

High-speed imaging of turbulent fluctuations in TJ-K

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Abstract

Mesoscale (i. e. larger than microscopic but smaller than the system size) turbulent fluctuations of high density, often referred to as “blobs”, may be a part of the explanation of the intermittent transport observed in the scrape-off layer (SOL) of many fusion experiments. The understanding of those mesoscale events has improved a lot over the recent years [1]. However, the details about the generation and the precise relevance for the SOL transport remain still unknown. Fast cameras are gaining more and more importance in studies of those events, since they can observe a large area of the plasma simultaneously, ideally without the need to disturb the plasma. However, the fact that they integrate the light signal along the line of sight makes the interpretation of the data more challenging. Yet it was possible to localize the turbulent fluctuations visible in the image data in the physical coordinates of TJ-K.

Experimental setup

The presented measurements were performed at the small stellarator experiment TJ-K [2, 3]. All shown experiments were helium discharges, heated with microwaves at 2.45 GHz. Deviating from the standard setup at TJ-K, two poloidal limiter were introduced into the vessel to toroidally screen off the heating region and define a clear SOL with homogeneous connection length. The camera view was almost tangential to the plasma column. A small deviation of about 10° (depending on the exact viewing angle, which can be varied in a certain range) results from geometrical constraints of the main field coils and the available viewing ports. This leads to a slightly different scale factor (mm/pixel) for the x and y direction in the image data.

TJ-K has a relatively cold plasma and a large neutral background density. This allows to observe the radiation emitted by the plasma without further gas injection. However, effects through the light integration along the line of sight can not be neglected for such a device.

The high-speed camera is a Photron SA-5 with a frame rate up to 775.000 fps (frames per second). It was operated with a lens with $f = 50\text{ mm}$ and $D/f = 0.75$, which provides a relatively small depth of focus.

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Data analysis

It is, at first, impossible to localize an intensity fluctuation in TJ-K coordinates, since the light gets integrated along the line of sight. The visible radiation of TJ-K is mainly line emission from the neutral background atoms. Thus, the radiated intensity mainly depends on electron temperature and density [4, 5]. Since temperature fluctuations are negligible in TJ-K, the intensity fluctuations should be caused by density fluctuations. Comparative correlation analyses between camera and ion saturation current measurements support this assumption.

Structure tracking

After normalizing the intensity fluctuations for every pixel by it's mean value ($\tilde{I} = (I - \langle I \rangle) / \langle I \rangle$), large intensity fluctuations with $\tilde{I} > 0.5$ become apparent. A certain threshold is defined for every single pixel (e.g. $0.5 \cdot \sigma_i$) which has to be exceeded for being counted as part of the structure. In order to localize the structure, the center of mass R_{cm} is computed as

$$\mathbf{R}_{cm} = \sum_i \mathbf{R}_i I_i / \sum_i I_i, \quad (1)$$

where \mathbf{R}_i is the position of pixel i and I_i is it's intensity count. The representation of a structure by it's center of mass is also known as the moment method [6]. Due to low frequency ($< 1\text{kHz}$) intensity variations, the quality of the structure detection is increased by working with a dynamical mean, taken over 5-10 images.

After detecting the structures, their velocities can be determined using *Particle Tracking Velocimetry* (PTV) [7]. PTV can be applied if a certain particle can be recognized in the subsequent image. This is valid, since only few blobs occur in every single image.

Conditional averaging

In order to compare the results of the PTV method with the established 2D probe measurements, the conditional averaging (CA) method is used. To this end, a reference probe was introduced into the SOL region where the

camera detects the majority of events. This reference probe was used to detect fluctuations $> 2 \cdot \sigma$ in the floating potential or ion saturation current. By calculating the CA for both, the image and probe data, conditionally averaged trajectories and, with PTV, velocities are obtained.

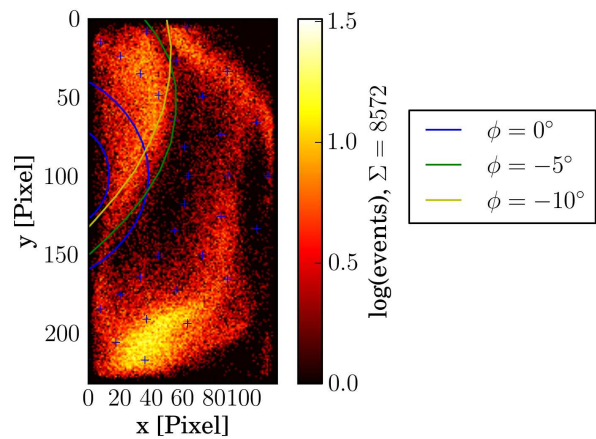


Figure 1: Projection of the separatrix for different angles to the focused plane (only three shown for illustration).

Results

Structure localization

In order to divide the image into the confinement region (left) and the SOL (right), the separatrix for different toroidal positions is projected onto a histogram of detected structures (fig. 1). It can be seen that the centers of mass of structures in the confinement region (upper left) are aligned to the separatrix 5° in front of the focused plane. On the right side of that line, the detected events are then located in the SOL. Since the integration of the light signal plays a larger role in the confinement region (higher intensity and the line of sight intersects with more plasma compared to the SOL) it cannot be concluded from this result that the observed centers of mass of structures in the SOL are also located 5° in front of the focused plane. As a matter of fact this is not the case, as it will be shown in the next section.

Comparison of probe and camera measurements

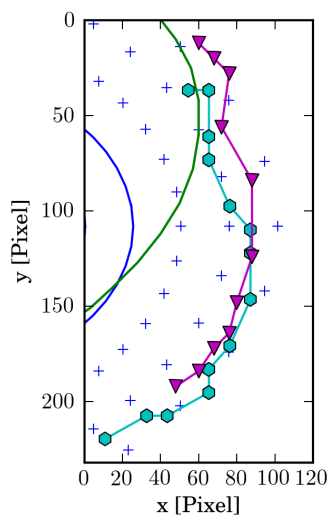


Figure 2: Comparison of the conditional average of the intensity (triangles) and ion saturation current (hexagons) fluctuations.

The dynamics of intermittent structures in the SOL of TJ-K have been studied in detail with langmuir probes, performing 2D measurements and applying conditional averaging and cross correlation techniques [8]. Such measurements were repeated with a similar setup, but additionally the camera observed the dynamics in the SOL simultaneously. The principal observations were the same for both diagnostics: Turbulent fluctuations are propagating clockwise in the confinement region and anti-clockwise in the SOL. Fig. 2 shows the trajectories of the centers of mass for both diagnostics. The good agreement indicates that the center of mass for the visual light fluctuation is located in the focused plain. This makes it possible to compute poloidal velocities in physical units. They are comparable in the upper and lower third (about 3 km/s). Only around the midplane, the camera data overestimates the velocity (almost 5 km/s for the camera, compared to about 3 km/s for the probes). The reason

for this observation is that the visual light structure grows in size with decreasing amplitude, thus becomes less prominent. Since no comparable behaviour is seen in the ion saturation current, this seems to be a limitation of the present setup. Nevertheless, it can be concluded that it is possible to reproduce the trajectory and velocity of the density fluctuations in a poloidal cross section, although the camera signal is integrated along the line of sight.

Structure tracking

A velocity map for the turbulent structures in the SOL can be obtained by averaging the computed single event velocities for every pixel. An exemplary result is shown in fig. 3. It can be seen that the detected events are crossing the separatrix in a distinct region of the poloidal cross section.

The change of the propagation direction is aligned with the separatrix 5° in front of the focused plane, this is another hint that the events in the confinement region are seen in that particular plane.

Conclusion

It was shown that, despite of the complex stellarator geometry of TJ-K, the observed fluctuations of the visual light intensity can be localized in the SOL in a poloidal cross section. This is not self-evident, since camera measurements are only the 2D projection of a 3D light field.

With this insight, it is possible to observe the dynamics of single intermittent events and compute their velocity field for the SOL on the low-field side of TJ-K (the high-field side is not in the field of view). An important observation is that density fluctuations with high amplitudes are not distributed homogeneously in the SOL and that they cross the separatrix in a distinct region of the poloidal cross section. The structure trajectories observed in the SOL can most likely be attributed to the background plasma potential and, hence, $E \times B$ flows evolving under the presented conditions of a limited discharge.

References

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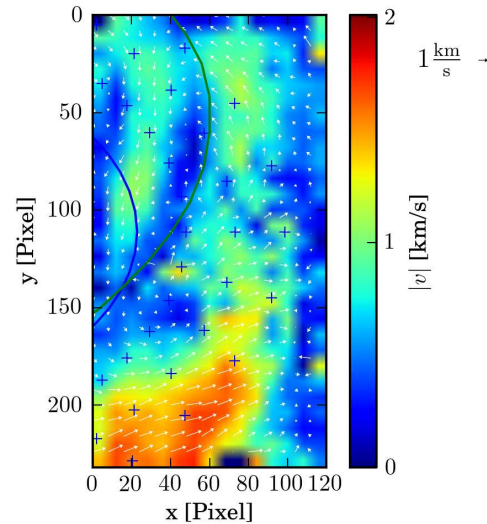


Figure 3: Sample velocity field of turbulent density fluctuations.