# REB REFLECTION FROM THE BOUNDARY PLASMA-VACUUM

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The necessary conditions of the experimentally observed reflection of "tail" of the dense relativistic electron beam from the plasma-vacuum boundary at once after full its injection into the plasma under condition of $n_b$>>$n_0$, are considered in this paper.

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## 1. INTRODUCTION

This paper is devoted to interaction of a dense relativistic electronic beam with rare-field plasma. In the paper the experimentally observed phenomenon of reflection of a part of a relativistic electronic beam from a plasma boundary is explained and described. In the paper the model of this phenomenon also is constructed. The problem under consideration is important for a problem of use of a plasma mirror, researched now, for management of an electron beam. The performed investigations also may provide values of parameters of a beam, at which it is not reflected from a plasma boundary of the lens, used for focusing of a relativistic electronic beam.

In the paper the spatial distribution of the electric potential, formed at reflection of a part of an electron relativistic beam from a plasma boundary, in which this beam is injected, is constructed. Necessary parameters of a beam and plasma, at which reflection of a part of an electron beam can take place, are derived.

In this paper the experimentally observed [1] reflection of the relativistic electron beam from plasma boundary is considered. Namely, the narrow relativistic electronic beam of final length, injected into the plasma, is reflected at certain conditions from the vacuum – plasma boundary.

We investigate theoretically phenomena, accompanying the injection of the relativistic electron bunch into the plasma with density, much greater the plasma density $n_b \gg n_o$. Proceeding from actual experimental conditions, we consider the bunch, the length of which is greater than its radius, $L_b \gg r_b$. 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, around the bunch the area of a positive charge is formed. 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 act.

$$F_{mf} \approx 2\pi e^2 n_b r (V_b/c)^2, \quad r<r_b$$

We choose such parameters of the bunch, that its self-focusing or increase of its radius is not performed. Then the following balance of the radial forces $eE_r(n_b-n_o)+F_{mf}(n_b)=0$ is realized. Here $E_r$ is the transversal component of an electrical field, created by the bunch and plasma ions at its electron evacuation in a radial direction from the area of the bunch propagation. In the 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 $E_r$ we have the following approximate expression

$$E_r \approx 2\pi e(n_o-n_b)r, \quad r<r_b;$$

$$E_r \approx 2\pi e(n_o r-n_b r_b^2/r), \quad r_b<r<R_o; \qquad (1)$$

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

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

Here $\gamma_b$ is the relativistic factor of the bunch, $V_b$ is the bunch velocity, $R_o$ 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 derive that around the bunch the broad area of the positive charge is formed

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

Below we will show that the spatial structure of the electric potential, created by the bunch and the above-mentioned 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.

## 2. REFLECTION OF THE ELECTRON BEAM

Let us consider the distribution of the electrical field along the axis z of the symmetry of the bunch in the case, when the back front of the bunch was separated from the boundary plasma - vacuum at its penetration into the plasma. The distribution of the electrical field along the 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

$$E_z(z)=2\pi e\{n_b[\mu+L_b+(r_b^2+(z-L_o)^2)^{1/2}-(r_b^2+(L_o+L_b-z)^2)^{1/2}]$$

$$+n_o[2z-L_o-L_b+(R_o^2+(L_o+L_b-z)^2)^{1/2}-(R_o^2+z^2)^{1/2}]\} \quad (4)$$

$$\mu\equiv 0\ ,\ 0<z<L_o$$

$$\mu\equiv 2(L_o-z)\ ,\ L_o<z<L_o+L_b$$

The distribution of the electric potential looks like

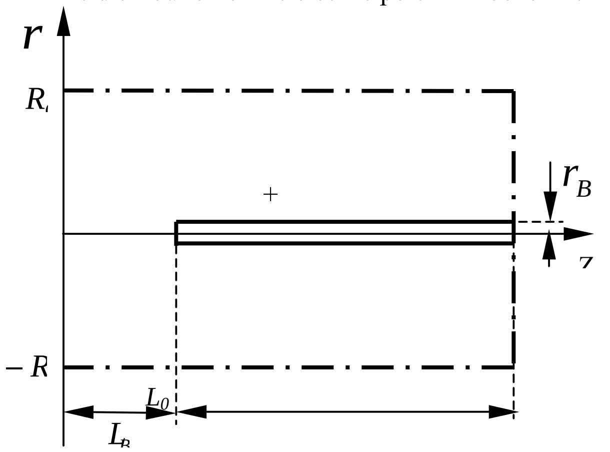


*Fig.1. Arrangement of the electron bunch, injected into the plasma, and of the region of the positive charge, shielding it, in a vicinity of the plasma – vacuum boundary*

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

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

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

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

The function $\phi(z)$ looks like, qualitatively shown in Fig.2.

One can see that 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 obtain:

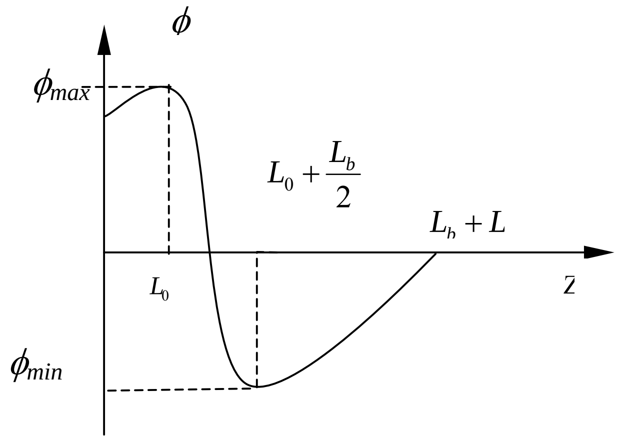


*Fig. 2. The distribution of the electric potential along the axis of the electron bunch*

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

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

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

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

Let us 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 the field of the bunch in a transverse direction. The latter condition can be approximately presented as follows

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

This condition is more easy fulfill in the case of the large bunch density $n_b$ and not so large $\gamma_b$. This condition, in the absence of a self-focusing or widening of the bunch, has the following form

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

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

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

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

At the time the moment $\tau$ of the plasma electron acceleration in the transversal direction is stopped:

$$V_b\tau \approx L_o+L_b \text{ , where } L_o \sim L_b \text{ .}$$

Then

$$\tau \approx 2L_o/V_b \text{ , where } V_b=c(1-\gamma_b^{-2})^{1/2} \quad (12)$$

On the other hand

$$\tau \approx R_o/V_{e\perp} \text{ , где } V_{e\perp}=c(1-\gamma_{e\perp}^{-2})^{1/2} \quad (13)$$

Then we have:

$$R_o/(1-\gamma_{e\perp}^{-2})^{1/2} \approx 2L_b/(1-\gamma_b^{-2})^{1/2} \quad (14)$$

Because (9) is fulfilled, let us assume $\gamma_{e\perp}^{-2} \sim 0$ , then from (14) the condition on $L_b$ , depending on $R_0$ and $\gamma_b$, we derive, namely

$$L_b \approx (R_o/2)(1-\gamma_b^{-2})^{1/2} \quad (15)$$

From (15), using the condition (3) on $R_0$ , we have:

$$L_b \approx (n_b/n_o)^{1/2}(r_b/2)(1-\gamma_b^{-2})^{1/2} \quad (16)$$

or, as $\gamma_b>>1$

$$L_b \approx (n_b/n_o)^{1/2}(r_b/2) \quad (17)$$

Substituting (17) in (8), we obtain, taking into account $\gamma_b>>1$ , that as the condition (8) is satisfied, then the condition (9) is fulfilled automatically with $L_b$ from (15). Thus, (8) is the unique condition on REB reflection if parities: (2), (3) and (15) are fair.

Then, substituting (17) in (8) and, using a condition of finite self-focusing of the beam (2), we obtain the condition of REB reflection as:

$$\pi e^2(n_b n_o)^{1/2} r_b^2/m_e c^2 \geq 1/[\ln(n_b/n_o)/2-\ln 2] \quad (18)$$

or

$$\alpha r_b^2 \geq 1/(n_b n_o)^{1/2}[\ln(n_b/n_o)-2\ln 2], \quad (19)$$

where $\alpha \equiv \pi e^2/2m_e c^2$.

Then from (19), taking into account (2) we can derive the following condition on the plasma density $n_0$, at given $r_b$ , $\gamma_b$:

$$n_o \geq 1/4\alpha\gamma_b r_b^2(\ln\gamma_b-\ln 2), \quad (20)$$

at which performance within the framework of the accepted model the "tail" of the electron beam should be reflected from the plasma – vacuum boundary.

## 3. CONCLUSIONS

Thus, we have shown, that the reflection of the "tail" of relativistic electron beam ($\gamma_b>>1$) from the plasma – vacuum boundary after time ($\tau \approx L_o/V_b$) after its injection is possible, if the inequality (20) is performed at validity of additional conditions (2), (3), (17).

At the given radius $r_b$ of the beam and plasma density $n_0$ the conditions (2), (3), (17) and (20) completely determine values of all parameters of the beam, which are necessary in this model for reflection of its "tail" from the plasma – vacuum boundary.

## REFERENCES


1. P.Muggli et al. // *Nature*. 2001. v.411, p. 43.


## ОТРАЖЕНИЕ РЭП ОТ ГРАНИЦЫ ПЛАЗМА-ВАКУУМ


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В статье рассматриваются необходимые условия экспериментально наблюдаемого отражения «хвоста» инжектируемого плотного $n_b>>n_0$ релятивистского электронного сгустка от границы плазма-вакуум после полного его проникновения в плазму.


## ВІДБИТТЯ РЕП ВІД ГРАНИЦІ ПЛАЗМА-ВАКУУМ


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У статті розглядаються необхідні умови відбиття, що експериментально спостерігається, «хвоста» інжектованого щільного $n_b>>n_0$ релятивістського електронного згустку від границі плазма-вакуум після повного його проникнення в плазму.