Intermittent Magnetic Fluctuations Associated with High-Temperature Bubbles in an ECR Plasma*)

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(Received 10 January 2019 / Accepted 15 March 2019)

Magnetic probe measurement has been performed in a cylindrical electron cyclotron resonance plasma in which localized high temperature electron region, i.e. high-temperature bubble, has been generated intermittently. It is found that the high-temperature bubble is accompanied by a pulsed magnetic fluctuation perpendicular to the external magnetic field. Polarities of the magnetic fluctuation suggest that it should be induced by a transient upstream electric current. This hypothesis has been validated by a simultaneous increase of electron flux in the downstream direction. No enhancement of electron flux in the upstream direction has been observed even under the existence of the bubbles. The result suggests that the electron velocity distribution function in the bubble should be an asymmetric one, which gives rise to an effective upstream electric current.

Keywords: intermittency, high-temperature bubble, magnetic fluctuation, electron cyclotron resonance plasma, HYPER-I device

DOI: 10.1585/pfr.14.3401081

1. Introduction

Intermittent and bursty behavior is a manifestation of nonequilibrium and nonlinear nature of plasmas, and it is an important research topic in plasma physics.

Recently, we have reported intermittent generation of high-temperature bubbles [1] in an electron cyclotron resonance (ECR) plasma. This phenomenon was first recognized as spontaneous excitation of sporadic large-amplitude negative spikes in the floating potential signal measured with a Langmuir probe [2, 3]. Although floating potential is generally used as a substitute of space potential in the case of constant electron temperature, it is also very sensitive to a change in electron temperature. This is because the abrupt change in electron temperature breaks the balance between electron current and ion current flowing into the probe electrode from which the floating potential is determined. In our previous experiment, the current-voltage characteristics taken by conditional sampling method revealed that the electron temperature inside the bubble (32 eV) was about three times higher than that outside the bubble (11 eV) [1]. Higher electron temperature increases electron influx by thermal diffusion, and the floating potential becomes more negative to draw more ion current. Therefore, the negative spikes in floating potential signal indicate the generation of high-temperature bubbles.

The cross-sectional structure of the high-temperature bubble can be visualized by two-dimensional measurement of floating potential using the high-impedance wire grid (HIWG) detector [4]. It was shown that the bubble has a circular cross-section of which diameter defined by full width at half maximum is typically 30 mm. This result was also confirmed by a line-emission intensity profile of He I at 668 nm taken by an ICCD camera, in which the floating potential of a reference Langmuir probe was used as a trigger signal. The image of He I line emission clearly showed a circular high intensity region of which diameter was about 30 mm. It should be mentioned that a similar result was obtained when the feeding gas was changed from helium to neon [5]. The high-temperature bubbles have been observed not only in helium gas discharge but in various gas discharges such as argon, neon and xenon.

Statistical analysis of floating potential time series revealed the randomness of high-temperature bubbles [6]. The probability density function of the waiting time [7] that is defined by a time interval between two consecutive bubble events was well fitted by an exponential distribution. This result indicates that the bubble is generated at a constant probability. In other words, the high-temperature bubble generation is a stationary Poisson process.

We have so far investigated many properties of high-temperature bubbles by means of electrical measurement such as Langmuir probes. In order to gain a much deeper understanding of the phenomenon, magnetic measurement using magnetic probes should be performed.

In this paper, we report the first observation of intermittent magnetic field fluctuations associated with the high-temperature bubbles and discuss the generation

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*) This article is based on the presentation at the 27th International Toki Conference (ITC27) & the 13th Asia Pacific Plasma Theory Conference (APPTC2018).

mechanism of them based on electron flux measurements using a directional Langmuir probe (DLP) [8]. The experimental device and diagnostic methods are described in Sec. 2. The experimental results of magnetic probe measurement are presented in Sec. 3. We discuss the generation mechanism of the magnetic field fluctuation in Sec. 4. The conclusion is given in Sec. 5.

2. Experimental Setup

The experiments were performed with the HYPER-I device [9] at the National Institute for Fusion Science. The HYPER-I device consists of a cylindrical vacuum chamber (30 cm in diameter and 2.0 m in axial length) and ten magnetic field coils. A schematic drawing of the HYPER-I device is shown in Fig. 1. The coordinate system used in this study is also shown in Fig. 1. The origin of z-axis is set to the vacuum side surface of the quartz window for microwave injection, and the origin of x- and y-axis is set to the center of circular cross-section of the vacuum chamber. The plasma is produced by ECR heating with a 2.45 GHz microwave injected from the high-field side of the weakly-diverging magnetic field configuration. The helium gas operation pressure and the microwave input power in this experiment were 1.5 mTorr and 21 kW, respectively. Under these externally controlled parameters, the high-temperature bubbles are spontaneously generated in the plasma. Typical electron temperature outside the high-temperature bubbles was 10 eV, and typical electron density 10^{18} m^{-3}.

A DLP, which was originally developed to measure angle-resolved ion saturation current, was used to measure the change of angle-resolved electron flux in the present experiment, and magnetic probes (MPs) were used to measure magnetic fluctuations. Figure 2 shows schematic drawings of DLP and MP. The DLP consists of a tungsten electrode (1.5 mm in diameter) covered with an alumina insulating tube (3.0 mm in diameter) of which side surface has a hole (1.0 mm in diameter) to collect plasma particles. In order to detect the change in electron flux, the DLP was connected to the ground through 50 Ω resistor to ensure frequency response, and the voltage across the resistor was measured. For the correspondence to change in floating potential, the DLP was not connected to a DC power supply. In the present experiment, the plasma potential was +30–40 V, and the floating potential +15–20 V. Therefore, the DLP received ion current in steady state. However, when the high-temperature bubble was generated, the floating potential sharply dropped to a negative value (up to −20 V) due to an abrupt increase in electron flux even though the plasma potential remained the same. Then, the DLP received electron current, and the voltage across the resistor showed a negative spike, which was used as an index of high-temperature bubble generation in this experiment. The DLP was installed on a radial port located at z = 1.175 m. Note that when the hole faces to upstream

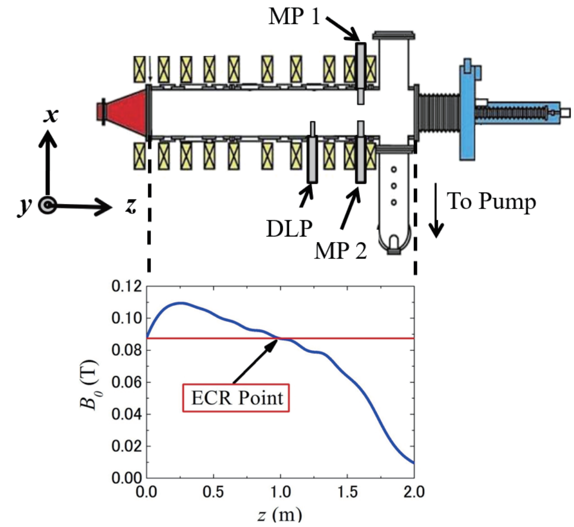

Fig. 1 Schematic drawing of the HYPER-I device with a typical magnetic field configuration. A directional Langmuir probe (DLP) and two magnetic probes (MP1 and MP2) are located at z = 1.175 m and z = 1.555 m, respectively.

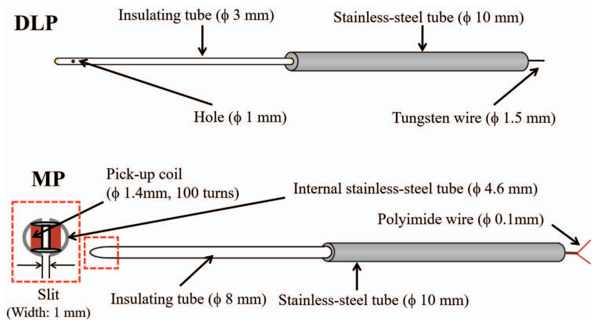

Fig. 2 Schematic drawings of DLP and MP.

(downstream) direction, the DLP detects electron flux in the downstream (upstream) direction. The MP has a 100-turn loop pick-up coil made of polyimide wire of which diameter is 0.1 mm. The pick-up coil is covered by an internal stainless-steel tube to prevent damage from heat, which has a 1 mm slit to allow the magnetic flux to pass through the coil. The stainless-steel tube is covered with an alumina insulating tube (8 mm in diameter). Since the output signal of MP is proportional to the time derivative of magnetic flux density, the signal should be numerically integrated when the amplitude of magnetic flux density is needed. The MP was calibrated by a preliminary experiment using a Helmholtz coil to obtain absolute value of magnetic fluctuation strength. Two MPs facing each other were installed at z = 1.555 m.

3. Experimental Results

At first, we measured the z-component (B_z) and y-component (B_y) of magnetic fluctuation by setting the normal vector of the pick-up coil parallel to and perpendicular to the external magnetic field. Figure 3 (a) shows

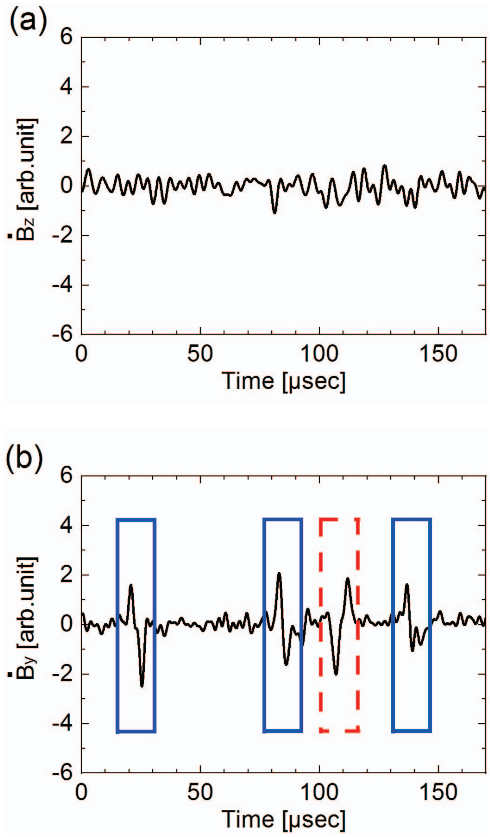

Fig. 3 (a) z-component and (b) y-component of magnetic fluctuation measured at $x = -20$ mm, $y = 0$ mm. Solid-line squares (blue online) indicate the positive polarity, and broken one (red online) the negative polarity.

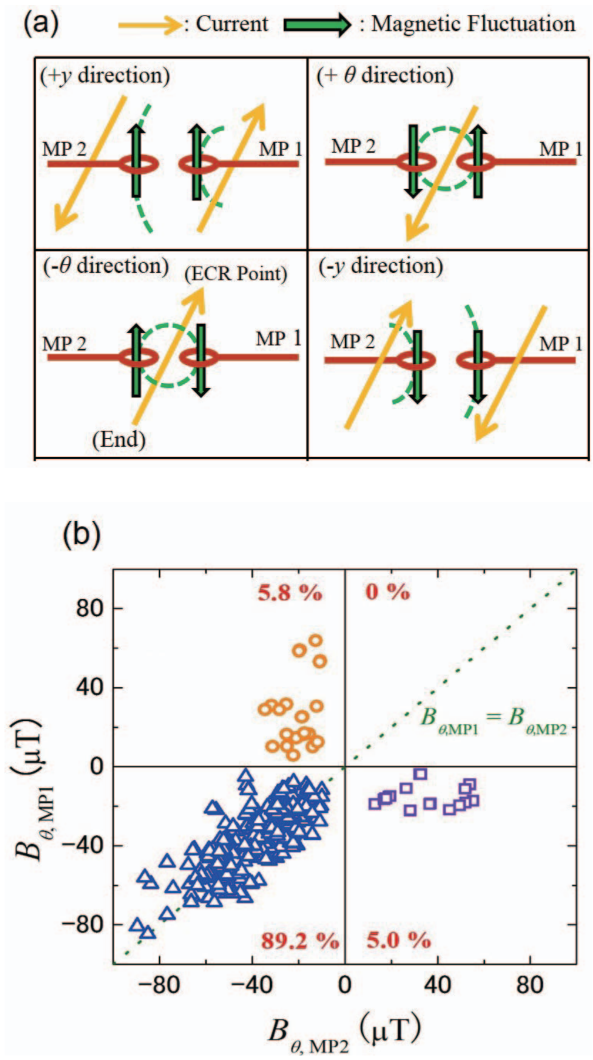

Fig. 4 (a) Illustrations of magnetic fluctuation directions and conceivable electric currents. (b) Relation between $B_{\theta,\mathrm{MP1}}$ and $B_{\theta,\mathrm{MP2}}$, which were simultaneously measured with MP1 and MP2.

that no distinct B_z fluctuation was excited in the plasma. On the other hand, Fig. 3 (b) clearly shows that B_y fluctuations were excited intermittently with unequal time intervals. Typical amplitude and duration of B_y fluctuations were about 40 μT and 10 μs, respectively. These results indicate that the magnetic fluctuations are excited by electric current parallel to external magnetic field in z-direction. Moreover, it should be pointed out that the B_y fluctuations include a mix of positive (marked by solid-line square) and negative (marked by broken-line square) polarities as seen from Fig. 3 (b).

In order to investigate the direction and the positions of electric current that induces magnetic fluctuations, measurement with two MPs located at $x = +20$ mm (MP1) and $x = -20$ mm (MP2) was performed. Combinations of possible magnetic fluctuation polarities and conceivable electric current directions are illustrated in Fig. 4 (a), where $+\theta$-direction is defined as a counterclockwise direction seen from the end of the vacuum chamber. Figure 4 (b) shows the results of simultaneous B_θ measurement with two MPs, where the detection threshold was set to 9.9 μT. Each quadrant in Fig. 4 (b) corresponds to the situation illustrated in the same quadrant in Fig. 4 (a). Since no data is plotted in the first quadrant in Fig. 4 (b), it is concluded that there is no downstream electric current that induces $+\theta$-direction magnetic fluctuations for both MPs at the same time. In addition, as seen from the second and the forth quadrants, it is more reasonable that the B_θ fluctuations are excited by upstream electric current because of the disparity of B_θ amplitudes. For example, the number of large $B_{\theta,\mathrm{MP1}}$ is greater than that of $B_{\theta,\mathrm{MP2}}$ in the second quadrant. Therefore, the electric current must be passing through near MP1, which agrees with the case of upstream current (the right-hand side arrow in the figure).

It should be mentioned that the result of Fig. 4 (b) does not mean the third quadrant case is the dominant one, because we set a threshold value condition to pick up B_θ data. When the upstream electric current passes through outside the MP1 (MP2), $B_{\theta,\mathrm{MP2}}$ ($B_{\theta,\mathrm{MP1}}$) can be small due to the distance from the current and be smaller than the threshold value.

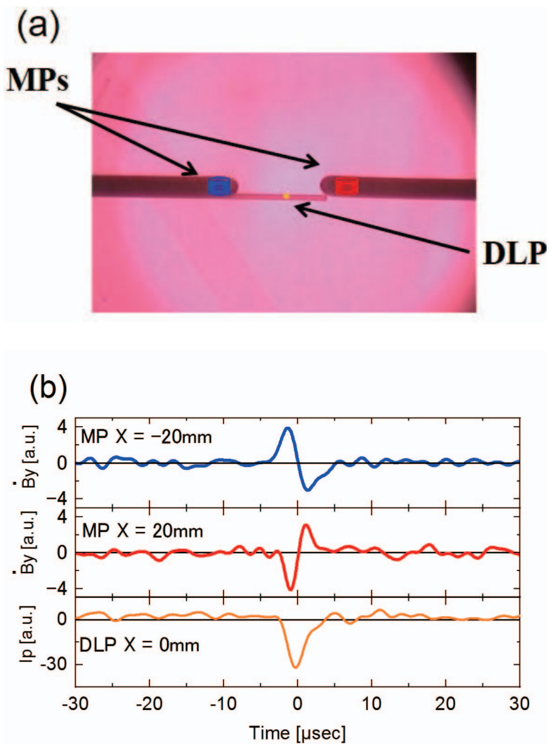

Fig. 5 (a) End-view image of the experimental arrangement. DLP is located at z = 1.175 m and x = 0 mm. MPs are located at z = 1.555 m and x = ± 20 mm. (b) Typical probe signals associated with a high-temperature bubble.

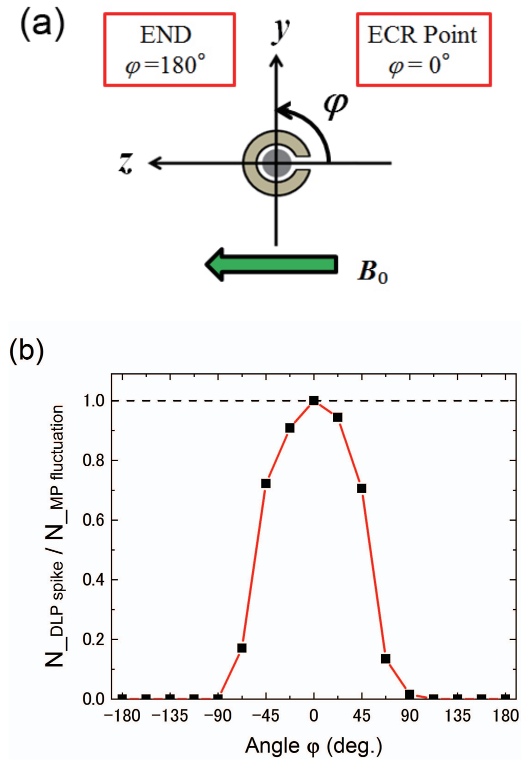

Fig. 6 (a) Cross-sectional view of DLP and coordinate system. φ is the angle of normal vector of probe surface with respect to z-axis. φ = 0 is set to upstream direction. (b) Angle dependence of the ratio of number of large amplitude negative spikes in DLP signal ($N_{\_DLP\,spike}$) to the number of large amplitude magnetic fluctuations ($N_{\_MP\,fluctuation}$).

4. Discussion

From the results shown in Sec. 3, we can build a hypothesis that the magnetic fluctuations are excited by transient upstream electric current flowing in the high-temperature bubble. In order to confirm the hypothesis, we performed a simultaneous measurement of electron flux and magnetic fluctuations. The experimental arrangement of a DLP and two MPs is shown in Fig. 5 (a), where the hole of the DLP was positioned at x = 0 mm and faced to upstream so as to detect the change in downstream electron flux, and two MPs were located at x = ±20 mm. Typical probe signals of single bubble event is shown in Fig. 5 (b). The polarities of magnetic fluctuations agree with the situation illustrated in the third quadrant of Fig. 4 (a). Moreover, a transient increase in downstream electron flux simultaneously takes place as seen in the bottom panel of Fig. 5 (b), which generates an effective upstream electric current. Although the change in ion flux was not measured in this experiment, it is not plausible that the ion flux plays an important role in the current that generates magnetic fluctuations discussed here. It is because the ion current measured with a Langmuir probe negatively biased at −90 V showed no noticeable change under the existence of the bubbles.

Next, we performed angle-resolved measurement of intermittent electron flux associated with magnetic fluctuation of which amplitude was larger than 40 μT by rotating the shaft of DLP as shown in Fig. 6 (a). The vertical axis of Fig. 6 (b) is the ratio of the number of large amplitude negative spikes in DLP signal to the number of large amplitude magnetic fluctuations simultaneously detected by two MPs. The detection threshold for the DLP signal was set to −30 mV (−0.6 mA). For each angle, the results of five different 100 ms time series were averaged. The typical number of large amplitude magnetic fluctuations in 100 ms time series was about 250, and the dispersion was less than 2%. When the angle φ = 0°, the hole of DLP faced to upstream so that downstream electron flux can be detected. Figure 6 (b) clearly shows that all large amplitude magnetic fluctuations were accompanied by large amplitude negative spikes in DLP signal. However, there is no negative spikes, i.e. intermittent enhancement of electron flux, when the hole of DLP faced to downstream (φ = 180°) even though the large amplitude magnetic fluctuations were excited. Slight spread of count seen within ± 45° is attributable to the aspect ratio of the hole (1 mm in diameter and 0.7 mm in depth) of DLP. Therefore, we can conclude that the magnetic fluctuations associated with the high-temperature bubbles are generated by the enhancement of downstream electron flux that forms an effective upstream current. This result also suggests that the velocity distribution function in the bubble is not symmetric one but an asymmetric one. Integrating this asymmetric velocity distribution function gives net downstream electron flux in the bubble.

5. Conclusion

We have observed magnetic fluctuations that are associated with high-temperature bubbles in an ECR plasma by magnetic probes. Relation between the polarities of magnetic fluctuations measured with two magnetic probes suggested that they were induced by upstream electric current. Angle-resolved measurement of electron flux using a directional Langmuir probe has revealed that enhancement of downstream electron flux takes place in the high-temperature bubble. This flux enhancement leads to an effective upstream current that induces magnetic fluctuations. Asymmetry of transient electron velocity distribution function has also been suggested. It is concluded that magnetic probe measurement in the present experiment has revealed a dynamic aspect of high temperature bubbles.

Acknowledgments

The authors thank Mr. K. Kanamoto (Kyushu Univ.), Mr. K. Furuta (Nagoya Univ.), Mr. Y. Kato (Kyushu Univ.), and Mr. E. Tanaka (Kyushu Univ.) for useful discussion and experimental assistance. This work was supported by JSPS KAKENHI (Grant No. 24540554) and NIFS Collaboration Research Program NIFS13KBAP016.

[1] K. Terasaka, S. Yoshimura and M.Y. Tanaka, Phys. Plasmas **25**, 052113 (2018).
[2] S. Yoshimura *et al.*, Europhys. Conf. Abstr. **36F**, P2.181 (2012).
[3] S. Yoshimura *et al.*, JPS Conf. Proc. **1**, 015030 (2014).
[4] K. Terasaka *et al.*, Rev. Sci. Instrum. **85**, 113503 (2014).
[5] S. Yoshimura *et al.*, IEEE Trans. Plasma Sci. **42**, 2554 (2014).
[6] S. Yoshimura *et al.*, Plasma Fusion Res. **10**, 3401028 (2015).
[7] M. Aschwanden, *Self-Organized Criticality in Astrophysics* (Springer, Berlin, 2011) Chap.5.
[8] K. Nagaoka *et al.*, J. Phys. Soc. Jpn. **70**, 131 (2001).
[9] S. Yoshimura *et al.*, J. Plasma Phys. **81**, 345810204 (2015).