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PROPAGATION OF HIGH-ENERGY LASER BEAMS THROUGH METALLIC AEROSOLS

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RECENT PUBLICATIONS, SUBMITTALS FOR PUBLICATION AND PRESENTATIONS:

A) A. Zardecki and R. L. Armstrong, "Energy Balance in Laser-Irradiated Vaporizing Droplets," Proceedings of the 1987 CRDEC Scientific Conference on Obscuration and Aerosol Research, In Preparation.

B) R. L. Armstrong, and A. Zardecki, "Diffusive and Convective Vaporization of Irradiated Droplets," J. Appl. Phys. **62**, 4571-4578 (1987).

C) S. A. W. Gerstl, A. Zardecki, W. P. Unruh, D. M. Stupin, G. H. Stokes, and N. E. Elliot, "Off-Axis Multiple Scattering of a Laser Beam in Turbid Media: Comparison of Theory with Experiment," Appl. Opt. **26**, 779-785 (1987).

D) A. Biswas, H. Latifi, P. Shah, L. J. Radziemski, and R. L. Armstrong, "Time-Resolved Spectroscopy of Plasmas Initiated on Single, Levitated Aerosol Droplets," Opt. Lett. **12**, 313-315 (1987).

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F) S. M. Chitanvis and A. Zardecki, "Effect of Thermal Blooming on Pulse Propagation through Vaporizing Aerosols," Appl. Opt. **27** 2495-2501 (1988).

ABSTRACT

By combining the results of the hydrodynamic code CONID and the beam propagation code LASER, we investigate the propagation of high-energy laser beams through vaporizing metallic aerosols in the regime for which the plasma generation becomes important. An effective plasma absorption coefficient allows us to set up a coupled system of equations describing the system consisting of the beam and vapor.

INTRODUCTION

When an aerosol particle is irradiated by a high-flux laser beam, plasma formation is one of many interactions modes that may occur. In this interaction, careful distinction must be made between absorbing aerosols, and aerosols which are minimally absorbing, or even effectively transparent, at the laser wavelength of interest.

In the case of absorbing aerosols,¹⁻³ deposition of laser energy results in the rapid liberation of high-temperature vapor at the aerosol surface. Free electrons present in this vapor serve as seed electrons for the avalanche ionization process producing a plasma fireball in the neighbourhood of the aerosol. Under suitable conditions, not known in quantitative detail, fireballs around individual aerosols can merge to form a beam-blocking plasma.

The process of plasma formation is slightly different for quasi transparent aerosols. In this case, the driving mechanism underlying plasma formation is the presence of field inhomogeneities either inside or near its surface.^{4,5}

Typically, a two-step process of plasma formation is initiated by seed electrons due to multiphoton ionization. In the second step, cascade ionization leads to a rapid growth in the number of ions.

In this paper, we study the initiation of plasma above absorbing, metallic surfaces irradiated with laser fluxes within the range of 10^6 – 10^9 W/cm². As discussed in the work of Pirri *et al.*⁶ and in the work of Weyl *et al.*⁷ the plasmas in an air environment grow rapidly, developing either a laser-supported detonation wave or a laser-supported combustion wave which absorbs the laser radiation and strongly influences the laser coupling to the surface. For moderate fluxes, where the diffusive vaporization regime prevails, a hydrodynamic model of plasma initiation off irradiated metallic aerosols in vacuum has recently been formulated by Chitanvis.⁸ For high laser fluxes, convective vaporization is accompanied by production of shock waves in the non-isobaric ambient medium.^{9,10} The increase in the ion number density, regarded as a special case of a chemical reaction, allows us to calculate the plasma absorption coefficient of a single metallic aerosol. To this end, the hydrodynamic code CON1D¹¹ is employed. The CON1D output is then utilized to analyze the nonlinear beam propagation with the aid of the propagation code LASER.

EQUATIONS OF MOTION

Consider an aerosol particle of radius r_d and density ρ_d uniformly irradiated by a time-varying electromagnetic flux F . At $t = 0$, the arrival time of the leading edge of the pulsed beam, the particle is assumed to be in equilibrium with the ambient gas at a temperature T_0 and a pressure p_0 . For times, $t > 0$, the particle absorbs energy from the beam, the particle temperature T_d rises, and the particle is no longer in equilibrium with ambient gas. A thin, nonequilibrium region, the Knudsen layer, is created at the particle surface. For low to moderate flux levels, diffusive and convective processes transport mass, momentum, and energy into the surrounding medium whereas, for high flux levels, the aerosol particle vaporizes explosively, creating shock waves.

The region surrounding the particle is a multi-component medium consisting of the particle vapor, which we take—for the sake of concreteness—as aluminum; the molecular gases: N_2 and O_2 ; the ions: Al^+ and e ; and the gas of Al^* , excited aluminum atoms. The basic two kinetic ionization reactions are:

If the index $k = 1, \dots, K$ denote species k , and the index $l = 1, \dots, L$ numbers the chemical reactions, the ionization process will induce additional chemical source terms in the species continuity and energy equations. In terms of the reaction rates ω_l , they are

$$\dot{\rho}_k^c = W_k \sum_{l=1}^L (b_{k,l} - a_{k,l}) \dot{\omega}_l \quad (3)$$

and

$$\dot{Q}_c = \sum_{l=1}^L \dot{\omega}_l Q_l. \quad (4)$$

Here Q_l is the negative of the heat of reaction l at absolute zero:

$$Q_l = - \sum_{k=1}^K (b_{k,l} - a_{k,l}) (\Delta H_f^0)_k, \quad (5)$$

where $(\Delta H_f^0)_k$ refers to the heat of formation of species k . The a 's and b 's in these equations are the stoichiometric coefficients; corresponding to reactions described by Eqs. 1 and 2, they are $a_{k,1} = 1, 0, 0, 0, 1, 0$; $b_{k,1} = 0, 0, 0, 0, 1, 1$; $a_{k,2} = 0, 0, 0, 0, 1, 1$; and $b_{k,2} = 0, 0, 0, 1, 2, 0$.

Finally, the reaction rates are given as

$$\begin{aligned} \dot{\omega}_l = & c_{f,l} T^{\eta_{f,l}} \exp(-E_{f,l}/T) \prod_{k=1}^K \left(\frac{\rho_k}{\mu_k} \right)^{a_{k,l}} \\ & - c_{b,l} T^{\eta_{b,l}} \exp(-E_{b,l}/T) \prod_{k=1}^K \left(\frac{\rho_k}{\mu_k} \right)^{b_{k,l}}, \end{aligned} \quad (6)$$

where the μ_k are the molecular weights, whereas the coefficients c , E and η are the appropriate forward and backward reaction constants.

The hydrodynamic equations of motion, supplemented by the source terms due to chemical reactions, now become:

(i) the mass conservation equations

$$\frac{\partial \rho_k}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (\rho_k u r^2) = \frac{1}{r^2} \left[\rho D r^2 \frac{\partial}{\partial r} \left(\frac{\rho_k}{\rho} \right) \right] + \dot{\rho}_k^c, \quad (7)$$

(ii) the momentum conservation equation

$$\frac{\partial \rho u}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (\rho u^2 r^2) + \frac{\partial p}{\partial r} = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \gamma_{rr}) - \frac{\gamma_{\phi\phi} + \gamma_{\theta\theta}}{r}, \quad (8)$$

(iii) the energy conservation equation

$$\begin{aligned}
& \frac{\partial \rho \epsilon}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (\rho \epsilon u r^2) + \frac{p}{r^2} \frac{\partial}{\partial r} (u r^2) \\
& = \frac{1}{r^2} \frac{\partial}{\partial r} \left(\kappa r^2 \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \left\{ \frac{\partial}{\partial r} r^2 \rho D \left[\sum_{k=1}^K h_k \frac{\partial}{\partial r} \left(\frac{\rho_k}{\rho} \right) \right] \right\} \\
& + \Sigma_{rr} \frac{\partial u}{\partial r} + (\Sigma_{\phi\phi} + \Sigma_{\theta\theta}) \frac{u}{r} + \dot{Q}_c.
\end{aligned} \tag{9}$$

In Eqs. 7-9, $\rho_k, \epsilon, \rho, u, p$, and T are the component mass densities, and the mixture internal energy, density, velocity, pressure, and temperature, respectively. Expressions for the stress tensor components ($\Sigma_{rr}, \Sigma_{\theta\theta}, \Sigma_{\phi\phi}$), and the transport coefficients (D, κ) are given in Ref. 9. Also given there are the expressions for the caloric equation of state for ϵ , the species enthalpy h_k , and the thermal (ideal gas) equation of state. Equations 7-9 need to be solved with appropriate boundary conditions, which are discussed in detail in Ref. 10.

The hydrodynamic equations in the vapor yield the density distribution of each species in the region surrounding the particle. The density of metallic ions determines the plasma absorption coefficient, σ_{plasma} .^{12,13} By writing a simple energy balance equation for the plasma, which is seen by the incoming beam as a spherical annulus with area A ,

$$\int \sigma_{plasma} dv = A Q_{pl}, \tag{10}$$

we can obtain an effective plasma absorption efficiency factor, Q_{pl} . This is the quantity that accounts for the coupling of plasma to radiation.

In the small-angle approximation, the irradiance at any spatial point is obtained from the transport equation for the intensity distribution function (radiance) I . If ϕ specifies the projection of the unit directional vector on the plane perpendicular to the beam axis, this equation has the form¹⁴

$$\left(\frac{\partial}{\partial z} + \phi \cdot \frac{\partial}{\partial \mathbf{r}} + \sigma_t \right) I(r, z, \phi, t') = \sigma_s \int p(\phi - \phi') I(r, z, \phi', t') d^2 \phi'. \tag{11}$$

In Eq. 11, $p(\phi - \phi')$ is the phase function; $t' = t - z/c$ is the retarded time; σ_s is the volume scattering coefficient due to aerosols, whereas σ_t is the total volume extinction coefficient. The small-angle, forward-scattered radiation flux (irradiance) is given as

$$F(r, z, t') = \int I(r, z, \phi, t') d^2 \phi'. \tag{12}$$

Equations 11-12 can be solved numerically by advancing from a plane $z = \text{const}$ to a neighbouring plane $z + \delta z$, where $\sigma_s \delta z \ll 1$. The effect of plasma absorption is included by modifying the σ_t on the left hand side of Eq. 11. We note that in the absence of the plasma

$$\sigma_t = \sigma_s + \sigma_a, \quad (13)$$

where σ_a is the aerosol absorption coefficient. We thus define the effective absorption coefficient as

$$\sigma_{eff} = \sigma_a + \sigma_{plasma}. \quad (14)$$

In actual computation, the absorption and scattering cross sections vary with space and time, depending on the value of the laser flux. Figure 1 shows the plasma absorption efficiency as a function of time for different flux levels of the laser beam.

NUMERICAL RESULTS

To illustrate our former considerations, we model numerically the propagation of a laser pulse through a 2 m slab filled with monodisperse aluminum particles having the radius of 10 μm . The laser wavelength is assumed to be 10.6 μm , which corresponds to the complex refractive index of $(2.66527 + 0.0519i)$. The pulse, which is Gaussian in time, has the width of 5×10^{-7} s, and the concentration of aluminum particles is adjusted to yield the linear (in the absence of plasma) optical depth of the order of 4 or 8.

In Figs. 2-3, we compare the behavior of the pulse—in the absence and in the presence of plasma—for aerosol concentration corresponding to optical depth of 4.21. It is evident that the plasma absorption quenches the punch-through effect, in which the high-energy pulse propagates through an aerosol cloud virtually unattenuated. A similar situation, for optical depth of 8.41, is illustrated in Figs. 4 and 5. Here, even in the absence of plasma, the punch-through effect is not so pronounced as in the former case, due to higher aerosol density.

CONCLUSIONS

We have investigated the propagation of an intense laser pulse interacting with a cloud of metallic particles, with the inclusion of plasma absorption. The plasma initiated by the laser beam leads to an additional coupling of the radiation to the medium; this is described in terms of a nonlinear absorption coefficient, which leads to enhanced attenuation of the beam. For metallic aerosols, the plasma formation, and its effects on beam propagation, should not be neglected if the pulse flux is of the order of 10^7 W/cm² or higher.

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$$R_0 = 1.0E-03 \text{ cm}$$

$$t_p = 5.0E-07 \text{ sec}$$

Figure 1. Plasma absorption efficiency as a function of time for different flux levels of the incoming laser pulse.

Figure 2. Pulse shape on-axis as a function of time and propagation distance. Optical depth $\tau = 4.21$. Plasma absorption suppressed.

Figure 3. Pulse shape on-axis as a function of time and propagation distance. Optical depth $\tau = 4.21$. Plasma absorption included.

Figure 4. Pulse shape on-axis as a function of time and propagation distance. Optical depth $\tau = 8.41$. Plasma absorption suppressed.

Figure 5. Pulse shape on-axis as a function of time and propagation distance. Optical depth $\tau = 8.41$. Plasma absorption included.