MODIFICATION OF NONLOCAL APPROACH FOR THE DISCHARGE SUSTAINED BY SURFACE WAVES IN THE RANGE OF THE LOW PRESSURE

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In the low pressure region, when the electron mean free path is larger then the discharge size, electron dynamics becomes nonlocal and nonequilibrium. In the present work, the self-consistent set of the equations, which take into account anomalous skin-effect, is received. It consists of the kinetic equation for electron energy distribution function (EEDF), nonlocal Maxwell equations and the equations of ion hydrodynamics. In expressions for power diffusion, "bounce" electrons are taken into account, which are responsible for anomalous skin - effect. The determining role of these effects in maintenance of the discharge sustained by surface waves are predicted in the low pressure region.

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1. INTRODUCTION

The plasma sources sustained by surface wave (SW), such as surfatron, waveguide, Ro-box et al, are intensively investigated in connection with numerous technological applications [1].

The basic problem in the theory is to connect external discharge parameters (electric fields intensity, wave frequency, pressure and a kind of gas, the geometrical sizes, etc.), with inner ones (plasma density distribution, electromagnetic fields, frequencies of ionization and recombination, diffusions, electron energy distribution functions (EEDF), etc.).

The occurrence of simplifying approach - the so-called nonlocal approach (see reviews [2, 3]) became significant achievement in this direction.

Electrons in this case are separated into flying and trapped ones. Big part of these electrons is closed and makes oscillations between points of turn. EEDF of such electrons depends only on full energy [2].

The nonlocal approach has been offered in the works [4,5] for the discharges sustained by surface wave and contains analytical, numerical and experimental results. In paper [6], the account of a plasma resonance is added in a vicinity of a point, where dielectric permittivity of plasma addresses in zero. Radial component of electric field is "swelled" that leads to possibility of linear and nonlinear mechanisms of acceleration of the tail electrons. Their existence corresponds to occurrence of additional quasylinear diffusion that has as a result of the change of kinetic equation and discharge parameters as well.

The mean free path λ sharply grows at low pressure ($p \leq 10 mTorr$) that excludes the possibility of Ohmic heating, so that Landau mechanism takes place only for longitudinal waves. It agrees with paper [7] that energy absorbed by plasma depends on the dissipation mechanism. Absorbed energy is determined in nonuniform plasma by a ratio:

$$P_{non} = 4\pi \int \sqrt{\varepsilon} D_{\varepsilon}(\varepsilon) \frac{\partial f(\varepsilon)}{\partial \varepsilon} d\varepsilon \; . \qquad (1)$$

Hence, a question on the SW dissipation mechanism in the field of low pressure appears.

In this case the dominating mechanism of the SW dissipation can be the mechanism of resonant interaction of waves with plasma on the anomalous skin-effect appearing at $\delta << \lambda$, where δ is depth of the skin -layer [8].

The abnormality is provided in a layer (or the cylinder) by the "bounce" electrons. The resonant interaction of such particles with a field takes place under condition of $\Omega_{bounce} \approx \frac{V}{d} \approx \omega$. Similarity of electrons interaction with changing fields at the border, has allowed the authors [9] to name the arising heating as stochastic.

2. SYSTEM OF EQUATIONS

Let's consider the nonuniform plasma layer of thickness d in which it is propagated HF electromagnetic SW with components of fields E_x, E_z, H_y . EEDF in such conditions is nonlocal and nonequilibrium [6]. The kinetic equation in this case is similar to [10] and has the following form:

$$\frac{d}{d\varepsilon}\{\overline{D_\varepsilon}\frac{\partial f_0^0(\varepsilon)}{\partial \varepsilon} + \overline{V_\varepsilon} f_0^0(\varepsilon)\} = \{\sum \overline{\nu}_k^*(\varepsilon + \varepsilon_k^*) \times$$
$$\times \frac{\sqrt{\varepsilon_k^* + \varepsilon}}{\sqrt{\varepsilon}} f_0^0(\varepsilon + \varepsilon_k^*) - \overline{\nu}_k^*(w) f_0^0(\varepsilon)\} - \{f_0^0(\varepsilon) \times \qquad (2)$$
$$\times \overline{\nu_{ion}}(\varepsilon) - \sqrt{\frac{\varepsilon + 2I}{\varepsilon}} f_0^0(\varepsilon + 2I)\overline{\nu_{ion}}(\varepsilon + 2I)\},$$

where the following notations are entered: ε_k^*, I are the excitation potentials on k power level and shock ionization of neutral atom from the basic condition, accordingly; $\overline{\nu}_k^*, \overline{\nu}^{ion}$ are the frequencies of excitation on k power level and the shock ionization, average over cross-section, accordingly; the badge $\overline{A}$ means procedure of averaging over the cross-section accessible to particles with energy ε .The coefficient of power diffusion is:

$$D_\varepsilon = D_1 + D_2 + D_{ql} \qquad (3)$$

where:

$$D_{1\varepsilon} = \frac{em}{8\pi}\mathrm{Re}\int\int d^3v dx F_z \, ; D_{2\varepsilon} = \frac{em}{8\pi}\mathrm{Re}\int\int d^3v dx F_x \, ;$$
$$F_z = \delta(\varepsilon - w + e\Phi_s(x)) v_z E_z(x) V_z^{rf}(x,\varepsilon) \, ;$$
$$F_x = \delta(\varepsilon - w + e\Phi_s(x)) v_x E_x(x) V_x^{rf}(x,\varepsilon) \, ;$$
$$V_z^{rf} = \{\int_{x_-}^{x} dx' G_{z1}(x,x') E_z(x') + \int_{x}^{x_+} dx' \times$$
$$\times G_{z2}(x,x') E_z(x')\}; \; V_x^{rf} = \{\int_{x_-}^{x} dx' G_{x1}(x,x') E_x +$$
$$+ \int_{x}^{x_+} dx' G_{x2}(x,x') E_x(x')\};$$

$$G_{z1}(x,x') = ch(\Phi_+ - \Phi(x))ch\Phi(x')sh^{-1}\Phi_+ ;$$
$$G_{z2}(x,x') = ch\Phi(x)ch(\Phi_+ - \Phi(x'))sh^{-1}\Phi_+ ;$$
$$G_{x1}(x,x') = ch(\Phi_+ - \Phi(x))sh\Phi(x')sh^{-1}\Phi_+ ;$$
$$G_{x2}(x,x') = -ch\Phi(x)sh(\Phi_+ - \Phi(x'))sh^{-1}\Phi_+ ;$$
$$\Phi(x) = \int_{x_-}^{x} \frac{dx'}{v_x}(-i[\omega - k_z v_z] + \nu_{en}) ;\ \Phi_+ = \Phi(x_+) .$$

Obviously, that the equation (1) to within designations coincides with the equation (21) works [6]. The diffusion coefficients (3) generalize resulted in (25) - (28), that is equivalent to the account of the bounce electrons. It should be noted, that at $E_x \to 0$ we have limiting transition to results of [10], and at $\nu >> \Omega$ we have limiting transition to results of [6].

Maxwell equations have nonlocal character since a plasma conductivity is nonlocal:

$$\frac{\partial^2 E_z}{\partial x^2} + \frac{\omega^2}{c^2} E_z = \alpha_1 j_z , \qquad (4)$$

where: $j_z = \int d^3 v \frac{\partial f_0}{\partial \varepsilon}\{\int_{x_-}^{x} dx' G_{1z}(x,x')E_z(x') + \int_{x}^{x_+} dx' \times$

$$\times G_{2z}(x',x)E_z(x')\} ;$$

However, if it is possible to take out intensity of a field from the integral (it can be made provided that the electron power mean free path is small in comparison with characteristic scale of inhomogeneity), then it is possible to proceed the results of local theory.

For closing of the equations (2) - (4) it is necessary the equation for ions by known way [10] to reduced to a kind (5) - (6):

$$\frac{d\varphi}{dx} = -T(x)\frac{d\ln[n(x)]}{dx} , \qquad (5)$$

$$\left[T(x) = \frac{1}{2n(x)} \int_{\varphi(x)}^{\infty} f(\varepsilon)\frac{d\varepsilon}{\sqrt{\varepsilon - \varphi(x)}} \right] . \qquad (6)$$

So, the system of the equations (2)-(6) generalized nonlocal approach for the discharge sustained by surface waves in the field of the low pressures. Comparing the quasylinear diffusion [6] with the diffusion (3) we receive relation of the quasylinear and bounce diffusion coefficients which has the following order $\frac{D_{ql}}{D_{2\varepsilon}} \sim (\frac{\nu_{en}}{\Omega_b})^2$.

From this relation follows, that in the collisionless limit (when the condition $\lambda >> \delta$ occurs, the diffusion with account for bounce movement at least is not less than the quasylinear diffusion.

3. CONCLUSIONS

On the basis of the estimations received from the required equations (2) - (6), it follows that in electron dynamics of the plasma sustained by SW, in low pressure range, nonlocal and nonequilibrium effects are essential. SW energy dissipation it is caused by the stochastic heating, corresponding to anomalous skin-effect. It is possible to assert, that the physical picture is much more difficult, than it seemed earlier.

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МОДИФИКАЦИЯ НЕЛОКАЛЬНОГО ПОДХОДА ДЛЯ ОПИСАНИЯ РАЗРЯДОВ, ПОДДЕРЖИВАЕМЫХ ПОВЕРХНОСТНЫМИ ВОЛНАМИ В ОБЛАСТИ МАЛЫХ ДАВЛЕНИЙ

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В области низких давлений, когда длина свободного пробега электронов больше размера разряда, электронная динамика становится нелокальной и неравновесной. Получена самосогласованная система уравнений, учитывающая аномальный скин-эффект. Она состоит из кинетического уравнения для функции распределения электронов по энергиям, нелокальных уравнений Максвелла и уравнений ионной гидродинамики. В выражения для энергетической диффузии учтены “bounce” электроны, ответственные за аномальный скин-эффект. Предсказана определяющая роль этих эффектов в определении параметров разряда, поддерживаемого поверхностными волнами в области низких давлений**.**

МОДИФІКАЦІЯ НЕЛОКАЛЬНОГО ПІДХОДУ ДЛЯ ОПИСУ РОЗРЯДІВ, ЩО ПІДТРИМУЮТЬСЯ ПОВЕРХНЕВИМИ ХВИЛЯМИ В ОБЛАСТІ НИЗЬКИХ ТИСКІВ

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В області низьких тисків, коли довжина вільного пробігу електронів більша за розмір розряду, електронна динаміка стає нелокальною та нерівноважною. Отримана самоузгоджена система рівнянь, яка враховує аномальний скін-ефект. Вона складається з кінетичного рівняння для функції розподілу електронів по енергіям, нелокальних рівнянь Максвелла і рівнянь іонної гідродинаміки. У виразах для енергетичної дифузії враховані “bounce” електрони, що відповідають за

аномальний скін-ефект. Передвіщена провідна роль цих ефектів у визначенні параметрів розряду, що підтримуються поверхневими хвилями в області низьких тисків.