DYNAMICS OF THE MODULATED ELECTRON BEAM IN THE INHOMOGENEOUS PLASMA BARRIER: ONE-DIMENTIONAL SIMULATION USING PIC METHOD

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Evolution of the modulated electron beam moving through the plasma barrier was studied via computer simulation using PIC method. Inhomogeneous plasma barrier with parameters corresponding to experimental conditions [1-2] was studied. Dependencies of the maximal signal amplitude and coordinate of this maximum at the modulation frequency upon the initial beam modulation depth were obtained. Simulation results were compared with experimental results and outcomes of the previous simulations.

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1. INTRODUCTION

Problem of the modulated electron beam's dynamics in plasma is of interest in various branches of plasma electronics such as electron beams' using as emitters of electromagnetic waves in ionosphere [3-4], transillumination of the plasma barriers for electromagnetic waves using electron beams [1-2, 5], inhomogeneous plasma diagnostics via transition radiation of electron beams and electron bunches [6] etc.

Evolution of the modulated electron beam in supercritical plasma barrier was studied experimentally in [2,7]. It was found out that signal at the modulation frequency reached its maximum inside the barrier, and magnitude of this maximum was directly proportional to the initial beam modulation depth. These results were explained in [8] by the concurrence between nonresonant (signal) and resonant (noise) modes of the beam-plasma system. But calculations presented in [8] correspond to the initial problem, whereas results of experiments [2, 7] correspond to the boundary problem. Consequently it was impossible to compare results of experiment and simulation.

Evolution of the linear space-charge waves (SCW) of electron beam in the barrier with parabolic plasma density profile was studied theoretically in [2]. Effect of mutual transformation of SCW in the inhomogeneous plasma was obtained.

In our previous works [9-10] evolution of the modulated electron beam in plasma for the initial-boundary problem was studied via computer simulation using PIC method [11-12]. But homogeneous plasma barrier in [9-10] doesn't correspond to the experimental one that is close to Gaussian shape [1-2, 7].

In this paper dynamics of the modulated electron beam moving through the barrier with Gaussian plasma density profile is studied via computer simulation using PIC method. 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 [11-12].

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, 7] 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→∞, $n_0 + n_m$ 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 table.

Simulation parameters

n_0	$5.5\cdot10^{10}$ cm^{-3}
n_m	$2.04\cdot10^{11}$ cm^{-3}
x_0	10 cm
Δ	3.87 cm
Simulation region length	20 cm
Plasma electrons' thermal velocity	$6\cdot10^7$ cm/s
Plasma ions' thermal velocity	$2{,}33\cdot10^6$ cm/s
Beam electrons velocity	$2\cdot10^9$ 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

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. So two local plasma resonance regions are presented 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.

3. SIMULATION RESULTS

3.1. SPATIAL EVOLUTION OF SPECTRA OF ELECTRON BEAM DENSITY AND ELECTRIC FIELD STRENGTH FOR SMALL INITIAL DEPTH OF THE BEAM MODULATION

All dependencies demonstrated in this section correspond to the initial modulation depth $m = 0.05$.

Space-time distributions of the beam electrons' density and electric field strength were obtained from simulation. Than temporal fast Furrier transformation was carried out.

Fig.1 demonstrates the spatial evolution of spectra of electron beam density (a) and electric field strength (b). Arrows mark the modulation frequency. One can see from Fig.1,a that only the modulation frequency is presented nearby the injector in the spectra of the electron beam density. During the beam motion inside the barrier in the region of plasma density increase the beam excites oscillations at the local plasma frequency according to Cherenkov mechanism. As long as plasma density depends on coordinate, local plasma frequency change up to coordinate too (in Fig.1,b it is noticeable near the modulation frequency). For the given frequency Cherenkov resonance conditions are not satisfied along the beam trajectory after the vicinity of the first plasma resonance point. So electric field in this region is decreased, but corresponding oscillations in the spectrum of beam modes remain (see bottom of Fig.1,a). Consequently oscillations with the wide band of frequencies are presented in the beam density spectrum along with the modulation frequency.

During the beam motion inside the barrier in the region of plasma density decrease the oscillations presented in the beam density spectrum excite the intensive electric fields in corresponding regions of local plasma resonance (top of Fig.1,b). At the same time the modulation of the beam at corresponding frequencies is increased (top of Fig.1,b).

The largest length of resonant beam-plasma interaction is obtained near the maximum of plasma density, and this length is decreased at the periphery. Therefore maximal growth of the electric field of characteristic oscillations is observed in the region of maximal plasma density (Fig.1,b).

Signal at the modulation frequency is noticeable at the whole simulation region both in spectra of electron beam density perturbation and electric field strength (Fig.1,a,b).

Fig.2 presents the spatial evolution of spectra of electron beam density at the modulation frequency (a), electric field strength at the modulation frequency (b) and at the doubled modulation frequency (c).

Similarly to the previous simulation [9-10], inside the barrier spectral amplitude of the electron beam density at the modulation frequency reaches the maximum value (Fig.2,a). Spatial evolution of the electric field strength spectrum at the modulation frequency (fig.2,b) doesn't demonstrate a maximum. Dependence of the field amplitude at the modulation frequency on coordinate contains a lot of fluctuations with considerable amplitudes.

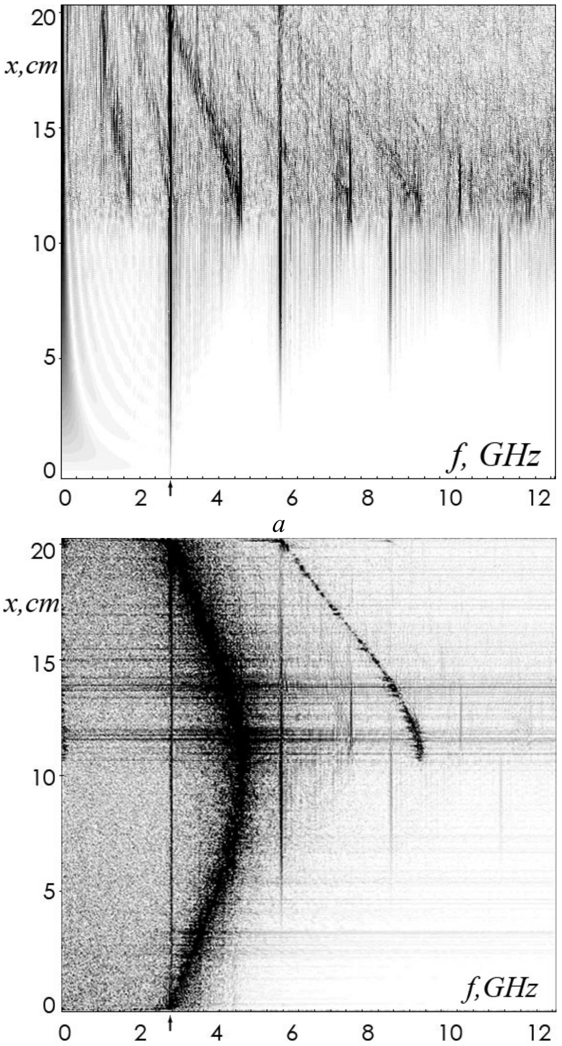

Fig.1. Spatial evolution of spectra of electron beam density (a) and electric field strength (b). Arrows mark the signal modulation frequency

The largest values of the field at the modulation frequency are reached in the regions of local plasma resonance at the edges of the barrier. High level of fluctuations is caused by presence of the wide-band oscillations in the electron beam spectrum. These fluctuations arise according to the mechanism of polarization beam-plasma instability (part of them are excited according to Cherenkov mechanism in local plasma resonance region as it was mentioned above). These fluctuations form the homogeneous gray background in the left side of Fig.1,b bounded by the frequency of local plasma resonance.

But at the doubled modulation frequency (Fig.2,c) there are no oscillations at the local plasma frequency as well as strong fluctuations. That's why spatial dependence of the signal at this frequency has the clear maximum, and it's position coincides with the position of the maximum in Fig.2,a. Notice that only a weak local peak is presented at this point in Fig.2,b.

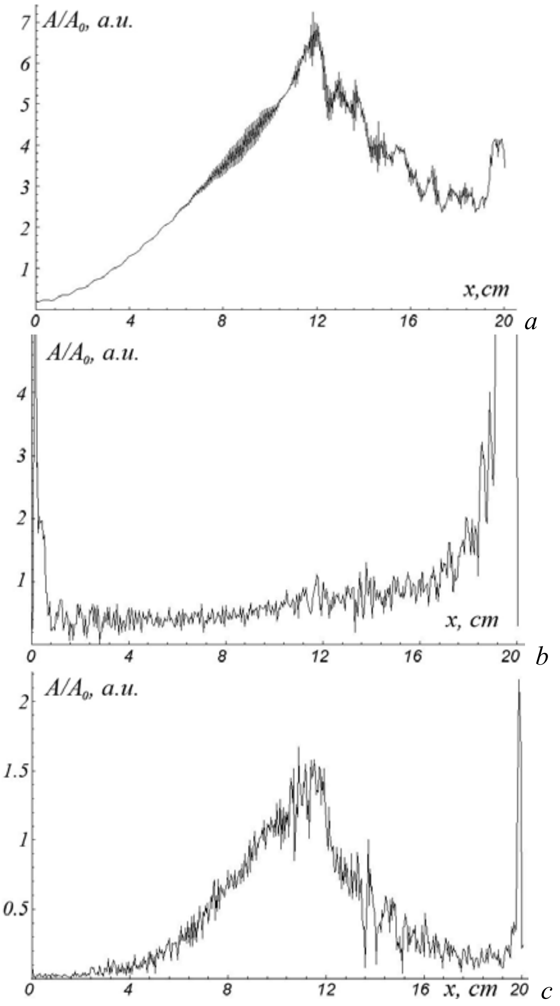

Fig.2. Spatial evolution of spectra of electron beam density at the modulation frequency (a), electric field strength at the modulation frequency (b) and at the doubled modulation frequency (c)

The position of the signal maximum at the modulation frequency (Fig.2,a,c) corresponds to x ≈ 11 cm. It is situated in the region where amplitude of the electric field strength at resonant frequencies grows considerably (Fig.1,b). So concurrence between resonant modes and signal at the modulation frequency takes place. As a result restriction of the signal amplitude occurs as it was described in [8]. But the shape of plasma barrier density profile determines the position where this effect takes place for the parameters of our simulation. Notice that for homogeneous plasma density in the barrier [8] this coordinate is determined by the start of non-linear stage of the beam-plasma instability for the resonant mode.

3.2. SPATIAL EVOLUTION OF SPECTRA OF ELECTRON BEAM DENSITY AND ELECTRIC FIELD STRENGTH FOR LARGE INITIAL DEPTH OF THE BEAM MODULATION

All dependencies discussed in this section correspond to the initial modulation depth *m*=0.28. They were obtained in the same way as in the previous section.

Spatial evolution of spectra of electron beam density and electric field strength doesn't differ drastically from the case of small initial depth of the beam modulation.

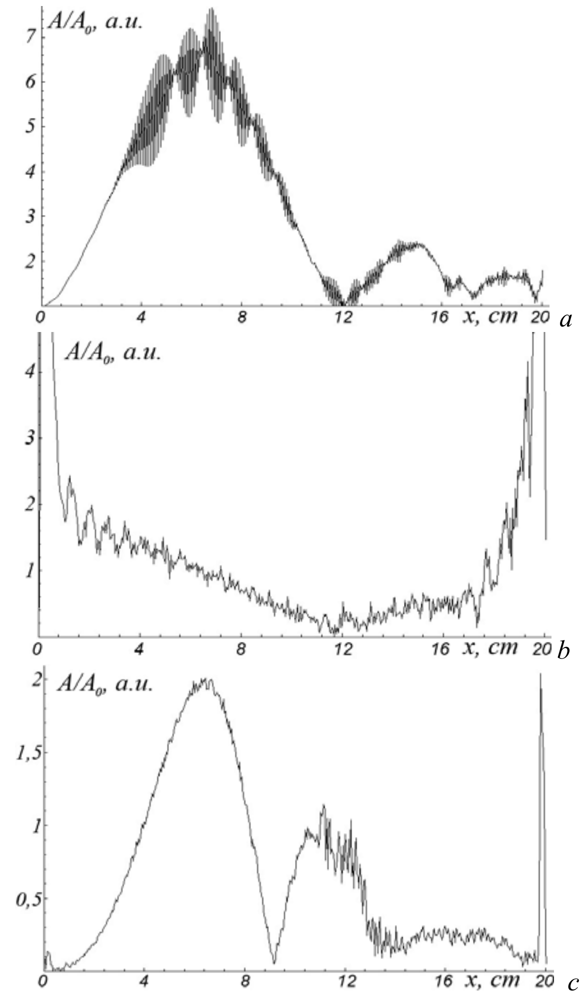

Fig.3. Spatial evolution of spectra of electron beam density at the modulation frequency (a), electric field strength at the modulation frequency (b) and at the doubled modulation frequency (c)

Just as in previous case maximal growth of the field of the characteristic oscillations is observed in the range of maximal plasma density – in the middle of the barrier.

In contrast to the case of small initial beam modulation depth, position of the maximal amplitude of the signal at the modulation frequency doesn't coincide with the region of the maximal growth of the field of characteristic oscillations (Fig.3,a). From comparison Fig.2,a,c and Fig.3,a,c one can conclude that in this case distance from injector to maximum of the signal amplitude at the modulation frequency is much smaller than in the case of small initial beam modulation depth. So maximum of the signal at the modulation frequency is reached due to the non-linear saturation of its instability. Furthermore in Fig.3,a,c oscillations of the signal amplitude at the modulation frequency are observed. These oscillations are not observed in the case of small initial beam modulation depth (compare with Fig.2,a,c). But similar oscillations take place for strong beams in the homogeneous supercritical plasma [10].

Spatial evolution of spectra of electric field strength at the modulation frequency (Fig.3,b) doesn't demonstrate any local maximums (contrary to Fig.2,b). This effect can be explained both by considerable removal of this maximum to injector and by its closeness to the first region of the local plasma resonance.

3.3. INFLUENCE OF THE INITIAL BEAM MODULATION DEPTH ON THE MAXIMAL SIGNAL AMPLITUDE AT THE MODULATION FREQUENCY AND POSITION OF THIS MAXIMUM

Fig.4 presents dependencies of maximal signal amplitude (a) and coordinate of this maximum (b) at the modulation frequency upon the initial beam modulation depth. Two characteristic regions of the initial beam modulation depth can be marked out from Fig.4.

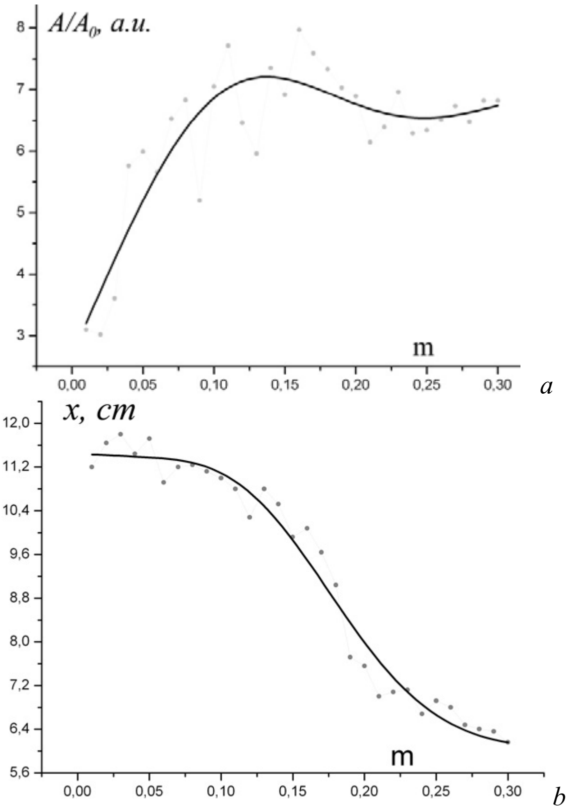

Fig.4. The dependencies of maximal signal amplitude (a) and coordinate of this maximum (b) at the modulation frequency on the initial beam modulation depth

For initial modulation depths m≤0.1 the signal maximal amplitude is reached due to the concurrence of the signal at the modulation frequency with the resonant modes. Electric field of the resonant modes traps beam electrons, and as a result modulation at the signal frequency is suppressed. These processes occur just after electron beam passing through the plasma density maximum. That's why maximal signal position remains constant in this range of initial modulation depths (Fig.4,b).

For initial modulation depths m≥0.1 formation of the signal amplitude maximum at the modulation frequency is caused by the non-linear saturation of instability. As a result maximum amplitude of the signal becomes approximately constant (Fig.4,a), and its position gradually moves to the injector (Fig.4,b).

CONCLUSIONS

Evolution of the modulated electron beam moving through the inhomogeneous plasma barrier was studied via computer simulation for 1D model using PIC method.

1. Spectrum of characteristic oscillations of the beam-plasma system competitive with the signal at the modulation frequency varies in space and depends on the barrier shape. The amplitude of these oscillations rises steeply in the region of plasma density decrease along the beam trajectory. Upper harmonics of characteristic oscillations of the beam-plasma system are presented in this region.

2. Concurrence between resonant modes and signal at the modulation frequency takes place for small initial modulation depths (m≤0.1). This effect moves to restriction of the signal amplitude at the modulation frequency, as it was observed earlier in case of homogeneous barriers [9-10]. But now the shape of plasma barrier density profile determines the position, where maximal signal amplitude at the modulation frequency is reached.

3. For large initial modulation depths (m≥0.1) the signal amplitude maximum at the modulation frequency is reached as a result of beam-plasma instability saturation at this frequency. Oscillations of the signal amplitude at the modulation frequency are observed. In general the beam dynamics doesn't differ from the case of homogeneous barriers [9-10].

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ДИНАМИКА МОДУЛИРОВАННОГО ЭЛЕКТРОННОГО ПУЧКА В НЕОДНОРОДНОМ ПЛАЗМЕННОМ БАРЬЕРЕ: ОДНОМЕРНОЕ МОДЕЛИРОВАНИЕ МЕТОДОМ ЧАСТИЦ

И.А. Анисимов, М.И. Соловьёва

Исследуется эволюция модулированного электронного пучка в плазменном барьере с помощью компьютерного моделирования методом крупных частиц. Рассматривается неоднородный плазменный барьер, соответствующий условиям лабораторного эксперимента. Получены зависимости максимальной амплитуды сигнала на частоте модуляции и положения данного максимума от начальной глубины модуляции. Результаты моделирования сопоставлены с экспериментальными данными и результатами предшествующих моделирований.

ДИНАМІКА МОДУЛЬОВАНОГО ЕЛЕКТРОННОГО ПУЧКА В НЕОДНОРІДНОМУ ПЛАЗМОВОМУ БАР'ЄРІ: ОДНОВИМІРНЕ МОДЕЛЮВАННЯ МЕТОДОМ ЧАСТИНОК

І.О. Анісімов, М.І. 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. Отримано залежності максимального значення амплітуди сигналу на частоті модуляції та положення даного максимуму від початкової глибини модуляції. Результати моделювання співставлено з експериментальними даними та результатами попередніх моделювань.