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Studies of Small Amplitude Ionization Waves in an Axially Magnetized Plasma of the Helium Discharge*

The experimental studies of the influence of an axial magnetic field on the propagation parameters of ionization wave are described.

The presented results were obtained in a helium discharge. They are compared with the predictions of the simple hydrodynamic theory as developed first by Pekarek and Krejči [12, 13]. This theory was extended here to take into account the influence of an axial magnetic field.

1. Introduction

Little work has been carried out to study, both experimentally and theoretically, the influence of an axial magnetic field on ionization waves (striations) in the positive column. Effects of such a field on the frequency and velocity of striations were investigated in an early work of Zaitsev and Vasilyeva [1]. Few other works are discussed in the review article by Oleson and Cooper [2] and also in the papers of Sato [3] and Duncan and Forrest [4]. There are, however, still insufficient data for a detailed description of the behaviour of the ionization waves in a magnetic field.

On the other hand, the ionization waves in the absence of magnetic field have been intensively investigated theoretically and experimentally for the last twenty years. It seems that this phenomenon is recently quite well understood and described, although some points still require further elaboration. General concepts and clarification of the issue have been made possible mainly due to the results achieved by Pekarek and co-workers (see the successive review papers [2] and [5÷8]).

Hitherto, the detailed theories of ionization waves have been elaborated only for some particular cases: for argon at high current densities by Wojaczek [9] and for neon and helium at low discharge currents by Pekarek and his co-workers [10, 11]. The theories for neon and helium are based on a direct solution of the Boltzmann equation for the electron gas and require numerical computation for the comparison with an experiment.

The physical nature and basic properties of the ionization waves can, however, be found using much simpler procedure, based on the hydrodynamic description of the discharge

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plasma. This has been done first by Pekarek and Krejči [12] [13] and further developed by Garscadden et al. [14, 15]. The continuity and momentum equations for both electrons and ions, Poisson equation, simplified electron energy equation and Schottky's model of diffusion were used. It is believed [8, 14] that this hydrodynamic theory does describe most of the experimentaly observed features of the ionization waves.

In this paper the measurements of the frequency and wavelength of the artificially excited ionization waves in an axial magnetic field are presented. The experimental results are compared with the predictions of a simple hydrodynamic theory modified to account for the influence of magnetic field.

The next section contains the description of the experimental arrangement and procedure. In section 3 the theoretical model is suggested. The results of measurements are presented and discussed in section 4. The conclusions form the last section 5.

2. Experimental arrangement and procedure

The described experiments were carried out in an axially magnetized glow discharge plasma in helium. The essential parts of the experimental apparatus are shown in Figure 1. The discharge tube length is about 300 cm between hollow electrodes and its diameter is 57 mm. This tube is inserted into a magnet 170 cm long. The axial magnetic field in the central 120 cm section of the tube is uniform ($\pm 1\%$) and variable up to 2.5 kGs (0.25 T).

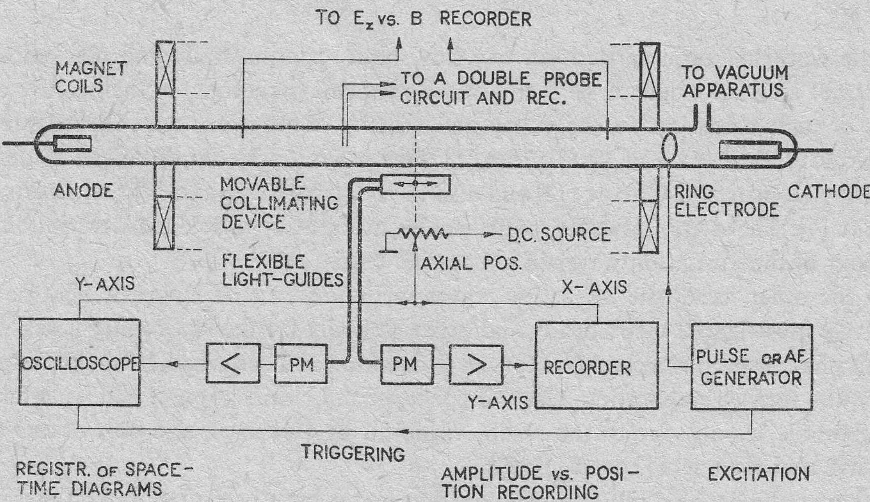

Fig. 1. The simplified diagram of the experimental apparatus

The discharge was run at defined pressure within the range of 0.1 - 1 Tr. The discharge current was electronically stabilized and continuously variable up to 250 mA.

Pekarek type [2] waves of stratification were excited in the positive column by applying a short (several μs) pulse to the auxiliary ring electrode placed near to the cathode end of the tube. The light perturbation connected with the excited wave was detected by photomultipliers situated outside the magnet coils and magnetically shielded. This light passed along a flexible light-guides from a collimators to photomultipliers. The collimators were placed on a carriage which could be driven axially.

During each run all the discharge parameters and the magnetic field intensity were fixed. The main results of measurements were directly photographed from the oscilloscope screen in a form of well known time-space diagram. The applied procedure was identical as that described by Štirand et al. [16]. Such diagrams yield, among other parameters, also the frequency and wavelength of the ionization wave of the greatest amplification (smallest attenuation).

The possibility of excitation of the wave with a sinusoidal signal using an A.F. power generator was also provided. This was used for measurement of dispersion curves in the magnetic field.

In both cases of the pulse and harmonic excitation the axially movable light detector was used to verify the constancy of the amplification factor along the tube axis. This way the possibility of occurrence of nonlinear effects was avoided.

The measurement of the potential difference between two axially separated floating probes yielded directly the value of an axial electric field in the column. A double probe with an appropriate circuit served for determination of the electron temperature.

3. Theoretical model

The simple hydrodynamic theory of wave of stratification in the absence of magnetic field has been presented [12, 13] by Pekarek and Krejči. They started with the equations of continuity of the positive and negative particles and the Poisson equation. A simplified energy balance equation for electrons was also included. The initial disturbance of density was chosen in form of a Dirac pulse. This corresponds to the experimental excitation of a wave of stratification by a sharp pulse.

The problem is considered to beone-dimensional in the space coordinate along the axis of the discharge in the direction from anode to cathode, and Schottky-type ambipolar diffusion to the walls is assumed to be established.

The basic equations are

$$\frac{\partial n_i}{\partial t}=D_i\frac{\partial^2 n_i}{\partial z^2}-\mu_i N_s\frac{\partial e}{\partial z}-\mu E_{zs}\frac{\partial n_i}{\partial z}-\frac{1}{\tau_{is}}(n_i-n_e)+Z_u N_s u_e, \tag{3a}$$

$$\frac{\partial n_e}{\partial t}=D_e\frac{\partial^2 n_e}{\partial z^2}+\mu_e E_{zs}\frac{\partial n_e}{\partial z}+Z_u N_s u_e+Z_N N_s n_e, \tag{3b}$$

$$\frac{\partial e}{\partial z}=-4\pi q_0(n_i-n_e), \tag{3c}$$

$$\frac{\partial u_e}{\partial z}-au_e=-be, \tag{3d}$$

where D_i, D_e, μ_i, μ_e are diffusion coefficients and mobilities for the positive ions and electrons, respectively, τ_i – the lifetime of the charge carriers to the walls, a^{-1} – the relaxation length of the electrons temperature and q_0 – the elementary electric charge, $b\cong\frac{3}{4}q_0$, $n_i=N_i-N_s$, $n_e=N_e-N_s$ represent the change of the ion and electron concentration from the equilibrium value, $e=E_z-E_{zs}$, $u_e=V_e-V_{es}$ – the changes of the electric field and the electron temperature. Subscript s is used for parameters in the undisturbed (steady) state of the discharge.

The general discussion of the method of solution is given by Pekarek [27].

Under the assumption of small Debye length the dispersion equation takes [8, 13] form

$$i\Omega=-K^2D_a+\bar{\alpha}+\frac{A}{jK-a}, \tag{3.1}$$

where

$$\bar{\alpha}=Z_u bV_{es}+Z_n N_s, \tag{3.2}$$

$$A=Z_u baV_{es}\left(1+\frac{E_{zs}}{aV_{es}}\right), \tag{3.3}$$

$$Z_u=\left(\frac{\partial v_i}{\partial V_e}\right)_s+\frac{1}{\tau_{is}^2}\left(\frac{\partial \tau_i}{\partial V_e}\right)_s, \tag{3.4}$$

$$Z_n=\left(\frac{\partial v_i}{\partial N_e}\right)_s, \tag{3.5}$$

v_i – the ionization frequency, D_a – ambipolar diffusion coefficient.

For real $K=k=2\pi/\lambda$, the real angular frequency and time increment φ are

$$\omega=\frac{Ak}{a^2+k^2}, \tag{3.6}$$

$$\varphi=-k^2D_a+\bar{\alpha}-\frac{Aa}{a^2+k^2}. \tag{3.7}$$

The approximate expression for the reciprocal of the electron thermal relaxation length a was given by Granovski [17] (see also [18])

$$a\cong\frac{32}{3\pi}\frac{V_{es}\kappa}{E_{zs}\lambda_e^2}. \tag{3.8}$$

In (3.8) κ denotes the average fraction of energy lost by an electron in one collision, determined [19] from

$$\frac{E_{zs}}{P}=(2\kappa)^{\frac{1}{2}}\frac{V_{es}}{\lambda_1}, \tag{3.9}$$

where $\lambda_i=\lambda_e p$ is the electron mean free path at 1 Torr and 0° C and depends on the kind of gas.

For the case of greatest amplification

$$\left(\frac{\partial\varphi}{\partial k}\right)_{k=k_M}=0, \tag{3.10}$$

the wavelength and angular frequency of the wave are

$$k_M=a\left(\frac{1}{\eta}-1\right)^{\frac{1}{2}}, \tag{3.11}$$

$$\omega_M = \frac{a^2 D_a}{\eta}\left(\frac{1}{\eta}-1\right)^{\frac{1}{2}}, \tag{3.12}$$

where

$$\eta = \left(\frac{a^3 D_a}{A}\right)^{\frac{1}{2}}. \tag{3.13}$$

For the sake of simplicity the subscript M will be dropped in further notation. The values of wave number k, wavelength λ and frequency $f=\omega/2\pi$ will correspond to the case of the greatest amplification.

Here an attempt is being made to account for the influence of the axial magnetic field on the wavelength and frequency of an ionization wave. It will be assumed, that the field affects those parameters only through its influence on the diffusion of the charged particles across the magnetic field. The direct effect is the change in the diffusion controlled lifetime τ_i of ions and electrons. The electron temperature V_e and axial electric field intensity E_z also vary to assure a balance in the generation and loss of charged particles. The diffusion along the tube axis remains unaffected by the magnetic field and the respective coefficient retains its Schottky value

$$D_a \cong \mu_i V_e. \tag{3.14}$$

In the Schottky theory of the positive column the ionization frequency is related [19] to the electron temperature by the equation

$$\nu_i \cong \mathrm{const}\left(\frac{V_e}{V_j}\right)^{\frac{1}{2}} \exp\left(-\frac{V_j}{V_e}\right) \tag{3.15}$$

valid for $V_e \ll V_j$, where V_j is the ionization potential. Further it will be assumed that this relation holds in the presence of a magnetic field.

As the recombination of charged particles is assumed to take place only on the wall, the lifetime τ_i is controlled by diffusion of these particles across the magnetic field

$$\tau_i \cong \frac{1}{D_t}\left(\frac{R}{2.4}\right)^2, \quad D_t = \frac{D_a}{1+\mu_e \mu_i B^2}. \tag{3.16}$$

In the steady state conditions $\tau_{is} = \nu_{is}^{-1}$. It may be shown that

$$Z_u \cong \frac{V_j}{V_{es}^2} \nu_{is}, \tag{3.17}$$

and consequently

$$A = ab\left(1+\frac{E_{zs}}{aV_{es}}\right)\frac{V_j}{V_{es}} \nu_{is}. \tag{3.18}$$

From (3.8) and (3.9) it follows that

$$a = \frac{16}{3\pi}\frac{E_{zs}}{V_{es}} \tag{3.19}$$

and $\left(1+\frac{E_{zs}}{aV_{es}}\right)\cong 1.6$ is a constant. As a result, the variations of the coefficient A with magnetic field can be calculated from the relation

$$A=\text{const}\, a\cdot V_{es}^{-\frac{1}{2}}\nu_{is}^{\frac{1}{2}}. \tag{3.20}$$

For the sake of simplicity the subscript s will again be dropped in the further notation. V_e and E_z will denote the steady state parameters. The subscript 0 will be introduced for values corresponding to the absence of magnetic field.

Under an assumption* that $\eta \ll 1$ the changes of the wavelength and frequency of ionization waves with a magnetic field result from (3.11) and (3.12). They are, respectively,

$$\frac{\lambda}{\lambda_0}=\frac{k_0}{k}=\frac{a_0}{a}\left(\frac{\eta}{\eta_0}\right)^{\frac{1}{2}} \tag{3.21}$$

and

$$\frac{f}{f_0}=\left(\frac{a}{a_0}\right)^2\left(\frac{\eta_0}{\eta}\right)^{\frac{3}{2}}=\left(\frac{\lambda_0}{\lambda}\right)^2\left(\frac{\eta_0}{\eta}\right)^{\frac{1}{2}}. \tag{3.22}$$

The above given relations may be expressed directly in terms of the steady state plasma parameters:

$$\frac{\lambda}{\lambda_0}=\left(\frac{E_{z0}V_e}{E_z V_{e0}}\right)^{\frac{1}{2}}\left(\frac{\nu_{i0}}{\nu_i}\right)^{\frac{1}{4}}, \tag{3.23}$$

$$\frac{f}{f_0}=\left(\frac{E_z V_{e0}}{E_{z0}V_e}\right)^{\frac{1}{2}}\left(\frac{\nu_i}{\nu_{i0}}\right)^{\frac{3}{4}}. \tag{3.24}$$

It follows from (3.11) that for $\eta \ll 1$ also Pekarek's theory predicts the dispersion relation in a simple form $\omega k=A$, which can be written as

$$\lambda=c\cdot f, \qquad c=\frac{4\pi^2}{A}. \tag{3.25}$$

When the influence of a magnetic field is taken into account in an identical way as before, the changes of a the slope of the dispersion curve may be directly obtained

$$\frac{c}{c_0}=\left(\frac{V_e}{V_{e0}}\right)^2\cdot\frac{E_{z0}}{E_z}\cdot\frac{\nu_{i0}}{\nu_i}. \tag{3.26}$$

4. Results and discussion

On the grounds of the above theoretical model the knowledge of relative changes of the electron temperature and the axial electric field are sufficient for the determination of relative changes of the striation parameters in a magnetic field.

* The validity of this assumption will be analysed later together with the discussion of the results of measurement.

Here the results obtained in a helium discharge plasma at pressure $p=0.45$ Tr and current $I_z=150$ mA are presented. The changes of the axial electric field intensity under the influence of the magnetic field will be analysed first. This will allow to find the main features of the discharge in the steady state conditions.

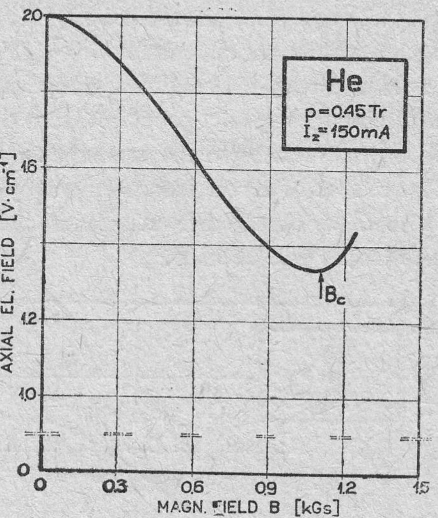

Fig. 2. The registered $E_z(B)$ curve

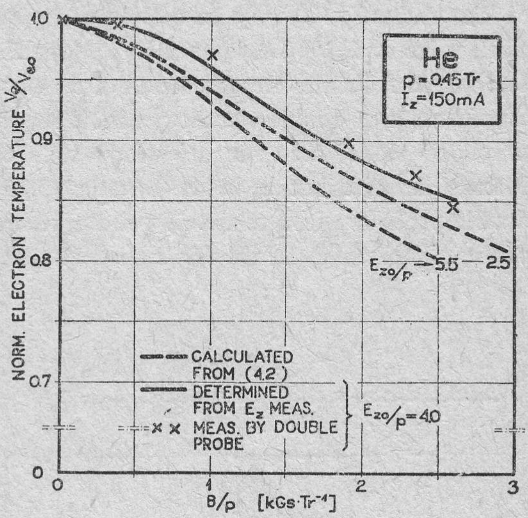

Fig. 3. The relative changes of electron temperature calculated from the theory of ambipolar diffusion and measured

The registered $E_z(B)$ curve is shown in Fig. 2. The plasma is quiescent for magnetic field intensities lower than the critical value B_c. Above the critical field a macroscopic current-convective instability [20, 21] sets up. All the further presented measurements were performed in the region $B<B_c$.

As Sheffield [22] pointed out, the relation between the electron temperature and the axial electric field in a helium positive column may be approximated by

$$V_e=(1.97\pm0.07)\left(\frac{E_z}{P}\right)^{\frac{1}{3}}, \tag{4.1}$$

if only $2.4<E_z/p<6.5$. It may be further assumed that this holds in magnetic field too.

Formula (4.1) holds in the whole region of parameters in the presented case (here $E_{zs}/p=4.4$). Then

$$\frac{V_e}{V_{e0}}\cong\left(\frac{E_z}{E_{z0}}\right)^{\frac{1}{3}}$$

and from (3.15)

$$\frac{v_i}{v_{i0}}\cong\left(\frac{V_e}{V_{e0}}\right)^{\frac{1}{2}}\exp\frac{V_j}{V_{e0}}\left(1-\frac{V_{e0}}{V_e}\right), \tag{4.2}$$

where the ratio V_j/V_{e0} depends only on E_{z0}/p.

On the other hand, from the requirement that the particles lost by diffusion must be replaced by ionization in the steady state of the discharge, one can [23] obtain:

$$\frac{\nu_i}{\nu_{i0}}=\frac{D_t}{D_a}=(1+\mu_e\mu_i B^2)^{-1}. \tag{4.3}$$

The ratio V_e/V_{e0} may be calculated by solving (4.2) and (4.3) simultaneously for a given value of E_{z0}/p (i.e. known V_j/V_{e0}). In Fig. 3 such results are compared with V_e/V_{e0} determined from the measurements of an electric field and with the results of direct measurement by a double electric probe. The evident discrepancy results probably from the simplified model used for the steady state conditions (for example the assumption of Maxwellian distribution in the formula (3.15)). The results of direct measurement by a double probe are in a relatively good agreement with those obtained from measurement of the electric field. In the further calculation the last ones will be used.

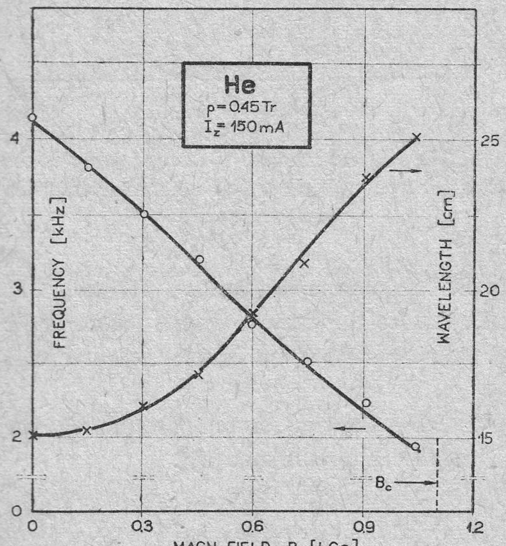

Fig. 4. The measured wavelength and frequency of the ionization wave

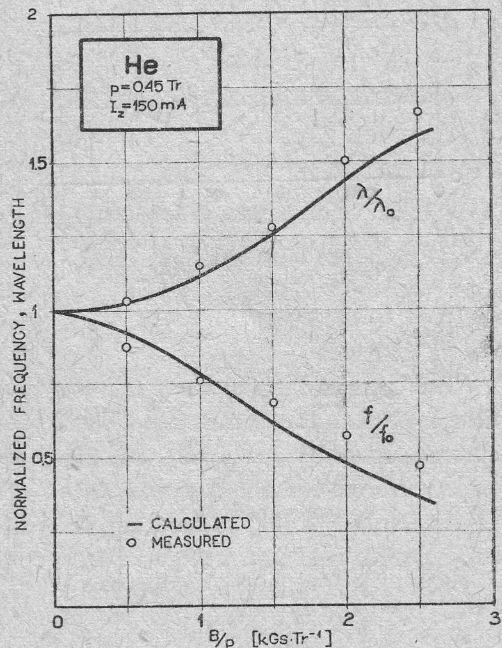

Fig. 5. The measured and calculated values of normalized wave parameters

In Fig. 4 the measured values of wavelength and frequency are shown. The relative changes of the measured and calculated parameters in the magnetic field are compared in Fig. 5. The agreement is quite good in the case of wavelength. The predicted changes of frequency agree at the very least qualitatively with the measured ones.

The assumption that $\eta \ll 1$, introduced a priori in the Chapter 3 can be verified now. The theory of Pekarek predicts that $a<k$ for a backward wave propagating in the noble gases. From the above and (3.11) - (3.12) the following results

$$\eta=aD_a\frac{k}{\omega}<\frac{k^2D_a}{\omega}. \tag{4.4}$$

In the present experimental conditions there is $\eta \lesssim 0.2$, and the approximation used is acceptable.

It is possible [24, 25] to determine the dispersion curve parameters from a transient wave in the case of pulse excitation. We have found, however, the direct measurement of the dispersion curve from the behaviour of a monochromatic wave to be more precise and convenient.

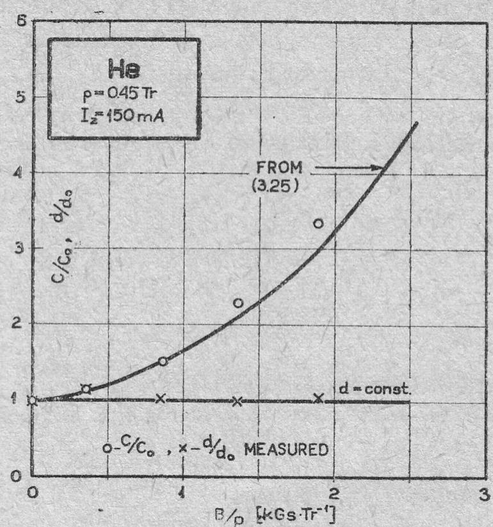

Fig. 6. The measured dispersion curves for different magnetic fields

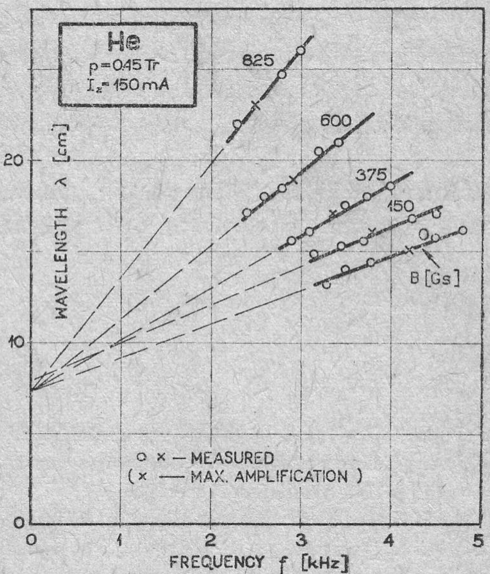

Fig. 7. The changes of the c and d coefficients of eq. (4.4) vs. reduced magnetic field

Typical results of such a measurement are drawn in Fig. 6. All the obtained curves can be approximated by straight lines of equation

$$\lambda = cf + d\,. \tag{4.5}$$

The measured relative changes of the slope factor with magnetic field are compared (Fig. 7) with those calculated from the simplified theory (the relation (3.25) gives c/c_0 calculated for $k^2 \gg a^2$). The same theory predicts $d=0$. The measurements yield value $d \cong 8$ cm independent on magnetic field.

A closer examination of the earlier results of Sato [3] and Rosenbaum [26] reveals the similar features of measured dispersion curves: linearity and independence of the factor d of the magnetic field. The deviation from linearity, observed by Sato at frequencies higher than the resonant one, may be almost certainly attributed to the undesired nonlinear effects.

5. Conclusion

Concluding it can be stated that the simple hydrodynamic theory of ionization wave, presented by Pekarek and Krejči [12, 13] and extended here to take into account the influence of an axial magnetic field, predicts the changes of wave parameters which at least qualitatively agree with the measured ones. The observed discrepancies may be attributed not only to the inadequacy of the simplified theory of ionization waves but also to the crude method of determination of the discharge parameters in the steady state.

Despite the existence of the recent and more sophisticated theories of the ionization waves the possibility of application of this simple hydrodynamic theory presents some unquestionable advantages. It discloses the basic mechanisms of influence of magnetic field on the striations parameters. The full quantitative description of the involved phenomena can not be achieved. Nevertheless the extended hydrodynamic theory yields simple analytical expressions for the relative changes of wave parameters in a magnetic field. The predicted results can than be easily compared with an experiment.

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Badanie fal jonizacji o małej amplitudzie w plazmie wyładowania jarzeniowego w He, w podłużnym polu magnetycznym

Streszczenie

Zbadano wpływ pola magnetycznego, równoległego do osi kolumny dodatniej, na częstotliwość i długość fal jonizacji w plazmie wyładowania jarzeniowego w He.

Pomiary wykonano w obszarze pola magnetycznego $B < B_c$ (B_c – pole krytyczne). Plazmę zaburzano krótkim impulsem napięcia doprowadzonego do pierścieniowej elektrody, znajdującej się w pobliżu katody. W tych warunkach powstawały fale jonizacji, których rozchodzenie się badano metodą Štiranda. Dokonano pomiarów częstotliwości i długości fal jonizacji w zależności od pola magnetycznego. Przy wyznaczaniu krzywych dyspersyjnych w polu magnetycznym, fale jonizacji wzbudzano sinusoidalnym sygnałem napięcia.

Wyniki badań doświadczalnych porównano z danymi otrzymanymi z prostej teorii hydrodynamicznej, zmodyfikowanej przez uwzględnienie wpływu pola magnetycznego. Przyjęto, że pole magnetyczne wpływa na parametry fal jonizacyjnych wyłącznie poprzez zmiany dyfuzji cząstek do ścianek rury, wywoływane przez to pole.

Przewidywane przez teorię zmiany parametrów fal są jakościowo zgodne z otrzymanymi wynikami eksperymentalnymi.

Исследование ионизационных волн малой амплитуды в продольном магнитном поле в плазме тлеющего разряда в He

Резюме

Исследовано влияние магнитного поля, параллельного оси положительного столба, на частоту и длину ионизационных волн в плазме тлеющего разряда в He.

Измерения производились в области магнитного поля $B < B_c$ (B_c — критическое поле). Плазма возмущалась кратким импульсом напряжения, подведенным к кольцевидному электроду, который находился вблизи катода. При этом возникали ионизационные волны, распространение которых исследовалось по методу Штиранда. Измерено частоту и длину ионизационных волн в зависимости от магнитного поля. При определении дисперсионных кривых в магнитном поле ионизационные волны возбуждались синусоидальным сигналом напряжения.

Экспериментальные результаты были сравнены с данными полученными на основе простой гидродинамической теории модифицированной для учета влияния магнитного поля. Принято, что магнитное поле влияет на параметры ионизационных волн исключительно через изменения, вызываемые полем в диффузии зараженных частиц к стенкам трубки. Предсказываемые теорией изменения параметров волн качественно согласуются с полученными экспериментальными результатами.