VORTICAL ELECTRON DYNAMICS IN PLASMA, OBSERVED AT INTERACTION OF LASER PULSE WITH FOIL

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The distribution of electrical potential and electron density near foil, resulting in vortical electron dynamics at interaction of an intensive laser pulse with a foil, is considered.

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1. INTRODUCTION

The interaction of an intensive laser pulse with a foil with the purpose of ion acceleration investigates in the world [1-9]. Laser acceleration of ions was observed from 1960s [10]. The electron semi-vortex or vortex is formed near an irradiated foil at certain conditions. We consider conditions of semi-vortex formation at foil irradiation by laser pulse.

At effect of an intensive laser pulse on a metal foil the high-energy electrons direct through it and form near to a surface of the foil electron layer [1]. Thus electrons of the foil receive a moment from the driver. During the moment exchange the electrons get longitudinal V_{qz} and radial V_{qr} velocities. At electron leaving from the isolated foil the positive charge with surface density σ collects on it. So besides the electrical potential of the volume charge with amplitude $-\varphi_d$, which is formed by an electron layer at the foil's surface [1], the polarized electrical potential φ_0 is formed between the foil and this electron layer. σ is arisen up to some value, when $\varphi_o+\varphi_d$ reaches the electron energy

$$\varphi_o+\varphi_d\approx(m_e c^2/e)(\gamma_q-1). \quad (1)$$

At not large $\varphi_d/\varphi_o<1$ one can write approximately

$$\sigma\approx m_e c^2(\gamma_q-1)/4\pi e^2\Delta\xi_q, \quad (2)$$

After that the electrons come back to the foil. They come back on larger radius, than they left foil. It is determined by initial radial electron velocity V_{qr}, and also by their scattering on r by an own volume charge. According to [11] it can be also determined by magnetic pressure. If radius of an electron flow, leaving the foil, r_q is less in comparison with the longitudinal dimension of area of their braking $r_q<\Delta\xi_q$, a coming back flow extends on r on $\Delta r_w\approx\Delta\xi_q$. At certain conditions $\Delta\xi_q$ is the Debye radius of high-energy (HE) electrons $\Delta\xi_q\approx r_{dq}$ [1]. Then we derive in nonrelativistic approximation

$$\sigma\approx(V_q/4e)(m_e n_q/\pi)^{1/2}. \quad (3)$$

This layer is extended $L_0(t)$ during ion acceleration up to 60 MeV [1].

If $r_q>>\Delta r_w$, the vortex is not formed. The vortex can be formed, if $r_q<\Delta r_w$. At achievement of the flow velocity $V_z\approx c$ one can derive for certain conditions

$$\Delta\xi_q\approx c(\gamma_q-1)^{1/2}/\omega_{pq},\ \sigma\approx(c/2e)(\gamma_q-1)^{1/2}(m_e n_q/\pi)^{1/2} \quad (4)$$

σ can be estimated from the balance of electron flows

$$\sigma\approx 2n_q r_q^2\Delta\xi_q/\pi(\Delta r_w)^2 \quad (5)$$

One can see that σ is depended on ratio $r_q/\Delta r_w$.

2. ELECTRIC POTENTIAL DISTRIBUTION AT ELECTRON FLOW LEAVING FROM FOIL

1D numerical simulation [12] has shown, that at injection of a cold electron beam into plasma 0<z<L the strongly nonlinear structure - jump of potential can be formed near the plasma boundary. We consider properties of similar connected jump and dip of electrical potential. These jump and dip are formed by electrons, which are accelerated by a driver at its interaction with a foil. We will show, that at leaving of HE electron flow with density n_q from isolated foil into vacuum the jump and dip of electrical potential, similar to [13], is possible to form near the foil. These jump and dip return electrons to the foil and accelerate ions. Let's consider at first the potential distribution along axis of HE electron flow in one-dimensional approximation in the case of relativistic HE electrons.

The longitudinal structure of electrical potential along axis of the narrow flow represents potential jump near the foil and potential dip in the flow. In the limiting case $r_q<<\Delta\xi_q$ the longitudinal electrical field along axis of the flow can be presented approximately in the following kind

$$E_z\approx 2\pi e\{\sigma+n_q[-2z+\Delta\xi_q+(r_q^2+z^2)^{1/2}-(r_q^2+(\Delta\xi_q-z)^2)^{1/2}]\} \quad (6)$$

The potential equals maximal value $\varphi_o=\varphi(z=0)$ on the foil and it equals zero in some point z_0 inside the flow. On the interval $z_0<z<\Delta\xi_q$ the electrical potential dip with amplitude $-\varphi_d$ is distributed.

We assume that electrons of a plasma layer formed near the foil's surface are low-energy. Then they quickly fall on the foil. Thus near the foil single group of electrons remains: HE electrons with density n_q. The longitudinal velocity of the polarized electrical potential and of the volume charge potential is approximately equal to velocity of front of accelerated ions. If HE electrons are possible to present as a beam with finite energy width, far from a point of their reflection their density grows from the foil's surface under the power law

$$n_q(z)=n_q(1-\gamma_q^{-2})^{1/2}[1-(1+e\varphi/mc^2)^{-2}]^{-1/2}. \quad (7)$$

The maximal negative charge $n_q^{(max)}=n_q(2V_q/V_{thq})^{1/2}/\gamma_q^{3/2}$ is reached on some distance from the foil. V_{thq} is the thermal velocity of HE electrons. If the distribution function of HE electrons can be presented as equilibrium Maxwell distribution function with temperature T_q, their density falls down from the foil's surface according the exponential law

$$n_q(z)=n_q\exp[(\varphi-\varphi_o)e/T_q]\ . \quad (8)$$

With the help (7) one can show that at $\varphi_c=(\varphi_o+\varphi_d)(2V_{qth}/c)\gamma_o^2$ the reflection of HE electrons begins.

For essential ion acceleration, the considered quasi-stationary distribution of the electrical potential should be supported during long time. Electrons transfer a momentum to the polarized electrical potential and to the volume charge potential. The flow of momentum transferred to the polarized electrical potential and to the volume charge potential by reflected HE electrons equals $2n_q mc^2(\gamma_q^2-1)/\gamma_q$ (or $n_q T_q$). In a field of polarized electrical potential and of volume charge potential ions receive a momentum. The speed of increase of an ion momentum is approximately equal to $m_i n_{0i} L dV_L/dt$. L is the width of area of ion acceleration. The ions also select energy from the polarized electrical potential and from the volume charge potential. The speed of energy selection by ions is approximately equal to $m_i n_{0i} L V_L dV_L/dt$. The HE electrons at interaction with the polarized electrical potential and with the volume charge potential lose energy. The flow of energy, transferred to the polarized electrical potential and to the volume charge potential by HE electrons equals $n_q mc^2 2V_L(\gamma_q^2-1)/\gamma_q$ (or $V_L n_q T_q$). One can see that the balance of energy flows is reduced to balance of momentum flows. Using the balance of momentum flows of particles, which interact with the polarized electrical potential and with the volume charge potential, one can derive approximately the expression for speed of ion acceleration:

$$dV_L/dt \approx 2n_q mc^2(\gamma_q^2-1)/\gamma_q m_i n_{0i} L. \qquad (9)$$

That the HE electrons effectively accelerate ions and not fall on walls, the radial forces should confine their in the region of ion localization. As the low-energy electrons quickly fall on the foil, one can write

$$n_{0i}(z) \geq n_q \gamma_q^{-2}. \qquad (10)$$

from the condition of radial confinement of the HE electrons. (10) is correct at semi-vortex or vortex formation. The inequality (10) is correct at $\gamma_q >> 1$, $n_{0i} << n_q$ and at $\gamma_q > 1$, $n_{0i} < n_q$.

Let's derive the equation, which describes a structure of the polarized electrical potential and the volume charge potential, and estimate their width. As the law-energy electrons fall quickly on the foil, the structure of the polarized electrical potential and of the volume charge potential is determined by the HE electrons and by ions. Integrating the Poisson's equation on φ, neglecting the small interval, closed $\varphi=-\varphi_d$, where the HE electrons are reflected, in one-dimensional approximation we derive

$$(\partial\varphi/\partial z)^2=(\partial\varphi_0/\partial z)^2-4\pi e\sigma(\partial\varphi_0/\partial z)+8\pi mc^2\gamma_q n_q(1-\gamma_q^{-2})^{1/2}\times$$
$$\times\{[[1-e(\varphi_0-\varphi)/\gamma_q mc^2]^2-\gamma_q^{-2}]^{1/2}-(1-\gamma_q^{-2})^{1/2}\}-4\pi e\int n_{0i}(z)d\varphi. \qquad (11)$$

Using the approached equality $(\varphi_0+\varphi_d) \approx mc^2(\gamma_q-1)/e$ and condition $\partial\varphi/\partial z=0$ at $\varphi=-\varphi_d$, we derive

$$\partial\varphi_0/\partial z=2\pi e\sigma+$$
$$+\{(2\pi e\sigma)^2+4\pi\gamma_q mc^2(1-\gamma_q^{-1})[2n_q(1+\gamma_q^{-1})-n_{0i}]\}^{1/2}. \qquad (12)$$

Let's obtain approximately width of the jump and dip:

$$\Delta z=(\varphi_0+\varphi_d)/\partial\varphi_0/\partial z\approx \qquad (13)$$
$$\approx(c/\omega_{pq0})\sqrt{\gamma_q}/[g+(g^2+2-n_{0i}/n_q)^{1/2}],\ g\equiv 2\pi e^2\sigma/\omega_{pq0}mc\sqrt{\gamma_q}$$

In the case of dense plasma its polarization $\delta n=n_q-n_{0i}$ is small. If selfconsistent ion dynamics follows for electric field distribution such that $\delta n\approx$const, one can obtain

$$\Delta z\approx(c/\omega_{pq0})\sqrt{\gamma_q}/[g+(g^2+\delta n/n_q)^{1/2}].$$

Using (4), (5) one can obtain $g\approx r_q^2/(\Delta r)^2$. One can see that the electrical field is strengthened near foil by σ.

In approximation of the HE electrons as a thin flow we obtain from (4)

$$\varphi(z)=\varphi_0-2\pi e\sigma z-\pi e n_q\{r_q^2\times$$
$$\times\ln\{[z+(r_q^2+z^2)^{1/2}][\Delta\xi_q-z+(r_q^2+(\Delta\xi_q-z)^2)^{1/2}]/r_q[\Delta\xi_q+(r_q^2+\Delta\xi_q^2)^{1/2}]\}+ \qquad (14)$$
$$+\Delta\xi_q^2/2-(\Delta\xi_q-2z)^2/2+z(r_b^2+z^2)^{1/2}+$$
$$+(\Delta\xi_q-z)(r_b^2+(\Delta\xi_q-z)^2)^{1/2}-\Delta\xi_q(r_b^2+\Delta\xi_q^2)^{1/2},$$

$0<z<\Delta\xi_q$. The minimal value of the potential φ_{min} equals approximately at $z\approx\Delta\xi_q/2$

$$\varphi_{min}\approx\varphi_0-\pi e\sigma\Delta\xi_q-\pi e n_q r_q^2\ln(\Delta\xi_q/2r_q) \qquad (15)$$

We derive approximately from (4)

$$\partial\varphi_0/\partial z\approx 2\pi e(\sigma+n_q r_q) \qquad (16)$$

One can see that with decrease r_q at n_q=const $\partial\varphi_0/\partial z$ decreases. However, at focusing of the HE electrons with their flow constancy the field, accelerating ions, increases. Also one can see that the field, slowing down of the thin flow of the HE electrons, is smaller in $\omega_{pq}r_q/c\sqrt{\gamma_q}$. Hence, the depth of penetration in plasma of the thin flow of electrons is more and longitudinal size of the semi-vortex or vortex in this case is more.

Because $\varphi_0\approx 2\pi\sigma e(c/\omega_{pq0})\sqrt{\gamma_q}$, then

$$\varphi_{min}/\varphi_0\approx-[\pi e n_q r_q^2\ln(\Delta\xi_q/2r_q)]/[2\pi\sigma e(c/\omega_{pq0})\sqrt{\gamma_q}].$$

Let's consider the stability of relative electron flows concerning HF perturbations on the basis:

$$1-\alpha/z^2-(1-\alpha)[(z-y)^{-2}+R(z+y)^{-2}]/2\gamma_q^3=0\ . \qquad (17)$$

$\alpha=n_{0e}/n_{0i}$, $z=\omega/\omega_p$, $y=kV_b/\omega_p$, R is the parameter of radial distance between direct and opposite electron flows. If R=1, the counter electron flows are on the same radius. From (17) it follows that in the region of jump and dip the noise with the large phase velocities can be generated. Similar to [12, 14] the noise does not destroy the jump and dip due to: width of electron distribution function; inhomogeneity of potential, which breaks the condition of wave - particle resonance; and due to large relative velocity of noise and jump. Also the noise does not destroy the jump and dip due to decrease of n_{0e}.

Let's consider the stability of relative electron flows concerning LF perturbations on the basis:

$$1+\alpha/(kd_0)^2-(1-\alpha)[(z-y)^{-2}+R(z+y)^{-2}]/2\gamma_q^3=0\ . \qquad (18)$$

$d_0=(T_{0e}/4\pi n_{0e}^2)^{1/2}$. From (18) one can show, that at R=1 and n_{0e}, below critical, determined by the inequality

$$(V_{tho}/V_q)^2/\gamma_q^3>\alpha+(kd_0)^2 \qquad (19)$$

the potential jump becomes unstable relative perturbations with small phase velocities. Thus, the realization of counter electron flows as a vortex can stabilize jump.

If the energy of the HE electrons concerns nonrelativistic case, let us also consider this case. From the kinetic eq. one can derive the electron distribution function in 1D approximation, integrating which on velocity, we obtain the density perturbation:

$$\delta n(\varphi)=n_e-n_i\approx-n_i+\beta, \qquad (20)$$

$$\beta=\left(n_q/\sqrt{\pi}\right)\left[2\int_{\left[\sqrt{\varphi_o-\varphi}-V_q\right]/\sqrt{T_q}}^{\left[\sqrt{\varphi_o}-V_q\right]/\sqrt{T_q}}+\int_{\left[\sqrt{\varphi_o}-V_q\right]/\sqrt{T_q}}^{\infty}\right]dV\times$$
$$\times\left[1-(\varphi_o-\varphi)/\left(V_q+V\sqrt{T_q}\right)^2\right]^{-1/2}\exp\left(-V^2\right)$$

From (20) one can see that the density of the HE electrons increases. This results in negative volume charge. The maximal value n_q is reached in the region of strong electron braking:

$$n_q(\varphi_c)\approx n_q V_q/(V_q(T_q/2)^{1/2})^{1/2}=n_q(V_q(2/T_q)^{1/2})^{1/2}\ . \qquad (21)$$

At $\varphi_1=\varphi_o-(V_q-(2T_q)^{1/2})^2$ the reflection of the HE electrons begins.

From balance of momentum flows we derive similarly to (9):

$$dV_L/dt \approx 2n_q m V_q^2/m_i n_{0i} L \quad (22)$$

We determine width of jump and dip from (20) similarly to (13):

$$\Delta z=(\varphi_0+\varphi_d)/\partial\varphi_0/\partial z. \quad (23)$$

$$\partial\varphi_0/\partial z=2\pi e\sigma+[(2\pi e\sigma)^2+8\pi m V_q^2(n_q-n_{0i}/4)]^{1/2}.$$

One can see that the charge accumulation on the foil strengthens the accelerating field. If the distribution function of HE electrons can be presented as equilibrium Maxwell distribution function with temperature T_q, in approximation $e\sigma \ll V_q(2mn_q/\pi)^{1/2}$ we obtain from (23) $\partial\varphi_0/\partial z \sim (T_q n_q)^{1/2}$. With increase n_q and T_q the field grows and reaches 10 GV/cm for $n_q \approx 10^{23}$ cm^{-3} and $T_q \approx 1$ keV [1]. Thus, using (3), we obtain

$$\Delta z \approx 4V_q/\omega_{pq}. \quad (24)$$

In the case of small polarization $\delta n=n_q-n_{0i} \ll n_{0i}$ of dense plasma, consisting from HE electrons and ions, one can estimate

$$\Delta z \approx 4(V_q/\omega_{pq})(n_q/\delta n)^{1/2}.$$

The electrons are extended in the first front of the flow due to the initial radial velocity, obtained as a result of scattering, and due to strong volume charge of the flow. On the foil large σ is supported, which influences on the electron flow dynamics. The electron dynamics can be represented as semi-vortex or vortex.

The vortical electron trajectories are described by

$$\partial_z[V_z^2/2-(e/m_e)\varphi]=-V_r\partial_r V_z,\ \partial_r[V_r^2/2-(e/m_e)\varphi]=-V_z\partial_z V_r.$$

Introducing radius of curvature of electron trajectories in the semi-vortex or vortex, one can derive balance of forces, effecting on electron. From this balance one can conclude that the vortex's radius is close to longitudinal its dimension.

Also the vortical electron trajectories are described by the equation

$$\nabla\varepsilon = [V, \eta],\ \varepsilon \equiv V^2/2-\varphi e/m_e \quad (25)$$

One can see that the spatial change of value $m_e V^2/2-e\varphi$ is determined by vorticity $\eta \equiv [\nabla \times V]$. From this relation we derive for η

$$\eta = -[V, \nabla\varepsilon]/V^2 . \quad (26)$$

The electron trajectories form the semi-vortex in the region of essentially 3D distribution of an electrical field.

For the vortex description we also use eq. [15]

$$d_t((\eta-\omega_{He})/n_e) = n_e^{-1}((\eta-\omega_{He})\nabla)V . \quad (27)$$

As $\eta = \vec{e}_\theta \eta$ and all is homogeneous on azimuth, for nonrelativistic electrons we obtain

$$(\vec{V}\nabla)(\eta/n_e) = 0,\ n_e=n+\Delta\varphi/4\pi e \quad (28)$$

One can see that the maximal vorticity is reached in the region of the largest electron density inside the region of volume charge.

In such electrical field the ions of a plasma layer, formed near foil, are accelerated [1]. The similar ion acceleration by the virtual cathode, formed by electron beam, was observed earlier. The ions are accelerated by volume charge of the HE electrons [1], and by polarized potential, appeared between the isolated foil and electron layer.

The energy of accelerated ions can be determined by potential of shock and dip $\varepsilon^{(i)} \approx T_q$. If the accelerated ions interact with shock and dip for a long time and ion velocity is achieved to velocity of electron flow, which determine structure and value of an accelerating field, the maximal ion energy $\varepsilon^{(i)}_{max}$ equals

$$\varepsilon^{(i)}_{max} \approx T_q m_i/m_e. \quad (29)$$

In experiments (see [1]) $\varepsilon^{(i)}_{max}$=60MeV was achieved.

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ВИХРЕВАЯ ДИНАМИКА ЭЛЕКТРОНОВ В ПЛАЗМЕ, НАБЛЮДАЮЩАЯСЯ ПРИ ВЗАИМОДЕЙСТВИИ ЛАЗЕРНОГО ИМПУЛЬСА С ФОЛЬГОЙ

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Показано, что при взаимодействии интенсивного лазерного импульса с фольгой распределение электрического потенциала и плотностей частиц таково, что в окрестности фольги динамика электронов может быть вихревой.

ВИХРОВА ДИНАМІКА ЕЛЕКТРОНІВ В ПЛАЗМІ, ЯКА СПОСТЕРІГАЄТЬСЯ ПРИ ВЗАЄМОДІЇ ЛАЗЕРНОГО ІМПУЛЬСУ З ФОЛЬГОЮ

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Показано, що при взаємодії інтенсивного лазерного імпульсу з фольгою розподіл електричного потенціалу і густин частинок є таким, що в околиці фольги динаміка електронів може бути вихровою.