KINETIC SIMULATION OF FIELDS EXCITATION AND PARTICLE ACCELERATION BY LASER BEAT WAVE IN NON-HOMOGENEOUS PLASMAS*

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Abstract

Resonance excitation of longitudinal plasma electrostatic wave by double-frequency laser radiation is investigated numerically to study in detail conditions of particle beat wave acceleration. The computer simulation is based on the highly specialized code SUR, using splitting technique. Both the space uniform and slightly non-uniform cases are investigated. Maintaining of phase synchronism between accelerated particles and exited longitudinal wave is provided by a choice of density plasma profile.

I. INTRODUCTION

The method of charged particle acceleration by charge density waves in plasmas and in non-compensated charged particles, which Ya.B. Fainberg proposed in 1956 [1], seems to be one of the promising methods of collective acceleration [2], [3]. The primary challenge in all plasma acceleration schemes is to produce a substantial plasma density perturbation with a phase velocity to be close to velocity of light c. At present the most promising concepts are plasma beat–wave acceleration and plasma wake field acceleration.

In the plasma beat–wave acceleration scheme [4], two copropagating laser beams with slightly different frequencies are injected into a plasma. C. Toshi at al (1993) obtained the electric field strengths of the charge–density wave of $0.7\cdot 10^7 \frac{V}{cm}$, and detected the accelerated electrons with an energy of $9.1 MeV$ (injection energy was $2MeV$). The resonant plasma density was $8.6\cdot 10^{15} cm^{-3}$, but already in January 1994, the $1cm$ length, the electrons acquired $28MeV$.

Resonance excitation of longitudinal plasma electrostatic waves by electromagnetic waves is investigated numerically with help of the SUR code. The SUR code is based on solving the finite–difference analogs of the Maxwell and Vlasov–Fokker–Planck equations through the successive use of the splitting technique over physical processes and variables of phase space.

In order to economize our machine time, we do not yet pose the problem to be solved with its real parameters [5].

II. COMPUTATIONAL MODEL

Consider a linearly polarized electromagnetic wave propagating in the x direction with the electric vector $\vec{E}$ directed along the y–axis and the magnetic field vector $\vec{B}$ oriented along the z–axis (p–polarization). The action of such a wave onto plasma particles can give rise only to the V_x and V_y velocity components. In the case where the distribution function does not depend initially on y and z, three phase space coordinates x, V_x, V_y are sufficient to describe subsequent plasma behavior; the relevant distribution function is $f(\vec{r},\vec{p}) = f(x,V_x,V_y)\delta(V_z)$.

The plasma electron dynamics may by described the Vlasov equation

$$\begin{aligned}\frac{\partial f_e}{\partial t} + V_x\frac{\partial f_e}{\partial x} \quad &- \quad e(E_x + \frac{V_y}{c}B_z)\frac{\partial f_e}{\partial p_x} \\ &- \quad e(E_y - \frac{V_z}{c}B_z)\frac{\partial f_e}{\partial p_y} = 0.\end{aligned}$$

This equation is solved by a variant of the method of splitting over phase–space coordinates[6].

Effects due to charged–particle collisions in the plasma cannot significantly affect the time of electromagnetic wave propagation through the simulated system. Because of this, we do not take the Fokker–Plank collision term in the equation into account.

The similar equation might be written for the plasma ions; however, in these computations the ions, being heavy compared to electrons, were assumed to be motionless.

The longitudinal electric field E_x is determined from the Poisson equation, which, in one–dimensional case, can be written as

$$E_x = E_x|_L + 4\pi e\int_{x_L}^{x}(n_i(\xi) - n_e(\xi))d\xi,$$

where $n_i(x)$ is the ion background; $n_e(x,t) = \int f d\vec{p}$ is the electron density; x_L and $E_x|_L$ represent the coordinate and field value on the system left boundary, respectively.

The transverse electromagnetic field must be satisfy the Maxwell equations:

$$\begin{aligned}\frac{1}{c}\frac{\partial B_z}{\partial t} \quad &= \quad -\frac{\partial E_y}{\partial x} \\ \frac{1}{c}\frac{\partial E_y}{\partial t} \quad &= \quad -\frac{\partial B_z}{\partial x} - \frac{4\pi}{c}j_y,\end{aligned}$$

where $j_y = -e\int f_e V_y d\vec{p}$ is the current density. The latter two equations can be written in a form more convenient for numerical computations:

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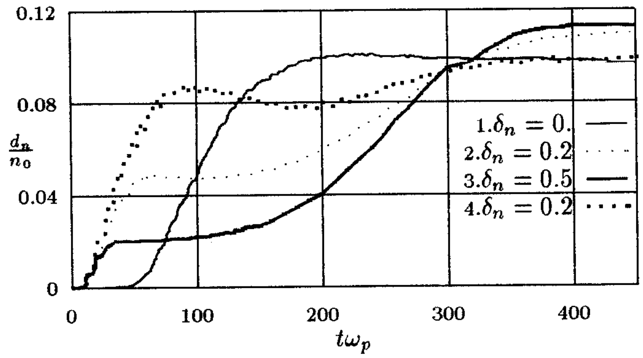

Figure 1. Temporal dependence of the maximum amplitude of the perturbed electron density d_n for different plasma density profiles along the x-axis: (1)$\delta_n = 0$; (2,3) rising profiles: $\delta_n = 0.2$ and 0.5; (4) descending profile: $\delta_n = 0.2$

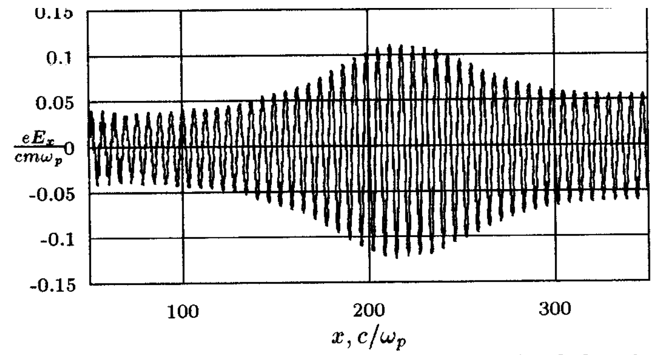

Figure 2. Spatial dependence of the longitudinal electric field E_x for the plasma density rising ($\delta_n = 0.2$) x–profile

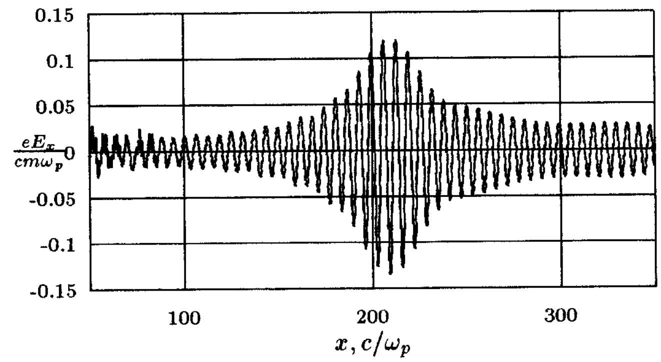

Figure 3. Spatial dependence of the longitudinal electric field E_x for the plasma density rising ($\delta_n = 0.5$) x–profile

$$(\frac{\partial}{\partial t} \pm c\frac{\partial}{\partial x})F^{\pm} = -4\pi j_y,$$

where $F^{\pm} = E_y \pm B_z$. This enables one to employ the integration over characteristics technique.

The simulated system represent a "plasma in a box" with total particle reflection from the rated–region boundaries. At the same time, these boundaries are radiation–transparent, radiation entering through the left system boundary and emerging through the right one. This is provided by the assignment of boundary conditions:

$$\begin{aligned} F^{+}|_L &= F(t)[F_1 \sin(\omega_1 t + \phi_1) + F_2 \sin(\omega_2 t + \phi_2)]; \\ F^{-}|_R &= 0 \end{aligned}$$

where the subscripts $|_L$ and $|_R$ denote the values of quantities on left–hand and right–hand boundaries, respectively. As the charge is not build up on the "walls" and the plasma is neutral as a whole, we can assume $E_x|_L = E_x|_R = 0$.

At the initial time, the values of ion and electron density are defined as $n_i(x) = n_e(x, t = 0) = n_0$ for the uniform plasma profile and

$$n_i(x) = n_e(x, t = 0) = n_0 \pm \delta_n(\frac{1}{1 + e^{-\kappa(x-L/2)}} - \frac{1}{2})$$

for a non–uniform one.

To describe the simulated system in dimensionless variables, let us rescale the time, length, velocity, electric field strength, and density by introducing the scale units $\omega_p^{-1}; c/\omega_p; c; mc\omega_p/e$ and n_0 respectively. Here

$$\omega_p = \sqrt{\frac{4\pi n_0 e^2}{m}}$$

represents the electron plasma frequency. The initial parameters of the problem are the frequencies ω_1 and ω_2 of the two incident electromagnetic waves, their dimensionless amplitudes

$$\alpha_{1,2} = \frac{eE_{1,2}}{m\omega_p c}\frac{\omega_p}{\omega_{1,2}},$$

the system length L, the electron thermal velocity V_{T_e}, and the initial plasma density profile (fixed ion density profile). In a given run we considered the following parameters values:

$$\begin{gathered} \omega_1 = 4;\ \omega_2 = 5; \\ \alpha_1 = 0.1;\ \alpha_2 = 0.08; \\ L = 400;\ V_{T_e} = 0.1; \kappa = 0.2; \\ F(t) = \frac{1}{1+\exp(-0.5(t-10))}; \\ \phi_1 = \phi_2 = 0. \end{gathered}$$

The difference between the runs consisted in the value and direction of the profile variation and in the se cases we took $\delta_n = 0; 0.2; 0.5$.

III. RESULTS

Figure 1 presents the perturbated electron density maximum amplitudes d_n as a function of time $t\omega_p$ for the uniform (curve 1), rising (curves 2 and 3) and descending (curve 4) plasma profile along $x-$axis. One can see that, at the early stage, a rise of d_n is in good agreement with theoretical results obtained in [7], [8], [9]

$$\frac{\partial d_n}{\partial t} = \frac{1}{4}\alpha_1\alpha_2\omega_p.$$

Then the amplitude d_n growth slows down and all the curves saturate at the level of about $0.1n_0$. The simulated saturation

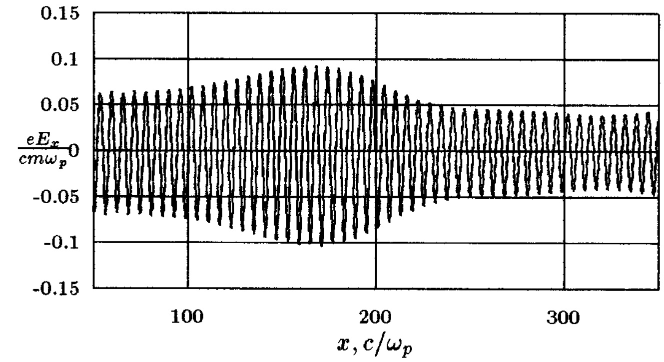

Figure 4. Spatial dependence of the longitudinal electric field E_x for the plasma density descending ($\delta_n = 0.2$) x–profile

level is considerably lower then the theoretically estimated one due to the relativistic shift of the Langmuir frequency obtained for cold plasma in [7], [8], [9]:

$$d_n^{sat} = \sqrt[3]{\frac{16}{3}\alpha_1\alpha_2} \sim 0.34$$

For nonuniform density profiles, the saturation level is higher than for the uniform one (curve 1). This is caused by the fact, for the case of uniform profile, the plasma density was chosen to ensure the exact equality of the Langmuir frequency to the beat frequency $\omega_s = \omega_1 - \omega_2$. During the transition to a steady state, the location of the perturbed electron density maximum is determined by the distance from the left boundary to some point, where the plasma density has such a value that the difference between the electron Langmuir frequency and the beat frequency is equal to a quantity $\delta\omega_{opt}$ (optimal frequency shift) proportional to $(\alpha_1\alpha_2)^{2/3}\omega_s$.

Figures 2-4 shows the steady-state spatial distributions of the longitudinal electric field E_z for the plasma density profile rising (Fig.2 and 3) and descending (Fig.4) along the x–axis. It is seen that the longitudinal electric field reaches its maximum at points where the local plasma frequency exceeds the beet frequency by a value of $\delta\omega_{opt}$ determined in its turn bu the amplitudes and frequencies of electromagnetic waves. The plasma density $\pm 10\%$ variation within the rated region results in an acceptable spatial distribution of E_x. This allows one to hope (see Fig.4) that the descending plasma profile may be of practical use in this beat-wave acceleration method: an appropriate density gradient may help to prolong the accelerated particle synchronism with a longitudinal beat wave [10].

References

[1] Ya. B. Fainberg. The use of plasma waveguides as accelerating structures in linear accelerators. In *Proc. Symp. CERN*, volume 1, page 84, 1956.

[2] Ya. B. Fainberg. *Plasma Physics Reports*, 20(7):549, 1994.

[3] J. S. Wurtele. *Physics Today*, (7):33, 1994.

[4] T. Tajima and J. Dawson. *Phys. Rev. Lett.*, 43:267, 1979.

[5] C. E. Clayton et al. In *Proc. 1993 IEEE Particle Accelerator Conference. IEEE*, volume 4., 1993.

[6] Cheng and G. Knorr. *J. Comp. Physics*, 22:330, 1976.

[7] M. Rosenbluth and C.S. Liu. *Phys. Rev. Lett.*, 29:701, 1972.

[8] C.M. Tang et al. *Phys. Fluids*, 28:1374, 1985.

[9] P. Chen, J. M. Dawson, R. W. Huff, and T. Katsouleas. Acceleration of electrons by the interaction of a bunched electron beam with a plasma. *Phys. Rev. Lett.*, 54:693, 1985.

[10] Ya. B. Fainberg. Acceleration of charged particles by space–charge waves excited on plasmas by laser beams and relativistic electron beams. *Sov. J. Plasma Physics*, 13(5):350, 1987.