In the case of a resonance on the first harmonic this phenomenon was noted in Ref. 2 for waves which propagate along an external magnetic field.

We note that the coordinated change of the quantities $k_z v_z$ and ω_B has made it possible earlier to consider the problem of autoresonant particle acceleration in a vacuum ($N_z = 1$) in the field of a circularly polarized wave.[16,17]

It follows from Ref. 12 that a nonrelativistic beam interacts most effectively with potential oscillations of a plasma in the case of transverse propagation ($k_{z0} \ll k_{x0}$). The results of Ref. 12 can be obtained from Eqs. (4.9) in the limit $k_{z0} \ll k_{x0}$, $\omega_0 \ll k_0 c$ (cf. the inequality (3.4a)).

In conclusion the authors express their gratitude to K. N. Stepanov for discussions of the results of this paper.

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Influence of a plasma on the interaction of laser radiation with a metal

B. M. Zhiryakov, N. I. Popov, and A. A. Samokhin

P. N. Lebedev Physics Institute, Academy of Sciences of the USSR, Moscow
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An investigation was made of the behavior of a plasma jet and recoil pressure during the action of quasicontinuous millisecond pulses from a neodymium laser on the surface of lead in air. Instability of the laser-beam maintenance of a plasma in the stream of the evaporated target materails was observed near the radiation intensity $I \approx 2$ MW/cm^2. The plasma appearance threshold was less than the intensity needed to maintain it continuously. The plasma jet instability was manifested by periodic detachment of the jet from the target surface and accompanied by oscillations of the recoil pressure $p(t)$. Characteristics of the behavior of $p(t)$ indicated that the effective optical thickness of the jet was $\sigma \lesssim 1$.

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1. Experimental and theoretical investigations of high-temperature characteristics of metals are difficult to carry out. Estimates indicate[1,2] that, for the majority of metals, the critical parameters T_c and p_c lie in the range of temperatures and pressures which are practically inaccessible under static experimental conditions. The use of laser radiation is one of the promising methods of maintaining and investigating high-temperature states of metals but the basic potentialities of this method have not yet been put into practice. However, before this is done, it is necessary to know the relative importance of the various physical properties which occur in the region of interaction of strong radiation with a metal.

Intense evaporation of a metal under the action of laser radiation in air is usually accompanied by the appearance of a plasma jet above the target surface.

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Much work has been done on various aspects of this phenomenon (see, for example, Refs. 3–14 and the literature cited there). The appearance of an absorbing plasma layer alters the interaction between the radiation and the target metal compared with the case of transparent vapors and even the sign of the resultant changes is not always clear *a priori* because there is competition between some of the processes occurring in the interaction zone.

Absorption by a plasma reduces the intensity of the laser radiation reaching the metal surface. For this reason, we find that under quasistatic conditions, other conditions being equal, the temperature of the metal surface T_0 and the recoil pressure p are less than in the case of transparent vapors. On the other hand, the temperature of a plasma jet is considerably greater than T_0 and additional energy and momentum may be transferred from the plasma to the metal. Such transfer may be the result of the emission of radiation by the plasma itself or of changes in the external gasdynamic situation due to the absorption above the target surface.

Evaporation from the target surface may stop completely after the formation of a strongly absorbing plasma cloud. In the intensity range $I \lesssim 10$ MW/cm², this may occur at elevated ambient gas pressures[4,5] or when far infrared radiation is used.[6] However, the appearance of a quasistatic strongly absorbing plasma layer near the target surface[9] is unlikely when near infrared radiation is used at atmospheric pressure in the ambient medium.[10] The influence of plasma emission on the process of evaporation of a metal by optical radiation has again been stressed recently[11] but the question of an increase in the energy flux to the target on formation of a plasma requires further study.

We investigated the behavior of a plasma jet and recoil pressure experienced by a lead partition irradiated in air by quasicontinuous millisecond pulses generated by a neodymium laser at a wavelength $\lambda = 1.06\ \mu$. The recoil pressure during a laser pulse was measured for the first time under the adopted conditions. When the radiation intensity was $I \approx 2$ MW/cm², fluctuations of the recoil pressure were recorded and these were due to instability in the process of laser maintenance of the plasma jet in the flux of evaporated metal. A characteristic feature of this fluctuation regime was the relatively weak absorption of the incident radiation in the plasma. The instability of a plasma jet associated with strong absorption of laser radiation during a "flash" from an initially transparent vapor[12] was found experimentally earlier,[4,6] when a metal interacted with radiation of wavelengths $\lambda = 1.06$ and $10.6\ \mu$, but the time dependence of the recoil pressure $p(t)$ was hardly investigated. However, the information on $p(t)$ is essential for an adequate description of the processes occurring in the irradiation zone. The features of $p(t)$ reported below demonstrate, in particular, that strong absorption is not a necessary condition for instability of a plasma jet resulting in its detachment from the target surface.

2. We employed a laser emitting quasicontinuous millisecond pulses with fairly smooth envelopes and of energy $E \approx 60$ J. In addition to the controlled time structure of the radiation, our spherical-resonator laser ensured[3] a very homogeneous distribution of the radiation intensity. Laser radiation was focused on the surface of lead into a spot, $d \approx 0.15$ cm in diameter, by means of an $f = 4$ cm lens. Radiation emitted from a plasma jet above the target surface was recorded with an image converter camera operated in the streak scanning mode.

The recoil pressure was measured with a lead zirconate-titanate (PZT) piezoelectric ceramic transducer (diameter $d_0 = 0.5$ cm and thickness $h_0 = 0.2$ cm), which was used as a voltage source with an RC constant of $\tau = 2.5$ msec. The constant-current regime, usually employed in recording pressures created by shorter laser pulses,[13,14] was unacceptable because of the restricted recording time. The transducer was placed on a massive base below a cylindrical anvil ($d_1 = d_0$, $h_1 = 1$ cm) on which a lead target, 0.2 cm thick, was placed. The transducer was calibrated directly by mechanical impact in which a known amount of momentum was transferred. The sensitivity of the transducer determined in this way was found to be $F_U = 1.65 \times 10^6$ dyn/V.

In the system described above, the quantity recorded directly was the recoil force

$$F = \int p\, dS.$$

In the case of a homogeneous distribution of the radiation intensity in a spot of area $S = \pi d^2/4$, the pressure was given by $p = F/S$. In our case, the distribution of the radiation intensity in the radiation zone was nearly rectangular, indicated—in particular—by the profiles of the craters formed on the target surface. We thus investigated an evaporation process whose characteristics depended little on the spatial distribution of the intensity in the interaction zone.

3. Figure 1 shows oscillograms of laser pulses and transducer signals together with the corresponding the streak patterns of the plasma jet. The thickness of the trace representing the photomultiplier signal was due to slight modulation of the radiation intensity with time. At the same scanning rate but in the spike regime, such smearing was equal to the photomultiplier signal amplitude and the signal from the transducer was also smeared out but the transducer did react to microsecond spikes, as shown in Fig. 2 (the time constant τ represented the distortion of the signal in the low-frequency range $\nu\tau \lesssim 1$).

Under the adopted conditions, there were brief flashes of plasma radiation even when the intensity was $I = 1.6$ MW/cm². When this intensity was $I = 2$ MW/cm² (Fig. 1a), the plasma radiation was observed throughout the major part of a laser pulse. However, at these laser radiation intensities, the plasma jet was not maintained continuously and it became detached many times from the target surface. A further increase in

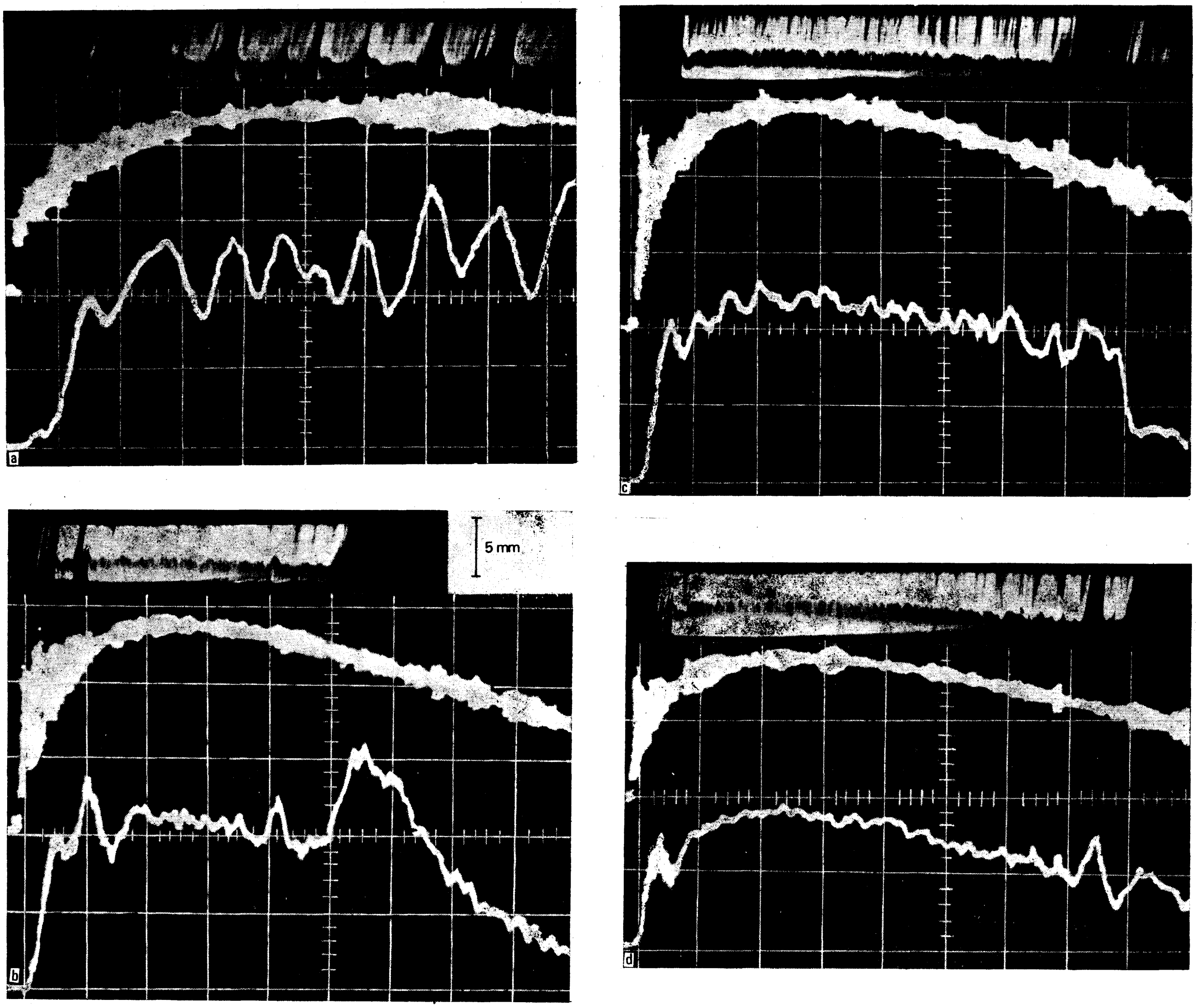

FIG. 1. Recoil force (lowest traces, plotted on a scale of 0.05 V/div. in cases a–c and 0.1 V/div. in case d), laser pulse envelope (upper trace) and plasma radiation (streak patterns at top of figure) obtained for different values of the incident radiation power N_{max} (kW): a) 36; b) 40; c) 43; d) 53. Horizontal scales: 50 μsec/div. (a) and 100 μsec/div. (b–d). The spatial scale of the streak patterns is shown Fig. 1b.

the laser radiation intensity stabilized the jet, with the exception of the end of a laser pulse (Figs. 1b-1d).

The transducer signal was relatively smooth in the intensity range $I < 1.6$ MW/cm², where intense evaporation without a plasma jet was observed (Fig. 3a). Similar behavior was also recorded at high intensities, $I > 2$ MW/cm², when the plasma jet was basically stabilized (Fig. 3b). In the plasma instability region, the transducer signal exhibited characteristic fluctuations correlated with the behavior of the plasma jet (compare Fig. 1a with Figs. 3c and 3d). The recoil pressure reached its maximum value during the periods of detachment of the jet from the target surface and began to fall at the moment the next flash was received by this surface.

This behavior of the recoil pressure demonstrates specifically that, under the adopted conditions, the appearance of a plasma reduces the intensity of the radiation absorbed by the metal surface. We recall that, in the case of static intense evaporation, the recoil pressure is approximately proportional to the intensity I_0 of the radiation absorbed by the target surface:

$$p=0.5p_c \exp[(1-T_c/T_0)\varepsilon_1/kT_c]=(0.5\pi mkT_0)^{1/2}(\varepsilon_1+c_1T_0)^{-1}I_0, \quad (1)$$

where $\varepsilon_1 = 3.3\times 10^{-19}$ J and $c_1 = 4.3\times 10^{-23}$ J/°K represent the heat of evaporation and the specific heat of lead per particle; $T_c = 5\times 10^3$ °K; $p_c = 2$ kbar; m is the mass of the evaporated particles. For lead, we have $T_0 = (2.6\text{-}3)\times 10^3$ °K in the range $p = 10\text{-}40$ kbar. If allowance is made for the slowness of the change in T_0 in this interval, we find that surface integration of Eq. (1) gives the relationship between the recoil force F and the absorbed power N_0:

$$F\approx bN_0, \quad b\approx 3.3\cdot 10^{-4}\ \text{sec/m}, \quad (2)$$

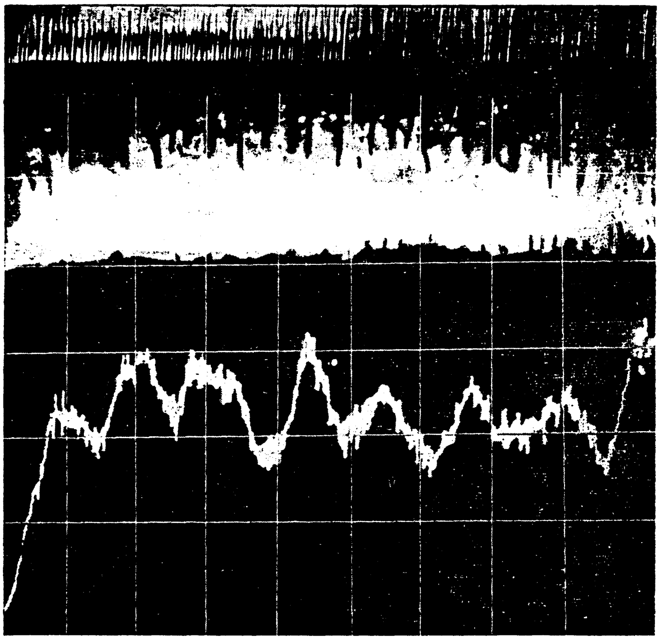

FIG. 2. Recoil force (lower trace, 0.05 V/div.), laser pulse envelope (upper trace), and streak pattern (top of figure) of a plasma jet obtained in the spike regime with $E\approx 48$ J. Horizontal scale: 50 μsec/div.

which no longer depends on the distribution of the intensity and recoil pressure over the area of the irradiated spot.

If the reflectivity R of the target surface does not change greatly during a flash, the relative fall in the transducer signal represents directly the effective screening influence of the plasma jet. The maximum relative fall in the recoil force $\eta = F_{max}/F_{min} \approx 1.6$ during the initial parts of the oscillograms in Figs. 1a and 1b corresponds to an effective optical thickness of the plasma jet $\delta = \ln\eta \approx 0.47$. In some cases, "dense" screening with $\delta \lesssim 1$ is observed.

The behavior of $F(t)$ also shows that, during a given flash, the optical thickness of the jet does not remain constant. It is clear from Fig. 1a that the absorption reaches its maximum value after 20 μsec from the appearance of the flash and then begins to fall. This

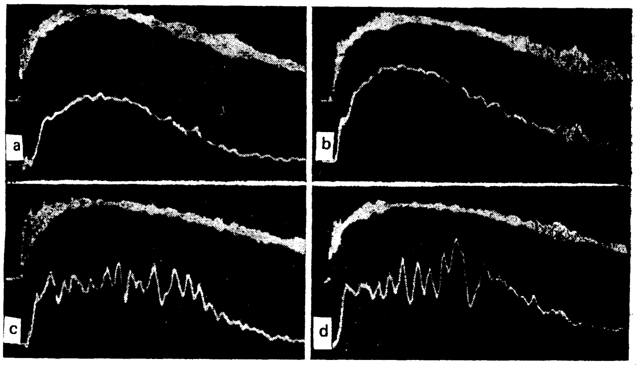

FIG. 3. Recoil force (0.02 V/div. in case **a**, 0.1 V/div. in case **b**, and 0.05 V/div. in cases **c** and **d**) recorded for different incident radiation intensities I (MW/cm^2): **a**) 1.1; **b**) 4.1; **c**), **d**) 2. Horizontal scale: 100 μsec/div.

increase in the jet transparency is terminated by its detachment from the target surface and quenching. In Fig. 1c, the gradual increase in the jet transparency before its quenching is manifested by the fact that the recoil force decreases more slowly than the envelope of a laser pulse. In this situation, the detachment of the plasma jet from the target is not accompanied by significant changes in $F(t)$.

The detachment of the jet from the target surface can also occur without a preliminary gradual reduction in its optical thickness. An increase in the recoil force, shown in the oscillograms in Figs. 1b and 1d after the disappearance of the plasma, demonstrates considerable absorption in the jet before its detachment. This is observed fairly regularly during the second half of the laser pulse. This behavior of the jet is clearly associated with the presence of liquid phase drops in the flux of the evaporated material. The streak patterns in Figs. 1b and 1d demonstrate that the quenching of the jet occurs approximately at the moment when droplet tracks intersect a static shock wave located at a distance $l \lesssim 0.5$ cm from the target surface. In this case, the direct reason for the quenching of the jet may be the perturbation of the thermodynamic and optical parameters of the plasma when a liquid droplet penetrates the hot zone of the shock wave.

The position of the shock wave relative to the target surface is governed by several factors. When a gas at an initial pressure p_1 enters a medium at a lower pressure $p_0 < p_1$ through an aperture of diameter d, the value of l is given by

$$p_1/p_0 = a(l/d)^2, \quad (3)$$

where, in the range of conditions of interest to us, the constant is $a \approx 2.2$. It follows from the experimental results that Eq. (3) is satisfied by gases with different specific-heat ratios γ and is independent of the process of condensation during the expansion of a gas stream.[15]

A specific feature of our case is the presence of a plasma jet which absorbs laser radiation. In comparison with the results obtained, it is convenient to write Eq. (3) in the form which contains only the directly measurable quantities F_1 and l:

$$F_1 = 0.25\pi a l^2 p_0. \quad (4)$$

The quantity F_1, found from Eq. (4) using the experimental value of l and $p_0 = 1$ bar, is approximately 1.5 times less than the recoil force F measured by the piezoelectric transducer. For example, the recoil force maximum of $F = 3\times 10^5$ dyn in Fig. 1d corresponds to the location of the shock wave at a distance $l = 0.35$ cm from the surface, which, substituted in Eq. (4), gives $F_1 = 2.1\times 10^5$ dyn.

This discrepancy may be due to the absorption of laser radiation in the hot zone of the shock wave, which effectively increases the counterpressure p_0 and correspondingly reduces l. This explanation is supported also by the observation that, in the unstable jet regime, the value of l changes more strongly at the moment of appearance of a plasma than deduced from Eq. (4) by substituting p_0 = const and the experimentally observed reduction in the transducer signal (Fig. 1a).

The velocity of liquid droplets in the flux of the evaporated metal is essentially subsonic. The vertical component of this velocity, deduced from the streak patterns in Figs. 1b and 1d, is $v \approx 6$-8 m/sec. These droplets appear after a delay of $\Delta t = 300$ μsec relative to the beginning of the laser pulse and are not accompanied by any special features in the behavior of $F(t)$. The value of Δt, which considerably exceeds the time needed to establish steady-state intense evaporation under the adopted conditions is clearly determined by the process of formation of a crater on the irradiated surface.

The absence of significant changes in the behavior of $F(t)$ after the appearance of the liquid phase in the erosion product also demonstrates the slight effect of the condensed phase on the screening of the target from the laser radiation. One must bear in mind that the scattering and absorption of light by a condensed phase of the erosion products may, nevertheless, play the dominant role in the attenuation of probe radiation.[10] Without allowance for this effect, the determination of the optical density of a plasma jet from the attenuation of a probe beam may result in grossly overestimated values. This is illustrated by the streak pattern in Fig. 1c, which shows the path of a relatively slowly moving liquid phase layer ($v \approx 1$ m/sec), screening completely the plasma jet radiation near the target surface.

According to the thermal model of the interaction of strong radiation with a metal,[3] the main mechanism of the liquid-gas phase transition in the irradiation zone is the thermal evaporation process. In this case, the maximum ratio of the recoil force F to the instantaneously absorbed power N_0 has an upper limit of b. Figure 4 shows the dependence of the ratio F/N on the incident radiation power N. The value of F/N should clearly be less than b because of the screening and reflection of the incident radiation by the metal surface. In the range of existence of a stable jet, these quantities differ by a factor of 5-6, i.e., $(1-R)/\eta \approx 0.17$–0.2. In the range under discussion, the value of F/N is slightly greater than the specific recoil force pulse $J/E \approx 4$ dyn/W reported earlier,[16] which may be due to the difference between the instantaneous and average (during a pulse) characteristics of the process.

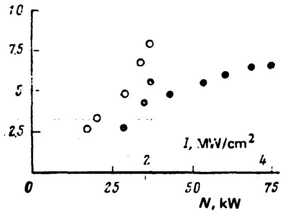

FIG. 4. Dependence of the ratio F/N on the incident radiation power in the presence (●) and absence (○) of a plasma.

The reduction in N from the maximum (in the present case) value of 75 kW to 36 kW is accompanied by a monotonic fall in the ratio F/N. For $N \approx 36$ kW, when the plasma jet is unstable, the ratio F/N assumes various values, depending on the presence or absence of a plasma. At lower intensities, when plasma does not appear at all, the recoil pressure begins to fall rapidly on reduction in N. The reason for this fall is the motion of a liquid metal in the irradiation zone, which is ignored in the thermal model framework. We shall not discuss this point in detail but note that the motion of the liquid phase may be the specific physical process which governs, under the conditions of "one-dimensional" approximation, the limit of validity of the thermal model and the threshold of intense evaporation.

4. The results obtained in the present investigations demonstrate that, in the investigated range of laser radiation intensities, the behavior of the recoil pressure is not in conflict with the surface evaporation mechanism adopted in the thermal model.[3] The observed behavior is evidence, in particular, of the relative stability of the metastable state of the overheated liquid metal in the irradiation zone. Fluctuations of the pressure occurring at $I \approx 2$ MW/cm^2 are due to the instability of the plasma jet, whose appearance is less than the intensity needed to maintain continuously a plasma in the flux of the evaporated target material.

The observed plasma jet instability is characterized by relatively weak absorption of laser radiation in the plasma. This distinguishes it from an absorption flash,[12] which is accompanied by strong screening of the illuminated surface and complete stoppage of the evaporation process. In our case, the pressure p falls, on the average, by a factor of less than two on the appearance of a plasma, whereas the stoppage of evaporation should have resulted in the fall of p to zero.

In studies of the processes occurring in the condensed phase, the appearance of a plasma is generally regarded as a "secondary" effect complicating the picture of the interaction between the incident radiation and matter. In such situations, it is desirable to ensure stable behavior of the plasma or, better still, prevent its appearance. In the case of interaction with laser radiation, an increase in the plasma appearance threshold is favored by placing a metal target in vacuum and by the use of short-wavelength optical radiation, characterized by a considerable increase in the absorptivity of metals. One should also note that strong absorption in the erosion plasma can be used to create a counterpressure in the flux of the evaporated substance, i.e., to alter in a controlled manner the degree of departure from equilibrium during the liquid metal-vapor phase transition.

We shall conclude by stressing that the measurements of the recoil pressure under intense evaporation conditions are of interest for reasons other than plasma effects. As mentioned earlier, at low radiation intensities, the behavior of the recoil pressure exhibits a feature which does not fit the thermal model and clearly indicates the appearance of multidimensional motion of the liquid metal in the irradiation zone. On increase in the absorbed intensity up to $I_0 \approx 10$ MW/cm^2, the temperature of the overheated liquid lead in the irradiation zone approaches the spinodal, where the state of the metastable phase becomes absolutely unstable. Measurements of the recoil pressure under such conditions can give new information on the behavior of the metastable state of the overheated metal in the near-critical region. Information on the rate of "decay" of the metastable phase is essential, particularly in the interpretation of experiments on the evaporation of shock-compressed metals.[17] When laser radiation acts on condensed matter, metastable states may only appear when the recoil pressure in the irradiation zone does not exceed a certain critical value p_c. This can be used to determine the critical pressure of metals.

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Structure of tails produced under the action of perturbations on solitons

V. I. Karpman and E. M. Maslov

Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation, USSR Academy of Sciences

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The asymptotic structure of "tails" produced by perturbations acting on solitons and also the evolution of the solitons themselves are studied by a perturbation theory based on the inverse scattering method. A detailed analytic description of the structure of the tail during the first stage of its formation (short times) is presented. A qualitative picture of the tail structure is given for sufficiently long times after switching on the perturbation. In particular, it is shown that the part of the tail adjoining the soliton has the shape of a plateau at both short and long times. The condition that the perturbation operator must satisfy if tail formation is not to occur is derived. Soliton deformation induced by a perturbation is studied in first order.

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1. INTRODUCTION

It has been shown previously[1] that one of the results of the action of a continuously operating perturbation (for example, dissipation) on a soliton is the formation of a "tail"—a wave packet of small amplitude—following the soliton; the length of the tail increases with time. The detailed description of the structure and dynamics of formation of such tails is generally rather complicated. The method developed in Ref. 1 contained an element of averaging at some stage, as a result of which an "averaged" tail was obtained. The contribution of such an averaged tail to the momentum, energy, and other quantities that are conserved in the absence of the perturbation is equal to the contribution of the real tail, as has been pointed out.[1] Thus, from the point

