RELATIVISTIC ELECTRON BEAM REFLECTION FROM THE PLASMA BOUNDARY

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The spatial distribution of the electrical field, accompanying reflection of the relativistic electronic bunch from the plasma boundary, has been investigated.
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INTRODUCTION

In paper [1] it has been shown, that injected in plasma from an insulated source the continuous beam of the relativistic electrons is reflected from a monotonic double layer, formed by it. In this paper the experimentally observed [2] and close to investigated in [1,3] the reflection of the relativistic electron beam from plasma boundary is considered, which, however, is implemented at other conditions. Namely, the narrow relativistic electronic beam of final length, injected in plasma, is reflected at certain conditions from vacuum – plasma boundary.

We investigate theoretically phenomena, accompanying the injection of the relativistic electron bunch in plasma with density, much greater the plasma density $n_b>>n_o$. Outgoing from actual experimental conditions, we consider the bunch, which length is greater than its radius, $L_b>>r_b$. We consider, that the effect of reflection is realized on electron time scale, i.e. the ions have no time to react on fields of the bunch, owing to their inertness. The plasma electrons under effect of the electrical field of the bunch are scattered in a transverse direction. As a result of it around of the bunch the area of a positive charge is formed, which scheme is introduced in Fig. 1 by area, designated by "+". On the bunch electrons, distributing in plasma, radial electrical scattering force $-eE_r$ and magnetic force of a self-focusing of the relativistic electron bunch F_{mf} act. We choose such parameters of the bunch, that its self-focusing or increase of its radius is not performed. Then following balance of the radial forces $eE_r(n_b-n_o)+F_{mf}(n_b)=0$ is realized. Here e is the charge of the electron, E_r is the transversal component of an electrical field, created by the bunch and plasma ions at its electron evacuation in a radial direction from area of the bunch propagation. In last ratio it is shown by brackets, that F_{mf} depends on the bunch density, and E_r depends on the difference of densities of the bunch and ambient plasma ions. For E_r and F_{mf} we have following approximate expressions

$$E_r\approx 2\pi e(n_o-n_b)r\ ,\ r<r_b;$$
$$E_r\approx 2\pi e(n_o r-n_b r_b^2/r)\ ,\ r_b<r<R_o; \qquad (1)$$
$$F_{mf}\approx 2\pi e^2 n_b r(V_b/c)^2,\ r<r_b$$

From balance of radial forces with the help of these expressions it is possible to receive for the relativistic bunch $\gamma_b=(1-V_b^2/c^2)^{-1/2}>>1$ presented above condition for densities

$$n_b=n_o\gamma_b^2>>n_o\ . \qquad (2)$$

Here γ_b is the relativistic factor of the bunch, V_b is the bunch velocity, c is the velocity of the light, R_o is the radius of area, from which the plasma electrons are escaped. From the condition that the electrical field, scattering the plasma electrons, equals zero at $r=R_o$ we receive, that around of the bunch the broad area of the positive charge is formed

$$R_o\approx r_b(n_b/n_o)^{1/2}>>r_b. \qquad (3)$$

Below we will show that the spatial structure of the electric potential, created by the bunch and the mentioned above area of the positive charge at a separation of tail of the bunch from the boundary plasma - vacuum, can be the cause of explained effect.

REFLECTION OF THE ELECTRON BEAM

Let's consider distribution of the electrical field along an axis z of the symmetry of the bunch in the case, when the back front of the bunch was separated from boundary plasma - vacuum at its penetration in the plasma. The distribution of the electrical field along a symmetry axis of the bunch on the interval between boundary plasma - vacuum and back front of the bunch $0<z<L_o$, and also between back and forward fronts of the bunch $L_o<z<L_o+L_b$ looks like

$$E_z(z)=2\pi e\{n_b[\mu+L_b+(r_b^2+(z-L_o)^2)^{1/2}-(r_b^2+(L_o+L_b-z)^2)^{1/2}]+$$
$$+n_o[2z-L_o-L_b+(R_o^2+(L_o+L_b-z)^2)^{1/2}-(R_o^2+z^2)^{1/2}]\} \qquad (4)$$
$$\mu\equiv 0\ ,\ 0<z<L_o$$
$$\mu\equiv 2(L_o-z)\ ,\ L_o<z<L_o+L_b$$

The distribution of the electric potential looks like

$$\phi(z)=-2\pi e\{n_o[z(z-L_o-L_b)-$$
$$-(R_o^2/2)\ln[(z+(R_o^2+z^2)^{1/2})(L_o+L_b-z+(R_o^2+(L_o+L_b-z)^2)^{1/2})/R_o[L_o+L_b+(R_o^2+(L_o+L_b)^2)^{1/2}]]-$$
$$-z(R_o^2+z^2)^{1/2}/2+(L_o+L_b)[R_o^2+(L_o+L_b)^2]^{1/2}/2- \qquad (5)$$
$$-(L_o+L_b-z)[R_o^2+(L_o+L_b-z)^2]^{1/2}/2]+$$
$$+n_b\alpha\}$$

$$\alpha\equiv L_b^2/4-(2L_o+L_b-2z)^2/4+$$
$$+(r_b^2/2)\ln[(z-L_o+(r_b^2+(z-L_o)^2)^{1/2})(L_o+L_b-z+(r_b^2+(L_o+L_b-z)^2)^{1/2})/r_b[L_b+(r_b^2+L_b^2)^{1/2}]]+(z-L_o)(r_b^2+(z-L_o)^2)^{1/2})/2+$$
$$+(L_o+L_b-z)(r_b^2+(L_o+L_b-z)^2)^{1/2})/2-$$
$$-L_b(r_b^2+L_b^2)^{1/2}/2\ ,\ L_o<z<L_o+L_b$$

$$\alpha\equiv(z-L_o)(r_b^2+(L_o-z)^2)^{1/2}/2+$$
$$+L_b(z-L_o)-L_b(r_b^2+L_b^2)^{1/2}/2+$$
$$+(L_o+L_b-z)(r_b^2+(L_o+L_b-z)^2)^{1/2}/2+$$

$$+(r_b^2/2)\ln[r_b(L_o+L_b-z+(r_b^2+(L_o+L_b-z)^2)^{1/2})/(L_o-z+(r_b^2+(L_o-z)^2)^{1/2})(L_b+(r_b^2+L_b^2)^{1/2})]+$$
$$+(z-L_o)(r_b^2+(z-L_o)^2)^{1/2})/2\ ,\ 0<z<L_o$$

here L_o is the distance from the plasma boundary to trailing edge of the bunch, L_b is the length of the bunch.

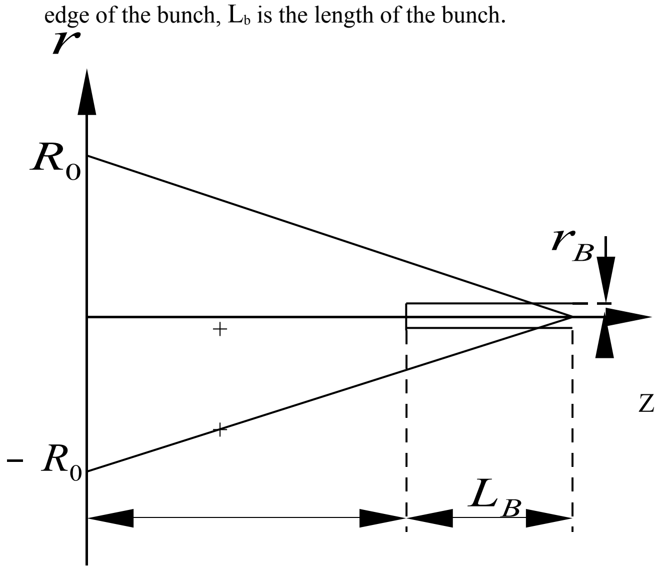

Fig.1. The arrangement of the electron bunch, injected in the plasma, and of area of the positive charge, screening its, in a neighborhood of the boundary plasma - vacuum

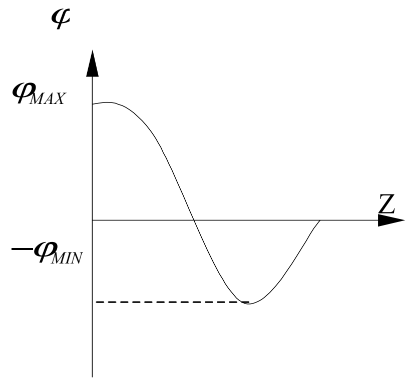

Fig.2. The distribution of the electric potential along an axis of the electron bunch

The function f(z) looks like, qualitatively shown in Fig. 2. As it is visible from this figure, the potential has a dip approximately in the center of the bunch. As the strong inequality $n_b>>n_o$ is realized, then the distribution of the electric potential between the plasma boundary and back front of the electron bunch is flat in comparison with the potential distribution in the region of the bunch. Minimum and maximum values of the potential we derive, using argument of the function (5), accordingly $L_o+L_b/2$ and 0. Then we receive:

$$\phi_{max}\approx-2\pi en_b[-L_bL_o-L_b(L_b^2+r_b^2)^{1/2}/2-L_o(L_o^2+r_b^2)^{1/2}/2+$$
$$+(L_o+L_b)((L_o+L_b)^2+r_b^2)^{1/2}/2-$$
$$-(r_b^2/2)\ln[(L_o+(r_b^2+L_o^2)^{1/2})\times$$
$$\times(L_b+(r_b^2+L_b^2)^{1/2})/r_b[L_o+L_b+(r_b^2+(L_o+L_b)^2)^{1/2}]]\approx$$
$$\approx\pi en_br_b^2\ln(2L_oL_b/(L_o+L_b)r_b) \qquad (6)$$

$$\phi_{min}\approx-2\pi en_b[L_b^2/4+L_b(L_b^2/4+r_b^2)^{1/2}/2-L_b(L_b^2+r_b^2)^{1/2}/2+$$
$$+(r_b^2/2)\ln[(L_o+L_b/2+(r_b^2+L_b^2/4)^{1/2})(L_b/2+(r_b^2+L_b^2/4)^{1/2})/r_b[L_o$$
$$+L_b+(r_b^2+L_b^2)^{1/2}]]\approx$$
$$\approx-\pi en_br_b^2\ln(L_o+L_b)L_b/(L_o+2L_b)r_b \qquad (7)$$

The condition of reflection of electron bunch part looks like: $mc^2(\gamma_b-1)<e\Delta\phi$, where $\Delta\phi=(|\phi_{max}|+|\phi_{min}|)$, m is the electron mass. This condition of reflection can approximately be presented as follows

$$mc^2(\gamma_b-1)<\pi e^2n_br_b^2\ln(L_b/r_b)\ . \qquad (8)$$

Let's present the following condition $\gamma_{e\perp}>\gamma_b$, which is necessary that the plasma electrons do not have time to retain behind the bunch and thus to neutralize the positive charge. Here $\gamma_{e\perp}$ is the relativistic factor of the plasma electrons, accelerated by field of the bunch in a transverse direction. Last condition can approximately be presented as follows

$$\pi e^2n_br_b^2\ln(n_b/n_o)>mc^2\gamma_b\ . \qquad (9)$$

This condition is more easy executed in the case of the large bunch density n_b and not so large γ_b. This condition, in absence of a self-focusing or widening of the bunch, receives the following kind

$$\omega_b^2r_b^2\ln\gamma_b>2c^2\gamma_b. \qquad (10)$$

or through full quantity of charges $Q=\pi r_b^2n_bL_b$ of the electron bunch

$$Q>L_b\varepsilon_b/2e^2\ln(\varepsilon_b/mc^2). \qquad (11)$$

Here $\omega_b^2=4\pi e^2n_b/m$, ε_b is the energy of the electron bunch.

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ВІДБИТТЯ РЕЛЯТИВІСТСЬКОГО ЕЛЕКТРОННОГО ПУЧКА ВІД МЕЖІ ПЛАЗМИ

С.В. Барчук, О.М. Єгоров, В.І. Маслов, І.М. Онищенко, Г.О. Скоробагатько

Теоретично досліджена просторова структура електричного поля при явищі відбиття релятивістського електронного пучка кінцевої довжини і малого радіуса від межі плазма-вакуум, що спостерігається експериментально.

ОТРАЖЕНИЕ РЕЛЯТИВИСТСКОГО ЭЛЕКТРОННОГО ПУЧКА ОТ ГРАНИЦЫ ПЛАЗМЫ

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Теоретически исследована пространственная структура электрического поля при экспериментально наблюдаемом явлении отражения релятивистского электронного пучка конечной длины и малого радиуса от границы плазма-вакуум.