# Measurement of Ion Temperature during the Intermittent Negative Spike in Floating Potential

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The ion temperature in an ECR plasma is determined from the ratio of wavelength-integrated spectra obtained using a spectrometer with sufficient time resolution. The ion temperature during the intermittent negative spikes in floating potential is extracted using the conditional averaging method. For the first time, we have successfully observed a decrease in ion temperature during intermittent events.



Keywords: ion temperature, high-temperature bubble, electron cyclotron resonance plasma, Doppler spectroscopy, conditional average

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Understanding intermittent phenomena in plasmas is an attractive topic. Negative spikes were observed in the floating potential of cylindrical plasmas, where plasmas were produced by electron cyclotron resonance (ECR) [1]. The spatial extent of the phenomena was elongated along the magnetic field line [2]. It emerged randomly in space and time and was sustained for a few to several tens of microseconds. Probe characteristics obtained using conditional averaging revealed that the electron temperature increases in the region where the phenomenon occurs. Changes in Doppler broadening in the ion line spectrum were also evaluated [3]. The results indicated a reduction in Doppler width, which intuitively suggests a decrease in ion temperature during the phenomena. Therefore, the phenomenon is interesting in terms of the energy transfer between electrons and ions and will be important to understand in general plasma physics. However, the previous work only mentioned the changes in the relative spectrum width. Absolute measurement of ion temperature during the intermittent event is required. In this paper, a calibration method for absolute ion temperature measurement is described. Then, the decrease in ion temperature during the intermittent phenomena in an ECR plasma is shown.

Experiments were performed in a linear plasma device, NUMBER [4] shown in Fig. 1(a). Helium plasma was produced by ECR in the magnetic beach configuration in one side of magnetic mirror. Typical electron density and temperature are $1 \times 10^{17}$ m$^{-3}$ and 10–30 eV, respectively. Fluctuation of the floating potential was measured by a Langmuir probe at the radial center and used as the condition of averaging the intermittent phenomena. Typical discharge is shown in Figs. 1(b) and (c). The magnetic field in the downstream region changes temporally (Fig. 1(b)). Frequent negative voltage spikes are observed in the floating potential, especially in $t$ = 10−30 ms (Fig. 1(c)). In the following analysis, a time range of $10 \leq t \leq 30$ ms is used.

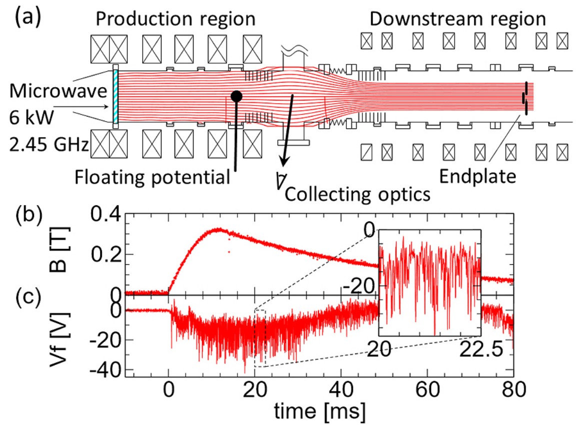


Fig. 1. (a) Schematic view of experimental setup in NUMBER. Typical temporal evolution of (b) magnetic field in the downstream region and (c) floating potential measured in the production region; an enlarged panel is also inserted.

The line emission of He II ($n$ = 3 − 4, $\lambda_0$ = 468.6 nm) was collected along a perpendicular line of sight passing through the center and was transferred to a high-resolution spectrometer. Details of the spectrometer are described in Ref. [3]. The spectrometer has two output ports with different slit widths, narrow ($2w$ = 50 μm) and wide (1,000 μm) slits. Photomultiplier tubes at the slits detect the photon intensities. Ratio $R$ of both outputs is used to evaluate the ion temperature $T_i$:

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$$R(T_{\mathrm{i}}) = \frac{\eta_{\mathrm{A}}}{\eta_{\mathrm{B}}} \frac{\int_{\lambda_0 - \Delta\lambda_{\mathrm{A}}}^{\lambda_0 + \Delta\lambda_{\mathrm{A}}} I(\lambda; T_{\mathrm{i}})\, d\lambda}{\int_{\lambda_0 - \Delta\lambda_{\mathrm{B}}}^{\lambda_0 + \Delta\lambda_{\mathrm{B}}} I(\lambda; T_{\mathrm{i}})\, d\lambda}, \tag{1}$$

where $\lambda$ represents wavelength. $\Delta\lambda_{\mathrm{A}} = 0.01$ nm and $\Delta\lambda_{\mathrm{B}} = 0.22$ nm are the half slit widths in the wavelength range for narrow and wide slits. $\eta_{\mathrm{A}}$ and $\eta_{\mathrm{B}}$ are the total efficiencies for narrow and wide slits, including port throughput and photomultiplier tube gain. The spectrum function $I(\lambda; T_{\mathrm{i}})$ includes the effects of Doppler broadening, instrumental width, and fine structure [5]:

$$I(\lambda; T_{\mathrm{i}}) = \pi^{-1/2} \lambda_{1/e}{}^{-1} \sum_{l=1}^{13} (2J_l + 1) A_l \exp\left[-(\lambda - \lambda_l)^2 / \lambda_{1/e}{}^2\right], \tag{2}$$

where $J_l$, $A_l$, and $\lambda_l$ are the total angular momentum quantum number, the Einstein coefficient, and the wavelength of the $l$-th fine structure, respectively. Gaussian line broadening $\lambda_{1/e}$ is expressed as a function of ion temperature: $\lambda_{1/e}{}^2 = 2k_{\mathrm{B}} T_{\mathrm{i}} \lambda_0{}^2 / Mc^2 + \delta^2$, where $k_{\mathrm{B}}$, $M$, $c$, and $\delta$ are the Boltzmann constant, the ion mass, the speed of light, and the instrumental width in wavelength, respectively. The effect of Doppler shift along the perpendicular line of sight is negligible. Zeeman effect is also negligible. The ratio $R(T_{\mathrm{i}})$ increases for low ion temperature because the numerator increases with a narrower Doppler width. However, we note that the ratio is finite even for zero Doppler broadening due to instrumental width.

Because the total efficiency $\eta_{\mathrm{A}}$ and $\eta_{\mathrm{B}}$ are different for each other, calibration standard is required for determining $\eta_{\mathrm{A}}/\eta_{\mathrm{B}}$. In this experiment, a neutral helium line emission (471.3 nm) is used under assumption that Doppler broadening for neutral atom is negligiblly small. Then $\eta_{\mathrm{A}}/\eta_{\mathrm{B}} = 0.719$ is experimentally determined; absolute value of ion temperature can be obtained from $R$-$T_{\mathrm{i}}$ curve indicated in Fig. 2.

In the experiment, a total of 2 s (100 shots of discharges) was acccumurated for each gas pressure condition. At a gas pressure $p = 0.045$ Pa, the ratio is $R = 0.374 \pm 0.008$, which deduces the ion temperature $T_{\mathrm{i}} = 3.52^{+0.36}_{-0.34}$ eV for the plasma without negative spikes in floating potential. Ion temperature during the negative spikes is obtained by the aid of conditional sampling. In the accumulated data over a total of 2 s, data points satisfying $(V_f - \mu)/\sigma < -2$ are extracted, where $\mu$ and $\sigma$ are the mean and standard deviation of the floating potential $V_f$ in every 2.5 ms interval. Then, a decreasing ion temperature, $T_{\mathrm{i}} = 1.90^{+1.26}_{-1.00}$ eV is obtained during the negative spikes in floating potential.

The same measurements were performed for other gas pressure conditions. Gas pressure dependence of the electron and ion temperatures are shown in Fig. 3. For ion temperature in Fig. 3(b), in the highest pressure case, error bar during the negative spikes is relatively large due to weak emission intensity. Because the excitation energy of the measured line emission ($\simeq$ 51 eV) is higher than the electron temperature, the emission intensity is sensitive to changes in the electron temperature. In the middle and low pressure cases, the ion temperature decreases during the negative spikes. This is the first observation of the ion temperature changes in intermittent phenomena characterized by negative spikes in floating potential. In addition, reduction of Doppler broadening in the line spectrum of helium ion was reported in Ref. [3] for another ECR device. Therefore the ion temperature decrease will be a common feature in the intermittent phenomena in ECR plasmas.

In summary, ion temperature in an ECR plasma is measured with sufficient time resolution to obtain the temperature during intermittent negative spikes in floating potential. A decrease in ion temperature during the intermittent event has been observed for the first time. The mechanism of the ion temperature decrease will be clarified in our future work. We have to note that the negative spike in floating potential is accompanied by an increase in electron temperature. In ECR plasmas, ions are heated by electron-ion Coulomb collision, the rate of which decreases with the increase in electron temperature. This is a possible mechanism. Another possible mechanism is increase of cold ions due to increasing electron collisional ionization rate. To quantitatively discuss these mechanisms, we will need the electron energy distribution during the intermittent phenomenon.

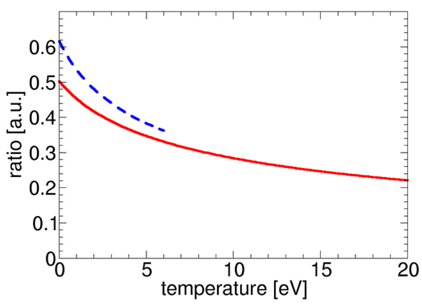


Fig. 2. Relation between ion temperature and the ratio $R$ for He II (468.6 nm, solid curve), and that between atom temperature and the ratio $R$ for He I (471.3 nm, broken curve) for slit width $2w = 50$ μm.

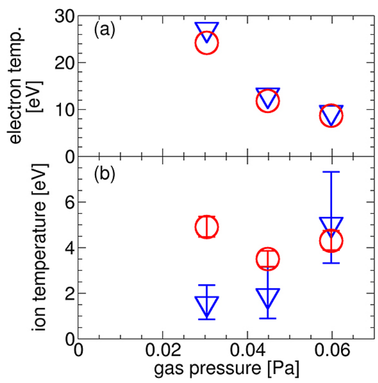


Fig. 3. Gas pressure dependence of (a) electron and (b) ion temperatures. Inverted triangle plot (▽) represents the temperature during negative spike in floating potential; circle (○) for steady state without the spike.

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