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# Comparison of hollow cathode and Penning discharges for metastable He production

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**Abstract**
The production of helium $2\,^1$S singlet metastable atoms has been investigated using a hollow cathode discharge and a Penning discharge, under dc discharge conditions. The density of metastable atoms was measured by atomic absorption using the $2\,^1$S–$3\,^1$P transition (501.57 nm). A range of plasma currents, varying from 16 to 180 mA, and a range of pressures, from 100 mTorr to 5 Torr, were investigated. This work is directed ultimately to the production of a supersonic metastable helium beam for plasma diagnostics, in particular the measurement of electric fields using laser induced fluorescence.

## 1. Introduction

Electric fields play an important role in many plasma applications, including magnetic fusion reactors, plasma processing and inertial electrostatic confinement devices. A laser induced fluorescence (LIF) technique, proposed by Takiyama *et al* [1] for measuring electric fields in plasmas, is based on the Stark-effect modification of the fluorescence from helium atoms in the singlet metastable state [2]. Numerical studies and measurements on electron cyclotron resonance (ECR) plasmas by Takiyama *et al* [3, 4] have shown that a metastable density $n_{2^1\mathrm{S}} > 1 \times 10^{16}\,\mathrm{m}^{-3}$ is required for successful electric field measurements [5]. The work presented here is a study of singlet helium metastable production under dc discharge conditions. The motivation is to develop a pulsed, bright metastable helium beam for measuring electric fields in the H-1 heliac [6].

Two types of discharges have been investigated: a hollow cathode discharge (HCD) and a Penning discharge (PD). The HCD, which is formed inside a hollow cylindrical cathode (details of the anode configuration are unimportant), requires a sufficiently high pressure for the cathode fall thickness to be less than the radius of the cathode. This allows the negative glow to locate within the cylindrical electrode. At lower pressures, the negative glow moves outside the hollow cathode and the discharge becomes a normal glow discharge. The dc HCD, and its temporal development following breakdown, has been studied extensively [7, 8]. Takiyama *et al* [9] have measured singlet metastable density at 0.7 Torr for cathode disks 4 cm diameter and 1.1 cm apart, and under pulsed operation [10] produced a metastable density of around $10^{16}\,\mathrm{m}^{-3}$ in a helium beam with a density of around $10^{22}\,\mathrm{m}^{-3}$. A beam with such a high density is, however, unsuitable for the proposed LIF diagnostic as it may disturb the plasma [11].

In an attempt to overcome this a PD has been proposed as an alternative, as it is able to operate at significantly lower pressures [12, 13]. The PD consists of two cathodes with an anode between them. There is a magnetic field normal to the surface of the cathode and, as a consequence, parallel to the axis of the discharge. Electrons that leave the cathode are confined by the magnetic field, are reflected between the two cathodes, and hence through the anode, many times, causing multiple collisions with neutral atoms to facilitate metastable production. This allows the PD to operate at lower pressures than the HCD.

In this paper we present results comparing over a range of pressures and discharge currents the production of singlet metastable helium atoms in a HCD and a PD.

## 2. Experiment

The HCD had a cylindrical cathode 1 cm in diameter and 2 cm in length. The anode ring was of the same diameter and was mounted ~3.5 cm from the cathode as shown in figure 1. The PD had two parallel cathodes with an anode between, and a magnetic field normal to the cathode surfaces. The cathodes were 6 cm long, 4 cm wide and 1 cm high. The anode, 7 cm long, 5 cm in wide and 1.5 cm high, had three orthogonal holes (see figure 2) to allow passage of the discharge and provide diagnostics access. Rare earth magnets were mounted in each of the cathodes to produce the magnetic field (see figure 2) which had a value of 0.3 T at the cathode surfaces. The same vacuum chamber with helium gas flowing through it was used for both discharges.

The metastable density was measured by atomic absorption, using a helium spectral line that terminates on the singlet metastable level, the $2\,^1\mathrm{S}$–$3\,^1\mathrm{P}$ transition at $\lambda = 501.57$ nm. The experimental arrangement is shown in figure 3. A hollow cathode lamp with helium as the background gas was used as the light source. The light was collimated, and after passing through the plasma, was focused into a

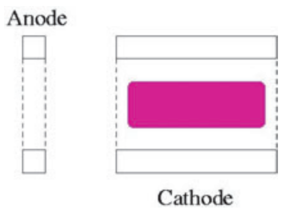


**Figure 1.** HCD for He metastable production.

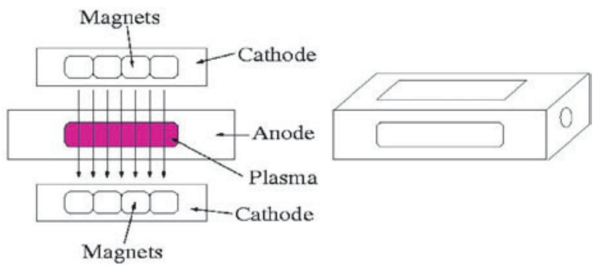


**Figure 2.** Schematic of the PD for He metastable production.

monochromator. By chopping the incident beam lock-in detection could be used to eliminate the background emission from the discharge. The output from the lock-in amplifier was displayed on a digital oscilloscope on a slow time base and the discharge switched on and off. The absorption of the light by metastable atoms produced an easily measured decrease in the signal from the lock-in amplifier.

The metastable density (in $\mathrm{m}^{-3}$) is given by equation (1) and is derived from Corney [14] and assumes Doppler broadening of both the light source and discharge. If a narrow line source is assumed, i.e. $T_1 \approx 0$, then this reduces to the equation by Otsuka *et al* [15]:

$$n_{2\,^1\mathrm{S}} = 8.613 \times 10^8 \frac{I_0 - I}{I_0} \frac{1}{\lambda f l} \sqrt{\frac{T_2 + T_1}{M}}, \tag{1}$$

where $I_0$ is the intensity of the incident beam, $I$ is the transmitted intensity, $\lambda$ and $f$ are, respectively, the wavelength and absorption oscillator strength of the transition, $l$ is the path length through the plasma, $T_1$ and $T_2$ are, respectively, the temperatures of the gas in the light source and in the discharge under investigation, both assumed to be 300 K for the present measurement. $M$ is the atomic weight of the gas used (in this case helium). For the HCD, $l$ was taken to be equal to the width of the cathode (2 cm); for the PD, $l$ was taken to be the width of the hole in the anode (4 cm). For both discharges singlet metastable atom density was measured for a range of gas pressures and discharge currents.

## 3. Results

### 3.1. Constant current, varying pressure

Figure 4 shows that the hollow cathode produced a maximum density of metastable atoms of $\sim 1.2 \times 10^{17}\ \mathrm{m}^{-3}$ at 800 mTorr and 160 mA. Below a pressure of 500 mTorr, the discharge ceased to be a HCD, i.e. the negative glow moved outside the cathode.

Above 800 mTorr, for all currents, the metastable density decreases with increasing pressure, due to collisional

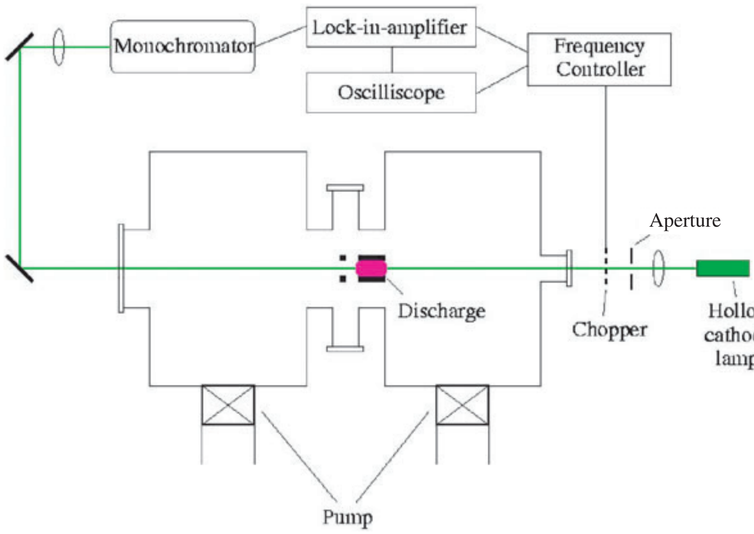


**Figure 3.** Experimental setup for the investigation of metastable He atoms.

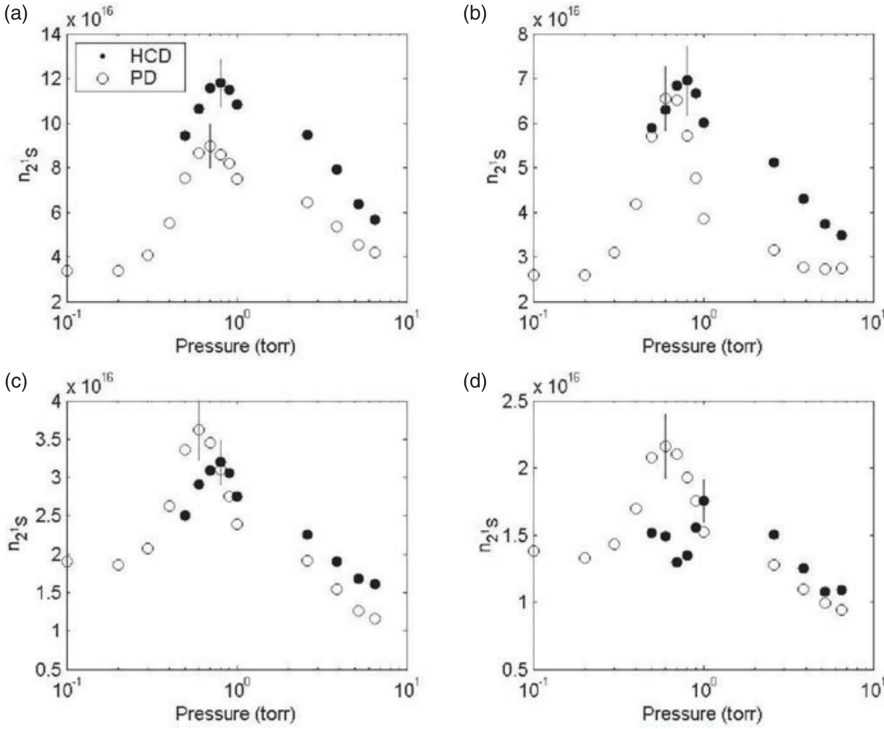


**Figure 4.** Metastable density measurements for HCD and PD for varying pressures at different currents (*a*) 160 mA, (*b*) 80 mA, (*c*) 32 mA, (*d*) 16 mA. The uncertainties in the metastable densities are indicated by representative error bars.

de-excitation by neutral helium atoms. For all currents investigated, the hollow cathode produced a maximum metastable density at 800 mTorr.

The PD at a current of 160 mA and a pressure of 600 mTorr produced a maximum metastable density of $\sim 9 \times 10^{16}\,\mathrm{m}^{-3}$, but unlike the hollow cathode, the PD continued to operate at pressures below 500 mTorr. At lower pressures the PD is better at producing metastables as shown in figure 4: at a pressure of 100 mTorr and 16 mA, it still produced a metastable density greater than $10^{16}\,\mathrm{m}^{-3}$.

### 3.2. Constant pressure and varying current

The metastable density was also measured as a function of discharge current for several constant values of pressure. Three pressures were investigated: 1 Torr ($n_{\mathrm{He}} = 3.3 \times 10^{22}\,\mathrm{m}^{-3}$), 500 mTorr ($n_{\mathrm{He}} = 1.65 \times 10^{22}\,\mathrm{m}^{-3}$) and 100 mTorr ($n_{\mathrm{He}} = 3.3 \times 10^{21}\,\mathrm{m}^{-3}$).

Results in figure 5 show that at pressures, around 1 Torr, the PD and HCD produce similar metastable densities over the whole range of currents investigated. For example, the density is $\sim 1.2 \times 10^{17}\,\mathrm{m}^{-3}$ for both discharges at a current of 180 mA. As the pressure decreases, metastable production by the PD exceeds that of the HCD. At a pressure of 500 mTorr and a current of 180 mA, the density for the PD is $\sim 1.2 \times 10^{17}\,\mathrm{m}^{-3}$, compared with $\sim 7 \times 10^{16}\,\mathrm{m}^{-3}$ for the HCD. At 100 mTorr, the negative glow is outside the cylindrical cathode and the discharge no longer operates in the hollow cathode mode. In these circumstances the absorption path is greater than the length of the cathode and difficult to determine with any precision. On the other hand, the PD still operates at this pressure, producing a metastable density of $\sim 3.3 \times 10^{16}\,\mathrm{m}^{-3}$ at a current of 180 mA.

## 4. Discussion

Since the excitation energy of the $2\,^1\mathrm{S}$ metastable state is slightly above 20 eV, electron excitation from the ground state will be due to the high energy tail of the thermal electron distribution. Hot non-thermal electrons could also contribute significantly. Both the HCD and the PD were investigated since each involves a trapping mechanism for electrons (radial electrostatic trapping in the case of the HCD, and magnetic trapping due to the longitudinal magnetic field in the case of the PD) leading to enhanced electron density and metastable excitation.

The results show that at higher pressures ($\sim$1 Torr), the metastable densities achieved in the HCD and the PD were similar in magnitude. The PD, however, is able to operate effectively at pressures below 500 mTorr, where the HCD has ceased to operate. At such lower pressures, the outside of the cylindrical electrode becomes the cathode, which will cause a dramatic drop in ionization, and consequently excitation of metastable atoms, inside the cylinder. In contrast, the PD operates over the entire pressure range investigated because the electrons are magnetized over this range, with $\omega\tau$, where $\omega$ is the cyclotron frequency and $\tau$ is the electron neutral frequency, varying $\sim$4–300, assuming an electron temperature of 3 eV, and electron neutral cross-section of $\sim 5 \times 10^{-20}\,\mathrm{m}^2$ [16]. As the Lamor radius for such electrons is $\sim 20\,\mu\mathrm{m}$, and assuming a random walk in the transverse direction, electrons will require $\sim 10^6$ steps to diffuse from the plasma of radius 2 cm. In the process, the electron will undergo a random walk parallel to the magnetic field and reflect many times between the cathodes, e.g. at 1 Torr $\sim$100 times.

Efficiencies of singlet metastable production ($n_{2\,^1\mathrm{S}}/n_{\mathrm{He}}$) of $\sim 1.1 \times 10^{-5}$ have been reported by Takiyama *et al* [9]

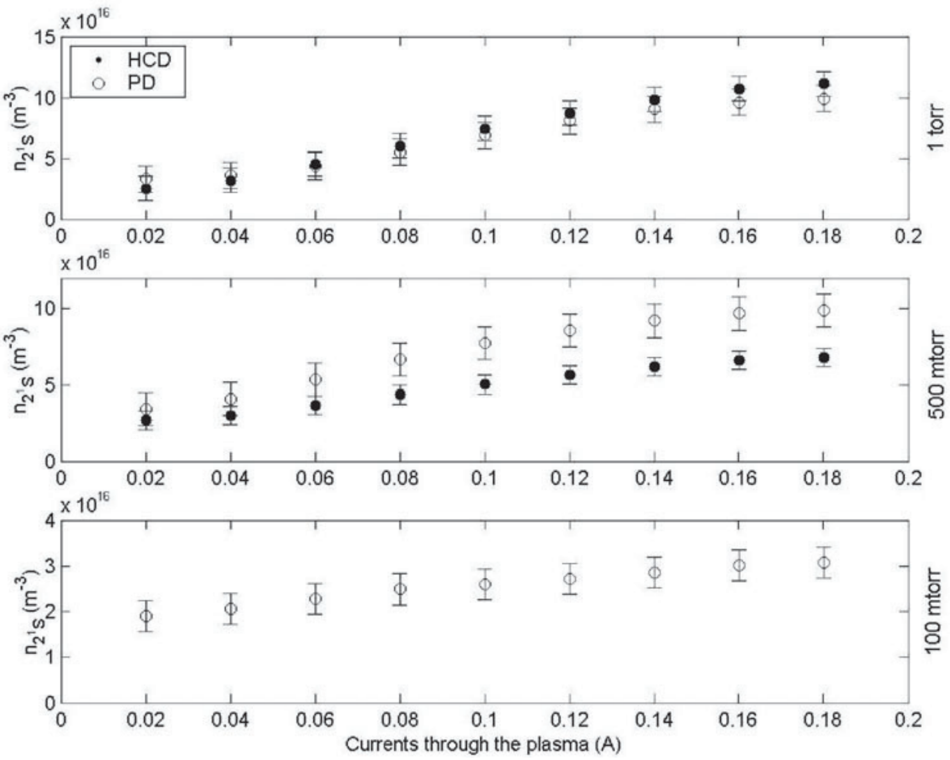


**Figure 5.** Metastable density measurements for HCD and PD for varying current: (*a*) 1 Torr, (*b*) 0.5 Torr, (*c*) 0.1 Torr.

for a pressure of 1.4 Torr in a HCD. In this investigation the efficiency for the production of metastable atoms increased with increasing discharge current and decreasing pressure for both discharges. The maximum efficiency for the HCD was $\sim 6 \times 10^{-6}$ at 500 mTorr and a current of 180 mA; for the PD, maximum efficiency obtained was $\sim 10^{-5}$ at 100 mTorr and 180 mA.

The ultimate aim of this work is to produce a supersonic beam of metastable singlet helium atoms for LIF diagnostics, with metastable densities $n_{2^1S} > 1 \times 10^{16}\,\mathrm{m}^{-3}$. Metastable densities of this order have been reported for a HCD with a beam density of $n_{\mathrm{He}} = 3.3 \times 10^{22}\,\mathrm{m}^{-3}$ ($\sim$1 Torr) [10].

For the diagnostic the density of the pulsed neutral He beam needs to be as low as possible so as not to disturb the plasma under investigation. At the same time the metastable density needs to be sufficiently high to allow adequate sensitivity for the LIF diagnostic. On the basis of the results presented here, it appears that the PD is a better option for metastable production than the HCD. Future work will concentrate on the production of metastable atoms in a pulsed helium source

## 5. Conclusion

The densities of singlet metastable helium atoms produced in a HCD and a PD have been measured for a range of pressures and discharge currents. At the highest pressures and currents used the density of metastable atoms produced by the HCD ($\sim 1.2 \times 10^{17}\,\mathrm{m}^{-3}$) was about 30% higher than that for the PD. At pressures below 500 mTorr, where hollow cathode operation was no longer possible the PD, was able to produce metastable densities greater than $10^{16}\,\mathrm{m}^{-3}$. The highest efficiency of metastable production ($10^{-5}$) was obtained using the PD at 100 mTorr and 180 mA.

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## References

[1] Takiyama K, Sakai H, Yamasaki M, Oda T and Kawasaki K 1993 *Proc. 6th Int. Symp. Laser-Aided Plasma Diagnostics (Bar Harbour, Maine, USA, 1993)* pp 43–8

[2] James B W, Andruczyk D, Feng P X, Howard J, Takiyama K and Oda T 2001 *Proc. 10th Int. Symp. Laser-Aided Plasma Diagnostics Conference (Fukuoka, Japan, 2001)* pp 214–19

[3] Takiyama K, Katsuta T, Wanatabe M, Li S, Oda T, Ogawa T and Mizuno K 1997 *Rev. Sci. Instrum.* **68** 1028–31

[4] Oda T, Takiyama K and Toyota H 1998 *The Japan-US Workshop on Plasma Polarization Spectroscopy and the International Seminar on Plasma Polarisation Spectroscopy (Kyoto, 26–28 January 1998)* pp 60–6

[5] Takiyama K, Mizuno K, Katsuta T, Ogawa T and Oda T 1995 *J. Nucl. Mater.* **220** 1057–60

[6] Harris J and the H-1 team 1998 *J. Plasma Fusion Res.* **1** 37–40

[7] Ngo M T, Schoenbach K, Gerdin G A and Lee J H 1990 *IEEE Trans. Plasma Sci.* **18** 669–76

[8] Schoenbach K H, El-Habachi A, Shi W and Ciocca M 1997 *Plasma Sources Sci. Technol.* **6** 468–77
[9] Takiyama K, Sakai H, Yamasaki M and Oda T 1994 *Japan. J. Applied Phys.* **33** 5038–45
[10] Takiyama K, Katsuta T, Toyota H, Watanabe M, Mizuno K, Ogawa T and Oda T 1997 *J. Nucl. Mater.* **241** 1222–7
[11] Takiyama K, Kondo T, Andruczyk D, Feng P X, James B W and Oda T 2001 *Proc. 10th Int. Symp. Laser-Aided Plasma Diagnostics Conf. (Fukuoka, Japan, 2001)* pp 299–304
[12] Haise C, Hollandt J, Kling R, Koch M and Kühne M 1994 *Appl. Opt.* **33** 5111–17
[13] Takiyama K, Wanatabe M and Oda T 1999 *J. Nucl. Mater.* **226** 935–57
[14] Corney A 1977 *Atomic and Laser Spectroscopy* (Oxford: Oxford University Press) pp 229–93
[15] Otsuka M, Ikee R and Ishii K 1979 *Quantum Spectrosc. Rad. Transfer* **21** 41–53
[16] Mitchner M and Kruger C H Jr 1973 *Partially Ionised Gases* (New York: Wiley) p 102