EMISSION OF A PLASMA FORMED BY THE ACTION OF A PULSE OF FAST PARTICLES ON A FOIL IN A VACUUM

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Vaporization of a barrier develops when it interacts with a powerful flux of laser radiation or a stream of fast particles. A dense and hot plasma forms which itself radiates intensely. The parameters of such a plasma and the characteristics of the radiation emitted by it during the action of powerful energy fluxes on an aluminum barrier in a vacuum were determined earlier for the case of laser radiation [1] and a proton beam [2]. In both cases a range of energy flux densities on the order of 0.1-10 GW/cm^2 was examined for pulses of microsecond duration. It was shown that modes of interaction can also occur when the energy supplied from outside is converted not only into thermal and kinetic energy of the vapors dispersing with a high velocity but also to a considerable extent into thermal emission of the plasma, emitted into the vacuum toward the incident laser radiation or particle beam. The interest in this phenomenon is connected with the fact that sufficiently powerful plasma emission, lying in the vacuum ultraviolet and even the soft x-ray region, can be used for various scientific and technological purposes, particularly to diagnose the parameters of the plasma and determine its coefficient of absorption, the ability of particles to penetrate the plasma, etc.

The problem of the influence of emission on the gas-dynamic processes, the plasma parameters, and the characteristics of the developing radiation pulse for the case of fast particles is analyzed here not through approximate estimates, as in [2], but through a direct solution of the corresponding one-dimensional, plane, nonsteady, radiative-gas-dynamic problem, as for the case of a laser in [1]. In contrast to [1], detailed allowance for the spectral composition of the emission is made here.

The use and analysis of the characteristics of a pulse of radiation emitted in the direction from which the flux of laser radiation or particles falls does not always prove suitable. Therefore, below we analyze the case of action on a foil, the thickness of which is chosen so that part of the radiation emerges beyond the foil, i.e., in the direction of propagation of the beam.

We specifically examined the interaction of a proton pulse with an aluminum barrier in a vacuum, the proton energy was varied in the range from 100 keV to 1 MeV, and the energy flux density was constant with time and equal to 1-10 GW/cm^2. With pulses lasting 0.1-1 μsec and an irradiated spot with a size on the order of 1-3 cm the dispersion of the vapors takes place under conditions close to a plane geometry. Electrostatic effects were ignored, assuming that the proton beam is neutralized by electrons, i.e., we essentially consider the action of a cluster of quasi-neutral hydrogen plasma on the barrier, not in a purely hydrodynamic approximation but with allowance for the penetration of fast particles into the target material and the vapors.

In [2] the mass penetrating power of fast particles was chosen on the basis of experimental data obtained for cold unionized target material. Here we allow for energy losses of a fast particle not only on bound electrons of the plasma [3] but also on free electrons [4, 5]. Since considerable plasma temperatures are reached in the interaction under consideration (on the order of 10 eV), at which the plasma is ionized, this considerably alters the proton range.

In calculating the transfer of radiation created in the hot plasma we used detailed tables of the spectral coefficients of absorption of aluminum vapor [6], found for a wide range of plasma temperatures and densities with allowance for braking absorption, the photoeffect from the ground and excited states of atoms and ions, and absorption and emission in lines. The tables of [6] were compiled on a nonuniform scale of quantum energies, allowing for the

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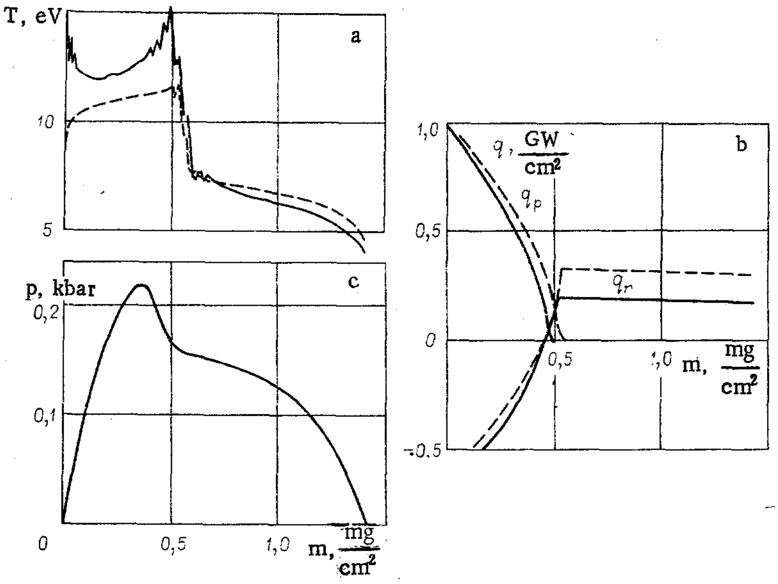

Fig. 1

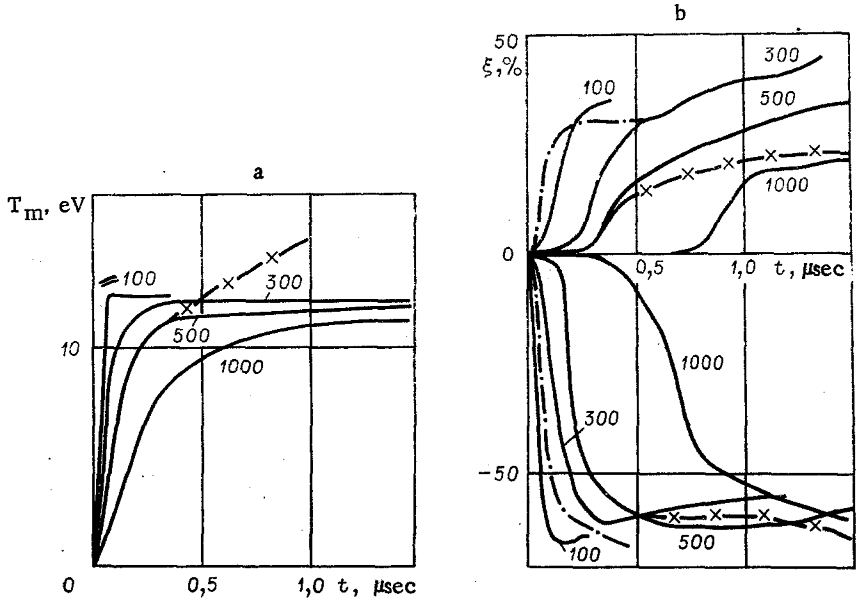

Fig. 2

character of the variation of the coefficients of absorption with frequency. Since the form of the emission spectrum was not known in advance, the radiation transfer was analyzed for all 1000 spectral intervals of the table of [6].

The averaging method of [7] was used to reduce the volume of calculations. The average coefficients of absorption were determined using the "true" emission spectra found through the solution of the spectral transfer equation. The integration was carried out over 11 groups with the following limits: 0...4...5...11...17...25...38...47...75...95...150 eV. The spectral radiative—gas-dynamic problem was also solved by the less laborious method of multigroup approximation. For this we used group coefficients of absorption calculated from the same tables of [6] but with averaging over a Planckian spectrum.

The thickness of the foil was chosen as equal to the proton range in the solid material. For initial proton energies ε_0 = 100, 300, 500, and 1000 keV the mass penetrating power was 0.288, 0.862, 1.53, and 3.94 mg/cm², respectively, and the foil thickness was 1.1, 3.2, 5.7, and 14 μm. In the process of action the thickness of the layer of expanding vapors exceeded the initial foil thickness by several orders of magnitude. The process of vaporization occurs at the very start of action of the pulse, and the energy expenditures on vaporization are negligibly small compared with the energy expenditures on heating and moving the vapors.

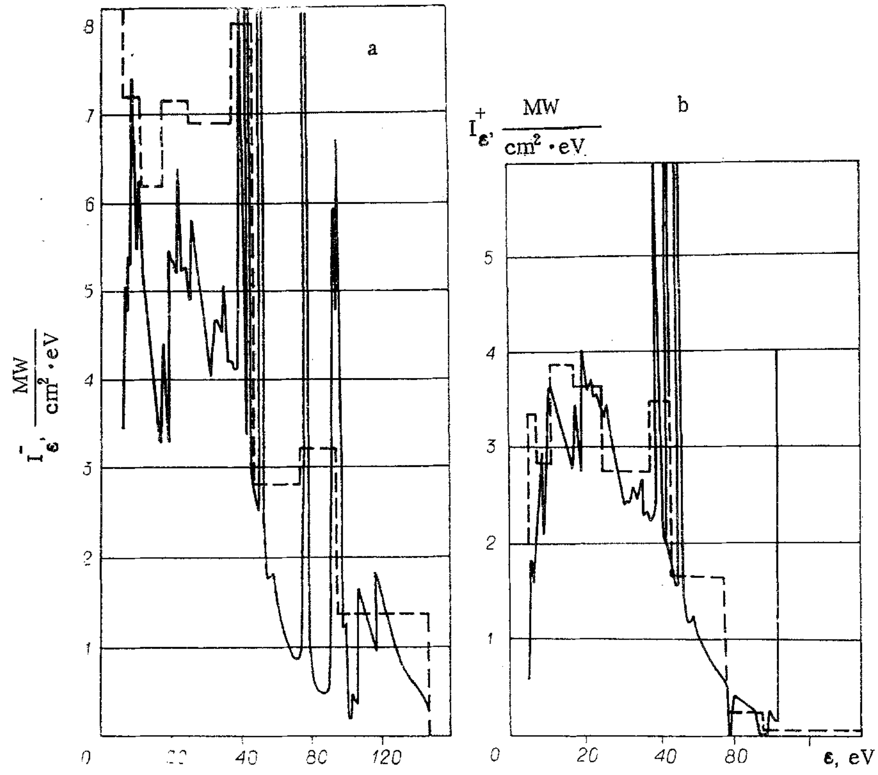

Fig. 3

The results of a calculation for the case of ε_0 = 500 keV and an energy flux density q = 1 GW/cm^2 are presented in Fig. 1. The results of a solution of the problem with detailed allowance for the spectrum are given by solid curves while the results of a solution in the multigroup approximation are given by dashed curves. Here T is the plasma temperature (Fig. 1a), q_p and q_r are the energy flux densities of the proton beam and of the self-emission of the plasma (see Fig. 1b), and p is the plasma pressure (Fig. 1c) at the time of 1 μsec. The protons heat only about one third of the entire mass of the foil. Thus, the decrease in the particles' penetrating power due to ionization of the vapors is quite pronounced. The remaining mass of the foil is heated by the radiation emitted by the hot plasma. About 60% of the proton beam energy is emitted back toward the incident particles and about 17% is emitted forward along the direction of incidence. In the region of m > 0.5 mg/cm^2, not heated by the protons, the flux of radiation passing through is practically constant with respect to mass because of the quasi-steadiness of the process.

As follows from a comparison of the results of solutions of the problem using the spectral and multigroup transfer equations, the difference in the plasma temperature in the hot region heated by protons does not exceed 30%, and it is far less in the relatively cool layer heated by plasma emission. At the same time, the difference in the self-emission fluxes, conversely, is small in the hot region and considerable in the cool layer (it reaches 1.8 times). Despite these differences, the solution of the multigroup problem is in qualitative agreement with the solution of the spectral problem and can be used in mass calculations to obtain quantitative estimates not pretending to a high accuracy.

In Fig. 2 we show the variation with time t of the maximum plasma temperature T_m and the fraction $\xi^{\pm} = q_r^{\pm}/q$ of emission in the direction of incidence (positive values of q_r and ξ) and toward the beam (negative values of q_r and ξ). The solid lines are the result of a solution of the multigroup problem for q = 1 GW/cm^2 and the value of ε_0 given near the corresponding curves and the dash-dot line is the result for q = 10 GW/cm^2 with ε_0 = 500 keV, in which case the maximum temperature reaches $T_m \approx 20$ eV by the time t = 0.4 μsec. The stabilization of the maximum temperature is connected with the important role of emission. The average degree of ionization in the vapor is stabilized accordingly, and with it the penetrating power of the protons, which proves to be two to four times lower than in the cold unionized material. As is seen, the back emission reaches 50-60% and the forward emission 20-30%. The values obtained with detailed allowance for the spectral composition of the radiation for $q = 1\ GW/cm^2$ and $\varepsilon_0 = 500$ keV are given with crosses. The forward emission is somewhat lower in this case than in the multigroup approximation. The maximum temperature grows with time. This growth pertains only to the region of the narrow temperature peak at the boundary with the vacuum, however, whereas the average temperature almost ceases to vary with time owing to the emission.

In Fig. 3 we show the spectrum, more precisely, the intensity $I_{\varepsilon}^{\pm}$, of the radiation emitted backward (Fig. 3a) and forward (Fig. 3b), indices − and +, respectively, for the case of $q = 1\ GW/cm^2$ and $\varepsilon_0 = 500$ keV at t = 1 μsec. The result of the calculation for the multigroup approximation is given by dashed lines. The spectrum differs considerably from a Planckian spectrum, and broadened and overlapping lines play an important role in it. In the region of photon energies of up to 40-50 eV the "backward" and "forward" spectra are qualitatively similar, only the radiation intensity of the first is about 1.5 times higher than that of the second. The contribution of quanta with energies up to 150 eV is noticeable for the radiation emitted backward, while such quanta are practically absent from the spectrum of radiation emitted forward. This is connected with the filtering role of the "heated" layer, which has a temperature of 5-7 eV.

With an increase in the radiation flux density the plasma temperature increases and the plasma emission spectrum becomes harder. It can be regulated not only by the parameters of the particle pulse but also by the thickness of the foil and by the optical and thermodynamic properties of its material at the temperatures reached in the process of action. Naturally, an analogous phenomenon of emission of radiation in both directions relative to a thin foil can also occur with the incidence on it not of protons but of other particles such as electrons or laser radiation.

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