TO THE MECHANISM OF MODULATED REB CURRENT INCREASE DURING ITS PROPAGATION THROUGH PLASMA

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The mechanism of full current increase is investigated in this paper. This current arises at transporting of the short relativistic electron bunches in the plasma, formed by them at gas of large pressure. This phenomenon is determined by the electric field, arising at motion of the relativistic electron bunches, having an angular divergence, in the plasma.

PACS: 52.40.Mj

In many experiments on research of transport of relativistic electron beam (REB) through plasma or neutral gas the electron current increase was observed, connected with the plasma electron drift in the same direction, in which the beam moves [1-8]. The different points of view about the mechanism of such drift have been stated. However main part of the authors connects the plasma current origin with of ponderomotive forces, of the plasma oscillations, excited due to beam-plasma interaction. Plasma electrons are carried along only if field amplitude is spatially nonuniform or is changing in time (increment).

In this paper new mechanism, different from early investigated one, of whole current increase ($I_o=I_b+I_p$, here I_b is the beam current, I_p is the plasma current), excited during transportation of a chain of short relativistic bunches in plasma, is considered at absence of beam-plasma interaction. In this concept the phenomenon is caused by an electric field, arising at motion of bunches with angular divergence in plasma. The angular divergence of the beam is determined by beam's electron scattering at their transit of a foil, through which the beam of relativistic electrons ejects from accelerator into atmosphere. As the longitudinal sizes of the bunch change insignificantly due to relativity of electrons and the transversal sizes of the bunch are increased, the charge density of the bunch decreases with distance from an exit foil. When behind the foil there are some bunches, whose charge density decreases with distance that results in originating a quasistationary electrical field. In the case, when the time of Debye shielding and charge decontamination of bunches is more than bunch duration, the presence of such field should result in drift of plasma electrons in the direction of bunch propagation.

In our experiments the linear electron accelerator was a source of relativistic electron beam REB as a train of short bunches. Energy of electrons is equal W=2 MeV, number of electrons in each bunch $N=2*10^9$, duration of the bunch $\tau_b\approx60$ ps (length of the bunch $l_b\approx1.5$ cm), frequency of bunches following $\omega_m\approx1{,}7*10^{10}\ s^{-1}$. The current impulse of the accelerator consists ~ $6*10^3$ such bunches (duration of the impulse 2 μs, current in a impulse 1A). REB injected in atmosphere or in the chamber, filled with air, through a titanium foil of thickness 50 μm. Radius of the beam before the exit foil was 0.8 cm. The chamber was the copper tube of length 100 cm and diameter 12 cm. At the end of the chamber the Rogovsky coil was placed. Behind it the lead collector was mounted for registration of the whole current. For measurement of the plasma electron current a mobile collector, manufactured from aluminum foil of thickness 0.1 mm, transparent for relativistic beam electrons, was used. The external magnetic field was absence.

The angular divergence of the electron beam, caused by scattering on a separating foil, was $<\theta>\approx10^o$-12^o. On the distance 100 cm, on which the whole current was measured, there were 10 bunches simultaneously.

The plasma was produced by bunches through the neutrals ionization at their injection in air. Density of plasma was estimated by measurements of its conductivity by the double HF-probe [9]. At air pressure P<1 Torr the electrical probe was applied. Steadied plasma density in the pressure range 10^{-1}-750 Torr is proportional to beam density and is weakly depended on pressure in chamber. At the pressure decrease from 750 Torr up to 0.5 Torr the plasma density on distance 10 cm from the separating foil decreases from $n_e\approx10^{11}\ cm^{-3}$ up to $n_e\approx10^{10}\ cm^{-3}$ at the density of beam electrons in the given cross-section, averaged over the impulse, $n_e\approx10^8\ cm^{-3}$.

From measurements of the current by Rogovsky coil and by aluminum and lead collectors the dependence of the whole current value I_o on air pressure near the chamber entrance, apart 1 m from the separating foil, was obtained (Fig. 1). The increase of the whole current appears at pressure P≈ 10^{-2} Torr and reaches maximum value at P≈ 10^{-1}-1.0 Torr. At further increase of pressure the whole current decreases due to increase of a collision frequency of plasma electrons with the neutrals. The increase of the whole current on different distances from the exit foil during the beam propagation through air at atmospheric pressure is shown in Fig. 2.

Observed amplification of the whole current is impossible to explain by mechanisms, proposed in [1-8]. The drift motion of plasma electrons in crossed fields (self azimuth magnetic and electrical radial fields of the electron beam) is impossible because of small duration and large duty parameter K of bunches: $\tau_b<1/\omega_p(z)$; here $\omega_p(z)=\{4\pi n_e(z)e^2/m_e\}^{1/2}$ is plasma frequency. $K=\lambda/l_b\approx6$; here λ is wavelength of accelerator wave.

The plasma current driven by fields, induced by bunch fronts, is negligible in the beam cross-section, as $\omega_p^2(z)r_b^2(z)/c^2<<1$ [10]. The hose instability doesn't develop because of small current I_b. The beam-plasma instability cannot be developed due to large dispersion of the electron distribution function over energy ($\Delta W/W>25\%$) and also large angular dispersion $\langle\Delta\theta^2\rangle$ [11].

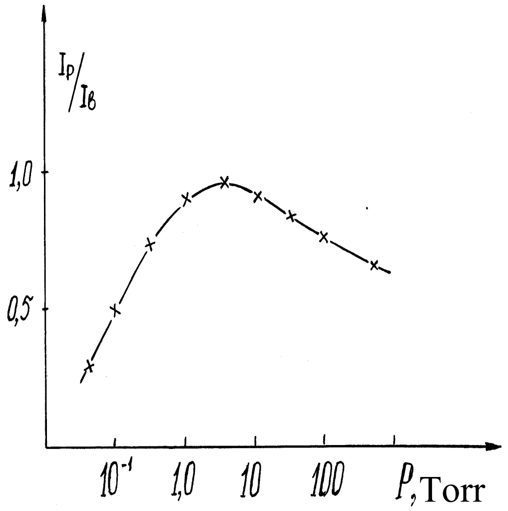

Fig. 1. The dependence of current value of the plasma electrons on pressure (l=100 cm)

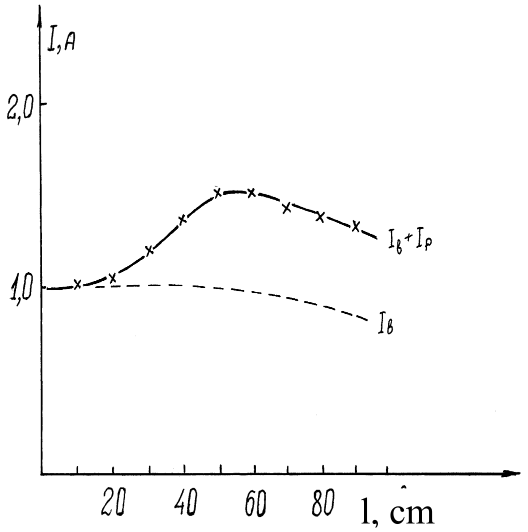

Fig. 2. The dependence of whole current value (I_b+I_p) on distance up to an output foil (P=700 Torr)

In our consideration the increase of the whole current is explained by existence of the quasistationary electrical field arising due to beam divergence at absence of Debye shielding and neutralization of space charge of electron bunches. The time of these processes can be estimated from [12]:

$$\tau_n=\begin{cases}1/\omega_e(z)=(4\pi e^2n_e(z)/m_e)^{-1/2}, & \omega_e>>\nu_{eo}/2\\ 1/4\pi\sigma=\nu_{eo}/\omega_e^2(z), & \omega_e<<\nu_{eo}/2\end{cases} \qquad (1)$$

here σ is the plasma conductivity, ν_{eo} is the collision frequency of plasma electrons with neutral molecules. In our case only in small region of length $l\sim10$ cm near to an exit foil the equality $\tau_n\approx\tau_b$ is fulfilled at high air pressure. In the other region of beam propagation we have $\tau_n>\tau_b$, so the charge of bunches is not neutralized and the electrical field of bunches exists on distances much more larger of the Debye screening radius. At bunches propagation along the chamber the value of the electric field, formed by the bunch as the disk of thickness δ, equals

$$E_z=-2\pi e(\delta/\gamma^2)n_b(z)[1-z/(z^2+r_b^2(z))^{1/2}],\ \gamma=(1-V_b^2/c^2)^{-1/2} \quad (2)$$

Here $n_b(z)$, $r_b(z)$ are the bunch density and radius at point z, V_b is its velocity. The values of the radial electrical, E_r, and azimuth magnetic, H_θ, fields in a neighborhood of an axis of the bunches equal

$$\begin{aligned}E_r&\approx-en_b(z)\pi r\delta\gamma r_b^2(z)/(z^2+r_b^2(z))^{3/2}\\ H_\theta&\approx-en_b(z)\pi r\delta\gamma(1-\gamma^2)^{1/2}r_b^2(z)/(z^2+r_b^2(z))^{3/2}\end{aligned} \qquad (3)$$

Because the charge neutralization of the short bunches is not realized, then the plasma electrons are oscillated in their fields in radial direction under effect of the force, equal eE_r. Thus, in collisional plasma they are radially oscillated with velocity $V_r=-(e/m\nu_{eo})E_r$. In longitudinal direction the plasma electrons are oscillated under action of two forces

$$e(E_z+H_\theta V_r/c)=e[E_z+(V_b/c^2)(e/m\nu_{eo})E_r^2]. \qquad (4)$$

Because in a neighborhood of an axis of the bunches the following expression is true $E_r\approx-\gamma^3(r/2)\partial E_z/\partial z$, then in the case $\gamma>>1$ second part can be larger than first one. In this case the plasma electrons are oscillated in longitudinal direction not under effect of the longitudinal electrical field of the bunches, but under effect of the transversal fields of the bunches.

Along with the longitudinal oscillations plasma electrons move with velocity V_{zo} under the action of the quasistationary longitudinal electrical field, E_{zo}, that leads to the appearance of the longitudinal current of the plasma electrons.

At bunches propagation their radius soon becomes equal to radius of the chamber and they can be represented as disks of small thickness with homogeneous charge density. As the charge density decreases with distance from the foil, the electrical field, exciting the plasma current, arises on large spatial interval. Let us consider the moment, when the chain of the bunches has been penetrated into the plasma on the depth L. On the distance L_1 as a result of the divergence of the bunches their radius $r_b(z)|_{z=L1}$ becomes equal to the radius of the chamber R. Then in fixed time on different spatial intervals the quasistationary longitudinal electrical current is realized in the field of the chain of bunches, firstly due to bunches widening and secondly due to density decrease in time. In this case the plasma electrons are propagated on different spatial intervals with following velocities:

$$V_{zo}=(e/m\nu_{eo})(2\pi e n_{bo}/\gamma^2)(L_b/L_m)\times$$
$$\times\{\int_o^{L1} dx\,[1-(z-x)/((z-x)^2+r^2_{bo}(1+\alpha x)^2)^{1/2}]/(1+\alpha x)^2+$$
$$+\int_{L1}^{L} dx\,[1-(z-x)/((z-x)^2+R^2)^{1/2}]/(1+\alpha x)^2,\ z>L$$

$$V_{zo}=(e/m\nu_{eo})(2\pi e n_{bo}/\gamma^2)(L_b/L_m)\times \qquad (5)$$
$$\times\{\int_o^{L1} dx\,[1-(z-x)/((z-x)^2+r^2_{bo}(1+\alpha x)^2)^{1/2}]/(1+\alpha x)^2+$$
$$+\int_{L1}^{z} dx\,[1-(z-x)/((z-x)^2+R^2)^{1/2}]/(1+\alpha x)^2-$$
$$-\int_{z}^{L} dx\,[1-(z-x)/((z-x)^2+R^2)^{1/2}]/(1+\alpha x)^2,\ L_1<z<L$$

$$V_{zo}=(e/m\nu_{eo})(2\pi e n_{bo}/\gamma^2)(L_b/L_m)\times$$
$$\times\{\int_o^{z} dx\,[1-(z-x)/((z-x)^2+r^2_{bo}(1+\alpha x)^2)^{1/2}]/(1+\alpha x)^2-$$
$$-\int_{z}^{L1} dx\,[1-(z-x)/((z-x)^2+r^2_{bo}(1+\alpha x)^2)^{1/2}]/(1+\alpha x)^2-$$
$$-\int_{L1}^{L} dx\,[1-(z-x)/((z-x)^2+R^2)^{1/2}]/(1+\alpha x)^2,\ 0<z<L_1$$

Here L_b is the length of the bunch, L_m is the distance between bunches.

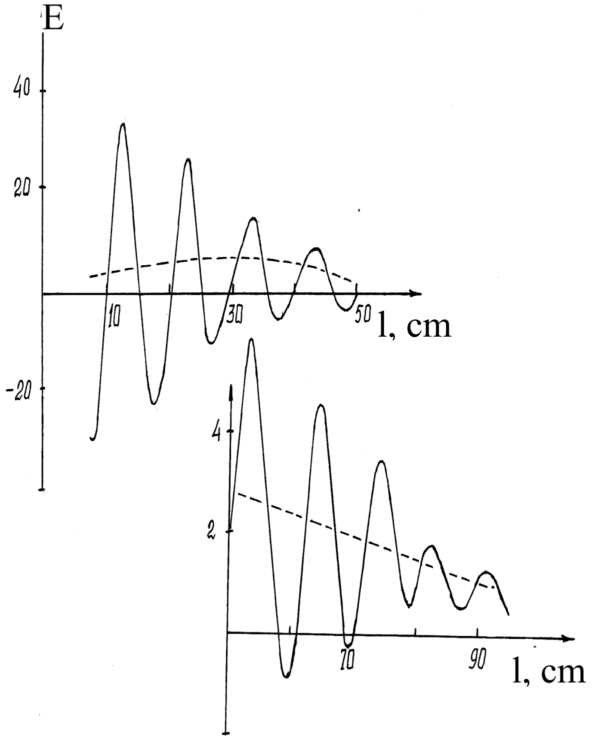

Fig. 3. Change of the electrical field on the axis of the chamber at presence of ten bunches of relativistic electrons

The value of the electrical field on the chamber axis from 10 bunches determined from (2), is shown in Fig. 3. The field has a stationary component E_{zo} and motion of the plasma electrons with velocity V_{zo} is excited in the same direction, in which bunches move. Thus the plasma current equals:

$$I_p=\sigma[E_{zo}+(V_b/c^2)(e/m\nu_{eo})\rangle\langle E_r^{2}\rangle]=$$
$$=[E_{zo}+(V_b/c^2)(e/m\nu_{eo})\langle E_r^{2}\rangle]e^2n/mN\nu_{ep} \qquad (6)$$

here n is the plasma density, N is the gas density, ν_{ep} is the collision frequency of plasma electrons with neutral molecules, ⟨⟩ is the spatial averaging. The frequency ν_{ep} depends on plasma electron velocity and cross-section of collisions. In weakly ionized gas ν_{ep} is only the function of temperature and is growing with increase of electron temperature T_e.

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