Plasma blob studies using a fluorescent probe

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Introduction

Blobs are coherent plasma structures that transport particles and energy across the scrape-off-layer of tokamaks and enhance the interaction of the plasma with the material boundaries [1]. In TORPEX [2], extensive observations have been performed on the formation of blobs as well as their dynamics. Many of these results have relied on the use of Langmuir-probe (LP) arrays, like HEXTIP-U [3], which enable spatially-resolved measurements. However, the resolution of LP arrays is limited to the separation between the probes. This distance cannot be arbitrarily reduced as the finite size of the probes and the support structures would perturb the plasma.

We have developed an optical system using a fast camera and a fluorescent probe to increase the spatial resolution of blob imaging. The method builds upon a diagnostic previously built in a linear device [4] based on the low threshold energy cathodoluminescence and short persistence time (~1 μs) of ZnO:Zn phosphor P-24. When coated on a surface and immersed in a plasma, this material produces light with luminance proportional to $n_e T_e^{2.25}$, where n_e and T_e are the electron density and temperature, whenever the coating is electrically floating [4]. This enables the visualization of plasma structures with higher resolution than traditionally possible with LPs.

A first set of experiments has been carried out with the new diagnostic and compared to information collected simultaneously with HEXTIP-U.

Cathodoluminescent coating and imaging system

The cathodoluminescent phosphor P-24 powder is available from ESPI Metals (Ashland OR, USA). Deposition on a thin (1.5 mm width), flat, stainless steel substrate is achieved with a sedimentation method. First, the powder (of particle size ~1μm) is heavily aggregated in an aqueous medium using 0.25 wt.% polyacrylic acid solution (for better dispersion) with a solution to powder weight ratio of 2:1. The suspension is then poured onto the steel substrate plate using a custom-made mould, and left at room temperature in a humid atmosphere (>95% relative humidity) to allow the liquid to gently evaporate. Once a uniform coating is obtained, the mould is removed. The steel plate is then introduced into an oven at 60°C in air and allowed to dry completely before installing it in TORPEX (see Fig. 1). The rectangular coating, of dimensions 15.5cm x 9.5cm, is not electrically conducting. Therefore, the exposed surface is isolated from the metal substrate and is effectively electrically floating.

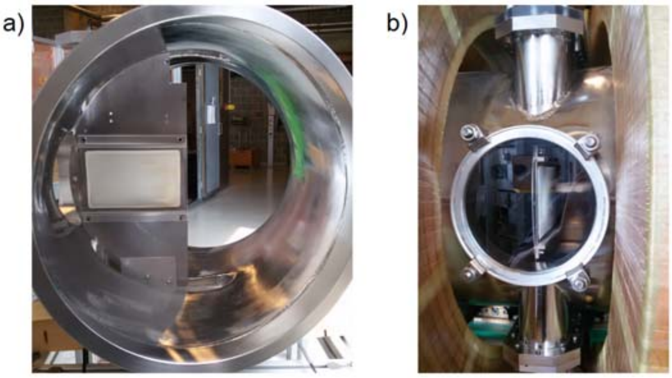

Figure 1: Stainless steel plate with cathodoluminescent coating. (a) Placement on limiter in a mock-up TORPEX sector. The limiter covers the Low Field Side (LFS) half of the poloidal cross section. (b) Limiter and plate after installation and under High Vacuum.

The coated plate is imaged with a Photron FastCam-APX RS model 250k [5] through an optical system designed to block external light and placed in a way so as to reduce the effect of plasma luminosity. Although this fast camera is able to achieve very high acquisition rates of up to 250 kfps (kilo-frames per second), in our experiments we consider only 50–100 kfps, since higher speeds would result in lower image resolution. To better discriminate light produced by cathodoluminescence of the coating, an optical filter centered near the expected peak emission of ZnO:Zn phosphor (~510 nm) is added to block the main emission spectrum of the plasma. The filtering and fast framing rate result in fewer photons collected in each video frame. Therefore, we use a Hamamatsu C10880-03F Image Intensifier Unit (IIU) to amplify the light signal arriving at the FastCam. The complete imaging system is shown in Fig. 2 [5].

Figure 2: Imaging system and its different components. (a) Dark box with mirrors to improve the view angle on the coating. (b) TORPEX vacuum vessel and toroidal magnetic field coils. (c) Configurable optical passband filter on movable arm for easy insertion and removal. (d) Image Intensifier Unit. (e) FastCam.

Experimental tests

With the limiter installed, turbulent plasmas can be generated in TORPEX using suitable choices of gas, toroidal magnetic field (with on-axis value B_ϕ) and vertical magnetic field (B_z) [6]. Their evolution can be followed with high temporal resolution over the entire poloidal cross section using the HEXTIP-U diagnostic [3]. In these experiments we use

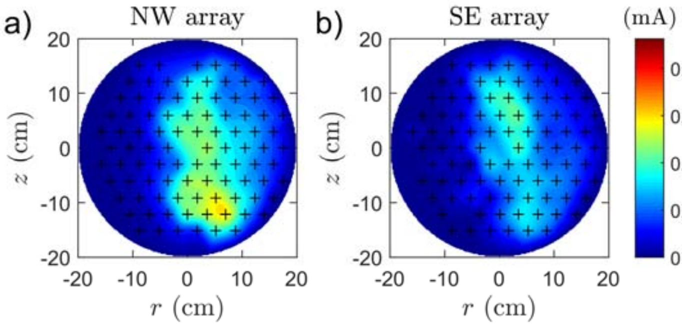

Figure 3: Interpolated time-averaged ion saturation current ‹ $I_{i,sat}$ › in shot 68899, as measured on the (a) NW array and (b) SE array of HEXTIP-U. Axes "*r*" and "*z*" are the usual horizontal and vertical coordinates in the poloidal cross section, with the origin coinciding with the torus axis. Black crosses mark the location of the active LPs. Note the varying plasma conditions across the toroidal distance separating the two arrays. The coated plate was installed on the side of the limiter facing the SE array.

helium, $B_\phi = 87.6$ mT, $B_z = 1.7$ mT, and generate a plasma using 2.45 GHz microwaves at a power of 800W, for an average location near the edge of the limiter, as shown in Fig. 3. We acquire 1000 images at a speed of 100 kfps (10 µs per frame), using 850V at the IIU for light amplification and 4µs IIU gating time. This last parameter is the amount of time that the IIU is active in each frame, so it constitutes an effective image integration time per frame. Figure 4 shows some time-statistics of the group of images, calculated by first cropping the area of the plate from the FastCam video files, projecting it to obtain a front view of the coated part, and then computing the corresponding statistic on the time-series of each pixel. The results show a clear signal from the cathodoluminescent coating and a comparatively small level of noise as evidenced by the low standard deviation in areas not directly exposed to the plasma, as well as the comparison of the maximum (Max) and minimum (Min) intensity levels.

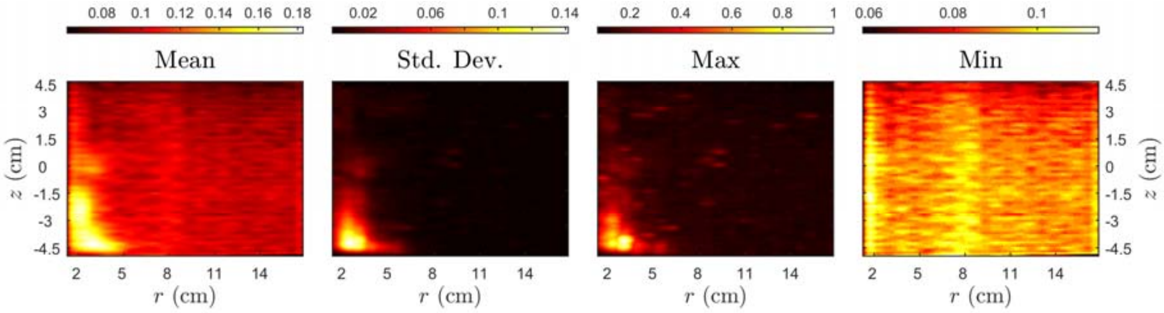

Figure 4: Some statistics of the images of the cathodoluminescent coating collected in a Helium plasma (see text for details). "*r*" and "*z*" are as defined in Fig. 3. The colorbars indicate the light intensity in arbitrary units, normalized such that the overall maximum is 1. The fact that Min is not 0 indicates that some spurious light found its way to the images; it is likely due to light emitted by the plasma which reflects off the coated surface.

The strength of the amplified luminescence signal allows us to distinguish signal from noise in each individual image. This means that no averaging is required and the evolution of the plasma can be tracked frame by frame. Figure 5 shows an example of the results obtained with a subsample of the data used in Figs. 3, 4.

We performed other experiments varying the values of B_ϕ, B_z, the FastCam frame rates and the working gas (we also used hydrogen). All these shots are under analysis. Preliminar results are in agreement with the interpretation of the data presented here.

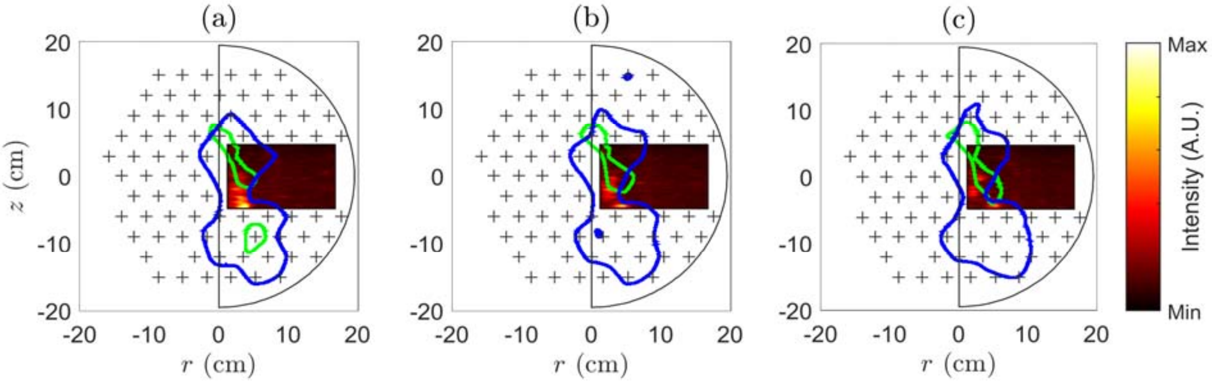

Figure 5: (a) – (c): Instantaneous luminescence data as it evolves in 3 consecutive frames (at 100 kfps; see text for details). The colored contours are HEXTIP-U data (blue for NW array, green for SE) for the same frames which show plasma structures with $I_{i,sat} \geq 0.4$ mA. The crosses indicate the location of some of the SE array probes, while the semicircle shows the edge of the metallic limiter. The colorbar is normalized to the maximum and minimum values of luminescence in the sequence. The correspondence between the cathodoluminescence signal and the SE array data can be recognized when one takes into account the vertical magnetic field line pitch introduced by B_z.

Conclusions and outlook

A technique using a fast camera and a cathodoluminescent coating has been developed to image plasma structures. Initial experiments show promising results, with images of very good quality acquired at up to 100 kfps. This allows tracking the evolution of TORPEX plasmas with remarkable resolution and at a speed suitable for blob dynamics studies. Data obtained under different plasma conditions is currently being analyzed to better characterize the potential of this diagnostic, and most notably, the correspondence with HEXTIP-U data. Some upgrades in the optics are envisioned to improve the overall aperture of the system and study plasma configurations for which the signal-to-noise ratio is still poor. Notably, when the average plasma location is on the High Field Side, away from the limiter. Finally, work is under way to improve the angle of view of the coating in order to further enhance the image resolution.

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[1] D.A. D'Ippolito et al., Phys. Plasmas 18, 060501 (2011)

[2] I. Furno et al., J. Plasma Phys. 81, 345810301 (2015)

[3] M. Baquero-Ruiz et al., Rev. Sci. Instrum. 87, 113504 (2016)

[4] A. Liebscher et al., Rev. Sci. Instrum. 72, 953 (2001)

[5] D. Iraji et al., Phys. Plasmas 17, 122304 (2010)

[6] C. Theiler et al., Phys. Rev. Lett. 108, 065005 (2012)