BRIEF COMMUNICATIONS

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Temporally and spatially resolved optical emission and electron energy distribution function related to ionization waves

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The variation of the electron energy distribution function (EEDF) to the radial direction is measured along the radially curved wave front of the ionization wave packets externally excited in a He positive column. The fluctuation of the high-energy tail caused by the wave is estimated from that of the radiation intensity.

In weakly ionized plasmas low-frequency fluctuations result in temporal fluctuations of the electron energy distribution function (EEDF). The ionization wave is one of the typical fluctuations in weakly ionized positive columns. There have been a few measurements[1–4] of the temporal variation in EEDF for the artificially controlled ionization wave packet, namely, the wave of stratification.[5] The wave causes the great temporal change in EEDF from its steady state, which has intrinsical deviation from the Maxwellian due to the inelastic collision between electrons and neutrals, eventually forming a double-humped EEDF in a time phase of strong electric field. Since the variation of EEDF is closely related to the fluctuation of radiation intensity, the simultaneous measurement of the temporal fluctuations in EEDF and the optical emission spectroscopically resolved may give useful information for the ionization wave.

In the present work we report simultaneous measurements of the ionization wave packet excited in a He positive column.

The glass discharge tube (diameter 5.5 cm, length 70 cm) used in the present experiment is identical to a previous one[6] except for installation of a tiny cylindrical Langmuir probe (0.2 mm diam and 3 mm length), which is movable to the radial direction, at $x=14$ cm (from the anode). An ionization wave packet is excited by applying 5 kHz sinusoidal burst voltage with 650 Hz repeating frequency to a wave-free He positive column at gas pressure $p=0.48$ Torr and dischange current $I_d=170$ mA through a tungsten-mesh grid installed at $x=60$ cm. In order to obtain the probe current of a certain time phase of the wave packet excited, the current i_e is sampled by 10 μsec width pulse with appropriate time delay for the burst voltage. The probe is swept by 0.1 Hz sawtooth voltage, so that the voltage-current probe characteristics is converted into the time-current one.

The detected i_e is secondarily differentiated by some conventional electric circuits. The differentiated i_e'' and the sawtooth voltage, which are digitized by a A/D converter with sampling width 4.88 msec and 12 bits resolution, are fed to a personal computer to compute the EEDF by the well-known Druyvesteyn method.[7] The details of the detection system have been previously reported.[8] The 388.9 nm spectral line (3^3p-2^3s) emitted from the column is detected by a slit monochromater on the position just installing the probe. The time-space (t–r) structure of the 388.9 nm intensity for the excited wave packet is reconstructed by computerized tomography technique (CT).[6,9] There was only small discrepancy between the wave radial profiles reconstructed by the CT[6] and measured by a Langmuir probe.[8] Phelps and Pack[10] reported that the optical absorption of 388.9 nm using an optical source of He capillary dischange tube is approximately equal to but no more than 4% for a dischange tube of few feet length. Their result shows that the He dischange plasma is optically thin enough to neglect the self-line absorption for the image reconstruction.

A large amplitude sawtoothlike waveform optically detected on the tube axis and its reconstructed t-r structure are shown in Figs. 1(a) and 1(c), respectively, where $\tilde{I}_t/I_0$, which is the ratio of the fluctuation to the steady state for the 388.9 nm line, $=0.48$. The fluctuations of the plasma potential $\tilde{V}_s$, the electron density, $\tilde{n}/n_0$, and the averaged electron energy, $\tilde{\bar{\epsilon}}/\bar{\epsilon}_0$, are shown in Fig. 1(b) as well. The values of $\tilde{n}$ and $\tilde{\bar{\epsilon}}$ are evaluated from $\tilde{n}=\int_0^\infty \tilde{F}(\epsilon)d\epsilon$ and $\tilde{\bar{\epsilon}} = \int_0^\infty \epsilon\tilde{F}(\epsilon)d\epsilon$ using the detected EEDF shown below. The excited ionization wave can be identified as the r varity,[11] which is the ion-guided wave, from the measured $E\lambda \cong 23$ V, where E and λ are the electric field and the wavelength of ionization wave, respectively. Thus the detected phase difference between $\tilde{n}$ and $\tilde{\bar{\epsilon}}$ agrees approximately with that predicted by the two-fluid theory for electrons and ions[12] in spite of the nonlinear wave. Figure 2(a) shows the time and radial variation of the EEDF detected on the tube axis for two time phases labeled by I and K in (a) are shown in (b) and (c), respectively. In the time phase of the large electric field,

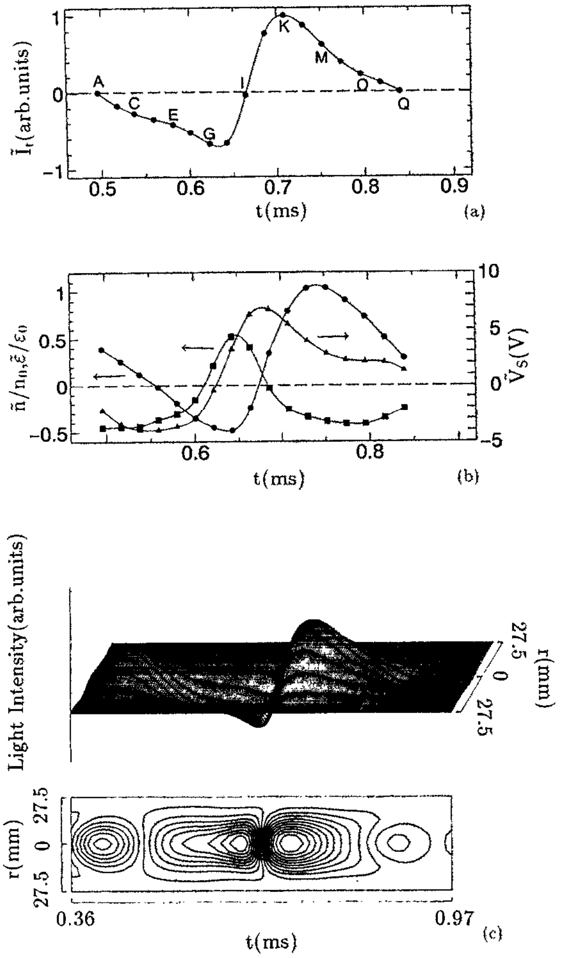

FIG. 1. Temporal and spatial variations of the excited wave packet. (a) The fluctuation of the 388.9 nm spectral line detected on the tube axis. (b) The fluctuations of $\tilde{n}/n_0$(●), $\tilde{\epsilon}/\epsilon_0$(■) and $\tilde{V}_s$(▲) detected at $r=0$. (c) The r-t reconstructed structure and its contour for the 388.9 nm spectral line.

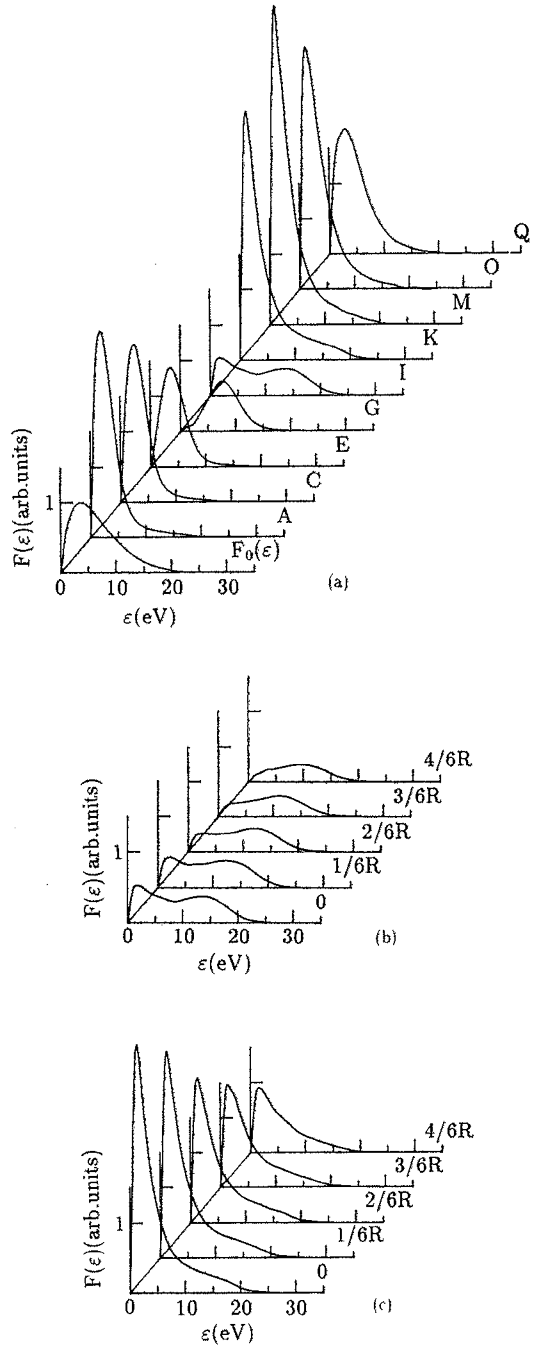

FIG. 2. Variations of EEDF. (a) $\tilde{F}(\epsilon)$ at $r=0$. The time phases labeled from A to Q are shown in Fig. 1(a). (b) and (c) The variations of $\tilde{F}(\epsilon)$ to the radial direction corresponding to I and K, respectively.

electrons are accelerated as shown by G and I in Fig. 1(a), forming a double-humped $F(\epsilon)$, while in the time phase of the large positive $\tilde{V}_s$ a large amount of slow electrons are trapped, resulting in a shift of the bulk $F(\epsilon)$ to the lower energy. The Druyvesteyn method to detected the EEDF can be applied to our steady-state plasma of $n_0=(2\sim3)\times10^{10}/\text{cm}^3$ with high accuracy because of the isotropic plasma. The strong anisotropy in plasma such as an beam one can cause even some negative values in the EEDF as previously discussed.[13] Our wave electric field is not so strong to produce such a value, thus allowing us to apply the method to all wave phases with small error.

As is known, since the wave front is convex toward the anode,[9] the radial variation of the EEDF is detected with an appropriate time-delay along the wave-front curvature evaluated from the r-t wave structure. The large amplitude wave causes some peculiar radial variation in $F(\epsilon)$, some of which are shown in (b) and (c). The EEDF $F(\epsilon)$ nearby the tube wall is not detected with good resolution, so only $F(\epsilon)$ from $r=0$ to $r=4/6R$ is shown, where the tube axis is $r=0$ and R the tube radius. In the time-phase I, the higher-energy part shows a little reduce to the radial direction, while the lower-energy part reduces rapidly, thus remaining the higher part of the double-humped EEDF at $r=4/6R$. On the contrary, the EEDF $F(\epsilon)$ in the time-phase K reduces its amplitude to the radial direction, because there are a large amount of trapped low-energy electrons. The radial variation shows that the low-energy electrons play a main role for the ambipolar diffusion in a plasma composed of two electron temperatures as discussed previously.[14]

The 388.9 nm spectral intensity I is expressed as,[15]

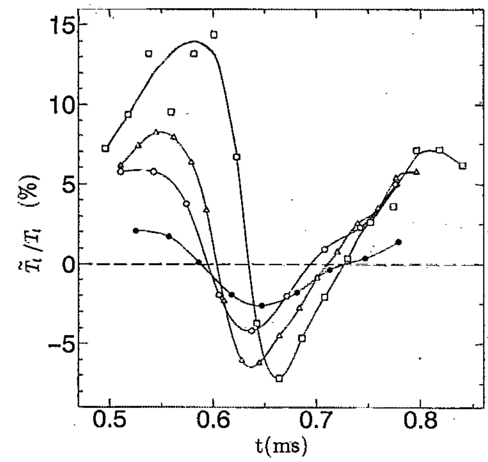

FIG. 3. Temporal variation of the ratio of $\tilde{T}_t/T_t$, where ● is $\tilde{I}_t/I_0=0.1$, ○0.22, △0.33, and □0.48.

$$I=C\int_{\epsilon_1}^{\infty} Q(\epsilon)\,\sqrt{\epsilon}F(\epsilon)d\epsilon, \quad (1)$$

where $Q(\epsilon)$ is the direct excitation cross section to 3^3p, ϵ_1 the excitation energy and C the constant. In weakly ionized plasmas the high-energy tail decreases due to the inelastic collisions between electrons and neutrals, then enabling us to approximate the steady-state EEDF by two Maxwellians.[14] The high-energy part of the EEDF $F_h(\epsilon)$ can be evaluated from the high-electron temperature T_t as follows:

$$F_h(\epsilon)=\frac{F(\epsilon_1)}{\sqrt{\epsilon_1}}\exp\left(-\frac{(\epsilon-\epsilon_1)}{T_t}\right)\sqrt{\epsilon}, \quad (2)$$

where $\epsilon > \epsilon_1$. Then the radiation intensity I_t is expressed as

$$I_t=C\int_{\epsilon_1}^{\infty} Q(\epsilon)\epsilon\frac{F(\epsilon_1)}{\sqrt{\epsilon_1}}\exp\left(-\frac{(\epsilon-\epsilon_1)}{T_t}\right)d\epsilon. \quad (3)$$

Since it is difficult to detect directly the fluctuating $\tilde{F}_h(\epsilon)$ over a wide electron–energy range with good resolution, the fluctuating $\tilde{T}_t$ is estimated from the fluctuation of the 388.9 nm spectral intensity $\tilde{I}_t$. The 388.9 nm intensity, which corresponds to the transition of 3^3p-2^3s, is used here by taking account of the following: (1) There is only a cascade transition to 2^1s except for that to 2^3s; (2) the transition probability to 2^3s is much larger than that to 2^1s; and (3) the 2^3s state, which is metastable, has strong influence on the ionization wave. The ratio of $\tilde{T}_t/T_t$ is determined by artificially varying T_t so as to fit the calculated $\tilde{I}_t/I_t$ with the detected one as shown in Fig. 3. The amplitude of $\tilde{T}_t$ is much smaller than $\tilde{I}_t$ even for the large amplitude wave, in spite of the large variation of the bulk EEDF. The time phase of $\tilde{T}_t$, which is preceded from $\tilde{\bar{\epsilon}}$ but delayed from $\tilde{I}_t$, may be caused by the metastable. Further investigations will be expected the time phase of the metastables which play an important role.

In conclusion the temporal and spatial variations of the EEDF are detected for the ionization wave packets externally excited in the wave-free He positive column. The large amplitude wave causes drastic change in EEDF, eventually forming a double-bumped one at a certain time phase corresponding to the strong electric field. The EEDF variation to the radial direction is measured along the radially curved wave front. The lower-energy part of the double-bumped EEDF reduces its amplitude to the tube wall more rapidly than the higher-energy one. The fluctuation of the high-energy tail caused by the ionization wave is estimated from that of the radiation intensity. The time phase of the fluctuation is preceded from the averaged electron energy, but delayed from the radiation intensity.

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