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TITLE: *EVIDENCE FOR A HOT-ELECTRON FLUX LIMIT IN LASER-PRODUCED PLASMA EXPERIMENTS*

AUTHOR(S): *Gene H. McCall*

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

EVIDENCE FOR A HOT ELECTRON FLUX LIMIT IN LASER-PRODUCED PLASMA EXPERIMENTS*

by

Gene H. McCall
Applied Theoretical Physics Division
Los Alamos National Laboratory
P.O. Box 1663, MS-B218
Los Alamos, NM 87545
(505) 667-1565

It has been found that it is necessary to impose a flux limit on the thermal electron transport in diffusion calculations of laser-produced plasmas to explain the observed partition of energy into fast and slow ions and x-rays[1-3]. The effect of such a limit is to retain the deposited energy in the corona of the target. This containment increases the energy loss to fast ions, reduces the x-ray emission, and reduces the hydrodynamic efficiency. Although calculations for plasmas produced by lasers having wavelengths of 1 μm or shorter agree with experiment when a flux limit which is 1/30 times the classical flux limit is applied to the electron thermal flux[2], I will show that such a flux limit cannot explain the results obtained for 10 μm lasers[4]. In this case it will be shown necessary to invoke a flux limit on the "hot" or suprathermal electrons[5].

First it will be shown that the thermal flux limit is more important for short-wavelength lasers than for long-wavelength lasers. Consider the situation where thermal conduction is unimportant for local energy balance in the plasma and where the local temperature is determined by the specific hot electron energy deposition. The plasma temperature, T_c, depends on the energy per unit mass as:

$$T_c = a\,(E/\ell\rho)^{\alpha}, \tag{1}$$

where E is the deposited energy per unit area, the material density is ρ, the deposition length is ℓ, and ,a, is a constant. The deposition length is assumed to be the range of an electron having an energy equal to the hot electron temperature, T_h. The exponent, α, can be derived from the equation of state of the material of interest[6]. For conditions usually encountered in laser-produced plasma experiments for polyethylene, for example, $\alpha = 3/4$. For the purposes of this paper, the monatomic ideal gas approximation of $\alpha = 1$ will be used. The temperature gradient can then be approximated as:

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$$\nabla T = T_c/\ell \sim E/(\ell^2\ \rho). \tag{2}$$

The dependence of the thermal conductivity, κ, on temperature is, from Spitzer[7]:

$$\kappa \sim T_c{}^{5/2}. \tag{3}$$

The thermal flux, Q, can be written as:

$$Q = \kappa\nabla T \sim E^{7/2}/(\ell^{9/2}\ \rho^{7/2}). \tag{4}$$

The temperature dependence of the free-streaming thermal electron flux, F, can be expressed as[1]:

$$F \sim T_c{}^{3/2} \sim E^{3/2}/(\ell\rho\ )^{3/2}. \tag{5}$$

The deposition mass, $\rho\ell$, for hot electrons can be written as[8]:

$$\rho\ell = K_r\ T_h{}^{3/2}, \tag{6}$$

where K_r is a constant. The hot electron temperature, T_h, can be expressed as[9]:

$$T_h = \alpha(E\ \lambda^2)^{1/3}. \tag{7}$$

The ratio of the thermal diffusion flux to the free-streaming flux in a region heated by hot electrons is:

$$\kappa\nabla T/F \sim E^{1/2}\ \rho/\lambda^3. \tag{8}$$

Thus, it is seen that the increase of the hot electron temperature with laser wavelength reduces the diffusion flux relative to the free-streaming flux. One would expect, then, that a thermal flux limit will have a smaller effect at long wavelengths than at short wavelengths. It has been shown by computer simulation that for certain problems setting the diffusion flux to zero has little effect for plasmas heated by a CO_2 laser[10].

If one performs a similar calculation for a plasma heated inverse Bremsstrahlung absorption, a different result is found. Following Spitzer the inverse Bremsstrahlung absorption coefficient, κ_ν, can be written as:

$$\kappa_\nu = 1/\ell \sim \rho^2/(T^{1/2}\ \nu^3). \tag{9}$$

Here, ℓ is the scale length established by the absorption process. The thermal diffusion flux can be approximated as in Equation (2) to obtain:

$$Q/F \sim E. \tag{10}$$

Therefore, one would expect that a flux limit used to simulate the results of short-wavelength experiments may depend on the deposited energy but not on the wavelength. This appears to be the case[3]. Because the heat flow tends to reduce the temperature gradient, the dependence of the flux limit on energy may be weaker than the linear dependence shown in Equation (8).

One can make some general comments about the effects implied by Equations (6) and (8). When the heating of the plasma is caused by hot electron deposition, the effect of imposing a flux limit on the thermal electron flux will become less important as one increases the laser wavelength. If the absorption is the result of inverse Bremsstrahlung absorption, the effect of a given flux limit should be independent of wavelength. Therefore, it it is necessary to confine the plasma energy to the corona of a plasma produced by a long-wavelength laser, one must impose a flux limit on the hot electrons. It is known, however, that flux limit on the thermal electrons produces simulation results which agree with experiment for 1 μm laser experiments where the energy is deposited almost entirely by hot electrons. In this case, both the hot electron depositon and the thermal diffusion away from the depositon region are important. The flow of hot electrons into the target can be retarded by the electric field produced by the return current which neutralizes the charge produced by the hot electron current. The electric field produced by the return current can be written as:

$$\epsilon = j / \sigma, \tag{11}$$

where ϵ is the electric field, j is the current density, and σ is the plasma electric conductivity. From Spitzer[7]:

$$\sigma \sim T_c{}^{3/2}, \tag{12}$$

$$j = nev_h \tag{13}$$

where n is the hot electron density and v_h is the hot electron average velocity. The retarding field, can then, be written as:

$$\epsilon \sim nev_h/T_c{}^{3/2}. \tag{14}$$

If the heat flow from the corona of the plasma is important in determining T_c, a reduction of this flow will increase the retarding field according to Equation 12. Therefore, a flux limit imposed on the thermal electrons also serves as a flux limit for the hot electrons. This is the case for experiments at 1 μm where the hot electron temperature is low compared to that at 10 µm. Then, according to Equations (2), (6), and (7), the reduced scale length will produce a larger diffusion flux.

Next, I will discuss the necessity of imposing a flux limit based on pheonomenological evidence from laser-produced plasma experiments. It has been shown that fast ions emitted by a laser-produced plasma can be described by a self-similar isothermal expansion[11]. In this description, the density, n, is expressed in terms of the initial density, n_0, at the rarefaction front as:

$$n = n_0 \exp(-1 - x/c_s t), \tag{15}$$

where c_s is the isothermal sound speed, x, is the distance from the initial plasma surface, and, t, is the time. The velocity can be written as:

$$v = c_s + x/t. \tag{16}$$

The kinetic energy, E_i, per unit area in the expansion is:

$$dE_i = m_i\, n_i\, v^2/2\, dx. \tag{17}$$

Then:

$$E_i = m_i\, n_0\, c_s^3\, t. \tag{18}$$

The flux, or power per unit area, I_i, is:

$$I_i = m_i\, n_0\, c_s^3. \tag{19}$$

Expressing c_s in terms of the hot electron temperature as:

$$c_s = (ZkT/m_i)^{1/2}, \tag{20}$$

where, Z, is the atomic number of the ion, and, m_i, is the ion mass, the ion flux can be written as:

$$I_i = n_0\, m_i^{-1/2}\, (ZkT)^{3/2}. \tag{21}$$

Next, assuming that the hot electron distribution is a one-dimensional Maxwellian, one can calculate the electron flux passing through the target surface. It can be shown[12] that when a two-temperature distribution exists, an electric potential is created at the boundary of the two distributions. If the density of cold electrons is much greater than the density of hot electrons and the hot electron temperature is much greater than the cold electron temperature, the magnitude of the potential is of order 3kT/2. This potential reduces the heat flow into the target. Therefore it will be assumed that the electrons entering the target have their energies reduced by the potential, V. The electron flux is, then:

$$I_e = n_e m_e \, (m_e/2\pi kT)^{1/2} \times \int_{(2V/m_e)^{1/2}}^{\infty} (v^2 - 2V/m_e)^{3/2} \exp(-m_e v^2/2kT)\, dv/2. \tag{22}$$

The integral can be evaluated to given:

$$I_e = n_0 \, m_e \, (m_e/2\pi kT_h)^{1/2} \, (2V/m_e)^2 \times \Gamma(5/2) \exp(-V/kT_h) U(5/2,3,v/kT_h), \tag{23}$$

where $\Gamma(a)$ is a gamma function, and $U(a,b,c)$ is a confluent hypergeometric function[13]. The effect of the electric potential can be displayed if one evaluates Equation (23) for the zero-field case. The flux, I_0, is:

$$I_0 = n_0 \, (2kT)^{3/2} \,/\, (\pi \, m_e)^{1/2}. \tag{24}$$

If one limits the hot electron flux into the target by a factor, f, the hot electron flux becomes fI_0. The ratio of the electron flux to its zero-potential value is:

$$I_e/I_0 = (V/kT)^2 \;\; \Gamma(5/2) \exp(-V/kT) \; U(5/2,3,V/kT). \tag{25}$$

The fast ion loss can be compared to the energy transported into the target by taking the ratio of Equation (21) to Equation (24) to obtain:

$$I_i/I_0 = (2 \; \pi \; ? \; m_e \; / \; m_i)^{1/2}. \tag{26}$$

Equation (26) can be evaluated for a hydrogen plasma, for example, where $Z = 1$ and $m_e/m_i = 1/1836$ to give:

$$I_i/I_0 = 0.059. \tag{27}$$

For carbon, where $Z = 6$ and $m_e/m_i = 4.5 \times 10^{-5}$, the ratio is 0.042.

At the time at which the laser is turned off, the deposited energy can be written as the sum of three terms. The energy conducted into the target by the flux-limited hot electrons, E_c, is fA_eI_0t, where A_e is the area of contact between the electron distribution and the target, and, t, is the time. The energy in the ion expansion, E_i, is given by Equation (19) multiplied by $A_e t$, and the internal energy remaining in the electrons, E_e, can immediately be written if one recalls that the number of electrons in an isothermal expansion is $n_0 Z c_s t A_e$ and the average energy per electron is kT/2. Using Equation (2) to eliminate kT_h:

$$E_e = n_0 m_i c_s^3 A_e t/2. \tag{28}$$

The energy remaining in the electrons is a substantial fraction of the energy in the motion of the ions. Therefore, an assumption must be made about its depositon. Since the conduction into the target and the ion kinetic energy both vary as $T_h^{3/2}$, it appears reasonable to apply the flux limit to this energy. Thus, a fraction, f, will be conducted into the target, and a fraction, 1 - f, will be delivered to the ions. The total energy conducted into the target, then, is:

$$E_c = f A_e t (I_0 + n_0 m_i c_s^3 / 2), \tag{29}$$

and the kinetic energy in the ion expansion is:

$$E_i = n_0 m_i c_s^3 A_e t (3 - f) / 2. \tag{30}$$

Setting the sum of E_c and E_i to the laser energy, E_ℓ, and defining the ratio of E_i to E_ℓ to be the fast ion loss fraction, ε_i, one finds that:

$$1/\varepsilon_i = 1 + f [1 + (2 m_i / \pi Z m_e)^{1/2}] / (3 - f). \tag{31}$$

Equation (31) can be solved for f to give:

$$f = 3(1 - \varepsilon_i)/[1 + \varepsilon_i (2 m_i / \pi Z m_e)^{1/2}]. \tag{32}$$

The flux limit as a function of the measured fast ion loss fraction is shown in Figure 1(a) for a hydrogen plasma and in Figure 1(b) for a carbon plasma.

Measurements of the energy in fast ion emission from plasmas created by a 1 µm laser[14] at intensities of 10^{15}w/cm^2 or higher have resulted in a fast ion loss fraction of, approximately, 50 percent. This result for a hydrogen plasma gives a flux limit of 0.08. Recent measurements at 10 µm by Ehler[15] using an ion time-of-flight detector give a fast ion loss fraction of 0.8, which implies a flux limit of 0.02. Measurements on the same experiment by Kephart[16] using calorimeters gave a loss fraction of, approximately, 0.5. This would imply a flux limit of 0.08 as in the 1 µm case. Experiments at 10 µm by Villeneuve *et al*[17] found at least 50 percent of the absorbed laser energy in fast ions, and, perhaps, as much as 75 percent. A fast ion loss fraction of 75 percent implies a flux limit of 0.02. The use of the parameters for hydrogen is believed to be justified. Experiments which use polyethylene targets have found that most of the fast ion energy was in fast protons. Experiments at 10 μm have shown that fast protons constitute most of the fast ion loss, even for targets such as gold which should not contain hydrogen[18].

If the source of the flux limit is an electric potential at the target surface, the potential can be estimated from Equation (23). If Equation (23) is solved for V/kT for $I_e/I_0 = 0.08$, one finds that $V/kT = 2.09$. This value is larger than that obtained by Bezzerides *et al*[12], but that calculation was done for a collisionless plasma, and the return current field which results from collisional processes was not included. It is possible, therefore, that a potential as large as $2.09kT_h$ could be created. For $I_e/I_0 = 0.02$, a potential $V/kT = 3.34$ is required. If $V/kT = 1.5$, the flux limit is $f = 0.15$, and the loss fraction, ε_i, is 0.35, which is too small to explain the observed results. Recent plasma simulation calculations by Forslund and Brackbill[19] indicate that a large magnetic field is created at the surface of a target which is heated by hot electrons. It is possible that these fields, which are in the megagauss range, could produce the required flux limit.

The implication of this study is that a hot electron flux limit is required to explain the observed fast ion loss for laser-produced plasmas which are heated by hot electrons. A fast-ion loss fraction of 0.5, rather than the .059 given by the isothermal model, requires that the area over which the ions are emitted be, approximately, ten times larger than the laser spot. Thus, the hot electrons occupy a large area and volume. Increasing the emitting area, however, would also increase the conduction into the target if no flux limit were applied. The application of a flux limit of 0.02 to 0.08 to give the experimental result causes the hot electrons to remain in the corona 12 to 50 times longer than if the flux limit were not present. The increase in the residence time increases the probability that the electrons will find new, undesirable conduction paths. If this result is substantiated by more detailed calculations, the prospect for producing efficient thermonuclear yield from targets driven by lasers having wavelengths of 1 μm or longer are, indeed, dim.

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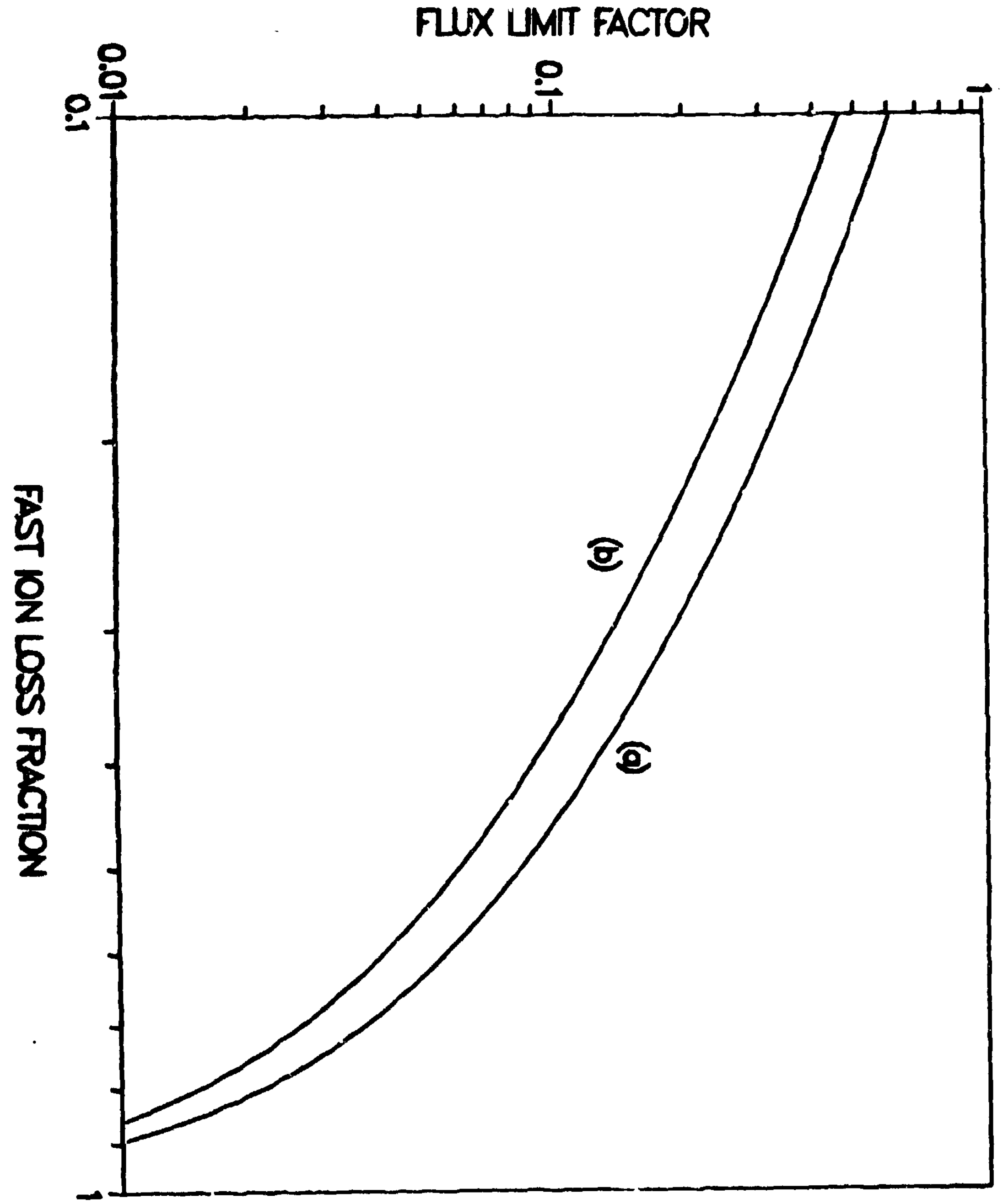

1. Flux limit as a function of fast ion loss.
   (a) Hydrogen plasma.
   (b) Carbon plasma.