Journal of Nuclear Materials 463 (2015) 757–760

Contents lists available at ScienceDirect

Journal of Nuclear Materials

journal homepage: www.elsevier.com/locate/jnucmat

Filamentary transport in the private flux region in MAST

J.R. Harrison [a,*,1], G.M. Fishpool [a], B.D. Dudson [b]

[a] CCFE, Culham Science Centre, Abingdon OX14 3DB, UK

[b] York Plasma Institute, Department of Physics, University of York, Heslington, York YO10 5DD, UK

ARTICLE INFO

Article history:
Available online 4 December 2014

ABSTRACT

Measurements of intensity fluctuation of light emission within the divertor volume of MAST provide strong evidence for the existence of filamentary structures within the private flux region (PFR). These filaments are observed in L-mode and H-mode confinement regimes. Correlation analysis of the camera data supports the hypothesis that the filaments observed in the line integrated camera data are genuinely within the PFR, as fluctuations at a given location in the PFR in the image are correlated with fluctuations elsewhere in the PFR, and these two regions are connected by field lines. The filaments appear to move from a position in the PFR of the inner divertor leg, moving towards the inner divertor target, whilst ejecting secondary blobs of plasma deeper into the PFR away from the separatrix.

1. Introduction

When extrapolating data from existing machines to predict the divertor heat loads in larger devices such as ITER, gaps in our understanding of transport processes parallel and perpendicular to field lines can be a large source of uncertainty. To this end, it is important to understand the *nature* of cross-field transport, i.e. convective, diffusive or a combination, particularly as enhanced cross-field transport can reduce localised particle and power loads to divertor plasma-facing surfaces. For the transport of particles into the private flux region (PFR), it is sometimes effectively assumed that diffusion transports particles and heat from the scrape-off layer [1,2]. Recent observations of light fluctuations in the divertor volume in MAST have provided strong evidence for the existence of filamentary structures occurring within the private flux region (PFR), suggesting that intermittent convective transport plays a role. The observation of intermittent transport in the private flux region is supported by measurements of ion saturation current fluctuations at the inner divertor target of JET [3] and MAST [4], suggesting the presence of fluctuations, of order 15% of the mean value, in both the SOL and PFR sides of the separatrix. Furthermore, modelling studies using BOUT [4,6] and analytic studies [7] predicted that fluctuations should occur in the bad curvature region of the PFR of the inner leg. The camera measurements and general observations of fluctuations in the divertor are presented in Section 2. In Section 3, results of correlation analysis of the fluctuations in the PFR are shown. A qualitative description is presented in Section 4, followed by a discussion and summary in Section 5.

2. Measurements of divertor fluctuations

Line integrated measurements of light fluctuations within the divertor were made using a Photron SA1.1 camera operated at 120 kHz and a lens assembly that allowed for full coverage of the divertor at a spatial resolution of 6 mm at the tangency plane. An illustration of the region viewed by the camera and a raw image are shown in Fig. 1. The data presented in this paper were acquired from an inter-ELM H-mode period in MAST shot 29564 (0.406–0.414 s), a pulse with 620 kA plasma current, core density $4 \times 10^{19}\,\mathrm{m}^{-3}$ and 1.2 MW of NBI heating. The plasma was in a lower single-null configuration, which is optimal for divertor imaging diagnostics. The data presented are representative of typical MAST discharges, and the observations are not specific to this shot.

In order to better illustrate the fluctuations observed in the camera data, a moving average background subtraction is applied to the raw data and subsequently contrast enhanced using the Spiceweasel code [4]. An output from the code applied to this data is shown in Fig. 2 (left image), clearly showing a variety of field-aligned fluctuations in several areas of the image. Observations from L-mode and H-mode discharges suggest that there appear to be three types of fluctuations that occur within the divertor. Firstly, filaments in the scrape-off layer on the low-field side, originating upstream and becoming highly elongated due to the strong shear near the X-point [5], indicated in blue in Fig. 2 (right image).

* Corresponding author at: Culham Centre for Fusion Energy, Culham Science Centre, Abingdon OX14 3DB, UK.

E-mail address: james.harrison@ccfe.ac.uk (J.R. Harrison).

[1] Presenting author.

http://dx.doi.org/10.1016/j.jnucmat.2014.11.125

Secondly, there are high frequency (several 10's of kHz) fluctuations of $\sim$1 cm extent localised to a region very close to the separatrix, indicated in gold. The precise location of these fluctuations relative to the separatrix is difficult to deduce accurately, given that the uncertainty in the separatrix position deduced by EFIT is $\sim$1 cm, nearly two pixels at the tangency plane. Lastly, there are filaments that appear brightest in the private flux region of the inner divertor leg, appearing to move towards the inner divertor target, indicated in green. The principal features of the image can be qualitatively re-produced using forward modelling techniques, by assuming that light is emitted uniformly with uniform brightness along field lines that appear to be illuminated in the experimental data to produce a 3D light distribution, through which line integrals can be calculated to simulate a camera image. The figure to the right of Fig. 2 shows the results of such forward modelling calculations for filaments in the main SOL (blue), fluctuations near the separatrix (gold) and in the PFR (green). In particular, instrumental effects giving rise to the filaments appearing brighter at the tangency plane and the filaments in the main SOL appearing sharper in the far-field are reproduced.

3. Correlations in the PFR

The camera viewing geometry, imaging the divertor volume, means that viewing chords that are tangential to flux surfaces in the PFR of the inner divertor leg also detect light being emitted from the outer divertor leg. Although camera measurements are normally strongly weighted to the region where the camera viewing cords are tangential, contributions to the measured signal from other regions of the plasma can be a source of uncertainty regarding where the detected light was emitted. Furthermore, uncertainties in equilibrium reconstruction are a concern in definitively identifying the location of the filaments. To ascertain whether

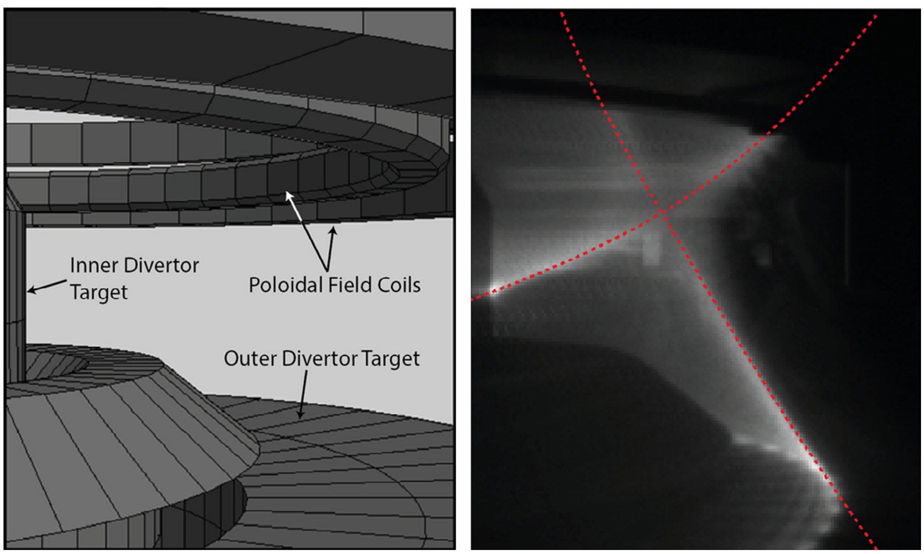

Fig. 1. Left: illustration of the MAST divertor volume imaged by the camera. Right: a raw image acquired by the camera from an inter-ELM H-mode period of a lower single-null discharge, showing the X-point and inner and outer divertor legs.

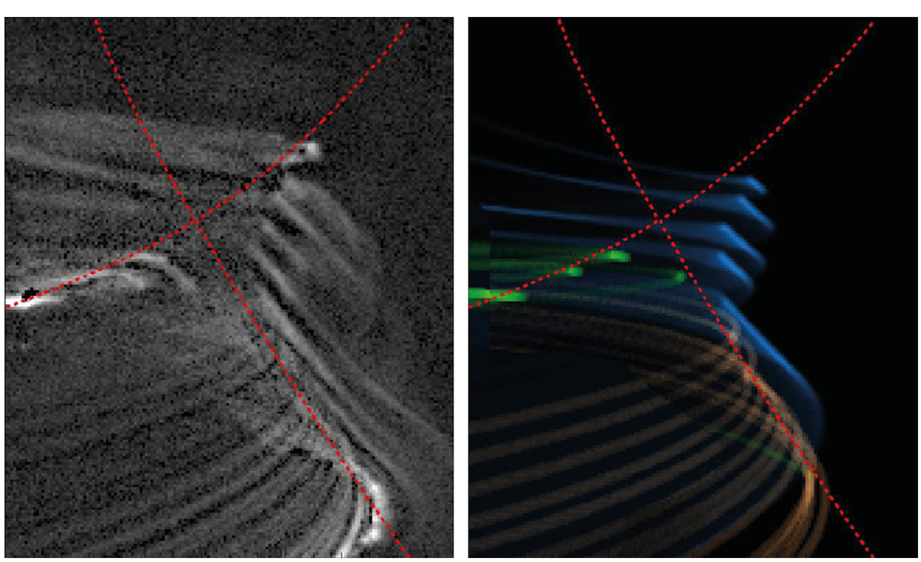

Fig. 2. Left: background-subtracted image from Fig. 1, showing fluctuations in the SOL, near the separatrix and in the PFR. The equilibrium separatrix mapped to the camera tangency plane has been overlaid as a red contour. Right: results of forward modelling calculations of the divertor fluctuations, calculated by calculating line integrals through field lines that correspond to the fluctuations observed in the left image. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

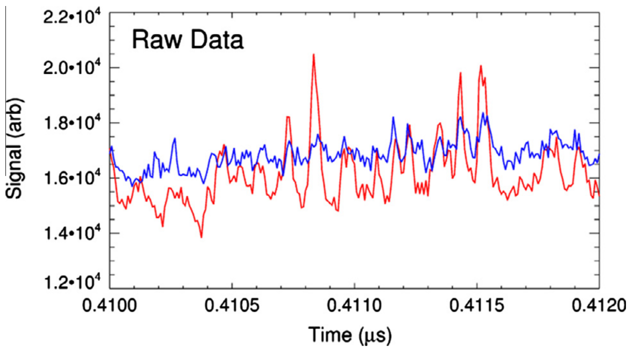

Fig. 3. A sample of raw data from two highly correlated pixels within the private flux region. The red trace is taken from a pixel viewing the PFR of the inner leg and the blue trace is taken from a pixel viewing the PFR of the outer leg. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

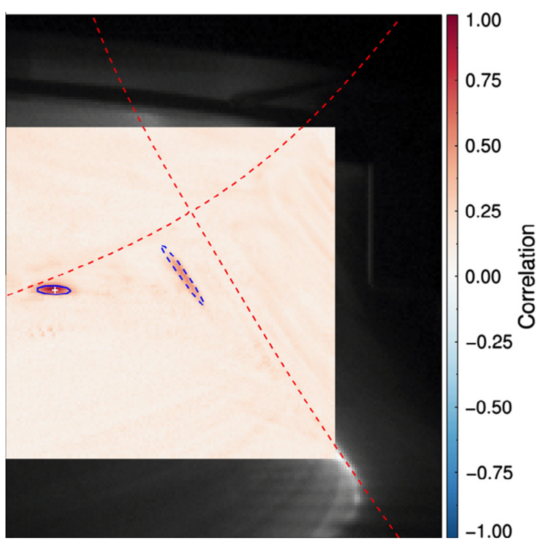

Fig. 4. Results of correlation analysis, where one pixel (indicated by a white cross) is cross-correlated with the pixels that view the plasma, over 1000 frames (8 ms total duration). The solid blue ellipse is fit around the region of local correlation for that pixel. The solid blue ellipse is mapped along the magnetic field to the tangency plane to produce the ellipse shown in dashes, which corresponds to the position of the second correlated region near the outer leg. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the observed fluctuations are genuinely due to processes local to the PFR, the correlation of light fluctuations was investigated.

The cross-correlation between two discrete time-series data, x and y (in arbitrary units), with mean values $\bar{x}$ and $\bar{y}$, for a given lag time L (integer; number of frames) is calculated using [8]:

$$P_{xy}(L) = \begin{cases} \dfrac{\sum_{k=0}^{N-|L|-1}(x_{k+|L|}-\bar{x})(y_k-\bar{y})}{\sqrt{\left[\sum_{k=0}^{N-1}(x_k-\bar{x})^2\right]\left[\sum_{k=0}^{N-1}(y_k-\bar{y})^2\right]}} & \text{for } L < 0 \\ \dfrac{\sum_{k=0}^{N-L-1}(x_k-\bar{x})(y_{k+L}-\bar{y})}{\sqrt{\left[\sum_{k=0}^{N-1}(x_k-\bar{x})^2\right]\left[\sum_{k=0}^{N-1}(y_k-\bar{y})^2\right]}} & \text{for } L \geqslant 0 \end{cases}$$

The cross-correlation between pairs of pixels was investigated using data from 1000 frames to investigate how fluctuations that occur in a given part of the image correlate with fluctuations elsewhere. A sample of raw data from two well correlated pixels separated by ∼30 cm in major radius is shown in Fig. 3. The pixel indicated at the centre of the solid blue ellipse in Fig. 4 indicated by a white cross was cross-correlated with a subset of the pixels that detected light from the plasma, which reveals a second region of correlation ∼30 cm away from the pixel of interest (measured in the camera tangency plane). The locations of the correlated regions are insensitive to the baseline subtraction method applied to the raw data, and are also detected in the raw data without a baseline subtraction applied. An outline of the region of good local correlation to the pixel of interest (shown in solid blue in Fig. 4) was mapped along the magnetic field back to the camera tangency plane, approximately one toroidal transit around the torus, which overlays well with the second correlated region (shown in dashed blue). This indicates that the two regions are well correlated because they are connected to the same field lines within the PFR. This provides strong evidence to suggest that these fluctuations in the camera data are genuinely in the PFR. Furthermore, the shapes of the correlated regions are in good agreement with the observed shape of the filaments in the raw data. In general, it is observed that fluctuations in the inner and outer leg private flux regions are correlated. The magnetic mapping of correlated regions in the PFR suggests that fluctuations in the PFR near the X-point should correlate with fluctuations in both inner and outer legs, however, it is difficult to observe the fluctuations in the outer leg experimentally due to the strong magnetic shear in this region and line integration effects resulting in a significant contribution to the signal from the SOL of the outer leg.

4. Filament propagation in the PFR

The filaments appear to move in the camera image plane along the inner divertor leg, originating from a given location in the leg

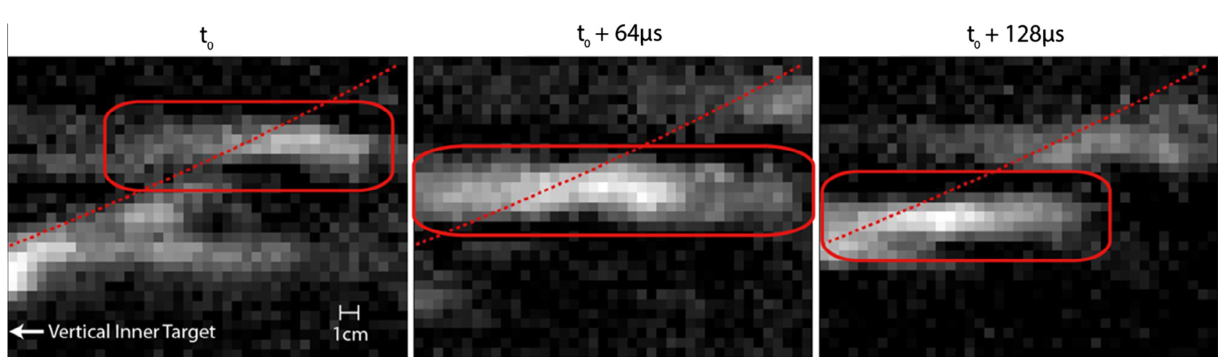

Fig. 5. Background-subtracted images showing the propagation of a filament in the PFR, indicated by a red box, starting near the x-point at the upper right part of the left images, propagating towards the inner divertor target at the bottom left as time advances. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and moving towards the inner target plate, as shown in Fig. 5. The analysis of the camera data carried out so far does not suggest the filaments originate preferentially from a given location along the divertor leg. The precise nature of the filament propagation along the inner leg is uncertain: due the helical field line geometry and the measurements were made using a single camera, it is not clear whether the apparent poloidal motion in the camera data is due to velocity components in the poloidal or toroidal direction. In the limiting cases where the filament motion is purely in the toroidal and poloidal directions, the propagation velocity is approximately -10 to -20 krad/s, or 1–2 km/s towards the inner divertor target respectively. As the filaments propagate towards the inner target, the filaments eject secondary blobs away from the separatrix.

5. Summary and discussion

Results from fast imaging of light fluctuations in the MAST divertor are presented, suggesting that there are three types of field-aligned fluctuations native to the divertor region: filaments in the SOL originating upstream that are highly sheared by the X-point, small centimetre scale fluctuations near the separatrix and filaments in the private flux region. Correlation analysis of the data from the PFR showed that fluctuations occurring in the PFR in one part of the image are correlated with fluctuations occurring elsewhere in the PFR, and that these regions are connected by field lines. Ambiguities due to the helical field line geometry and the limited camera data available means that it is currently unclear whether the velocity of the filaments is due to a toroidal rotation, poloidal propagation or a combination. Tracking the filaments in the image plane for the H-mode period considered suggests a toroidal angular velocity of -10 and 20 krad/s, or a poloidal velocity of 1–2 km/s towards the inner divertor target. These observations are in broad agreement with velocity measurements made of inter-ELM filaments on MAST in the SOL [9]. The radial expansion of the filaments ejected deeper into the PFR is somewhat consistent with their moving under the influence of the ExB drift brought about by polarization of the filament due to curvature drift, where the dominant component of the curvature vector and magnetic field are in the direction of decreasing major radius and the toroidal direction respectively, resulting in a net motion in the direction of increasing major radius.

The data suggests that intermittent cross-field transport, in the form of filaments, is present in the PFR. The role these filaments play in determining the time-averaged particle and heat fluxes to divertor PFCs is an open question, not least because there is further analysis of experimental data, from cameras and other diagnostics, and also input from modelling are required. However, recent observations of radiated power fluctuations in the inner leg at the onset of detachment in AUG [10] and blobs observed in the PFR of LHD after the onset of detachment [11] suggest that intermittency in the inner leg could play a role in several observed phenomena in the divertor.

Acknowledgements

This work was funded by the RCUK Energy Programme under grant EP/I501045 and the European Communities under the contract of Association between EURATOM and CCFE. The views and opinions expressed herein do not necessarily reflect those of the European Commission. We acknowledge the use made of the Photron SA1.1 which was borrowed from the EPSRC (Engineering and Physical Sciences Research Council) Engineering Instrument Pool.

References

[1] T. Eich et al., Phys. Rev. Lett. 107 (21) (2011) 215001.
[2] R.J. Goldston, Nucl. Fusion 52 (2012) 013009.
[3] I. Garcia-Cortés et al., PPCF 38 (1996) 2051–2062.
[4] B.D. Dudson, Ph.D thesis.
[5] J. Terry et al., J. Nucl. Mater. 390–39 (2009) 339–342.
[6] M.V. Umansky et al., J. Nucl. Mater 337–339 (2005) 266–270.
[7] R.H. Cohen, D.D. Ryutov, Contrib. Plasma. Phys. 46 (2006) 678–684.
[8] Exelis Visual Information Solutions, IDL User Guide, Exelis Visual Information Solutions, Boulder, Colorado, 2010.
[9] N. Ben Ayed et al., Plasma Phys. Controlled Fusion 51 (2009) 035016.
[10] S. Potzel et al., J. Nucl. Mater. 438 (2013) 285–290.
[11] H. Tanaka et al., Phys. Plasmas 17 (2010) 102509.