RELATIVISTIC ELECTRON BUNCH EXCITATION OF PLASMA WAKE-FIELD AND CHARGED PARTICLE ACCELERATION IN THE PRESENCE OF EXTERNAL MAGNETIC FIELD

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The report is devoted to the theoretical study and numerical simulation of the excitation of wake-fields in plasma and their application for charged particle acceleration. It is shown that at a given relationship between the parameters of the "plasma bunch - magnetic field" system in the magnetoactive plasma owing to the hybrid space-surface character of wake-field waves excited by a relativistic electron bunch (REB), the accelerated bunch energy $\varepsilon_{\max}$ can appear essentially higher than the exciting bunch energy even if the longitudinal REB charge density profiling is not used. With the help of 2.5 D numerical simulation of wake-fields excited by a single REB or a REB sequence it has been established the following: the ion channel is formed owing to transverse ion motion in self-consistent electromagnetic fields, this channel stabilizes REB propagation and thus serves to increase the REB excited fields; the self-modulation of a long pulsed REB is a very promising way both to obtain high rates of charged particle acceleration and to modulate the bunch and plasma densities (this gives evidence that the linear approach cannot be used to describe the plasma even in the low beam density case). These results make it possible to clarify the prospects and to evaluate the possibility of creating new-type charged particle accelerators which will have acceleration rates much higher than the conventional resonant accelerator has.

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1 INTRODUCTION

The ideas of using collective fields for acceleration in the plasma and noncompensated charged beams were stated as early by Veksler (1956), Budker (1956), Fainberg (1956). The appearance and development of new powerful energy sources such as lasers, high-current relativistic electron beams, super - high - power microwave generators, gave another impetus to the development of the collective methods of charged particle acceleration. As a result, Tajima and Dawson (1979) and Chen et. al (1985), there appeared new modifications of the method of charged particle acceleration in a plasma by charge density waves (see reviews: Dawson (1999), Fainberg (1987), Fainberg (1994), Fainberg (1997), Fainberg (2000), Power et. al. (1999), Suk et al. (2001), where it was proposed that the accelerating fields should be excited by laser pulses and relativistic electron bunches. The charged particle acceleration by charge density waves in a plasma and in uncompensated charged beams, Fainberg (1956), appears to be a most promising trend in the collective methods of acceleration. The variable part of the charge density can be made to be very high (up to n_0, where n_0 is the unperturbed plasma density); therefore, the accelerating fields can reach 10^7 to 10^9 V/cm. Chen et al. (1985) have proposed a modification of the Fainberg (1956) acceleration method, consisting in using a train of bunches. The experiments undertaken in Rosenzweig (1990) on wake-field acceleration have demonstrated the importance of three-dimensional effects. The excitation of nonlinear stationary waves in the plasma by a periodic train of electron bunches has been studied by Amatuni et al. (1979), Rosenzweig (1990), where it was shown that the electric field of the wave in the plasma increases with γ_b at commensurable plasma/beam densities.

2 2.5-D NUMERICAL MODELING OF THE FORMATION OF A PLASMA CHANNEL AND OF THE LONG REB SELF-MODULATION

The excitation of wake fields is investigated with an aid of the 2D3V axially symmetric version of the SUR code being, in turn, a further development of the COMPASS code Batishchev et al. (1994a), Batishchev et al. (1994b). Earlier, this code has been used to simulate the induction accelerator Karas' et. al. (1992), the modulated relativistic electron beam Batishchev et al. (1993), and a single REB or a train of these bunches in a plasma Batishchev et. al. (1994a), Batishchev et al. (1994b), Karas' et al. (1996), Karas' et al. (1997), Karas' et al. (1998), Karas' et al. (2000a).

2.1 Mathematical model and methods

The REB dynamics is described by the relativistic Belyaev-Budker equations for the distribution functions $f_\alpha(r,p)$ of plasma particles of each species and by the Maxwell equations for the self-consistent electric E and magnetic B fields. We assume that, initially, a cold two - component background plasma ($m_i/m_e = 1840$, where m_i and m_e are the ion and electron masses) fills the entire region $[0,L] \times [0,R]$, where $L = 100$ cm and $R = 10$ cm. In order to analyze the dependence of the amplitude of the excited fields on the number of bunches injected into plasma, we carried out series of calculations. A finite sequence of REB, which are specified by the expression

$$n_n(r,z,t) = n_b \theta\left(R_0 - r\right) \times$$

$$\times\theta\left(v_b t - z + (n-1)\lambda_p\right)\theta\left(z - v_p t + Z + (n-1)\lambda_p\right).$$

Here n is the number of the injected bunch; $V_b = c\sqrt{1 - 1/\gamma_b^2}$ is the bunch velocity; c is the speed of light; the initial bunch sizes are equal to 0.4× (0.1-0.5) cm; n_b is the mean density of a relativistic electron bunch; $\lambda_p = 2\pi c/\omega_{pe}$. The scale on which the electric and magnetic fields vary is $m_e c\omega_{pe}/e$. We assume that the plasma/bunch particles escape from the calculated region through the $z = 0$ and $z = Z$ boundary surfaces and are elastically reflected from the $r = R$ surface. We also assume that cold background electrons and ions can return to the region under consideration from the buffer zones $z < 0$ and $z > Z$. The boundary conditions for the fields correspond to the metal wall at the cylindrical surface $r = R$ and free emission of electromagnetic waves from the right and left plasma boundaries. The weight of the model particles was a function of the radial coordinate, and the total number of these particles was about 10^6. All the calculations were carried out on a Pentium-166 personal computer using the modified particle-in-cell simulation algorithm.

2.2 Numerical Simulation of the formation of a plasma channel due to ion redistribution

Barov and Rosenzweig (1994) pointed out that, in the immobile - ion approximation, a channel with an neutralized positive charge can arise in the plasma when the background electron escape from the region through which the REBs propagate. It has already been noted that, in order to analyze the formation of an ion channel in a realistic situation, we must take into account, along with the electron motion, the ion motion in self-consistent electromagnetic fields. We will show that the ion dynamics plays a key role in the formation of an ion channel. Figures 1 and 2 illustrate the formation of an ion channel. The parameters of the plasma channel are governed by the ratio between the bunch and plasma densities and by the ratio between the bunch radius and the collisionless skin depth.

It is shown that the effective sizes of the plasma channel and its depth increase monotonically with time and in the direction against the z-axis. Also it is shown that substantial variations of electron density are associated only with the wake-field wave and have not permanent component contrary to ion density distribution [1].

2.3 Self-modulation of a long relativistic electron bunch

The present results show that the nonlinear picture in the plasma-REB system drastically differs from both the initial picture corresponding to the rigid REB and the one by the scenario following from the one-dimensional numerical modulation (cf. Balakirev et al. (1996)). This supports in full measure the conclusion given in ref. Rosenzweig (1990) about the necessity of taking into complete account the three-dimensional effects and the nonlinear behavior of both the plasma and the bunch.

Fig. 1. 2-D distribution of the longitudinal electric field E_z for the instances of time $t = 60\omega_{pe}^{-1}$ and $t = 100\omega_{pe}^{-1}$.

The spatial density distributions of REB and plasma electrons obtained for the instances of time $t = 60\omega_{pe}^{-1}$ and $t = 100\omega_{pe}^{-1}$ show that the density ratio n_b/n_0 (the initial value being 0.018) reaches 0.04 as early as at $t = 60\omega_{pe}^{-1}$. At $t = 100\omega_{pe}^{-1}$, the highest beam particle density becomes commensurable with the plasma density, i.e., a very strong modulation of beam particle density is observed. The spatial distributions of the longitudinal E_z and transverse E_r electric fields show that the E_z and E_r amplitudes grow owing to the enhancement in the density modulation. At $t = 100\omega_{pe}^{-1}$ the highest longitudinal-field amplitude reaches $0.8 m_e c\omega_{pe}/e$, and the highest transverse-field amplitude is equal to $0.4 m_e c\omega_{pe}/e$. It is essential that the amplitude growth occurs only within a moderate REB length. Therefore, there is little point in using the REB of the length greater than that corresponding to the highest longitudinal-field amplitude, otherwise no increase in the excited wake field will be attained.

Fig. 2. 2-D distribution of the plasma electron density $el.Q$ for the instances of time $t = 60\omega_{pe}^{-1}$ and $t = 100\omega_{pe}^{-1}$.

The undertaken numerical experiments have demonstrated that the nonlinear dynamics of the particles of plasma components and bunches results in the following effects: (i) the transverse dimension of bunches varies within a very wide range; (ii) close to the axis of the system, an ion channel is formed, which is a contributory factor for the stabilization of bunch propagation and the growth of bunch-generated fields; (iii) an essential increase in the amplitudes of excited electric fields takes place in the case of a long bunch as a result of its self–modulation [2]. However, bunches of optimum length should be used, since any excess of the optimum length of the bunch fails to provide, even at self-modulation, the growth in the amplitudes of excited electric fields.

3 WAKE-FIELDS IN MAGNETOACTIVE PLASMAS

We attained the characteristic radial distribution of the longitudinal electric-field component at the following plasma and waveguide parameters: $\frac{\omega_{He}}{\omega_{pe}} = 6.3$, $\frac{\omega_{pe}a}{c} = 23.3$, $\frac{b}{a} = 2.4$, $\gamma_b = 4.6$. The wake hybrid wave frequency is here equal to 0.35 ω_{pe}. It is shown that for the radius $\frac{r}{a} = 0.8$ the magnitude of the longitudinal electric-field component has a deep maximum corresponding to the energy transformation coefficient $R_E = \left|\frac{E_{z\max}}{E_{z(r=0)}}\right| = 37$.

Note that a great value of the transformation coefficient corresponds to a significant (R_E times) excess of the maximum energy obtained by the accelerated bunch as compared to the energy of the bunch exciting the wake field, because the energy transformation coefficient R_E is equal to the ratio of the amplitude of the electric field accelerating the guided bunch to the amplitude of the electric field decelerating the bunch that excites the accelerating wake field. So, it has been demonstrated that a multiple excess of the accelerated bunch energy $\varepsilon_{\max}$ over the energy of the exciting. REB is possible in a magnetoactive plasma at a certain relationship between the parameters of the “plasma - bunch - magnetic field” system (owing to a hybrid volume - surface character of REB-excited wake-fields), even without using the REBs contoured in the longitudinal direction, a namely: $\varepsilon_{\max} = mc^2\left(R_E\gamma_b - 1\right)$ [3].

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