Measurement of Blob-Like Structures in Plasma with a Langmuir Probe and Fast Camera on QUEST

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This paper presents a scheme for combining a Langmuir probe with a fast camera for measurement of the behavior of blob-like structures in the boundary region of an electron cyclotron resonance (ECR) heating plasma in Q-shu University Experiment with a Steady-State Spherical Tokamak (QUEST, major radius, $R = 0.68$ m, minor radius, $a = 0.40$ m, and toroidal magnetic field, $B_t = 0.25$ T at $R = 0.64$ m). The frame rate of the camera was typically set to 40,000 frames per second (FPS) with 192×144 pixels per frame. Radial motion of blob-like structures was observed in the half of the plasma space where the probe head was located. A radially movable and rotatable probe system was used to measure the floating potential from single unbiased tips, the potential of the positively biased tip, and the ion saturation current in two orthogonal directions in the outboard midplane region. Time series of the ion saturation current measured by the Langmuir probe and of pixels in a 40,000 FPS movie were compared and cross-correlated. The results of the two diagnostics agreed well, and the spatial scale was found to be of the same as the size of the probe head. The ion saturation current was asymmetric in terms of the time the blob-like structure was passing; fast camera imaging also clearly demonstrated the blobs' filamentary structures and radial motion at the edge of QUEST. This means that plasma in the blob-like structure hunches over, like blobs in other devices. The typical radial velocity of the structures is ~1 km/s, and the structures were accelerated along their path of radial motion from the inner to the outer parts of the vacuum vessel.

Keywords: fast camera, Langmuir probe, combined, blob-like structure, QUEST

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1. Introduction

Understanding and characterizing blobs in the plasma boundary region of magnetically confined plasmas is important and may actually be crucial for ITER. This is because the blob structures contain excess density and temperature compared with the background plasma and could cause serious wall erosion, impurity production, heat and particle load, and particle recycling in the plasma boundary region. The study of plasma blobs and the resulting intermittent convective transport is one of the most active research areas in plasma physics [1–4]. While substantial progress has been made in understanding blobs, the mechanism of blob formation remains an open question. Recent experimental results from a simple magnetized torus shed some light on this mechanism [5].

Recently, some two-dimensional fluctuation measurements, such as those from fast cameras, beam emission spectroscopy (BES), and probe array measurements in several devices, have been used to investigate blob structures in the plasma boundary region [6–8]. However, it is difficult to use individual measuring methods to study their three-dimensional structures and polarization properties simultaneously. A combination of a Langmuir probe and fast camera has already been demonstrated as a powerful tool for studying filamentary structures in Heliotron J [8]. In the Q-shu University Experiment with a Steady-State Spherical Tokamak (QUEST), a scheme for combining a new movable and rotatable Langmuir probe and a fast camera was used to measure blob-like structures with intermittent and frequent bursts simultaneously in the edge plasma of a fundamental plasma magnetic configuration characterized by a slab plasma and open field lines. This paper compares time series of the ion saturation current measured by the Langmuir probe and of pixels in a 40,000 frames per second (FPS) movie. The features and radial motion of the observed blob-like structures are reported.

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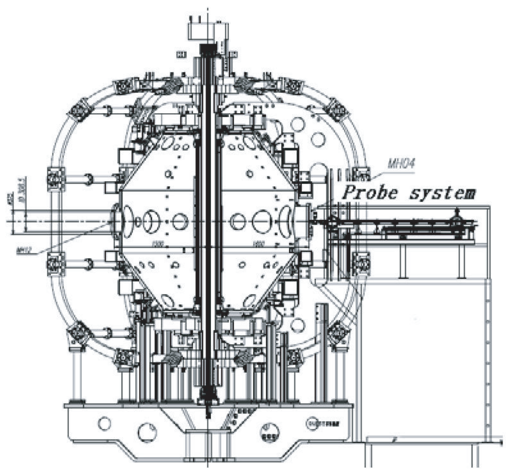

Fig. 1 Schematic of the probe system installed on QUEST.

2. Description of Experiments

QUEST is a medium-sized spherical tokamak with improved high-beta stability compared to conventional tokamaks; the purpose here is to study issues related to steady-state operation. It has a major radius of $R = 0.68$ m and a minor radius of $a = 0.40$ m; the diameters of the center stack and the outer wall are ~0.2 m and ~1.4 m, respectively, and flat divertor plates are located at a vertical distance from the midplane of $Z = \pm 1$ m, as shown in Fig. 1. In this experiment, hydrogen plasmas were initiated using electron cyclotron resonance heating (ECRH) at 2.45 GHz in a magnetic configuration with vertical and toroidal magnetic fields B_z and B_t, respectively. The injected microwave power for ECRH was about 10 kW.

2.1 Radially movable and rotatable Langmuir probe

A new radially movable and rotatable Langmuir probe was installed in the midplane of QUEST, as shown in Fig. 1. The probe has five tungsten pins, whose diameter and length are 1 mm^{Ø} × 1 mm^{L}, separated by ~7 mm in the toroidal and poloidal directions; the A, B, C pins and the D, E pins are radially separated by ~5 mm, as shown in Fig. 2. Two measurement methods are used. The first, illustrated in Fig. 2 (a), allows simultaneous measurement of the floating potential (A, D, and E), positive bias (B), and ion saturation current (C) in two orthogonal directions (toroidal and poloidal) in the outboard midplane region. The second method uses A, B, and C to measure the floating potential in the poloidal direction. Thus, fluctuations in the poloidal electric field can be deduced from the difference in the floating potential signals V_f, as shown in Fig. 2 (b). The probe head can be rotated 360° around its center. The probe signals were sampled at 1 MHz. For measuring ion saturation current, a sample resistance of $R_s = 100\,\Omega$ was used, as shown in Fig. 2 (d). In this experiment, the radial position was scanned by the probe head shot by shot with a highly reproducible ECRH plasma.

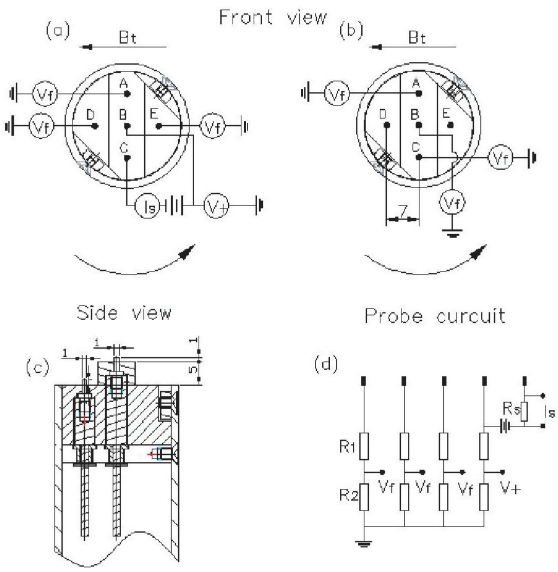

Fig. 2 Schematic view of the Langmuir probe array in the QUEST tokamak.

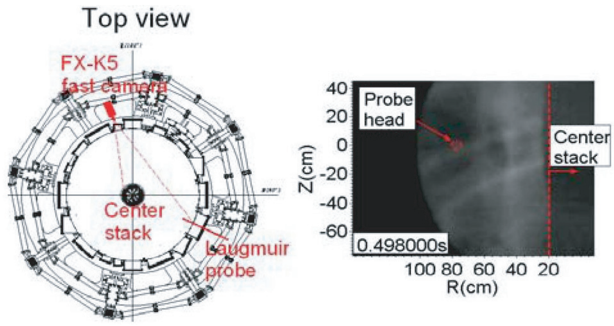

Fig. 3 (Left) Schematic of combined Langmuir probe and fast camera. (Right) Image from fast camera as a blob-like structure passes through the probe head area. $B_t = 229$ G, $B_z \sim 96$ G, shot no. 4212.

2.2 Combination of Langmuir probe and fast camera

The left side of Fig. 3 shows that for observing blob-like structures with the probe, the camera's frame rate was typically set to 40,000 FPS with 192 × 144 pixels per frame; the viewing area was half the plasma space where the probe head was located. The viewing angle was 28° in the midplane. To compare the probe signals and camera images, the number of pixels was selected according to the size of the probe head, which is 2.5 cm in diameter. In this paper, the selected pixels cover an area of 3 × 3 cm^2 where the Langmuir probe head is located, which is slightly bigger than the probe head's area. Although no filter was used, the observed visible image was attributed mainly to H_α emission ($\propto n_0 n_e$) [8]. The right side of Fig. 3 shows one picture taken by the fast camera when a blob-like structure passed through the probe head. It clearly shows that blob-like structures extended along the magnetic field lines and had rather small cross sections in the perpendicular plane, whose diameter is about 3 ~ 5 cm, as they propagated to the outer wall. The probe head area brightens when the blob-like structures pass through. The probe recorded the floating potential, the potential of the positively biased tip, and the ion saturation current.

3. Experimental Results

3.1 Comparison of light-intensity fluctuations from the fast imaging camera and ion saturation current fluctuations from the Langmuir probe

For observing the various properties of blob-like structures by the combined Langmuir probe and fast camera, it is important to first check the agreement of these two diagnostics. Therefore, we first compare the fluctuations measured by the Langmuir probe biased toward the ion saturation current (I_{sat}) to those using the fast camera (I_{hv}). I_{sat} is proportional to the density and the sound speed, $I_{sat} \sim nT^{1/2}$, whereas the light intensity is proportional to nT^{α}, where α is about 3/4. Accordingly, neglecting temperature fluctuations, both diagnostics reflect mainly density fluctuations. Hereafter, though, we shall not make this assumption, and we shall deal with the ion saturation current and light-intensity fluctuations. The Langmuir probe's trigger is synchronized with that of the fast camera. The acquisition frequency is set to 1 MHz; however, for comparison purposes, only 1 of 25 points is used as the camera operates at a rate of 40,000 FPS. The light intensity at pixels in the probe head area is used to obtain the other time series. Two 30 ms time interval series signals were used Figure 4 shows the raw signals from the camera (I_{hv}) and the Langmuir probe (I_{sat}). Visual inspection reveals rather good correlation between the two diagnostics. High-intensity bursts appear in both, but the details often differ. The cross-correlation coefficient offers a reliable quantitative measurement of the correlation between the two signals. In Fig. 4 (b), the amplitude of the coefficient is more than 0.3 at $\tau \approx 0$, where τ is the time difference between the two signals, indicating a true correlation between them. The fact that the correlation amplitude is high but not close to unity results from complications in determining the camera's resolution. The first limit on spatial resolution is determined by the pixel size and the field of view. Each pixel of the fast camera is about 1 cm in size. The selected pixels covered a $3 \times 3\,\text{cm}^2$ area, which is bigger than the diameter of the probe head, i.e., 2.5 cm. The second limit to the resolution is line integration. The camera was installed at a QUEST port opposite the probe. This limit on the resolution is hard to determine accurately since it depends on various parameters such as the light intensity distribution and the focusing properties. Sometimes blob-like structures passed through but did not touch the probe head, so the visible radiation intensity in the probe head area viewed by the fast camera increased, but no burst occurred in the ion saturation current. Sometimes when blob-like structures passed through the probe head area, their leading or trailing part touched the probe head, but the fast camera caught the full light intensity. In the ion saturation current measured by the probe, very weak bursts occurred when such high-intensity bursts occurred in the camera signal. However, even if these limits exist, the light-intensity fluctuations and those measured by the probe are correlated well in our experiment.

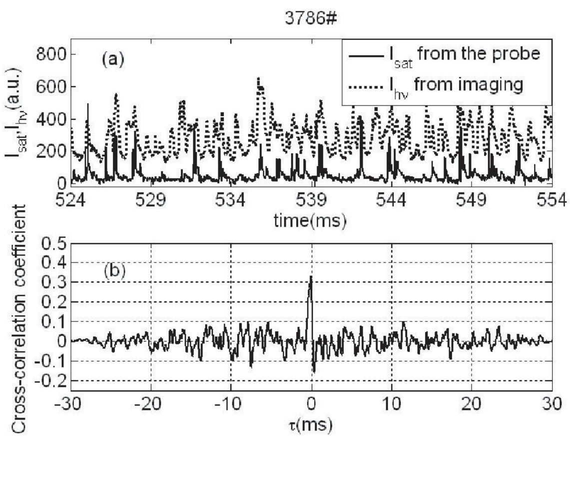

Fig. 4 (a) Raw ion saturation current signal from the Langmuir probe and the signal from the light-intensity fluctuations of pixels in the probe head area as a function of time. (b) Cross-correlation coefficient between probe and camera signals. Shot no. 3786.

3.2 Isolated blob-like structures, and the radial motion and features of blob-like structures

Figure 5 shows the electron density signal at 25 cm inside the wall in the outboard midplane region of QUEST. An abundance of intermittent large-amplitude bursts appears in the time series and appear to have an asymmetric waveform. These bursts are markers of blob-like structures from the local probe signals, based on their major characteristics [9]; namely, the pulse amplitude is higher than the root-mean-square (rms) fluctuation level. The bursts ex-

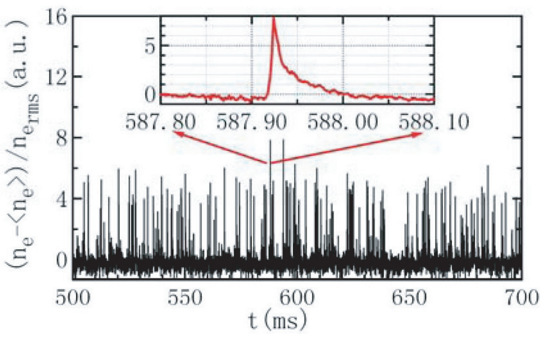

Fig. 5 Probe recording of electron density. Inset is one burst, showing the development of a steep front and a trailing wake.

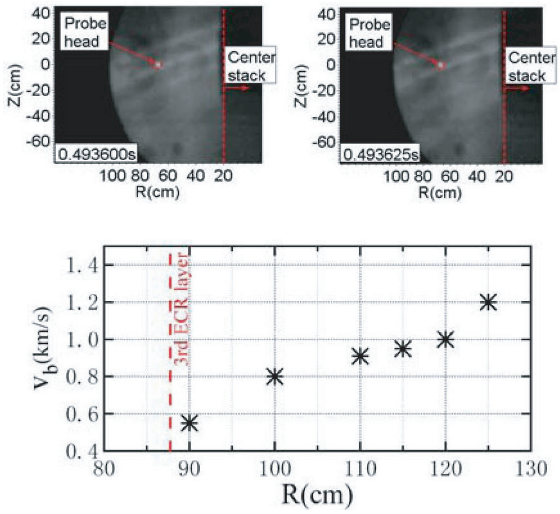

Fig. 6 (top) Fast camera images of filamentary structures elongated along the magnetic field, which agree with asymmetric blob-like structures measured in the probe's time series. Shot no. 4215. (bottom) Average radial velocity spatial profile of blob-like structures estimated by fast camera imaging.

hibit a steep front (sharply rising) and trailing wake (slowly decaying), as shown in the inset of Fig. 5. The asymmetric burst shape is believed to be induced by radial motion of the blob-like structure. The typical duration of one burst event, which corresponds to the width at 15% of the peak values in a burst, is about 60 μs, which is the same as blobs in other devices [3, 10]. Fast camera imaging also clearly demonstrated their filamentary structures and radial motion in this experiment, as shown below.

The top panel in Fig. 6 shows a typical two-dimensional image at 40,000 FPS in ECRH discharge. The blob-like structures are clearly elongated along the magnetic field lines. B_z plays an important role as an experimental control parameter via its action on the magnetic topology. With different ratios of B_z/B_t, the helix angle and vertical wavelength λ_z of initial helix-sinusoidal perturbations differ [11, 12]. In this experiment, to focus on the characteristics of the blob-like structures under the same magnetic topology, B_z and B_t were set to 96 G and 229 G, respectively. The lifetime of the blob-like structures is roughly 300 μs to 700 μs, and the frequency of the intermittent blob-like structures is from 0.7 kHz to 4 kHz, with an average value of about 1.4 kHz [13]. The bottom of Fig. 6 shows the average radial velocity spatial profile of blob-like structures estimated by fast camera imaging. The initial propagation velocity is $V_b \sim 0.55$ km/s near the main plasma source region around the ECR layer, but the velocity increases to 1.2 km/s near the wall. This suggests that blob-like structures are accelerated along their path of radial motion. The average radial velocity of blob-like structures is about 1 km/s in the intermediate region.

4. Conclusions

A powerful tool consisting of a fast camera and movable Langmuir probe was used to study edge plasma phenomena. The most important feature of this combination is that good agreement exists between time series from the two instruments. The cross-correlation amplitude between the probe and camera signals was found to be more than 0.3, which indicates true correlation between the two. The correlation amplitude is still far from 1 mainly because of line integration measurement by the fast camera.

Blob-like structures were observed extending along the magnetic field lines and moving across the magnetic field. The ion saturation current measured by the Langmuir probe revealed that each turbulent burst had a similar asymmetric wave form with a typical duration of about 60 μs. This is the same as blobs in other devices. The radial motion and features of blob-like structures were estimated from the images. The blob-like structures are accelerated along their path of radial motion from the inner to the outer part of the vacuum vessel. More details of blob-like structures will be observed by this effective combined tool in the near future.

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[1] S. J. Zweben *et al.*, Plasma Phys. Control. Fusion **49**, S1 (2007).
[2] O. E. Garcia, V. Naulin, A. Nielsen and J. J. Rasmussen, Phys. Rev. Lett. **92**, 165003 (2004).
[3] O. E. Garcia *et al.*, Plasma Fusion Res. **4**, 019 (2009).
[4] S. I. Krasheninnikov, Phys. Lett. A **283**, 368 (2001).
[5] I. Furno *et al.*, Phys. Rev. Lett. **100**, 055004 (2008).
[6] S. J. Zweben *et al.*, Nucl. Fusion **44**, 134 (2004).
[7] S. H. Muller *et al.*, Phys. Plasmas **14**, 110704 (2007).
[8] N. Nishino *et al.*, J. Nucl. Mater. **363-365**, 628 (2007).
[9] J. A. Boedo *et al.*, Phys. Plasmas **10**, 1670 (2003).
[10] G. Y. Antar *et al.*, Phys. Rev. Lett. **87**, 065001 (2001).
[11] H. Zushi *et al.*, presented at the 19th International Conference on Plasma Surface Interactions, May 24-28, 2010, San Diego, CA, USA.
[12] S. H. Muller *et al.*, Plasma Phys. Control. Fusion **51**, 055020 (2009).
[13] H. Q. Liu *et al.*, *the 7th General Scientific Assembly of the Asia Plasma and Fusion Association*, Oct. 27-30, Aomori, Japan.