UDC 533.9.01

EXCITATION AND PROPERTIES OF SOLITARY PERTURBATION OF LARGE AMPLITUDES IN NONEQUILIBRIUM PLASMAS WITH NEGATIVE IONS

V.I.Maslov, V.L.Stomin

NSC Kharkov Institute of Physics & Technology, Kharkov, Ukraine
e-mail: vmaslov@kipt.kharkov.ua, fax: 38 0572 351688, tel: 38 0572

The properties of electrostatic potential hollow of solitary kind are investigated theoretically. The potential hollow is excited in current-carrying plasma. The equation, describing the hollow of any amplitude, is derived.

A growing interest has been given to plasmas with negative ions due to various their applications in technology and due to that negatively charged particles exist frequently in laboratory and space plasmas. In experiment [1] the solitary perturbation of large amplitude has been formed in nonequilibrium plasma with negative ions. In present paper the plasma with electron current relative to nonpropagating positive and negative ions is considered. The case of any densities of negative ions n_{oi-} is considered. This plasma is nonequilibrium. Perturbations are excited. At certain conditions the excited perturbations could be solitary types. Therefore properties of electrostatic potential hollow of solitary kind are investigated. Plasma, containing electrons, positive ions, and also heavy negative ions is considered. The electrons propagate relative to ions with small velocity in comparison with electron thermal velocity. The electrostatic potential hollow reflects the electrons with energy smaller than the hollow depth. This leads to hollow depth growth.

The equation describing the shape and time evolution of electric field structure is derived. It is obtained that the ion-acoustic hollow of electrostatic potential is excited due to current-carrying instability. The case of large amplitude of excited perturbation is considered, when there are no traditional small parameters, permitting to describe properties and excitation of perturbation. It is shown that the hollow propagates with velocity which strongly depends on amplitude of perturbation and is close to ion-acoustic velocity of positive ions $(T_e/M_{i+})^{1/2}$.

We use hydrodynamic equations for negative and positive ions

$$\partial n_\pm/\partial t+\partial(n_\pm V_\pm)/\partial z=0, \qquad (1)$$
$$\partial V_\pm/\partial t+ V_\pm\partial V_\pm/\partial z\pm(q_\pm/M_\pm)\partial\varphi/\partial z=0$$

Here $q_\pm$, $n_\pm$, $V_\pm$, $M_\pm$ are charges, densities, velocities and masses of positive and negative ions. φ is the electrostatic potential.

For description of electron dynamics we use Vlasov equation for their distribution function f_e

$$\partial f_e/\partial t+V\partial f_e/\partial z+(e/m_e)(\partial\varphi/\partial z)\partial f_e/\partial V=0 \qquad (2)$$

and Poisson equation

$$\partial^2\varphi/\partial z^2=4\pi(en_e+q_-n_- -q_+n_+) \qquad (3)$$

Electrons propagate relative to ions with some current velocity V_o. Let us assume that the initial distribution function is the Maxhollow distribution

$$f_{oe}(0,z,V-V_o)=(m_e/2\pi T_e)^{1/2}\exp[-m_e(V-V_o)^2/2T_e] \qquad (4)$$

The initial potential perturbation is a hollow with width δz, smaller than the system length L. The potential hollow with initial conditions (4) is nonequilibrium. It reflects the resonant particles and obtains energy from them. The amplitude (depth) of the hollow grows φ_o.

Due to reflection of resonant electrons with nonsymmetric relative to hollow velocity V_c distribution function from potential hollow the quasineutrality brakes near the hollow: before the hollow the electron density decreases and after the hollow the electron density increases. The quasineutrality is realized due to formation of potential jump $\Delta\varphi$ near the hollow.

At increasing of hollow amplitude up to critical value, when inverse time

$$\tau^{-1}=V_{tr}/\delta z=(2e\varphi_o/m_e)^{1/2}/\delta z(\varphi_o) \qquad (5)$$

of resonant electron (with velocities $|V - V_c| \ll V_{tr}(\varphi_o)$) interaction with the hollow becomes larger than growth rate $\gamma(\varphi_o)=\partial\ln\varphi_o/\partial t$ of hollow amplitude

$$V_{tr}(\varphi_o)>\gamma(\varphi_o)\delta z(\varphi_o), \qquad (6)$$

the slow evolution of the hollow starts in comparison with electron dynamics. The resonant electron distribution function changes. The front with this changed distribution function propagates from the hollow with relative velocity equal V_{tr}.

We use slow evolution of hollow for its description using small parameter $\alpha=\gamma\delta z/V_{tr}$. In zero approximation on α phase trajectories of electrons, described by equations of characteristics of Vlasov equation in rest-frame of hollow are determined by relation

$$\varepsilon=m_eV^2/2-e\varphi(t,z)=\text{const} \quad (7)$$

In this approximation the distribution function before the hollow $z>0$ after it $z<0$ depends only on ε . Here $z=0$ corresponds to $\varphi(z)=-\varphi_o$.

Resonant region before the hollow is wider on the velue of potential jump.

Taking into account that the resonant electrons are reflected from the hollow one can derive from (2), (4) the expression for electron distribution function

$$f_e=f_{oe}[-(V^2-2e(\varphi\pm\Delta\varphi)/m_e)^{1/2}\pm V_o],\ V^{>}_{<}A(\varphi)\text{sign}(z) \quad (8)$$

$A(\varphi)=[2e(\varphi_o+\varphi)/m_e]^{1/2}$.

We use the normalized values: $\phi\equiv e\varphi/T_e$, $N_-\equiv n_{o-}/n_{o+}$, $N_e\equiv n_{oe}/n_{o+}$, $Q_\pm=q_\pm/e$, $V_{s\pm}=(T_e/M_\pm)^{1/2}$. We normalize x on Debye radius of electrons r_{de}, V_o on electron thermal velocity, time t on plasma frequency of positive ions ω_{p+}^{-1} , ion velocities and velocity of solitary perturbation on ion-acoustic velocity of positive ions $(T_e/M_+)^{1/2}$. Here T_e, is the temperature of electrons, n_{o-}, n_{o+} are unperturbed densities of negative and positive ions.

Integrating (8) over velocity, one can derive the expression for electron density which in first approximation on V_o is of type

$$n_e\approx n_{oe}\exp(\phi)[1-(2\Delta\phi/\sqrt{\pi})\int_o^\beta dx\, \exp(-x^2)-$$
$$-2V_o(2/\pi)^{1/2}\int_o^\beta dx\, (x^2-\phi)^{1/2}\exp(-x^2)] \quad (9)$$

Far from the hollow the plasma is quasineutral $n_e(z)\big|_{z\to\infty} = n_e(z)\big|_{z\to-\infty} =1$. From here one can derive, using (9), the expression for potential jump near the hollow

$$\Delta\phi=V_o(2/\pi)^{1/2}(1-\exp(-\phi_o))/[1-(2/\sqrt{\pi})\int_o^{\sqrt{\phi_o}} dx\exp(-x^2)] \quad (10)$$

From hydrodynamic equations for ions (1) one can obtain for perturbations of densities of positive and negative ions

$$n_{i\pm}=n_{\pm NL}+n_{\pm\tau},$$
$$n_{\pm NL}=n_{o\pm}/[1-(\pm q_\pm)2\varphi/M_\pm V_c^2]^{1/2}, \quad (11)$$
$$\partial n_{\pm\tau}/\partial z=\pm2(\partial\varphi/\partial t)(n_{o\pm}q_\pm/M_\pm V_c^3)\times$$
$$\times[1-(\pm q_\pm)\varphi/M_\pm V_c^2]/[1-(\pm q_\pm)2\varphi/M_\pm V_c^2]^{3/2}$$

Substituting (9) , (11) in Poisson equation one can derive nonlinear evolution equation

$$\partial^3_z\phi+\{Q_+^2V^2_{s+}(1-2\phi Q_+V^2_{s+}/V_c^2)^{-3/2}(1-\phi Q_+V^2_{s+}/V_c^2)+$$
$$+Q_-^2N_-V^2_{s-}(1+2\phi Q_-V^2_{s-}/V_c^2)^{-3/2}(1+\phi Q_-V^2_{s-}/V_c^2)\}2\partial_t\phi/V_c^3$$
$$+(\partial_z\phi/V_c^2)\{Q_+^2V^2_{s+}(1-2\phi Q_+V^2_{s+}/V_c^2)^{-3/2}+$$
$$+Q_-^2N_-V^2_{s-}(1+2\phi Q_-V^2_{s-}/V_c^2)^{-3/2}\}- \quad (12)$$
$$-\{\exp(\phi)-\text{sign}(z)V_o(2/\pi)^{1/2}\{(\phi_o/(\phi_o+\phi))^{1/2}\exp(-\phi_o)-$$
$$-\int_{\sqrt{-\phi}}^{\sqrt{\phi_o}} dy(1-2y^2)\exp(-y^2)/(y^2+\phi)^{1/2}+$$
$$+(1-\exp(-\phi_o))[1-(2/\sqrt{\pi})\int_o^{\sqrt{\phi_o}} dx\exp(-x^2)]^{-1}\times$$
$$\times[\exp(-\phi_o)/(\phi_o+\phi)^{1/2}+2(\phi_o+\phi)\exp(-\phi_o)+$$
$$+4\int_{\sqrt{-\phi}}^{\sqrt{\phi_o}} dy\, y(y^2+\phi)^{1/2}\exp(-y^2)]/\sqrt{\pi}\}\}\partial_z\phi=0$$

Integrating (12), one can get

$$(\partial_z\phi)^2/2=(V_c/V_{s-})^2[N_-((1+Q_-2\phi V^2_{s-}/V_c^2)^{1/2}-1)+$$
$$+(1-Q_+2\phi V^2_{s+}/V_c^2)^{1/2}-1]+N_e\{\exp(\phi)-1-$$
$$-2\text{sign}(z)V_o(2/\pi)^{1/2}[\exp(-\phi_o)\sqrt{\phi_o}((\phi_o+\phi)^{3/2}-\phi_o^{3/2})2/3+$$
$$+\exp(-\phi_o)(1+\phi_o+\phi_o^2 2/3)-\exp(\phi)(1-\phi+\phi^2 2/3)+$$
$$+(1-\exp(-\phi_o))[1-(2/\sqrt{\pi})\int_o^{\sqrt{\phi_o}} dx\exp(-x^2)]^{-1}\times$$
$$\times[\exp(-\phi_o)((\phi_o+\phi)^{3/2}-\phi_o^{3/2})2/3+ \quad (13)$$
$$+\sqrt{\phi_o}\exp(-\phi_o)(1+\phi_o 2/3)-\sqrt{-\phi}\exp(\phi)(1-\phi 2/3)-$$
$$-\int_{\sqrt{-\phi}}^{\sqrt{\phi_o}} dy\exp(-y^2)]/\sqrt{\pi}]\}$$

From (13) and $\partial_z\phi|_{\phi=-\phi_o}=0$ one can show that the hollow velocity is close to the ion-acoustic velocity of the positive ions and essentially depends on the hollow amplitude.

References

1. W.Oohara, S.Ishiguro, R.Hatakeyama, N.Sato. Electrostatic potential modification due to C_{60}^- generation // *Proc. of Symp. on DL-PFNL-96*. 1996. p.19.