ELECTROMAGNETIC FIELD ORIGINATING DURING METAL EVAPORATION AT A LASER FOCUS

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The effectiveness of investigations in the plasma physics is determined to a signficant extent by the variety and reliability of the diagnostic methods utilized. One of the main methods is recording of plasma electromagnetic radiation in the frequency range from the x radiation to the microwave radiation bands. Broadening of the frequency range yields additional information about a plasma and permits increasing the confidence in the results obtained earlier.

Results of recording the electromagnetic signal in the radio frequency band (1 MHz-1kHz) generated by the plasma, and produced during the concentration of a powerful ($\sim 10^5$ W) light pulse on a metal target are described below and discussed.

1. A neodymium pulsed laser of the type GOS-301 operating in the free generation mode was used in the experiments. The total energy per pulse of ~ 1 msec duration reached 150 J. Steel plates of 2.5-cm diameter and 0.5-cm thickness were used as targets. The light was focused on the target by a beam perpendicular to the axis by a lens with the focal length 10 cm. Measurements were performed by using a dipole antenna with a 5-cm arm length connected to the differential input of an oscilloscope. The antenna was parallel to the laser beam at 5-10 cm from the target and the beam. In order to check the light flux, part of it was deflected by a plane-parallel plate to a FÉK-09 device from which the signal went to the second ray of the oscilloscope. Operation of the supply circuit and ignition of the laser pumping lamp were accompanied by intense electromagnetic interference. Special noise countermeasures were undertaken during the experiments (double shielding of the cables and the working space in which the plasma was produced and the field was measured, selection of the grounding sites and of the apparatus, etc.). These measure permitted a 50-60 dB reduction in the noise level. Nevertheless, a setting produced by the pumping lamp ignition pulse was recorded in the experiment. The sufficiently stable interference mode (it was recorded on an oscillogram obtained during sparkover of the laser beam (Fig. 1)) permits it to be isolated on the working oscillograms, of which an illustration is presented in Fig. 2 (the arrow in Figs. 1 and 2 denotes the time of the beginning of laser operation, the sweep is 200 μsec/div, and the sensitivity is 1 mV/div).

An electromagnetic signal is a sign-varying pulse with a characteristic time scale $t_p \sim 20$-50 μsec (subsequent field variations are longer: they are characterized by the time scale ~ 200-500 μsec). The pulse amplitude is 200-500 μV, which corresponds to a field intensity of $E_p \sim 50$-100 μV/cm. A considerably higher frequency noise is superimposed on this signal, whose amplitude grows in the time $t_n \sim 100$-200 μsec (this same time also characterizes the subsequent drop in the noise amplitude). While the radiation field pulse is a sufficiently stable signal being duplicated under invariant test conditions, the noise amplitude can vary significantly. Examples of two oscillograms, obtained under invariant test conditions, are presented in Fig. 2 and on which a considerable difference in the noise amplitude is recorded (steel target).

2. A number of hypotheses can be made relative to the physical phenomena assocaited with any feature of the signal being generated. Firstly, simple estimates show that metal evaporation should start practically simultaneously (in the sweep scales) with the laser emission. Actually, the energy flux density q of the laser beam focused on the target surface is directly related to the temperature gradient T (along the x axis): $q \sim -\varkappa T/x$. The depth X of the heated metal layer increases with the time t as $X \sim (\varkappa t/c\rho)^{1/2}$ [1] ($\varkappa$ is the coefficient of heat conduction, c and ρ are the specific heat and the density of the target material). Therefore, the temperature on the target surface grows at the initial times according to the law

$$T \sim q(t/c\rho\varkappa)^{1/2}.$$

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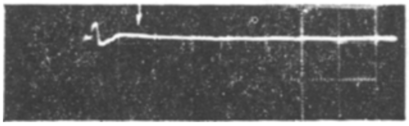

Fig. 1

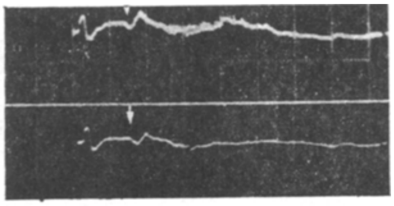

Fig. 2

Metal evaporation starts at those times t_b when the surface temperature reaches the boiling point. Taking the parameter values [2] $c = 5 \cdot 10^2$ J/kg · deg, $\rho = 8 \cdot 10^3$ kg/m^3, $\varkappa = 70$ J/sec · m · deg, $T_b = 3 \cdot 10^3$°K for the steel target as well as the energy flux density $q = 6 \cdot 10^{11}$ J/sec · m^2, we obtain that evaporation starts $t_b = 10^{-8}$ sec after the beginning of the laser radiation.

One of the above-mentioned hypotheses about the nature of the electromagnetic signal is the assumption that the pulse observed in synchronism with the beginning of laser radiation is a quadrupole field formed by charges separated because of kinetic effects on the front of the dispersing metal vapor, and charges induced on the surface of the metal target. The magnitude of the electric field due to this effect can be estimated on the basis of the following considerations.

Let charge separation occur on the front of the dispersing vapor, then the electron pressure p ($p = nkT$, where n is the electron density and T their temperature) is equalized by the polarization field E_0 which exists within a double charge layer with surface density Σ

$$p = E_0\Sigma = 4\pi\Sigma^2, \quad \Sigma = (p/4\pi)^{1/2} = (nkT/4\pi)^{1/2}.$$

The thickness L of the double layer on the front can be determined from the balance conditions for the thermal energy and the charge separation energy at the front of the dispersing metal vapor: since $eE_0L = kT$, then $L = (kT/4\pi ne^2)^{1/2}$. As is seen, this quantity agrees with the Debye radius in the plasma [3].

The total dipole moment D of the double layer on the front of vapor dispersing at a distance R

$$D \sim \Sigma LR^2 \sim kTR^2/e$$

together with the charges induced on the metal target surface, produces a field E_p outside the dispersing metal layer which agrees with the quadrupole field

$$Q \sim DR \sim kTV/e,$$

where R is the dimension of the dispersing vapor, and V is their volume. Therefore, the amplitude E_p of the electric field generated can be estimated at the distance r from the relationship

$$E_p \sim kTV/er^4.$$

According to this formula, the magnitude of the electric field outside the system of polarization charges can be expressed in terms of the total thermal energy W of the metal vapor and the density N

$$E_p \sim W/eNr^4,$$

which permits a specific estimate. For instance, by giving the quantity $W = 150$ J and $N = 10^{26}$ m^{-3}, we obtain the value $E_p = 100$ μV/cm at the distance $r = 5 \cdot 10^{-2}$ m. A potential difference of 500 μV, which corresponds approximately to the amplitude of the signals actually observed, should be recorded in such a field with the 5 cm long arms of the antenna actually used in the experiments. This circumstance might be a confirmation of the hypothesis expressed about the nature of a pulse synchronized with the beginning of laser radiation.

3. Having related the regular pulse to processes accompanying vapor dispersion, it is natural to explain such features of the time dependence of the field as the noisy signal component by the features of vapor dispersion, the flow turbulization. Agreement between the estimates of certain quantitative turbulent vapor dispersion characteristics and the observed electromagnetic noise characteristics indicates this. For instance, it can be assumed that vapor turbulization occurs during the passage of the isotropic dispersion from the metal surface at the initial times to the mode of jet escape from the crater formed at the target after evaporation of the metal. Let us estimate the time of the change in modes. The rate u at which the crater depth grows is estimated by the ratio between the radiant energy flux density q and the sum of the energies needed to heat the target to the boiling point T_b and the evaporation energy θ

$$u \sim q/\rho(cT_b + \theta)$$

The time t during which the crater depth is commensurate with its diameter d (in order of magnitude coincident with the diameter of the focused laser beam, at the initial times in every case) will be the desired time for the change of modes. Substituting the quantitative characteristics of the metal ($\rho = 8 \cdot 10^3$ kg/m^3, $c = 5 \cdot 10^2$ J kg · deg, $T_b = 3 \cdot 10^3$°K, $\theta = 6 \cdot 10^6$ J/kg) and of the laser beam ($q = 6 \cdot 10^{11}$ J/sec · m^2, $d = 5 \cdot 10^{-4}$ m) in the relationship $t \sim d/u$, we obtain the value $t \sim 50$ µsec, which agrees, in order of magnitude with the observed time t_V for the amplitude of the noisy signal component to grow. It should also be noted that the turbulent efflux of the vapor is characterized by the same frequencies as the observed noisy electromagnetic signal component. Let us show this. As is known (see, e.g., [4]) a continuous energy flux ε due to the motion with external scale l to small pulsations with the internal scale l_0 exists in a turbulent flow. The velocity v of the large pulsations with scale l agree approximately with the velocity of metal vapor escape. Therefore, the minimal frequency of the turbulent pulsations is $f_{min} \sim v l$. The maximum frequency of the turbulent pulsations is l_0. The maximal frequency of the turbulent pulsations is determined by the vapor motion in the domain of inner scales l_0 with the characteristic velocity v_0, i.e., $f_{max} \sim v_0/l_0$. For small scales the main flow parameters l_0 and v_0 depend on the energy flux ε and the gas coefficient of viscosity ν: $l_0 \sim (\nu^3/\varepsilon)^{1/4}$, $v_0 \sim (\varepsilon\nu)^{1/4}$ (see, e.g., [4]). Therefore

$$f_{\max} \sim v_0/l_0 \sim (\varepsilon/\nu)^{1/2} \sim v/l(vl/\nu)^{1/2} \sim (\mathrm{Re})^{1/2} f_{\min},$$

where $\mathrm{Re}\,(\mathrm{Re} \equiv vl/\nu)$ is the Reynolds number. Let us estimate the magnitude of the Reynolds number for the flow under consideration. Expressing the coefficient of viscosity ν in terms of the sound speed a and the molecule mean free path λ in the metal vapor $\nu \sim a\lambda$ and setting $a \sim v$, we obtain $\mathrm{Re} \sim l/\lambda$. The mean free path in a plasma heated to the temperature T_V is $\lambda \sim 1/\sigma N \sim (4\pi\varepsilon_0 k T_V)^2/Ne^4$ (where $\sigma \sim (e^2/4\pi\varepsilon_0 k T_V)^2$ is the Coulomb collision cross section, see [3], for instance). Therefore the Reynolds number is expressed in terms of the metal vapor concentration N, the temperature T_V, and the characteristic dimension p of the jet flow:

$$\mathrm{Re} \sim e^4 N l/(4\pi\varepsilon_0 k T_V)^2.$$

Since $T_V \sim W/kNR^3$, then by setting $W = 150$ J, $N = 10^{26}$ m^{-3}, $l = R = 10^{-2}$ m, we obtain $T_V = 10^5$°K. The value $\mathrm{Re} \sim 10$ corresponds to such a vapor temperature. This means that the flow of metal vapor is essentially turbulent. Under the assumption $v \sim a$ for $T_V = 10^5$°K, we obtain $v \sim 10^3$ m sec. Assuming the external pulsation scale l to be on the order of the size of the dispersing vapor cloud 10^{-2} m, we obtain $f_{min} \sim 10^2$ kg. Hence, $f_{max} \sim \sim \sqrt{\mathrm{Re}}\, f_{min} \sim 10$ kHz. Therefore, the interval of the turbulence frequency spectrum in the metal vapor cloud overlaps the spectrum of the radio frequency band studied in this paper.

4. The assumption was expressed above that turbulence occurs because of the formation of a jet flow in the metal vapors. Direct observations of the dispersing vapor cloud structure can be an indirect confirmation of the reality of the proposed mechanism to generate the high-frequency noise present in the electromagnetic signal. The appearance of jet flows was observed in [5] in an investigation of the interaction between laser radiation and a plasma corona during beam focusing on the metal surface. It was noted in x-ray photographs of the plasma corona that the quite definite hemisphericity of the vapor cloud was spoiled in a significant part of the cases, and the formation of jets of elevated luminance occurred. Moreover, the intrinsic electromagnetic field of the explosion domain of a high explosive was investigated in [6]. The recorded signal is a field pulsation in which the characteristic frequency varies with time from low to higher frequencies. Photographs of the explosion products, obtained simultaneously with the measurement of the electromagnetic field in [7], permitted the disclosure of a cellular structure of the front of the dispersing products, which is possibly associated with the turbulence of the flow behind the front. It should be noted that a change in the pulsation frequency f_{max} and f_{min} permits determination of the Reynolds number in the plasma corona, i.e., it can be the basis of an express method of determining the nature of the hydrodynamic flows in the corona. Such a method could turn out to be useful in investigating the problem of corona stability, which is one of the central problems on the road to laser thermonuclear fusion [8].

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DYNAMICS OF A SOLID MICROPARTICLE IN A PULSED LASER RADIATION FIELD

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The propagation of intense optical radiation in a medium containing a solid aerosol causes a number of thermal effects resulting in a change in the energetics and structures of the optical beam. Thus, turbidization of a medium containing solid microinclusions (soot conglomerates of the dimension $\sim(2\text{-}5)\ 10^{-4}$ cm) which increase with the increase in the power flux of the active radiation, has been detected in [1]. The authors of [1] assume that the main reason for the turbidization is the destruction of the soot conglomerates, however, the fractionation process itself was not investigated in detail.

The purpose of this paper is to study the dynamics of a single act of soot conglomerate destruction in a field of intense laser radiation and the investigation of certain characteristics of this process.

Experiments on the action of an intense laser pulse on individual aerosol particles were performed on the apparatus whose block diagram is shown in Fig. 1. Neodymium–glass laser radiation 1 of the type GOS-1001, with up to 10^3 J energy operating in the free generation mode with the pulse duration $\sim(1\text{-}1.9)\ 10^{-3}$ sec and the wavelength $\lambda = 1.06\ \mu$m was used as the active source. The powerful radiation was focused by the lens 2 with the focal length F = 150 cm into the working volume of the chamber 8 in which soot particles were dispersed by an air flow. The particles obtained were conglomerates of irregular shape with the mean effective diameter $\sim 5 \cdot 10^{-4}$ cm.

A signal from the FÉU-28 3 was supplied to the oscilloscope C 8-2 6 in order to determine the beginning of the action, and to check the duration and shape of the radiation pulse. The flow of the soot particles during the action was recorded at a 90° angle to the direction of propagation of the active radiation by using a FÉU-28 7 from which the signal was supplied to the oscilloscope. To eliminate the influence of scattered radiation of the active laser, a filter with almost 100% reflection coefficient for $\lambda = 1.06\ \mu$m was placed in front of the photomultiplier. The time of the beginning of action on the aerosol and the beginning of recording its glow on the oscilloscope was synchronized by using the delay module 5. The oscillograms characterizing the particle glow process in the channel and the pulse shape were photographed.

The energy of the active radiation was checked during the measurements by using the IMO-2 4.

Mounting of a photographic apparatus with a microphoto attachment in place of the FEU 7 permitted obtaining an integrated picture of the destruction of the soot particles. A typical photograph of the process is presented in Fig. 2. The arrow indicates the direction of the acting radiation. Photography yields a graphic representation of the dispersion diagram of the destruction products, an important characteristic in analyzing the transfer of optical radiation in aerosol media subjected to the effect of intense light pulses. The mean velocity of particle motion is $\sim 2 \cdot 10^2$ cm $\cdot$ sec^{-1}. It is interesting to estimate the contribution of the light pressure force and the reactive force, which govern during interaction between a powerful laser pulse and an aerosol, to the particle motion.

Let us estimate the velocity of the motion of an individual soot particle in a laser beam because of the light pressure force. The equation of particle motion in air can be written in the form [2]

$$F_p + F_d = Mdv/dt, \tag{1}$$

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