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NUMERICAL MODELING OF THERMAL SELF-FOCUSING OF ELECTROMAGNETIC WAVES IN A WEAKLY IONIZED PLASMA

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UDC 535+534.222

The results of numerical modeling of self-focusing of electromagnetic waves in the millimeter range in low-temperature weakly ionized plasma (coefficient of ionization less than or of the order of 0.01) are presented.

The system of equations describing self-focusing consists of the parabolic equation for the slowly varying envelope of the amplitude of the electric field intensity [1, 2] and the equations of two-temperature hydrodynamics for slow motions of the plasma [1-6]. In axially symmetrical geometry, the system of equations is written in the form

$$\frac{\partial N}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}rvN=0,\ \frac{\partial n}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}rvn=0,$$
$$\frac{\partial Nv}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}rv^2N=-\frac{1}{M}\frac{\partial}{\partial r}(P_e+P_h),$$
$$\frac{\partial W_e}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}rv(W_e+P_e)=\sigma n|E|^2+\frac{3}{2}n\frac{T_e-T_h}{\tau_{eh}}+\frac{1}{r}\frac{\partial}{\partial r}rq_e\frac{\partial T_e}{\partial r},$$
$$\frac{\partial W_h}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}rv(W_h+P_h)=-\frac{3}{2}n\frac{T_e-T_h}{\tau_{eh}},$$
$$2ik\frac{\partial E}{\partial z}+\Delta_\perp E+\frac{4\pi}{c^2}\sigma n\omega\left(i-\frac{\omega}{\nu}\right)E=0, \tag{1}$$

where n is the electron density, N is the density of atoms and ions v is the radial velocity of the plasma, ω and E are the frequency and amplitude of the intensity of the electromagnetic field

$$\mathscr{E}=\frac{1}{\sqrt{2}}(Ee^{-i\omega t}+E^*e^{i\omega t}),$$

W_e and W_h are the total energy of the electron and heavy components of the plasma and m and M are the mass of the electron and of an ion, respectively,

$$\sigma=\frac{e^2}{m}\frac{\nu}{\omega^2+\nu^2},\quad \tau_{eh}=\frac{M}{2m}\frac{1}{\nu},$$

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 8-10, September-October, 1983. Original article submitted July 14, 1982.

0021-8944/83/2405-0611$07.50

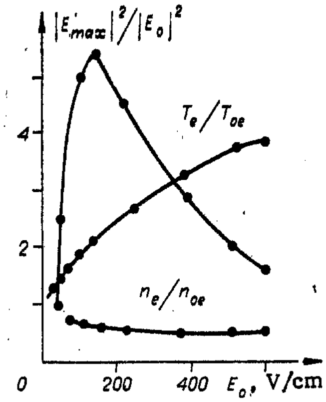

Fig. 1

and $\nu = \nu_{ea} + \nu_{ei}$ is the sum of the electron-atom and electron-ion collision frequencies ν_{ea} and ν_{ei}, respectively. The dependence of these frequencies on the plasma parameters is presented in [1, 2]. The coefficient of thermal conductivity is taken in the form

$$q_e = \frac{5}{2}\frac{nT_e}{\sum\limits_k \nu_{ek}}.$$

It is assumed that the temperatures of the ionic and neutral components coincide, i.e., $T_i = T_a = T_h$. The motion of the plasma in the direction of propagation of the electromagnetic wave and the thermal conductivity of the heavy component are assumed to be negligibly small. Inelastic ionization and excitation of atoms are neglected.

We are examining the incidence of a Gaussian electromagnetic pulse

$$E(z=0) = E_0 \exp\left(-r^2/r_0^2 - t^2/\tau_0^2\right)$$

on the boundary of a semi-infinite plasma. The parameters for which the modeling is performed are oriented toward the range of conditions of real experiments [7, 8].

We present below the results of the solution of the system (1) for the following parameters: $n = 7 \cdot 10^{13}$ cm^{-3}, $N = 5 \cdot 10^{15}$ cm^{-3}, $\lambda = 2\pi/k = 3$ mm, $\tau_0 = 4 \cdot 10^{-4}$ cm, $T_e = T_h = 0.3$ eV, $M = 14$ (nitrogen), $r_0 = 1$ cm.

Figure 1 shows the dependence of the efficiency of self-focusing on the intensity of the incident field. Here, the efficiency of self-focusing is taken to mean the quantity $|E_m|^2/E_0^2$, where E_m is the maximum field intensity attainable in the self-focusing process. As is evident from Fig. 1, self-focusing begins to appear at an amplitude of the intensity envelope of the incident field $E_0 = 40$ V/cm and grows rapidly with increasing E_0 up to self-focusing efficiencies close to 5.5 at $E_0 = 150$ V/cm. Further, as E_0 increases, the efficiency of self-focusing decreases slowly, so that at $E_0 = 600$ V/cm, we have $|E_m|^2/E_0^2 \sim 2$. This dependence is explained by the change in the dimensions of the perturbed region of the plasma in connection with the increase in the electronic thermal conductivity with increasing plasma temperature. As soon as the transverse size of the perturbed region exceeded the width of the pulse, self-focusing stopped.

For $E_0 = 150$ V/cm, a multifocused structure of the field, characteristic for all self-focusing mechanisms, appears. However, in contrast to Kerr self-focusing, when the foci represent small moving oscillations of the pulse profile, in the mechanism of self-focusing being examined here, the pulse divides into separate foci which are practically stationary in space. In addition, the position of the peaks is nearly independent of the intensity of the incident field E_0. Thus the peak of the first focus occurred in the region $z \sim 6$–10 cm and the peak of the second focus occurred in the region 20–30 cm with E_0 varying in the entire range indicated.

It is natural that for a finite (in z) plasma layer, the self-focusing efficiency will depend considerably on the thickness of the layer not only due to absorption of the wave by the plasma but also due to the appearance of a multifocus structure of the field. Figure 2 shows the dependence of the ratio $|E(z)|^2/|E(z = 0)|^2$ on time at points $z = 12$ and 8 cm with $E_0 = 60$, 210, 370, and 520 V/cm (lines 1–4, respectively).

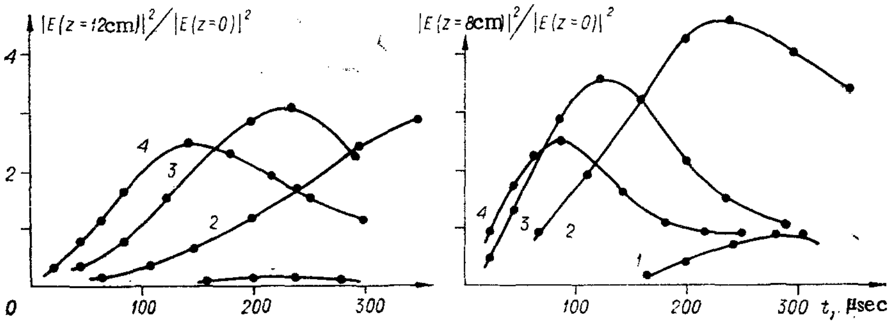

Fig. 2

As E_0 increases, the time required for the appearance of self-focusing decreases. Thus, at E_0 = 60 V/cm, this time is approximately 0.5 τ_0, i.e., approximately one-half the duration of the pulse; at E_0 = 150 V/cm, it is about 0.25 τ_0, and, at E_0 = 500 V/cm, it is about 0.1 τ_0.

As far as the duration of the existence of self-focusing is concerned, it decreases with increasing E_0 after E_0 = 150 V/cm, i.e., in the region where the self-focusing efficiency decreases.

As E_0 increases up to values E_0 ~ 150 V/cm, the minimum electron density on the axis drops monotonically and for E_0 > 150 V/cm, the drop slows down and stabilizes at a level of 0.6-0.7 of the initial density. The maximum attainable electron temperature in this case increases monotonically from a value exceeding the initial temperature by a factor of 1.5 (T_e ~ 0.5 eV) at E_0 = 60 V/cm to a magnitude exceeding the initial value by a factor of four (T_e = 1.3 eV) at E_0 = 600 V/cm.

Modeling for E_0 > 600 V/cm was not performed since for temperatures that are attainable within the framework of the system (1) T_e > 1 eV, it is already necessary to take into account ionization and excitation of atoms.

The system (1) was also solved with the following parameters: $n = 2 \cdot 10^{13}$ cm^{-3}, N = 10^{16} cm^{-3}, $T_e = T_n$ = 0.3 eV, λ = 5 mm, $\tau_0 = 4 \cdot 10^{-4}$ sec, r_0 = 1.5 cm, M = 14.

The modeling showed that self-focusing does not arise for E_0 varying from 100 to 1200 V/cm. The appearance of self-focusing is prevented by the large magnitude of the electronic thermal conductivity.

For a two times higher electron density and with the remaining parameters unchanged, self-focusing arose for E_0 > 300 V/cm. However, the self-focusing efficiency was low and did not exceed 1.3-1.5.

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