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Asymmetry of velocity distribution function and inhomogeneity-induced flow associated with neutral depletion structure in an ECR plasma

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A neutral depletion structure with strong inhomogeneity in the radial direction has been observed in an electron cyclotron resonance plasma. We have measured the velocity distribution function of neutrals with a high resolution laser-induced fluorescence system and examined the relationship between asymmetry of distribution function and flow induced by inhomogeneity. It has been revealed that the third order moment of distribution function, that is, skewness, is proportional to the inhomogeneity-induced flow, and a simple relation between the skewness and the normalized flow velocity has been obtained and confirmed in the experiment. *Published by AIP Publishing.*
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I. INTRODUCTION

Velocity resolution of laser-induced fluorescence (LIF) spectroscopy[1] has been greatly improved by using diode lasers.[2–10] Precise measurement of velocity distribution function has become possible in the experiments. We have measured the velocity distribution function of neutrals in an electron cyclotron resonance (ECR) plasma, and examined the relationship between asymmetric distribution function and flow generated by inhomogeneity.

In the usual theoretical treatment, flow generated by asymmetric distribution function has been analyzed by expansion approximation with respect to small deviation from the equilibrium distribution.[11] Since the conventional perturbative approach is based on the equilibrium distribution, the physical significance of skewed distribution function itself has been obscure so far. In this paper, we show that the third order moment of distribution function, that is, skewness, is the fundamental quantity that describes inhomogeneity-induced flow.

We have observed a neutral depletion structure in a cylindrical ECR plasma, which exhibits a strong inhomogeneity of density in the radial direction and a homogeneous profile in the azimuthal direction. This structure is considered to be suitable for examining the relationship between asymmetry of distribution function and inhomogeneity-induced flow. A high resolution LIF method[9,10] has been used to measure the distribution functions with velocity component parallel and perpendicular to the neutral density gradient. It has been found that the asymmetry of distribution function is generated in the direction of density gradient of neutrals.

To quantitatively characterize the asymmetric distribution function, we have utilized the third order velocity moment (skewness), and obtained a simple relation between the skewness and the flow generated by inhomogeneity, which has been confirmed in the experiment. It has been found that flow induced in an inhomogeneous plasma can be analyzed by using skewness of distribution function.

II. OBSERVATION OF NEUTRAL DEPLETION STRUCTURE IN AN ECR PLASMA

The experiment was carried out in the HYPER-I device at National Institute for Fusion Science.[12] The HYPER-I device consists of a cylindrical vacuum chamber (0.3 m in diameter and 2.0 m in axial length) and 10 magnetic coils, which is schematically shown in Fig. 1. A microwave (2.45 GHz) was launched from the high magnetic field side of a magnetic beach configuration. An electron cyclotron wave (right-hand circular polarized mode) was excited in the plasma and absorbed in the ECR layer.[13] There is no cutoff for electron cyclotron wave, and hence high density plasmas exceeding the critical density of ordinary wave were produced. In this experiment, an argon gas was used, and a steady state argon plasma was produced by ECR heating. The filling gas pressure was set at 7.5 mTorr. The typical electron density and electron temperature measured with a Langmuir probe were 5 eV and a few $\times 10^{18}\,\mathrm{m}^{-3}$, respectively, and the high-energy tail of electrons has not been observed at this pressure. The detailed description of the HYPER-I device is presented in Ref. 12.

In order to measure the velocity distribution function, a high resolution LIF method developed by Aramaki *et al.*[9] was used. The schematic diagram of the high resolution LIF system is shown in Fig. 2. An external cavity diode laser (DL100, TOPTICA) was tuned to 696.73 nm (vacuum) to excite the argon neutral atoms from a $4s[3/2]_2^{\mathrm{O}}$ energy level to a $4p[1/2]_1$ level, and the emission from the $4p[1/2]_1$–$4s[1/2]_1^{\mathrm{O}}$ transition, 826.68 nm (vacuum), was detected by a collection optics consisting of a convex lens and a photo multiplier tube

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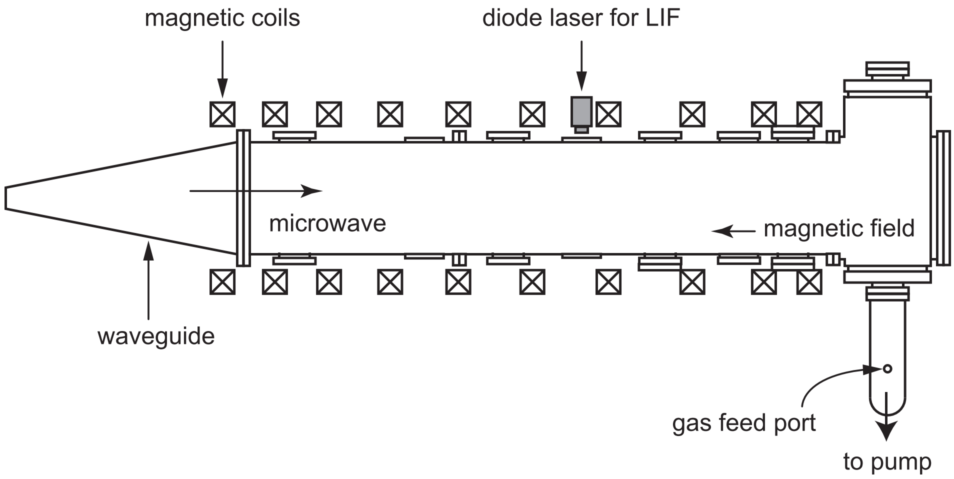

FIG. 1. Schematic diagram of the HYPER-I device.

(R3896, Hamamatsu). The spatial resolution of the LIF collection optics is about 2 mm, which is much smaller than the scale length of the depletion structure. The laser beam was modulated by an electro-optical modulator (LM0202P, LINOS) and a polarization beam splitter at 100 kHz, and the LIF signal was lock-in detected to improve the signal-to-noise ratio. The laser power was 17 mW, and the polarization of electric field was set to be parallel to the direction of magnetic field to avoid the effect of Zeeman splitting.[10] The saturated-absorption-spectroscopy (SAS) system was installed in the LIF system, and the Lamb dip was obtained on the SAS spectrum, the position of which was used as the frequency standard and also used as the velocity origin in the laboratory frame.

We have carried out the collisional-radiative (CR) model calculations to obtain the neutral density profile.[14–16] It has been confirmed that the excited atoms used in the LIF target are predominantly produced by the electron excitation collision from the ground state and that the recombining component can be neglected in our circumstance. Hence, the population of excited atoms is proportional to that of ground state, which makes it possible for us to evaluate the density profile by that of LIF intensity. Figure 3 shows the radial profile of neutral density. As in the figure, a neutral depletion structure is generated in the central region of the plasma. A strong inhomogeneity is present in the radial direction, while the constant profile has been observed in the azimuthal direction.

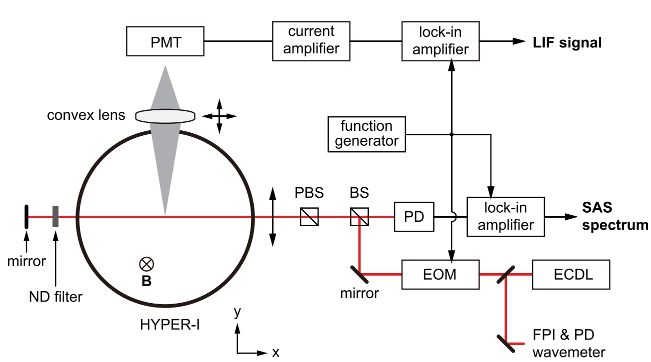

FIG. 2. Schematic diagram of a high resolution LIF system. ECDL: external cavity diode laser; EOM: electro-optical modulator; FPI: Fabry-Pérot interferometer; (P)BS: (polarization) beam splitter; PD: photo detector; PMT: photomultiplier tube, SAS: saturated-absorption-spectroscopy.

The distribution functions of radial velocity component (referred to as radial distribution functions in the following) have been measured with the laser beam propagating along the x-axis at a $y = 0$ vertical position, by changing the focal position of the collection optics, where the origin ($x = y = 0$) is set at the center of vacuum chamber. The distribution functions of azimuthal velocity component (referred to as azimuthal distribution functions in the following) have been measured along the y-axis, by changing the vertical position of the laser beam.

III. ASYMMETRY OF VELOCITY DISTRIBUTION FUNCTION IN A NEUTRAL DEPLETION STRUCTURE

The measured LIF spectra (velocity distribution functions) are shown in Fig. 4, in which the upper figures are the azimuthal distribution functions and the lower figures the radial distribution functions. The position of LIF measurement is schematically indicated in each figure. As seen in Figs. 4(a), 4(b), and 4(c), the azimuthal distribution functions show a good agreement with the Maxwellian distribution function (temperature 0.08 eV), which is indicated by the solid lines in the figure. On the other hand, the radial distribution functions are systematically skewed [Figs. 4(d) and 4(e)].

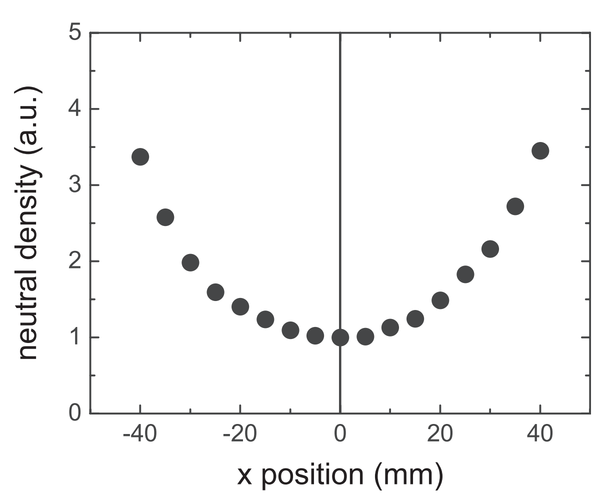

FIG. 3. Radial profile of neutral density in a neutral depletion structure. The position $x = 0$ is the center axis of vacuum chamber.

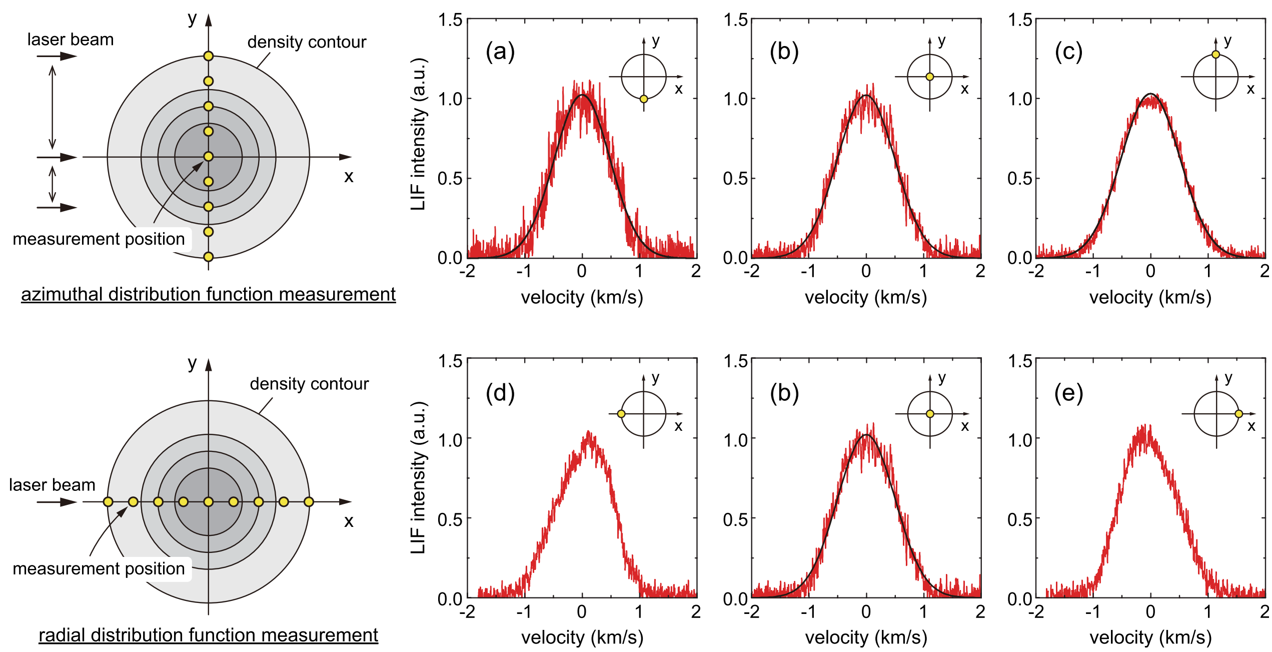

FIG. 4. Velocity distribution functions at different positions. Upper figures (a), (b), and (c): azimuthal distribution functions; lower figures (d), (b), and (e): radial distribution functions.

To quantitatively characterize the asymmetry of velocity distribution function, we utilize the third order moment (skewness), which is defined as

$$S = \frac{1}{\sigma^3}\int_{-\infty}^{\infty}(v-\bar{v})^3 f(v)\mathrm{d}v = \frac{1}{\sigma^3}\sum_{j_{min}}^{j_{max}}(v_j-\bar{v})^3 f_{\mathrm{LIF}}(v_j)\Delta v, \quad (1)$$

where the normalized velocity distribution function is denoted by $f(v)$ and the normalized LIF spectrum by $f_{\mathrm{LIF}}(v_j)$ ($\sum_j f_{\mathrm{LIF}}(v_j)\Delta v = 1$). The quantity $\bar{v}$ is the average velocity defined as $\bar{v} = \sum_j v_j f_{\mathrm{LIF}}(v_j)\Delta v$, and the quantity σ is the standard deviation. In calculating the skewness from the experimental data, the infinite integration of Eq. (1) is approximated by a finite integration, where j_{min} and j_{max} are so determined that the magnitude of LIF spectrum is larger than 1/10 of the peak value (10% offset). The integration has been executed with more than 10^4 data points and the velocity interval is $\Delta v = 0.4$ m/s.

Figure 5 shows the radial profiles of skewness; the closed circles and the closed rectangles are for the radial distribution functions and the azimuthal distribution functions, respectively. As seen in the figure, the skewness of radial distribution function takes non-zero values, while that of azimuthal distribution function vanishes. The experimental result indicates that the asymmetry of distribution function is generated in the direction parallel to the density gradient, suggesting that the inhomogeneity-induced flow is probably related to the skewness of distribution function.

IV. SKEWNESS AND NORMALIZED FLOW VELOCITY INDUCED BY INHOMOGENEITY

Figure 6 shows the radial profiles of inverse characteristic scale length of neutral density $L_n^{-1} = (1/n)(\partial n/\partial x)$ in Fig. 6(a), the radial flow velocity in Fig. 6(b), and the temperature in Fig. 6(c), which are calculated from the radial distribution functions. As seen in the figure, the flow velocity is highly correlated to the density scale length, while the temperature is fairly constant. Although asymmetry in distribution function is generated by inhomogeneity in both the density and temperature, the present result means that the asymmetry of distribution function is generated by density inhomogeneity.

According to the definition, skewness is generally expressed as

$$S = -3\frac{\bar{v}}{v_t} + \frac{\langle v^3\rangle}{v_t^3} - \left(\frac{\bar{v}}{v_t}\right)^3, \quad (2)$$

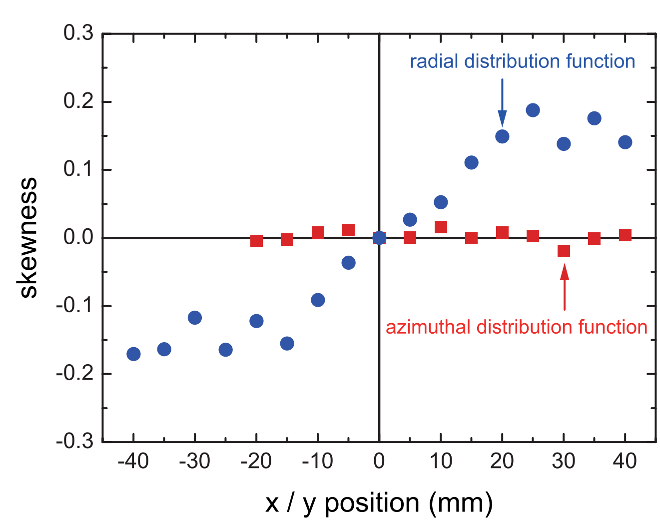

FIG. 5. Skewness of velocity distribution functions as a function of radial position with and without inhomogeneity. The circles and rectangles are for the radial distribution functions and azimuthal distribution functions, respectively.

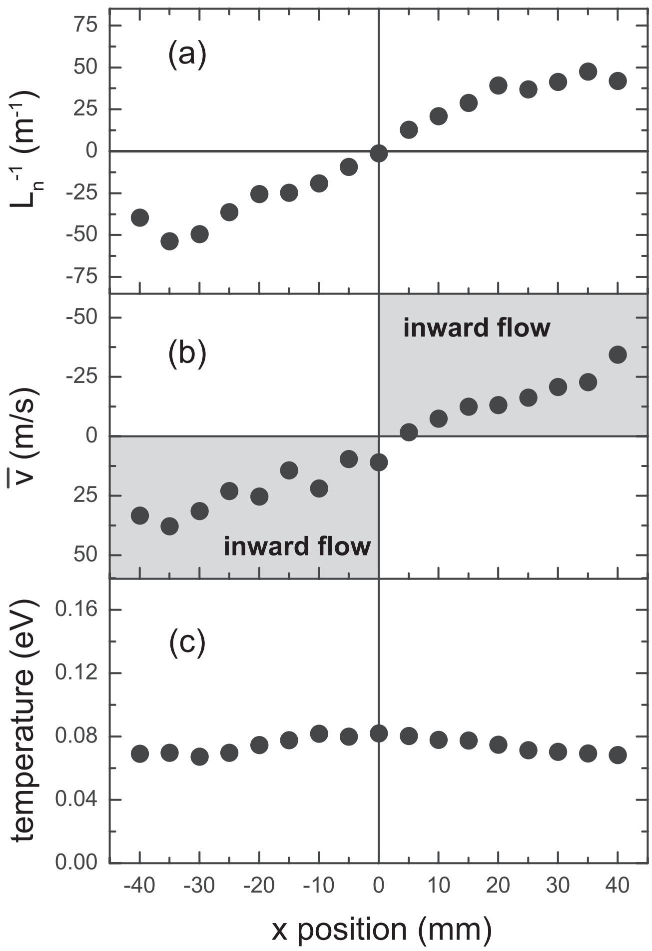

FIG. 6. Radial profiles of (a) inverse characteristic scale length of density, $L_n^{-1} = (1/n)(\partial n/\partial x)$, (b) radial flow velocity, $\bar{v}$, and (c) temperature.

where the standard deviation σ is approximated by the thermal velocity ($\sigma \approx v_t$) and $\langle v^3 \rangle = \sum_j v_j^3 f_{\rm LIF}(v_j)\Delta v$ is the third order moment in the laboratory frame. When the inhomogeneity is weak, the induced flow velocity is very slow compared with the thermal velocity ($\bar{v}/v_t \ll 1$). In such a case, the skewness is expressed by the first term of Eq. (2), and then we have a simple relation between skewness and normalized flow velocity as

$$\frac{\bar{v}}{v_t} = -\frac{S}{3}. \quad (3)$$

Figure 7 shows the normalized flow velocity as a function of skewness, and Eq. (3) is indicated by a solid line in this figure. There is a good agreement between Eq. (3) and the experimental data.

It is worth pointing out that skewness is a geometrical form factor to characterize asymmetric profile of distribution and that the relationship between the skewness and corresponding physical process has not been clarified yet. The present experiment has shown that the geometrical form factor of distribution function (skewness) is related to the flow generated by inhomogeneity.

We have observed a neutral depletion structure in an ECR plasma. There is a strong inhomogeneity of density in the radial direction. It has been found that the asymmetry of distribution function is generated in the direction parallel to the density gradient. The radial flow induced by inhomogeneity has been directly related to the skewness of distribution function. The present experiment has clarified the physical significance of the third order moment of distribution function and related the geometrical form factor to the dynamical property (flow) in an inhomogeneous system for the first time.

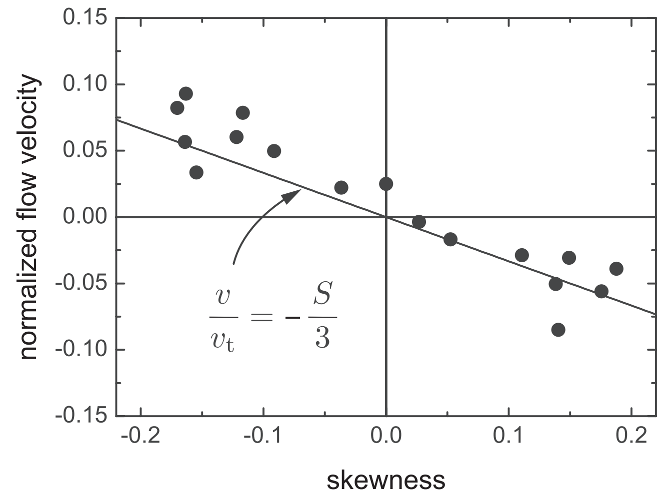

FIG. 7. Normalized flow velocity as a function of skewness. The solid line indicates Eq. (3).

V. CONCLUSION

We have precisely measured the velocity distribution function in an inhomogeneous neutral depletion structure generated in an argon ECR plasma. It has been experimentally found that asymmetry of distribution function is generated in the direction parallel to the density gradient, and the relation between skewness and inhomogeneity-induced flow is obtained. It is concluded that the skewness is the fundamental quantity that describes inhomogeneity-induced flow.

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