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Predicting Scrape-Off Layer profiles and filamentary transport for reactor relevant devices

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[5]*See author list of "Overview of the JET preparation for Deuterium-Tritium Operation" by E. Joffrin et al. to be published in Nuclear Fusion Special issue: overview and summary reports from the 27th Fusion Energy Conference (Ahmedabad, India, 22-27 October 2018)*

The plasma exhaust, if uncontrolled, can severely harm reactor relevant machines, challenging the viability of magnetic confinement fusion as an energy source. A new theoretical framework is introduced [1-3], together with extensive numerical and experimental studies to support it. Importantly, its successful application to present day devices (MAST and JET, see Fig. 1 and [3-4]) will be discussed.

The theoretical framework was developed to clarify the relation between radial SOL profiles and the fluctuations that generate them. The framework predicts and interprets the experimental features of the profiles and of the turbulence statistics on the basis of simple properties of the filaments, such as their radial motion and their draining towards the divertor. L-mode and inter-ELM filaments are described as a Poisson process where each event is independent and modelled with a wave function of amplitude and width statistically distributed according to experimental observations and evolving according to fluid equations. The final result (derived in [1-3]) relates the upstream radial profile of the density (but it could be other thermodynamic quantities as well), $N(x)$ with the dynamics (contained in n, which contains parametric dependencies on the parallel and perpendicular motion of the filaments) and statistics of the fluctuations (contained in the PDFs of the initial toroidal positions, P_{y0}, initial amplitudes, P_{n0}, and width, P_w):

$$N(x) = \frac{1}{\tau_w}\int_{-\infty}^{\infty} dy_0 \int_{-\infty}^{\infty} dt \int_0^{\infty} dn_0 \int_0^{\infty} dw\left[n(x,y_*,t)P_{y_0}(y_0)P_{n_0}(n_0)P_w(w)\right], \quad (1)$$

where τ_w is the waiting time of the Poisson process (i.e. the typical time separation between a filament and the next) and y_* is an arbitrary toroidal position. Using this expression, it was found that radially accelerating filaments, less efficient parallel exhaust (see below, experimental discussion) and also a statistical distribution of the radial velocities can contribute to induce flatter profiles in the far SOL and therefore enhance plasma-wall interactions.

In parallel, innovative experimental analysis techniques making use of deep machine learning were developed on MAST in order to provide a statistical basis for the framework, but also to thoroughly characterise the filaments. Due to its open configuration, MAST was ideally suited for SOL transport studies: measurements of filaments over a large database of discharges were performed with fast wide-angle visual cameras. The newly developed ELZAR code [5] automates data analysis by using an inversion of the 2D fast camera images, which relies on the alignment of the filaments with the magnetic field. Our filament detection algorithm achieves a precision (true detections/all detections) of 98% and a sensitivity (detections/all filaments) of 36%. Convolutional neural networks were also deployed in order to improve the amplitude, size, radial and toroidal position identification, obtaining a higher sensitivity (73%) with only a marginal loss of precision (93%). It was found that the filaments are emitted uniformly and randomly, thus lacking a well-defined toroidal mode number, compatibly with the assumptions of the theoretical framework. Comparison with Langmuir probe measurements in similar discharges was favourable, recovering conditionally averaged profiles and similar statistics (see Fig 1c and 1d).

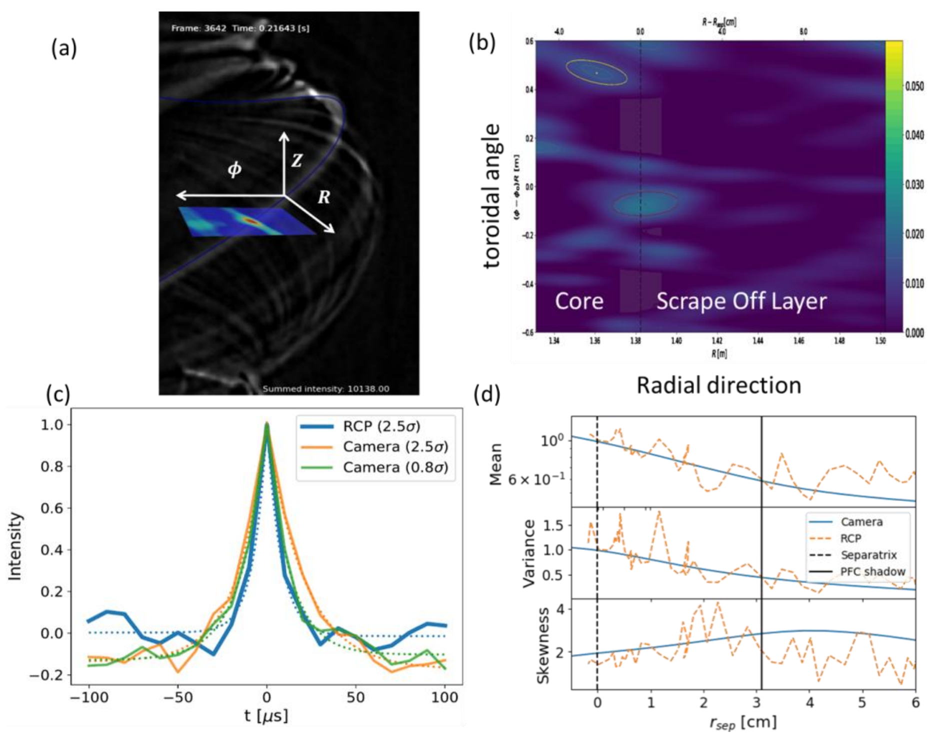

Figure 1: raw camera image (a); ELZAR map (b); comparison between camera and reciprocating probe conditional average (c); comparison between camera and probe mean, variance and skewness radial profiles at the midplane (d).

Reliable first principles predictive capability for future machines can only be achieved by validating models and codes for the plasma edge, and the new data analysis techniques discussed above allow this in a systematic way, even beyond the needs of the theoretical framework. Indeed, the final test of any model and theory should be the comparison with experimental data. The theoretical framework was used to interpret JET [4] and MAST [3] data. In the first case, simultaneous match of profiles and turbulence data at the midplane wall was obtained in different regimes of fueling, see Fig.2. While low density, almost exponential profiles could be matched with filaments following simple dynamics (constant radial velocity and exponential in time draining), high density discharges showing a broadening of the profiles required a simultaneous increase in the outward velocity and an increase of the typical draining time. Such a change in the filament dynamics could be correlated with stronger plasma/neutral interactions, as suggested in [1-3] and observed with divertor diagnostics in the modelled discharges. In particular, charge exchange or ionization could 'clog' the divertor, thus slowing down the motion of the plasma towards the target while neutral wind at the midplane could increase the filaments' drive and therefore induce an acceleration.

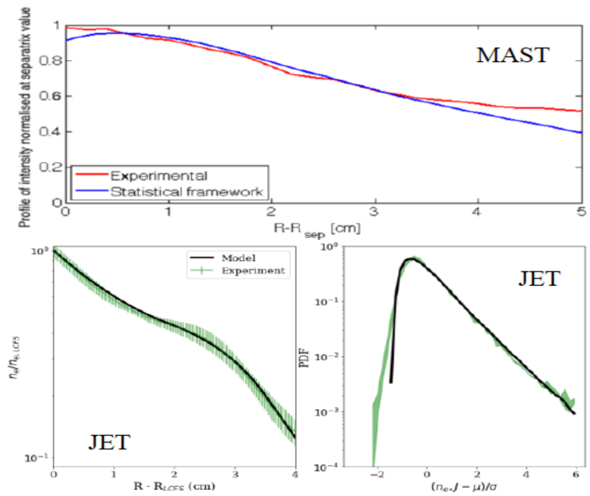

Figure 2 Upper panel: comparison between radial profile of the experimental light intensity and theoretical match of the framework. Bottom panels: density profile from JET Li-beam (high density case) and theoretical framework prediction (left); Comparison of experimental and theoretical probability distribution functions of the fluctuations at the midplane wall.

Similarly, MAST low density radial profiles of the mean and variance, obtained with visual cameras and processed with ELZAR, were properly matched by the theoretical ones by using again constant velocity of the filaments and exponential draining. It is useful to remark that, for both MAST and JET, the theoretical velocity and draining time used were compatible with those typically observed in experiments (i.e. radial velocity of ~1Km/sec, corresponding to 1-5% of the sound speed, and draining time comparable with the parallel transit time).

The framework assumptions were also tested using high performance numerical simulations. The STORM code, a 3D drift fluid solver for boundary turbulence, was used to compare numerical and experimental isolated filaments [6] and turbulence [7], finding agreement within the experimental errorbars. After this validation, the code was used to study how pairs of filaments interact [8]. The interaction occurs through the dipolar electrostatic field generated by the filaments, which is significant only when they are in close proximity (separation comparable to their width in the drift plane), thus justifying the independence hypothesis in the theoretical framework. To understand how to capture in the theoretical framework the different dynamics between L-mode and inter-ELM filaments, STORM was used to investigate the effect of finite-β electromagnetic physics on filaments. The electrical connection between the midplane region of the filament and the target, mediated by Alfven waves, can be severed if β is sufficiently large (but still of the order of a fraction of a percent) or if the divertor leg is sufficiently long, leading to a radial speed-up of the perturbations by more than a factor two in large filaments (diameter larger than 10 Larmor radii). This has consequences on the design of Super-X or Snow Flake divertors, where perpendicular transport could be enhanced by this mechanism.

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