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Effects of discharge current and voltage on the high density of metastable helium atoms*

Feng Xian-Ping(冯贤平)[a)†], D Andruczyk[b)], B W James[b)], K Takiyama[c)], S Namba[c)], and T Oda[d)]

[a)] *Department of Physics, Donghua University, Shanghai* 200051, *China*
[b)] *School of Physics, University of Sydney, NSW* 2006, *Australia*
[c)] *Graduate School of Engineering, Hiroshima University, Hiroshima* 739-8527, *Japan*
[d)] *Faculty of Engineering, Hiroshima Kokusai Gakuin University, Hiroshima* 739-0321, *Japan*

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Both hollow-cathode and Penning-type discharges were adopted to excite helium atoms to a metastable state. Experimental data indicate that Penning discharge is more suitable for generating high fractions of metastables in a low-density helium beam for laser-induced fluorescence technique in measuring electric fields at the edge of a plasma. The metastable density increases with increasing helium gas pressure in the range of 1.33×10^{-2}–66.7Pa. The highest metastable density of $3.8\times10^{16}\mathrm{m}^{-3}$ is observed at a static gas pressure of 66.7Pa. An approximately linear relationship between the density of metastable helium atoms and the plasma discharge current is observed. Magnetic field plays a very important role in producing a high density of metastable atoms in Penning discharge.

Keywords: Penning discharge, hollow-cathode discharge, metastable atoms, electric field
PACC: 3150, 3440, 5270

1. Introduction

Measurements of electric fields in high-temperature magnetically confined plasmas have been confined to large tokamaks with high-energy neutral hydrogen beams for plasma heating. The latter has fortuitously provided a means for measuring current profiles based upon the motional Stark effect. With some modifications of this diagnostic it has been possible to measure also the radial electric field in the plasma. It is, however, important to measure the radial fields in stellarator-like devices such as H-1 where confinement is achieved without the use of a toroidal current.[1,2] As H-1 does not have a high-energy neutral hydrogen beam for plasma heating, another measurement technique is required. It is proposed to use laser-induced fluorescence (LIF) on a pulsed, supersonic helium metastable beam[3,4] technique to measure the plasma internal electric field in H-1. Preliminary studies[5,6] have been conducted but results indicate that a metastable density $n_{2\,^1\mathrm{s}} > 1\times10^{16}\mathrm{m}^{-3}$ is needed in order to detect the electric field. Currently, two types of discharge devices have been used for producing high-density of the metatstable helium atoms.

In 1997 Schoenbach *et al*[7] studied quite extensively the hollow-cathode discharge (HCD) in high-pressure discharges and their temporal development. dc measurements have been made of the metastable density by Takiyama *et al.*[8] Indeed, a density up to $1\times10^{16}\mathrm{m}^{-3}$ of metastable beam has been produced[9] using HCD under a beam density of $1\times10^{22}\mathrm{m}^{-3}$.

Penning-type discharge (PD) is another type of powerful discharge device. It can operate at very low pressures and create a plasma source with a high electron temperature. Heise *et al.*[10] reported their study of radiometric characterization of PD in the vacuum ultraviolet at a low gas pressure condition. Takiyama *et al.*[11] studied plasma spectral emissions from a PD source. Recently, a preliminary investigation of supersonic metastable helium beams using PD is also reported.[12]

This paper aims at the study of supersonic metastable helium beams used in measuring electric

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†Author to whom correspondence should be addressed. E-mail: xpfeng@dhu.edu.cn

field in a plasma. Both HCD and PD have been used for producing high-density metastable helium atoms. Results of the two types of plasma discharges at static gas pressures are presented. We are devoted to the characterization of the relationships between the density of the metastable atoms and the discharge power, current, static gas pressure. Based on the obtained results, we develop a pulsed supersonic metastable helium beam for plasma diagnostic application.

2. Experimental set-up

Experiments were performed using two vacuum chambers connected through a pipe. Each chamber had an independent pump so that differential gas pressures between the two chambers could be maintained. The pressure inside the chamber was regulated during operation by varying the gas inlet with a valve. Gas pressure was measured using an Edwards ionization gauge for < 0.14Pa, a MKS Baratron gauge for 0.14–200Pa and an Edwards gauge for 133–6670Pa. The chamber included a discharge device for producing plasma and metastable atoms. A fast ionization gauge (FIG), CCD camera and other detectors were used to characterize the pulsed metastable atoms. The density of metastable atoms was detected using atomic absorption spectroscopy based on a monochromator together with a lock-in amplifier, and plasma emission spectra were recorded using a multi-channel spectrograph.

As is known, HCD is normally used for the several tens Pa gas pressure discharge because of the limitation that $0.8 < Pd$, where P is the gas pressure in [Pa] and d is the inner diameter of the cylindrical HCD in [m]. Whereas, the PD can operate under very low pressure, such as 1.33×10^{-2} Pa and generate a plasma with an electron temperature higher than 5eV.

The structure of HCD is very simple. It consists of a cylindrical cathode with a length of 14.5mm and a diameter of 10mm, and a ring anode with a width of 6mm and a diameter of 10mm. The gap between the anode and the cathode can vary from 12 to 36mm depending on the experimental measurements. The structure of PD is shown in Fig.1. A pair of disc-type cathodes with a gap of 26 mm is set perpendicularly to the x-axis. To apply a magnetic field in the x-direction, we place the permanent magnet discs behind the cathodes. The magnetic field is about 0.08 T at the origin. The magnets will always remain on PD during the experiment. If no magnetic field is applied, then no discharge will take place. The cathode and anode bodies are made of stainless steel. A PD source is designed and fabricated in our laboratory based on Takiyama *et al.*'s[11] and Heise *et al.*'s[10] works. However, we make the present PD longer in order to increase helium atom-plasma interaction. The length of the discharge region is 38mm along z-axis. Along y-axis the anode has a hole with a large cross section of 10mm×36mm so that we have a better diagnostic access to the plasma source. Two holes with ϕ12mm aligned in the z-axis direction in the anode are the inlet and outlet for the helium beam or absorption measurement. The anode has another rectangular hole along the x-axis with a cross section 20mm×38mm and a length of 18mm. The discharge plasma is produced in this hole. Emission and LIF spectra from the plasma can be observed through the two holes on the x-axis. Detailed descriptions of the PD device can be found in an earlier paper.[12]

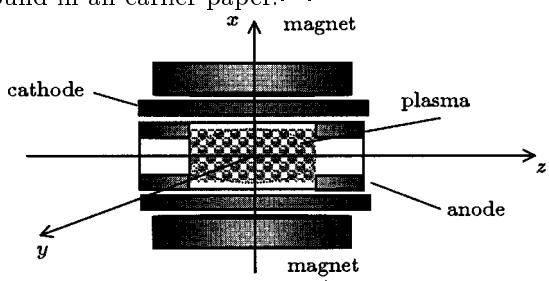


Fig.1. Structure of PD to excite the helium beam. Cathode: 36mm×56mm, anode: 54mm×18mm×74mm, hole along y-axis: 10mm×36mm, along x-axis: 20mm×38mm, and along z-axis: ϕ12mm. Magnetic field at the origin: B=0.08T.

The helium gas discharge operates at pressures from 1.33×10^{-3} to 1.33×10^{3}Pa. A dc power supply with a maximum current 0.5A together with a ballast 25kΩ resistor is used. The discharge voltage ranges from 0 to 5kV.

3. Experimental results

In the current experiments, we characterize both HCD and PD plasmas and report a study of the effects of discharge current and voltage on the density of the metastable helium atoms.

3.1. Hollow-cathode discharge

In order to produce high-density metastable helium atoms for LIF observation, and obtain the relationships between the density of the metastable atoms and the discharge voltage or discharge current, a high-voltage dc power supply is used to produce the helium gas plasma and create helium metastable atoms. Experimental set-up for measuring discharge voltages

and currents is the same as that we used before.[12] A meter is used to connect two electrodes for measuring the discharge voltage, and the other is used to connect two ends of the ballast resistor in the electric circuit for obtaining discharge current.

Figures 2(a) and 2(c) show variations of the discharge current and voltage as functions of the static helium gas pressure for different power supply voltages, where the ballast resistance in the circuit is 100kΩ and the gap between two electrodes is 12mm. Both the discharge current and voltage are larger for power supply voltage of 5kV than that for 1kV in the range of the static gas pressure larger than 13.3Pa. Below 13.3Pa, the gas discharge hardly occurs because of the limitation of $0.8 < Pd$. This problem can be overcome using a PD as shown later. Maximum discharge current of 50mA is obtained for a power voltage of 5kV and 10mA for 1kV at the gas pressure of 13.3Pa. With increasing helium gas pressure, the discharge current decreases slightly but the discharge voltage increases. At the gas pressure of 133.3 Pa, a phase change of the plasma discharge appears. Evidence is a quick change of the discharge voltage and discharge current as shown in Figs.2(a) and 2(c). The phase change of the plasma discharge would become more obvious at a higher power voltage. After the plasma phase change, both the discharge current and voltage remain almost unchanged. This behaviour is similar to that in a HCD lamp. Therefore, we may conclude that a real, traditional HCD can be operated only under a high gas pressure, as shown in Fig.2. Different shapes of the plasma sources before and after the phase change were also observed. As would be mentioned later, the highest density of metastable helium atoms was obtained before the plasma phase change.

In order to further increase the discharge current, a ballast resistor R=25kΩ is used in the circuit, which results in a plasma discharge current nearly four times as large as that in Figs.2(a) and 2(c). In Figs.2(b) and 2(d), variations of the discharge current and voltage are plotted as functions of the static gas pressure for an impedance of R=25kΩ and the power voltages of 1 and 5kV. A larger discharge current can be obtained if a smaller ballast resistor is used in the circuit, but we have not worked with it because of a limitation of the power supply. An interesting fact is that after changing the ballast resistor, occurrence of the plasma discharge phase change appears at the gas pressure of 266 Pa. It is not clear why the phase change of the gas plasma discharge is related to the discharge current.

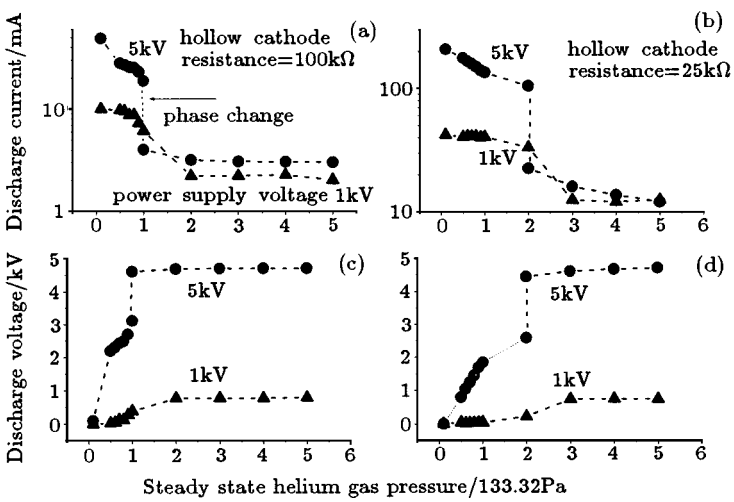


Fig.2. Discharge current and voltage plotted as functions of the static gas pressure for different power supply voltages and (a) and (c): a ballast resistor of R=100kΩ and (b) and (d) R=25kΩ (the gap between the anode and cathode is d=12mm).

It is seen that the discharge current plays a very important role on the plasma properties. We expect that the density of the metastable helium atoms is closely related to the discharge current. A simple method for measuring the density of metastable helium atoms is to use a spectral absorption technique. In Fig.3, the percentage of spectral absorption for a wavelength of 501.6nm (a line of 3p-2s emission) is plotted as a function of the static gas pressure, where the electric power for the plasma discharge is also pre-

sented. The absorption value quickly increases with increasing the static gas pressure. As the static gas pressure is up to 133.32Pa, the percentage of the spectral absorption suddenly drops from 30.2% to 17.5%, as is seen in Figs.3(a) and 3(c). Then, it gradually decreases with further increase of the gas pressure. A quick change of the spectral absorption is due to the phase change. Experimental results show that high-density $2\ ^1S$ atoms can be obtained before the plasma phase change, as shown in Fig.2. This is also an indication that a high fraction of metastables ($N_{2\ ^1S}/N_{He}$) at a low gas pressure can be obtained.

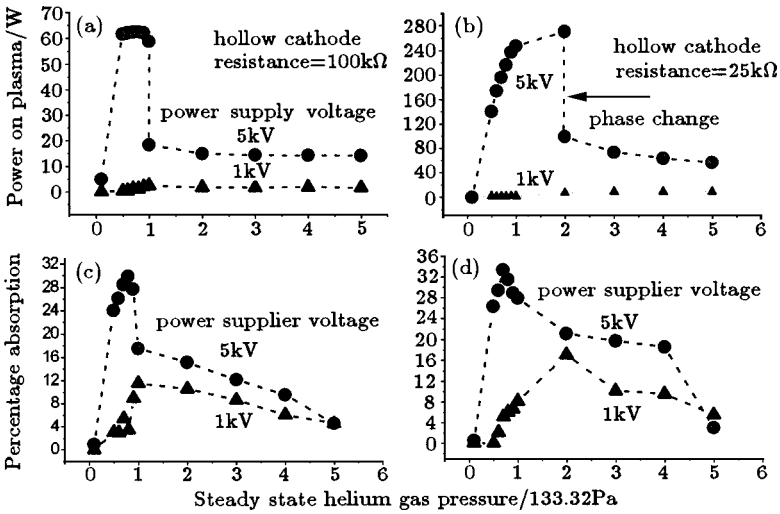


Fig.3. Percentage of absorption for 501.6nm plotted as a function of the static gas pressure for different power voltages and ballast resistors (a) and (c): R=100kΩ and (b) and (d) R=25kΩ (the gap between the anode and the cathode is d=12mm).

As a comparison, similar experiments are also performed for the case of R=25kΩ. A maximal value of the absorption is found for a helium gas discharge at 93.3 Pa at the power voltage of 5kV. Further increasing the gas pressure results in decreasing the absorption. Variation of the absorption shown in Figs.3(b) and 3(d) is similar to that in Figs.3(a) and 3(c). The difference is that a great change in spectral absorption occurs at 266 Pa, which is related to the plasma phase change. Owing to the change of the ballast resistor in the circuit from 100 to 25kΩ, we can increase the peak power for a plasma discharge from 65 to 260W, as shown in Figs.3(a) and (b). Correspondingly, we obtain the maximal percentages of the spectral absorption from 30% (Fig.3(c)) to 33% (Fig.3(d)). The density of metastables is dependent on the discharge power, but increasing the metastable density is little with increasing the discharge power.

3.2. Penning-type discharge

Experimental results obtained from HCD show that: (a) using a small impedance in the discharge circuit, a large discharge current can be created, which results in a large percentage of the spectral absorption; (b) HCD is not suitable for a very low-pressure gas discharge. Therefore, in the following experiments, we are just concerned with using a small impedance of R=25kΩ in the discharge circuit, and then adopt a PD instead of HCD. PD can operate under a low gas pressure, such as 0.01 Pa, and generate plasma with a high electron temperature. Discharge current created by PD almost linearly increases with increasing the power supply voltage, as shown in Fig.4.

Maximal discharge current of 200mA is obtained for a power voltage of 5kV, similar to that in the HCD case, but the present gas pressure is much lower than that in the case of HCD. The discharge voltages remain nearly unchanged. The differences of the discharge currents or voltages between the gas discharges for the range of gas pressures from 0.013 to 6.5Pa are very small, indicating that the property of PD is obviously different from that of HCD. In Fig.4, discharge current and voltage are plotted as functions of power supply voltage for the gas pressures of 0.013 and 6.5Pa.

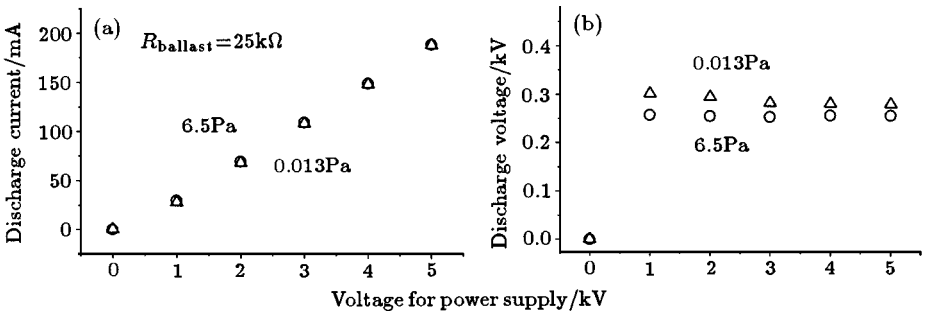


Fig.4. Discharge current and voltage plotted as functions of power supply voltage for the static gas pressures of 0.013 and 6.5Pa.

In the case of helium gas pressures between 13.3Pa and 65Pa, experimental data indicate that the discharge currents increase gradually from zero to 30mA, but the discharge voltage does not increase further after the power voltage increases up to 400V. This electric feature is similar to that of very low-pressure gas discharge. However, we are not able to further increase the power voltage because an electric arc occurring between the anode of PD and the vessel was observed. A possible reason for this arc is that the discharge current is too large, and the present strength of the magnet field is not strong enough to confine the plasma. In order to avoid arcing at the high-pressure gas discharge, two pieces of glass are used to cover PD for preventing the discharge plasma from PD to the metal wall of the vessel. In Fig.5, the discharge current and voltage are plotted as functions of power voltage for different static gas pressures after using two pieces of glass. It can be seen that the discharge voltage initially increases with the power supply voltage, and then gradually reach its saturation. The maximal discharge voltage for 106.7Pa gas discharge is around 300V, slightly larger than that for 21.3Pa. The discharge current increases almost linearly with the power voltage. Based on the experimental data shown in Fig.5, we obtain the relationship between the discharge current and the discharge voltage, which shows the discharge current increases quickly with the discharge voltage.

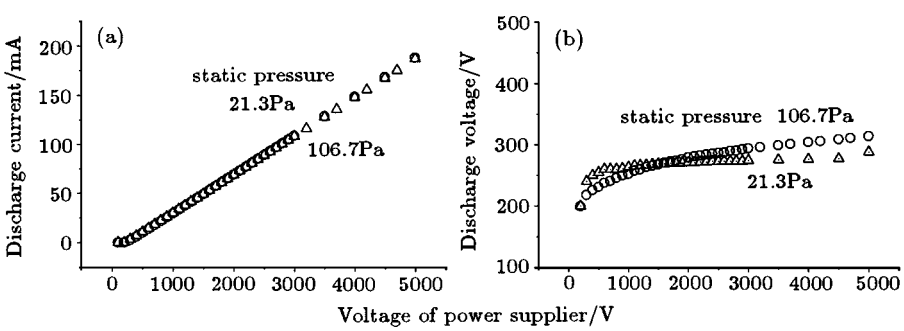


Fig.5. Discharge current and voltage plotted as functions of supply voltage for static gas pressures of 21.3 and 106.7Pa.

As is known, PD can operate at a very low gas pressure. Therefore, we expect that PD can produce a high density of metastable atoms. In Fig.6 the percentage of the spectral absorption for a wavelength of 501.6nm (a line of 3p-2s emission) is plotted as a function of discharge current for the static gas pressures of 1.33, 13.3, and 66.7Pa. Experimental results show that the density of the metastable helium atoms increases with increasing the static gas pressure and discharge current. Under the condition of a maximal discharge current of ~190mA, the spectral absorption percentages of 20.2%, 16.3% and 13.5% are obtained for the cases of 1.33, 13.3, and 66.7Pa gas discharges, respectively.

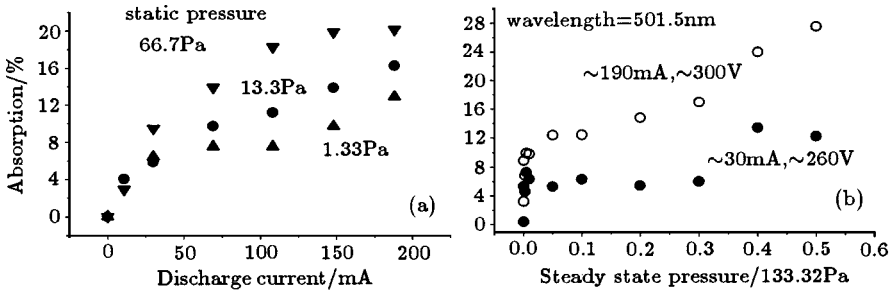


Fig.6. The percentage of absorption for 501.6nm (relative density of metastable helium atoms) plotted as a function of (a) the discharge current and (b) static gas pressure for R=25kΩ at different power voltages.

In Fig.6 the spectral absorption percentage is also plotted as a function of the discharge current and the static gas pressure at different voltages. All the experimental data indicate that the densities of the metastable atoms increase with increasing the static gas pressure and discharge current. The maximal percentage of spectral absorption is 28% for a discharge current of 190mA and 13% for 30mA at the static gas pressure of 26.7Pa. The relationships between the spectral absorption and the metastable density can be obtained based on a simple formula[13]

$$\ln\frac{I_0}{I} = 1.161\times10^{-6}\lambda_{ik}f_{ik}\left(1-\beta\frac{g_i}{g_k}\right)\sqrt{\frac{A}{T}}\int_0^l n_i(x)\mathrm{d}x,$$

where I_0 and I are the intensities of the lamp (501.6nm line) emission obtained before and after the plasma discharge, respectively, λ is the wavelength (501.6nm for a line of 3p-2s emission), f is the oscillator strength, β is the population ratio, A is the atomic weight, T is the gas temperature, l is the length of the plasma, and n is the metastable density. After considering the length of the plasma source of 3.8cm and assuming a uniform plasma source and $\beta = n_k(x)/n_i(x) \to n_{3\,^1\mathrm{p}}/n_{2\,^1\mathrm{s}} \approx 0$, from the experimental absorption data we obtain the highest density of the metastable helium atoms to be $3.87\times10^{10}\mathrm{cm}^{-3}$ for a discharge current of 190mA, and $1.47\times10^{10}\mathrm{cm}^{-3}$ for a discharge current of 30mA. These metastable densities are high enough to be used in LIF project for an electric field measurement at the edge of a plasma source. An approximately linear increase of the spectral absorption with gas pressure is observed from PD in the range of the static gas pressure from 6.67 to 66.7Pa, probably indicating that a larger absorption percentage or the density of the metastable helium atoms can be obtained at a higher gas pressure. However, we are not able to verify it since a discharge is observed between the anode of PD and the vessel even if two pieces of glass have been used on both sides of PD.

4. Discussion

The LIF technique, in diagnosing plasma, mainly uses the forbidden transition-excitation of the $2\,^1\mathrm{S}$–$n\,^1\mathrm{D}$ by a laser and Stark mixing between the $n\,^1\mathrm{P}$ and $n\,^1\mathrm{D}$ levels to measure the electric field.[12] This technique depends on high-density metastable atoms. Both HCD and PD have been adopted to excite the beam. HCD can create high density $2\,^1\mathrm{S}$ atoms of $\sim10^{16}\mathrm{m}^{-3}$ for a supplied gas density of $1\times10^{21}\mathrm{m}^{-3}$.

A phase change in HCD is observed, which is related to the discharge current and gas pressure. According to the literature, the phase change is also dependent on the radius of the cathode. At a gas pressure below that for the phase change, we have also observed obvious plasma discharge outside the hollow cathode.

Considering that HCD is not very suitable for low-pressure gas discharge, we have used PD in the present experiments, and the results indicate that PD produces high fractions of the metastables in a low density of helium atoms. Even if the helium gas discharge occurs at a pressure of 6.67×10^{-2}Pa (density: $1.6\times10^{19}\mathrm{m}^{-3}$), we still achieve a metastable density up to $0.6\times10^{16}\mathrm{m}^{-3}$. The metastable density increases almost linearly with increasing discharge current. This is an indication that a higher density of metastable atoms can be created if we choose a smaller ballast resistor in the circuit. The magnetic field in PD plays a very important role for producing a high density of metastable atoms. Due to the field of permanent magnets located behind the cathodes, the electrons are confined to their radial starting position,

and are reflected between the two cathodes through the anode many times, causing multiple collisions with neutral atoms to create metastables. This allows the PD to operate at lower pressures than HCD. Finally, it should be mentioned that the appearance of some slightly unstable plasma source has been observed, resulting in errors around 5% in measurement. We have also some errors in data processing. The relationship between the spectral structures and the atomic energy states need be further calculated for a complicated plasma system since it involves some effects of ions.[14,15]

5. Conclusion

Both HCD and PD have been adopted to excite helium atoms. A phase change in HCD has been observed, which is related mainly to the discharge current and gas pressure. HCD can create a metastable density of helium atoms up to $\sim 1 \times 10^{16}\mathrm{m}^{-3}$, but this requires the gas pressure to be above approximately $\sim 1 \times 10^{21}\mathrm{m}^{-3}$, and might have a great influence on the plasma operated at a low pressure of less than 1.33Pa. PD is more suitable for generating high fractions of metastables in a low-density helium beam, which is enough for LIF technique used in measuring electric fields at the edge of a plasma. The metastable density produced using PD increases with increasing helium gas pressures in the range of 1.33×10^{-2}–26.7Pa, but the metastable density is dependent mainly on the plasma discharge current. We expect that a higher density of metastable atoms can be created if a smaller ballast resistor is used in the circuit. A new power supply with a larger electric current is needed for LIF investigation.

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