Large Plasma Wake-Field Acceleration of Charged Particles by Selfmodulated Long Relativistic Electron Bunch

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High-amplitude plasma wake-waves are excited by high-density relativistic electron bunches (REB) moving in a plasma. The wake- fields can be used to accelerate charged particles, to serve as electrostatic wigglers in free-electron plasma lasers (FEL), and also can find many other applications.

The electromagnetic fields in the region occupied by the bunch control the dynamics of the bunch itself. In particular, the transverse forces cause a strong compression (pinching) of bunches having small transverse dimensions $k_p r_b \ll 1$, where $k_p = \omega_p/c$, ω_p is the plasma frequency, c is the light velocity, and r_b is the radius of the bunch). This phenomenon is at the basis of operation of plasma lenses that can be used to focus ultra-high energy particles. The longitudinal fields give rise to longitudinal modulation of an electron bunch. Specifically, an originally uniform bunch evolves into individual microbunches.

This paper presents the results of 2.5-dimensional numerical simulation of both the modulation of long REB in a plasma and the excitation of wake fields by these bunches. The previous one-dimensional study has shown that the density profile modulation of a long bunch moving in plasma results in the growth of the wake wave amplitude. This is explained by the fact that the wake fields generated by microbunches being due to the evolution of the initially uniform bunch during the modulation, are coherent. The bunch modulation occurs at the plasma frequency. The present study is concerned with the REB motion, taking into account the plasma and REB nonlinearities. It is demonstrated that the radial REB dynamics exerts primary effect on both the REB self-modulation and the wake field excitation by the bunches formed.

1 Introduction

The charged particle acceleration by charge density waves in a plasma and in uncompensated charged beams appears to be a most promising trend in the collective methods of acceleration [1-3]. The variable part of the charge density can be made to be very high (up to , where is the unperturbed plasma density); therefore, the accelerating fields can reach 10^7 to 10^9 V/cm. Chen et al [4] have proposed a modification of the Fainberg acceleration method [1], consisting in using a train of bunches. In [5], Katsouleas has considered electron bunches with different profiles, namely, a bunch with a slow build-up in the density and its very quick fall-off, and also the bunch with the Gaussian-type distribution for different rise and fall-off times. It was established in [5] that the use of these nonsymmetric bunches instead of symmetric ones can provide the accelerating field E_α value to be many times (10 to 20) higher than the retarding field E_{st} value. The so-called transformation coefficient $T = E_\alpha/E_{st} = \Delta\gamma_\alpha\gamma_\beta^{-1}$ is equal to $2\pi N$, where N corresponds to the number of wavelengths along the bunch length. The excitation of nonlinear stationary waves in the plasma by a periodic train of electron bunches has been studied in refs. [6, 7], where it was shown that the electric field of the wave in the plasma increases with γ(γ is the relativistic factor of the beam) at commensurable plasma and beam densities. The experiments undertaken in refs. [7, 8] on wake-field acceleration has demonstrated the importance of three-dimensional effects.

Here, we consider two different regimes with high amplitudes of plasma wake fields that are employed in the accelerator physics. The first regime makes use of an extended short beam, then the high-amplitude waves excited by this beam and having high-gradient longitudinal electric fields can be used to accelerate other bunches. In the second case, a strong focusing can be attained with a long narrow beam, making use of its intrinsic magnetic field which is unbalanced because of space charge compensation by the plasma.

Apart from the transverse forces, the bunch particles are also influenced by powerful longitudinal forces on the side of electric wake fields. The longitudinal fields will give rise to a longitudinal modulation of the electron bunch, i.e., to a splitting of an originally uniform bunch into microbunches with a modulation period $\lambda_p = 2\pi c/\omega_p = 3.36 \times 10^6 n_0^{-1/2}$cm. In particular, in the plasma with a particle density of 10^{16}

cm^{-3} the modulation period is 0.3 mm. The effect of longitudinal REB modulation by wake fields can be used for developing plasma modulators of dense electron beams. It is pertinent to note one more feature of this phenomenon. Since the modulation frequency is coincident with the plasma frequency, the wake fields of microbunches are then combined coherently. Therefore, the electron bunch modulation will involve an increase in the amplitude of the wake field behind the bunch. This effect opens up a possibility of using long-pulse electron bunches to excite intense wake fields in a plasma. It is particularly remarkable that the effect of longitudinal modulation at a plasma frequency takes place for a long laser pulse, too [9].

2 Physical model and equations

Previously in [10], a theoretical study has been made into the process of modulation of long electron bunches in a plasma by longitudinal wake fields. Results were reported there for one-dimensional numerical simulation of nonlinear dynamics of bunch modulation. It was demonstrated in ref. [10] that the particle modulation of a long bunch moving in the plasma causes an increase in the wake wave amplitude. This effect is accounted for by coherent combining of fields excited by microbunches, into which the bunch is split in the course of modulation. The bunch is modulated at a plasma frequency. The investigation of the one-dimensional approximation is justified in the case of great transverse dimensions ($2\pi r_b/\lambda_p \gg 1$).

The present report deals with the 2.5-dimensional numerical simulation of wake fields by long REB.

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 [11]. Earlier, this code has been used to simulate the induction accelerator [12], the modulated relativistic electron beam [13], and a single REB or a train of these bunches in a plasma [11, 13-16].

The dynamic of REB is described by the relativistic Belyaev-Budker equations for the distribution functions $f_\alpha(\overrightarrow{r}, \overrightarrow{p})$of the plasma particles of each species and by the Maxwell equations for the self-consistent electric and magnetic fields. We assume that, initially, a cold two-component back-ground 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.

The scale on which the electric and magnetic fields vary is $.m_e c\omega_p/e$ We assume that the plasma and bunch particles escape from the computation 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 computation region from the buffer zones $z < 0$ and $z > Z$. The boundary conditions for the fields corresponds to the metal wall at the cylindrical surface 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-90 personal computer using the modified particle-in-cell simulation algorithm.

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.

3 Results and discussion

We considered spatial distributions of the electric charge density of electrons el.Q, longitudinal electric field dfld , longitudinal current density of electrons el.Jhz, respectively, for the instants of time $t = 60\omega_p^{-1}$ and $t = 100\omega_p^{-1}$.

It is shown that the longitudinal electric field rapidly grows reaching $.0.8 m_e c\omega_p/e$ Note that the original beam particle density was only 6% of the plasma electron density. The radial electric field E_r also grows, but it reaches a somewhat lower value $0.4 mc\omega_p/e$. It is significant that: (i) the finite length of the initial bunch is responsible for the formation of the growing electric field; (ii) the electric field has a rather high amplitude near the axis, this being due to microbunch pinching; (iii) the evolution of the instability, giving rise to microbunches, leads to some decrease in the phase velocity of the perturbed wake wave.

It is shown that the electric charge density distributions of plasma electrons *el Q* are similar to the spatial distributions of the longitudinal electric field $.E_z$. The highest density value is attained for the

8th microbunch and is $.4.5n_0$ It is of importance to note that the maximum of the beam particle charge density corresponds to the 5th microbunch rather than to the 8th microbunch and is equal to $1.6n_0$, this being two orders of magnitude higher than the initial beam particle density value in the long bunch.

The spatial distribution of the longitudinal current density of plasma electrons $el.Jhz$ also correlates rigidly with the longitudinal electric field E_z distribution. Here attention must be given to the peak current value for the 8th microbunch, which is two orders of magnitude higher than the initial longitudinal current value of REB particles.

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. [10]). This supports in full measure the conclusion given in ref. [7] about the necessity of taking into complete account the three-dimensional effects and the nonlinear behavior of both the plasma and the bunch.

4 Conclusion

The spatial density distributions of REB and plasma electrons obtained for the instances of time $t = 60\omega_p^{-1}$ and $t = 100\omega_p^{-1}$ show that the density ratio n_b/n_0 (the initial value being 0.018) reaches 0.04 as early as at $t = 60\omega_p^{-1}$. At $t = 100\omega_p^{-1}$, 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 $t = 100\omega_p^{-1}$ the highest longitudinal-field amplitude reaches $0.8m_e c\omega_p/e$, and the highest transverse-field amplitude is equal to $0.4mc\omega_p/e$. 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.

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. 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.

References

[1] Ya.B.Fainberg in Proc. Symp. CERN, Geneva, Vol. 1 (1956) 84

[2] Ya.B.Fainberg , Sov.J. Plasma Physics 13 (1987) 350

[3] Ya.B.Fainberg , Plasma Physics Reports 20 (1994) 549

[4] P.Chen, J.M.Dawson, R.W.Huff, T.Katsouleas, Phys. Rev. Lett. 54 (1985) 693

[5] T.Katsouleas, Phys. Rev. A 33 (1986) 2056

[6] A.Ts.Amatuni et.al. , Sov. J. Plasma Physics 11 (1985) 417

[7] J.Rosenzweig, FERMILAB Conf.90/40, FNAL, Batavia, Illinois, 1990

[8] J.Rosenzweig et.al., Phys. Rev. A. 44 (1991) 6189

[9] C.Joshi et al., IEEE J. Quant. Electr. . QE-23, No. 23, (1987) 1571

[10] V.A.Balakirev et. al., Fizika Plazmy 22 (1996) 165

[11] O.Batishchev, V.Karas', V.Levchenko, Yu.Sigov , Plasma Physics Reports 20 (1994) 587

[12] V.Karas', O.Batishchev, Yu.Sigov, Ya.Fainberg , Particle Accelerators 37-38 (1992) 281

[13] O.Batishchev, Yu.Sigov et.al., Sov. J. Plasma Physics. 19 (1993) 738

[14] O.Batishchev, V.Karas', Yu.Sigov, Ya.Fainberg , Plasma Physics Reports 20 (1994) 583

[15] V.Karas', Yu.Sigov, Ya.Fainberg et. al., Plasma Physics Reports 23 (1997) 285

[16] V.Karas', V.Balakirev, G.Sotnikov, Yu.Sigov, Ya.Fainberg, V.Levchenko.in Proc. of 1997 Particle Accelerator Conference, Vancouver, Canada, May 1997.