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PROPAGATION OF RELATIVISTIC INTENSE ELECTROMAGNETIC WAVES IN PLASMA

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PROPAGATION OF RELATIVISTIC INTENSE ELECTROMAGNETIC WAVES IN PLASMA

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One of the important problems of the modern plasma physics is the investigation of the interaction of the high-power electromagnetic radiation with plasma. Such interest to this problem is mainly caused by the possibility of plasma heating up to high temperature in the installations for CTR. Recently, due to the problem of the plasma particle acceleration - electrons and ions to very high velocities by means of the powerful lasers the interest to this question increased significantly. On the other hand, studies of these phenomena helps better understanding of certain processes, occuring in a space plasma, where kvazars, pulsars and other astrophysical objects are the sources of the powerful electromagnetic radiation.

At the interaction of the intense electromagnetic waves with medium, the latter becomes inhomogeneous optically. The polarization vector, dielectric constant, the index of refraction and other values, characterizing physical properties of the medium, become dependent of the amplitude of the incident wave. Powerful radiation changes the medium physical properties, that in its turn affects the wave propagation, i.e. there is self-effect of the wave. Unlike other nonlinear effects such as harmonics generation, the stimulated Raman and Mandelstamm-Brillouin scattering and parametric processes, where interactions take place at slightly differing frequencies, the wave frequency does not change in the

process of self-effect, and the effect is observed in the change of its amplitude, polarization, shape of the angular and frequency spectrum.

Out of these phenomena, however, the effect of nonlinear refraction of the light beams, can be especially separated by its importance and influence upon other processes. In the general case in the nonlinear medium

$$n^2 = \varepsilon = \varepsilon_0 + \Delta\varepsilon(|E(\vec{r},t)|^2) \qquad (1)$$

where ε_0 - linear part of the dielectric constant, $\Delta\varepsilon$ - its nonlinear adding, n - refractive index of the medium. If the function $\Delta\varepsilon(|E|^2)>0$ and grows with the increase of the intensity, in the range, where the intensity is maximum, the medium becomes at the same time the most optically dense. Generally, the distributions of the intensities of the powerful lasers have inhomogeneous structure, and besides the inhomogeneities arise as perturbations as well. In this case nonlinear refraction starts to prevent the beam diffraction and can result in the energy concentration in the so called focal regions - peripheral rays deviate into the range, where the field is maximum, the central part of the wave front is slightly behind the peripheral one and the wave becomes convergent. The transverse dimensions of the beam decrease and the beam is compressed into focal range, where almost all the wave energy is concentrated. This phenomenon is called the beam self-focusing. Difraction, aberration prevent the increase of the intensity in focal points, as well as the mechanisms of dissipation of the energy (heating, scattering, etc.) which are small beyond the focus region. When nonlinear refraction and difraction compensate each other, the effective width of the beam does not change and the wave propagates in the self-supporting waveguide. This process is called the beam self-trapping. The beam intensity, for which difraction and nonlinear refraction are compensated, is called the critical intensity of self-focusing.

If the intensity of the beam exceeds much the critical intensity of the self-focusing, the beam has no time for self-focusing as the unity, and breaks for narrower beams, the so called "filaments". The cause of filamentation can be transverse to the direction intensity perturbation waves and certain physical parameters of the medium and azymuthal divergence, of the beams. Even weak increase of the intensity in certain region leads to the energy concentration there, and consequently, to stronger effect of nonlinear refraction, that increases the intensity, and the process develops avalanche-like.

The idea of the possibility of self-focusing was stated by Askarian [1] in 1962. In works of Chiao, Garmize, Townes [2], Talanov [3] and Kelly [4] the dynamics of the process was discussed first, and critical power, self-focusing length, their dependence upon the medium and beam parameters for the nonlinearity and the type

$$\varepsilon = \varepsilon_0 + \varepsilon_2 \cdot |E|^2 , \qquad (\varepsilon_2 > 0)$$

have been found.

Then, narrow glowing filaments and focal points have been recorded [5,6]. Since that time much had been done for the investigation of these phenimena, several reviews have been published [7-10]. Great attention to the studies of these effects is caused

by the fact, that they affect other nonlinear processes, change their dynamics and many quantitative relationships.

First publications [1,3] had been devoted to possibilities of self-focusing of electromagnetic waves in plasma, as in the medium, where the nonlinearity is achieved at comparatively low power of radiation and when the problem of LTR arose, the detailed investigation of self-focusing and filamentation in plasma became expedient. In the irradiation experiments of special targets by powerful lasers, transverse inhomogeneities, filaments, focal spots [11] are observed in the plasma corona, which are the causes of the implosion inhomogeneity, cause the enlightening of plasma in certain places, affect the damping and scattering of pumping wave, generation of strong magnetic fields. Self-focusing of the intense laser beam can be the cause of the plasma particle acceleration, due to which one can obtain the electron or ion beam with the energy of some MeV and higher [12], that is rather important for the development of the nuclear and elementary particle physics.

At not very high intensities of the electromagnetic waves, the main mechanism of nonlinearity, causing the self-focusing and filamentation in the collisionless plasma, is striction, and in plasma, where particle collisions should be considered, - thermal effects [13,14]. The striction is caused by redistribution of the plasma particle densities - electrons and ions-under the action of the ponderomotive force. Thermal effects are connected with ohmic heating.

Fast development of laser and UHF technology in recent years allow to obtain such fields, when $q_0 \cdot \lambda \sim 10^{17} \div 10^{18}$ wt $\cdot$ cm^2

q_0 - intensity of the incident laser radiation, λ - wavelength). To achieve thermonuclear conditions it is necessary to increase this parameter of radiation by an order of magnitude and higher. The incident wave with such parameters is sufficiently powerful in order to induce the relativistic effevt connected with oscillation of electron mass in a high frequency field.

In the weakly relativistic case when $I = V_E^2/c^2 = \frac{e^2|E|^2}{m^2\omega^2 c^2} \ll 1$ (where ω - is the pumping wave frequency, I - is the oscillation velocity of plasma electrons) just relativistic effect is the main cause of self-focusing and filamentation. In this case the nonlinearity is cubic, and like other cases, results, obtained in general optical theory of nonlinear refraction are valid for this case as well [14,15]. One should only write the value of nonlinear adding of dielectric constant for certain model of plasma.

Obviously, it is of interest to study nonlinear refraction in the case of arbitrary relativism. Moreover, in [16,17] it has been shown that the soliton structure, the character of modulational instability change, and apart, the considerable increase of the energy absorption effectiveness of electromagnetic waves in plasma [18]. The increased electron effective mass decreases the electron plasma frequency and makes possible penetration of the waves in ultradense region beyond the critical surface of plasma [19].

At arbitrary relativism, the nonlinearity is not cubic and in this case together with relativistic effect, one should take into account electron striction as well. Both relativistic effect and electron striction due to small electron inertia works much faster than ordinary strictional or thermal nonlinearities and

causes the beam compression and formation of filaments.

The present paper considers specificities of the stationary self-focusing and filamentational instability of the relativistic intense circularly polarized waves in transparent ($\omega_{pe}^2 \ll \omega^2$) collisionless inhomogeneous [20] plasma. Due to the complexity of the problem of the wave theory of self-focusing, the analytical results can be obtained only for some models of the medium and the beam. Therefore, in order to obtain more detailed qualitative and quantative results it is impossible not to use numerical methods of soliton of the relevant equations in the quotient derivaties [21]. Certain important information, however, can be obtained also without solution of complicated equations in the framework of simpler approximations, as for instance, in the theory of self-effect, is aberrationless paraxial approximation.

As it has been shown in [17], for the waves with relativistic intensities, one can neglect thermal pressure of plasma electrons as compared with that of the field of the incident electromagnetic beam. Then Euler's equation for "cold" electrons ($T_e \ln n_e/mc^2 \ll$ $\ll I/\sqrt{1+I}$) is

$$\frac{\partial \vec{P}_e}{\partial t} + (\vec{V}_e \nabla)\vec{P}_e = -e\vec{E} - \frac{e}{c}[\vec{V}_e \times \vec{B}], \quad \vec{P}_e = \frac{m\vec{V}_e}{\sqrt{1 - V_e^2/c^2}} \tag{2}$$

where $\vec{V}_e$, $\vec{P}_e$, n_e - velocity, momentum and concentration of electons, respectively. In the high frequency field the characteristic values of plasma and the field together with slow dependence upon the time, contain the fast dependence as well with characteristic time $\tau \sim \omega^{-1}$, therefore each of the value $A \equiv (\vec{E}, \vec{B}, n_e,$

$\vec{V}_e$, $\vec{P}_e$) can be searched as

$$A = \langle A \rangle + \tilde{A}$$

where brackets $\langle \quad \rangle$ mean averaging over the time τ :

$$\langle A \rangle = \frac{1}{2\tau} \int_{t-\tau}^{t+\tau} A(t')\,dt' \qquad (4)$$

If the characteristic times of self-focusing and filametation t_F are such, that $t_F \ll \omega_{pi}^{-1}$ the ions can be considered the times of these processes as statipnary ($n_i = n_o$) and only compensating the volume charge of the electrons. We restrict ourselves by consideration of the case when constant magnetic field is absent $\vec{B}_o = 0$. In the case, when all values are changing rather smoothly, so that inequalitie are fulfilled

$$\frac{\lambda}{\tau}, \frac{L}{\tau} \gg |\langle \vec{P}_e \rangle|, |\vec{\tilde{P}}_e| \qquad (5)$$

(where λ, L - characteristic distances of the change of fast variable and slow changing values), using the calculations, described in [22], it follows from the equations of continuity and motion, that

$$\frac{\partial \vec{\tilde{P}}_e}{\partial t} = -e\vec{\tilde{E}} \qquad (6)$$

$$\frac{\partial \langle \vec{P}_e \rangle}{\partial t} + (\langle \vec{V}_e \rangle \nabla) \langle \vec{P}_e \rangle = -e\langle \vec{E} \rangle - \langle (\vec{\tilde{V}}_e \nabla) \vec{\tilde{P}}_e \rangle - \frac{e}{c} \langle [\vec{\tilde{V}}_e \vec{\tilde{B}}.] \qquad (7)$$

$$\frac{\partial \tilde{n}_e}{\partial t} + \mathrm{div}(\langle n_e \rangle \vec{\tilde{V}}_e) = 0 \qquad (8)$$

$$\frac{\partial \langle n_e \rangle}{\partial t} + \mathrm{div}(\langle n_e \rangle \langle \vec{V}_e \rangle + \langle \tilde{n}_e \vec{\tilde{V}}_e \rangle) = 0 \qquad (9)$$

For circularly polarized waves, if one neglects electron nonlinearities and electron inertia, i.e. take that $t_F \gg \omega_{pe}^{-1}$ it is easy to obtain from Maxwell's and Poisson's equations, that

$$\vec{\tilde{B}} = \frac{c}{e} \,\mathrm{rot}\, \vec{\tilde{P}}_e \qquad (10)$$

$$e\langle \vec{E} \rangle = \vec{F}_{pe} \qquad (11)$$

$$\vec{F}_{pe} = -mc^2 \,\mathrm{grad} \sqrt{1+I} \qquad (12)$$

$$\frac{\langle n_e \rangle}{n_o} = 1 + \frac{c^2}{\omega_{pe}^2} \Delta \sqrt{1+I} \qquad (13)$$

where $\omega_{pe}^2(z) = \frac{4\pi e^2 n_o(z)}{m}$ plasma frequency of electrons, $n_o(z) = n_{oo} W(z)$ - initial density distribution, $W(z)$ - profile of plasma inhomogeneity. As it is seen from Eqns(11) and (13), quasi-neutrality of plasma in the range of wave propagation is distorted and the spatial charge is caused by ponderomotive force $\vec{F}_{pe}$. By means of these equations the wave equation for fast oscillating part of the field electric strength vector can be written as

$$\Delta\vec{\tilde{E}} - \mathrm{grad}(\mathrm{div}\,\vec{\tilde{E}}) - \frac{1}{c^2}\frac{\partial^2\vec{\tilde{E}}}{\partial t^2} = \frac{\omega_{pe}^2}{c^2}\frac{1}{\sqrt{1+I}}\left(1+\frac{c^2}{\omega_{pe}^2}\Delta\sqrt{1+I}\right)\vec{\tilde{E}} \quad (14)$$

Studying the task of self-focusing, for the sake of simplicity, we consider beams with Gaussian profile of intensity distribution

$$\vec{E}\cdot\vec{E}^*\big|_{z=0} = E_{0c}^2 \exp[-r_\perp^2/a^2] \quad (15)$$

(where $r_\perp^2 = x^2+y^2$, a – initial effective width of the beam) and assume that the beam front falls on the plasma boundary along axis Z. Then in aberrationless approximation in the stationary case the strength vector of the electric field can be represented as

$$\vec{\tilde{E}} = \vec{E}(\vec{r})(\hat{x}+i\hat{y})\exp[i\varphi(\vec{r},t)] \quad (16)$$

$$\varphi(\vec{r},t) = -\omega t + \int_0^z K_\parallel(z')dz' + \frac{r_\perp^2}{2}\beta(z) \quad (17)$$

$$I = I_0(z)\exp[-r_\perp^2/a^2 f^2(z)] \quad (18)$$

where $I_0(z)$ – field intensity on the beam axis, $\beta(z)$ – curvature of the phase front, $f(z)$ – dimensionless beam width.

As it is shown in [22], investigation of the self-focusing of powerful beams in the framework of parabolic type equation is incorrect in the range where nonlinear perturbation of the dielectric constant of plasma is not small and ellyptic type equations should

be solved. Taking into account the plot of longitudinal wave number of the beam $K_\parallel(z)$, nonlinear perturbation of the medium dielectr: constant in the approximation of the wave optics $(K_0^2 a^2 f^2 \gg 1)$ for paraxial rays $(r_\perp^2 \ll a^2 f^2)$ we obtain the set of equations simila: to that given in [23], but with other dielectric constant:

$$K_\parallel^2(z) = \frac{\omega^2}{c^2} - \frac{2}{a^2 f^2(z)}\frac{1}{1+I_0(z)} - \frac{\omega_{pe}^2(z)}{c^2}\frac{1}{\sqrt{1+I_0(z)}} \quad (19)$$

$$-2\beta(z)/K_\parallel(z) = \frac{d}{dz}\ln[K_\parallel(z) I_0(z)] \quad (20)$$

$$K_\parallel\beta' + \beta^2 + \frac{\omega_{pe}^2}{c^2}\frac{1}{a^2 f^2}\frac{I_0}{(1+I_0)^{3/2}} + \frac{I_0(4+I_0)}{a^4 f^4 (1+I_0)^2} - \frac{1}{a^4 f^4} = 0 \quad (21)$$

$$\beta'' + \beta'(\ln I_0)' - \frac{4}{a^2 f^2}\left[\beta - K_\parallel(\ln f)'\right] = 0 \quad (22)$$

Boundary conditions are of the form

$$I_0(z=0) = I_{00}, \quad f(z=0) = 1, \quad \beta(z=0) = \beta_0$$

$$\omega_{pe}^2(z=0) = \omega_{pe0}^2 = \frac{4\pi e^2 n_{00}}{m}, \quad W(z=0) = 1 \quad (23)$$

In equation (21) the third, the forth and the fifth terms are specifiзied by relativistic effect, electron striction and diffraction, respectively. In the case of ultrarelativistic waves $(I_0 \gg 1)$ the effect of the nonlinear refraction caused by electron striction, compensates the wave diffrection, but at the same time the relativistic term, responsible for self-focusing, starts to decrease. Nonlinearity is saturated. Strictional nonlinearity plays a major role in the determination of minimum transverse dimensions of the beam. Since $\langle n_e \rangle \geq 0$, the minimum effective width of the beam from equation (13) is

$$r_{\perp\, min} = a \cdot f_{min} = a \left\{ \frac{2c^2}{\omega_{pe}^2 a^2} \frac{I_0}{\sqrt{1+I_0}} \right\}^{1/2} \tag{24}$$

Even in aberrationless approximation we failed to solve the equation set (19)-(22) without numerical calculations. In order not to have these calculation beyod the frame in our model the following limitations have been superimposed at numerical count

$$K_{\parallel}^2(z)\, a^2 \geq 10^2 \,, \quad f^2(z) \geq 0.1 \,, \quad z < V_g/\omega_{pi} \,,$$
$$f^2(z) > \frac{2c^2}{\omega_{pe}^2 a^2} \frac{I_0(z)}{\sqrt{1+I_0(z)}} \tag{25}$$

where V_g - group velocity of the wave.

Plasma inhomogeneity affects substantially the character of propagation of relativistic intense waves. For various profiles different modes of propagation are possible. As it is seen from Fig.1, in which the plot of dimensionless beam width f vs z/a is given for different characteristic lengths of plasma inhomogeneity at linearly growing density profile, for the focusing beams $(I_{00} > I_{cr1})$ the self-focusing length z_{SF} with the decrease of the characteristic length of inhomogeneity L decreases and then grows. The further decrease L results in fast broadening of the beam, focused to certain extent. Then with the increase of the inhomogeneity the beam starts to defocusing. In occurs, because the dielectric constant

decreases due to the growth of the density, faster, than increases on account of the relativism and electron striction

$$\varepsilon\big|_{r_\perp=0} = 1 - \frac{\omega_{pe0}^2}{\omega^2} \frac{W(z)}{\sqrt{1+I_0(z)}} \left(1 - \frac{2c^2}{f\omega_{pe0}^2 a^2 W(z)} \frac{I_0(z)}{\sqrt{1+I_0(z)}}\right) \tag{26}$$

As it seen from Fig.2 there are three various modes of propagation of electromagnetic waves for different boundary intensities I_{00} : a) the beam is focused to critical surface of plasma immediately or after certain initial broadening (curves 1,2), creates self-supporting channel near the beam axis and penetrates into ultra-dense plasma. Diffraction rings which form of peripheral parts of the beam and have intensity less than critical, are rellecting from the critical surface and do not penetrate into ultra-dense plasma. In paraxial part of the beam the intensity of the formed channel is almost homogeneous, dielectric constant of the medium, in this range is higher than zero, and density jump and associated effects do not affect this process. Glowing depth of plasma is limited. When the characteristic time of self-focusing and self-channeling will become of the order of ω_{pi}^{-1} one should take into consideration the ion dynamics and assume that the force of the nonlinear refraction will decrease and the beam begins to broaden; b) the beam is focused to certain dimensions after which it broadens fastly (curve 3). When at self-focusing the intensity increases $(I_0(z) \gg 1)$, the electron mass becomes very high, nonlinearity decreases and then due to inhomogeneity and diffraction starts to predominate over nonlinear refraction; c) the beam defocuses of the boundary immediately. It occurs both at small $(I_{00} < I_{cr1})$ (curve 4) and at large $(I_{00} > I_{cr2})$ (curve 5) intensities. In the case of arbitrary relativism we did not secceed in calculation of these critical intensities, but estimation show that $I_{cr1} \sim \omega_{pe}^{-2} a^{-2}$ and $I_{cr2} \sim \omega_{pe}^{-4/3} a^{-4/3}$. In some cases for broad beams $(a/\lambda \gg 10^2)$ when the relativistic nonlinearity exceeds much the diffraction, electron striction can be neglected and analytical length of the self-focusing of the relativistic intense beams is found [24].

Fig.2 shows that normed length of the self-focusing Z_{sf}/a grows with the increase of the initial width of the beam, normed dimensions of local points being decreased. By this the self-focusing of the relativistic waves differs from weakly relativistic case (for it as well as for general media with cubic nonlinearity, $Z_{sf} \sim a$ [25]).

Studying the filamentational instability of circularly polarized electromagnetic waves inhomogeneous plasma for the some of simplicity, we represent the pumping wave, propagating along axis z, as

$$\vec{E} = [E_0 + E(\vec{r})](\hat{x} + i\hat{y}) \exp[-\omega t + \int_0^z k(z')dz'] \tag{27}$$

where E_0 is the electric field strength of the plane homogeneous wave, $E(\vec{r})$ - its perturbation. Substituting (27) into (14) in the zero approximation, we obtain

$$\omega^2 - k^2(z)c^2 = \omega_{pe}^2(z) / \sqrt{1 + I_0(z)} \tag{28}$$

where $I_0 = \dfrac{e^2 E_0^2}{m^2 \omega^2 c^2}$. In the first approximation, taking into account symbols of

$$I = \frac{e^2}{m^2 \omega^2 c^2} (E_0 E^* + E_0^* E) \tag{29}$$

$$I = I_1(z) \exp[k_x \cdot x + k_y \cdot y], \quad k_x^2 + k_y^2 = k_\perp^2 \tag{30}$$

we obtain

$$\frac{d^2 I_1}{dz^2} + \frac{d}{dz} \ln k(z) \frac{dI_1}{dz} - \left\{ \frac{k_\perp^4}{4k^2(z)} \left[\frac{\omega_{pe}^2}{k_\perp^2 c^2} \frac{I_0}{(1+I_0)^{3/2}} + \frac{I_0}{1+I_0} - 1 \right] - \frac{1}{2k(z)} \frac{d^2 k(z)}{dz^2} \right\} I_1 = 0 \tag{31}$$

For homogeneous plasma in the linear approximation $(I_1(z) = I_{10} \exp(i k_z \cdot z))$ equation (31) is easy solved. When

$$\frac{\omega_{pe}^2}{k_\perp^2 c^2} \frac{I_0}{\sqrt{1+I_0}} > 1 \tag{32}$$

the filamentational instability develops, the growth rate of which is

$$\gamma = \frac{k_\perp^2}{2k_0} \left[\frac{\omega_{pe}^2}{k_\perp^2 c^2} \frac{I_0}{(1+I_0)^{3/2}} + \frac{I_0}{1+I_0} - 1 \right]^{1/2} \tag{33}$$

The first term in square brackets corresponds to the relativistic effect, the second one - to electron striction, and the third - to diffraction. The growth rate reaches maximum value over $k_\perp$, when

$$\bar{k}_\perp = \left(\frac{\omega_{pe}}{2c^2} \frac{I_0}{(1+I_0)^{1/2}} \right)^{1/2} \tag{34}$$

and it equals to

$$\gamma_{max}|_{\bar{k}} = \frac{\omega_{pe}^2}{4kc^2} \frac{I_0}{1+I_0} \tag{35}$$

In the ultrarelativistic case the therms of equation (33), caused by striction and diffraction, are diminished and $\gamma = \frac{k_\perp \omega_{pe}}{2kc} I_0^{-1/4}$ i.e. with the increase of the intensity, the growth rate decrease slowly, whereas in the case $I_0 \ll 1$ we have $\gamma \sim I_0^{1/2}$. Maximum value of γ over I_0 is reached when

$$I_0 = 2\left[1 + \frac{1}{\theta^2}\left(1 + \sqrt{3\theta^2 + 1}\right)\right], \qquad \theta = \frac{\omega_{pe}^2}{k_\perp^2 c^2} \tag{36}$$

If one assumes that $k_\perp c \sim \omega_{pe}$, then filamentation will occur more effectively when $I_0 \sim 1 \div 10$

From equation (33) one can also find the threshold intensity of filamentation and critical dimensions of the perturbation

$$I_{cr} = \frac{1 + \sqrt{1 + 4\theta}}{2\theta}$$

$$d_{cr} = \left(\frac{c^2}{\omega_{pe}^2} \sqrt{1 + I_0}/I_0\right)^{1/2} \tag{37}$$

(33)

In the case of weak inhomogeneity of plasma $(W = 1 + z/L,\ z/L \ll 1)$ (31) is reduced to

$$\frac{d^2 I_1}{dz^2} - \frac{1}{2}\delta z \frac{dI_1}{dz} - \gamma(1 + \delta z) I_0 = 0 \tag{39}$$

where $\delta = \pm \frac{\omega_{pe}^2}{Lk^2c^2}(1 + I_0)^{-1/2}$. This equation belongs to the Weber equations class and its solution can be written analytically [26].

Equation (31) for arbitrary inhomogeneity of plasma was studied numerically. Fig.3 gives plots of I_1 vs z for different characte-

ristic lengths of plasma inhomogeneity. In the case of linearly growing profile (Fig.3a) stationary radiation becomes nonstationary with the decrease of the inhomogeneity length. It is caused mainly by the fact, that with the increase of plasma density $\omega_{pe}^2(z)$ increases and inequality (32) becomes to be satisfied. For linearly decreasing inhomogeneity profile, with the decrease of L unstationary beam becomes stationary (Fig.3b). Following from the above results, one can conclude that filamentation and self-focusing of electromagnetic waves with arbitrary relativistic intensities differs significantly from nonrelativistic and weakly relativistic cases. In particular:

1. Nonlinearity of the medium is not cubic.

2. Apart from relativistic effect on the character of wave propagation, electron striction also acts, that in especially essential in the region of focus and plays a decisive role in the determination of the minimum transverse dimensions of the beam.

3. When $I \gg 1$, electron striction compensates diffraction, but relativistic nonlinearity decreases as well.

4. Self-focusing and filamentation develops more effectively, when $I_0 \sim 1 \div 10$

5. Plasma inhomogeneity can change the mode of propagation.

6. Normed length of self-focusing depends upon the boundary effective beam width.

7. Self-focusing and filamentation occurs earlier than other mechanisms of nonlinear refraction due to relativistic effect and electron striction.

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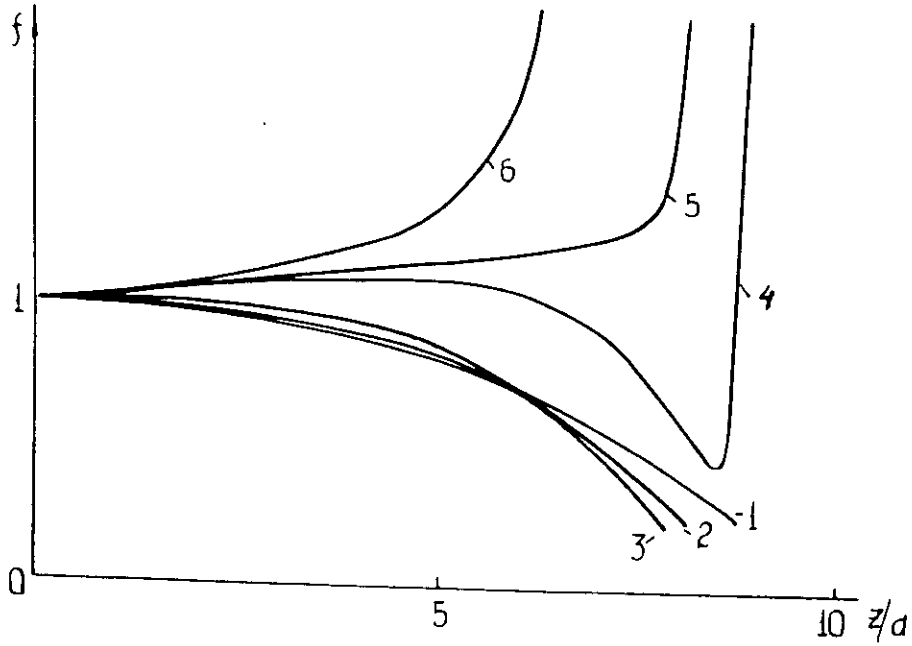

Fig. 1

Fig.1 Plot of f vs z/a for different L at $\omega_{pe0}^2/\omega^2=0.1$, $\omega^2 a^2/c^2=400$; $\beta_0=0$; $I_{00}=0.5$; $W = I + z/L$. Curves: 1 - L/a = 100, 2 - L/a =10, 3 - L/a =5, 4 - L/a =2.9, 5 - L/a =2.75, 6 - L/a =2.5.

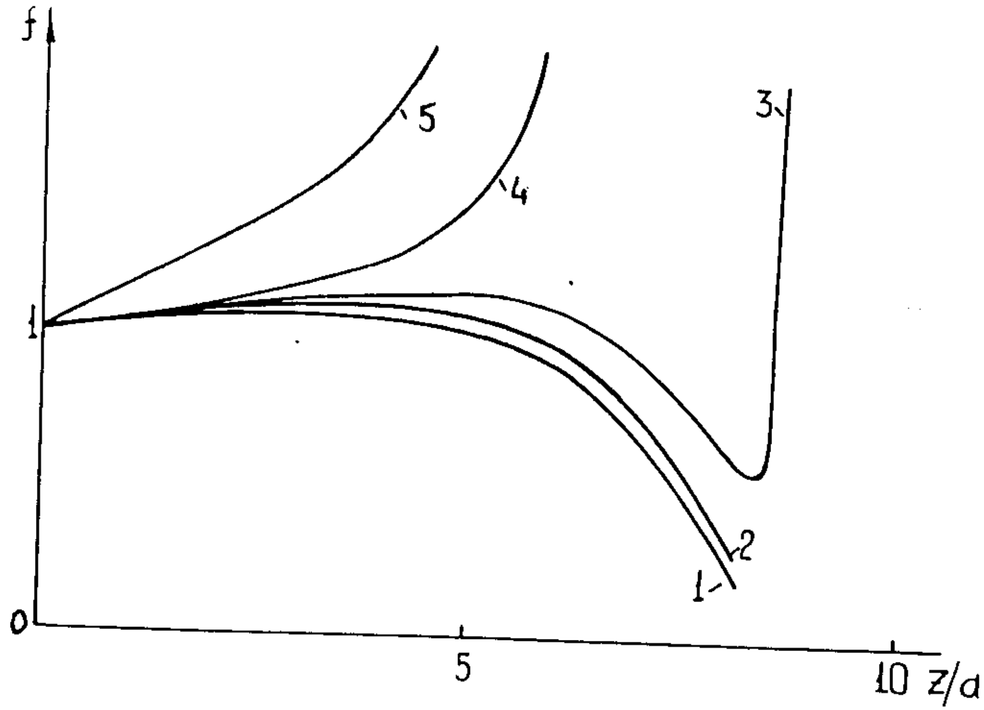

Fig. 2

Fif.2 Plot of f vs z/a for different I_{00} at ω_{pe0}^2/ω^2 =0.4; $\omega^2 a^2/c^2$=400; L/a =3.2; β_0 =0;, $W = I + z/L$; Curves: I - I_{00} =0.5; 2 - I_{00} =0.75; 3 - I_{00} =1, 4 - I_{00} =0.05; 5 - I_{00} =2.

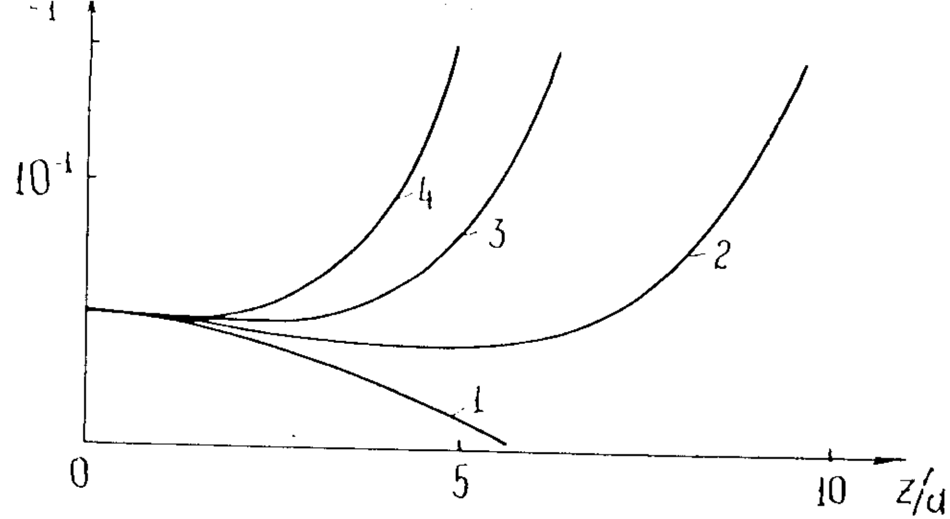

Fig. 3a

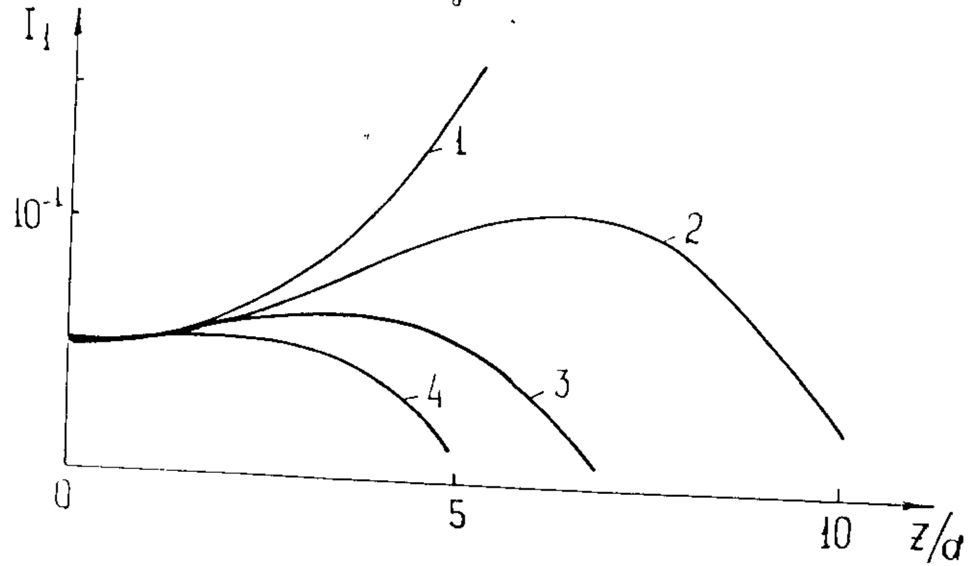

Fig. 3b

Fig. 3 Function of $I_1(z)$ for different characteristic lengths of linear growing a) and linear decreasing b) of inhomogeneity profiles $W = 1 \pm z/L$, where L/d =100(1), 10(2), 7.5(3), 5(4), 6(5) at $\omega_a^2 d^2/c^2$=0.1, $\omega^2 d^2/c^2$=800(a) and 1000(b), $K_\perp^2 d^2$=40, T_0=0.5, $T_{0\parallel}$=0.1 T_0.