INVERSE BREMSSTRAHLUNG EFFECTS IN THE CORONAE OF LASER-IRRADIATED PELLETS AND SLABS

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In recent, quasi-steady analyses of the spherical, ablative corona of a laser-irradiated pellet, absorption was assumed to occur at the critical density n_{cr} /1/-/4/. Both classical and saturated heat-flux, and ion-electron energy exchange where taken into account. If the ion charge number Z_i and mass per unit charge $\overline{m} \equiv m_i/Z_i$, the instantaneous pellet radius r_a and laser power W_L, and its wavelength (or equivalently n_{cr}), are given, one can obtain quantities of interest such as the ablation pressure P_a, the critical radius r_{cr}, and the mass ablation rate $4\pi\overline{m}\mu$, as dimensionless functions ($\overline{P}_a \equiv P_a/\rho_{cr}V^2$, r_{cr}/r_a, and $\overline{\mu} \equiv \mu/r_a^2 n_{cr}V$) of the parameters Z_i, $\hat{W} \equiv W_L/r_a^2\rho_{cr}V^3$, and heat-flux limit factor f. We have introduced $\rho_{cr} \equiv \overline{m}n_{cr}$, a convenient speed $V \equiv (r_a n_{cr}/\overline{m}^{5/2}\overline{K})^{1/4}$, and the factor $\overline{K}$ of Spitzer's classical heat-flux ($\equiv -\overline{K}T^{5/2}\,dT/dr$, the electron temperature T being in energy units).

Lately the search for more ablative conditions in laser-irradiation of targets has moved the interest into shorter wavelengths (larger n_{cr}) and larger pellet radii. For such conditions inverse Bremsstrahlung absorption in the underdense flow can be substantial /5/. Here we attempt to quantitatively determine that absorption using the model of Refs. /3/ and /4/. Inverse Bremsstrahlung introduces into the model the electron mass m_e and the light speed c, and is found here to be parametrized by the ratio $\overline{m}V/m_e c$, which lies close to unity for all cases of interest. Large values of n_{cr} and r_a lead to relatively low $\hat{W}$ (1-10^4 typically). Recently Sanmartín et al. have considered effects due to a suprathermal electron population generated by resonant absorption, at higher values of $\hat{W}$ (10^5-10^8); it was found that hot-electron effects are parametrized by the ratio $\overline{m}V/m_e c$ too /6/.

Using the continuity equation $nvr^2 = \mu$ (independent of r), the momentum and energy equations for the quasineutral ion-electron fluid read

$$\overline{m}v\frac{dv}{dr} = \frac{T}{r}\,\frac{2 - d\ln T/d\ln r}{1 - T/\overline{m}v^2}\,, \qquad (1)$$

$$\frac{\mu}{r^2}\left(\frac{1}{2}\overline{m}v^2 + \frac{5}{2}T\right) - \overline{K}T^{5/2}\frac{dT}{dr} = 0\,, \qquad r < r_{cr} \qquad (2a)$$

$$= I\,, \qquad r > r_{cr} \qquad (2b)$$

where v is the ion velocity and I the laser irradiance, which is given by

$$\frac{1}{r^2}\frac{d}{dr}r^2 I = KI\ ; \qquad (3)$$

here K is the absorption coefficient /7/. Equations (1)-(3) can be solved for v(r), T(r), and $W(r) \equiv 4\pi r^2 I(r)$, and the eigenvalues μ, r_{cr}, and P_a, by using the conditions

$$T = 0\,, \quad v/T = \mu/r_a^2 P_a \qquad \text{at} \quad r_a$$

$$T \to 0 \ , \quad W \to W_L \qquad \text{as} \quad r \to \infty$$

$$vr^2 = \mu / n_{cr} \qquad \text{at} \quad r_{cr}$$

$$\text{either } r = r_{cr} \quad \text{or} \quad 2 = d \ln T / d \ln r \quad \text{where} \quad \overline{m} v^2 = T.$$

In Eqs. (2b) and (3) we assumed that the light power W_{cr} reaching the critical surface is absorbed there by some unspecified anomalous process. We also assumed that $Z_i >> 1$; in this way the ion temperature is uncoupled (ion pressure and internal energy are negligible) and the problem is simplified. We use classical heat-flux everywhere, an approximation justified, for the $\hat{W}$ values of interest, in Refs. /4/ and /6/.

The ratio r_{cr}/r_a decreases as $\hat{W}$ decreases with $\overline{m}V/m_e c$ fixed. We find that for $r_{cr} > 1.215\ r_a$ the flow at r_{cr} is supersonic (the sonic speed is reached at $r \equiv 1.215\ r_a$); the solution for the range $r_a < r < r_{cr}$ is the same one given in Ref. /3/. The flow at r_{cr} is sonic if $\eta^* r_a < r_{cr} < 1.215\ r_a$; here η^* is a function of $\overline{m}V/m_e c$, and lies within the range 1--1.215. For $r_a < r_{cr} < \eta^* r_a$ the flow at r_{cr} is subsonic. When $(r_{cr} - r_a)/r_a$ is small heat conduction is restrictied to a thin layer surrounding the pellet.

If $(r_{cr}/r_a) - 1 = O(1)$, the results of Ref. /3/ are recovered for $\overline{m}V/m_e c$ small. If $(r_{cr}/r_a) - 1 << 1$, those results are recovered when $10^2 \times (\overline{m}V/m_e c)/\hat{W}$ is small. The ratio $(\overline{m}V/m_e c)/\hat{W}$ is proportional to the quantity $I\lambda^4/r_a$ ($\lambda \equiv$ wavelength) introduced by Mora /5/.

In Fig. 1(a) we have represented the fraction of laser power absorbed by inverse Bremsstrahlung, as a function of $\hat{W}$ for several values of $\overline{m}V/m_e c$; also shown is the ratio r_{cr}/r_a. In Fig. 1(b) we represented the ablation pressure P_a normalized to its value for $\hat{W} \to 0$, $\overline{m}V/m_e c \to 0$. The curves change behaviour when $r_{cr}/r_a = 1.215$, and again when $r_{cr}/r_a = \eta^*(\overline{m}V/m_e c)$. Numerical data for $r_{cr}/r_a < \eta^*$ are not shown in the figure. Asymptotic results for low $\hat{W}$ ($r_{cr}/r_a \to 1$) are also presented. The mass ablation rate $4\pi\overline{m}\mu$ is the same of Ref. /3/ for $r_{cr}/r_a > 1.215$.

We have also considered large focal-spot irradiation of slabs, leading to one-dimensional, unsteady problems. We approximated the irradiance I in the rising-half of the laser pulse by a law $I(t) \approx I_0 (t/\tau)^s$. For large Z_i and classical heat-flux one has the equations $(x > 0,\ t > 0)$

$$\frac{\partial n}{\partial t} + \frac{\partial}{\partial x} nv = 0 \ , \qquad \overline{m} n \left(\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} \right) = - \frac{\partial}{\partial x} nT$$

$$nT \left(\frac{\partial}{\partial t} + v \frac{\partial}{\partial x} \right) \ln \frac{T^{3/2}}{n} - \frac{\partial}{\partial x} \overline{K} T^{5/2} \frac{\partial T}{\partial x} = \frac{\partial I}{\partial x} = KI \ .$$

There are two dimensionless parameters, as in the spherical case,

$$\hat{I} \equiv \frac{I_o}{\rho_{cr} U^3} \ , \quad \frac{\overline{m} U}{m_e c} \ ,$$

where $U \equiv (\tau n_{cr} / \overline{K} \overline{m}^{5/2})^{1/3}$. If $\hat{I} << 1$, conduction is restricted to a thin deflagration layer, which is quasisteady /8/. If, in addition, $s = 3/2$ the flow outside that layer is self-similar. We have determined all quantities for $\hat{I} << 1$ and $(\overline{m}U/m_e c)^{3/2}/\hat{I}$ large and small (when the results of Ref. /8/ are recovered). The ratio $(\overline{m}U/m_e c)^{3/2}/\hat{I}$ is proportional to $I_0 \lambda^5/\tau^{3/2}$ a quantity

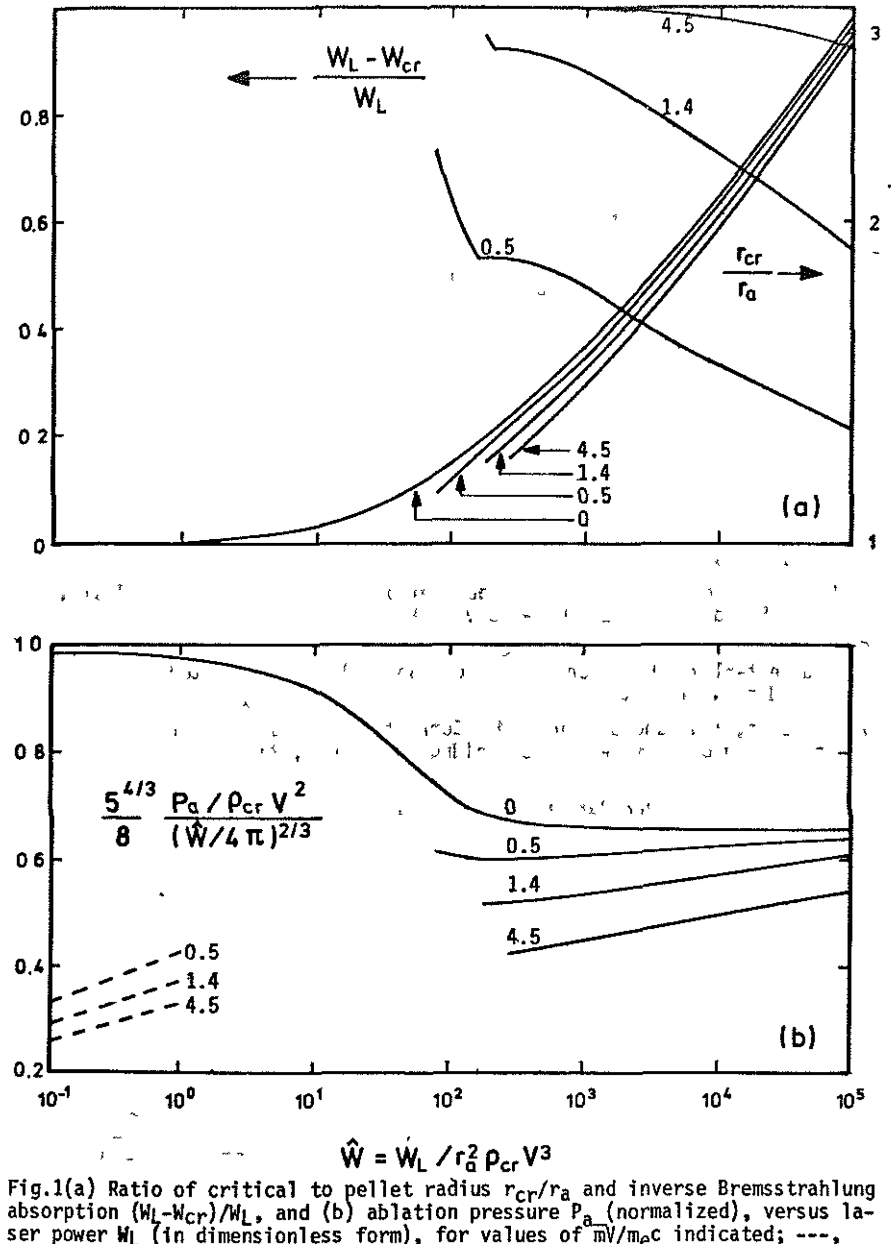

Fig.1(a) Ratio of critical to pellet radius r_{cr}/r_a and inverse Bremsstrahlung absorption $(W_L-W_{cr})/W_L$, and (b) ablation pressure P_a (normalized), versus laser power W_L (in dimensionless form), for values of $\bar{m}V/m_ec$ indicated; ---, behaviour at low power.

introduced by Mora /5/. For the ablation pressure P_a at $t = \tau$ we get

$$\frac{P_a}{\rho_{cr}^{1/3} I_o^{2/3}} = \frac{8}{5^{4/3}} , \quad \frac{\bar{m}U/m_e c}{\hat{I}^{2/3}} << 1$$

$$= 0.45\left(\frac{\hat{I}^{2/3}}{\bar{m}U/m_e c}\right)^{1/8} , \quad \frac{\bar{m}U/m_e c}{\hat{I}^{2/3}} >> 1 .$$

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