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Experimental evaluation of space charge limited emission current from tungsten surface in high density helium plasma

Y. Hagino [a], N. Ohno [a,*], S. Takamura [a], M.Y. Ye [b]

[a] *Department of Energy Engineering and Science, Graduate School of Engineering, Nagoya University, Nagoya 464-8603, Japan*
[b] *Max-Planck-Institut Für Plasmaphysik, EURATOM Association, Boltzmannstrasse 2, D-85748 Garching, Germany*

Abstract

A space charge effect on thermoelectron emission current from a tungsten plate has been experimentally investigated in a high density helium plasma. Experimental result shows that the space charge limited current from the tungsten target plate, which is heated by the plasma irradiation, tends to be saturated with an increase in a sheath voltage, which can be predicted by the developed new formula based on the boundary condition of zero electric field on the material surface.

Keywords: Plasma-wall interactions; Divertor; Thermoelectron emission; Space charge limited current; Sheath; Tungsten

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1. Introduction

Control of plasma heat flow onto plasma-facing materials is very long term subject through next generation fusion device, such as International Thermonuclear Experimental Reactor (ITER) to reactor. In particular, intermittent plasma heat pulse associated with edge localized mode (ELM) phenomena is one of the most critical issues in the edge plasma of fusion devices. Such a huge intermittent heat load due to the ELM is expected to be limited by sheath formed in front of plasma-facing materials, which is so called thermal insulation effect in the sheath. However, when the plasma-facing materials are heated up by the plasma heat flow to a high temperature, thermoelectrons emit to reduce the sheath voltage between the plasma and the material surface [1]. The degradation of the thermal insulation due to the reduction of the sheath voltage enhances the electron heat load onto the material surface. Due to this positive feedback, hot spots could be formed to generate a lot of impurities emitted from the surface. This is a typical nonlinear system. Our recent experiment demonstrates the nonlinear interaction between plasma with high heat flux and plasma-facing materials with thermoelectron emission, clearly showing bifurcation and phase transition phenomena [2,3].

In order to estimate the heat load onto the material surface, precise evaluation of the electron emission current is quite important. When the electron emission from the material surface is enough large, the emission current may be regulated by a space charge effect in the sheath region. In vacuum, the space charge limited current can be described by well-known Child–Langmuir formula. In plasmas, Hobbs and Wesson discussed the space charge effect of emitted electrons from the material by using the boundary condition of zero electric field on the material surface when the material is electrically floated [4]. Recent theoretical works based on the zero electric field on the material surface give new formula to describe the space charge limited current for not only floating voltage but also arbitrary sheath voltage [1,5]. However, few experimental evaluation of the new formula has been done. Since the past experiment troubled by a contamination of impurities on the emitting surface

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[*] Corresponding author. Fax: +52-789 3944.
E-mail address: ohno@ees.nagoya-u.ac.jp (N. Ohno).

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(LaB_6) at a relatively low temperature. In this study, a higher temperature has been employed for tungsten (W) emitting surface. In this paper, we will report the experimental observation of the thermoelectron emission current from the W surface in a high density helium plasma and the comparison between the experimental result and the theoretical prediction.

2. Theoretical analysis

In this section, we will briefly mention our formula describing the space charge limited current J_e^s in a plasma. As mentioned before, J_e^s in vacuum is well described by Child–Lamgmuir formula, which is expressed by

$$J_e^s = \frac{4\varepsilon_0}{9}\sqrt{\frac{2e}{m_e}}\frac{\phi^{3/2}}{d^2}, \tag{1}$$

where ϕ and d are potential difference and distance between two electrodes. One attempt has been done to describe J_e^s for electron emission from the material in a plasma based on the Child–Langmuir formula. By employing $d = 2.2\lambda_d$ as the effective sheath thickness in the Child–Langmuir formula, the J_e^s can be well described when the material in a plasma is floated. This result was confirmed by using self-consistent 1-D PIC simulation [6]. The Eq. (1) with $d = 2.2\lambda_d$ is referred to as the modified Child–Langmuir formula hereafter.

Another attempt is to expand the analysis of Hobbs and Wesson [4] to obtain the analytical formula, which is valid for arbitrary sheath voltage. Kuwabara et al. has analytically solved 1-D sheath equations to obtain the following formula [5]:

$$\frac{J_e^s}{J_{es}} = 2.0\exp(-0.5)\frac{G\sqrt{-\pi\Phi}}{1+G}, \tag{2}$$

where J_{es} is electron saturation current $(= 1/4en_e\sqrt{8T_e/\pi m_e})$ and Φ is the sheath voltage normalized by electron temperature T_e. G is given by

$$G = \frac{-\beta_1 + \sqrt{\beta_1^2 - 4\beta_0\beta_2}}{2\beta_2}, \tag{3}$$

where

$$\beta_0 = -4\Phi^2 - 2\Phi(\exp(\Phi) - 1)(\exp(\Phi) - 3), \tag{4}$$

$$\beta_1 = -4\Phi^2(1 - 2\exp(\Phi)) + 8\Phi(\exp(\Phi) - 1) - (\exp(\Phi) - 1)^2, \tag{5}$$

$$\beta_2 = -8\Phi^3 + 4\Phi^2. \tag{6}$$

Eq. (2) matches the formula derived by Hobbs and Wesson when the target plate is floated. Fig. 1 shows the J_e^s calculated by the modified Child–Langmuir formula and the new formula, Eq. (2) as a function of the normalized sheath voltage Φ. Both values match around $\Phi = -1$, which is corresponding to the floating voltage with the space charge limited electron emission. At large negative Φ, the J_e^s values calculated by Eq. (2) are found to be saturated in comparison with those of the modified Child–Langmuir formula. Experimental evaluation of J_e^s is necessary.

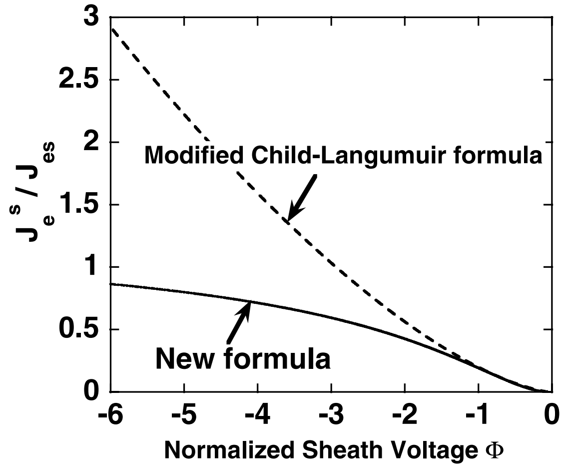

Fig. 1. Calculated space charge limited currents J_e^s normalized by the electron saturation current J_{es} as a function of the normalized sheath voltage Φ. Solid line is calculated by Eq. (2) and dashed one with Eq. (1) by employing $d = 2.2\lambda_d$, where λ_d is Debye length.

3. Experimental setup and results

Experiments have been performed in the linear divertor plasma simulator, NAGDIS-II as shown in Fig. 2. High density helium plasma more than 10^{19} m^{-3} can be generated in steady state by using modified TP-D discharge. Typical electron temperature T_e is around 5 eV. A tungsten target plate (ϕ2 mm × 0.1 mm) is mounted on the head of movable probe system, which is

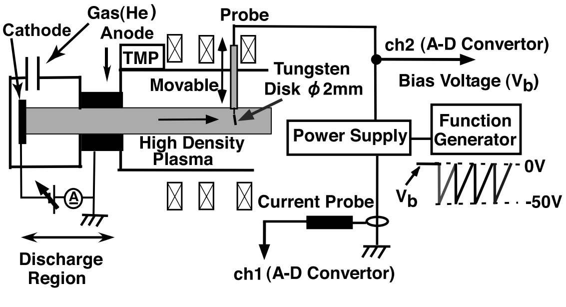

Fig. 2. Experimental setup.

irradiated by the high density helium plasma. Bias voltage, whose waveform can be controlled by a function generator, is applied to the target plate. Before the voltage sweeping to obtain current–voltage (*I–V*) characteristics, the target plate potential is set to 0 V with respect to the grounded vacuum vessel as shown in Fig. 3. The plasma potential is around -10 V so that electron heat flux heats up the target plate to a temperature for sufficient thermoelectron emission which provides space charge limited condition. After pre-heating of the target plate, the measurement of *I–V* characteristics starts at $t = 0$ s by applying the sawtooth bias voltage (-50 to 0 V) with a period of 5 ms to the target plate. Due to the reduction of plasma heat flux to the target plate, the target temperature decreases gradually in time. Finally, the target temperature reaches a temperature without thermoelectron emission through the temperature limited emission condition. Fig. 4 shows the typical change of the *I–V* characteristics in time. It is found that at the bias voltage larger than -35 V, the *I–V* characteristics do not change in time until 30 ms. Independence of the change in surface temperature indicates that a space charge limited condition can be achieved. Subtracting the *I–V* characteristics without thermoelectron emission at 1.28 s from those in the space charge limited condition gives the space charge limited electron emission current J_e^s. Fig. 5 shows the normalized J_e^s calculated from Fig. 4 as a function of the normalized sheath voltage Φ, where T_e is 3 eV. Experimental values are found to be in a good agreement with the theoretical prediction made by Eq. (2) rather than those calculated by the modified Child–Langmuir formula. In Fig. 5, the tendency that the J_e^s is saturated at relatively larger negative Φ is clearly observed. It can be concluded that the Eq. (2) can give the space charge limited electron emission currents from the material in a plasma.

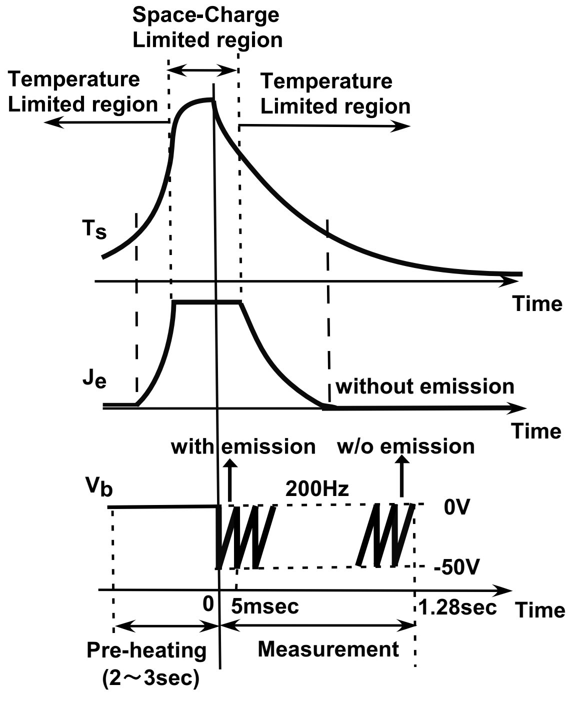

Fig. 3. Schematic of the time evolution of the target temperature T_s and thermoelectron emission current J_e and biased voltage to the target plate V_b.

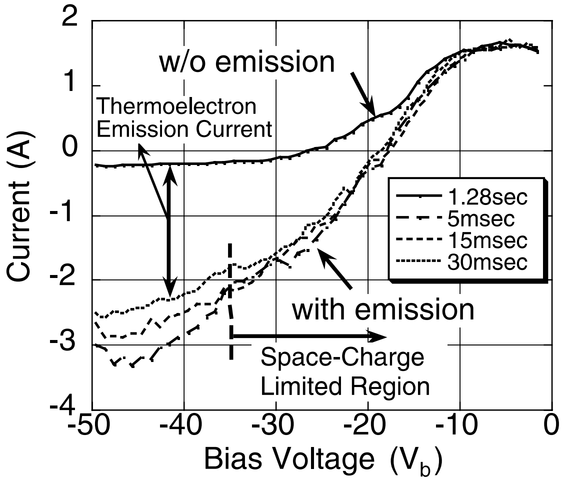

Fig. 4. Measured *I–V* characteristics at each time.

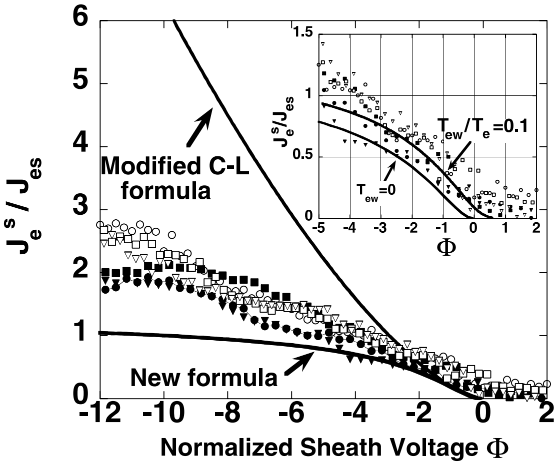

Fig. 5. Measured space charge limited current normalized by the electron saturation current J_{es} as a function of the normalized sheath voltage Φ.

4. Summary and discussion

A space charge effect on the thermoelectron emission current from a tungsten plate has been experimentally investigated in high density helium plasmas in order to evaluate the new developed formula, Eq. (2). The space charge limited currents observed in our experiments reasonably match the theoretical values predicted by Eq. (2).

However, the experimental results always show that the experimental values are slightly larger than the theoretical prediction. Eq. (2) was derived by assuming that the temperature of thermoelectrons T_{ew} is zero. The inset of Fig. 5 shows dependence of J_e^s on Φ by taking a finite T_{ew} into account. A finite T_{ew} gives larger J_e^s. Experimental values quantitatively agree with the theoretical ones at $T_{ew}/T_e = 0.1$, which is estimated by using that T_{ew} is the target temperature (2800 K) and $T_e = 3$ eV.

On the other hand, at Φ less than -8, the deviation between theory and experiment tends to enlarge as shown in Fig. 5. This could be explained by an influence of ionization due to the thermoelectrons. The $\Phi = -8$ means a sheath voltage of 24 V. When Φ is less than -8 with the thermoelectron emission, the thermoelectrons are accelerated in the sheath to have an energy of more than 24 eV. Then, ionization occurs because an ionization energy of helium is 24.6 eV. This ionization results in an enhancement of plasma density, leading to a larger J_e^s. On the other hand, the observed electron saturation current J_{es} does not change because there is no additional ionization at the time when the J_{es} is obtained at $\Phi = 0$. Then, J_e^s/J_{es} becomes large, which suggests the limitation in this experiment. Gases with large ionization potential like helium could be suitable for J_{es} evaluation experiments.

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