Optical emission spectroscopy for electron parameter determination in xenon plasma and its application in a magnetized discharge chamber

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Abstract: As a non-intrusive diagnostic method, optical emission spectroscopy (OES) is barely affected by magnetic field and bombard of heavy particles. These factors are essential which may lead to trouble when one use Langmuir probe in thruster diagnostics. A lot of researches on OES method for xenon plasma are published in recent years, and it is capable of diagnosing electron temperature using atomic lines now. However, ionic lines of emission spectrum are not used in current method, which may be the key to obtain some important plasma parameters, e.g. electron density. In this work, the relation between line ratios and plasma parameters are analyzed using a comprehensive xenon collisional-radiative model that has ionic excited levels incorporated. Based on which an OES method that is capable of diagnosing electron temperature and electron density simultaneously is developed. Using this novel OES method, electron parameters in magnetized and unmagnetized discharge chamber are determined and then compared with Langmuir probe results. This method has the potential to develop into image diagnostic method, which is highly competitive in on-orbit diagnostics.

Experiment is performed on discharge chamber of an Ion thruster. A LaB6 hollow cathode is used as electron source and a barrel made of stainless steel is used as anode. The hollow cathode is located along the center line of the barrel, and has both diameter and length of 90 mm.

I.Introduction

Optical emission spectroscopy (OES) is widely used in diagnostics of low-temperature plasmas[1-4]. With a simple experimental setup, it is capable of diagnosing plasma parameters non-invasively, or even more, determining the 2-D distribution of parameters[5]. As a passive diagnostics method, it doesn't disturb the discharging status, and is highly applicable in determining plasma parameters of electric propulsion (EP) devices, especially for narrow places such as the thruster channel and the discharge chamber.

In 1993, researchers from NASA Lewis Research Center and Sverdrup Technology Inc. measured emission spectrum in the plume of a SPT-100 Hall thruster. They analyzed the distribution of excited states, and found it is hard to obtain reliable information about plasma temperatures without a proper collisional-radiative (CR) model, because of the non-equilibrium nature of EP plasma[6]. In 1997, researchers from CNRS built a CR model, which is capable of predicting emission intensity of 10 xenon lines and 6 helium lines. Based on the model, they studied the electron energy distribution function (EEDF) of a specially designed Hall thruster by analyzing the variation of relative strength xenon lines and helium lines. They found that by using the intensity ratios of HeI to XeI, preliminary results on the ionization degree and the shape of EEDF could be obtained[7]. In 2006, through a cooperative study of the TSNIIMASH and the Air Force Research Laboratory of the USA, researchers built a CR model which could provide reliable

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predictions of several XeI spectral lines[8]. Based on the model, they tried to determine the electron temperature and ion density in the discharge channel and the plume region of an anode layer thruster. Besides, they found that ion-impact process plays a role in the plume region of the thruster. In 2009, using cross sections calculated by an R-Matrix method and by a distorted-wave method, the CR model used for OES is improved by considering the effect of metastable levels more reasonable[9]. Based on this model, a multi-line OES method is used in determination of electron temperature on two different types of Hall thruster. In 2010, through a cooperative study of the Northwestern Polytechnic University of China and the University of Tokyo, based on another Xe CR model which includes 173 atomic levels, researchers determined plasma parameters by OES method in a Hall thruster[10].

By reviewing former researches, it is found that the previous OES method barely uses information of ionic lines due to lack of ionic levels in the CR models they used. As a result, emission intensity of the ionic lines which are highly related to ion density are hardly determined.

In this work, an OES line-ratio method utilizing the emission lines from the Xe(6p) and Xe+(6p) levels is proposed, which is based on a comprehensive collisional-radiative model for electric propulsion devices. Using the very OES method, electron parameters in the magnetized discharge chamber are determined, and are compared with those measured by a Langmuir probe.

II.The Line Ratio Method

The CR model is capable of predict the spectrum by solving a set of rate balance equations. Using a set of plasma parameters, coefficients in the rate balance equations could be calculated, plus fundamental data describing processes, e.g. cross sections for collision processes, the rate balance equation is solvable, density distribution of excited species and emission spectrum could be obtained. The basic idea of the OES method is to rebuild the spectrum measured in experiment by adjusting plasma parameters inputted in the CR model.

Figure 1 gives the schematic diagram of the OES method. Since the rate balance equations are a set of non-linear equations due to self-absorption process, solution seeking of these equations takes some time. To boost the "spectrum-rebuilding" process, the equations are solved under series of plasma parameter sequences to generate a spectra database. "Spectrum-rebuilding" process is actually done by seeking the most similar spectrum in the database.

Due to uncertainties of fundamental physical data, the model have different errors in predicting densities of excited states and the corresponding emission lines intensities; besides, emission lines are sensitive to different plasma parameters due to diverse kinetic mechanisms of excited states. For the purpose of determining different plasma parameters, one should choose different emission lines. Thus a line feature analysis procedure is required. Figure 1 takes the diagnostics of electron density and electron temperature as an example. Line sensitivity could be evaluated by calculating the partial differences of line intensities to electron temperature and electron density. Information about precision of line predicting could be get from studies of the CR model, while measurement uncertainties could be get by analyzing experimental data. By making comprehensive evaluation of line sensitivity, precision of line predicting, accuracies of lines in measurement, a set of line sequence will be chosen.

Since in experiment, line intensities are the counts of photons captured by the detector mounted on the spectrometer. It is actually a sum of photons emitted by plasma in the visual field of the optical system. However, line intensity modelled by the CR model is photon count emitted by a unit volume of plasma. The spectrum measured in experiment are not comparable to modelled line intensity, thus the relative line intensities are used by calculating line ratios.

$$L_{ratio} = I_i / \sum_{i=1}^{i=n} I_i \quad , \tag{1}$$

Searching relative intensities of the chosen lines in the database and find which is the most similar to measured one, the plasma parameters corresponds to the very spectrum is the possible result. The difference between the modelled relative intensities and the measured intensities is evaluated by a residual function:

$$Err = \sum_{i=1}^{i=n} \left[k_i \left(L_{ratio\_Mi} / L_{ratio\_Ei} - 1 \right) \right]^2 \quad , \tag{2}$$

The CR model used in this work includes both atomic and ionic 6s, 6p and 5d levels of xenon, thus is capable of predicting intensities of ionic lines, which allows us to use ionic lines in OES method. The information about energy levels included in the model is given in table 1. The model includes the lowest levels of each group, quantities of energy levels in different group are listed in the column named "Quantity", while the energy ranges covered by the levels of each group are also given.

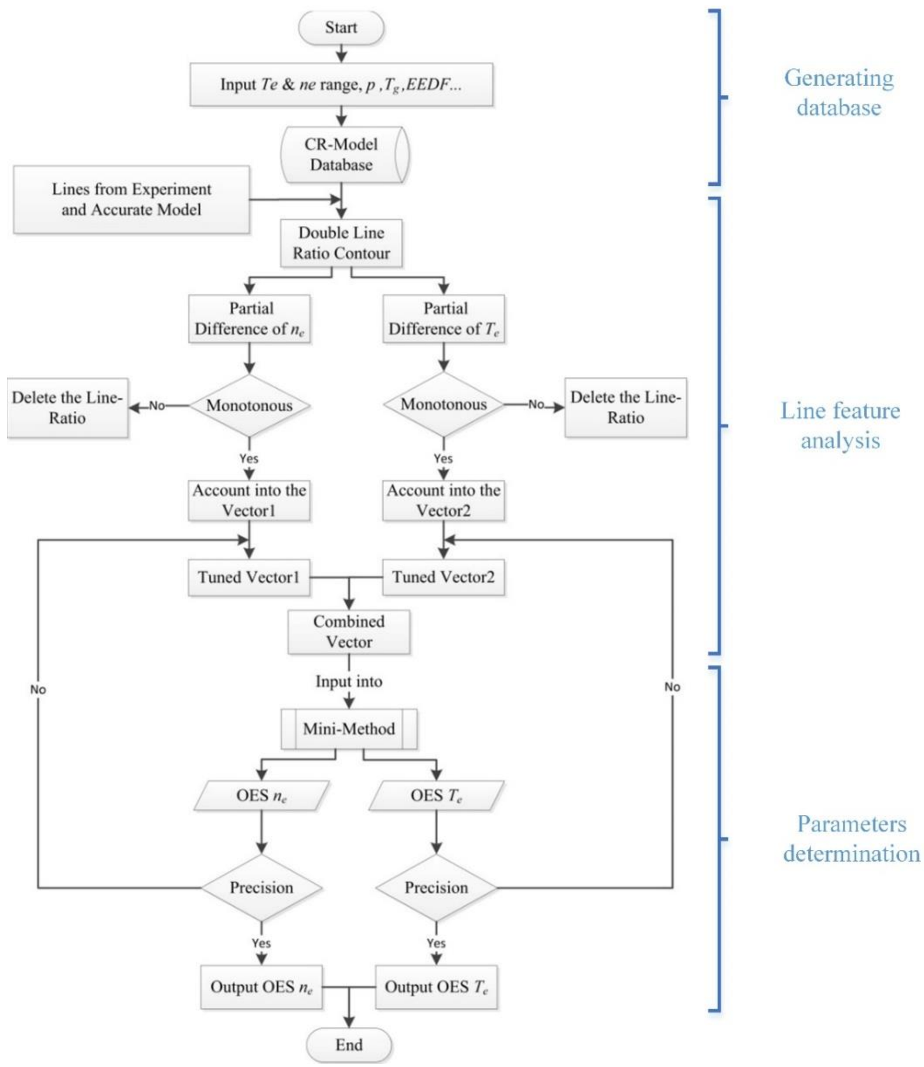

Figure 1 Schematic diagram of the line ratio method.

Table 1 Energy levels included in the CR model

Group	Quantity	Energy range (eV)	Group	Quantity	Energy range (eV)
$5s^25p^6$	1	0	$5p^56d$	8	10.972 ~ 11.163
$5p^56s$	4	8.315 ~ 9.570	$5p^58s$	2	11.258 ~ 11.274
$5p^56p$	10	9.580 ~ 11.141	$5p^54f$	8	11.263 ~ 11.276
$5p^55d$	12	9.890 ~ 11.607	$5p^57d$	8	11.423 ~ 11.498
$5p^57s$	4	10.562 ~ 11.878	$5p^58p$	6	11.426 ~ 11.475
$5p^57p$	6	10.902 ~ 11.015	$5p^59s$	2	11.580 ~ 11.583
$5s^25p^5$	2	12.130 ~ 13.436	$5p^46s$	8	23.669 ~ 28.155
$5s5p^5$	1	23.367	$5p^46p$	21	25.991 ~ 30.627
$5p^46p$	28	23.958 ~ 29.248			

The model used in the OES method considers electron-impact process, ion-impact process as well as charge exchange process. For radiation-related processes, both spontaneous radiation process and self-absorption are considered, which allows usage of the OES method in optical thick plasmas. Processes considered in the model are listed below.

(a) Electron collision processes:

$$e + X \leftrightarrow e + X^* \ , \tag{1}$$

$$e + X^q \leftrightarrow e + X^{q+1} \ , \tag{2}$$

$$e + X^q \leftrightarrow e + X^{(q+1)*} \ . \tag{3}$$

(b) Ion-impact processes:

$$Xe^+ + X \leftrightarrow Xe^+ + X^* \ , \tag{4}$$

$$Xe^+ + X^q \leftrightarrow Xe^+ + X^{(q+1)*} \ . \tag{5}$$

(c) Photon-related processes:

$$X^* \rightarrow X + hv \ , \tag{6}$$

$$X + hv \rightarrow X^* \ . \tag{7}$$

(d) Charge exchange process,

(e) Diffusion process.

Consider all these processes, rate balance equations are written as:

$$\sum_{y \neq x} R_{y \to x}^{col} + \sum_{y > x} R_{y \to x}^{rad} + \sum_{y < x} R_{y \to x}^{abs} = \sum_{y \neq x} R_{x \to y}^{col} + \sum_{y < x} R_{x \to y}^{rad} + \sum_{y > x} R_{x \to y}^{abs} + R_x^{d/t} \ , \tag{15}$$

where R is the process rate. Processes are distinguished by superscript: superscript *col* means collision process, *rad* means radiation process, and *abs* means self-absorption process. $R^{d/t}$ means the loss rate caused by diffusion or transport process. The subscript *y* and *x* tells different energy levels, while *y*<*x* means level *y* is lower than level *x* in energy.

III.Experiments and Results

The OES method is demonstrated on a magnetized discharge chamber, structure of which is shown in figure1. The discharge chamber is composed of a hollow cathode, a cylindrical anode, and a set of magnets to form a particular configuration of magnetic field. A slot is made in the wall of the anode to measure emission spectra inside the discharge chamber. To ensure the sealing of the discharge chamber, a barrel made of quartz is mounted outside the anode. Figure 1 (a) shows the configuration of magnetic field in the discharge chamber when the magnetic field is arranged as cusped-field. Figure 1 (b) shows a picture of the discharge chamber, while pictures of discharge is shown in figure 1 (c).

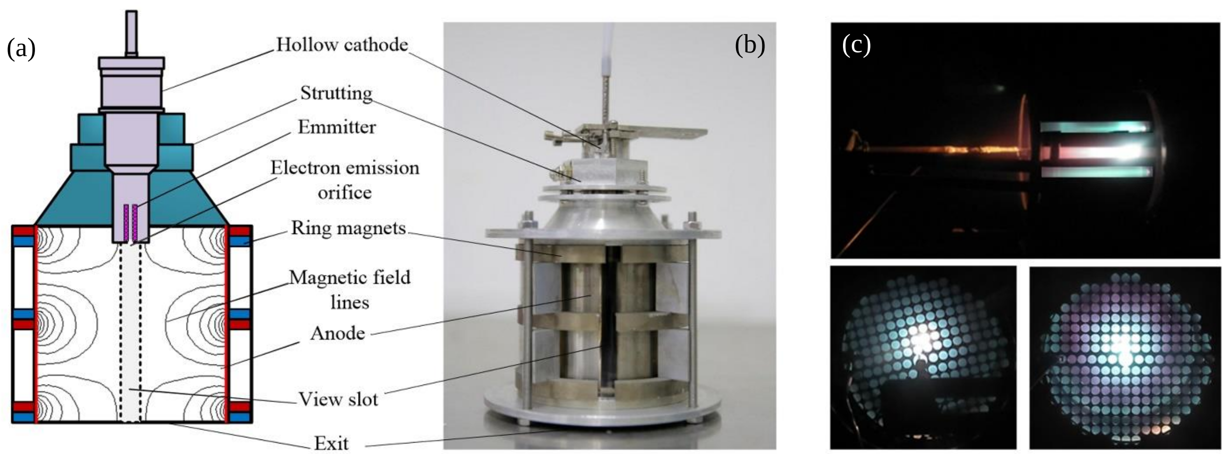

Figure 2 Discharge chamber used in the experiment. (a) shows the configuration of magnetic field in the discharge chamber when the magnetic field is arranged as cusped-field; (b) shows a picture of the discharge chamber, while pictures of discharge is shown in figure 1 (c).

A ceramic tube with inner diameter of 1 mm and length of 100 mm is used for collimating. Using this set of collimating optics, spatially resolved spectra emitted by plasma inside the discharge chamber could be obtained, which means spatial distribution of electron parameters along the axial could be get. The spectra are measured using a Horiba 1000 spectrometer and a CCD detector. The resolution of the optical system is 0.05 nm. Figure 2 shows an emission spectrum measured in the discharge chamber. Both XeI and XeII lines are observed in the spectrum, and strong lines are marked out with their wavelengths. In general, ionic 6p lines are mainly located in the wavelength range of 450 nm ~ 700 nm, while atomic 6p lines are mainly located in 800 nm ~ 1000 nm.

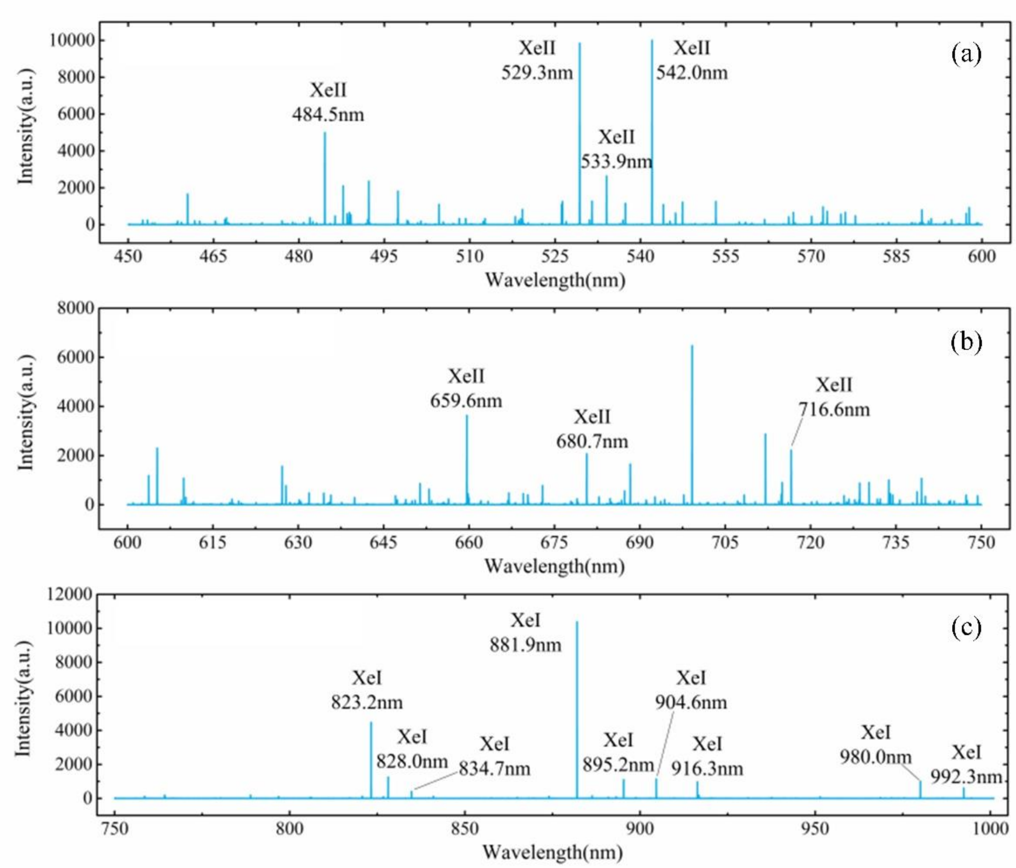

Figure 3. Emission spectrum measured in experiment.

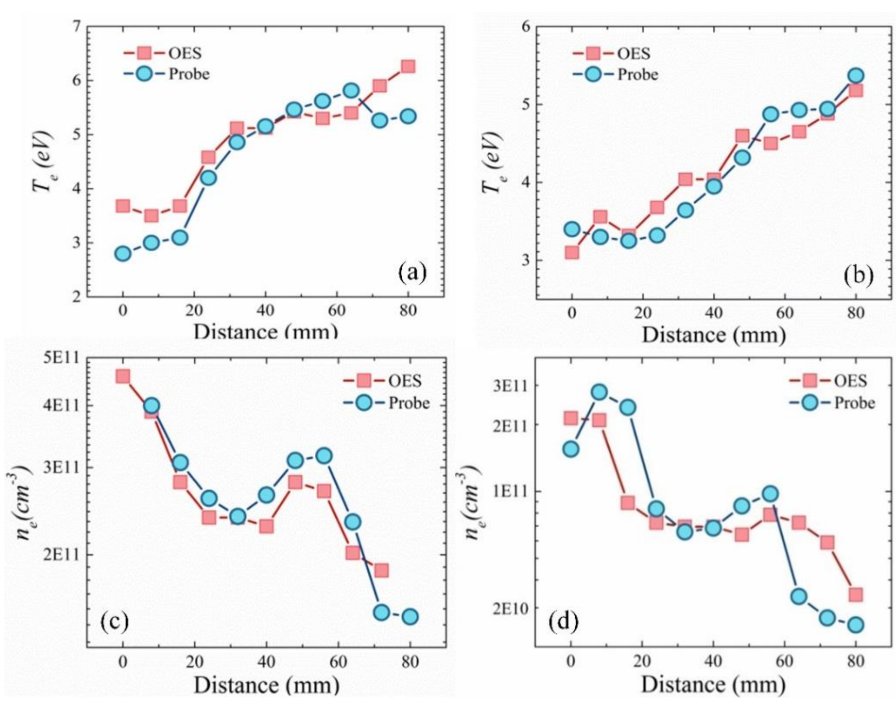

Figure 4. Electron parameters determined by OES method and by Langmuir probe under different discharge condition. The panels (a) and (c) is results in operating condition with 5sccm flow rate, and 5A current, while (b) and (d) shows

results of 5sccm flow rate, and the discharge current is 3A. Panels (a) and (b) shows results of electron temperature, while panels (c) and (d) shows results of electron density.

Using the OES method introduced in section II, spatially resolved electron temperature and electron density distribution in the magnetized discharge chamber are determined under two different operating conditions. Both operating conditions have flow rate of 5sccm, while the discharge current is 5A and 3A respectively. Results of electron parameters are given in figure 4.It is found that the results from OES method and from Langmuir probe are generally in agreement. Comparing results from different operating condition, it is found that the distribution of electron temperature barely evolve with the change of discharge current, while electron density decreases as the discharge current abates.

IV.Conclusion

In this work, an OES line-ratio method utilizing the emission lines from the Xe(6p) and Xe+(6p) levels is presented. The method is based on a comprehensive collisional-radiative model which includes both atomic and ionic levels, and is built for study electric propulsion plasmas. Electron parameters in the magnetized discharge chamber are determined using OES method, and the results are in agreement with the results from Langmuir probe.

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