Study on the optical emission spectrum diagnosing of the low-temperature plasma using a collisional-radiative model based on the detailed-term-accounting approximation

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Abstract. Considering the difficulty of large computation and the characteristic of helicon plasma, a modified collisional-radiative model was proposed for the diagnosis of low-temperature helicon argon plasma. A simplified 47-level is proposed due to the lack of experimental support of transition data at high levels as well as heavy computation to obtain macroscopic parameters of helicon argon plasma, e.g., electron number density $n_e$ and electron temperature $T_e$. A creative twice-matching method is proposed in the model because the current double-line intensity ratio method shows significant sensitivity in diagnosing low-temperature electrons. Calculations based on this model shows the spectrum intensity depends on the electron temperature as well as density for low-temperature plasma, especially when it’s below 6eV. The twice matching process based on the priori knowledge chooses 15 spectrums cognizable within the wavelength from 680nm to 860nm, adopting the absolute values of the lines to match with the results calculated by the collisional-radiative model. This method greatly reduces the average error to 13.7%. The result indicates that the precision of the electron temperature and density has been improved a lot and the relative errors are 25% and 40%, respectively. Within the accuracy range above, the research shows when RF power is 500-800W and the pressure is 0.5-1.3Pa, the electron number density rises with the increasing RF power and decreases with the increasing magnetic field strength (450-900G) and gas pressure. Moreover, comparing to the number density of electrons, the electron temperature changes less and rises with the decreasing pressure.

1. Introduction

Langmuir probe is easily subjected to electromagnetic interference[1] so that the diagnostic method of optical emission spectrum (OES) show its unique value in diagnosing the helicon plasma.

The first step in the diagnosis of emission spectrum is to determine the plasma state model and the spectrum description model. According to Clarenbach’s [2] job, the state of helicon plasma is between the local thermodynamic equilibrium (LTE) model and the corona equilibrium model (CEM) and needs to be described by the collisional-radiative model (CRM).
This paper intends to adopt the Vlček's model [3] [4] as the basis. Firstly, simplifying the model to make it higher computationally efficient. Secondly, designing a multi-spectrum matching method with a higher precision.

This paper will be developed as follows: Section 2 introduces the detailed construction relationship of the velocity coefficient formula and the composition of CRM for the parameters diagnosis of low temperature plasma. Section 3 describes the diagnosis method of argon plasma by CRM and shows the diagnosis result and analysis of helicon argon plasma under different working conditions. The last section is a summary of the full paper.

2. Simplified CRM mode

The CR model with the basis of Vlček’s work is developed and simplified in the paper. The larger the main quantum number contained in the CRM is, the more accurate it becomes, while the computation increases with the multiplier relationship of the number of spectrums. On the other hand, unlike the work of Vlček and Bogaerta which aims at clarifying the mechanisms by which the excited levels are populated [3][4], the target of the article is to determine the macroscopic parameters such as electron number density \( n_e \) and temperature \( T_e \). We need to calculate each pair of \( (n_e, T_e) \) according to CRM. The final results are obtained by fitting in parameter space \( (n_e, T_e) \). During this process, simplification of energy level system can significantly reduce the computation and improve the efficiency.

Moreover, particles with high energy only takes a small percentage, especially in low-temperature-low-pressure helicon plasmas. In addition, transition data of atoms at higher energy levels often lacks experimental and computational support (e.g., CRM with max main quantum number \( n=19 \) proposed by Vlček ignores a considerable number of transitions at high levels [3][4]), so the CRM with excessive principal quantum numbers has little practical values.

During this article, the 65-level system is simplified into 47 effective levels for heavy computation as well as lack of actual data support of transitions at high level. Based on the reasons above, the simplification of the model is reasonable. We explore the feasibility of low-temperature argon plasma CRM containing ground state to \( n=10 \) for OES diagnosis. Based on the effective level method proposed in the literature [3] and [4], the model divides the spectrums into 47 effective levels to reduce the computation. The energy level subdivision is shown in Table 1.

Table 1. Details on 47 effective levels, including the term, energy, statistical weight and the data characterizing the transition and ionization from the ground state.

| Number | The term | Energy (eV) | Statistical weight | The data characterizing the transition | Ground-excited check | Ionization check |
|--------|----------|-------------|--------------------|--------------------------------------|---------------------|-----------------|
|        |          |             |                    |                                      | \( \alpha_{1n} \) | \( \beta_{1n} \) | \( \alpha_n \) | \( \beta_n \) |
| 1      | 3p61S    | 0.0         | 1                  | -                                    | -                   | -               | 0.51           | 1               |
| 2      | 4s[3/2]2 | 11.548      | 5                  | S                                    | 6.7E-2              | -               | 0.35           | 4               |
| 3      | 4s[3/2]1 | 11.624      | 3                  | A                                    | 1.92E-2             | 4               | 0.35           | 4               |
| 4      | 4s'[1/2]0| 11.723      | 1                  | S                                    | 9.5E-3              | -               | 0.35           | 4               |
| 5      | 4s'[1/2]1| 11.828      | 3                  | A                                    | 4.62E-2             | 4               | 0.35           | 4               |
| 6      | 4p[1/2]1 | 12.907      | 3                  | P                                    | 3.5E-2              | -               | 0.45           | 4               |
| 7      | 4p[3/2]1.2+[5/2]2.3 | 13.116 | 20 | P | 1.15E-1 | - | 0.39 | 4 |
| 8      | 4p'[3/2]1.2 | 13.295 | 8 | P | 3.5E-2 | - | 0.39 | 4 |
| 9      | 4p'[1/2]1 | 13.328      | 3                  | P                                    | 7E-3                | -               | 0.39           | 4               |
| 10     | 4p'[1/2]0 | 13.273      | 1                  | P                                    | 7E-3                | -               | 0.32           | 4               |
| 11     | 4p'[1/2]0 | 13.480      | 1                  | P                                    | 3.5E-2              | -               | 0.32           | 4               |
| 12     | 3d[1/2]0.1+[3/2]2 | 13.884 | 9 | S | 1.5E-1 | - | 0.67 | 1 |
| 13     | 3d[7/2]3.4 | 13.994 | 16 | S | 9E-2 | - | 0.67 | 1 |
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| 14 | 3d'[3/2]2+[5/2]2.3 | 14.229 | 17 | P | 4.2E-2 | - | 0.67 | 1 |
| 15 | 5s' | 14.252 | 4 | A | 3.71E-3 | 4 | 0.67 | 1 |
| 16 | 3d[3/2]1+[5/2]2.3+5s | 14.090 | 23 | A | 3.33E-2 | 4 | 0.67 | 1 |
| 17 | 3d'[3/2]1 | 14.304 | 3 | A | 1.79E-2 | 2 | 0.67 | 1 |
| 18 | 5p | 14.509 | 24 | P | 7E-2 | - | 0.67 | 1 |
| 19 | 5p' | 14.690 | 12 | P | 5E-2 | - | 0.67 | 1 |
| 20 | 4d+6s | 14.792 | 48 | A | 5.15E-2 | 1 | 0.67 | 1 |
| 21 | 4d'+6s' | 14.976 | 24 | A | 3.06E-2 | 1 | 0.67 | 1 |
| 22 | 4f' | 15.083 | 28 | - | - | - | 0.67 | 1 |
| 23 | 4f | 14.906 | 56 | - | - | - | 0.67 | 1 |
| 24 | 6p' | 15.205 | 12 | - | - | - | 0.67 | 1 |
| 25 | 6p | 15.028 | 24 | - | - | - | 0.67 | 1 |
| 26 | 5d'+7s' | 15.324 | 24 | A | 6.5E-4 | 1 | 0.67 | 1 |
| 27 | 5d+7s | 15.153 | 48 | A | 3.69E-2 | 1 | 0.67 | 1 |
| 28 | 5f',g' | 15.393 | 64 | - | - | - | 0.67 | 1 |
| 29 | 5f,g | 15.215 | 128 | - | - | - | 0.67 | 1 |
| 30 | 7p' | 15.461 | 12 | - | - | - | 0.67 | 1 |
| 31 | 7p | 15.282 | 24 | - | - | - | 0.67 | 1 |
| 32 | 6d'+8s' | 15.520 | 24 | - | - | - | 0.67 | 1 |
| 33 | 6d+8s | 15.347 | 48 | A | 2.4E-2 | 1 | 0.67 | 1 |
| 34 | 6f',g',h' | 15.560 | 108 | - | - | - | 0.67 | 1 |
| 35 | 6f,g,h | 15.382 | 216 | - | - | - | 0.67 | 1 |
| 36 | 8p' | 15.600 | 12 | - | - | - | 0.67 | 1 |
| 37 | 8p | 15.423 | 24 | - | - | - | 0.67 | 1 |
| 38 | 7d'+9s' | 15.636 | 24 | - | - | - | 0.67 | 1 |
| 39 | 7d+9s | 15.460 | 48 | - | - | - | 0.67 | 1 |
| 40 | 7f',g',h',l' | 15.659 | 160 | - | - | - | 0.67 | 1 |
| 41 | 7f,g,h,i | 15.482 | 320 | - | - | - | 0.67 | 1 |
| 42 | 8d',f',... | 15.725 | 240 | - | - | - | 0.67 | 1 |
| 43 | 8d,f,... | 15.548 | 480 | - | - | - | 0.67 | 1 |
| 44 | 9p',d',f',... | 15.769 | 320 | - | - | - | 0.67 | 1 |
| 45 | 9p,d,f,... | 15.592 | 640 | - | - | - | 0.67 | 1 |
| 46 | 10s',p',d',f',... | 15.801 | 400 | - | - | - | 0.67 | 1 |
| 47 | 10s,p,d,f,... | 15.624 | 800 | - | - | - | 0.67 | 1 |

Note: i) S-Spin forbidden, P-Parity forbidden, A-Optical allowed.
ii) $\alpha_{i,n}$ presents the transition-dependent parameters: $\alpha_{i,n}^A, \alpha_{i,n}^P, \alpha_{i,n}^S$.

The atoms and ions in helicon plasma can be regarded as cold compared with electrons since their energy is low. Therefore, excitation and ionization caused by collisions among fast atoms and fast ions are neglected when analyzing the balance of particles. Excitation/de-excitation and ionization/recombination (singly ionized) caused by electron-atom inelastic collisions, spontaneous emission and radiation excitation (photo-induced excitation) are the three main sources for the change of particle number in helicon plasmas with lower energy. In addition, the diffusion losses of particles to the wall in the discharge tube is also an important loss mechanism. This article takes into account the diffusion losses of two 4s metastable states. In summary, the particle reaction contained in the model is:
where $m$ and $n$ are different energy levels of argon atoms, $C_{mn}$ is the excitation and de-excitation rate coefficient, $S_i$ is the ionization rate, $\alpha_i$ is the three-body recombination rate, and $A_{nm}$ is the Einstein spontaneous emission coefficient from the $n$th to the $m$th level, $\Theta_{ik}$ is escape factor in the fluorescence capture effect.

According to the reaction contained in the model, the time rate of change in particle number density is:

$$\frac{dN_i}{dt} = \sum_{k=3}^2 \left( N_k C_{ik} + \sum_{k=1}^3 N_k A_{ik} \Theta_{ik} + n_i^2 N_i \alpha_i \right)$$

$$- N_i \left( \sum_{i=3}^2 C_{ii} + n_i S_i + \sum_{i=1}^3 A_{ii} \Theta_{ii} \right)$$

$$- \begin{cases} \frac{N_i D_i}{\Lambda^2}, & \text{if } i = 1, 3 \\ 0, & \text{elsewhere} \end{cases}$$

where $N_i$ is the number density of the $i$th level, $N_i$ is the number density of argon ion, and $N_i=n_e$ is established only under the condition of singly-ionization; $D_i$ and $\Lambda$ are the diffusion coefficient and the characteristic length respectively.

The radial loss is dominant for cylindrical discharge cavities whose length is much larger than diameter (i.e. $L>>R$). The diffusion coefficient determined by experiment is related to the atom temperature $T_a$ and the ground state atom population $n_1$:

$$D_i = 2.4 \times 10^{-3} T_a^{1/2} / n_i$$

For steady-state plasma, the time-dependent term on the left side of equation (2) is 0. Clarenbach et al. pointed out that when the plasma density is not less than $10^{17}$ m$^{-3}$, the steady-state condition is established even for the plasma source operating on the pulse, or it can called metastable state: $dN_i / dt \approx 0^{[2]}$.

When $i$ takes from energy level 2–47 in Table 1, the 46-order linear equations are constructed by equation (2), which takes the particle number density of each energy level as unknown quantities. In this model, excitation, de-excitation, ionization and three-body composite rate coefficients are calculated as follows:

$$C_{mn} = \sqrt{2e / m} \int_{-\infty}^{\infty} \varepsilon \sigma_{mn}(\varepsilon) f(\varepsilon) d\varepsilon \quad ; \quad n < m$$

$$C_{nm} = \sqrt{2e / m} \int_{-\infty}^{\infty} \varepsilon \sigma_{nm}(\varepsilon) f(\varepsilon - u_m) d\varepsilon \quad ; \quad n < m$$

$$S_i = \sqrt{2e / m} \int_{-\infty}^{\infty} \varepsilon \sigma_i(\varepsilon) f(\varepsilon) d\varepsilon$$

$$O_i = \sqrt{2e / m} \int_{-\infty}^{\infty} \sigma_i(\varepsilon) f(\varepsilon - u_m) d\varepsilon$$

where $u_{nm}$ is the energy difference between the $n$th and the $m$th energy level, $u_n$ is the ionization energy of $n$th level, $g$ is the atomic statistical weight, $\sigma_{nm}$ is the excitation cross section, $\sigma_n$ is the ionization cross section.
section, \( h \) is the Planck constant, and \( T_e \) is the electron temperature. \( g_+ \) is the statistical weight of ions at ground state, \( f \) is the electron energy distribution function (EEDF). The experiment found that in the source chamber of the helicon plasma, the EEDF is not too far from the Maxwell distribution\(^2\). The preliminary study greatly simplifies the calculation process by using Maxwell distribution EEDF.

Cross sections for optically allowed transitions and forbidden transitions are taken into account when calculating the excitation cross sections\(^3\). When excited atoms at level 1 collides with electrons with energy \( E \), the ionization cross sections and composite cross sections are calculated based on the method proposed in literature\(^3\) and\(^5\), respectively.

3. Another section of your paper

3.1 Testing

Figure 1 shows a helicon plasma discharge image in a vacuum maintenance system.

![Figure 1. The image of helicon discharge \( P_r=600W, B=450G, P_0=0.91Pa \)](image)

![Figure 2. Schematic diagram of experimental set-up for OES diagnosing and calibration](image)

The evacuation system of the vacuum chamber (\( \Phi1.2\times2m \)) can keep the background pressure not more than \( 2\times10^{-2} \text{ Pa} \) during the discharge. Figure 2 is a schematic diagram of the experimental setup of the emission spectrum. The fluorescent signal emitted from the measurement point passes through the optical acquisition component and coupled into the multimode fiber, then transmitted to the monochromator, and diffracted by the grating in the monochromator. The selected frequency components are recorded by an enhanced intensified charge coupled device (ICCD).

In the study of this paper, the spectrum measurement point is located at the center of the discharge tube, but the gas pressure here is not directly measured in the real discharge chamber. It is tested...
afterwards in the metal mold with the same internal dimensions and the same gas flow rate. The measured pressure values under different gas flow rate are shown in Table 2.

| Gas flow rate (SCCM) | 10 | 15 | 20 | 25 | 30 |
|----------------------|----|----|----|----|----|
| Pressure (Pa)        | 0.49 | 0.70 | 0.91 | 1.10 | 1.31 |

Table 2. The gas pressure at different mass flow rate.

The Ar atomic line of 680nm~870nm has been recorded in this study. There are 17 identifiable lines with higher intensity. Because of the dispersion caused by optical components in the actual measurement path, and different sensitivity ICD shows for energy of light with different frequency, in this study, the broadband calibration light source (Ocean Optics, DH-2000-CAL) is used to calibrate the spectrum intensity measurement. The intensity distribution after intensity calibration is shown in Figure 1, where the intensity calibration coefficient is shown on the right vertical axis of Figure 1. When the wavelength is changed from 680 nm to 870 nm, the photoelectric conversion efficiency of the spectrum decreases rapidly with increasing wavelength since the blazed wavelength of the monochromator is 550 nm. Figure 3 shows a helicon plasma discharge image in a vacuum maintenance system.

Figure 3. The calibrated intense of the measured lines ($P_{rf}$=600W, $B$=450G, $P_0$=0.91Pa) and the calibration coefficient

In the 17 lines of Figure 3, the intensity of spectrum with a wavelength of 811.5 nm is too high so the spectrum is easy to be saturated. The intensity of 727.1 nm spectrum is too low so the error is large. The ion spectrum with high intensity (4p'4F1/2 $\rightarrow$ 3d4F3/2) is mixed near 810.4 nm line and is hard to separate. Based on the factors above, 15 lines are finally selected for analysis. The parameters are shown in Table 3.

| number | wavelength (nm) | $A_g$ (s$^{-1}$) | Lower level | Upper level |
|--------|-----------------|-----------------|-------------|-------------|
|        |                 |                 | energy (eV) | spectrum level | energy (eV) | spectrum level |
| 1      | 696.543         | 6.39E+06        | 11.548      | 4s[3/2]$_2$ | 2           | 13.327        | 4p'[1/2]$_1$ | 9           |
| 2      | 706.721         | 3.80E+06        | 11.548      | 4s[3/2]$_2$ | 2           | 13.302        | 4p'[3/2]$_2$ | 8           |
| 3      | 738.398         | 8.47E+06        | 11.623      | 4s[3/2]$_1$ | 3           | 13.302        | 4p'[3/2]$_2$ | 8           |
| 4      | 750.386         | 4.45E+07        | 11.828      | 4s'[1/2]$_1$ | 5           | 13.479        | 4p'[1/2]$_0$ | 11          |
3.2 Multi-line secondary matching diagnosis method

After determining the particle density of each energy level by the particle balance equation of CRM, the spectrum emissivity is obtained according to the formula below:

$$\varepsilon_{sk} = \frac{hc}{4\pi \cdot \lambda_k} N \Theta_{sk}$$ (8)

Where c represents the speed of light and $\lambda_k$ refers to the wavelength. The spectrum emissivity should be proportional to the measured light intensity since the plasma radius studied in this paper is small and the absorption on the propagation path is ignored.

According to the aforementioned CRM, the spectrum emissivity in the range of $T_{\text{gas}}=1000\text{K}$, $T_e:0.1\sim20\text{eV}$, and $n_e:10^{11}\sim10^{20}\text{m}^{-3}$ is calculated. It is found that all the double-line intensity ratios are dependent on both $T_e$ and $n_e$. Figure 4 is a typical contour plot of the double-line intensity ratio, where Figure 4(a) shows the ratio of line 7 to line 8, and Figure 4(b) shows the ratio of line 10 to line 13. The figure shows that the spectrum intensity ratio is similar to be controlled by single factor only when the electron temperature is higher than 6eV. When the electron temperature is lower than 6eV, the line intensity ratio is sensitive to the changes of $T_e$ and $n_e$. The electron temperature of the helicon plasma is usually not higher than several electron volts, so the double-line method cannot be directly used for diagnosis.

Figure 4. The intense ratio of calculated lines by CRM(a)I7/I8;(b)I10/I13
The double-line intensity ratio of the plasma exhibits extremely different characteristics in different electron temperature regions, which may be caused by inconsistent sensitivity of the reaction cross sections at different electron temperatures. The spontaneous emission coefficient and fluorescence capture factor have no relation with overall plasma parameters. The line intensity $I_{ik}$ of the specified energy level $i$ to $k$ is proportional to the upper element particle number density $N_i$, i.e., $I_{ik} \propto \varepsilon_{ik} \propto N_i$; and the particle number density is the solution of the linear non-homogeneous equation (2). Therefore, the sensitivity of the spectrum intensity to temperature is essentially the sensitivity of the rate coefficient to temperature. In the low temperature region, the ionization and collision cross sections of each excited state show non-monotonously drastic changes following the change of electron temperature. While in the high temperature region, the collision cross sections gradually tend to be stable monotonously, and the collision rate coefficient in the particle balance equation also has a little change. Given the failure of double-line ration method in such situation, a multi-spectrum matching method is designed in this paper. Firstly, the objective function is defined:

$$E_{\text{error}} = \frac{1}{K} \sum_{i}^{K} \left| \frac{I_{i,c} - I_{i,m}}{\min(I_{i,c}, I_{i,m})} \right|$$

(9)

Where $I_{i,c}$ is the normalized spectrum emission rate; $I_{i,m}$ is the normalized measured spectrum intensity. Due to the lack of reference information, the relative intensity of the line is measured; $K$ is the number of lines used for diagnosis. Equation (9) shows that the variable $E_{\text{error}}$ defines the normalized average relative error. Each group $(T_e, n_e)$ of the parameter space corresponds to an $E_{\text{error}}$. When $K$ is large enough and the parameter space is sufficiently dense, the minimum $E_{\text{error}}$ can be considered to be approximately equal to spectrum simulation error of CRM.

Figure 5 shows the line matching results under sample conditions (RF power 600W, magnetic field strength 450G, discharge pressure 0.91Pa). The average error of the line intensity is 13.7%.

**Figure 5. The comparison on the line intense between calculation and experiment**

According to the matching result of equation (9), the normalized average relative error of the absolute intensity information of the spectrum is lost. When the spectrum intensity is sensitive in the plasma parameter space, the true parameter pair $(T_e, n_e)$ may be located within a circle which is
centered on the minimum error with a certain radius. In order to estimate the measurement error of the real plasma parameter, the error limit of the spectrum is determined by the following equation:

$$E_{\text{error,lim}} = E_{\text{error,min}} + E_m$$  \hspace{1cm} (10)

$E_{\text{error,lim}}$ is the spectrum error limit, $E_{\text{error,min}}$ is the minimum error of the parameter space, and $E_m$ is the measurement error.

Figure 6 represents the results of a single matching of the relative intensity of the spectrum under sample conditions. It shows the error limit, the parameter distribution range, and the minimum error parameter point. The figure shows that the possible distribution of plasma electron density and electron temperature is wide. It means there is a big error in the matching result if only the relative intensity information is used. When the minimum error value is taken as the measurement result, the parameter error limit is about: $\Delta T_e/T_e \approx 230\%$, $\Delta n_e/n_e \approx 250\%$.

Figure 6. The probable distribution of plasma parameters by single matching

According to the knowledge of helicon plasma, the electron number density increases with the rise of RF power (monotonously not falling). Based on this, a twice matching method using the prior knowledge is proposed, and the absolute intensity information of the spectrum is adopted during the twice matching. The possible distribution range of the parameter pair ($T_e, n_e$) is obtained by single matching of the spectrum. For each parameter pair ($T_e, n_e$) within the error limit, the correspondence relationship between the absolute light intensity and the spectrum emissivity is established by constructing spectrum correction coefficient (K-element array) via measured strength and spectrum emissivity, and the absolute light intensity value of the calculated spectrum is obtained by dividing the spectrum emissivity of the whole space by the correction coefficient. The calculated intensity is respectively twice matched with the measured light intensity value under different powers by the formula (10). The minimum $E_{\text{error}}$ corresponds to the parameter value ($T_e, n_e$) under the respective working conditions; the calculation result is selected by the prior knowledge. It is thought that the parameter pairs which show that the electronic number density increases monotonously with the increase of RF power is reasonable.

In this paper, the spectrum of different RF incident powers (500W, 600W, 700W and 800W) under the condition of magnetic field strength 450G and discharge gas pressure 0.91Pa are matched twice. The sample spectrum (600W) parameter distribution is shown in Figure 7. The comparison between Figure 6 and Figure 7 shows that the range of plasma parameters diagnosed by a priori knowledge and absolute spectrum intensity information has been greatly reduced, and the limit error interval is: $\Delta T_e/T_e \approx \pm 25\%$, $\Delta n_e/n_e \approx \pm 40\%$ ne.
3.3 Analysis of influencing factors based on emission spectrum diagnosis

The parameters of discharge gas pressure, magnetic field strength and RF incident power were changed to measure the parameters of helicon plasma of argon under different working conditions. The variation trend of plasma parameters is shown in Figure 8.

Figure 8(a) shows the change of electron number density with that of RF power when the gas pressure is 0.91 Pa and the magnetic field is 450G, which indicates that the electron number density increases with the rise of RF power, but the increased amplitude is smaller and exhibits a "saturated" characteristic when higher than 700W. Therefore, for the small-sized helicon plasma source studied in this paper, the excessive RF power cannot bring about a significant plasma density increase under the conditions of the same discharge gas pressure and magnetic field as expressed above.

Figure 8(b) shows the change of the electron number density with that of magnetic field strength when the gas pressure is 0.91 Pa and the RF power is 600 W. It indicates that the electron number density decreases with the rise of the magnetic field strength, and the decreasing trend is approximately linear. Considering the number density of electrons in helicon plasma under low power (hundreds of watts) has a peak with the increase of the magnetic field (the peak magnetic field is usually several tens of gauss to hundreds of gauss) [6][7][8]. It indicates that the magnetic field applied in the experiment has exceeded the value of the peak magnetic field strength. The excessive magnetic field has a "supersaturation characteristic" on the plasma generation, so it is not necessary.
Figure 8. Plasma parameters at different discharge condition ($n_e$ vs. $P_{rf}$ (RF power) ($B=450$ G, $P_0=0.91$ Pa); (b) $n_e$ vs. $B$ (magnetic strength) ($P_{rf}=600$ W, $P_0=0.91$ Pa); (c) $n_e$ vs. $P_0$ (discharge pressure) ($P_{rf}=600$ W, $B=450$ G); (d) $T_e$ vs. $P_0$ ($P_{rf}=600$ W, $B=450$ G)

Figure 8(c) shows the electron density at different gas pressures when magnetic field strength is 450 G and RF power is 600 W, indicating that the electron number density decreases when pressure rises. It shows a steep drop between 0.9 Pa and 1.1 Pa, while it changes little in other pressure point. In the discharge experiment, as the gas pressure drops, it can be observed that the glow of the plasma is brighter and bluer (radiation tends to shorter wavelength).

Unlike the electronic number density, the electron temperature is kept relatively stable under all the conditions. Figure 8(d) shows the electron temperature at different gas pressures when magnetic field strength is 450 G and RF power is 600 W, indicating that the electron temperature shows a slight downward trend with increasing pressure. This trend is consistent with the experimental values of Toki[9] as well as the calculation and analysis of Xiong Yang et al [8]: the number of neutral particles in the discharge chamber increases with the increase of gas pressure. Collisions between electrons and neutral particles are more frequent, eventually leading to more energy loss of electrons. Electron temperature drops to a lower value.

4. Conclusion
The collisional-radiative model with the basis of Vlček’s CRM is developed and simplified in the article. Unlike the work of Vlček and Bogaerta which aims at clarifying the mechanisms by which the excited levels are populated, the target of the article is to determine the macroscopic parameters such as electron number density $n_e$ and temperature $T_e$. The final results are obtained by fitting in parameter space ($n_e$, $T_e$) after calculating each pair of ($n_e$, $T_e$) according to CRM. The 65-level system is simplified into 47 effective levels for heavy computation as well as lack of actual data support of transitions at high level. Meanwhile, during helicon plasma studied in the article, the plasma is relatively cold and the transitions at high energy level only takes a small percentage. Based on the reasons above, the simplification of the energy level system is reasonable.

The calculation results of the helicon argon plasma emission spectrum show that the rate coefficient is extremely sensitive to temperature in the low temperature region ($T_e<6$ eV), causing that the traditional double-line intensity ratio method cannot be applied to the diagnosis of such low-temperature plasma. The creative twice matching method based on multi-line diagnosis is adopted to match with the CRM calculation results by adopting all identifiable 15 lines in the wavelength range within 680–860 nm of helicon argon plasma emission spectrum. The error of the emission spectrum diagnosis is very large (>200%) when only the relative intensity information of the lines is adopted. And the error reduces significantly: $\Delta T_e/T_e \approx \pm 25\%$, $\Delta n_e/n_e \approx \pm 40\%$, by using the absolute strength information of the spectra proposed in this paper and the multi-spectrum matching method based on a priori-knowledge. Within the accuracy range above, the research shows that under the condition of RF power 500–800 W, magnetic field strength 450–900 G, gas pressure 0.5-1.3 Pa, the electron number
density increases with the increasing RF power, and decreases with the increasing magnetic field strength and gas pressure. While electron temperature changes a little and increases with the decline in gas pressure.

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