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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machinery

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Experimental Investigation of Ion Current to Cylindrical Langmuir Probe in Transitional Regime, Using Microwave Technique*

An experimental study of dependence of the ion current collected by a cylindrical probe on the collisional effects is described. The main achievement is a direct evidence that the ion current in the orbital motion limit (OML) region does not decrease monotonically with growing pressure, this being contrary to the recent theoretical predictions.

Nomenclature

e – electron charge,
E_z – axial electric field,
I_i – ion current density,
I_{i0} – random ion current referred to electron temperature,
i_i – normalized ion current,
I_z – discharge current,
k – Boltzman constant,
l_p – probe length,
M – mass number,
m_i – ion mass,
n_e – electron density,
λ_p – normalized probe potential,
n_0 – axial electron density,
p – gas pressure,
R – glass tube radius,
r_p – probe radius,
S – sheath thickness,
T_e – electron temperature,
v_i – average thermal ion velocity,
V_e – electron temperature [eV],
V_p – probe potential,
V_f – probe floating potential,
λ_D – Debye radius,
λ_i – ion mean free path,
μ_i – ion mobility,
μ_{i0} – ion mobility (at 760 Torr, 300 K),
μ_e – electron mobility.

1. Introduction

Recently several attempts have been made [1÷5] to explain the response of Langmuir probes in the transitional regime. From an analytical point of view the kinetic theory approach of Chou, Talbot and Willis (C.T.W) is perhaps the most rigorous one, however the numerical computations presented in [5] are not extensive enough for the purposes of the experimenter. Recently Talbot and Chou [6] have completed an approximate analysis of the probe response which permits the calculat ionof the effect of collisions on the ion-satura-

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tion current flowing to a cylindrical probe. Their theory predicts the monotonic decrease of the probe current when an average number of ion collisions in the probe sheath is growing. The decrease is assumed to be in a transitional regime between the value as predicted by the collisionless theory of Bernstein, Rabinovitz-Laframboise and the value as predicted by the diffusion theory. According to the collisionless B.R.-L. theory [7, 8] it is regarded that for V_p=const in an Orbital Motion Limit (OML) region $r_p/\lambda_D<3$ the saturation ion current collected by a perfectly absorbing probe attains a maximum possible value, and all other processes in a sheath involve the ion current reduction. However, several experiments have disclosed the existence of a current peak in the OML region, with measured values of the current exceeding that regarded as the maximum one.

Zakrzewski and Kopiczyński [11] have introduced a model of physical phenomena occurring in the probe sheath of space charge. They have also given a procedure for the calculation of the normalized probe current. The results of computations have been presented in a diagram showing the dependence of the normalized probe ion current on λ_D/λ_i parameter, for constant magnitude of a normalized radius (r_p/λ_D=const) and constant normalized probe potential $\chi_p=eV_p/(k\cdot Te)=15$. For $S\sim\lambda_i$ the characteristic maximum was observed, which was becoming flattened when increasing r_p/λ_D parameter. The authors have derived this theory under the assumption that in the collisionless limit (low pressure – small λ_D/λ_i) and for $r_p/\lambda_D\leqslant 3$ an ion current collected by a perfectly absorbing probe is saturated because of orbital motions in a sheath, and is described by the B.R.-L. theory. Elastic collisions of ions with neutral particles have two consequences: the destruction of orbital motions and the elastic scattering of ions. Comparing to the B.R.-L. theory the destruction of orbital motions leads to an increase of the current collected by a probe, but its value is lower than the value of the current reaching the sheath edge as it is considered in the A.B.R. theory [15]. This effect predominates for lower pressures (λ_i is greater or comparable to the sheath thickness S). The elastic scattering of ions causes a monotonic decrease of ion current and dominates for higher pressures (with growing λ_D/λ_i). As a result the current peak appears at a pressure corresponding to approximately one collision in the sheath. The purpose of the present paper is to provide a direct experimental evidence for the occurrence of the ion current maximum observed previously by Kopiczyński et al. [10].

The theory [11] had been designed for constant r_p/λ_D so it was necessary to keep this ratio constant during the measurements. Hence the microwave X-band reflectometer was employed for the determination of relative values of electron density. The applied method enabled a direct comparison between experimental and theoretical results.

2. Experimental arrangement

Measurements were carried out in a positive column of a glow discharge plasma in helium and neon. Fig. 1 presents an experimental arrangement. It consisted of a glass tube, vacuum apparatus, power supplies and measuring circuits. The measuring circuits were: an X-band reflectometer, a conventional double probe arrangement and a set of single probes. The supply system allowed changing the plasma potential and setting it nearly

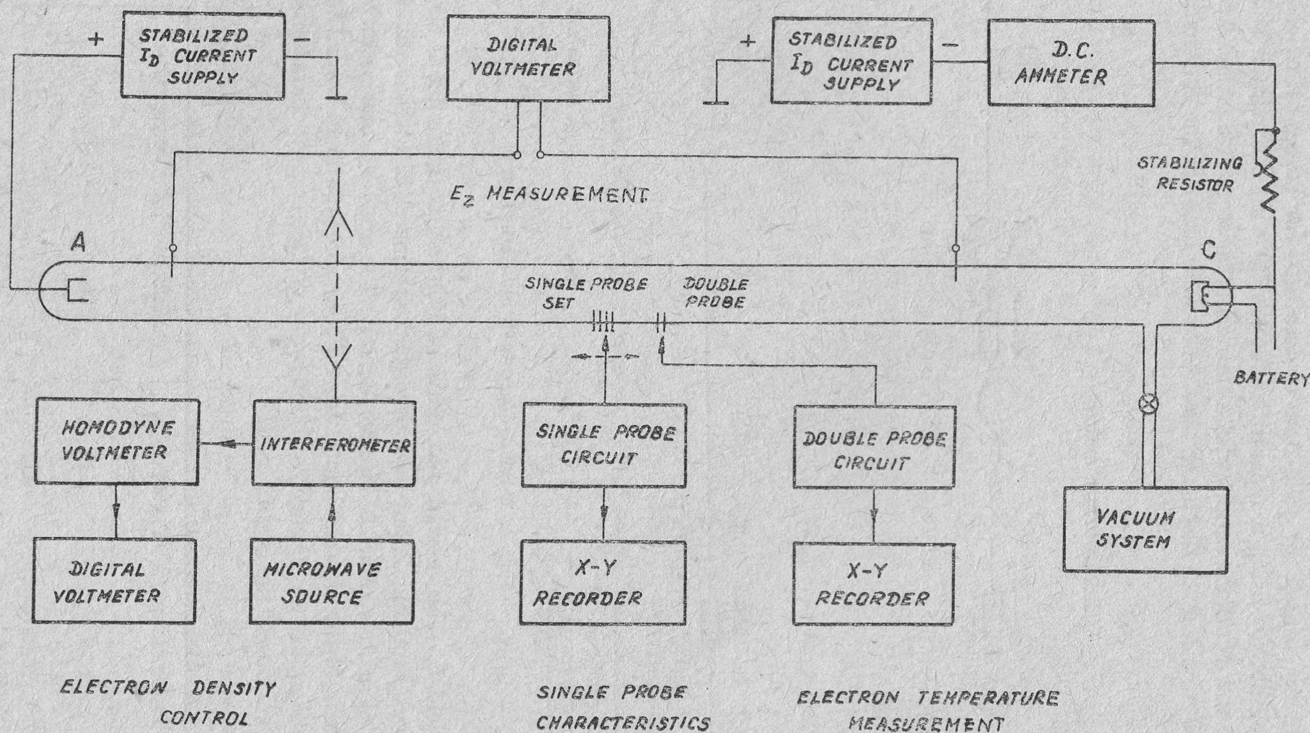

Fig. 1. Block diagram of the experimental arrangement

equal to the ground potential at the point where electric probes were fixed. Low input voltages should be ensured for solid-state devices used for taking probe characteristics. It was accomplished by using a separate anode supply with a regulated and adjustable output voltage and a cathode supply with a stabilizing resistor. Two probes were fixed at a distance of 100 cm along the discharge tube. They were used for the determination of the

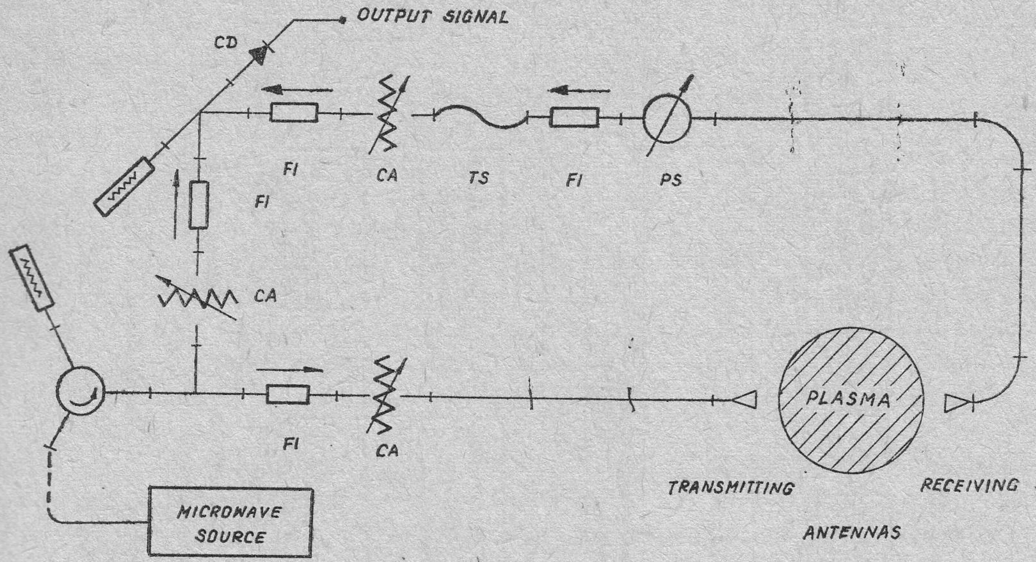

Fig. 2. *X*-band microwave interferometer

axial electric field E_z. The X-band microwave interferometer operating at a frequency of 9.375 GHz ($\lambda = 32$ mm) Fig. 2, has been described elsewhere [12]. It was employed for the determination of relative values of electron density. The double probe circuit was used for the determination of the electron temperature V_e, in a conventional way. The set of four single cylindrical probes was applied to obtain probe voltage-current characteristics. Table 1 shows the dimensions of the probes used.

Table 1

Probe radius [μm]	Probe length [mm]	Material	Aspect ratio
12.5	5.0	W	400
25.0	5.2	Pt	210
50.0	6.2	Pt	125
200.0	8.5	W	42

A special insulating support was applied to protect the probes from the undesired increase of their effective area. The probes were coated with PYREX glass with the tips jutting out.

3. The method and results of measurements

A single probe characteristics were recorded for the probe potential V_p in the range below the floating potential. The gas pressure was defined within the range $30 \div 700$ m Torr and the Debye radius was kept constant during a series of measurements. The electron temperature V_e was determined independently, from double probe characteristics. Simultaneously relative values of the electron density were measured with the aid of the microwave interferometer. The experiment was performed as follows: For a defined gas pressure the discharge current was varied to keep the ratio V_e/n_e and consequently λ_D, constant. The interferometer readings and V_e computations were used to determine this ratio. The probe current corresponding to the chosen polarization $V_p = -14V_e$ was determined from the single probe characteristics. The absolute value of the electron density was independently calculated from the discharge current balance. The distribution of charged particles in a discharge tube is, for the experimental conditions as described above, controlled by the ambipolar diffusion. Therefore, the axial electron density in a plasma may be expressed [10] as

$$n_0 = \frac{2}{\pi e R^2} \frac{I_z}{\mu_e E_z}. \tag{3.1}$$

Values of I_z, E_z and R were measured.
The measured values of an electron mobility presented in [13] may be approximated by the following analytical expression – for helium, for $2 \leqslant E_z/p \leqslant 5$

$$\mu_e \cong 0.8 p^{-1} \cdot 10^6, \tag{3.2}$$

– for helium, for $5 \leqslant E_z/p \leqslant 12$

$$\mu_e \cong \left(1 - \frac{2p}{E_z}\right) p^{-1} \cdot 10^6, \tag{3.3}$$

– for neon, for $6 \leqslant E_z/p \leqslant 12$

$$\mu_e \cong \left(\frac{3.5p}{E_z} + 0.66\right) p^{-1} \cdot 10^6. \tag{3.4}$$

For the purpose of evaluation of the collisional effect on a probe the ion current and the ion-neutral mean free path should be computed. The following expression for λ_i was used

$$\lambda_i = \frac{m_i}{e} \bar{v}_i \mu_i. \tag{3.5}$$

This expression can be simplified if an ion mobility does not change with the electric field. Then

$$\lambda_i = 2.9 M^{\frac{1}{2}} \mu_{i0}\, p^{-1}. \tag{3.6}$$

Taking the values of μ_{i0} collected by McDaniel [13], the mean free path of ions in helium may be expressed

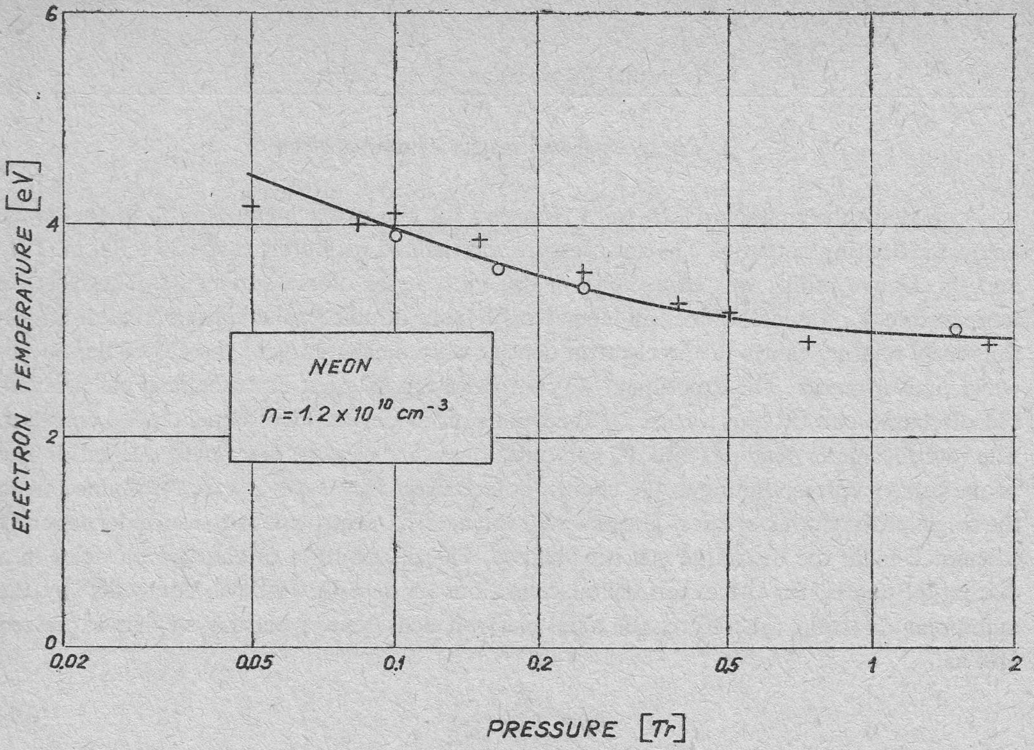

Fig. 3. Electron temperature V_e for gas discharge neon plasma vs. pressure, $R=2.75$ cm, $\lambda_D=\text{const}$

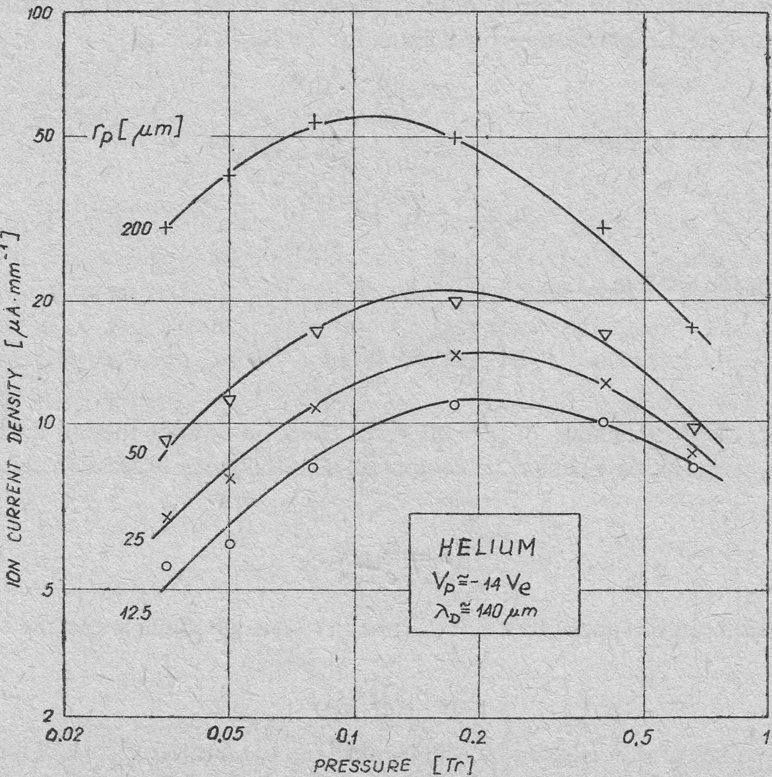

Fig. 4. Probe ion current density $I_i(V_f-10V_e)$ vs. gas pressure p, $\lambda_D=140$ μm, helium

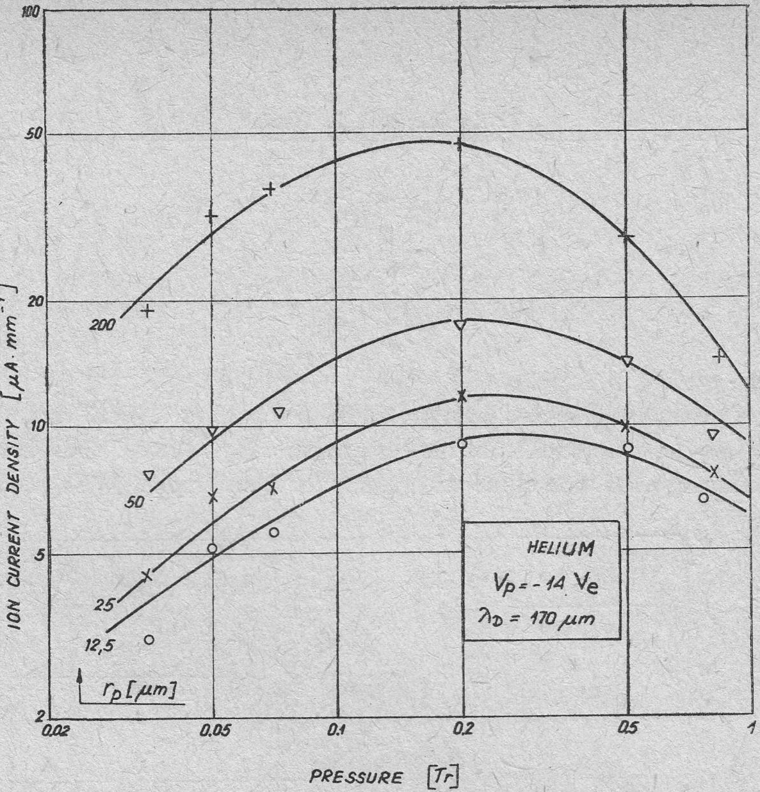

Fig. 5. Probe ion current density $I_i(V_f-10V_e)$ vs. gas pressure p, $\lambda_D=170$ µm, helium

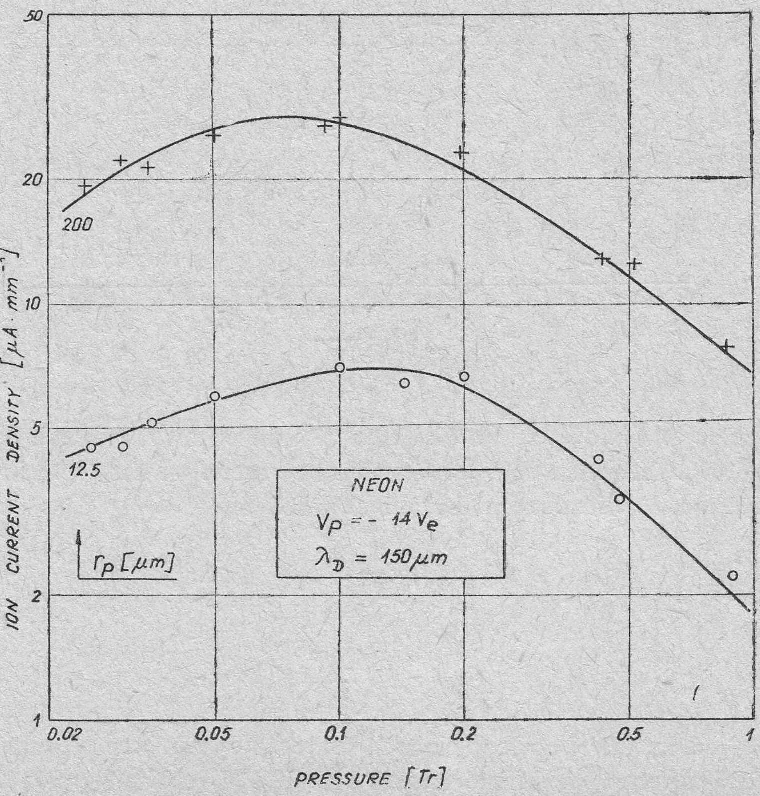

Fig. 6. Probe ion current density $I_i(V_f-10V_e)$ vs. gas pressure p, $\lambda_D=150$ µm, neon

$$\lambda_i \cong \frac{60}{p}\ [\mu m] \tag{3.7}$$

and for neon

$$\lambda_i \cong \frac{52}{p}\ [\mu m], \tag{3.8}$$

where p is the presure in Torrs.

Results of measurements have been presented in Figs. 3 to 7. Fig. 3 shows the electron temperature in neon as a function of the gas pressure. Figs. 4 and 5 show the ion current density in helium as a function of the gas pressure for Debye radii $\lambda_D = 140$ μm and $\lambda_D = 170$

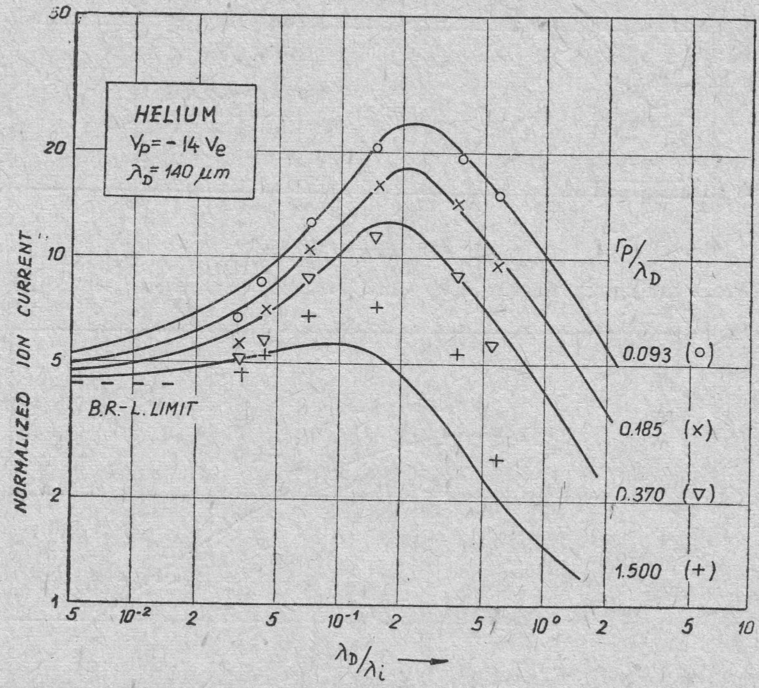

Fig. 7. Normalized probe current $i_i(V_f - 10V_e)$ vs. λ_D/λ_i, $\lambda_D = 140$ μm, helium

μm, respectively. The probe current has been determined for the chosen probe potential $V_p = V_f - 10V_e$. The results obtained for neon have been shown in Fig. 6 for the Debye radius $\lambda_D = 150$ μm. A normalized probe current in helium

$$i_i = \frac{I_i}{I_{i0}}, \tag{3.9}$$

where

$$I_{i0} = n_e r_p l_p \left(\frac{2kT_e}{m_i}\right)^{\frac{1}{2}} \tag{3.10}$$

is the random ion current referred to electron temperature, has been presented in Fig. 7. The normalized current i_i has been determined for $V_p = V_f - 10V_e$, $\lambda_D = 140$ μm, and has been drawn as a function of the gas pressure.

4. Conclusions

A simple model of the ion collection by a cylindrical probe in the transitional regime has been already presented [11]. It was based on the assumption that the main features of the current collection in the OML region were determined by two separate mechanisms: the destruction of orbital motions and the elastic scattering of ions.

The curves in Fig. 4, 5 and 6 show the current peak for both helium and neon plasmas. This is the confirmation that there exist conditions when the measured ion current does exceed the values supposed to be the maximum ones according to the B.R.-L. theory. Investigations of a neon discharge did not give a well pronounced maximum as expected, but the data were taken in the presence of strong instabilities in the plasma column. Those instabilities might be responsible for the pecularities in the curve shape. In Fig. 7 the dependence of the ion current in helium – normalized with respect to the random ion current referred to electron temperature – on the dimensionless parameters r_p/λ_D and λ_D/λ_i is shown. This approach makes it possible to compare the experimental results with the simple theory, from which

$$i_i = \gamma_1 \gamma_2 i_i^{(L)}, \tag{3.11}$$

where $i_i^{(L)}$ – current predicted by the B.R.-L. theory for the collisionless limit, γ_1, γ_2 – functions of r_p/λ_D and λ_D/λ_i describing the increase or decrease of the current due to collisions, respectively.

Modified results of numerical computations of Chen [16] based on the A.B.R. theory were used to determine both the sheath radius and the ion current reaching the edge of the sheath. The agreement between the measured and the calculated values is good.

The widely recognized theory of Talbot and Chou predicts values of the ion current collected by a probe in the transitional regime. Some experimental results [14, 17] show a good agreement with those predictions. However, it should be noted, that the data were obtained for values r_p/λ_D and λ_D/λ_i outside the region of the current peak. Predictions of Talbot et al. should be considered therefore as valid outside this region.

The experimental results obtained give the direct evidence for the existence of the maximum of a probe current in the OML regime. This is in contradiction with the widely recognized theories (Talbot et al). At the same time the results give at least a quantitative confirmation of the validity of the model described in [11].

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Eksperymentalne badania prądu jonowego cylindrycznej sondy Langmuira w przejściowym zakresie ciśnień, przy użyciu techniki mikrofalowej

Streszczenie

W pracy przedstawiono wyniki pomiarów prądu jonowego sondy cylindrycznej w funkcji ciśnienia gazu, przy stałej wartości stosunku V_e/n, a więc i stałym λ_D, w obszarze występowania ruchów orbitalnych. Do pomiaru względnej koncentracji elektronów w plazmie zastosowano interferometr mikrofalowy pracujący w pasmie X. Pomiary przeprowadzono w plazmie wyładowania jarzeniowego w helu i neonie.

Stwierdzono występowanie maksimum prądu jonowego w zakresie $r_p/\lambda_D \leqslant 3$ (obszar występowania ruchów orbitalnych). Rezultat ten definitywnie potwierdza teoretyczne przewidywania Zakrzewskiego i Kopiczyńskiego [11], jest natomiast sprzeczny z przewidywaniami teorii Talbota i Chou [6].

Экспериментальные исследования ионного тока цилиндрического зонда Лангмуира в переходном диапазоне давлений с использованием микроволновой техники

Резюме

В работе представлены результаты измерений ионного тока цилиндрического зонда в функции давления газа, при постоянном значении отношения V_e/n, т.е. и при постоянном значении λ_D, в диапазоне выступания орбитальных движений. Для измерений относительной концентрации электронов в плазме применяется микроволновой интерферометр, работающий в полосе X.

Измерения проводились в плазме тлеющего разряда в гелие и неоне. Констатируется появление максимума ионного тока в диапазоне $r_e/\lambda_D \leqslant 3$ (диапазон выступания орбитальных движений). Этот результат окончательно подтверждает теоретические предвидения Закшевского и Копичиньского [11], но является противоречивым предвидениям теории Талбо и Чу.