A MODEL OF THE INTERACTION BETWEEN A POWERFUL ION BEAM AND A METALLIC ABSORBING MATERIAL

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The development of acceleration technology and the specifics of ions interacting with materials have expanded the range of scientific and practical problems whose solution is related to the utilization of powerful ion beams (PIB): research in the field of material science and nuclear physics [1], work on thermonuclear synthesis [2, 3], problems in the generation of powerful electromagnetic radiation [4], etc. The physical foundation on which each of these cases is based involves the correct description of the dynamics of the PIB system, namely the absorbing material.

The action of an ion beam with a power density of $>10^{12}$ W/m^2 on metal is accompanied by the simultaneous occurrence of several competing processes of energy redistribution [5]. The basic mechanisms of PIB energy relaxation include the hydrodynamic, heat-conducting, and radiant. The qualitative behavior and quantitative understanding of these processes is governed both by the PIB parameters and the characteristics of the irradiated material. The substantial energy released by the ions in small spatial intervals (10-20 μm) within short periods of time (30-60 nsec) complicates the instrumental experimental study of the dynamics of one of the channels of beam energy redistribution simultaneous with and subsequent to the interaction event. In numerical experiments all of the energy relaxation mechanisms are taken into consideration selectively and their analysis presents no particular difficulty. The quality of the results depends on the completeness with which these processes have been described.

In the present study we propose a model for the interaction between the PIB and the absorbing material, we offer a mathematical formulation of the problem, we have developed an algorithm and a solution program, and we present computational results. Unlike existing methods (see the review in [6]) we take into consideration the parameters of the beam which affect the interaction process: the presence of impurity ions, spatial nonuniformity, and the extent to which the energy and current density are dependent on time. Material thermodynamic parameters are derived from broadly based equations of state. The model is based on a two-dimensional hydrodynamic approximation which includes the mechanisms of electron and radiant heat conduction. We present results from a calculation of the action of a powerful proton-carbon beam on aluminum foil. The bicomponent composition of the ions and the space–time nonuniformity of the beam current density qualitatively defines, in contrast to existing concepts, the behavior of the forming gas-plasma subsystem.

1. The Model and the Computational Algorithm. The process of decelerating the beam ions in the area near the surface of the absorbing material is accompanied by release of energy and high-speed heating. The fields of resulting pressures and temperatures are characterized by pronounced nonuniformities and correspondingly high gradients. The pressure difference generates a shock wave that is propagated into the target, and a plasma cloud is formed at the irradiated surface. The dimensions of the beam thermalization area depend both on the energy and type of ions, as well as on the parameters of the irradiated material. For the duration of the current pulse the stopping power of the plasma flare corresponds to a high rate of evolution, which affects the deceleration process. When we deal with a multicomponent beam the ions exhibit various capacities of penetration, which leads to a separation of spatial energy localization. In the case of proton-carbon beam the carbon component is virtually totally decelerated in the region of the plasma flare and leads to an increase in the quantity of energy lost through radiation. The presence of current density nonuniformity is accompanied by the appearance of radial components in the parameters of motion for the irradiated barrier.

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In the calculations conducted in [6, 7] and in the experiment from [8] it was established that with an ion beam power density of $\sim 10^{13}$ W/m^2 and higher the pressure in the surface area amounted to $\sim 10^{11}$ Pa, the temperature $\sim 10^5$-10^6 K, and the speed with which the plasma flare spread out was $\sim 10^4$-10^5 m/sec. In order to describe the dynamics of interaction by means of these system parameters we can make use of the hydrodynamic model in which the energy dissipation channels for the impinging ions are appropriately taken into consideration. In its most general form the formulation of the problem is accomplished in the two-fluid, two-temperature approximation. Such an expanded system of equations is complete, but virtually insoluble in dealing with such large spatial intervals as ~0.01-0.02 m and time intervals $\sim 10^{-7}$-10^{-6} sec. With regard to the description of the medium by means of the above-examined parameters it is possible to introduce into the model a series of simplifications which yield insignificant error in the final result: 1) the Debye radius of shielding in the plasma under consideration is smaller than the mean free path of the electrons, and the behavior of the medium, with a high degree of accuracy, is therefore described in the one-fluid approximation; the characteristic interval time of hydrodynamics is considerably greater than the time required to establish equilibrium between the electron and ion temperatures, thus making it possible to use the single-temperature model.

The system formed by the PIB and the absorbing material exhibits axial symmetry, and the hydrodynamic equations for the Euler variables in a cylindrical system of coordinates have the form [9]

$$\partial\rho/\partial t + \operatorname{div}(\rho\mathbf{W}) = 0,\ \partial\rho u/\partial t + \operatorname{div}(\rho u\mathbf{W}) + \partial P/\partial z = 0,$$
$$\partial\rho v/\partial t + \operatorname{div}(\rho v\mathbf{W}) + \partial P/\partial r = 0,$$
$$\partial\rho E/\partial t + \operatorname{div}(\mathbf{W}(\rho E + P)) + Q_{\text{rad}} - \operatorname{div}(\varkappa \operatorname{grad} T) = Q,$$

where r is the radial coordinate; ρ is the density of the material; P is the pressure; $\mathbf{W}$ is the vector for the velocity, with the components (v, 0, u); $E = \varepsilon + \mathbf{W}^2/2$ represents the total energy per unit mass, while ε represent the internal energy per unit mass; T is the temperature; $\varkappa = \varkappa_e(\rho, T) + \varkappa_r(\rho, T)$ is the coefficient of thermal conductivity (the sum of the electron and radiant conductivities); Q_{rad} is the loss of power to radiation; Q is a function which describes the release of energy by the PIB.

When we take into consideration the specifics of the problem (the material of the target may simultaneously be in the solid, liquid, and gaseous state) to close the hydrodynamic equations we use the broad-ranged equations of state [10, 11], determining $P = P(\rho, \varepsilon)$ and $T = T(\rho, E)$ over a large interval of changes in density and energy.

The mechanisms of ion deceleration change in proportion to the number of layers through which they pass, these layers found to be in various thermodynamic states. The stopping power of the absorbing materials is a function of the substance parameters and of the impinging ions:

$$\frac{1}{\rho}\frac{dE}{dx} = S_{be} + S_{fe} + S_{nu} + S_{fi}$$

[S_{be} (S_{fe}) represent deceleration at the bound (free) electrons and S_{nu} (S_{fi}) represent deceleration at the nuclei (ions) of the medium]. For an ion energy of $\geq$0.1 MeV the predominant contribution is made by scattering at the electron subsystem S_{be} and S_{fe}, and the deceleration of the ion is described in classical Bethe theory. With energies lower than 0.1 eV the Bethe model is not used correctly, the deceleration at the nuclear and ion components of the materials is increased, and for purposes of determining the efficiency of deceleration it becomes necessary to employ the Linhardt model. The methods of calculation currently at hand are based either on the Bethe theory which involves the introduction of correction terms for low energies, or on the unified Bethe–Linhardt model. We have undertaken a series of calculations involving use of both the former and the latter methods. Analysis of the results showed that with regard to the hydrodynamic calculations explicit consideration of the nuclear S_{nu} and ion S_{fi} components exerts no significant influence on the energy-release function and for purposes of describing ion deceleration it is sufficient to account for scattering at the electron component with implicit correction for the nuclear subsystem. For the purposes of this determination we make use of the analytic expression proposed by Mehlgorn [12], which is an expansion of the classical Bethe theory:

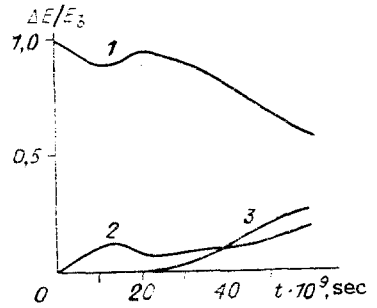

Fig. 1

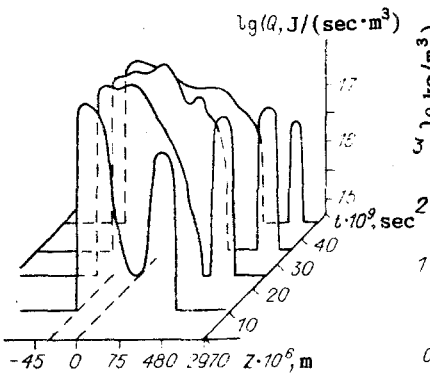

Fig. 2

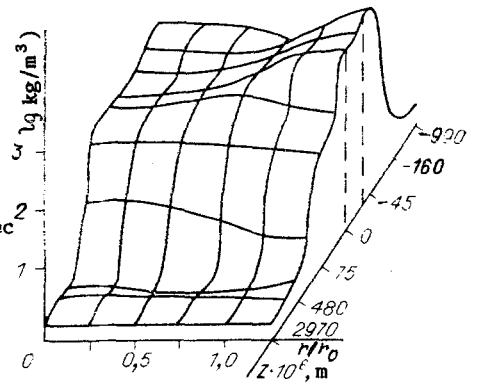

Fig. 3

$$\frac{1}{\rho}\frac{dE}{dx} = 143\frac{A_1 Z_1^2 Z_2}{E A_2}\left[\frac{Z_2 - \bar{Z}_2}{Z_2}\ln\bar{\Lambda}_b + \frac{\bar{Z}_2}{Z_2}\ln\Lambda_f\right],$$

where Z_1 (Z_2) and A_1 (A_2) represent the charge and atomic weight of the beam ions (of the absorbing material); E is the energy of the ions; $\bar{Z}_2$ is the average level of absorbent ionization; Λ_f ($\bar{\Lambda}_b$) is the Coulomb logarithm of free (bound, when ionization is taken into consideration) electrons. The results from the calculation of the energy release and the mean free path of the ion, obtained through these expressions, are in agreement with the results of the methods employed in [13, 14], including, explicitly, the scattering at the nuclear and ion components.

The redistribution of energy by the mechanism of heat conduction is dealt with in quasi-uniform approximation [15]. The transfer coefficients have been found on the basis of logarithmic interpolation of tabulated data [16].

The loss of energy to radiation from the dense hot plasma becomes substantial at temperatures above $5\cdot10^5$-10^6 K and is defined by the optical characteristics of the substance. The radiation of an optically thin plasma is three-dimensional in nature, while for an optically thick material the radiation emanates only out of the peripheral layers which have limited optical thickness. Taking into consideration the energy redistributed by radiation is accomplished for the optically thick region by solving the equation of radiant heat conduction, while for an optically thin region the solution is achieved in approximation of three-dimensional luminescence. Multigroup calculations of radiative transfer for an aluminum plasma [14] demonstrated that the radiative intensity of the spectral lines is insignificant. Therefore, the integral line-radiating capabilities of the substance are utilized in the model for the continuous spectrum [17].

Numerical integration of the system of hydrodynamic equations is accomplished by the large-particle method [18] with approximation of the second order of accuracy in terms of the spatial variables and with approximation of the first order of accuracy with respect to time. Depending on the geometry of the system the condition of "occurrence" or "nonoccurrence" are modeled in the fictitious boundary cells [18]. A stable complete count with a disrupted coefficient of thermal conductivity is carried out in accordance with an implicit uniform difference scheme [19]. To obtain the volumetric profile of PIB energy release in

the absorbing substance we make use of a nonuniform Euler grid in which the interval of the spatial variables is increased as the distance from the surface of the absorbent is increased.

The described algorithm enables us to obtain information regarding the dynamics of the PIB-absorbent system: the fields of hydrodynamic variables **W**, ρ, E; the thermophysical characteristics of the irradiated substance T, P, κ, $\bar{Z}$ representing the multiplicity of ionization, $\bar{I}$ denoting the averaging ionization potential; the profiles of ion energy release Q as a function of the space–time and mass characteristics of the beam; the radiative capacity of the plasma subsystem.

The proposed model thus makes it possible to interpret the experimentally integrated results and to obtain quantitative parameters for the individual PIB energy redistribution channels in the material.

2. Calculation Results. The acceleration systems currently at hand, such as KALIF [20], REIDEN [7], PBFA-1 [3], TONUS, VERA [21], and ones analogous to these, generate ion beams lasting for 30-100 nsec with a power density from 10^{11} to $3\cdot10^{16}$ W/m^2. The PIB produced by each of these accelerators exhibit characteristic features. By means of a model we have carried out calculations for various beams with densities of 10^{11} to $2\cdot10^{17}$ W/m^2.

As an example, let us present the results obtained in computing a PIB with a power density of $1.5\cdot10^{15}$ W/m^2 as it interacts with aluminum foil having a thickness of 21 μm (greater by a factor of 1.5 than the mean-free path of a proton with an energy of 1 MeV in cold aluminum). The beam parameters are as follows: the composition is 50% H^+, 50% C^+; the pulse duration is 50 nsec; the current density increases from 0 to $1.5\cdot10^5$ kA/m^2 within the first 20 nsec, it remains constant over the next 20 nsec and at 50 nsec it drops off to zero; the distribution of the current density over the radius is Gaussian in form, $I(r) = I_0 \exp - (r/r_0)^2$ (I_0 denotes the density of the current at the axis of symmetry, r_0 = 0.01 m is the effective radius of the beam); the energy of the carbon protons and ions is 1 MeV. The PIB energy reserve amounts to 1.23 kJ.

Figure 1 shows the integral characteristics of the interaction process and all of the quantities [1 (2) which represents the change in internal (kinetic) energy of the irradiated substance and 3, which represents the loss of energy to radiation] have been normalized to the instantaneous energy value E_b, lost by the beam as it interacts with the absorbing material. Initially the entire energy of the beam relaxes to the internal energy of the target, and there is a high-speed heating of the surface layers. Within 10 nsec after the onset of the interaction an intense plasma formation develops at the irradiated surface, and the kinetic energy of the system increases. However, this increase in the loss of beam energy in the region of the plasma flare (Fig. 2, the profiles of energy release at the axis of symmetry at various instants of time) leads to a reduction in the energy transmitted to the less heated areas of the absorbing material. This results in a reduction in the kinetic energy of the foil as the potential energy increases in the time interval from 1 to 20 nsec (curve 2, Fig. 1). The significant degree of substance ionization in the plasma flare and the corresponding increase in the stopping power lead to a rise in the PIB energy losses and to a loss of energy to radiation. The presence of two beam components exerts significant influence on the dynamics of the system being simulated. The carbon fraction, which has a smaller mean free mass path, initiates the formation of a high-ionized region in front of the main foil mass. This area, as it moves in the direction toward the beam, functions in the role of a unique additional shield to reduce the energy supplied by the PIB to the internal regions of the foil. The carbon fraction of the beam is completely absorbed in this region, and the flow of energy to the "cold" portion of the foil is achieved exclusively with protons. Figure 3 shows the absorbent density profile at the instant of 35 nsec. The main removal of mass from the area initially occupied by the foil occurs at the rear and in a radial direction. At the instant at which the ion current pulse comes to a halt, the redistribution of the PIB energy over the various channels is characterized by the following: 60% relaxes to the internal energy of the substance, 20% is converted into kinetic energy and 20% is removed from the system by radiation. The pressure following the end of the radiation pulse in the area occupied by the material changes in the interval from 10^6 to $1.5\cdot10^{10}$ Pa, which is in agreement with the data of [7].

Satisfactory agreement with the computational results of other authors [13, 14] and the integral experimental results from [7] confirms the adequacy of the proposed model realistically to describe the processes taking place within the PIB-absorbent system. Correct

consideration of the energy and space–time parameters of the beam made it possible to establish the characteristic features of PIB interaction with the substance (the absence of a Bragg peak for the beam, the effect of "dual" shielding of the absorbent by the plasma cloud) and to refine the characteristic of hydrodynamic motion.

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