PLASMA DYNAMICS IN THE VICINITY OF THE LOCAL PLASMA RESONANCE POINT EXCITED BY PUMPING ELECTRIC FIELD OR MODULATED ELECTRON BEAM

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Excitation of the HF electric field in the local plasma resonance region (LPRR) of inhomogeneous plasma by pumping electric field or modulated electron beam results to appearance of the ponderomotive force that presses plasma out of this region. Density cavity is formed in the LPRR due to this field. Further dynamics in this region depends on the plasma properties. For plasma with hot electrons ion-acoustic pulses run away from the cavity. At the local density maximum the new peak of electric field is excited. It results to the formation of new density cavity, etc. For isothermal plasma the density jump is formed.

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1. INTRODUCTION

Excitation of the HF electric field in the local plasma resonance region (LPRR) of inhomogeneous plasma results to appearance of the ponderomotive force that presses plasma out of this region. This problem is of interest both for the problem of strong electromagnetic waves interaction with inhomogeneous plasma (when oscillations in LPRR are excited by electric field of the wave, see, e.g., [1-3]) and for plasma electronics (when the similar oscillations are excited by the modulated electron beam, see, e.g., [4-6]).

Analytic solution of this problem can be obtained for the case of small amplitudes of electric field, when the influence of the plasma density perturbation upon the electric field excitation can be neglected [4]. For this case the density perturbation has a shape of density cavities with the depth proportional to the local intensity of electric field. Establishing of this perturbation is accompanied by excitation of two ion-acoustic waves moving away from LPRR. But this solution is evidently unstable (Fig.1).

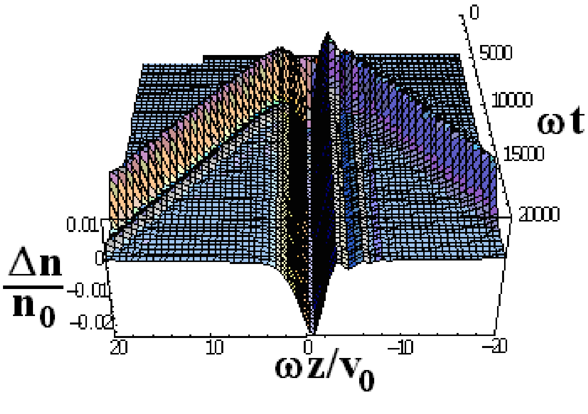

Fig. 1. Space-time dependance of the plasma density perturbation for the weak nonlinear regime: $(4\pi e j_m)^2/(m\omega k_B T_e)=3\cdot10^{-5}$, $3T_e/mv_0^2=0.01$, $\nu/\omega=0.02$, $\omega L/v_0=10$

Numerical solution of Zakharov equations' set that describes the electric field excitation by the given pumping field or by the given current of modulated electron beam and synchronous deformation of the plasma density profile by this field, is valid only for the initial period of time [5] (Fig.2).

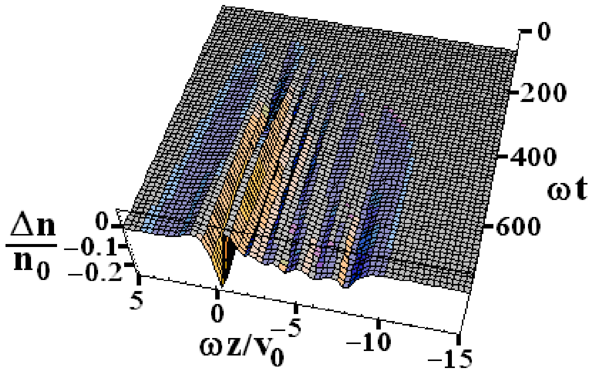

Fig. 2. Space-time dependance of the plasma density perturbation for $(4\pi e j_m)^2/(m\omega k_B T_e)=3\cdot10^{-5}$*, other parameters are the same as on Fig.1. The beam moves into plasma*

The clear picture of evolution of the inhomogeneous plasma in the vicinity of the local plasma resonance point can be obtained using simulation via PIC method [7]. The results of such simulation for excitation of LPRR by the pumping electric field and by modulated electron beam are presented in this article.

2. SIMULATION METHOD AND PARAMETERS

Simulation of the modulated electron beam interaction with inhomogeneous plasma was carried out via particle-in-cell method using the modified package PDP1 [7-8]. In this package plasma layer is located between two conductive electrodes. The plasma treated was fully ionized. Initial plasma density profile was linear. Density modulated electron beam (modulation depth is 100%) moved from left electrode to right one. The beam current and velocity v_0 as well as the characteristic inhomogeneity length L were selected so that the charge density profile in LPRR did not differ strongly from the sinusoidal shape (Fig.3). These results confirm the validity of the given current approximation [4-5] for some range of parameters. For all the cases treated electron density in the beam was small relatively to the background plasma.

Simulation for the case of pumping electric field was carried out for the similar model, but instead of electron beam the RF voltage was applied between the electrodes. The electric induction of the pumping field satisfied the condition $D_m=4\pi j_m/\omega$, so the electric field magnitudes in plasma were equal for both methods of excitation.

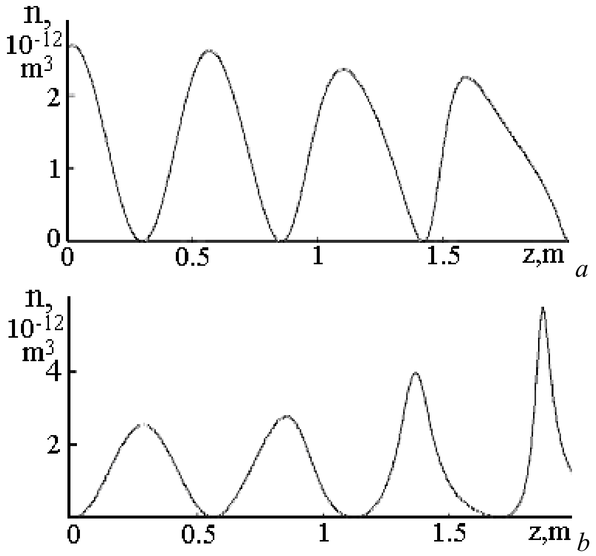

Fig. 3. Density profile of the electron beam (a – beam moved into the dense plasma, b – beam moved into the low-dense plasma

Simulation was carried out for various parameters. The typical values are given below: plasma density $n=(1\ldots3)\cdot10^{14}m^{-3}$ ($f_{pe}=(0.74\ldots2.20)\ 10^8Hz$), length of the simulation region l=2m (characteristic length of inhomogeneity L=1.5m), plasma electrons' temperature T_e=22eV; plasma ions' temperature T_i=0.1eV (for non-isothermal plasma), beam velocity $v_0=7\cdot10^7$m/s ($v_0/v_{Te}=35$, $v_0/c=0.23$). beam modulation frequency $f=1.1\cdot10^8$Hz (critical density $n_c=1.5\cdot10^{14}m^{-3}$), beam current magnitude $j_m=3A/m^2$. Ions' mass corresponds to hydrogen.

3. INITIAL STAGE OF THE BEAM-PLASMA INTERACTION

Electric field increase in the LPRR takes place at the initial stage after the beam injection or pumping started. The space-time distributions of the field are similar for both cases (Fig. 4, a-b). It is accompanied by intensive oscillations of electron concentration (Fig. 4, c-d). At the same time Langmuir wave moving from LPRR against the plasma concentration gradient was excited according to the prediction of the linear theory [4, 9-10]. For the same moments acceleration of electrons in the LPRR was detected [11] similarly to [1].

Deformation of the ion concentration profile was observed in the LPRR later (Fig. 5, a-b). Firstly the short-wave perturbation (in the scale of the LPRR width) appeares, and then the cavity is formed in the same region. Deformation of the ion density profile interrupts the Langmuir waves' excitation (compare Fig. 4, c-d and Fig. 5, a-b).

Local maximum was often formed in the bottom of density cavity. Its position corresponded to maximum of the HF electric field intensity (ponderomotive force caused by this field is directly proportional to its intensity gradient).

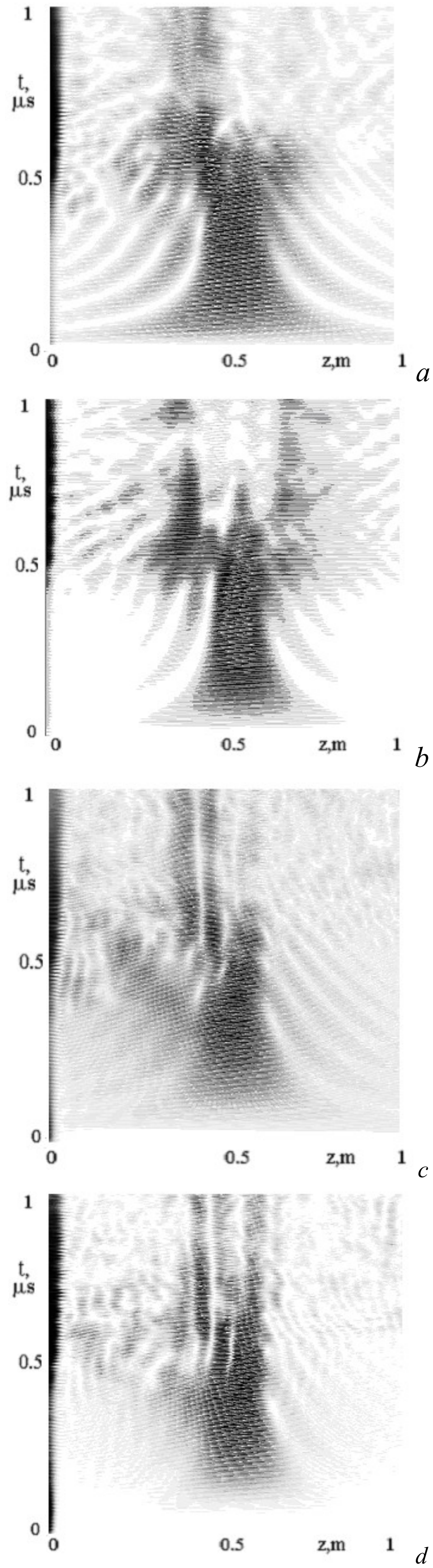

Fig.4. Space-time distribution of the electric field (a, b) and electron density perturbation (c, d) for inhomogeneous plasma excitation by the modulated electron beam moving into plasma (a, c) and by pumping electric field (b, d). Non-isothermal plasma is treated

Density gradient of the cavity side from the dense plasma was larger due to the similar character of spatial distribution of the electric field intensity.

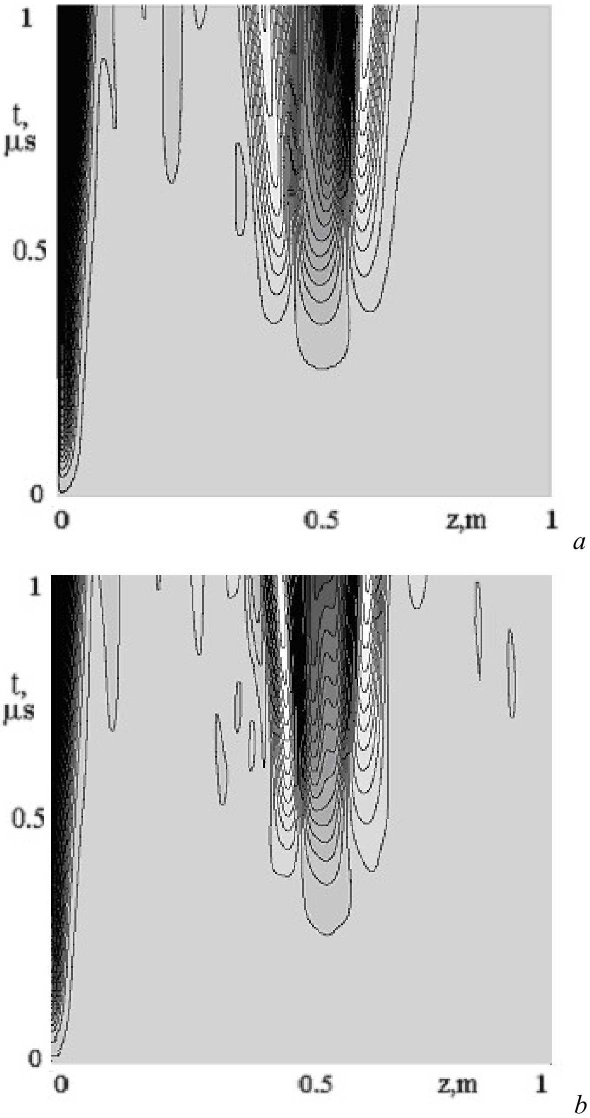

Fig. 5. Space-time distribution of the ion density perturbation for inhomogeneous plasma excitation by the modulated electron beam moving into plasma (a) and by pumping electric field (b)

Analytic estimations show that plasma density profile deformation can be treated as slow process relatively to electric field excitation in plasma with the given density profile. Consequently, electric field slaved adiabatically to variation of the plasma density profile caused by this field.

Further dynamics of plasma in LPRR differs strongly for plasma with hot electrons and isothermic plasma. This effect is connected with the strong damping of ion-acoustic waves in isothermic plasma and weak damping of these waves in plasma with hot electrons.

4. LATE STAGE OF INTERACTION FOR PLASMA WITH HOT ELECTRONS

In plasma with hot electrons ($T_e >> T_i$) the ion-acoustic type perturbations propagated to both sides from the cavity [5] (see Fig. 6, a, compare with Fig. 1).

The new peaks of electric field appeared on the local maximums of the subcritical plasma resulting to new cavities formation. This process is demonstrated on Fig. 3, b where space-time distribution of the electric field absolute value is presented. Line 1 corresponds to the boundary between subcritical and supercritical plasma. Position of the electric field maximums coincide with the region of plasma density in the range (0.93…1.00)n_c (black spots). Excitation of strong electric fields on the local maximums of subcritical plasma (for n_c-n_{max}<<n_c) was also demonstrated by computer simulation for the modeling profiles of plasma density.

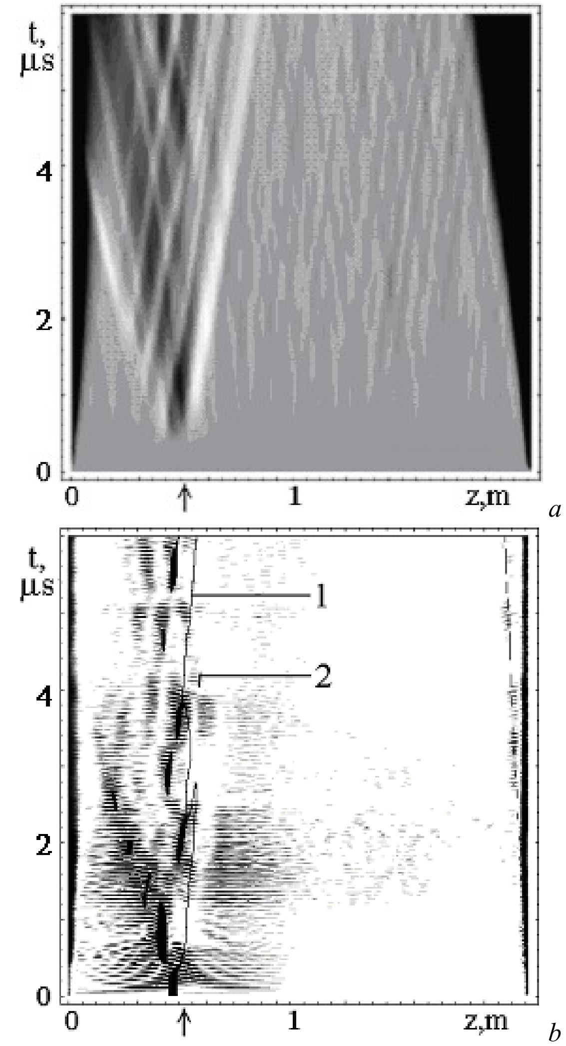

Fig. 6. Space-time distributions of ion density perturbation (a) and electric field magnitude superposed with the regions of plasma density (0.93÷1.00)n_c (b) in plasma with hot electrons. Local plasma resonance point in unperturbed plasma is shown by arrow

Consequently, in the late stages the ion concentration profile in plasma with hot electrons was strongly indented in the wide region around LPRR due to the short ion-acoustic pulses. These pulses were excited irregularly near the local plasma resonance point in subcritical plasma. The time dependence of electric field in some points of subcritical plasma looks like transition to chaos via intermittence.

Our results somewhat differ from those obtained in [1] via numerical solution of the modeling equations. On one hand, in that solution cavitons were formed every time in LPRR and then moved to the low-dense plasma. On the other hand, on some stage of caviton evolution its collapse took place. This collapse was accompanied by the sharp growth of electric field in the region, where cavity became deep and narrow. These features were not observed in our simulation (including the case when oscillations in LPRR were excited by the pumping electric field similarly to [1]).

5. LATE STAGE OF INTERACTION FOR ISOTHERMAL PLASMA

In the isothermal plasma (T_e=T_i) due to the strong damping of ion-acoustic waves the cavity is gradually transformed into the diffused jump of plasma density at the late stage (see Fig. 7 a, c). Position of electric field peak approximately coincides with the position of this jump (compare Fig. 7 a, b). The density jump moves inside the dense plasma, its velocity is of order of ion thermal velocity. Parameters of concentration jump correspond to analytic estimations based on the theory similar to [3].

6. PRELIMINARILY RESULTS OF 2D SIMULATION

Now we have started simulation of this problem for 2D plane geometry using electrostatic PIC code for plane geometry [12]. The simulation volume is bounded by two parallel planes x=const and y=const. In the present version of the package ions are fixed.

The plasma density varies linearly along x axis, so that plasma is homogeneous in the y direction. The electron beam moves along x direction. Its width in y direction is small relatively to the width of plasma layer.

Fig. 8 presents the spatial distribution of the plasma electrons' distribution for several consecutive moments of time in the steady-state regime. Langmuir waves are excited by the beam in LPRR. They propagate to the region of subcritical plasma. The fronts of waves in xy plane have quasi-circular shape because the part of local plasma resonance layer excited by the beam can be treated as the point source of waves.

7. CONCLUSIONS

1. Results of 1D simulation show that dynamics of plasma in the LPRR for excitation by the modulated electron beam and by the pumping electric field are similar.

2. Non-linear deformation of the plasma density profile in LPRR caused by the strong RF electric field interrupts the Langmuir waves excitation an acceleration of the plasma electrons. Due to this effect transitional radiation of the modulated electron beams from LPRR (see, e.g., [13]) can be significant only during the time intervals less then characteristic time of the plasma profile deformation.

3. Plasma dynamics in the LPRR excited by the external source depends strongly on the plasma properties. In plasma with hot electrons quasi-periodic sequence of cavities is formed. Formation of the cavities results to the excitation of ion-acoustic pulses. In the isothermal plasma the density jump is formed.

4. Preliminary results of 2D simulation for thin beam show that on the linear stage of the process the point were the beam crosses the plasma resonance layer plays the role of the Langmuir waves' source.

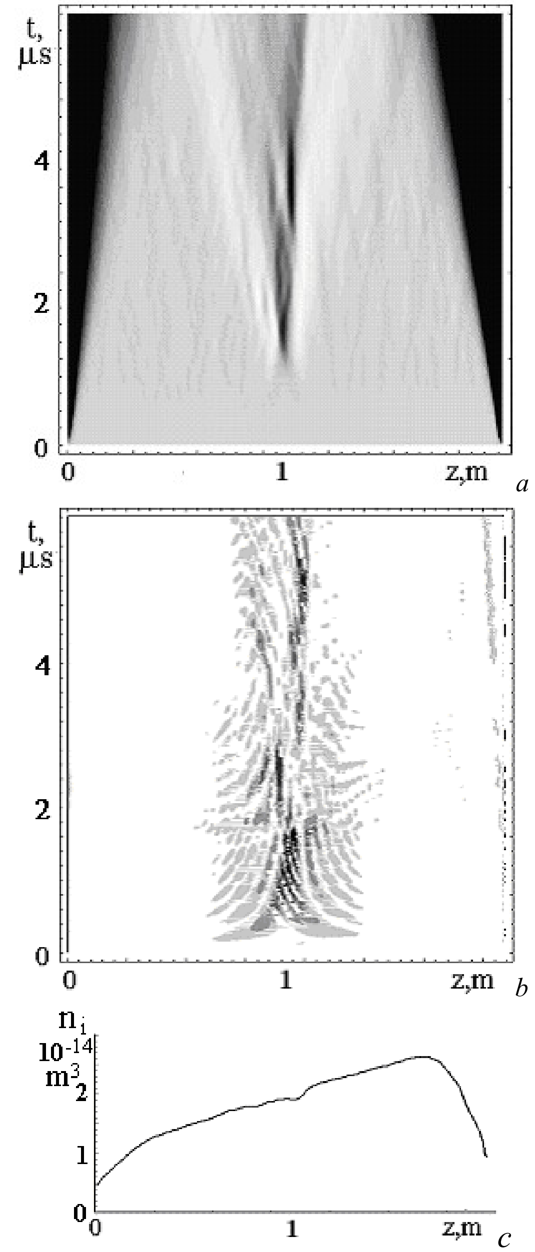

Fig. 7. Space-time distributions of ion density perturbation (a) and electric field magnitude (b) and spatial distribution of ion density for t=3 μs (c); j_m=1 A/m²

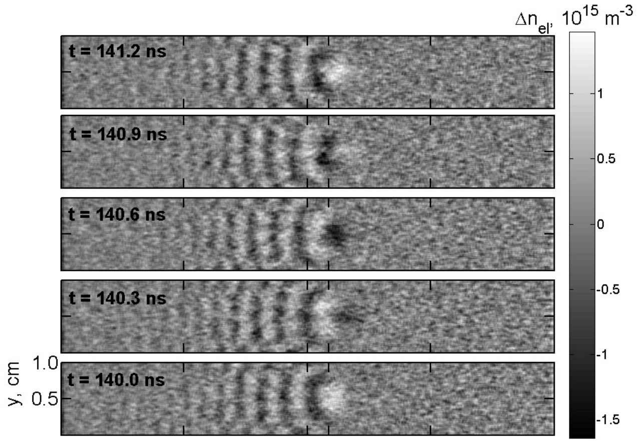

Fig. 8. Spatial distribution of electron density perturbation for 2D model with the thin electron beam

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ДИНАМИКА ПЛАЗМЫ В ОКРЕСТНОСТИ ТОЧКИ ЛОКАЛЬНОГО ПЛАЗМЕННОГО РЕЗОНАНСА, ВОЗБУЖДАЕМОЙ ЭЛЕКТРИЧЕСКИМ ПОЛЕМ НАКАЧКИ ИЛИ МОДУЛИРОВАННЫМ ЭЛЕКТРОННЫМ ПУЧКОМ

И.А. Анисимов, А.И. Кельник, Т.Е. Литошенко, Т.В. Сиверский, С.В. Сорока, Д.М. Великанец

Возбуждение высокочастотного электрического поля в области локального плазменного резонанса (ОЛПР) неоднородной плазмы электрическим полем накачки или модулированным электронным пучком приводит к появлению пондеромоторной силы, выдавливающей плазму из этой области. Под действием этого поля в ОЛПР формируется ямка плотности. Последующая динамика в этой области зависит от свойств плазмы. Для плазмы с горячими электронами ионно-акустические импульсы разбегаются от ямки плотности. На локальном максимуме концентрации возбуждается новый всплеск электрического поля, приводящий к формированию новой ямки плотности, и т.д. В изотермической плазме формируется скачок плотности.

ДИНАМІКА ПЛАЗМИ В ОКОЛІ ТОЧКИ ЛОКАЛЬНОГО ПЛАЗМОВОГО РЕЗОНАНСУ, ЩО ЗБУДЖУЄТЬСЯ ЕЛЕКТРИЧНИМ ПОЛЕМ НАКАЧУВАННЯ АБО МОДУЛЬОВАНИМ ЕЛЕКТРОННИМ ПУЧКОМ

І.О. Анісімов, О.І. Кельник, Т.Є. Літошенко, Т.В. Сіверський, С.В. Сорока, Д.М. Великанець

Збудження високочастотного електричного поля в області локального плазмового резонансу (ОЛПР) неоднорідної плазми електричним полем накачування або модульованим електронним пучком приводить до появи пондеромоторної сили, яка витискає плазму з цієї області. Під дією цього поля в ОЛПР формується ямка густини. Подальша динаміка в цій області залежить від властивостей плазми. Для плазми з гарячими електронами іонно-акустичні імпульси розбігаються від ямки густини. На локальному максимумі концентрації збуджується новий сплеск електричного поля, що приводить до формування нової ямки густини, і т.д. В ізотермічній плазмі формується стрибок густини.