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KINETIC PROCESSES FOR HIGH-ENERGY PARTICLES OF THE LASER-PRODUCED PLASMA

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Much attention has been paid of late to the problem of interaction of some groups of high-energy particles with high-density laser fusion plasma. The first group of the particles includes high-energy nuclei and nucleons. They are the primary thermonuclear particles produced in the fusion of plasma nuclei; the secondary thermonuclear particles produced in the fusion reaction between primary thermonuclear particles and plasma nuclei; the plasma knock out nuclei produced at elastic scattering of thermonuclear neutrons. The energy of these particles is E_j = 1-20 MeV. The second group of high energy particles includes hot electrons of tens keV energy. They are generated in an evaporated part of the target "corona" as the laser absorption occurs either in the plasma resonance region (with near-critical density), or in the quarter-critical-density region, where the stimulated processes are developed.

The basic mechanism of the particle interaction with matter is the Coulomb collisions with electrons and ions of the plasma.

The energy and impulse of the thermonuclear particles and the knock out nuclei transferred to the plasma characterize the thermonuclear burning and the development of fusion. In particular, the energy transfer by primary particles and knock out nuclei turns out to be the leading mechanism for the propagation of self-sustained wave of thermonuclear burning in a nonhomogeneous plasma of spherical targets under the central initiation of the

reactions. Of great interest is just the opposite task, i.e. to investigate the characteristics of thermonuclear particles and knock out nuclei interacting with the laser target. It is necessary to determine the spectra and the output particles flowing out of the target in order to investigate possible utilizations of the microexplosion energy in various schemes of power facilities, and to develop the corpuscular diagnostics of the laser plasma.

The energy transfer by hot electrons proves to be one of the main processes of the target compression under the action of the longwave CO_2-laser emission. In this case, almost all the absorbed laser energy is transformed into the energy of fast particles. The energy transfer by hot electrons represents the basic mechanism for the heat-conductivity in the corona of CO_2-laser irradiated target. It supplies the greater part of the absorbed energy from a low-density region of the plasma resonance to the surface of the evaporated matter, with increase in the ablation pressure. On the other hand, the energy transfer by hot electrons to a compressible part of the target is another source of the enthropy which prevents the effective compression of the plasma.

In the lecture we present the theory of the kinetic processes for charged thermonuclear particles and hot electrons of the laser plasma. The theory is based on analytical solutions of the boundary kinetic problems for high-energy particles in the confined medium. We consider the application of this theory to the plasma compression and ignition problem, as well as to the plasma diagnostics.

1. Kinetic processes for thermonuclear particles and knock out nuclei.

1) General solution of the kinetic equation.

The kinetic problem for thermonuclear particles and knock out nuclei is based on the interaction of charged high-energy particles with dense laser plasma /1/. The velocities of high-energy particles are considerably higher than those of thermal ions of the plasmas. Therefore, the interaction of particles with the plasmas is considered as a stationary process, and one can neglect the particle diffusion in the energy space, by taking that at Coulomb collisions the energy is transferred only from the particles to the plasma components.

Then, in the wide temperature range up to 30 keV, the frequency of Coulomb collisions of high-energy nuclei with the electrons is considerably higher than the collision frequency with the ions. As a result, the slowing of thermonuclear particles and knock out nuclei occurs, when they interact with the plasma electrons without changing of the motion direction.

The Landau kinetic equation for the spherically-symmetric plasma derived in frames of the given approximation, has the form: /1/:

$$v_j\left(\mu\frac{\partial f_j}{\partial r}+\frac{1-\mu^2}{r}\frac{\partial f_j}{\partial \mu}\right)+\frac{\partial}{\partial v_j}a_j f_j+f_j v_j n_k\sum\sigma_{jk}=R_j \qquad (1)$$

where $f_j(r,\mu,v_j)$ is the distribution function of the high-energy particles of j-type at the point of r and $\vec{v}_j$ coordinates in the phase space; μ is the coside angle between the

particle velocity direction, $\vec{v}_j$, and the radius-vector of the particle position; R_j, the particle source which is the initial spectrum by the velocity; n_k, the density of the plasma ions of k-type; $\sigma_{jk}(v_j)$, the cross-section of the secondary thermonuclear reaction;

$a_j(v_j,r)=dv_j/dt$, the velocity of the particle slowing. For the electrons slowing we get:

$$a_j=\begin{cases}-3\pi^{1/2}(e_j e)^2 L n_e m_e^{1/2} v_j/3T_e^{3/2} m_j\,, & T_e>m_e E_{j0}/m_j\\ -2\pi(e_j e)^2 L n_e/m_j m_e v_j^2\,, & T_e<m_e E_{j0}/m_j\end{cases} \qquad (2)$$

where e and m_e are the charge and mass of the electron; L, the Coulomb logarithm; e_j, m_j, the charge and mass of the particle.

The kinetic equations for a variety of high-energy nuclei have different functional dependences of the initial spectra.

The primary thermonuclear particles have, practically, a mono-velocity initial spectrum, i.e. the ratio of the spectral width to the initial velocity of the particle, $(m_j T/m_i E_{j0})^{1/2}\ll 1$. One can, therefore, assume that /1/:

$$R_{j1}=\dot{n}_f\,\delta(v_{j1}-v_{j10}) \qquad (3)$$

where $\dot{n}_f=n_{k_1}n_{k_2}\langle\sigma_{r1}v\rangle/2$ is the number of fusion reactions per unit volume per unit time, and $\langle\sigma_{r1}v\rangle$ is the velocity of the fusion reaction averaged by the Maxwellian distribution.

In contrast to the primary particles, the secondary thermonuclear particles and knock out nuclei have the prolonged initial spectra, which are determined, respectively, by the distributions of primary particles, that is, the reagents of the secondary reaction and the thermonuclear neutrons.

For the secondary particles we have /2/:

$$R_{j2}=m_{j2}v_{j2}\int_0^{v_{j10}} f_{j1}n_k\sigma_{j1k}(v_{j1})\,F(v_{j2},v_{j1})\,d\vec{v}_{j1}\,, \tag{3}$$

where $F(v_{j2},v_{j1})$ is the probability of the secondary particle emission with the velocity v_{j2} in one interval of energies.

In frames of the single scattering of thermonuclear neutrons, we have for the knock out nuclei /3/:

$$R_{js}=\dot{n}_s(r)\,m_{js}v_{js}E_{jsm}^{-1}\,, \tag{4}$$

where $\dot{n}_s$ is the number of events of the elastic scattering of the thermonuclear neutrons on plasma nuclei per unit time, per unit plasma volume; $E_{jsm}=4A_j E_{no}(A_j+1)^{-2}$, the maximum energy of the knock out nuclei; $A_j=m_{js}/m_n$, E_{no} , the initial energy of a neutron; v_n , its velocity.

The boundary condition for the case when outer particle do not fly into the sphere:

$$S_j\Big|_{r=R,\,\mu<0}=0, \tag{5}$$

where $S_j=\int_{-1}^{1} f_j\,\mu\,d\mu$, the flow of the particles.

The solution of the kinetic problem (1,5) for the general form of the particle source, $R_j=R_j(r,\mu,v_j)$, $0\le r\le R$, $-1\le\mu\le 1$, $v_2\le v_j\le v_1$ which is the continuous func-

tion of the spatial coordinates and the particle velocity, is found from the method of characteristics. The solution is of the form /3/:

$$f(r,v_j,\mu)=|a_j^{-1}|\cdot\int_{v_d}^{v_u} R_j(r',\mu',v_j')\,dv_j'\,, \tag{6}$$

where $r'=\left[r^2+\lambda^2(v_j')-2r\lambda(v_j')\mu\right]^{1/2}$; $\mu'=\left[r\mu-\lambda(v_j')\right]r'^{-1}$;

$\lambda(v_j')=\int_{v_j'}^{v_j} v_j\,dv_j/a_j$, the length of the particle slowing from the initial velocity, v_j' , to the current velocity, v_j .

The integration limits in (6) are found from the boundary condition (5). Their values depend on the shape of the initial spectrum of particles.

a) If the initial spectrum of the particles is limited by $v_2\le v_j'\le v_1$, $v_1\ne\infty$, then for $v_2\le v_j\le v_1$ we get:

$$v_d=v_u\,;\quad v_u=\begin{cases} v_1 & \text{for}\quad \lambda_1\le l_j\,,\\ v_* & \text{for}\quad \lambda_1\ge l_j\,,\end{cases} \tag{7}$$

where v_* is found from the condition:

$$\int_{v_*}^{v_j} v_j\,dv_j\,a_j^{-1}=l_j\,,\quad l_j=r\mu+\left(R^2+r^2(\mu^2-1)\right)^{1/2},\quad \lambda_1=\int_{v_1}^{0} v_j\,dv_j\,a_j^{-1}\,,$$

for $0\le v_j\le v_2$

$$v_d=v_2\qquad v_u=\begin{cases} v_1, & \text{if}\ \ \lambda_1\le l_j\\ v_*, & \text{if}\ \ \lambda_2\le l_j\le\lambda_1\\ v_2, & \text{if}\ \ \lambda_2\ge l_j\end{cases} \tag{8}$$

where $\lambda_2 = \int_{v_2}^{0} v_j\, dv_j\, a_j^{-1}$.

b) If the initial spectrum of the particles is not limited from above, $v_2 \le v_j' \le \infty$, then always $\lambda_1 \ge \ell_j$, and in Eqs. (7) and (8), therefore, there are no first lines for the upper integration limit.

2. Energy and Pulse Transfer.

Consider the physics of these processes at the example of the homogeneous confined plasma. The efficiency of the energy and pulse transfer is determined by the plasma transparency parameter equal to the ratio of the plasma radius, R, to the length of the particle slowing , λ_j . The calculation made on the basis of the kinetic equation solution yields the following results for fractions of the energy transferred to the plasma by various particles.

The primary thermonuclear particles /1,3/

$$\eta_{j1} = \begin{cases} 3/2\ \tau_{j1} - 4/5\ \tau_{j1}^2, & \tau_{j1} = R/\lambda_{j1} \le 1/2, \\ 1 - (4\tau_{j1})^{-1} + (160\,\tau_{j1}^3)^{-1}, & \tau_{j1} \ge 1/2 \end{cases} \qquad (9)$$

the knock out nuclei

$$\eta_{j3} = \begin{cases} 2\ \tau_{j3} - 8/5\ \tau_{j3}^2 + 16/35\ \tau_{j3}^4, & \tau_{j3} = R/\lambda_{j3} \le 1/2, \\ 1 - (5\tau_{j3})^{-1} + (280\,\tau_{j3}^3)^{-1}; & \tau_{j3} \ge 1/2, \end{cases}$$

here λ_{j10} is the length of the particle slowing with the initial velocity v_{j0} ; λ_{j3} is the length of the knock out nuclei slowing occurring with the maximum velocity in the spectrum v_{jm} . For D-T plasma, the length of α -particle slowing with the initial velocity $v_{\alpha 0}$ = 1.3x10^{9}cm/s is /1/:

$$\lambda_\alpha \simeq 1.1 \cdot 10^{-1}\, T_e^{3/2} / \rho L \qquad , \text{cm}$$

where T_e is in keV, ρ in g/cm^3.

The lengths of D-T knock out nuclei slowing of the maximum velocities(3.5, 2.6)x10^{9}cm/s respectively,and the charges reduced by nearly one half, as compared to the charge of α -particle, are essentially higher than mean free path of α -particle:

$$\lambda_d = 5\,\lambda_\alpha, \quad \lambda_t = 6.2\,\lambda_\alpha$$

Figures 1 and 2 illustrate the data of the energy transfer by α -particles and the knock out nuclei for the particular parameters of the plasma. In Fig. 1 the transferred energy is normalized by the own initial energy of the particle. These data show that D-T plasma is much more transparent for the knock out nuclei than for α -particles. In Fig. 2, the transferred energy is normalized by the total amount of the thermonuclear energy released in the plasma. These dependences illustrates the comparative contribution of α -particles and the knock out nuclei into the processes of heating of the combustion regime and the energy transfer in the ambient region of the cold fuel. The latter process ~~of the thermonuclear wave propagation~~ determines, in fact, the velocity of the thermonuclear wave propagation. Note that at $\rho R \gtrsim 1$ g/cm^3, when the efficiency of neutron scattering in the plasma is high, the contribution of the energy transfer by the knock out nuclei, dueing the wave propagation, is comparable with the contribution of α -particles.

The process of the pulse transfer from thermonuclear particles and knock out nuclei to the confined plasma is anisotropic. As a result, the particles have a strong effect on the plasma. The anisotropy is the greater, the more transparent is the plasma for these particles. For example, for the homogeneous plasma with the parameter $\tau_{j1} \leq 1/2$, the value of the volume force of primary thermonuclear particles is /4/:

$$\mathcal{F} = 2^{-1} \cdot m_{j1} v_{j10} \cdot \dot{n}_f \cdot \frac{4}{3} \tau_{j1} z , \qquad z = r/R$$

and for the plasma with the thermonuclear parameters it can reach 10-20% of the hydrpdynamic pressure.

3. The Wave of the Fusion Reaction

The energy transfer by α-particles is the main heat-conductivity mechanisms which is effective in the wide range of DT-plasma parameters (0.2 g/cm^2 $\leq \rho R \leq$ 2 g/cm^2, $T \geq$ 10keV). It is of interest from the viewpoint of the fusion wave initiation. The development of the fusion reaction starting from the central initiation wave region heated up to thermonuclear temperatures, is determined by two parameters. One of them is the transparency $\tau = R/l_\alpha$. The second is the ratio of α-particle energy released within the characteristic time of the wave propagation, $\dot{R}/R$, to the thermal energy of the plasma /5/:

$$\alpha = \dot{W}_f R / \varepsilon \dot{R} ,$$

where $\dot{W}_f = \dot{n}_f E_{\alpha 0}$, $E_{\alpha 0}$ = 3.6 MeV, $\dot{R} = \left[\frac{\gamma^2 - 1}{2} \cdot C \cdot \frac{\rho_1}{\rho_{2}} T_1 \right]^{1/2}$, ρ_1 and ρ_2, the plasmadensities, respectively, in the regions of the initial initiation and the ambient matter; α, the specific heat-conductivity; T_1, the temperature of the initiation region.

The velocity of growth of the plasma mass is /5/:

$$\dot{M}/M = \left[1 - \eta(\tau) \right] \cdot \alpha \cdot \dot{R}/R ,$$

where the part of the α-particle energy in the ignition region is given by Eq. (9).

Then, from the energy equation one can easily derive:

$$\frac{\dot{T}}{T} = \frac{\dot{R}}{R} \left[\eta(\tau) \alpha - 3(\gamma - 1) \right], \quad \frac{\dot{\rho}}{\rho} = \frac{\dot{R}}{R} \left\{ \left[1 - \eta(\tau) \right] \alpha - 3 \right\} \quad (10)$$

Figure 3 illustrates the solution of the system of equations (10) in terms of the parameters α and τ. The waves with the temperature rising behind the front are plotted as the trajectories above the lines 1 -0-2. That means that the initiation needs rather high values of the parameter α. For example, for $\tau \simeq 0.5$, the energy of α-particles must be higher than the internal energy by 3.

The initiation can take place both at large and small values of τ. It is interesting to note that in both cases the parameter τ tends to the values 0.2-0.4, as the energy of α-particles is spent approximately equally for the plasma heating and the wavefront propagation.

However, at large values of $\tau \sim 1$ the initiation is optimal, because in this case lesser values of α are needed.

At T_1 = 10 keV and from $\alpha_1 > 3$ and $\tau > 0.3$ the conditions of the initiation follow /5/:

$$\rho_{10} R_{10} > 0.34 \left(\rho_{10} / \rho_{20} \right)^{1/2}, \ g/cm^2$$

which in terms of the internal energy gives:

$\mathcal{E}_{10} >$ 5.5 x $10^6 \, T_{10} \, \rho_{10}^{-2} (\rho_{10}/\rho_{20})^{3/2}$, J.

Hence at ρ_{10} = 20 g/cm^3, ρ_{10}/ρ_{20} = 1/4 and T_{10} = 10 keV, for the value of the required internal energy we get: $\mathcal{E}_{10} \sim 2 \times 10^4$ J, which corresponds to the laser energy of $\sim$ 1 MJ.

4. The laser plasma diagnostics uses dependence of the spectra and yield of thermonuclear particles and the knock out nuclei on the plasma density and temperature, due to the Coulomb slowing. Such a dependence can be illustrated by the output of secondary particles. For the transparent plasma with $\tau_{j1} = \frac{R}{\lambda_{j1}} < 1/2$ the ratio of the yield of the secondary and primary particles is, by the order of magnitude, /2/:

$$N_{j2} / N_{j1} \simeq n_K \sigma_{j1K} (E_{j10}) R$$

and depends on the plasma parameter, ρR, only. Here $\sigma_{j1K}(E_{j1K})$ is the cross-section of the secondary reaction at initial energy of a primary particle.

With decrease in the plasma transparency at $\tau_{j1} > 1$, the ratio of output is:

$$N_{j2} / N_{j1} \simeq n_K \sigma_{j1K} (E_{j1K}) \lambda_{j1} .$$

Since $\lambda_{j1} \sim T_e^{3/2}/n_K$, the ratio of output is $N_{j2}/N_{j1} \sim T_e^{3/2}$, and depend on the plasma temperature only.

II. Energy Transfer by Hot Electrons.

In contrast to high-energy nuclei, the plasma interaction of hot electrons is accompanied by strong scattering of the electrons on the ion component. The scattering of hot electrons in the plasma with high ion charge proceeds faster than their slowing. In the target corona the energy is transferred by hot electrons of the low-energy part of the spectrum with energies $E_f \leqslant$ (2-3) T_f, where T_f is the temperature of Maxwellian hot electrons. The process is stationary. With increase in the initial energy of hot electrons the time of Coulomb slowing of these particles increases as $t_d \simeq \frac{\lambda_f}{v_f} \sim E_f^{3/2}$, and can exceed the time of the target compression. Therefore, the energy transfer by hot electrons in high-energy part of the spectrum must be investigated on the basis of the nonstationary kinetic equation.

1) Energy Transfer in the Target Corona.

The process of energy transfer by hot electrons can be investigated in one-group approximation by the energy of particles. Hot electrons are generated in a narrow region of the plasma resonance. The kinetic problems can be set for these particles in the form of a homogeneous kinetic equation with the boundary conditions which describe the generation of particles and their reflection from the plasma boundaries. To get the analytical solutions one should use the approximate description of the angular part in the distribution function by the "back-and-forth" method. The particles, in this approximation, are divided into two groups, those flying in the positive ($\mu > 0$) and negative ($\mu < 0$) directions of the radius-vector. The kinetic equation is divided into two equations for the distribution functions for these groups of the particles /6/ :

$$\begin{cases} \frac{1}{2}\frac{df_+}{dr} + \frac{f_+ - f_-}{r} + \frac{f_+}{\lambda_d} + \frac{f_+ - f_-}{\lambda_s} = 0 \\ \frac{1}{2}\frac{df_-}{dr} - \frac{f_-}{\lambda_d} + \frac{f_+ - f_-}{\lambda_s} = 0 \end{cases}$$

where $\lambda_d(r) = A_i m_p E_{f0}^2 / 4\pi e^4 L z_i \rho$, $\lambda_d = \frac{2}{(1+z_i)}\lambda_s$, are respectively, the lengths of slowing and scattering of a hot electron; A_i, z_i, the atomic number and the plasma ion charge; m_p, the proton mass; e, the electron charge; $\rho(r)$, the plasma density depending on the radius.

The boundary problem has the analytical solution for the hyperbolic profile of the plasma density, $\rho(r) = \rho_c(r_c/r)$, which describes qualitatively the density distribution in the corona of the laser target. For the density of hot electrons this solution has the form:

$$n = f_+ + f_- = \frac{\dot{N}\xi(\kappa+2)\, y^{\kappa}}{4\pi r_c^2 v_{f0}}\,\delta(v_f - v_{f0}),$$

where $\kappa = \left[1 + \frac{4}{\xi}\left(1 + (1+2\ell)/\xi\right)\right]^{1/2} - 1$, $y = r/r_c$, $0 \le y \le 1$,

$$\xi = \lambda_d(r_c)/r_c\,, \quad \ell \equiv \lambda_d/\lambda_s = (1+Z_i)/2$$

and $\dot{N}$ is the power of the hot electron source.

For the distribution of the absorbed energy of hot electrons, by the plasma mass, one can easily obtain:

$$\frac{dW}{d\mu} = \frac{m_1}{\rho(r)}\int_0^{v_{f0}} n\cdot\lambda_d^{-1}E_f\, v_f\, dv_f = \xi^3\left(\frac{\kappa}{2}+1\right)\left(1-\xi^3\mu\right)^{\kappa/2},$$

where $\mu = m/m_1$, $m_1 = 2\pi\lambda_d(r_c)\rho_c$ is the characteristic scale of the corona mass; the corona mass, m, is calculated from the critical-density surface to the inside of the plasmas.

Figures 4 and 5 show the distribution of the specific energy yield by the plasma mass at different values of the parameter and the ion charge. If $\xi = \lambda_d/R_c \gg 1$ (the problem is strongly spherical) the scattering process has a small influence on the distribution of the absorbed energy which is close, in this case, to the mass-homogeneous distribution. Such a distribution is due to the fact that at $\lambda_d(r_c) \gg r_c$ the greater part of hot electrons transfers the energy to the plasma as a result of multiple passages

through the plasma region with $r < r_c$. If $\xi \le 1$ the solution is close to the limiting case of the solution in the plane approximation. For the plasma of the laser target the parameter $\xi \gg 1$. Therefore, the solution of the kinetic equations yields the important result about the homogeneous distribution of the absorbed energy in hot electrons.

2). Nonstationary Energy Transfer by Hot Electrons.

The nonstationary energy transfer by hot electrons is considered in frames of the kinetic equations in the plane approximation. We take that a source of mono- energy hot electrons of the power $\dot{N}$ is effective at the boundary of the infinite semi-space within the time t_o. The duration t_o corresponds to the time of the target compression.

To get an approximate calculation of the hot electron scattering effect we use the functional relation between the flow and density of particles in the stationary approximation (see (11)):

$$S = \left[2(1+2\ell)^{1/2}\right]^{-1} n$$

Then the nonstationary kinetic equation, in the plane approximation, has the form:

$$\frac{\partial n}{\partial t} + \frac{v_f}{2(1+2\ell)^{1/2}}\cdot\frac{\partial n}{\partial x} + \frac{\partial a_f n}{\partial v} = 0$$

Its solution in the case when $\dot{N}$=const yields for the part of energy transferred to the plasma by hot electrons within time t_o:

$$\eta = \begin{cases} 1 - \frac{3}{5}\tau_c^{-1}, & 1 \le \tau_c, \\ 1 - \frac{3}{5}\tau_c^{-1} + \frac{3}{5}\tau_c^{-1}(1-\tau_c)^{5/3}; & \tau_c \le 1 \end{cases} \tag{12}$$

where $\tau_c = t_o/t_d$, $t_d = \frac{4}{3}\frac{\lambda d}{v_f} = 7.5\cdot 10^{-3}\frac{A_i}{m_i}m_e^{1/2}\frac{\varepsilon_{f0}^{1/2}}{\rho}$, c

Figure 6 illustrates Eq(12). As the target is irradiated by CO_2-laser pulse the calculations show that for $E_{f_0} \simeq T_f$, the parameter $\tau_c \simeq (7-8)$ and η is about 90%, i.e. the process of the energy transfer, for this spectral group, can be taken stationary. But already for $E_{f_0} \simeq 3T_f$, $\tau_c \simeq 1-2$ and $\eta \simeq 40-50\%$. The hot electrons with $E_{f_0} \simeq (5-6)T_f$ transfer less than 10% of its energy to the plasma. The nonstationary energy transfer decreases significantly the efficiency of the preliminary heating of the compressible part of the target by hot electrons.

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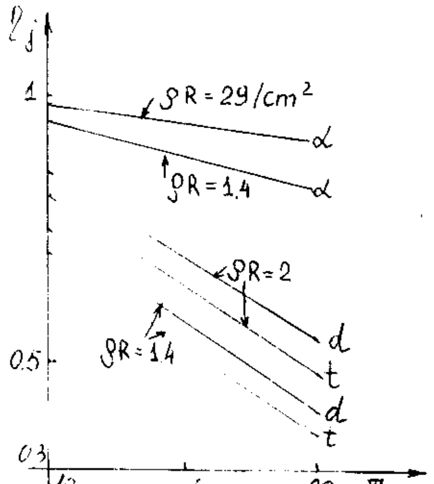


fig 1

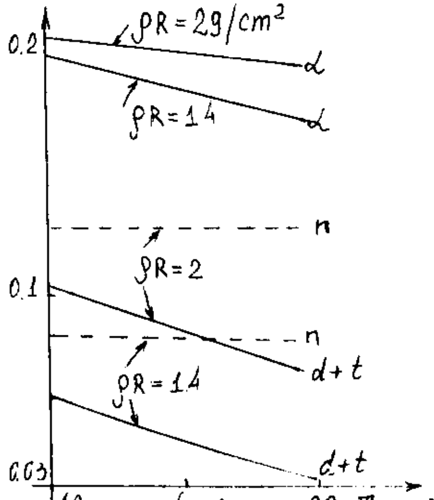


fig. 2

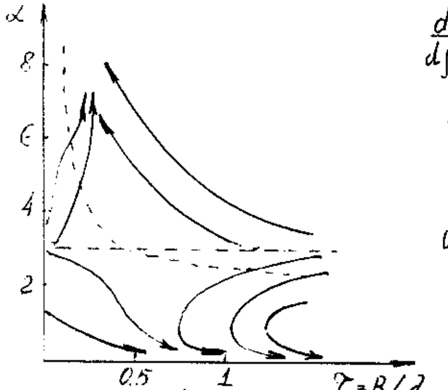
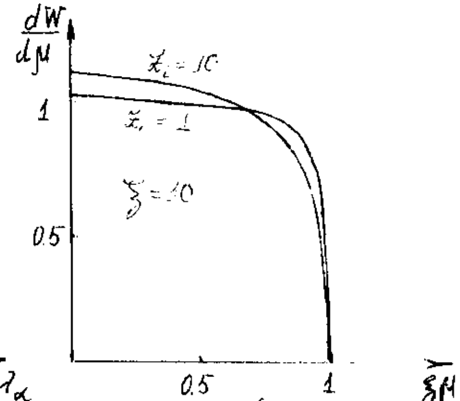


fig. 3



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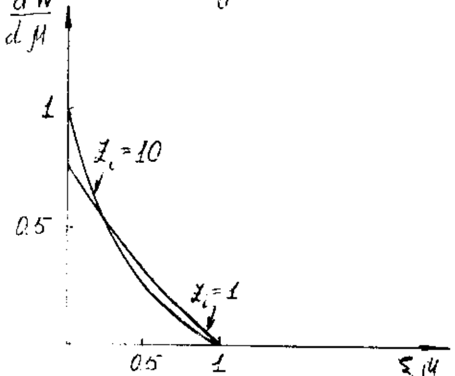

fig. 5

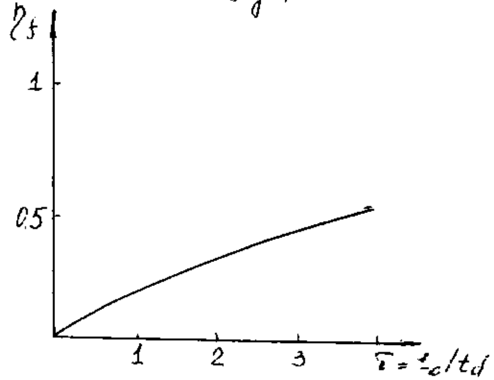

fig 6