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Gas Discharge in Magnetic Field Sustained by a Quadrupolar SW and Influence of Dust on SW Properties

N.A. Azarenkov[1], V.P. Olefir[1], A.E. Sporov[2], Yu.O. Tyshetskiy[1]

[1]*Department of Physics and Technology, Kharkiv State University, 310077 Kharkiv, Ukraine*
[2]*Electro-Physical Scientific & Technical Centre of National Academy of Sciencies of Ukraine, 310002 Kharkiv, Chernyshevskogo st. 28, P.O. Box 8812, Ukraine*

We consider the discharge sustained by nonsymmetric nonpotential electromagnetic surface wave (SW), that propagates along cylindrical magnetized plasma column of radius R bounded by vacuum. External steady magnetic field is directed along the discharge. Plasma is considered in hydrodynamic approximation as cold and weakly collisional radially uniform media with effective frequency of electron - neutral collisions ν, that is significantly smaller than wave frequency ω. .

The system of equations that governs the axial plasma structure consists of the dispersion equation, wave energy balance equation along the discharge and the equation that connects energy Q absorbed per unit of discharge length with local plasma density n. Such equation is determined by the discharge kinetics and can be written as [1]:

$$Q = Q_\beta N,$$

where $N = \omega_{pl}^{2}\omega^{-2}$ - dimensionless plasma density, ω_{pl} - electron plasma frequency, Q_β - constant of proportionality.

Waves that sustain the discharge are the eigen waves of discharge structure on whole length of the plasma column. The possibility of plasma source parameters axial variation is mainly determined by the features of that part of dispersion curve on which the wave lies. Such

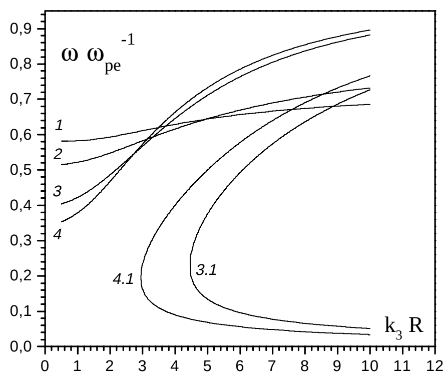
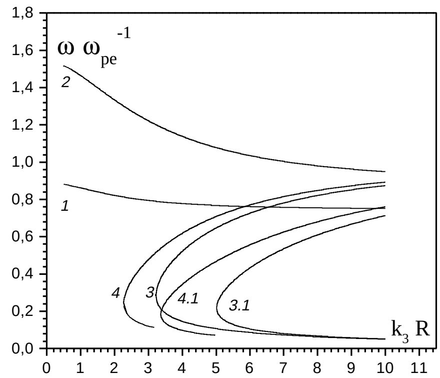


Figure 1.



Figu

circumstances determined the detailed investigation of the dispersion properties of nonsymmetric waves, that are used for the discharge sustaining. The dispersion dependencies of quadrupolar mode $m = -2$ upon external magnetic field value are given on Fig.1 for $\sigma = \omega R c^{-1} = 0.5$, c - light velocity. Curves marked by the numbers *1-4* correspond to the parameter $\Omega = \omega_{ce}\omega^{-1}$ *0.4, 0.8, 2.0, 3.0*, ω_{ce} - electron cyclotron frequency. For the weak magnetic fields the area of backward dispersion is observed. With the increasing of external magnetic field value the width of backward dispersion area decreases, and then disappears. In the case, when $\Omega > 1$ the dispersion of the $m = -2$ mode becomes of a zoned type. At the Fig.1. curves *3* and *4* correspond to the eigen waves with the maximum phase velocity at the given frequency (zero zone). The curves *3.1* and *4.1* correspond to the first dispersion zone for $\Omega = 2.0, 3.0$, respectively. In the region of a straight dispersion the wave is of a pseudo-surface type and is a superposition of pure surface and pure volume modes. In the region of backward dispersion the wave is of a pseudo-surface type and has a character of dominant volume mode. The increasing of external magnetic field value leads to the increasing of the greatest posibble electron concentration value. It is shown that for the waveguides of small radius $(k_3R \sim \sigma)$ for the fixed magnetic field value wave dispersion is of a backward type. With the increasing of σ parameter the area of wave with backward dispersion decreases, and then dissapears.

The dispersion properties of the nonsymmetric waves essentially depends on the sign of azimuthal wave number m. The dependence of the dispersion properties of $m = 2$ mode upon external magnetic field for dimensionless plasma radius $\sigma = 0.5$ is represented on Fig.2. Numbering of curves and respective magnetic field values and zone numbers are similar to Fig.1. Under the conditions of weak magnetic fields $(\Omega < 1)$ wave dispersion is of a backward type and its frequency increases with the increasing of external magnetic field value (curves *1,*

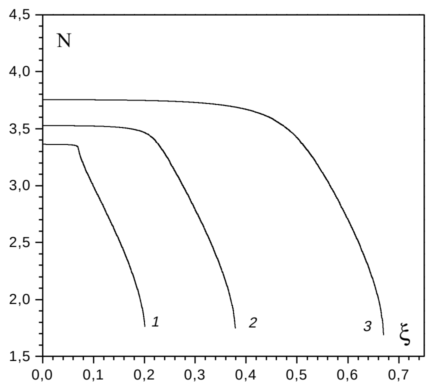


Figure 3.

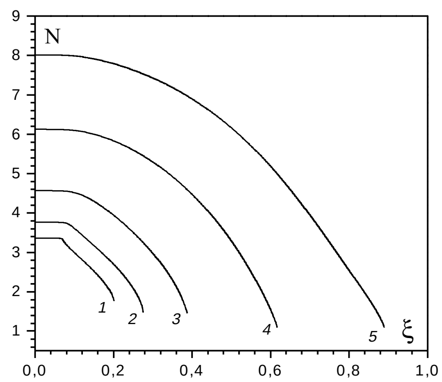


Figure 4.

2). If $\Omega > 1$ then zones dispersion structure appears. The investigation of the plasma column radius influence on the dispersion properties of $m = 2$ mode for the given magnetic field value shows that with the increasing of the parameter σ the dispersion changes its type in the region of k_3R, close to σ - from backward it becomes straight.

The numerical calculations of dimensionless plasma density N axial distribution dependence upon dimensionless distance from generator $\xi = \nu z(\omega R)^{-1}$ (z - axial coordinate, that is measured from the generator) were carried out. The dependence of axial structure of plasma density N, that is sustained by $m = -2$ mode, upon plasma column radius under weak magnetic field $\Omega = 0.6$ is shown on Fig.3. The curves *1-3* correspond to the value of parameter $\sigma = 0.5, 0.7, 0.9$. Increasing of plasma column radius R results to increasing both dimensionless plasma density N near the generator and dimensionless discharge length L, that is the distance when total wave energy flux in plasma and vacuum areas turns to zero. The dependence of axial plasma density profile N, that is sustained by $m = -2$ mode for various magnetic field values at given $\sigma = 0.5$ is shown on Fig.4. Numbers of curves *1-5* correspond to Ω values: $0.6, 0.8, 1.2, 2.0, 3.0$. Axial plasma density profiles for strong magnetic field $(\Omega > 1)$ correspond to the zero dispersion zone. The increasing of external magnetic field leads to the increasing both of the plasma density N and discharge length L.

In a case of weak external magnetic field $(\Omega < 1)$ wave changes its type from generalized

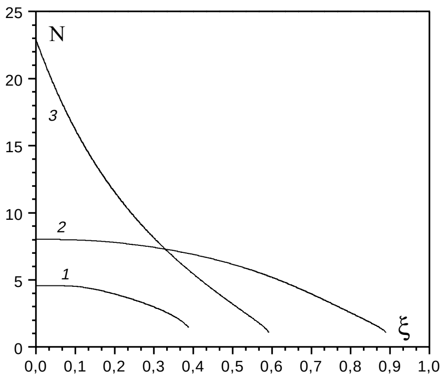


Figure 5.

surface type from the generator to pure surface type at the end of the discharge. Under strong magnetic fields *($\Omega > 1$)* the wave changes from generalized surface type near the generator to pseudo-surface type at the end of the discharge for zero zone. The wave is of the pseudo-surface type over all discharge length in the region of straight dispersion for higher zones. In the region of backward dispersion the wave can be either of pseudo-surface type over all discharge length, or (under significant magnetic fields) can change the type from volume near the genetaror to pseudo-surface at the discharge end. Fig.5 demonstrates axial structure of plasma density N in the discharge, that is sustained by $m = -2$ mode for various values of magnetic field at $\sigma = 0.5$. The curves *1-2* correspond to such Ω values: *1.2*, *3.0* for zero dispersion zone. The curve *3* corresponds to the discharge that is sustained by a wave from the first dispersion zone with a straight dispersion at $\Omega = 3.0$. Increasing of the dispersion zone number leads to significant growth of plasma density N near the generator. Thus, dimensionless length of discharge L changes weakly, and electron concentration axial gradients increase.

The studies in the field of dusty plasma are carried on intensively last time. The particles of dust can appear in plasma as a result of wall erosion in the devices of controlled thermonuclear fusion, or they can be emitted to plasma during material processing in plasma devices. Due to their large mass and charge the dust particles can influence the properties of plasma significantly. It is known that the presence of dust can cause the anomalous damping, frequency shifts, instabilities, etc. That is the reason for studying the wave properties of dusty plasma.

In this work the properties of ion-acoustic surface wave (SW) on the interface between low temperature dusty plasma and vacuum are studied. The homogeneous plasma with the dust is considered. The plasma occupies the region $x < 0$ and the vacuum - $x > 0$. The interface between plasma and vacuum is assumed to be sharp (the depth of transition layer is much less than the depth of penetration of the wave field into plasma). The plasma contains massive dust particles of constant negative charge $q_d = -|Z_d| e$, where e is the electron charge, Z_d is the charge number of dust particles. The size of dust particles is assumed to be much less than the distance between them as well as the electron Debye radius.

The system of equations describing the waves in dusty plasma consists of the equations of quasihydrodynamic approach for three liquids (liquid of electrons, liquid of ions and liquid of dust particles) and Maxwell equations. Noting that for ion-acoustic waves $V_{ph} << c$ (V_{ph} is a phase velocity, c is light speed), we can consider our waves to be potential waves. The plasma is quasineutral in equilibrium: $|Z_i| n_{0i} = n_{0e} + |Z_d| n_{0d}$. The SW propagating along the interface is considered. Linearizing the system of equations and taking into account that the ion-acoustic SW propagate in strongly non-isothermal plasma where the condition $T_e >> T_i$, T_d is satisfied [2] (here T_e, T_i, T_d are the temperatures of electrons, ions and dust particles gas respectively) one can obtain the following SW potential in plasma region:

$$\varphi_p(x) = A_1 \exp(k_3 x) + A_2 \exp(\kappa x), \qquad x < 0, \qquad (1)$$

where $\kappa^2 = k_3^2 - \frac{\varepsilon\,\omega(\omega + i\nu_e)}{\varepsilon_{id} V_{Te}^2}$, $\varepsilon = \varepsilon_{id} + \chi_e$, $\varepsilon_{id} = 1 + \chi_i + \chi_d$, $\chi_j = -\omega_{pj}^2 / \omega(\omega + i\nu_j)$,

$\omega_{pj}^2 = 4\pi e^2 Z_j^2 n_{0j} / m_j$,and r_{De} is electron Debye radius. The SW potential in vacuum can be noted as: $\varphi_v(x) = A_v \exp(-|k_3|x)$, $x > 0$. (2)

Here A_1, A_2, A_v are the constants defined from the boundary conditions.

Using the standard boundary conditions for this geometry (considering the model of mirror reflection of electrons from the interface) one can easily obtain the following dispersing equation of the waves being considered: $\varepsilon_{id}\kappa + k_3 = 0$ (3)

(here we consider the frequencies of the order of ion plasma frequency).

From this equation one can obtain for the case of dusty plasma with small frequencies of interparticle collisions (ν_e/ω , ν_i/ω, $\nu_d/\omega << 1$) the following expressions for wavenumber k_{30} and the space decrement of wave damping δk_3 under little SW frequencies $\omega^2 << \omega_{pi}^2$:

$$k_{30} = \frac{\omega}{V_{sd}} \quad , \quad \delta k_3 = \frac{1}{2}\frac{\nu_i}{V_{sd}} , \tag{4}$$

where $V_{sd} = V_s \cdot g$, $g = (1 + n_{0d} Z_d / n_{0e})^{1/2}$. It is seen from here that the presence of dust in plasma can cause a significant increase of ion sound velocity as well as of phase velocity of the wave because $g \geq 1$.

The depths of penetration of SW field into plasma are the following:

$$\lambda_1 = k_3^{-1} = \frac{V_{sd}}{\omega}\sqrt{\frac{\varepsilon_{id}^r + 1}{\varepsilon_{id}^r}} \quad , \quad \lambda_2 = \kappa^{-1} = \frac{V_{sd}}{\omega}\sqrt{\varepsilon_{id}^r(\varepsilon_{id}^r + 1)} \tag{5}$$

All the results obtained have been analyzed numerically. It turns out that if the density of dust in plasma increases the phase velocity increases too, as well as the depths of penetration of SW field into plasma. The increase of phase velocity can lead to decrease of efficiency of interaction between SW and plasma ions. The increase of penetration depths can lead to deeper plasma heating. The space decrement of SW increases with the increase of dust density in low frequencies and decreases in high frequencies of SW. In terms of gas discharge sustained by the SW this means that in case of low frequencies the discharge length will decrease and the intensity of discharge will increase in dusty plasma compared to plasma without dust. On the other hand, in case of high frequencies of SW the discharge sustained by it will become more uniform and its length will increase in dusty plasma compared to pure plasma.

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