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Abstract

Vaporization kinetics from a surface into vacuum is investigated for various transient heating regimes due to intense irradiation of the surface. One-dimensional theoretical model of the process includes heat conduction into the surface, vapor flux through a Knudsen layer, and vapor flow without plasma formation. Transient vaporization kinetics turns out to be more complicated than it was assumed previously. Results of numerical calculations show that there are transient solutions of the nonlinear vaporization problem with a constant value of the flow Mach number $M = 1$ at the outer edge of the Knudsen layer. Evolution of M depends strongly on variation of radiation intensity.

Radiation-induced vaporization process depends essentially on pressure p and temperature T distributions in irradiated substances. If p is greater than a critical value p_c for liquid-gas phase transition in the region where $T < T_c$ then the vaporization process can be described with the help of continuous equation of state /1/. In the case of lower values $p < p_c$ there is a sharp vaporization front which separates liquid and vapor states. At this front usual conservation laws for mass, momentum, and energy fluxes are supposed to hold as well as some other relations which describe nonequilibrium vaporization kinetics.

For collisionless vapor flow the mass flux across the phase transition front is given by a well-known formula

$$j_0 = \rho_s (2\pi R T_s)^{-\frac{1}{2}} = \rho_\ell V \qquad (1)$$

where ρ_ℓ is the liquid density, $p_s(T_s)$ is the saturation pressure corresponding to the surface temperature T_s, and $R = k/m$ is the gas constant. Relation (1) follows straightforwardly from an assumption that vapor distribution function at the evaporating surface has a Maxwellian form and there are no backscattered particles. Expressions for momentum and energy fluxes can be obtained in the same manner. However, these three relations are incompatible with hydrodynamic expressions for the fluxes so that in collisional regime backscattered particles should be taken into account.

With the help of some assumptions on nonequilibrium distribution function /2/ in refs. /3,4/ expressions for vapor flow parameters in terms of p_s and T_s were obtained in the case when the flow Mach number just outside the Knudsen layer is equal to unity.

The case M = 1 corresponds to vaporization into vacuum or low-pressure external atmosphere. If the external pressure is not small compared to p_s then M < 1. Stationary vaporization kinetics with M ≤ 1 is investigated in many papers /5-10/ with the help of various approaches. An example of the model approach is described in some details in Appendix A.

It should be mentioned that the external gas pressure is not the only reason for decreasing of M. If the surface temperature varies too fast the value of M does not remain constant during transient vaporization from the surface into vacuum because previously evaporated mass plays the same role as external gas atmosphere.

Vaporisation kinetics can also be affected by plasma formation in vapor flow /10-12/. Decreasing of radiation intensity at the absorbing surface due to plasma formation is investigated in many papers /13,14/, while little attention is payed to plasma effect on vaporization kinetics.

In this paper evolution of M is investigated for various transition regimes of surface vaporization into vacuum sustained by intense irradiation of the surface below plasma formation threshold. This problem is important for several reasons.

The value of M characterizes nonequilibrium properties of the vaporization process. The case M= 0 corresponds to phase equilibrium while at M = 1 mass flux $j = 0.82\, j_0$ and momentum flux (recoil pressure) $p_r = 0.55\, p_s$ have respectively their maximum and minimum values.

If the relation M = 1 holds during vaporization process then the behaviour of the condensed phase is independent of the exterior vapor flow. In this case the vaporization problem

for condense phase reduces to one-phase version of the Stephan problem, the surface temperature T_s being a slowly changing function of the vaporization front velocity /15/. Such an approach is widely used for description of radiation-induced vaporization process below plasma formation threshold /16-23/.

Evaluation of M is essential also in the vaporization front stability problem /22,23/. The vaporization surface can be drastically affected by perturbations in exterior vapor flow when $M < 1$. This situation has much in common with the stability problem of subsonic combustion front which was discussed a long time ago. by G.Darrieus and L.Landau /24/.

As it is stated in /24/, the combustion is unstable in the theory while a stable behavior of the front is very often observed experimentally. This disagreement is discussed in many papers /24,25/ and will not be dealt with here.

In the Darrieus-Landau theory a dispersion relation for small perturbations $h \sim \exp(\Omega t + ikx)$ at the burning liquid surface is as follows

$$\Omega^2 + 2\Omega k V - k^2 V u + k^3 \sigma/\rho_e = 0 \qquad (2)$$

where σ is the surface tension and u is the gase flow velocity, the gas density being supposed negligibly small compared to the liquid density ρ_e. Eq (2) means that deformation of the combustion front (which coincides with liquid surface) results in the recoil pressure modulation

$$\tilde{p}_r = \sigma k^2 h + \rho_e V \Omega h - \rho_e V u k h \qquad (3)$$

Such pressure reaction gives rise to augmentation of the

surface perturbations.

Under the condition M = 1 recoil pressure response to small and smooth surface perturbations is determined by T_s. If T_s remains constant then instead of (3) and (2) one has

$$p_r = \sigma k^2 h \,, \tag{4}$$

$$\Omega^2 + \Omega k V + \sigma k^3/\rho_\ell = 0 \tag{5}$$

In contrast to eq.(2) in eq.(5) there is no term which gives rise to unstable behavior of the surface perturbations.

To clarify the difference between these two cases let us consider an equation for the pressure perturbations in the vapor flow

$$\left(\frac{\partial}{\partial t} - u\frac{\partial}{\partial z}\right)^2 \tilde{p} = u_c^2\left(\frac{\partial^2 \tilde{p}}{\partial z^2} + \frac{\partial^2 \tilde{p}}{\partial x^2}\right), \tag{6}$$

where Z-axis is normal to unperturbed vaporization front Z = 0 and U_c is the sound velocity. For two-dimensional pressure perturbations $\tilde{p} \sim \exp(\Omega t + ikx - \lambda z)$ from (6) it follows

$$\lambda^2(u^2 - u_c^2) - 2\Omega u\lambda + u_c^2 k^2 = 0, \tag{7}$$

$$\lambda = \left[\Omega u \pm u_c\left(\Omega^2 + u_c^2 k^2 - u^2 k^2\right)^{\frac{1}{2}}\right](u - u_c)^{-1}, \tag{8}$$

where for a given wave number $K > 0$ parameters Ω and λ should be determined from a linearized version of hydrodynamic equations.

At $u \ll u_c$ eq.(8) gives $\lambda_{1,2} = \pm K$. In this case only the value $\lambda_1 = K$ is used in expression for pressure perturba-

tions /24/. If $u_c > u - u_t > 0$ then

$$\lambda_1 = \frac{\Omega}{u+u_c} + \frac{u_c k^2}{2\Omega} \; ; \quad \lambda_2 = \frac{\Omega}{u-u_c} - \frac{u_c k^2}{2\Omega} \qquad (9)$$

Now both values of λ should be taken into account because real parts of λ_1 and λ_2 have the same signature.

In ref./26/ only the value $\lambda = \lambda_1$ is used in expression for $\tilde{p}$. Such form of the solution is valid in subsonic regime and cannot be used in the case when $u - u_c > 0$.

Solution of eq.(6) given by linear combination of exponents with $\lambda = \lambda_1$ and $\lambda = \lambda_2$ needs an extra boundary condition which cannot be obtained in the framework of linear analysis. The same question also arises in one-dimensional perturbation problem which is discussed in Appendix B.

In some cases the relation $M = 1$ can be probably used as an additional boundary condition /22,23/ though its applicability limits are not known. This question is closely connected with nonlinear properties of hydrodynamic equations.

The Mach number drops from its maximum value M=1 if T_s diminishes so fast that $p_s(T_s)$ decreases faster than the recoil pressure. It is evident that a sudden interruption of vaporization process has the same effect on the vapor flow as that produced by an extraction of piston from a gas atmosphere with velocity $u = u_c$. In the latter case initial gas pressure on the piston p drops abruptly to lower value p_1

$$p_1 = p\left(1 - \frac{\gamma-1}{2}\right)^{2\gamma/(\gamma-1)} \qquad (10)$$

At $\gamma = 5/3$ eq.10 gives $p_1 = 0.132\,p = 0.0495\,p_r = 0.027\,p_s$ because the recoil pressure $p_r = (1+\gamma M^2)p$ and $M = 1$.

Thus, a sudden drop of p_s to the value $p_1 = 0.027\, p_s$ drives the Mach number to zero. For deeper drop of p_s condensation process begins at the surface which will not be considered here.

In ref.27 C.J.Knight has analyzed transient surface vaporization numerically on the basis of theoretical model which includes transient heat conduction into the surface, vapor flux through a Knudsen layer at the surface, and transient one-dimensional flow of vapor into the surrounding vacuum without plasma formation. The examples are given for aluminium and only the case of a top-hat absorbed radiation intensity is considered. It is concluded in /27/ that the Knudsen layer attached to the surface tends to be choked when the absorbed intensity is constant or increasing and unchoked when the intensity is decreasing, the vaporization problem being fully coupled in the latter case.

However, this conclusion cannot be applied to different regimes of radiation-induced vaporization. As it is shown in the present paper evolution of M is more sophisticated in other cases.

A theoretical model is essentially the same as in /27/

$$c\rho\left(\frac{\partial T}{\partial t} - V\frac{\partial T}{\partial z}\right) = \frac{\partial}{\partial z}\left(\varkappa\frac{\partial T}{\partial z}\right), \quad -\ell < z < 0,$$
$$\varkappa\frac{\partial T}{\partial z} = 0, \quad z = -\ell. \tag{11}$$

$$\rho_e V = \rho u, \quad p_e + \rho_e V^2 = p + \rho u^2, \quad \varkappa\frac{\partial T}{\partial z} = \rho_e V L - I, \; z = 0 \tag{12}$$

$$\frac{I}{I_s} = \left\{1 + \pi\left(\frac{\gamma}{2}\frac{\gamma-1}{\gamma+1}\right)^2\right]^{\frac{1}{2}} - \sqrt{\pi}\,\frac{\gamma}{2}\frac{\gamma-1}{\gamma+1}\Bigg\}^2 \tag{13}$$

$$\frac{p}{p_s} = \sqrt{\frac{T_s}{T}}\left[\left(\beta^2+\frac{1}{2}\right)e^{\beta^2}\operatorname{erfc}(\beta) - \frac{\beta}{\sqrt{\pi}}\right] + \frac{T_s}{2T}\left[1-\sqrt{\pi}\,\beta e^{\beta^2}\operatorname{erfc}(\beta)\right], \quad \beta = M\sqrt{\gamma/2}. \tag{14}$$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho u) = 0, \quad \frac{\partial S}{\partial t} + u\frac{\partial S}{\partial z} = 0, \tag{15}$$

$$\frac{\partial}{\partial t}(u-v) + u\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z}, \quad 0 < z < \ell,$$

$$p = \rho RT, \quad p_s = \rho_s R T_s = p_\beta \exp\left[12.4\left(1-\frac{T_\beta}{T_s}\right)\right] \tag{16}$$

where common notations are used. Numerical calculation of the system (11-16) is carried out with the help of iteration procedures described in /28/. Details of the calculation procedures will be published elsewhere.

Figs.1 and 2 show that switch out of the absorbed radiation intensity $I = I_0$ at $t = t_0$ results in rapid drop of the saturation pressure p_s (T_s) and the Mach number M. In contrast to /27/, however, at $I_0 = 10\ MW/cm^2$ and $t_0 = 1\ \mu s$ the Mach number does not reach zero value and begins to increase after the minimum $M_m = 0.12$ is reached at $\Delta t = t - t_0 = 48$ ns. This difference is probably due to some numerical reasons. In particular, an excessive enlargement of time step in the calculation gives rise to decreasing of M_m.

Examples of evolution of p_s and M for various step-like and smooth decreasing of the absorbed intensity are shown in Fig.3 and 4. The drop of M becomes vanishingly small at small

changes of I. If $I = I_0 = 10$ MW/m^2 drops to $I = qI_0 = 0.95I_0$ at $t_0 = 1\,\mu$s then M remains constant with an accuracy up to 10^{-4}. For $I_0 = 5$ MW/cm^2, $t_0 = 1$ and $2\,\mu$s when $p_s = 40.5$ and 70.6 bar respectively, M is constant with the same accuracy if $q = 0.8$. From Fig.4 it is also seen that the change of M is delayed with respect to decreasing of I and p_s. Fig.5 shows evolution of p_s and M induced by intensity modulation $I(t) = I_0[1 - q\sin(2\pi t/\tau)]$, $\tau = 20$ ns, imposed at the absorbed intensity $I_0 = 5$ MW/cm^2 at $t \geq t_0 = 2\,\mu$s. The Mach number deviates from unity only after an appreciable decreasing of I and $\delta M = 1 - M$ remains positive even during increasing I. Evolution of M depends strongly on modulation parameter q. At $q = 0.5$ δM is of the order of surface temperature variation $\delta T_s / T_s$ and rapidly diminishes at lower values of q, so that $\delta M < 10^{-4}$ at $q = 0.2$. In the case of Gaussian pulse $I(t) = I_0 \exp(-t^2/\tau^2)$, $\tau = 30$ ns, (Fig.6) $\delta M < 10^{-4}$ when $I_0 = 28$ MW/cm^2 and saturation pressure $p_s \leq 22$ bar. Such a behaviour of δM supports a suggestion that the Mach number can be constant in some time-dependent vaporization regimes.

The results obtained in this paper reveal a rather complicated nature of transient vaporization kinetics which is due to nonlinear properties of hydrodynamic equations. Linearized version of the vaporization problem needs an extra boundary condition at the outer edge of the Knudsen layer. For this purpose the relation M = 1 can be used though its applicability limits are not well defined. Numerical calculations show that the relation M = 1 holds for a variety of transient vaporization regimes in-

duced by time-dependent radiation intensity striking on a metal surface in vacuum.

Appendix A

At a large evaporation rate the vapor near the phase interface is not in translational equilibrium which is restored by collisions between particles in a region adjacent to the surface. This Knudsen layer region can be considered as a gasdynamic discontinuity provided a mean free path is small enough.

It is usually supposed that evaporated particles are described by a Maxwellian distribution function $n_s f_0(T_s)$ with zero mean velocity, T_s and $n_s(T_s)$ being the surface temperature and saturation concentration, while backscattered particles are described by a distribution function $\beta n f(u,T)$, which is proportional to a Maxwellian function $n f(u,T)$ with vapor concentration n, mean velocity u, and temperature T /6/. Parameters n, u, and T are expressed in terms of n_s, T_s, and β with the help of three conservation laws for mass, momentum and energy fluxes at the gasdynamic discontinuity. In this model β increases from 1 to 6.3 as u increases from zero to a sonic value /6/.

In such a treatment an exact form of nonequilibrium distribution function remains unknown. For this reason it is useful to consider other approximations which result in different expression for mass, momentum and energy fluxes on nonequilibrium vapor flow.

In ref./8/ (see also /10/) the following expressions for the fluxes are used

$$mnu = j = j_0(1-\beta) \qquad \text{(AI)}$$

$$nkT + mnU^2 = p_r = 0{,}5\,p_s(1+\beta) \tag{A2}$$

$$5\,kT + mU^2 = 2\varepsilon \tag{A3}$$

where εj is the energy flux. In equilibrium $\beta = 0$, $j = 0$, and $p_r = p_s$. In contrast to /6/ β in (AI), (A2) decreases as the evaporation rate increases. According to (AI), (A2), there is a relation between mass and momentum fluxes

$$j = 2j_0(1 - p_r/p_s) \tag{A4}$$

From (AI)-(A3) it follows a quadratic equation for U with a solution

$$U = \frac{5}{8}\frac{p_r}{j} - \left(\frac{25}{64}\frac{p_r^2}{j^2} - \frac{\varepsilon}{2m}\right)^{\frac{1}{2}} \tag{A5}$$

In (A5) $U = 0$ if $j = 0$ while maximum velocity value is given by an expression

$$U_c = \frac{5}{8}\frac{p_r}{j} = \sqrt{\frac{\varepsilon}{2m}} \tag{A6}$$

which coincides with the sound velocity $U_c = \sqrt{5kT/3m}$ in monoatomic vapor as it is seen from (A3) at $U = U_c$.

If for the sake of simplicity it is supposed that $\varepsilon = 5kT_s/2$ then eq.(A1)-(A3) give

$$U = M\sqrt{5kT/3}\,, \quad p = p_s\frac{3}{(3+5M^2)(1+g)}\,, \tag{A7}$$

$$T = \frac{3T_s}{3+M^2}\,, \quad g = \frac{p_s M\left[5kT_s(3+M^2)m\right]^{\frac{1}{2}}}{2j_0(3+5M^2)}$$

where

$$j_0 = \rho_s (2\pi R T_s)^{-\frac{1}{2}} \qquad (A8)$$

This model approach results in relatively simple expressions for gasdynamic parameters which give approximately the same numerical values as in /6/.

Appendix B

Linear response of steady-state vapor flow to the surface temperature modulation $\widetilde{T}_s \sim \exp(i\omega t)$ is described by linearized version of the system (15)

$$\frac{\partial \widetilde{\rho}}{\partial t} + u \frac{\partial \widetilde{\rho}}{\partial z} = -\rho \frac{\partial \widetilde{u}}{\partial z}, \quad \frac{\partial \widetilde{S}}{\partial t} + u \frac{\partial \widetilde{S}}{\partial z} = 0, \qquad (B1)$$

$$\frac{\partial}{\partial t}(\widetilde{u} - \widetilde{v}) + u \frac{\partial \widetilde{u}}{\partial z} = -\frac{1}{\rho} \frac{\partial \widetilde{p}}{\partial z},$$

where $\widetilde{\rho}$, $\widetilde{u}$, $\widetilde{p}$, $\widetilde{S}$ and $\widetilde{v}$ are small deviations from the corresponding steady-state values. At $u < u_c$ from (B1) it follows

$$\widetilde{p} = A p \exp(i\omega t - \lambda_1 z) = \rho u_c (\widetilde{u} + \widetilde{v}); \quad \lambda_1 = \frac{i\omega}{u + u_c} \qquad (B2)$$

Such a form of the expression for $\widetilde{p}$ corresponds to that used in /24,26/.

Instead of eq.(13,14) now it is more convenient to describe vaporization kinetics with the help of relations

$$\rho = \rho(T_s, M), \quad u = u(T_s, M) \qquad (B3)$$

which give after linearization

$$\tilde{p} = \frac{\partial p}{\partial T_s}\tilde{T}_s + \frac{\partial p}{\partial M}\tilde{M}\,; \quad \tilde{u} = \frac{\partial u}{\partial T_s}\tilde{T}_s + \frac{\partial u}{\partial M}\tilde{M} \tag{B4}$$

The same procedure gives for $\tilde{v}$

$$\tilde{v} = \frac{\partial v}{\partial T_s}\tilde{T}_s + \frac{\partial v}{\partial M}\tilde{M} \tag{B5}$$

From (B2), (B4) and (B5) it follows

$$\tilde{M}\left(u_e + \frac{\partial v}{\partial M} - \frac{1}{\rho u_e}\frac{\partial p}{\partial M}\right) = -\tilde{p}\left(\frac{\partial u}{\partial T_s} + \frac{\partial v}{\partial T_s} - \frac{1}{\rho u_e}\frac{\partial p}{\partial T_s}\right) \tag{B6}$$

Taking into account that $\tilde{v} \ll \tilde{u}$ one obtaine from (A7) and (B6) in the limit $\tilde{M} < 1 - M \ll 1$

$$\tilde{M} = \frac{\tilde{T}_s}{15\,T_s}\left(6\,\frac{T_s}{p_s}\frac{dp_s}{dT_s} - 5\right) \tag{B7}$$

Eq.(B7) means that $\tilde{M} \geq \tilde{T}_s/T_s$ because $T_s\,dp_s/p_s\,dT_s \simeq 1.0$

If the difference 1 - M becomes negative then the second term which is proportional to $\exp(i\omega t - \lambda_2 z)$ with $\lambda_2 = i\omega(u - u_e)^{-1}$ should be taken into account in (B2). Now $\tilde{p}$ and $\tilde{u}$ as well as $\tilde{M}$ and $\tilde{T}_s$ are linearly independent and an extra boundary condition is needed to determine the solution of (B1). As it is shown in this paper in some cases the relation $\tilde{M} = 0$ at M = 1 can be used for this purpose.

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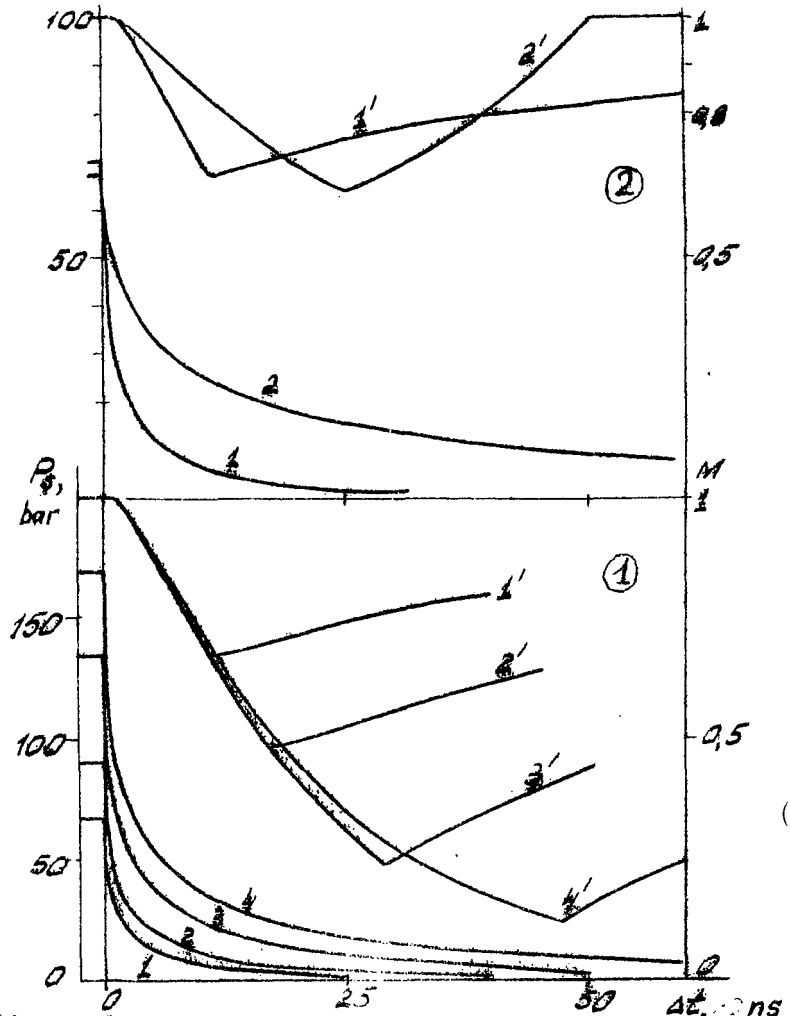

Fig.1. Evolution of p_S(1-4) and Δt(1'-4'), $\Delta t = t - t_0$, after the absorbed intensity of [illegible] MW/cm^2 is switched off at t_0 = 0.25(1), 0.3(2), 0.[illegible], [illegible] 1(4) /us.

Fig.2. I_0 = 10(1) and 5(2) MW/cm[illegible], [illegible] 5(1) and 2(2) /us.

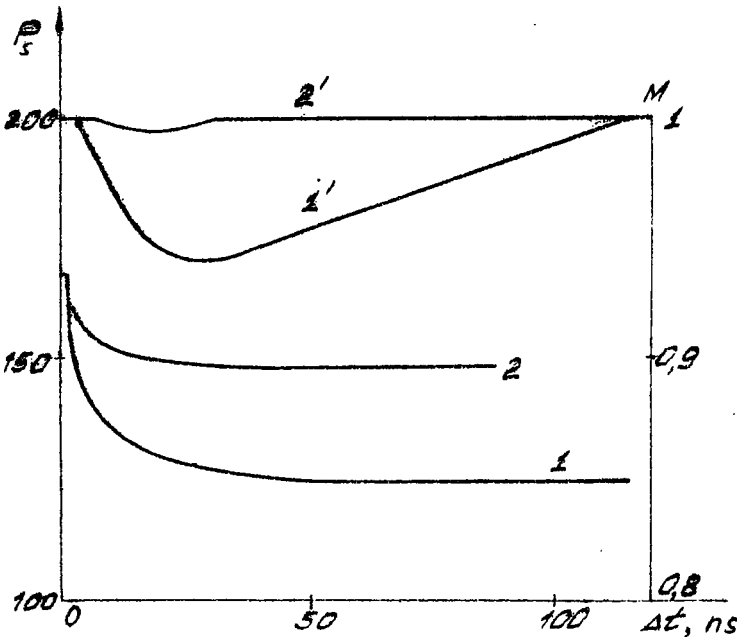

Fig.3. Evolution of $p_S(1,2)$ and $M(1',2')$, $\Delta t = t - t_o$, in the case of step-like intensity decreasing $I = qI_o$, $q = 0.8(1)$ and $0.9(2)$, $I_o = 10$ MW/cm^2, $t_o = 1$ /us.

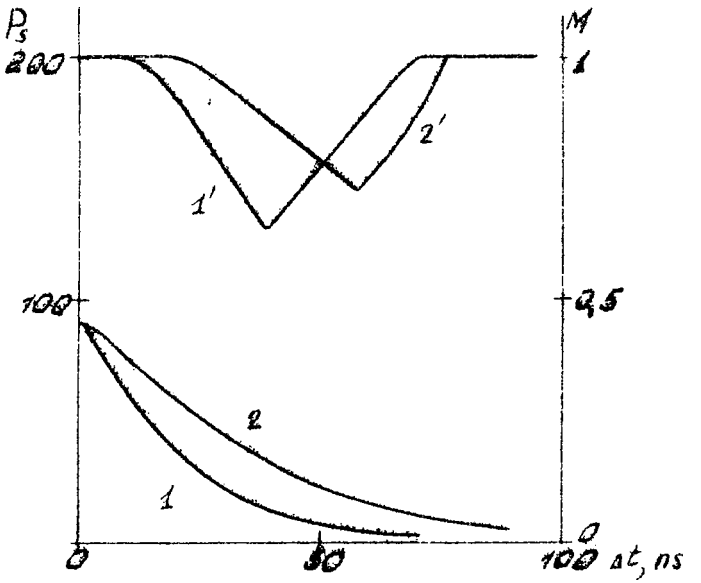

Fig.4. Evolution of $p_s(1,2)$ and $M(1',2')$ during smooth intensity decreasing $I = I_0 \exp(-\Delta t/\tau)$, $\Delta t = t - t_0$, $t_0 = 0.3$ /us, $I_0 = 10$ MW/cm^2, $\tau = 25(1)$ and $50(2)$ ns.

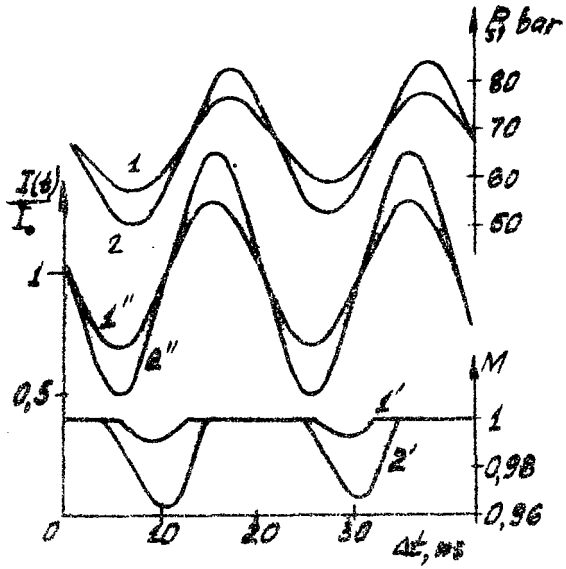

Fig.5. Evolution of $p_g(1,2)$ and $M(1',2')$ induced by intensity modulation $I/I_o = [1 - g\sin(2\pi\Delta t/\tau)](1'', 2'')$. $\Delta t = t - t_o$, $I_o = 5$ MW/cm^2, $t_o = 2$ /ns, $\tau = 20$ ns, $g = 0.3(1)$ and $0.5(2)$.

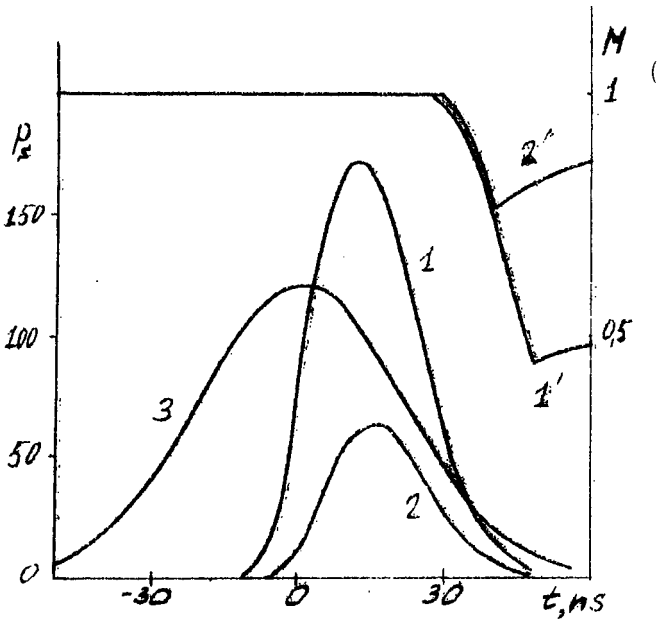

Fig.6. Evolution of $\rho_S(1,2)$ and $M(1', 2')$ induced by Gaussian intensity pulse $I/I_o = \exp(-t^2/\tau^2)$(3), τ = 30 ns, I_o = 30(1) and 25(2) MW/cm^2.