REFLECTION OF NORMAL INCIDENCE RELATIVISTIC ELECTRON BUNCH FROM SEMI-BOUNDED PLASAMA

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In [1] was obtained the model and analytic describing of the relativistic electron beam reflection from plasma boundary. This phenomenon was experimentally observed in paper [2]. Lack of experimental information compels us to make the new theoretical model. Numerical realisation of this one obtained in present work. Before numerical investigation the relations described reflection of a relativistic electron beam of finite length and small radius (Lb>>rb) from vacuum-plasma boundary and given in [1] are made more accurate. In particular, the influence of the posisitive volume charge in front of the high density electron beam is taken into account.

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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 monolithic double layer, formed by it. In this paper the reflection of the relativistic electron beam from plasma boundary is considered. Similar reflection was experimentally observed in [2]. Namely, the narrow relativistic electronic beam of finite length, injected in plasma, is reflected at certain conditions from semi-bounded plasma.

We investigate theoretically phenomena, accompanying the injection of the relativistic electron bunch in plasma with density, much greater the plasma density $n_b >> n_o$.

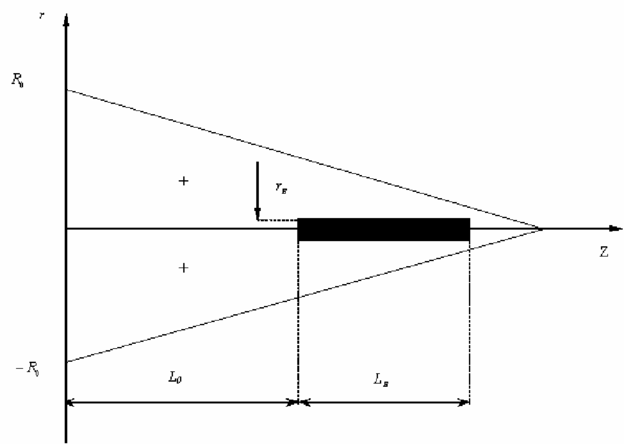

Fig.1. The arrangement of the electron bunch, injected in the plasma, and of area of the positive charge, screening its, in a neighborhood of the plasma boundary

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 it's 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

$$E_r \approx 2\pi e(n_o - n_b)r,\ r < r_b$$
$$E_r \approx 2\pi e\left(n_o r - n_b \frac{r_b^2}{r}\right),\ r_b < r < R_o \qquad (1)$$
$$F_{mf} \approx 2\pi e_2 n_b r\left(\frac{v_b}{c}\right)^2,\ r < r_b$$

From balance of radial forces with the help of these expressions it is possible to receive for the relativistic bunch $\gamma_b = \left(1 - \frac{v_b^2}{c^2}\right)^{-\frac{1}{2}} >> 1$ 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

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

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 plasma boundary, can be the cause of explained effect.

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 plasma boundary at its penetration in the plasma. The distribution of the electrical potential of the bunch on the interval between plasma boundary and back front of the bunch $0 < z < L_o$, and also between back and forward fronts of the bunch, 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.

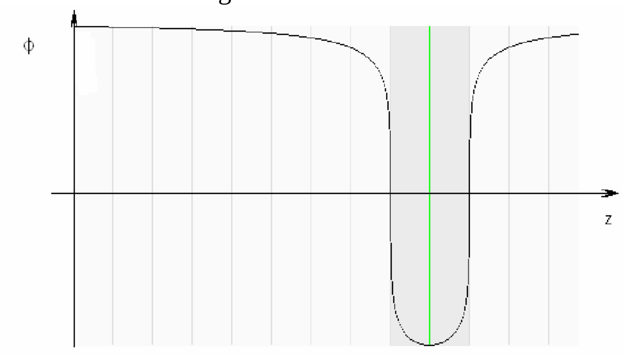

Fig. 2. The distribution of the electric potential along an axis of the electron bunch

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:

$$mc^2(\gamma_b - 1) < \pi e^2 \psi n_b r_b^2 \ln\left(\frac{L_b}{r_b}\right). \qquad (4)$$

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

$$mc^2\gamma_b < \pi e^2 n_b r_b^2 \ln\left(\frac{n_b}{n_o}\right). \qquad (5)$$

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

$$\omega_b^2 r_b^2 \ln\gamma_b > 2c^2\gamma_b, \qquad \omega_b^2 = \frac{4\pi e^2 n_b}{m}, \qquad (6)$$

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

$$Q > \frac{L_b \varepsilon_b}{2e^2 \ln\left(\frac{\varepsilon_b}{mc^2}\right)}. \qquad (7)$$

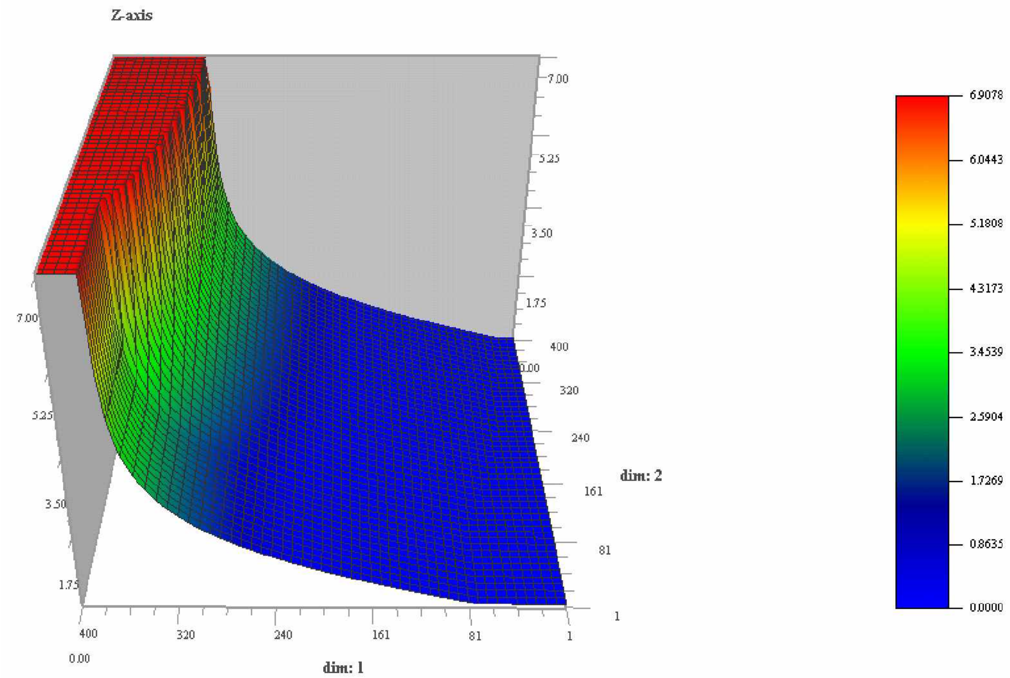

Fig. 3. Region of the electron beam reflection from semi-bounded plasma

On Z-axis (Fig. 3) we have shown bunch energy in GeV, on dim 1-axis – depth of beam penetration in plasma in comparative units (“400” according to situation where distance between back front of the bunch and plasma boundary equal L_b, and “1” - 0), on dim 2-axis – ratio of beam and plasma densities n_b / n_{pl} (“400” – 23,3×103, “1” – 14,88×103). Using this result we can say that in borders of our model relativistic electron beam reflection is strongly depend on n_b / n_{pl} and E_b but almost independent from penetration depth.

We find out that in our model reflecting part of the beam arrange not more than 50 % in whole investigated scale of parameters and depend on relations of plasma and the beam densities. Reflecting part of the beam depends on beam density n_b and its length L_b.

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ОТРАЖЕНИЕ НОРМАЛЬНО ПАДАЮЩЕГО РЕЛЯТИВИСТСКОГО ЭЛЕКТРОННОГО ПУЧКА ПОЛУОГРАНИЧЕННОЙ ПЛАЗМОЙ

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В [1] приведена модель и теоретическое описание отражения релятивистского электронного пучка от границы плазмы. Это явление исследовано экспериментально в работе [2]. Недостаток информации об эксперименте вынудил создать новую теоретическую модель. В настоящей работе приведена ее численная реализация. Перед численным изучением были уточнены отношения, описывающие отражение релятивистского электронного пучка конечной длины и малого радиуса (Lb>>rb) от границы вакуум-плазма, представленные в [1]. В частности, было учтено влияние положительного объемного заряда, образующегося перед пучком.

ВІДБИТТЯ НОРМАЛЬНО ПАДАЮЧОГО РЕЛЯТИВІСТСЬКОГО ЕЛЕКТРОННОГО ПУЧКА НАПІВОБМЕЖЕНОЮ ПЛАЗМОЮ

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У [1] наведена модель і теоретичний опис відбиття релятивістського електронного пучка від межі плазми. Це явище досліджено експериментально в роботі [2]. Недостатність інформації про експеримент змусила створити нову теоретичну модель. У цій роботі наведена її чисельна реалізація. Перед чисельним вивченням були уточнені відношення, що описують відбиття релятивістського електронного пучка кінцевої довжини та малого радіуса (Lb>>rb) від межі вакуум-плазма, наведені в [1]. Зокрема був врахований вплив позитивного об'ємного заряду, що утворюється перед пучком.