

# PROPAGATION OF MULTICOMPONENT PLASMA OSCILLATIONS ALONG THE MAGNETIC FIELD IN THE PULSED REFLEX DISCHARGE

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The angular velocity of equal-density plasma layer rotations along the magnetic field has been measured. The values obtained in different points are similar that is in accordance with the isorotation law. It has been established that in the plasma the oscillations are propagating along the magnetic field with a velocity value close to the Alfvén velocity  $V \sim V_A$ .

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The plasma in the crossed  $\mathbf{E} \times \mathbf{B}$  fields is of interest for solving a wide range of scientific and applied problems in plasma physics, namely, in the field of investigations on laboratory, fusion and space plasma [1]. A distinct feature of the plasma being in the crossed  $\mathbf{E} \times \mathbf{B}$  fields is its drift rotation that in the case of a multicomponent plasma leads to the spatial separation of an ion component. Possibility to use rotating-plasma devices for substance separation promotes the plasma investigations and development of facilities and complexes designed for substance separation into the mass groups and elements [2]. Among the large class of rotating plasma devices a reflex discharge is a particular case. The reflex discharge study has many years' history, but, by now some problems are not considered or are studied insufficiently. Examples of such problems are the excitation and propagation of reflex-discharge plasma oscillations along the magnetic field.

The investigation [3] on the low-frequency oscillations of helium plasma in the stationary reflex discharge with an heated cathode has shown that there are regions with different behavior of oscillations depending on the magnetic field ( $B \leq 0,4$  T). The correlation analysis of probe signals permitted to establish that the phase velocity of low-frequency oscillation propagation along the magnetic field is equal to  $2 \cdot 10^7$  cm/s. This value lies in the range between the velocity of sound ( $\sim 10^6$  cm/s) and the Alfvén velocity ( $10^9$  cm/s). In [4] measurements were carried out of the low-frequency ( $f = 10 \dots 100$  kHz) helium plasma oscillations under different initial conditions ( $P \approx 0,013 \dots 0,133$  Pa,  $B \leq 0,03$  T,  $I_d \leq 30$  A) in the stationary reflex discharge with an heated cathode. From the plot of oscillation frequencies versus plasma parameters we concluded that the oscillations observed are due to the excitation in the plasma of ion-acoustic, slow magneto-compression and Alfvén waves. In [5] the low-frequency oscillations of the pulsed reflex-discharge plasma in the glass chamber were investigated using a slit scan of the plasma column glow by the electron-optical converter. The dependences of the oscillation frequency on the magnetic field ( $B \leq 1,2$  T), pressure ( $P \approx 0,133 \dots 13,3$  Pa) and atomic weight of gas ( $H_2, He, Ar, Kr$ ) evidence that the oscillations observed belong to the class of drift Alfvén waves in the inhomogeneous plasma.

So, the reflex-discharge plasma oscillation propagation along the magnetic field is not clearly understood and requires further investigations.

The present paper gives preliminary experimental results on the character of multi-component gas-metal reflex-discharge plasma oscillation propagation along the magnetic field. The work continues previous investigations [6-8] on the multi-component gas-metal plasma formed in the pulsed high-current reflex discharge. The gas-metal plasma has been formed by the discharge in the medium of firing gas  $Ar$  ( $P \approx 0,133 \dots 1,33$  Pa) and sputtered cathode material ( $Ti$ ). The maximum plasma density was  $N_p \geq 1 \cdot 10^{14}$  cm<sup>-3</sup>. The discharge voltage and the current were  $U_{dis.} \leq 4$  kV and  $I_{dis.} \sim 1,8$  kA, respectively. The pulsed magnetic field of 18 ms duration had a mirror configuration with a limiting induction value  $B_\theta \leq 0,34$  T in the installation center.

The voltage onto the discharge gap was applied after magnetic field induction with delay of 2 ms. Plasma oscillation propagation along the magnetic field was studied using the microwave fluctuation spectrometry. Plasma location was carried out with an O-wave having a wave length of  $\lambda = 8$  mm.

The angular rotation rate of plasma layers with equal critical density  $N_{cr.} \geq 1,7 \cdot 10^{13}$  cm<sup>-3</sup>, distributed along the magnetic field (see Fig. 1), was determined using the autocorrelation function (ACF) of reflected microwave signals which can be calculated by formula [9]:

$$C_{xx}(\tau_k) = \frac{1}{N} \sum_{t=0}^{N-1} x(t)x(t+\tau_k), \quad (1)$$

where  $C_{xx}(\tau_k)$  – is the ACF of signal,  $N$  – is the number of points in the signal realization,  $\tau_k$  – is the phase shift. We determine the ACF period and then find the angular rotation velocity that for the case of a circular symmetry is obtained from the relation:

$$\omega_\phi = 2\pi/T, \quad (2)$$

where  $\omega_\phi$  is the plasma rotation angular velocity,  $T$  is the ACF period.

Comparison of ACF periods of reflected microwave signal distributed along the magnetic field have shown that the ACF periods are similar (see Fig. 2,a), i.e. the angular rotation velocities have close values (see Fig. 2,b).

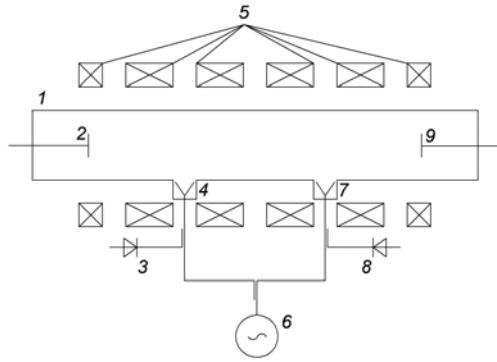


Fig. 1. Schematic representation of the experimental assembly and diagnostic facilities. 1 – vacuum chamber (anode), 2, 9 – cathodes, 3, 8 – detectors, 4, 7 – horn antennas of microwave reflectometers, 5 – solenoid magnet, 6 – microwave oscillator

This relationship is in accordance with the isotropy law [1] or with the Ferraro theorem [10], the angular velocity is constant along the magnetic field lines  $\omega = \omega_0 = \text{const}$ .

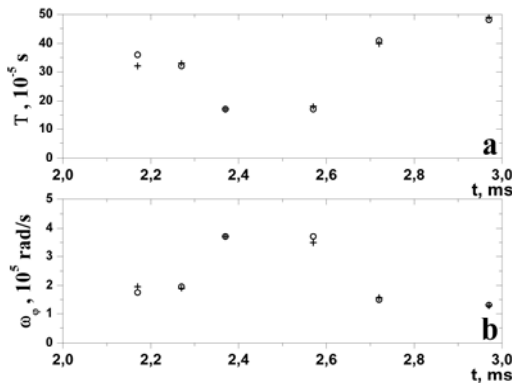


Fig. 2. ACF period (a) and angular velocity of plasma layers distributed along the magnetic field as a function of time (for signals received by antennas 4 (○) and 7 (×) see Fig. 1).  $P \approx 0,93 \text{ Pa}$ ,  $U_{dis.} = 3,8 \text{ kV}$

Using the phase shift of reflected signals we determined the radial size of reflected layers and, respectively, calculated the rotation velocity ( $v_\varphi = \omega_\varphi r$ ) which was not higher than  $v_\varphi \leq 1 \cdot 10^6 \text{ cm/s}$ , that is in accordance with results obtained in [7,8].

To determine the time of plasma oscillation propagation along the magnetic field used were cross-correlation functions calculated in [9] by formula:

$$C_{xy}(\tau_k) = \frac{1}{N} \sum_{t=0}^{N-1} x(t)y(t+\tau_k), \quad (3)$$

where  $C_{xy}(\tau_k)$  is the cross-correlation function (CCF) between the signals  $x(t)$  and  $y(t)$ ,  $N$  is the number of points I the realization of signals  $x(t)$  and  $y(t)$ ,  $\tau_k$  is the delay time between two signals. Analysis of CCF for reflected signals has shown that the CCF shift  $\tau$  practically decreases with time, and, consequently, the CCF shift dependence  $\tau$  differs from the ACF period dependence on time (see Fig. 2.a). It means that the CCF provides data on the plasma oscillations propagating along the magnetic field. To be sure that on both the reflectometers the same fluctuations are observed, we have in-

vestigated the coherence function of signals from the reflectometers which is determined as [9]:

$$\gamma_{xy}^2(f) = \frac{|G_{xy}(f)|^2}{G_x(f)G_y(f)} \leq 1, \quad (4)$$

where  $G_{xy}(f)$  is the function of cross-spectral density of two signals,  $G_x(f)$  and  $G_y(f)$  are the functions of spectral density of signals  $x(t)$  and  $y(t)$  respectively. A high degree of oscillation coherence (see Fig. 3) recorded at both the reflectometers evidences that the same oscillations are moving along the magnetic field.

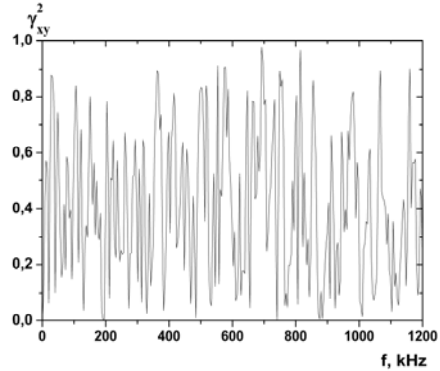


Fig. 3. Coherence function of reflected microwave signals

If the CCF phase shift  $\tau$  and the distance  $l$  between the horns of microwave reflectometers are known it is possible to determine the plasma fluctuation propagation velocity as:

$$V = l/\tau, \quad (5)$$

The calculation results based on experimental data obtained by formula 5 are given in Fig. 4 for  $l \approx 64,5 \text{ cm}$ . As is seen from Fig.4 the plasma fluctuation propagation velocity is slightly increasing with time. The explanation may be the following: Under conditions of this experiment the plasma layer density  $N_{cr.} \approx 1.7 \cdot 10^{13} \text{ cm}^{-3}$  is constant in time and the magnetic field increases by  $\Delta B = \pm 7\%$ , as compared with the average value. Consequently, the plasma fluctuation propagation velocity can be dependent on the magnetic field value.

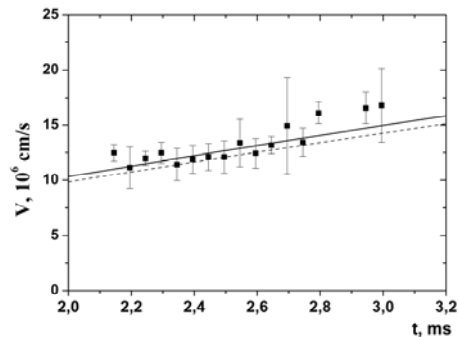


Fig. 4. Velocity of oscillation propagation along the magnetic field, points – experiment, solid line – calculation by formula 6, dashed line – calculation by formula (7). ( $P \approx 0,93 \text{ Pa}$ ,  $U_{dis.} = 3,8 \text{ kV}$ )

The wave velocity in the plasma can be determined from the dispersion equation. We evaluate the ion sound

velocity  $V_S$  and the Alfvén velocity  $V_A$  as a first approximation. The ion sound velocity is equal to  $V_S = (kT_e/m_i)^{1/2}$ . Taking  $kT_e \sim 10$  eV and  $m_i = \text{Ar}$  ion mass we obtain  $V_S \approx 5 \cdot 10^5$  cm/s, that is by two orders of magnitude less than the measured one. The Alfvén velocity is determined from the relation of [11]:

$$V_A = \frac{B}{\sqrt{\mu_0 \rho}}, \quad (6)$$

where  $\mu_0$  is the magnetic constant,  $\rho$  is the plasma density. For the multicomponent plasma the Alfvén velocity can be found as in [12].

$$V_{A, \text{mult}} = \frac{B}{\sqrt{\mu_0 (m_1 N_1 + m_2 N_2)}}, \quad (7)$$

where  $m_1$  and  $m_2$  are the masses of ions (sort 1 and sort 2),  $N_1$  and  $N_2$  are their concentrations. The results of Alfvén velocity evaluation by formulas 6 and 7 for  $\rho = 1.137 \cdot 10^{-9}$  g/cm<sup>3</sup> (100% Ar) and  $N_1 = N_2 = 8.5 \cdot 10^{12}$  cm<sup>-3</sup> (50% Ar, 50% Ti) are given in Fig. 4. As is seen, the measured velocity value is close to the Alfvén velocity  $V \sim V_A \sim 10^7$  cm/s.

## CONCLUSIONS

The presented paper reports about the initial stage of investigations on the oscillations of multicomponent gas-metal plasma in the pulsed reflex discharge.

The summary of investigation results is the following:

1. Comparison of the autocorrelation functions of reflected microwave signals, distributed along the magnetic field, has shown that the periods of these functions are similar, i.e. the angular rotation velocities are close and such a relationship is in accordance with the isorotation law or with the Ferraro theorem.
2. Investigation of the cross-correlation functions of reflected microwave signals distributed along the mag-

netic field permitted to determine the time of plasma oscillation propagation along the magnetic field and to calculate the propagation velocity that is close to the Alfvén velocity  $V \sim V_A$ .

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## РАСПРОСТРАНЕНИЕ КОЛЕБАНИЙ МНОГОКОМПОНЕНТНОЙ ПЛАЗМЫ ВДОЛЬ МАГНИТНОГО ПОЛЯ В ИМПУЛЬСНОМ ОТРАЖАТЕЛЬНОМ РАЗРЯДЕ

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Проведены измерения угловой скорости вращения плазменных слоев одинаковой плотности вдоль магнитного поля, значения которой оказались в различных точках близкими друг к другу, что согласуется с законом изоротации. Установлено, что в плазме вдоль магнитного поля распространяются колебания со скоростью, близкой по величине к альфвеновской скорости  $V \sim V_A$ .

## РОЗПОВСЮДЖЕННЯ КОЛИВАНЬ БАГАТОКОМПОНЕНТНОЇ ПЛАЗМИ УЗДОВЖ МАГНІТНОГО ПОЛЯ В ІМПУЛЬСНОМУ ВІДБИВНОМУ РОЗРЯДІ

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Проведено вимірювання кутової швидкості обертання плазмових шарів однакової густини уздовж магнітного поля, значення якої в різних точках виявилися близькими одне до одного, що узгоджується із законом изоротації. Встановлено, що в плазмі уздовж магнітного поля розповсюджуються коливання із швидкістю, близькою по величині до альфвеновської швидкості  $V \sim V_A$ .