DYNAMICS OF THE MODULATED ELECTRON BEAM IN THE INHOMOGENEOUS PLASMA BARRIER: KINETIC EFFECTS

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Evolution of the modulated electron beam moving through the inhomogeneous plasma barrier with parameters corresponding to experimental conditions [1-2] is studied via computer simulation using PIC method. Electrons' energy distribution function of the initially density modulated electron beam moving through the barrier with Gaussian plasma density profile is studied. Initial-boundary problem is solved, and results obtained are compared with results of experiments and previous simulations.

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1. INTRODUCTION

Study of dynamics of electron beam in plasma was started as far back as 1930-th by Langmuir. The last works devoted to this problem use computer simulation [3-4] as well as laboratory experiments [5]. But in the most cases only non-modulated beams were treated.

Evolution of the modulated electron beam in super-critical plasma barrier was studied experimentally in [1-2]. In our previous works [6-9] evolution of the modulated electron beam in plasma for the initial-boundary problem was investigated via computer simulation using PIC method. But homogeneous plasma barrier in [6-8] doesn't correspond to the experimental one that is close to Gaussian shape [1-2]. The first simulation results for such barriers were presented in [9]. In this paper electrons' energy distribution function of the initially density modulated electron beam moving through the barrier with Gaussian plasma density profile is studied. Initial-boundary problem is solved, and results obtained are compared with results of experiments and previous simulations.

2. MODEL DESCRIPTION, SIMULATION METHOD AND PARAMETERS

Warm isotropic collisionless plasma with initial Gaussian density profile is studied. Simulation is carried out via particle-in-cell method using modified program package PDP1 [10].

1D region between two electrodes is simulated. Interelectrode space is filled with fully ionized hydrogen plasma. Initial plasma density profile is obtained by the approximation of experimental axial plasma density profile [1-2] by Gaussian function. So initial electron and ion plasma density is set as

$$n(x) = n_0 + n_m \exp\left[-\left(\frac{x - x_0}{2\Delta}\right)^2\right], \qquad (1)$$

where n_0 is the plasma density for $x \to \infty$, $n_0 + n_m$ is the peak plasma density inside the barrier at $x = x_0$, and Δ is half-width of the plasma density profile. Simulation parameters are presented in the Table.

Electron beam is injected into plasma barrier from the left electrode. It moves to the right one. Electrodes absorb both plasma and beam particles. Initially electron beam is density-modulated:

$$\rho(t) = \rho_0 (1 + m \cos \omega t), \qquad (2)$$

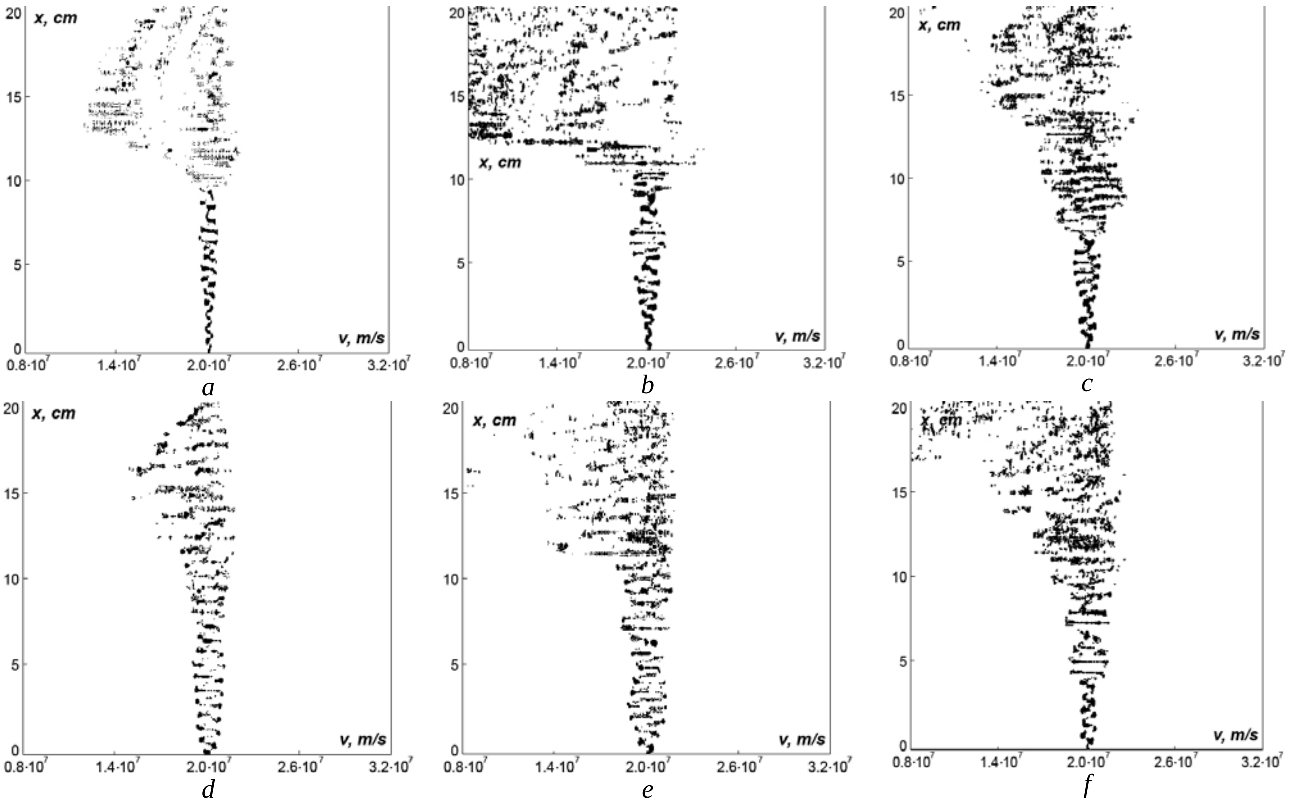
where *m* is the modulation depth.

Modulation frequency was selected in the range $\omega_p(n_0) < \omega < \omega_p(n_0 + n_m)$, where $\omega_p(n)$ is electron plasma frequency corresponding to the plasma density *n*. Two local plasma resonance regions are located inside the barrier at the modulation frequency.

The simulation was carried out during the time interval of approximately 200 electron plasma periods or 5 ion plasma periods. During this time electron beam reached the opposite electrode, and quasi-stationary regime was settled.

Simulation parameters

n_0	$5.5 \cdot 10^{10}$ cm^{-3}
n_m	$2.04 \cdot 10^{11}$ cm^{-3}
x_0	10 cm
Δ	3.87 cm
Simulation region length	20 cm
Plasma electrons' thermal velocity	$6 \cdot 10^7$ cm/s
Plasma ions' thermal velocity	$2{,}33 \cdot 10^6$ cm/s
Beam electrons velocity	$2 \cdot 10^9$ cm/s
Electron beam modulation frequency	2.77 GHz
Electron beam modulation depth	0.01 – 0.3 with the step 0.01
Simulation time step	10^{-13} s



a b c

d e f

Fig. 1 Velocity distribution functions of beam electrons for weak-modulated (m=0.05 – a, b, c) and strong-modulated (m=0.28 – d, e, f) electron beam at the time points: $t=10^{-8}$s (a, d), $t=2\cdot10^{-8}$s (b, e), $t=4\cdot10^{-8}$s (c, f)

3. SIMULATION RESULTS

Fig. 1 presents velocity distribution functions of beam electrons for weakly modulated (m=0.05) and strongly modulated (m=0.28) electron beam for various time moments. In x-v plane these figures present phase portraits of the electron beam. For the first time points these distribution functions are similar to sinusoids. In comparison with the case of homogeneous barrier [7] these sinusoids are more smeared. This fact can be explained by excitation of quazi-continuous spectrum at the frequencies $\omega_p(z)$ in the electron beam during it's propagation inside the barrier.

3.1 SMALL INITIAL MODULATION DEPTH OF THE BEAM

All dependencies discussed in this section correspond to the initial modulation depth m=0.05. The width of the beam electrons' velocity distribution function slightly decreases at the late stage of the simulation in comparison with the case of non-modulated beam. Two time intervals with characteristic behavior of the velocity distribution function can be marked out from Fig. 1,a-c: (i) *t = 9–30 ns* - one can see gradual beam electrons' velocity smearing in the direction of energy decrease in the space region of plasma density recession; (ii) *t = 35–45 ns - b*eam electrons' velocity spread decreases. This fact can be connected with electric field strength reduction caused by deformation of the ion density profile (Fig. 2). This deformation is characterized by strong irregularity. This effect can be explained by l-s decay of the resonant mode that results in ion-acoustic waves' excitation [6-8].

3.2 LARGE INITIAL MODULATION DEPTH OF THE BEAM

All dependencies discussed in this section correspond to the initial modulation depth m=0.28. Deep initial beam modulation leads to the noticeable suppressing of the resonant instability development [11] just as in the case of homogeneous barriers [7]. This effect is connected with beam electrons' trapping by non-resonant mode (at the modulation frequency) [6-8].

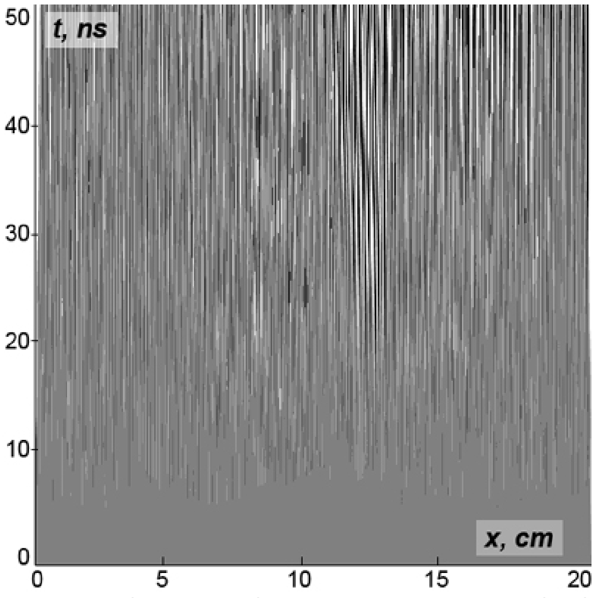


Fig. 2 Deformation of the ion concentration profile for initial modulation depth m=0.05

For the case of large initial beam modulation depths behavior of the velocity distribution function differs from one described in section 3.1 (Fig. 1, d-f).

In the time interval t = 9–30 ns beam electrons' velocity smearing is noticeably smaller than for small initial modulation. Simultaneously in the region of plasma density decrease electric field strength amplitude is twice smaller than for small modulation. Accordingly non-linear plasma density deformation decreases noticeably. As a result in the time interval t = 35–45 ns beam electrons' velocity distribution function spreads distinctly more than for small initial modulation depth. But even in this case at the time point t = 50 ns width of the beam electrons' velocity distribution function decreases in comparison with previous time moments. As in previous case this result can be connected with the non-linear deformation of the plasma density profile.

4. CONCLUSIONS

Electrons' energy distribution function of the initially density modulated electron beam moving through the barrier with Gaussian plasma density profile was studied.

1. Effect of the suppression of the resonant beam-plasma instability by the deep initial beam modulation takes place as in the case of homogeneous barrier. This leads to smaller spreading of beam electrons' velocity distribution function.
2. At the late time points spread of the beam electrons' velocity distribution function decreases due to the deformation of the plasma density profile. This deformation can be explained by ion-acoustic waves excitation caused by l-s decay of the resonant mode [6-8].
3. Deformation of the plasma density profile is more noticeable in the case of small initial modulation depth and becomes more valuable in the region of plasma density decrease where resonant mode's electric field strength increases distinctly [9].

REFERENCES

1. I.A. Anisimov, S.M. Levitsky, O.V. Opanasenko, L.I. Romanyuk. Experimental observation of the plasma wave barrier transillumination via electron beam // *JTPh.* 1991, v.61, N.3, p.59-63.
2. I.O. Anisimov, I.Yu. Kotlyarov, S.M. Levitsky, O.V. Opanasenko, D.B. Palets, L.I. Romanyuk. The investigation of the transillumination of the plasma barriers for electromagnetic waves using electron beams. 2. Evolution of the space charge waves in the barrier // *Ukr. Fiz. Zhurn.* 1996, v.41. N 3, p.164-170.
3. E.P. Kontar. Dynamics of electron beams in the solar corona plasma with density fluctuations // *Astronomy & Astrophysics.* 2001, v. 375, p.629-637.
4. G. Lizunov, A. Volokitin, I. Blazhko. Dynamics and relaxation of an artificial electron beam // *Advances in Space Research.* 2002, v. 29, N 9, p. 1391-1396.
5. F.do Prado, M.V. Alves, R.S. Dallaqua, D.M. Karfidov. Measurements of beam relaxation length in an electron beam plasma experiment // *Brasilian Journal of Physics.* 1997, v. 27, N 4, p. 481-487.
6. I.O. Anisimov, M.J. Kiyanchuk. Evolution of the modulated electron beam in supercritical plasma: simulation of initial-boundary problem // *Probl. of Atomic Sci. and Techn. Series "Plasma electronics and new acceleration methods" (5).* 2006, N 5, p. 24-27.
7. I.O. Anisimov, M.J. Kiyanchuk, S.V. Soroka, D.M. Velykanets'. Interaction of the modulated electron beam with plasma: kinetic effects // *Probl. of Atomic Sci. and Techn. Ser. "Plasma physics" (13).* 2007, N1, p. 113-115.
8. I.O.Anisimov, M.J.Kiyanchuk. Evolution of the modulated electron beam in plasma for different modes of beam-plasma turbulence // *Ukr. Fiz. Zhurn.* 2008, v. 53. N4, p. 382-388.
9. I.O. Anisimov, M.J. Soloviova. Dynamics of the modulated electron beam in the inhomogeneous plasma barrier: one-dimensional simulation using PIC method // *Probl. of Atomic Sci. and Techn. Ser. "Plasma electronics and new acceleration methods"(6).* 2008, N4, p.209-213.
10. Ch.K. Birdsall, A.B. Langdon. *Plasma Physics via Computer Simulation.* "McGraw-Hill Book Company". 1985.
11. A.K. Berezin, Ya.B. Fainberg, I.A. Bezjazichniy. Experimental study of the possibility to control beam instability via modulation // *Pis'ma v ZhETF.* 1968, v. 7, N5, p. 156-160.

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ДИНАМИКА МОДУЛИРОВАННОГО ЭЛЕКТРОННОГО ПУЧКА В НЕОДНОРОДНОМ ПЛАЗМЕННОМ БАРЬЕРЕ: КИНЕТИЧЕСКИЕ ЭФФЕКТЫ

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Исследуется эволюция модулированного электронного пучка в плазменном барьере с помощью компьютерного моделирования методом крупных частиц. Рассматривается неоднородный плазменный барьер, соответствующий условиям лабораторного эксперимента. Изучается функция распределения электронов пучка по скоростям. Полученные результаты решения начально-граничной задачи сравниваются с результатами экспериментов и выводами предыдущих моделирований.

ДИНАМІКА МОДУЛЬОВАНОГО ЕЛЕКТРОННОГО ПУЧКА В НЕОДНОРІДНОМУ ПЛАЗМОВОМУ БАР'ЄРІ: КІНЕТИЧНІ ЕФЕКТИ

І.О. Анісімов, М.Й. Соловйова

Досліджено еволюцію модульованого електронного пучка в плазмовому бар'єрі шляхом комп'ютерного моделювання методом крупних частинок. Розглядається неоднорідний плазмовий бар'єр, що відповідає умовам лабораторного експерименту. Вивчається функція розподілу електронів пучка за швидкостями. Отримані результати розв'язку початково-гранично задачі порівнюються з результатами експериментів та висновками попередніх моделювань.