Review Paper

A Brief Review of Electron Kinetics in Radio-Frequency Plasmas

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Abstract

Electron kinetics, which shows two distant discharge regimes (nonlocal and local), has attracted major interest in both plasmas physics and industrial applications. In this paper, the nonlocal and local electron kinetics in radio frequency plasmas are briefly reviewed.

Keywords: Nonlocal and local electron kinetics, Radio frequency plasmas, Electron heating, Electron energy relaxation, Inductively coupled plasma, Capacitively coupled plasma

I. Introduction

Electron kinetics, which shows nonlocal or local property in plasmas, has attracted major interest in both plasma physics and industrial applications [1-13] as it provides the fundamental discharge mechanism and control-knob of many applications, such as semiconductor/display/solar-cell processes, nuclear-fusion operations, spacecraft propulsion, discharge lamps, gas reformation, and structuring of nanomaterials. To address the electron kinetics of radio-frequency (RF) plasmas, the electron heating depending on plasma generation source types and the electron energy relaxation process such as momentum, excitation, and ionization collisions should be understood in a given characteristic dimension. In this paper, the nonlocal and local electron kinetics in RF plasmas are reviewed with plasma sources, electron heating mechanism, and electron energy relaxation.

II. Plasma generation sources

In plasmas, electrons are accelerated by electric field and heated via phase breaking process such as electron-neutral collisions. Therefore, it is important to understand the generation and spatio-temporal propagation mechanisms of the electric field inside the plasmas. The representative examples of the electron heating source in RF plasmas are electromagnetic and electrostatic fields.

There are typically two types of plasma sources: capacitively coupled plasma (CCP) and inductively coupled plasma (ICP). The CCP, which consists of two electrodes in a chamber, is generated by the electrostatic field. Because of the spatial distribution of the electron density in the plasmas, the electrostatic field applied from the electrode is almost damped at the sheath scale. Therefore, the electron heating region in the CCP is located at the plasma boundary where the electrostatic field intensity is maximum.

The ICP is sustained by the electromagnetic field. When the time-varying current flows to the antenna coil, the magnetic field is generated, which reproduces the electric field inside the chamber. Because of the diamagnetic property of the plasma, the electromagnetic field is damped at the skin-depth scale [11-13]. Therefore, electron heating in the ICP occurs in the vicinity of the antenna coil.

III. Electron energy relaxation

In plasmas, the electrons experience various collisions with neutral and charged (ions, electrons, and negative ions) particles. Among these collisions, the main process is elastic and inelastic collisions with neutral gases in low-temperature plasmas. Owing to the collision frequency and mass-dependent energy transfer mechanism, the dominant energy loss (relaxation) mechanism is the inelastic collisions with neutral gases and/or electron-electron collisions. Therefore, the energy...
of heated electrons is mainly relaxed with these collision processes.

From these facts, the electron energy relaxation length (EERL) \( \lambda_e \) is defined as

\[
\lambda_e = \left( \lambda \lambda' \right)^{1/2}
\]

where \( \lambda \) and \( \lambda' \) are the electron mean free paths for the elastic and inelastic collisions, respectively. The low-energy electrons’ \( \lambda_e \) is given as [14]

\[
\lambda_{el} = \lambda_{en} \left[ (2m_e/M) + (\nu_{en}/\nu_{en}) \right]^{1/2}
\]

The high-energy electrons’ \( \lambda_e \) is given as [14]

\[
\lambda_{eh} = \lambda_{en} (\nu_{en}/\nu)'^{1/2}
\]

Here, \( m_e, M, \nu_{en}, \nu_{en}, \) and \( \nu' \) are the electron mass, ion mass, electron-electron collision frequency, electron-neutral collision frequency, and electron inelastic collision frequency, respectively. As mentioned, inelastic collisions (ionization and excitation) are the dominant electron cooling processes. It means that the EERL for high-energy electrons is much shorter than that for low-energy electrons in rare gas plasmas because the inelastic collision cross sections start at a certain threshold value above a high electron energy. In the example shown in Fig. 1, the excitation of Ar plasma occurs above the electron energy of 11.56 eV, and the EERL significantly decreases above the excitation threshold energy. However, it should be noted that the EERL even for the low-energy electrons can be considerably shortened in molecular gas plasmas because of the presence of various inelastic collisions (vibration excitation collisions, rotation collision, and dissociative attachment collisions) in the entire electron energy region [15].

IV. Local electron kinetics

At high gas pressure, heated electrons from the plasma boundary experience numerous collisions with background gases near the same place (plasma boundary); thus, they lose energy and become low-energy electrons. It means that the EERL is much shorter than the characteristic dimension (such as chamber length), and the maximum electron heating region corresponds to the maximum ionization region. This is the so-called local electron kinetics. Therefore, owing to local electron kinetics, at high gas pressures, the plasma density, electron temperature, and plasma potential are maximum near the plasma boundary where the electron heating source is located. It is noted that applying a magnetic field to the plasma can generate local properties even at low gas pressures because the electrons are confined by the magnetic field [16].

V. Non-local electron kinetics

It was observed that at low gas pressure, the plasma density is maximum at the plasma center rather than the plasma boundary (electron heating region) (see Refs. 17 and 18). This inconsistency between the electron heating region and maximum ionization region is a representative property of non-local electron kinetics.

At low gas pressure, in which the EERL is much longer than the chamber length, the heated electrons from the plasma source at the plasma boundary can travel across the entire chamber length before losing their energy. In this situation, the ionization process can occur everywhere. As a result of the ambipolar diffusion of electrons and ions in plasmas, however, there is a little potential drop inside the plasma bulk, called the ambipolar potential. In the total electron kinetic energy scale (kinetic energy plus potential energy), the electrons’ energy is maximized at the plasma center because the electrons are additionally accelerated by the ambipolar potential; thus, maximum ionization occurs at the plasma center where the
plasma potential is maximum. Therefore, even though electrons are heated near the plasma boundary, the maximum ionization region can be at different positions (such as the center of the chamber with maximum plasma potential) in low gas pressure plasmas. This is an interesting characteristic of non-local electron kinetics. Wiesemann [19] and Tsendin et al. [20,21] first observed nonlocal characteristics from electron energy distribution (EED) measurements. They observed identical EEDs at all spatial positions, which is direct evidence of nonlocal electron kinetics.

VI. Antenna size effect on the electron kinetics

The criteria for evaluating the electron kinetics regime are determined by comparison between the EERL and chamber length. In the CCP, the criterion is quite reasonable because the electron is heated by electrodes with large area. However, it is uncertain whether the criterion is appropriate in all cases of plasma sources. Godyak et al. [22] and Hartig and Kushner [23] reported that nonlocal coupling occurs in the regime where EERL = chamber length. Therefore, the criteria for determining the electron kinetics regime should be evaluated in some other plasmas. Outstanding results have been obtained from the evaluation of electron kinetics regimes in the ICPs. Lee et al. [15,17,24-27] observed that the transition of electron kinetics from nonlocal to local regimes is strongly dependent on the antenna size and configuration in the ICPs. This is because electron heating occurs in the vicinity of the antenna coil, and the electrostatic and electromagnetic fields are differently coupled to the plasma depending on the plasma parameters [13,28,29].

VII. Conclusions

In this paper, the electron kinetics in plasmas was briefly reviewed. This will be helpful for both understanding plasma physics and industrial applications.

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