EVOLUTION OF THE MODULATED ELECTRON BEAM IN SUPERCRITICAL PLASMA: SIMULATION OF INITIAL-BOUNDARY PROBLEM

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Evolution of the modulated electron beam moving through the supercritical plasma was studied in this work via computer simulation using PIC method. Results obtained correspond qualitatively to the experimental data. It was shown that concurrence between the resonant mode growing from the noise level and the non-resonant signal mode leads to the suppression of the non-resonant mode In contrast to previous calculations it is shown that the resonance instability occurs in the broad frequency band. Dependence of the peak amplitude of the signal on its' initial value was obtained. Frequency band expansion (for the resonant instability) can be explained by processes of l-s decay of initial Langmuir wave.

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1. INTRODUCTION

The problem of the modulated electron beam evolution in plasma is of interest in various branches of plasma electronics. In this report we have studied evolution of the modulated electron beam in supercritical plasma. Such conditions are typical for the transillumination of the plasma barriers using electron beams [1]. Evolution of the modulated electron beams in subcritical plasma is important for the problem of radio waves emission via transition radiation of the modulated electron beams in the inhomogeneous plasma [2] and diagnostics of the plasma inhomogeneities via transition radiation [3].

Study of the polarization beam-plasma instability at single frequency demonstrated its saturation due to the beam electrons' trapping by the potential electric wave [4]. But for non-resonant instability these results can be changed strongly due to the concurrence with the resonant mode (i.e., the mode in synchronism with the beam). If the initial modulation depth is not too large the beam electrons can be trapped by the resonant mode, and further increase of the non-resonant mode can be suppressed. This effect results to the linear dependence of the peak signal amplitude on its initial value [4].

Simulation in previous works [5] was carried out for the initial problem. But real experiments [6] correspond to the initial-boundary problem. Computer simulation results for such kind of the problem are given in this report.

2. SIMULATION METHOD AND PARAMETERS

Simulation was carried out via particle-in-cell method using modified program package PDP1 [7-8]. This package allows to define the initial modulation depth and to save intermediate modeling results.

One-dimensional model was treated. Initially homogeneous background plasma layer was located between two plane conductive electrodes. Electron beam was injected from left electrode and moved to right one. The plasma particles were absorbed by electrodes.

Plasma was formed by hydrogen ions, and it was completely ionized. Simulation parameters (table) corresponded approximately to the conditions of laboratory experiment [1].

The beam density was modulated harmonically with the depth over the range of 0.05…0.4.

Simulation was carried out during the time interval of $5 \cdot 10^{-8}$ s that contained approximately 200 electron plasma periods or 5 ion plasma periods. During this time electron beam reached the opposite electrode, and approximately stationary processes were settled (as it was observed in experiments).

Simulation parameters

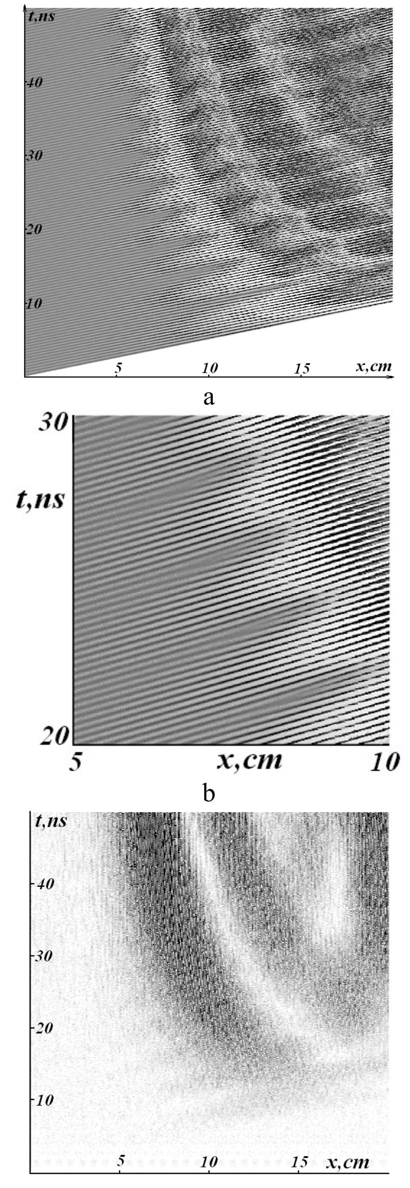
Plasma density	10^{11} cm^{-3}
Simulation region length	20 cm
Plasma electrons' thermal velocity	$6 \cdot 10^{7}$ cm/s
Plasma ions' thermal velocity	$2{,}33 \cdot 10^{6}$ cm/s
Beam velocity	$2 \cdot 10^{9}$ cm/s
Beam modulation frequency	2,6 GHz

3. SIMULATION RESULTS

Space-time distributions of ion and electron densities as well as electron beam density and electric field strength were obtained. All the presented plots correspond to the modulation depth m=0.3.

Fig.1 presents the space-time distributions of the electron beam density (a,b) and electric field strength (c). The darker areas correspond to the larger density and field strength. Incidence of the lines of constant density (or strength) corresponds to the beam velocity.

Density of the injected beam was modulated by the signal frequency that was some smaller than $\omega_p=(4\pi ne^2/m)^{1/2}$. During further beam propagation the resonant instability developed from the noise level. As its increment exceeded the signal's increment, at some stage electric field of the resonant instability trapped the beam electrons and caused modification of the modulation period (see Fig.,1,b, which is fragment of Fig.,1,a). This result corresponds to the outcomes obtained in [5].



a

b

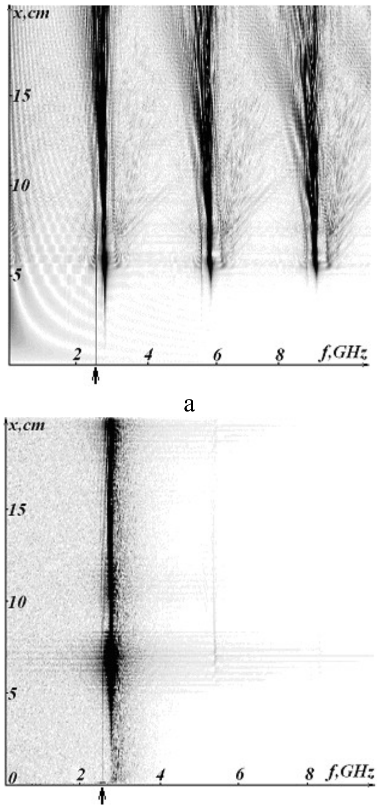
c

Fig.1. The space-time distributions of the electron beam density (a, b) and electric field strength (c)

Character of the further instability development corresponds to the previous results (see, e.g., [4]). After the start of injection maximum of the electric field moves to the injector and exchange of energy between the electric field and the beam electrons occurs (compare Fig.1,a and Fig.1,c).

Fig.2 shows space evolution of the spectra of electric field and electron beam density. Only signal frequency (2.6 GHz) is presented nearby the injector in the spectrum of the electron beam density. During the motion from injector the resonant instability develops from the noise level. It evolves at frequencies close to the frequency of the wave-particle synchronism. It can be calculated from the dispersion equation for the Langmuir waves, where phase velocity of the wave is equal to the velocity of the electron beam:

$$\omega = \frac{\omega_p}{\sqrt{1 - v_{Te}^2 / v_b^2}} . \qquad (1)$$



a

b

Fig.2. The spatial evolution of spectra of electron beam density (a) and electric field (b). Arrows mark the signal modulation frequency

For selected parameters this frequency (2.84 GHz) lies close to the electron Langmuir frequency.

In contrast to previous works [5] (in [5] periodic boundary conditions resulted to the discrete frequency spectrum) in our simulation the resonance instability occurs in the broad frequency band. This data corresponds with the experimental results [9].

Fig.2,a,b presents the frequency band corresponding to the excitation of the resonant instability and its harmonics. Arrows mark the signal modulation frequency (2.6 GHz). It is significant that upper harmonics in the spectrum of the electric field are considerably smaller, then in the spectrum of the electron beam density. Plasma acts as high durable resonator tuned in the frequency ω_p, so upper harmonics of electric oscillations are suppressed.

Fig.2 demonstrates at a distance of 6 cm electric field of resonant mode amplitude increases so strongly that it can trap the beam electrons (compare with the Fig.1,b). As a result the signal frequency disappears in the spectrum of the electron beam density.

Frequency band expansion on Fig.2,a (for the resonant instability) can be connected with processes of l-s decay of the initial Langmuir wave. Perturbation of the ion density for the late moments of time represents the ion-acoustic waves' excitation (Fig.3).

From the synchronism condition for three waves interaction one can obtain relation between k_1 of the initial Langmuir wave and k_3 of ion-acoustic wave:

$$k_1 = \frac{k_3}{2} + \frac{c_s}{3\omega_p r_D^2}\left(1 - k_3^2 r_D^2\right), \qquad (2)$$

where c_s is the ion-acoustic velocity, r_D is Debye radius. The values of k_1 and k_3 estimated from Fig.1,a and Fig.3 respectively satisfy this relation.

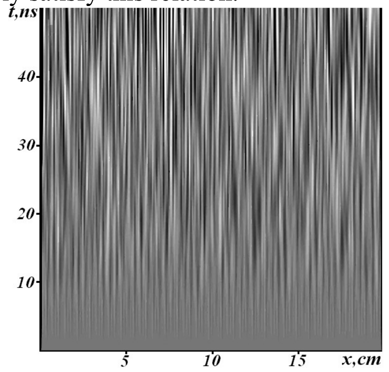
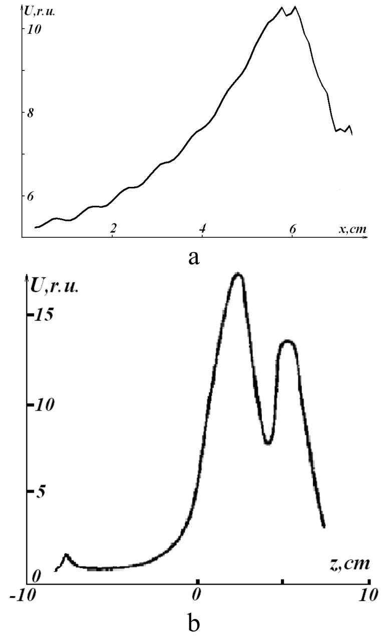


Fig.3. The space-time distributions of the ion density perturbations

Fig.4 shows estimated spatial dependence of the signal amplitude at the modulation frequency (a) and the same dependence obtained from experiment [10] (b). In experiments plasma density profile had parabolic shape. Consequently, first and third maximums correspond to excitation of oscillations in the local plasma resonance region on the modulation frequency. Central part of experimental dependence corresponds to the simulation results.



a

b

Fig.4. Space dependence of amplitude of the signal at the modulation frequency: a – simulation results; b – experimental data from [10]

Fig.5 presents dependence of the peak amplitude of the signal on its initial value. It is known that restriction of this amplitude can be caused by the beam electrons' trapping of the signal mode or by resonant mode [5]. The growing part of the curve on Fig.2,a corresponds to the second case. First case results to the saturation of the peak amplitude. In fact, trapping of the beam electrons occurs after the resonant mode reached certain level. This happens in some fixed point x=d. That's why the peak amplitude of the signal $U_0\exp(\gamma d)$ (γ is the non-resonant instability increment) depends on its initial value linearly.

4. CONCLUSIONS

Evolution of the modulated electron beam moving through the supercritical plasma was studied in this work via computer simulation using PIC method. Results obtained correspond qualitatively to the experimental data. It was shown that concurrence between the resonant mode and the signal mode leads to the suppression of the non-resonant mode, as it was proposed in [5] on the basis of simulation results of initial problem with periodic boundary conditions.

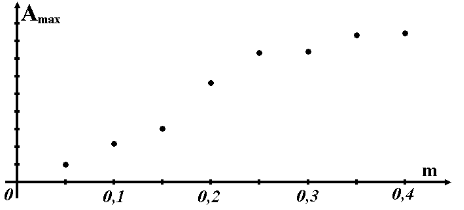


Fig.5. Dependence of the peak amplitude of the signal on the initial modulation depth

In contrast to previous simulation [5] it is obtained that the resonance instability occurs in the broad frequency band. This fact adjusts with experiment. Frequency band expansion (for the resonant instability) can be explained by the processes of l-s decay of the initial Langmuir wave.

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ЭВОЛЮЦИЯ МОДУЛИРОВАННОГО ЭЛЕКТРОННОГО ПУЧКА В НАДКРИТИЧЕСКОЙ ПЛАЗМЕ: МОДЕЛИРОВАНИЕ ВРЕМЕННО-ГРАНИЧНОЙ ПРОБЛЕМЫ

И.О. Анисимов, М.Я. Киянчук

Эволюция модулированного электронного пучка, который движется в надкритической плазме, исследована путем численного моделирования с использованием метода частиц в ячейке. Полученные результаты находятся в качественном соответствии с экспериментальными данными. Показано, что конкуренция между резонансной модой, которая возрастает от флуктуационного уровня, и нерезонансной сигнальной модой ведет к подавлению нерезонансной моды. В отличие от предыдущих расчетов, показано, что резонансная неустойчивость имеет место в широком диапазоне частот. Получена зависимость пиковой амплитуды сигнала от его начального значения. Расширение диапазона частот (для резонансной неустойчивости) может быть объяснима процессом распада первоначальной ленгмюровской волны.

ЕВОЛЮЦІЯ МОДУЛЬОВАНОГО ЕЛЕКТРОННОГО ПУЧКА У НАДКРИТИЧНІЙ ПЛАЗМІ: МОДЕЛЮВАННЯ ЧАСОВО-МЕЖОВОЇ ПРОБЛЕМИ

І.О. Анісімов, М.Я. Кіянчук

Еволюція модульованого електронного пучка, що рухається у надкритичній плазмі досліджена шляхом чисельного моделювання з використанням методу частинок у вічку (PIC). Отримані результати знаходяться у якісній відповідності до експериментальних даних. Показано, що конкуренція між резонансною модою, яка зростає від флуктуаційного рівня, та нерезонансною сигнальною модою веде до пригнічення нерезонансної моди. На відміну від попередніх розрахунків, показано, що резонансна нестійкість має місце у широкій зоні частот. Отримана залежність пікової амплітуди сигналу від його початкового значення. Розширення діапазону частот (для резонансної нестійкості) може бути пояснено процесом розпаду первісної ленгмюрівської хвилі.