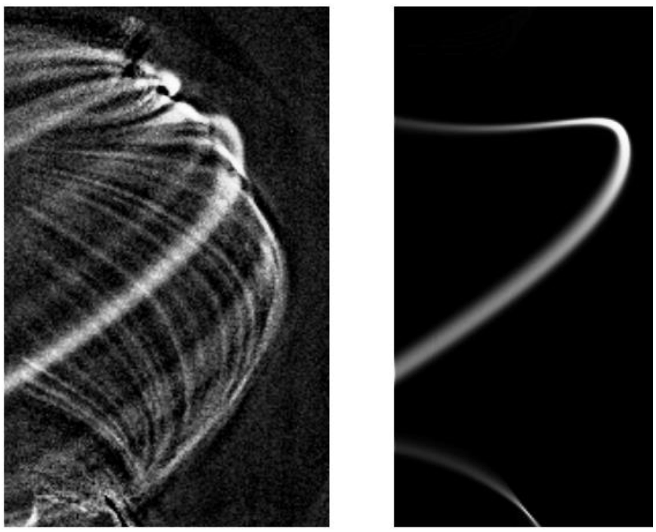

Fig. 4. Comparison between a large experimental filament from visual imaging (left) and one generated with STORM and plotted using a synthetic D_α emission diagnostic (right).

filaments.

7. Advanced configurations

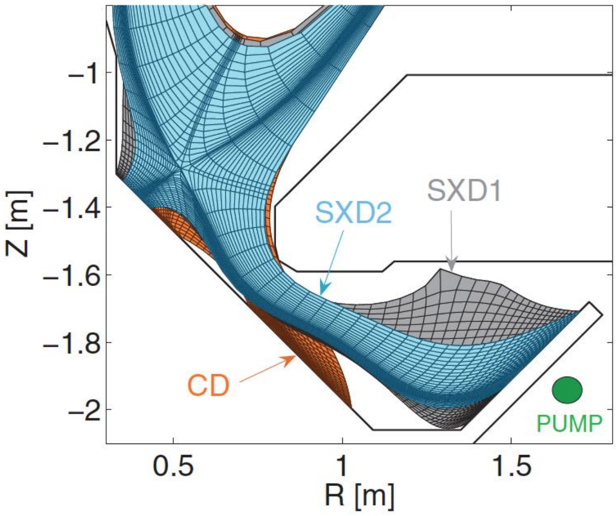

Fig. 5. Magnetic geometry in the MAST-U divertor considered in the simulation: CD is the conventional divertor (orange), SXD1 (black), SXD2 (blue) are super-X configurations with large and small flux expansion at the target.

Understanding solutions based on advanced magnetic configurations represents an indispensable risk mitigation strategy for divertor power handling in future devices. Multi-fluid simulations of the MAST-U Super-X configuration [14] were performed with SOLPS and show that the plasma will detach at lower density (×1/3) or higher power (×4) with respect to the conventional divertor, see Fig. 5. The new divertor is predicted to significantly reduce the target power load through magnetic geometry and baffling as the tight closure of the divertor region leads to a strong increase in neutral density with concomitant power losses. The beneficial effects of the Super-X were shown to depend on the radial location of the target, and were independent of the poloidal flux expansion.

8. Summary and conclusions

Integrating the analysis of mean profiles and fluctuations, from both an experimental and theoretical point of view, allows clarifying of several features of SOL physics in L-mode. The comparison between upstream and downstream profiles suggests that the heat and particle exhaust in the near SOL might be governed by different mechanisms. The failure of diffusive models to connect midplane and target density profiles suggests that non-local structures like the filaments might play an important role in determining the perpendicular particle transport. This is confirmed also by our theoretical framework, which shows that the filaments statistics and dynamics are the two elements that determine the features of the mean profiles as well as the probability density function of the turbulent fluctuations. In this respect, the flattening and the broadening of the midplane density profiles can be explained by a number of possible models for the filaments. Constraints are provided by the experimental results, which indicate that interactions with neutral particles at the divertor (charge exchange, elastic collisions) might affect the upstream decay lengths, while fast camera imaging shows filaments moving at a roughly constant radial velocity. Similarly, it is observed that higher plasma currents affect in a compatible way both the decay lengths and the cross field motion of the filaments (and also show small changes in the perpendicular width of the perturbations). In addition, 3D theoretical modelling suggests that even extremely large changes in the divertor collisionality would lead only to moderate changes in the filament velocities and target temperatures below 1eV would be required to see measurable effects.

Filaments also retain a significant amount of ion energy, which is eventually deposited on the first wall. In addition, they are responsible for the heat fluxes reaching the target, at least in the far SOL. On the other hand, near SOL electron heat fluxes to the target seem to be compatible with a diffusive behaviour and appear to be independent from plasma conditions (i.e. they depend only on magnetic quantities like the plasma current and confining magnetic field).

Advanced configurations were also investigated to prepare for the Super-X divertor in MAST-U. Beneficial effects were observed in multi-fluid simulations, indicating that detachment threshold, target temperature and parallel heat flux will be more favourable. Radial location of the target and divertor closure were identified as the main factors for these improvements.

9. Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053, from the RCUK Energy Programme [grant number EP/I501045]. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ccfe.ac.uk. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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