Plasma density profile influence on electron cooling and plasma density decay in early afterglow of low pressure argon plasmas

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Abstract: The spatio-temporal evolution of the electron density and the electron temperature in early afterglow are investigated by both Langmuir probe measurement and a fluid model in capacitively coupled argon discharges within the pressure range of 5 ~ 90 mTorr. It is found that, depending on the discharge conditions, the plasma density profile and its evolution can have a significant influence on the plasma density decay rate in the afterglow. As a result, electron cooling will also be affected due to diffusive cooling mechanism. This influence from different plasma density profiles is investigated at various gas pressures. The measured evolution of the plasma density in the afterglow are compared with the modeling results in this work as well as those from other different models.

Keywords: afterglow, density profile, electron cooling, Langmuir probe

1. Introduction

In the early afterglow when the electron temperature is much higher than the ion temperature, diffusion is the dominating process for the density and energy loss of the charged particles [1] in noble gas low pressure discharges. This period is characterized by fast plasma density decay and rapid electron cooling, which attracts constant attention for many years [2-5].

A volume-averaged (global) model is proposed to describe electron cooling and plasma density decay in an afterglow for different noble gases at low pressure [2-4]. From this model the time evolution of the electron temperature and the plasma density in the afterglow can be obtained. The model assumes plasma density is spatially uniform in the bulk and drops sharply at edge, which is appropriate for collisionless discharges. Celik et al [5] improves this global model by considering the plasma density spatial profile, and the model predicted electron cooling rate agrees well with the measured results. However, a constant plasma density profile in the afterglow was assumed and this may not be the case under different discharge conditions. In fact, depending on the discharge conditions, the spatial distribution of the plasma density in the afterglow can have various profiles and can change with time. It is expected that different plasma density profiles and their time-evolution have a significant impact on the rate for both plasma density decay and electron cooling. This effect is investigated in this work.

2. Experimental setup

The experimental configuration is given in figure 1. The pulsed rf power system consists of an rf amplifier (150A250, Amplifier Research Inc.), an arbitrary function generator (DG4162, Rigol Inc.), and a digital delay generator (DG645m, Stanford Research Systems Inc.). The experiments are carried out in a pulsed noble gas (argon, krypton and xenon) CCP discharges at low pressure (10~40 mTorr). The rf frequency is 60 MHz unless stated otherwise. The peak rf power is 100 W. The pulse repetition rate and the duty cycle are 3 kHz and 15%, respectively. The two dielectric discharge electrodes have a diameter of 30 cm and a gap of 5 cm.

A 77 GHz microwave interferometer is applied to obtain the line-integrated electron density through the discharge center. A single Langmuir probe SPL2000 (Plasmart, Inc.) is applied to obtain the temporally resolved electron density and temperature in the afterglow. The Langmuir probe can move in both radial and axial direction for the spatially resolved measurement. The probe tip is made of a tungsten wire with the length of 10 mm and the diameter of 0.06 mm. The ceramic probe holder for the probe tip has a diameter of 1 mm and a length of 17 cm. No choke or
compensation electrode is used on the Langmuir probe since there is no rf distortion in the afterglow.

3. Fluid Model

A fluid model is developed in this section to describe the evolution of the electron density and the electron temperature in early argon afterglow at low pressure. The electron energy distribution function (EEDF) is assumed to be Maxwellian. The electron temperature is assumed spatially homogenous based on the nonlocal theory [6]. Assume the plasma is generated between the two parallel plates with the diameter much larger than the gap distance. Therefore only the axial variation in the plasma density is considered in this model.

In the quasi-neutral region of the afterglow, the time-resolved ambipolar diffusion equation for the plasma density \( n \) is

\[
\frac{\partial n}{\partial t} = \frac{\partial}{\partial z} \left( D_n \frac{\partial n}{\partial z} \right), \quad \left( \frac{L}{2} \leq z \leq \frac{L}{2} \right)
\]

(1)

Here \( z \) is the axial coordinate between the discharge electrodes. \( D_n = \mu_i (T_e + T_i) \) is the ambipolar diffusion coefficient. \( \mu_i = 4.3 \times 10^{21} \text{ (V}^{-1} \text{m}^{-1} \text{s}^{-1}) \) \( n_g \) is the argon number density. Notice that, \( \mu_i n_g \) is taken as a constant which is valid in low reduced field condition. This condition is satisfied in the afterglow. \( T_e (\sim 0.026 \text{ eV}) \) is the ion temperature. \( e_0 \) is the electron charge. \( T_e \) is the effective electron temperature. \( L \) is the length of the quasi-neutral region. The gap length \( L \) is 5 cm. The boundary condition for equation (1) is given by the Bohm flux:

\[
-D_n \frac{\partial n}{\partial z} = n_0 c_s
\]

(2)

Here \( n_0 \) is the plasma density at the sheath boundary. \( c_s = [e_0 (T_e + T_i)/M_i]^{1/2} \) is the ion sound speed. \( M_i \) is the argon ion mass.

The one dimensional fluid equation for the electron temperature \( T_e \) evolution in the afterglow is [7]

\[
\frac{\partial}{\partial t} \left( \frac{3}{2} n T_e \right) \approx -\frac{\partial}{\partial z} \left( \frac{5}{2} T_e \Gamma_e \right) - \Gamma_e E
\]

(3)

where \( \Gamma_e \) is the electron flux, \( E \) is the electric field. The right hand side of equation (3) represents two processes leading to electron cooling. The former process is caused by electron thermal diffusion. This process is favored by energetic electrons due to their high diffusion rate. The second process represents the electron energy loss associated with the ion-pulling due to ambipolar field. Averaging equation (3) in the bulk region, one obtains

\[
-\frac{1}{T_e} \frac{d T_e}{d \tau} \approx \frac{2 n_0 c_s}{\langle n \rangle L} \times \frac{2}{3} \left( 1 + \frac{\Delta \Phi}{T_e} \right)
\]

(4)

In summary, the electron density and the electron temperature evolution in the afterglow can be obtained by solving equations (1) and (3). The values of the electron temperature and the electron density measured by the Langmuir probe in the early afterglow are used as initial conditions.

In the argon afterglow at low pressure (8–14 mTorr), Shin et al [4] and Celik et al [5] use their models to predict the electron cooling rate. In one dimensional case, both of their models can be expressed in the same form as equation (3). However, the treatment on the density decay time \( \tau_c \) is different. Both of these two other models have imposed certain constraint on the evolution of the density profile. In Shin et al’s global model, \( \tau_c \) is calculated by using a constant boundary-to-center density ratio \( h_i \):

\[
\tau_c^{-1} = \frac{2 h_i c_e}{L}
\]

(5)

In Celik et al’s fluid model, \( \tau_c \) is calculated by assuming that the plasma is in the fundamental diffusion mode at all times in the afterglow:

\[
\tau_c^{-1} = D_n \left( \frac{\pi}{L} \right)^2
\]

(6)

While in our model, the evolution of the plasma density profile as well as \( \tau_c \) are obtained by solving the diffusion equation (1). Under a given discharge condition, \( \tau_c \) has to be calculated numerically and there is no analytical expression for this quantity.

4. Results And Discussion

The electron temperature \( T_e \) can be obtained from Langmuir probe measurement by using the Druyvesteyn method [7], which is the so-called "effective electron temperature" (Te-Eff). However, when \( T_e \) is very low, this method will significantly overestimate the effective electron temperature. This is because usually there is a gap between the measured EEPF peak and the zero point of the electron energy axis, due to the resistance in the probe measurement circuit. In this work, the gap is about 0.2 eV. Therefore, when \( T_e \) is smaller than 0.2 eV, the influence of this gap on the obtained effective electron temperature can be significant. In order to avoid this effect, the reciprocal of the EEPF slope at low energy part is used in this work to determine the electron temperature, which is the so-called "local temperature" (Te-Local).

The plasma density at the discharge center (nC) can either be obtained from Langmuir probe measurement using the Druyvesteyn method [7], or obtained from microwave interferometer measurement using the radial density profile measured by the Langmuir probe.

Figure 2 shows the comparison between the measured and the model predicted evolution of the electron temperature and the plasma density in the afterglow at 10 and 40 mTorr. It can be seen that electron cooling and plasma density decay is slower at higher pressure. Besides, in the late afterglow (>100 μs), the electron temperature should be represented by Te-Local rather than Te-Eff, due to the existence of the gap in the measured EEPF. Notice that, the model results at high pressure may not be accurate due to the assumption of the Bohm velocity at the sheath boundary. Therefore, it can be expected that the difference between our model results and the measurement would increase with pressure.
The measured and the calculated evolution of the electron temperature $T_e$ (left) and the plasma density $n_C$ (right) at the discharge center in the afterglow at two pressures. (a) and (b) correspond to the gas pressure of 10 and 40 mTorr. The error bars denotes the random error estimated by repetitive acquisition.

In general, the plasma density profile is non-uniform and time-dependent in the afterglow. With the diffusion equation, the profile can be expressed by the sum of an infinite number of eigen-modes. Even though high order modes decay much faster than the low order modes [7], both the zeroth and the first mode (the so-called fundamental mode) should be retained to describe the profile evolution in the afterglow. Figure 3(a) shows three typical density profiles in the afterglow under different discharge conditions. A parameter $\alpha$ is defined to characterize these profiles:

$$\alpha \equiv -\frac{1}{L} \left[ \frac{1}{n_0} \frac{\partial n_0}{\partial z} \right] = \frac{D_i}{L_c} \approx \frac{\lambda_i}{L} \sqrt{\frac{T_e}{T_i}}$$

(7)

Here $\lambda_i$ is the ion mean free path. The physical meaning of $\alpha$ is the ratio of the characteristic decay length of the plasma density at the boundary to the discharge scale $L$, as is shown in figure 3(a). Equation (7) shows that the value of $\alpha$ is basically determined by two ratios: $L/\lambda_i$ and $T_e/T_i$. The contour plot of $\alpha$ versus these two ratios is given in figure 3(b). When $\alpha$ is large (e.g., $>1$), the plasma density is nearly uniform in the bulk region. In this case, the zeroth mode is dominant over the first mode. While $\alpha$ is small (e.g., $<0.01$), the density profile can be well described by the fundamental mode alone. In the transition regime (0.01<$\alpha$<1), both the zeroth and the fundamental mode should be considered.

If both the pressure and $T_e$ as a function of time are known, the parameter $\alpha$ can be used to characterize the plasma density profile evolution in the experiment. When pressure is low (10 mTorr), the parameter $\alpha$ is ~0.6 in the early afterglow ($T_e$~1 eV) and decreases to 0.15 in the late afterglow ($T_e$~$T_i$). This indicates the contribution to the density profile from the zeroth mode is significant at all times in the afterglow. While at high pressure (90 mTorr), $\alpha$ is ~0.07 in the early afterglow ($T_e$~1 eV) and decreases to 0.02 in the late afterglow ($T_e$~$T_i$). Thus the first mode dominates over the zeroth mode at all times. These predictions of the plasma density profile evolution are consistent with the measurement results, as shown in figure 4. In this figure, the comparison between the measured plasma density profiles and the calculated results at different time in the afterglow at three pressures (10, 40 and 90 mTorr) is given. Also presented is the first mode profile in black solid line as a reference. It can be seen that at 10 mTorr, the measured profile indicates that the contribution from the zeroth mode is significant, even in the late afterglow (100 us). At 90 mTorr, the measured profiles at all times can be well represented by the first mode.

Fig. 2. The measured and the calculated evolution of the electron temperature $T_e$ (left) and the plasma density $n_C$ (right) at the discharge center in the afterglow at two pressures. (a) and (b) correspond to the gas pressure of 10 and 40 mTorr. The error bars denotes the random error estimated by repetitive acquisition.

Fig. 3. (a) Physical meaning of the parameter $\alpha$. (b) The contour plot of the parameter $\alpha$.

Even though using the fundamental mode alone may introduce significant error in the description of the density profile evolution at low pressure, this will not be a serious problem if the plasma dimension $L$ is large. In fact, under the experimental condition in Celik et al [5] (1 Pa, $L$~50 cm and $T_e$=1 eV), their density profile can be well described by the first mode assumption. This is because $\alpha$~0.07 in their experiment. On the other hand, in Shin et al’s experiment [4] (14 mTorr, $L$~4 cm and $T_e$~1 eV), one obtains $\alpha$~0.6, hence the uniform plasma (i.e., zeroth mode) can be a good assumption in their model.
Fig. 5. Comparison between the measured and the calculated plasma density ($n_e$) evolution at the discharge center in the afterglow at 10 mTorr in (a) and 90 mTorr in (b). “Probe” and “MWI” denote the measured results by Langmuir probe and microwave interferometer, respectively. The pink dash lines show the model results with the fundamental mode assumption. All the measured results are from figure 2(b).

However, in this work $L \approx 5$ cm. The gas pressure changes in the range 5~90 mTorr and the measured $T_e$ is in the range of 0.1~1.5 eV. Thus the value of $\alpha$ varies in the range of 0.02~1.3. Therefore, in order to describe the density profile for all conditions, it is important to include both the zeroth and the first mode. The measured and the calculated plasma density evolution in the afterglow are compared at 10 mTorr in figure 5(a) and at 90 mTorr in figure 5(b). It can be seen that our model results (in blue line) agree with the measurement at both pressures. On the other hand, the model results (in pink line) with the first mode assumption are also presented in figure 5. It shows that at 10 mTorr, this model gives a much faster decay compared with the measurement. This is because at low pressure, the first mode assumption gives a larger gradient of the plasma density compared with the measurement (figure 4(a)), leading to a higher diffusion loss rate. While at 90 mTorr the results of this model agree with the measurement, since the first mode approximation is valid at high pressure (figure 4(b)). In addition, the green lines in figure 5 represent the global model results. It shows that at 10 mTorr the global model results agree with the measurement. While at 90 mTorr, the global model gives a much faster decay compared with the measurement. This indicates that in the afterglow the boundary-to-center ratio $h_1$ is more appropriate to be used at low pressure.

5. Conclusions

The spatiotemporal evolution of the electron density and energy is experimentally investigated and it can be reproduced by a simple fluid model in the afterglow of noble gas. At the initial phase of a collisionless afterglow, the diffusion process is so strong that the plasma density is large at the bulk-sheath boundary, and the zeroth diffusion mode should be considered for the plasma density profile. In this case, using the fundamental diffusion mode to approximate the density profile will cause a large error on the estimation of the electron density decay rate, especially in the early afterglow.

6. References


7. Acknowledgements

The author is deeply indebted to Professor Uwe Czarnetzki, Drs Tsanko V Tsankov, Xi-Ming Zhu and Mr Wen-Cong Chen, Zhen-Bin Wang for their very helpful comments. The work is supported in part by the National Natural Science Foundation of China under Grant No. 10935006 and the Advanced Micro-Fabrication Equipment Inc.