Gas-discharge plasma diagnostics by a continuous spectrum of optical radiation

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Abstract. In the present work, plasma diagnostics method based on the measurement and theoretical analysis of continuous emission spectrum of a gas discharge was discussed. Using the method, electron temperatures of a DC glow discharge and ferromagnetic enhanced inductive discharge were determined for inert gases in the gas pressure range of 20-200 Pa. Experimental results were compared with the results of numerical calculations for the ferromagnetic enhanced inductive discharge and DC glow discharge. A satisfactory agreement between the optically measured and numerically calculated values of electron temperature was shown.

1. Introduction

Measurements of plasma parameters are very important for studying gas discharge processes and development of plasma technologies. To date, the most common plasma diagnostic technique is Langmuir probe method, which allows determining the electron energy distribution function (or electron temperature) by measuring the current-voltage ($I-V$) characteristics of the probes immersed into plasma. However, there are a number of limitations in the use of the probe method for plasma diagnostics. With an increase of the plasma forming gas pressure above several tens of Pa, the theory of charged particles motion in the probe sheath region is complicated due to particles collisions, thus the interpretation of the probe $I-V$ characteristics becomes difficult [1]. In the case of radio-frequency (RF) discharges, a problem of $I-V$ characteristics distortion arises because of a non-linear response of the probe sheath to the alternate voltage [2]. To reduce the alternating component of voltage on the probe sheaths, systems of resonant filters are used at frequencies that are multiples of the discharge driving frequency (RF compensated probes). If the discharge-driving voltage is not sinusoidal and contains a large number of harmonics, the problem of the Langmuir probe RF compensation is significantly complicated. Besides, $I-V$ characteristic can be distorted due to electron emission (heating of the probes) or the presence of contaminants on the probe surface. Abovementioned factors significantly limit the scope and accuracy of the probe technique.

The use of optical methods for plasma diagnostics allows overcoming the above limitations and performing the measurements under conditions when the probe method application is associated with significant experimental or theoretical difficulties (high gas pressures or temperatures, RF plasma, plasma of aggressive gases, film deposition on the probe surface). In the framework of the paper, we consider the application of an optical method based on measuring a continuous spectrum of optical radiation for the diagnostics of gas discharge plasma in a wide range of current densities and gas pressures.
2. Experimental setup

A principal scheme of experimental setup which allows igniting a low-current DC glow discharge and a high-current AC ferromagnetic enhanced inductive discharge [3] in the same discharge chamber is shown in figure 1. Gas discharge chamber 1 is made of quartz tubes in the form of rectangle, with the long side length of 50 cm (internal diameter of 5.5 cm), and the short side length of 10 cm (ID of 3.5 cm). For the glow discharge generation, a high voltage from DC power supply 2 is applied to aluminum electrodes 3. The typical values of the DC glow discharge current are 10–20 mA and the typical values of discharge voltage are 600–700 V.

To maintain a ferromagnetic enhanced inductive discharge, ferrite cores 4 with the total cross-section of 106 cm² are installed on the gas discharge chamber 1. The main purpose of the ferrite cores is to enhance magnetic coupling between the inductive discharge and the induction coil 5. The enhancement of magnetic coupling allows reducing the inductive discharge driving frequency and increasing the power transfer efficiency [3]. A matching network 6 (variable LC circuit) is used for inductive discharge ignition, discharge current stabilization and power regulation. As a power supply, 12 kVA 50–100 kHz power supply 7 for induction heating is used. It should be noted that the power supply generates a non-sinusoidal (rectangular) output voltage, which would significantly complicate the task of Langmuir probe RF compensation due to the presence of a large number of the driving voltage harmonics to be suppressed. Inductive discharge current I is measured with a current transformer (Rogowski coil) 8. The typical values of inductive discharge current are 1–10 A. Inductive discharge voltage U is measured with a voltage loop 9 encircling the ferrite cores and collecting the alternating magnetic flux $\Phi(t)$ that drives the discharge ($U = -d\Phi/dt$). The typical values of inductive discharge voltage are 100–200 V.

To determine plasma parameters, spectrum of gas discharge radiation is measured in a spectral range of 400–600 nm. In the case of ferromagnetic enhanced discharge, the continuous spectrum intensity is sufficiently high to use a fiber optic spectrometer AvaSpec-2048 10 with a spectral resolution of 0.12 nm. Optical emission of plasma is collected from the axis of a short side of discharge chamber 1 and focused with a lens on the optical fiber of the spectrometer.

In the case of DC glow discharge with a weak intensity of gas discharge radiation, continuous spectrum is measured in the positive column of gas discharge using an optical system combining MDR-3 monochromator, a photo electron multiplier (FEU-100) and an A/D converter. Having much higher sensitivity, this system requires much more time to perform a mechanical spectrum scan. Before the measurements, the system was calibrated with a reference incandescent lamp with a known dependence of the color temperature on the incandescent current.

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**Figure 1.** Experimental setup:

1. gas discharge chamber,
2. DC power supply,
3. electrodes,
4. ferrite cores,
5. induction coil,
6. matching network,
7. AC power supply,
8. current transformer,
9. voltage loop,
10. spectrometer,
11. vacuum meter,
12. forevacuum pump.

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3. Continuous spectrum theory
There are several processes which determine the continuous spectrum of optical radiation of gas discharge plasma. They can be divided into free-bound and free-free radiation. If a free electron turns out to be in a bound state as a result of photo or dielectronic recombination, a photon emission in continuous spectrum takes place. In this case, continuous spectrum has bands determined by atomic or molecular energy levels. If initial and final states of the electron are free, the emission of quant of continuous spectrum occurs due to the electron scattering on ions or neutral gas. In this case, continuous spectrum is determined only by the corresponding collision cross-section and electron energy distribution function. At typical gas discharge plasma ionization degree $\delta < 10^3$, the main process determining the continuous spectrum radiation is the electron scattering on neutral particles [4]. As a result of elastic scattering on a neutral particle, the electron is accelerated. At this moment, the electron emits radiation and the power of radiation can be found in accordance with equation [4]:

$$dQ_m = 4 \frac{e^2 v^2}{3 \pi c} \nu_m (v) dv \omega, \quad (1)$$

where $v$ is the electron velocity, and $\nu_m$ is the effective frequency of electron–atom elastic collisions. For the known electron energy distribution function $f(v)$, the total spectral density of electrons emission in the electron-atom elastic collisions is determined by equation:

$$J_s d\lambda = \frac{8 \pi}{3 c} \frac{1}{\lambda^2} \int_0^\infty v^3 f(v) \nu_m (v) dv d\lambda, \quad (2)$$

where $\nu_{\text{min}} = (2hc/\lambda)^{1/2}$ is the lowest electron velocity for emission of photon with energy of $hc/\lambda$. At a high electron density and a high frequency of Coulomb collisions respectively, a Maxwellian electron energy distribution function can be used in the equation (2).

Using equation (2), the temperature of electrons $T_e$ can be determined by fitting the measured continuous spectrum of gas discharge emission (without atomic and molecular spectral lines) with the calculated one. The temperature corresponding to the best matching between the measured and the calculated spectrum is considered as the electron temperature of gas discharge plasma. Besides the electron temperature, the electron density can also be determined by equation (2) if the intensity of continuum spectrum is measured in absolute units.

A simplified way for electron temperature calculation is to determine the ratio of continuous spectrum intensity for two different wavelengths. In this case, it is necessary to choose two different spectral intervals where continuous spectrum is not overlapped by molecular and atomic emission lines. As an example, dependences of the continuous spectrum intensities ratio $J_s(\lambda_1)/J_s(\lambda_2)$ on the electron temperature are shown in figure 2, calculated for argon plasma with Maxwellian electron energy distribution function using equation (2). It is seen that the ratio grows with an increase of the electron temperature non-linearly. Moreover, at the electron temperature above a certain level, changes in temperature do not practically affect the value of the ratio $J_s(\lambda_1)/J_s(\lambda_2)$. In particular, for argon plasma, this electron temperature level is about 1.5–2 eV, which is a typical electron temperature for many types of argon gas discharges. For helium plasma, the level is a bit higher (up to 3 eV). For higher electron temperatures, it is necessary to measure the ratio $J_s(\lambda_1)/J_s(\lambda_2)$ with a great accuracy.

4. Results and discussion
In figure 3, dependence of the measured electron temperature on the gas pressure is shown for an argon ferromagnetic enhanced inductive discharge. The electron temperature is measured using the ratio of intensities of continuous spectrum for 447.5 nm and 530.0 nm wavelengths. It is seen that with an increase of gas pressure, the electron temperature of the inductive discharge is decreasing. The measured electron temperature values are in good agreement with the calculated ones for the argon ferromagnetic enhanced inductive discharge at the same discharge conditions [5].
**Figure 2.** Continuous spectrum intensities ratio $J_{\lambda_1}/J_{\lambda_2}$ vs. electron temperature, for different wavelengths $\lambda_1$, $\lambda_2$ (argon plasma).

**Figure 3.** Electron temperature vs. argon pressure, for the ferromagnetic enhanced inductive discharge (discharge current 5 A).

**Figure 4.** The emission spectrum of DC glow discharge in helium (solid line) and the corresponding continuum spectrum for $T_e = 2.4$ eV (dashed line). Gas pressure $p = 200$ Pa, discharge current $I = 10$ mA, and voltage drop $U = 620$ V.

In figure 4, a typical emission spectrum of a positive column of DC glow discharge in helium is shown. The continuous spectrum of the glow discharge evaluated by equation (2) corresponds to the electron temperature $T_e$ of 2.4 eV. The electron temperature of the positive column of DC glow discharge measured by optical method is in a good agreement with the value calculated by means of Schottky’s theory at the same discharge conditions [6].
Conclusion
Analyzing a continuous spectrum of optical radiation, the electron temperature of the low frequency (100 kHz) argon ferromagnetic enhanced inductively coupled plasma has been obtained for the gas pressure of 20–100 Pa. Furthermore, the electron temperature of a positive column of DC glow discharge in helium has been measured for the gas pressure of 200 Pa. The measured values of the electron temperature agree pretty well with the result of the Schottky’s theory calculation (for DC glow discharge) and numerical simulations (for the ferromagnetic enhanced inductive discharge) that confirm the possibility of using the method for plasma diagnostics. The method can be applied for the case of low and moderate electron temperatures \( (T_e < 2–3 \text{ eV}) \), which are typical for gas discharges at medium and high plasma densities. For the higher electron temperatures measurements, the sensitivity of a spectral tool or an optical interval should be increased.

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References
[1] Lochte-Holtgreven W 1968 Plasma Diagnostics (Amsterdam: North-Holland)
[2] Chen F F 2003 Lecture notes on Langmuir probe diagnostics (electronic materials of the Int. Conf. on Plasma Science ICOPS 2003, Jeju, Korea)
[3] Godyak V 2013 Journal of Physics D: Applied Physics 46 283001
[4] Raizer Yu P 1997 Gas Discharge Physics (Berlin: Springer)
[5] Isupov M V, Fedoseev A V, Sukhinin G I and Ulanov I M 2015 High Temperature 53 179–87
[6] Engel A 1955 Ionised Gases (Oxford: Clarendon Press)