DETERMINING THE ROTATIONAL VELOCITY OF GAS-METAL MULTICOMPONENT PLASMA IN A REFLEX DISCHARGE

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For the first time the rotational velocity of plasma layers with $n_p = n_{cr}^{1,2}$ in the gas-metal plasma medium of the reflex discharge was determined using the two-frequency microwave fluctuation reflectometry. The measurement results demonstrated that the angular frequency of plasma layer rotation is varying and therefore the plasma rotates not as a single whole. The maximum rotation velocity increases with magnetic field increasing. The values of the electric field strength in two layers and the plasma particle separation coefficient α were determined.

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One of the features of the plasma, formed and located in the crossed $E\times H$, is its drift rotation. Under certain conditions in the rotating plasma the development of different instabilities can take place that results, for example, in the plasma ion component heating [1,2]. In the case of multicomponent plasma the plasma column rotation leads to the spatial separation of the ion component [3]. Efficiency of the radial ion separation directly depends on the rotational velocity. In connection with the above, the determination of the rotational velocity of multicomponent plasma is of undoubted interest.

To determine the plasma rotation velocity one applies different techniques: charge-exchanging spectro-scopy based on the plasma sounding by high-energy heavy ion beams [4] and on the determination of the Doppler shift of the spectral lines of heavy ions; measurement of the Doppler shift of the spectral line of excited atom or ion [5-8]; microwave Doppler reflectometry based on the sounding wave frequency shift in the case of wave reflection from the moving plasma layer [9]; microwave fluctuation reflectometry [10]; use of spaced electric probes, measurement of the cross correlating function of signals from the probe [11].

Experimental determination of the plasma rotation velocity in the reflex discharge (Penning discharge) has been carried out in [6-9]. The Doppler spectroscopy was used for both the stationary discharge in hydrogen [6], and the pulsed discharge in pure gases Ar, Kr, Xe and mixed gases Ar+Xe, Xe+H_2, Ar+H_2 [7,8]. In [9] (pulsed discharge in hydrogen) the microwave Doppler spectroscopy was used. Experiments in the reflex discharge aimed to determining the rotational velocity were carried out for the plasma formed in the mono- or two-component gaseous medium. The velocity of metal plasma rotation was determined in the vacuum-arc centrifuge for pure metals Mg, Zn, Cd, Pb using electrical probes. Thus, there have not been carried experiments in the reflex discharge in order to determine the gas-metal plasma rotation velocity.

A purpose of the present work was to measure the parametric dependences on the rotational velocity of the gas-metal multicomponent plasma formed in the pulsed reflex discharge.

A peculiarity of the work is the use, for the first time, of the two-frequency microwave fluctuation reflectometry for determining the rotational velocity of plasma layers with c $n_p = n_{cr}^{1,2}$ in the reflex discharge. The microwave fluctuation reflectometry is based on the determination of the intercorrelation function of two poloidally spaced signals reflected from the plasma layer of an equal density. The plasma sounding frequency was chosen so that, firstly, the formed plasma should contain a layer being equal to $n_p = n_{cr}$, secondly, the plasma layers with different n_{cr} should be spaced at some distance. Two chosen sounding frequencies were f^1 = 37,13 GHz and f^2 = 72,88 GHz with n_{cr}^1=1,7×10^{13} cm^{-3} and n_{cr}^2 = 6,5×10^{13} cm^{-3} respectively. Plasma location was performed by the microwave (O-mode) across the plasma column in one and the same cross-section for both frequencies. As distinct from the measurements by the Doppler frequency shift characterized by the tilt sounding and reflection points not coinciding with the layer having $n_p = n_{cr}$, the correlation method is based on the normal sounding. Therefore, it is possible to determine simultaneously the spatial position of the layer and its rotational velocity.

Gas-metal plasma was formed as a result of the discharge in the working medium of a substance composed of H_2, Ar or a gaseous mixture of 88.9%Kr-7%Xe-4%N_2-0,1%O_2 and a sputtered cathode material. Cathodes were made of a monometallic Ti or a composite material, namely, Cu with Ti deposited by the vacuum-arc method. A maximum plasma density was $n_p \geq$ 6,5 ×10^{13} cm^{-3}, discharge voltage $U_{dis.} \leq$4 kV, duration and maximum value of the discharge current intensity were ~ 1 ms and I_{dis} ~ 1,8 kA, respectively. A pulsed mirror-configuration magnetic field (mirror ratio of 1.25) of 18 ms duration was formed by a solenoid composed of six coils having a maximum magnetic field induction $B_0 \leq$ 0,65 T.

Due to the use of two types of cathodes in both cases the cathode material (Ti) enters into the plasma that is confirmed by the spectrometric measurements [12,13]. The titanium content in the discharge, for composite cathodes determined in [14], is at a level of 40-50% and the same value is confirmed by the volume-mass measurements of the cathode material consumption after more than 3000 discharge pulses.

The experimental values of the rotational velocity of the plasma layer with $n_p \geq$ 1,7×10^{13} cm^{-3} for mixtures of H_2+Ti and Ar+Ti and different initial values of the magnetic field are presented in Figs. 1 and 2 (experiments with a composite cathode). Maximum rotational velocities of the gas-metal plasma for the mixture of H_2+Ti were $v_{\varphi 1}$=25×10^5 cm/s (B_1=0,253T) and $v_{\varphi 2}$=8,7×10^5 cm/s (B_2=0.126 T), for the mixture of Ar+Ti $v_{\varphi 1}$=18,5×10^5 cm/s (B_1=0,247 T) and $v_{\varphi 2}$=7,76×10^5 cm/s (B_2=0,107T).

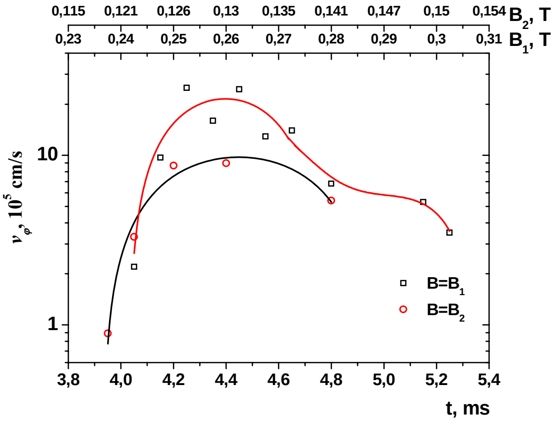

Fig. 1. Time dependence of the rotational velocity of the plasma layer with $n_p \geq 1{,}7\ 10^{13}$ cm^{-3} for the mixture of H_2+Ti and different initial values of the magnetic field (p =2×10^{-3} Torr, $U_{dis.}$ = 3,6 kV, composite cathodes)

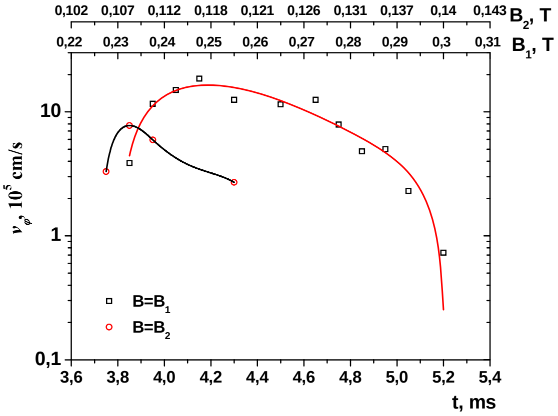

Fig. 2. Time dependence of the rotational velocity of the plasma layer with $n_p \geq 1{,}7\ 10^{13}$ cm^{-3} for the mixture of Ar+Ti and different initial values of the magnetic field (p =1×10^{-3} Torr, $U_{dis.}$ = 3,2 kV, composite cathodes)

As is seen from the Figs. 1 and 2 the maximum rotational velocity of the plasma layer increases with magnetic field increasing. Naturally, that in this case the electromagnetic force increases too, $I_r \times B$ ($I_r = 2\pi r L i_r(r)$ [6], assuming I_r=const). Consequently, the velocity should be increased proportionally to B, i.e. $B_1/B_2 \approx v_{\varphi 1}/v_{\varphi 2}$. In the experiment with the gas-metal mixture (Ar+Ti) the ratios B_1/B_2=2,31 and $v_{\varphi 1}/v_{\varphi 2}$=2,38 were obtained that is in good agreement with the above assumption. For the H_2+Ti plasma the ratios B_1/B_2=2,08 and $v_{\varphi 1}/v_{\varphi 2}$=2,87 were obtained. The rotational velocity increase with magnetic field increasing has been also observed in the earlier experiments [5-7].

The time dependences of the rotational velocity of plasma layers with $n_p \geq 1{,}7\times10^{13}$ cm^{-3} and $n_p \geq 6{,}5\times10^{13}$ cm^{-3} for the mixtures of Ar+Ti and Kr+Xe+N_2+O_2+Ti are presented in Figs. 3 and 4 (experiments with monometallic cathode). The maximum values of the gas-metal plasma for the layer **A** with $n_p \geq 1{,}7\times10^{13}$ cm^{-3} are v_φ^A = 8,7×10^5 cm/s (Ar+Ti), v_φ^A= 7,6×10^5 cm/s (Kr+Xe+N_2+O_2+Ti), for the layer **B** with $n_p \geq 6{,}5\times10^{13}$ cm^{-3} they are v_φ^B = 7,9×10^5 cm/s (Ar+Ti), v_φ^B= 6,7×10^5 cm/s (Kr+Xe+N_2+O_2+Ti). The maximum radii of the layers **A** and **B** determined by the change of a phase reflected from the microwave wave were 4,4 and 3 cm respectively, for both gas-metal mixtures. In the case, when the plasma rotates as a single whole, the rotation frequency ω_φ, of layers having different radii should be equal for all the layers, and the rotational velocity should increase linearly with radius increasing. In the given case the rotation frequencies of the layers **A** and **B** do not coincide with each other, i.e. $\omega_\varphi^A \neq \omega_\varphi^B$ for both gas-metal layers. The rotation frequency of the layer **B** $\omega_\varphi^B > \omega_\varphi^A$, i.e. the layer **B** with a shorter radius has a higher rotation frequency than the layer A with a longer radius. Similar results were obtained in [6].

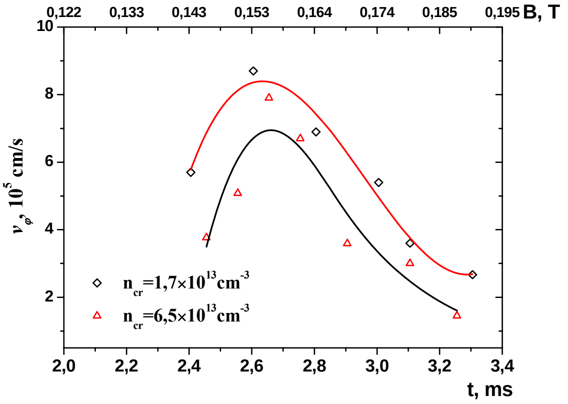

Fig. 3. Time dependence of the rotational velocity of the plasma layer with $n_p \geq 1{,}7\times10^{13}$cm^{-3} and $n_p \geq 6{,}5\times10^{13}$ cm^{-3} for the mixture of Ar+Ti (p =6×10^{-3} Torr, $U_{dis.}$ = 3,8 kV, monometallic cathodes)

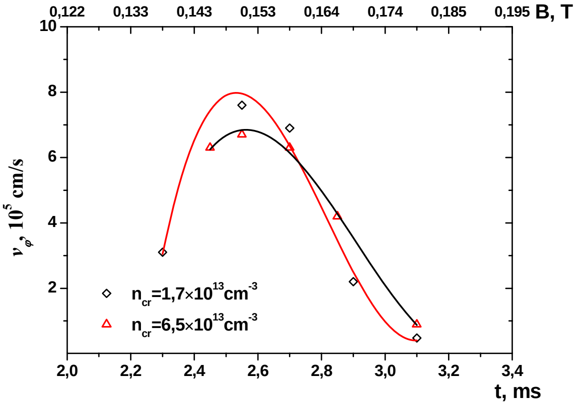

Fig. 4. Time dependence of the rotational velocity of the plasma layer with $n_p \geq 1{,}7\times10^{13}$ cm^{-3} and $n_p \geq 6{,}5\times10^{13}$ cm^{-3} for the mixture of Kr+Xe+N_2+O_2+Ti (p =6×10^{-3} Torr, $U_{dis.}$ = 3,8 kV, monometallic cathodes)

The rotational velocity of the plasma electron component, respectively the rotation frequency, is determined as $v_\varphi = -E/B$ and from this the electric field strength can be evaluated. For the case of the Ar+Ti plasma it is equal to 13,3 V/cm (layer **A**) and 12,2 V/cm (layer **B**), and for the Kr+Xe+N_2+O_2+Ti plasma to 11,6 V/cm (layer **A**) and 10,2V/cm (layer **B**) respectively. In the rotating plasma a spatial ion separation occurs due to the centrifugal effects. The separation coefficient α is determined as in [15]:

$$\alpha = exp(\Delta m\, v_\varphi^2/2kT), \qquad (1)$$

where Δm is the mass difference of various elements, v_φ is the rotational velocity, T is the temperature, k is the Boltzmann constant. Using the experimental value of the plasma rotational velocity and taking $T_i \sim 10$ eV, we obtain the plasma particle separation coefficient α: for Ar+Ti $\alpha \leq 4$, for Kr+Ti $\alpha \leq 3$ and for H+Ti α is from 7 to $\geq 10^3$.

CONCLUSIONS

The conclusions, based on our experimental measurements and evaluations, are as follows.

1. For the first time the rotational velocity of the plasma layer with $n_p = n_{cr}$ in the gas-metal plasma medium of the reflex discharge at frequencies f = 37,13 and 72,88 GHz was determined using the two-frequency microwave fluctuation reflectometry.
2. The measured angular rotation frequency of plasma layers with $n_p \geq 1{,}7\times10^{13}$ cm^{-3} and $n_p \geq 6{,}5\times10^{13}$ cm^{-3} is different for these layers and $\omega_\varphi^A \neq \omega_\varphi^B$. Consequently, the plasma rotates not as a single whole that is in accordance with the results of other papers for a discharge of similar type.
3. The electric field strengths in two plasma layers of a different density were determined. It has been established that their values are close and are at a level of 10…13 V/cm.
4. The maximum rotational velocity increases with magnetic field increasing and reaches the values $v_{\varphi 1}=25\times10^5$ cm/s (H_2+Ti), $v_{\varphi 1}=18{,}5\ 10^5$ cm/s (Ar+Ti).
5. The plasma particle separation coefficient α was evaluated: for Ar+Ti α is from 1.3…1.4 to 4, for Kr+Ti α is ~ 2-3, and for H+Ti α is from 7 to $\geq 10^3$.

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ОПРЕДЕЛЕНИЕ СКОРОСТИ ВРАЩЕНИЯ ГАЗОМЕТАЛЛИЧЕСКОЙ МНОГОКОМПОНЕНТНОЙ ПЛАЗМЫ ОТРАЖАТЕЛЬНОГО РАЗРЯДА

Ю.В. Ковтун, А.И. Скибенко, Е.И. Скибенко, Ю.В. Ларин, В.Б. Юферов

Впервые для определения скорости вращения плазменных слоев с $n_p = n_{cr}^{1,2}$ в среде газометаллической плазмы отражательного разряда была применена двухчастотная СВЧ-флуктационная рефлектометрия. Результаты измерений показали, что угловая частота вращения плазменных слоев различна и, таким образом, плазма вращается не как единое целое. Максимальная скорость вращения увеличивается с увеличением магнитного поля. Проведены оценки величин напряженности электрического поля в двух слоях и коэффициента α разделения частиц плазмы.

ВИЗНАЧЕННЯ ШВИДКОСТІ ОБЕРТАННЯ ГАЗОМЕТАЛЕВОЇ БАГАТОКОМПОНЕНТНОЇ ПЛАЗМИ ВІДБИВНОГО РОЗРЯДУ

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Вперше для визначення швидкості обертання плазмових прошарків з $n_p = n_{cr}^{1,2}$ в середовищі газометалевої плазми відбивного розряду була застосована двохчастотна НВЧ-флуктаційна рефлектометрія. Результати вимірювань показали, що кутова частота обертання плазмових прошарків різна і, таким чином, плазма обертається не як єдине ціле. Максимальна швидкість обертання збільшується зі збільшенням магнітного поля. Проведено оцінки величин напруженості електричного поля в двох прошарках і коефіцієнта α розділення частинок плазми.