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High-speed 2D measurement of edge turbulence phenomena with a fast camera in Heliotron J

N. Nishino [a,*], T. Mizuuchi [b], Z. Feng [c], S. Kobayashi [b], K. Nagasaki [b], H. Okada [b], Y. Torii [b], K. Kondo [d], F. Sano [b]

[a] *Graduate School of Engineering, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima 739-8527, Japan*
[b] *Institute of Advanced Energy, Kyoto University, Japan*
[c] *Southwestern Institute of Physics, Chengdu, China*
[d] *Graduate School of Energy Science, Kyoto University, Japan*

Abstract

Using *g*as *p*uff *i*maging technique (GPI) the filamentary structure in edge plasma was firstly observed in Heliotron J. A combination of GPI and simultaneous movable Langmuir probe measurement shows that filamentary structure identified the turbulent burst in edge plasma, which was reported already in Heliotron J. In low electron density ($<1 \times 10^{19}$ m^{-3}) the filamentary structure moves very fast, and its direction is the same as the $E_r \times B$ drift. On the other hand, in high electron density ($>2 \times 10^{19}$ m^{-3}) the motion of the filamentary structure is relatively slow, and typical lifetime of the filamentary structure is about 300–900 μs.

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1. Introduction

Recently the technique of the fast camera has made rapid progress and the fast camera enabled extensive to observe peripheral plasma behavior. In the previous work in Heliotron J, by using a combination method of a fast camera (Ultima-SE, Photron; http://www.photron.com/) and a small movable carbon target, a structure of a low frequency (5–6 kHz) edge plasma oscillation relating to the core plasma oscillation in high electron density ECH discharges was discussed [1]. However, no clear spatial structure of high frequency edge plasma turbulence was observed due to the shutter speed of 40 500 FPS (*f*rames *p*er *s*econd) and the sensor sensitivity. Recently, the spatial profile of turbulent burst was firstly observed in the edge plasma with a combination of a new fast camera with 105 000 FPS (fx-K4, NAC image technology; http://www.nacinc.com/) and a short pulse of directional gas puff in Heliotron J. Bright emission can be obtained by the local strong gas puff and it makes possible to take movies with very high

* Corresponding author. Fax: +81 551 5591310.
E-mail address: nishino@hiroshima-u.ac.jp (N. Nishino).

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time-resolution. The gas puff quantity was chosen by trial and error not to damage serious effects on plasma performance. The obtained images show that the turbulent burst has the filamentary structure. It seems to be along the magnetic field; also it moves across the magnetic field. Similar filamentary structure of the peripheral plasma was observed in Tokamak/ST [2–4], and some blobby structure was also reported even in a linear machine [5]. In Heliotron J, turbulent fluctuation with frequent bursts was already observed in the ion saturation current, which is measured by a movable Langmuir probe located near the observation area of the fast camera [6]. In this paper the features of the observed turbulence are reported.

2. Experimental setup

Heliotron J is a medium sized Heliotron device, and it has $L = 1/M = 4$ helical axis which can form various magnetic configurations [7]. To visualize the edge turbulence and to study the characteristics of turbulent burst, a fast camera, a directional gas puff and single movable Langmuir probe were used. The schematic of experimental setup for this experiment is shown in Fig. 1. A poloidal cross-section of Heliotron J plasma changes at toroidal section. In the figure, the poloidal cross-section of the standard magnetic configuration of Heliotron J is also shown. A directional gas puff is injected to plasma from the outside of the torus. A fast camera (FX-K4) views the plasma almost horizontally from the horizontal upper port at the same toroidal section of above gas puff. To avoid the effect of the magnetic field on the camera electronics, a fiber bundle (400×400 fibers, IG-154, Schott; http://www.us.schott.com/) and the telecentric optical system were used. Very low F number lenses ($F = 0.95$, $f = 25$ and 50 mm) were used for this measurement, and they enable us to operate the fast camera with up to 105 000 FPS (*f*rames *p*er *s*econd). The movable probe of which head diameter is 0.024 m was installed at the same toroidal section and it was inserted into the peripheral plasma from the horizontal lower port. The probe head has one molybdenum probe tip. The distance between the probe head and the last closed flux surface (LCFS) is about 0.02 m. The diameter and length of the probe tip are $0.0015^{\varnothing} \times 0.003\ \mathrm{m}^{L}$, respectively.

3. Experimental results and discussion

3.1. Visualization of edge turbulence

Fig. 2 shows test results of *g*as *p*uff *i*maging with 105 000 FPS for the low electron density plasma ($n_e = 0.51 \times 10^{19}\ \mathrm{m}^{-3}$) of the second harmonic ECH discharges. In all figures the filamentary structure was clearly observed. Time duration of each figure is about 9.524 μs. Fig. 2(d) shows the one filamentary structure hits the probe from the image of Fig. 2(c), and the ion saturation current by simul-

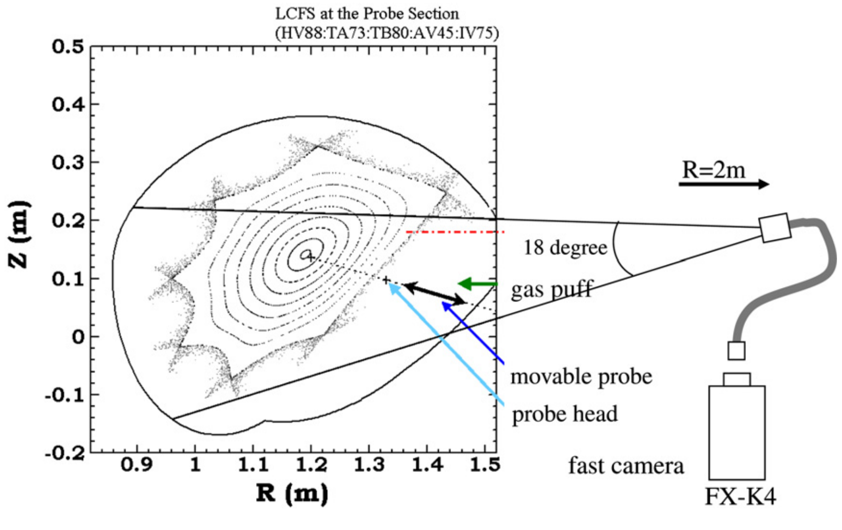

Fig. 1. Experimental setup in Heliotron J for gas puff imaging experiments. A directional gas puff and an object lens of the fast camera are set in the same toroidal section, also there is a single movable Langmuir probe at the same toroidal section.

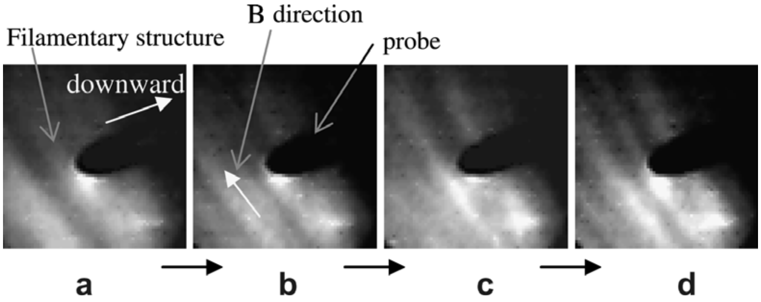

Fig. 2. Typical images of visible light emission. Filamentary structure of the burst was observed by the fast camera. The structure seems to be along the magnetic field. The arrow indicated the direction of B is shown in the left image. Time duration of each image is about 9.524 μs (105000 FPS).

taneous probe measurement show the burst signal at the same time. It means that ion density and/or electron temperature in the filamentary structure region are higher than those of the background plasma, and the motion of the filamentary structure produce the turbulent burst of the ion saturation current. Without gas puff period, it is difficult to observe any spatial structure in plasma because of the lack of the light intensity, and it was only observed that the light intensity in the vicinity of the probe head was frequently changed. The filamentary structure moves very fast in this shot, therefore the camera image with lower shutter speed does not show any spatial structure. At this time the gas puff was not calibrated, however, if the gas puff quantity is small (not too small to observe something), the plasma performance was not degraded. The region size of the recycling by the probe head was estimated by the contour plot of the camera image (not shown in the figure). This size was about 0.02–0.03 m, and it is almost the same as that of the probe head. Using the gas puff the contour plot became flatter. At that time the region size mentioned above was estimated by the contour plot subtracted averaged-background (=the time-averaged light intensities at each pixel), and its size was not changed by the gas puff. The obtained results show that the effect of the local recycling due to the probe head is lesser by the gas puff, but the size of the recycling region did not change. Therefore, the gas puff was operated with good condition and *g*as *p*uff *i*maging (GPI) in Heliotron J was successfully demonstrated even in low electron density plasmas.

3.2. Features of the filamentary structure

To study the features of the filamentary structure, a set of 'electron density scan' experiments were performed for the second harmonic ECH discharges. The plasma discharge began at 180 ms and ended at about 330 ms. In this discharge set the strong turbulent fluctuation period was observed in the ion saturation current and the camera images. The density waveforms of these discharges were reproducible, and the strong fluctuation period was observed at more than half numbers of the discharges. Fig. 3(a) shows typical waveform of the light intensity of the pixels near the probe position in the camera image, the ion saturation current and its ratio. In this figure, period I–IV are corresponding to the strong turbulent fluctuation period, 'normal' L-mode period, H-mode period, and after gas puff period, respectively. The end of period IV is somewhat ambiguous. According to the previous our work [1], the light intensity of the visible emission of the recycling region is mainly D_α, and also D_2 was used by the gas puff. Then almost visible emission taken by the fast camera is most likely electron excited D_α emission. The ratio of the intensity of D_α and the ion saturation current is $I_{h\nu}/I_{\rm sat} \propto n_0\langle\sigma v\rangle_{\rm ex}/\sqrt{T_{\rm e}}$, and using edge electron temperature (15–80 eV), the value of $\langle\sigma v\rangle_{\rm ex}/\sqrt{T_{\rm e}}$ term changes at most 16%. Thus, it is inferred that this ratio is the index of the local neutral density. For example, the ratio during period III is somewhat smaller than that of period II. Because the particle confinement of H-mode is better than that of L-mode in Heliotron J [8], the neutral particle density of H-mode in the scrape-off layer is expected to be smaller than that of L-mode. However, the variation of the ratio of H-mode is larger than that of L-mode. During period I the deviation of the ratio is more than two times larger than that of period II ('normal' L-mode), but the time-averaged value of this ratio in period I were only 20% large. The main gas puff system during period

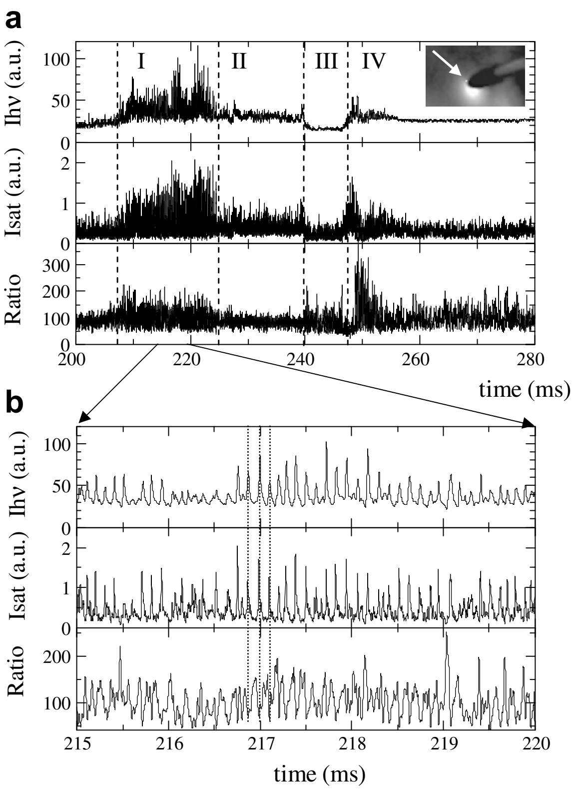

Fig. 3. Time evolution of the visible intensity $I_{h\nu}$ by the fast camera, I_{sat} and its ratio. Upper: Period I: Strong fluctuation period, II: 'normal' L-mode, III: H-mode, IV: After gas puff injection. The point of the light intensity taken in the image is shown in the top figure. Lower: Time elapsed figure during period I.

I provided a lot of gas to make dense plasma. Therefore, this ratio is used to estimate the neutral density condition at the same shot. During burst this ratio rapidly dropped. For example, many synchronous bursts in the light intensity and ion saturation current are shown in Fig. 3(b). According to the above inference the neutral density may decrease during the bursts. This decrease may be account for the increase of the electron impact ionization due to the hot particle flux. It is suggested that the burst will be at least the hot electron regions, and it is not clear the burst will be high electron/ion density region up to now.

One-dimensional analysis on the image are tried to study the motion of the filamentary structure. Fig. 4(b) shows the time evolution of the light intensity of each pixel on the line shown in Fig. 4(a). To see the motion of the filamentary structure easily, the light intensity of time-averaged background was subtracted at each pixel. The measurement

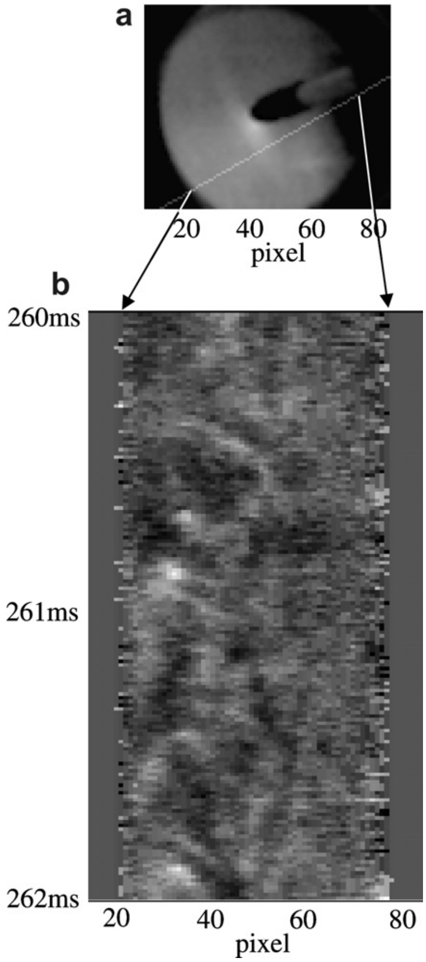

Fig. 4. Time evolution of the intensity of each pixel on the line shown in the image. Second harmonic ECH discharge and high electron density plasma with gas puff condition: (a) the line to take time evolution of the filament shown in typical camera image and (b) the intensity of each pixel on the line shown in (a).

condition of this shot was high electron density ($n_e = 3.4 \times 10^{19}\ m^{-3}$) plasma with the local gas puff. In Fig. 4(b), the bright position shows the location of each filamentary structure. In high electron density plasma the motion is not so fast. The filamentary structure sometimes changed its apparent speed in Fig. 4(b), and its motion was somewhat complex. Random motion of the filamentary structure across the magnetic field was already reported in Refs. [3,4]. They measure the filamentary structure along the magnetic field. Unfortunately our measurement is not along the magnetic field. Due to the various magnetic configuration of Heliotron J, it is not so easy to find the velocity of the filamentary structure. However, it is able to measure the lifetime of the filamentary structure, if it appears and disappear in the image as shown in Fig. 4(b). The average lifetime of the filamentary structure in high electron density plasma, which was very roughly estimated by eye, was about 600 μs, and the standard variation was about 300 μs. Total number of sample was 106, the standard error was about 10%. In low electron density ($n_e < 1.0 \times 10^{19}\ m^{-3}$) plasma of second harmonic ECH discharge, the motion of the filamentary structure was very fast, and it was unable to measure the lifetime of each filamentary structure. This was already shown in Fig. 2(a)–(d). In these figures, the filamentary structure moved downward. The radial electric field E_r of the peripheral region in STD Heliotron J plasma measured by Langmuir probe was negative [9] and the $E_r \times B$ direction is downward in the image. Therefore, it is expected that the motion of the filamentary structure is affected by the $E_r \times B$ drift in edge plasma [10]. The critical electron density for the H-mode transition is $1.2 \times 10^{19}\ m^{-3}$ in Heliotron J. The density that accounted for the motion difference obtained at this time was between 1×10^{19} and $2 \times 10^{19}\ m^{-3}$. This value was ambiguous due to the lack of data. The information on the turbulent fluctuation in Heliotron J is not enough. We do not have clear explanation of these bursts phenomena now. Edge fluctuation was studied in many machines experimentally and theoretically because it is widely believed that it related to the anomalous transport [11]. From this point of view, more information on edge fluctuation is desirable, and we believe firmly that a combination of GPI and simultaneous Langmuir probe measurement is the powerful tool for this study.

4. Conclusion

A combination of gas puff imaging technique (GPI) and a movable Langmuir probe was very powerful tool to study edge plasma behavior, and peripheral turbulence of the filamentary structure was observed using the fast camera with gas puff in Heliotron J. The camera images with very high frames per second revealed that each turbulent burst of the ion saturation current had a filamentary structure. This spatial structure is along the magnetic field, and it moves across the magnetic field. In low electron density ECH discharges the filamentary structure moved very fast and it was unable to see the generation and distinguish position in the image. However, in high electron density ECH discharges the motion of the filamentary structure could be seen in the image.

Comparison of the light intensity at the position near the probe in the image and the ion saturation current of the movable probe showed that turbulent burst seems to induce the particle flux. By this inference the particle flux during H-mode is somewhat smaller than that of L-mode. This is consistent with the previous result of Heliotron J.

Study on the turbulent fluctuation including burst in Heliotron J peripheral plasma is still under consideration and more quantitative research on the filamentary structure and/or fluctuation is desired. The experiments from this point of view will be performed in the near future.

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