Preliminary Study of a Hybrid Helicon-ECR Plasma Source

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Abstract A new type of hybrid discharge is experimentally investigated in this work. A helicon source and an electron cyclotron resonance (ECR) source were combined to produce plasma. As a preliminary study of this type of plasma, the optical emission spectroscopy (OES) method was used to obtain values of electron temperature and density under a series of typical conditions. Generally, it was observed that the electron temperature decreases and the electron density increases as the pressure increased. When increasing the applied power at a certain pressure, the average electron density at certain positions in the discharge does not increase significantly possibly due to the high degree of neutral depletion. Electron temperature increased with power in the hybrid mode. Possible mechanisms of these preliminary observations are discussed.

Keywords: helicon, plasma, ECR, hybrid, discharge

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(Some figures may appear in colour only in the online journal)

1 Introduction

High electron density plasma sources are important in many areas of plasma science. Relatively low density plasma sources are used in plasma processing. However, such sources e.g. capacitively coupled plasmas suffer from inefficiency as roughly 10% of the power is absorbed to produce plasma. The need for plasma sources with much higher density and higher ionization efficiency is one of the main reasons for pursuing novel plasma sources.

Two of the major high density low pressure plasma sources that are well developed are the helicon source and the electron cyclotron resonance (ECR) source. Early experimental helicon investigations were carried out by Boswell [1]. Extensive review on helicon sources can be found in Refs. [2–4]. As for the ECR sources, they were first studied in the 1960’s by Miller et al. [5,6] as a system for space craft propulsion. After that there were many studies that used ECR in fusion research [7,8]. In addition, ECR based ion sources were developed due to their high plasma density at low pressure [9–14].

In this paper a description of a hybrid helicon-ECR plasma source is given. Section 2 illustrates the experimental set-up and section 3 introduces a technique to measure the electron temperature and density by optical emission spectroscopy (OES). The results are given and discussed in section 4. Finally the conclusion is given.

2 Experimental setup

The general system design is shown in Figs. 1 and 2. The discharge chamber consists of a cylindrical quartz vacuum tube 4.8 cm in diameter and 70 cm in length. The chamber was kept under a low base pressure of 6×10⁻⁵ Pa. by a turbo pump backed by a mechanical pump. The pressure was measured with convection and ionization gauges. Argon was used as a feed gas. A 10 cm long Nagoya type III RF antenna was placed around the tube for RF power coupling to the plasma. The antenna was driven by a 13.56 MHz RF power supply of power up to 3 kW with an automatic matching network. Two DC driven variable magnetic field coils were placed at each end of the antenna so as to produce an axial magnetic field of up to 0.1 Tesla. The two coils were 10 cm in diameter each with 4 cm spacing between them. The main elements for the ECR setup were a 2.45 GHz magnetron source, a circulator, and a stub tuner which has the dimensions of 72×34 mm² rectangular output. Microwave power of up to 2000 kW was obtained. The coupling of the microwave was direct to one end of the vacuum tube without a coupling element. For OES measurements, an Ocean Optics HR4000 spectrometer was used. The radiation from the center of the region between the two magnetic coils was collected by an optical fiber.
3 Optical emission spectroscopy method

This section describes the line-ratio method for the optical emission spectroscopy (OES) diagnostics. This method was used in Refs. [15–17] to determine the electron temperature and density. First, we need to build a collisional-radiative model of argon to predict the population density of the Ar(1s) and Ar(2p) states (in Paschen’s notation). From the general CR model in Ref. [18], the important processes under the conditions here (pressure 0.13–1.3 Pa electron density $\sim 10^{11–10^{12}} \text{cm}^{-3}$) can be identified as: (a) electron-impact excitation from the ground state, (b) electron-impact excitation from the Ar(1s) states to the Ar(2p) states, (c) electron-impact quenching of excited states, (d) electron-impact ionization of Ar(1s) states to the Ar(2p) states, (e) electron-impact ionization and Penning ionization of excited states, (e) diffusion and collisional deactivation at the wall, and (f) radiation and radiation trapping.

Therefore, the rate balance equation of an excited state $i$ can be written as:

$$n_e \cdot n_g \cdot Q_{g \rightarrow i} + n_e \cdot \sum_{j \neq i} n_j \cdot Q_{j \rightarrow i} + \sum_{j \neq i} \Gamma_{j \rightarrow i} \cdot A_{j \rightarrow i} \cdot n_j$$

$$= n_e \cdot n_i \cdot Q_{i \rightarrow g} + n_e \cdot n_i \cdot \sum_{j \neq i} Q_{i \rightarrow j} + \sum_{j \neq i} \Gamma_{i \rightarrow j} \cdot A_{i \rightarrow j} \cdot n_i$$

$$+ n_i \cdot n_i \cdot Q_{i \rightarrow g} + 2n_i^2 Q_{i \rightarrow g} + n_i \sum_{j \neq i} n_j \cdot Q_{j \rightarrow g}^i + K_{wall} \cdot n_i \cdot n_i .$$

Here $j$ refers to another excited state. $n_e$ is the electron density, $n_g$ is the ground state density, and $n_i$ and $n_j$ are the excited state densities. $Q$ refers to the rate coefficients of the collisional reactions. The electron energy distribution function becomes a Maxwellian function when the electron densities are as high as $\sim 10^{11–10^{12}} \text{cm}^{-3}$ as measured in Ref. [17] at pressures $\sim 0.13–1.3 \text{ Pa}$. Therefore, we can calculate the excitation and ionization rate coefficients using a certain electron temperature and the same set of cross sections as in Ref. [16]. The coefficients $Q_{\text{Penni}}$ for the Penning processes are taken from Ref. [18]. $K_{\text{wall}}$ is the loss frequency by the wall deactivation process. It depends on the diffusion coefficient and thus on the heavy species density (atoms and ions) as shown in Ref. [18].

Notice that the gas depletion effect is very significant in the discharge investigated here. One needs to include the following relationship in addition to the CR model [17]:

$$n_g + \sum_{i} n_i = p/kT_g - n_e \cdot (1 + T_e/T_g).$$

Here $k$ is the Boltzmann constant, $p$ is the pressure, $T_g$ is the gas temperature, and $T_e$ is the electron temperature. We assume the same temperature for all heavy species and the ion density is equal to the electron density. Atoms in the excited states are higher than Ar(2p) and ions with multiple charges are ignored.

Another important assumption above is that of a homogenous plasma. Only in this case, one can use the concept of an escape factor to account for the radiation trapping processes ($\Gamma$ is the escape factor and $A$ is the Einstein coefficient in Eq. (1)). Actually, the discharge studied here can be inhomogeneous and the average values of species density and temperature are used in Eqs. (1) and (2). Using the average density but not the value in the plasma center, the escape factor leads to a very small difference in the effective frequency of radiation decay in comparison with an inhomogeneous model [19].

The excited state densities are obtained by solving the steady-state rate Eq. (1) for the 14 excited states together with Eq. (2), which are used to calculate the intensities of emission lines from Ar(2p) to Ar(1s):

$$I_{i \rightarrow j} = \Gamma_{i \rightarrow j} \cdot A_{i \rightarrow j} \cdot n_i .$$

The emission lines are numbered with $k$ and we define a relative intensity $R$ as:

$$R_k = \frac{I_k}{\sum_{k} I_k} \times 100.$$  

The calculated $R_k$ values by the CR model (CRM) are compared with those measured by OES:

$$\sigma^2_R = \sum_{k = 1}^{N} [R_{k \text{OES}} - R_{k \text{CRM}} (T_e, n_e)]^2 .$$

$N$ is the total number of emission lines. From the CR model above, $R_k$ is a function of $T_e$ and $n_e$. In this way,
the electron temperature and density can be obtained simultaneously by solving this non-linear least squares problem (minimizing the value of Eq. (5)) using the fitting program in MATLAB®.

4 Results and discussion

4.1 Emission spectrum and fitting procedure

Fig. 3 shows a typical emission spectrum measured at the pressure of 1.33 Pa. Both ECR (power 500 W) and helicon (power 500 W) sources are used. Here we use 14 emission lines as listed in Table 1. Note that for the numbers 4, 6, 8, 9, and 11, two lines with similar wavelength are combined, since the CCD spectrometer that was used cannot separate them completely. Fig. 3(a) shows the original spectrum recorded by the spectrometer. It has a better response at short wavelengths (e.g. 600–700 nm) than at long wavelengths (e.g. 800–900 nm). Therefore, we need to consider the response of the spectrometer (calibration by a tungsten ribbon lamp) to give the actual emission intensity $R_k$ in Fig. 3(b). Several low peaks in Fig. 3(a) can also be identified as lines from Ar(2p) to Ar(1s) but are not used due to low signal-to-noise ratios. As shown in Fig. 3(b), we can find a best-fit of the line-ratios from the OES and CR model, with only a very small residual in Fig. 3(c).

![Fig. 3](image)

**Fig. 3** Typical emission spectrum (a) and the best-fit result of relative emission intensities from the CR model and the OES measurement (b). (c) is the difference between the two intensities in (b). The condition here is a pressure of 1.3 Pa, ECR power of 500 W, and helicon power of 500 W.

### Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Wavelength (nm)</th>
<th>Upper level</th>
<th>Lower level</th>
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<tr>
<td>1</td>
<td>696.54</td>
<td>2p(1)</td>
<td>1s(2)</td>
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<tr>
<td>2</td>
<td>706.72</td>
<td>2p(2)</td>
<td>1s(2)</td>
</tr>
<tr>
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<td>2p(2)</td>
<td>1s(1)</td>
</tr>
<tr>
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<td>750.39</td>
<td>2p(0)</td>
<td>1s(2)</td>
</tr>
<tr>
<td>5</td>
<td>751.47</td>
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<td>1s(1)</td>
</tr>
<tr>
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<td>763.51</td>
<td>2p(0)</td>
<td>1s(2)</td>
</tr>
<tr>
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<td>772.38</td>
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<td>1s(2)</td>
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<tr>
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</tr>
<tr>
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</tr>
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<tr>
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<td>2p(2)</td>
<td>1s(1)</td>
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</table>

4.2 Electron temperature and density

Fig. 4 shows the electron temperature obtained from the above fitting procedure. The left figure investigates $T_e$ variation versus the pressure. It decreased from $\sim 7$ eV to $\sim 4$ eV at pressures of 0.13–1.3 Pa. The right figure studies the variation with the helicon power when the ECR power is a constant at 500 W. $T_e$ increases by about 10% in this case. In brief, the electron temperature was increased by combining the two discharges or increasing the applied power. This can be explained by considering the enhancement of the heating electric field, which lifts the tail of the electron energy distribution function up as seen in Ref. [17]. In this section we use a constant gas temperature ($T_g = 800$ K). As measured in Ref. [20] (in a helicon discharge in the same pressure and power range as in this work), the gas temperature is in the range of 600–1000 K. The error bars in Fig. 4 (as well as in the figures below) show the change of result considering the possible uncertainty in the gas temperature.

Fig. 5 shows the results of electron density. It increased significantly with the pressure as can be expected. However, when increasing the helicon discharge power, $n_e$ almost remains a constant (within the error bar). There are two possible explanations: (a) the depletion degree of the neutral gas is already quite high with ECR power at 500 W alone and not increased further (as discussed in section 4.3) and (b) the discharge length increases significantly with the power as observed in our experiment and thus
the energy absorbed per unit length is not increased much. On the other hand, the prediction of the CR model could be affected by the inhomogeneous plasma parameters. That is to say, there is an uncertainty in the current zero-dimensional model, because of which we can obtain the order of magnitude of \( n_e \) but cannot measure a small change very accurately. Especially, in Fig. 5(a), the electron density seems nearly the same for the three types of discharges at the pressure 0.13 Pa. The underlying mechanism needs to be further studied using a more accurate method e.g. a microwave interferometer. A future work is planned to overcome this limitation.

![Electron temperature given by the OES method with the CR model](image1)

Fig. 4 Electron temperature given by the OES method with the CR model: (a) versus the pressure at ECR power of 500 W, helicon (HEL) power of 500 W, and the combination of the two discharges, and (b) versus the helicon power at pressure 5 mTorr and a constant ECR power of 500 W. The result is obtained using a gas temperature of 800 K and the error bars show the possible change of result if using a gas temperature of 600 K or 1000 K.

![Electron density from the OES method with the CR model under the same conditions as in Fig. 4](image2)

Fig. 5 Electron density from the OES method with the CR model under the same conditions as in Fig. 4.

4.3 Gas depletion degree

After the parameters \( T_e \) and \( n_e \) are obtained, one can calculate the gas depletion degree as:

\[
D_{\text{depletion}} = \frac{n_g + \sum n_i}{p/kT_g} = \frac{p/kT_g - n_e \cdot (1 + T_e/T_g)}{p/kT_g}.
\]

(6)

This equation describes how significant the effect of gas depletion is due to the electron and ion pressures. It increased from 0 to 1 with the increase of \( n_e \) and \( T_e \). As shown in Fig. 6, the gas depletion degree here is \(~0.5\) under different conditions. Actually, a depletion degree of \(~0.9\) in the plasma center is reported in Ref. [20] under similar conditions. This is reasonable since the discharge in this work is inhomogeneous and the OES method only provides a measurement of the average value; the depletion degree is possibly \(~1\) in the center and as small as \(~0\) at the wall.

![Gas depletion degree calculated from the electron temperature and density obtained above](image3)

Fig. 6 Gas depletion degree calculated from the electron temperature and density obtained above.

5 Conclusion

The optical emission spectroscopy method was used for a preliminary study of a hybrid plasma source. The method obtains the variation trend of the electron temperature and density with operating parameters. Especially, the electron density at certain positions was found not to increase with power when the gas depletion degree is already as high as \(~1\). On the other hand, the electron temperature increased with power in the hybrid mode. This work provides a general characterization of this type of a hybrid discharge. Future study will focus on revealing the physical mechanisms of electron heating in hybrid plasmas.

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