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ABLATION PROCESSES IN LASER IRRADIATED
PLANAR SOLID TARGETS

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INTRODUCTION

It is a well known fact that success of laser driven fusion eventually depends on successful isentropic compression ($\sim$ 1000 fold) of spherical fusion targets. The high pressure required for compression is derived from laser induced ablation of target surface. Most of the laboratory experiments, to study ablative acceleration utilize planar foil targets because of diagnostic simplicity. Physics-wise also such a geometry offers many advantages. However, a true planar ablation is an idealization and in practice it can be only reached when the laser spot radius at the target surface is sufficiently large. If the spot radius is small, the plasma flow quickly diverges and the situation becomes nearer to a spherical expansion.

As an intense laser radiation strikes the solid planar target, the target surface evaporates and is converted into an expanding plasma cloud due to further heating. The density of the plasma falls from nearly solid to zero along the target normal. It is a well known fact that the laser radiation can not proceed beyond a plasma electron density $n_c = 10^{21} \times \lambda_{\mu m}^{-2}$ electrons cm^{-3} where λ μm is the laser wavelength in microns. Corresponding mass density is given by $\rho_c = 3.3 \times 10^{-3} \lambda_{\mu m}^{-2}\ g/cm^3$ for a fully ionized plasma [2 x Atomic number (Z) = atomic mass (A)].

The plasma density and temperature profiles thus obtained are shown in Fig.1. At short laser wavelength, small intensity and long pulse duration the laser radiation is absorbed via classical collisional process over an extended region in the sub-dense corona (at densities lower than ρ_c). However, for longer wavelength, high intensities and short pulse duration, the dominant absorption is via resonant process or highly localized collisional process near the critical density ρ_c .

The energy absorbed in the subdense region or at the critical density is carried away to the colder solid interior of the target via classical conduction or free streaming electron transport (when the electron mean free path becomes comparable to the local temperature scale length the classical conduction breaks down) and ablates it. The blow off mass, while passing through the hotter part of the conduction and absorption zone is accelerated down the density gradient(Fig.1) producing an ablation pressure.

In this talk, we shall first discuss a simple case of planar ablation with localized absorption at the critical density and derive scaling laws for ablation parameters like mass ablation rate ($\dot{m}$), ablation pressure (P_A) and Coronal temperature (T_e). We shall later discuss consequences of non-localized absorption in planar as well as non-planar geometry. A brief attention will also be given to energy transport in the conduction zone and consequences of its inhibition. We shall also briefly discuss hot electron assisted ablation at higher laser intensities and longer wavelengths.

BASIC EQUATIONS:

The pressure created due to laser irradiation comprises of the following:

1. Thermal pressure (P_T)
2. Ablation pressure (P_A, due to momentum transfer)

Thermal Pressure : The pressure is defined as

$$P_T = n_e k T_e + n_i k T_i = \rho \left[\frac{k T (Z+1)}{A m_p} \right] = \rho c^2 \qquad \text{— (1) a}$$

where C is the isothermal velocity of sound, Z and Amp are mean ionic charge and mass respectively, $T_e = T_i = T$ is the plasma temperature.
Ablation pressure: It is defined as ρu^2 , where ρ and u are mass density and flow velocity respectively.

Assuming a steady state ablation, in the reference frame of the deflagration, the situation can be treated as a flow across a discontinuity, Fig.2. Applying equations of conservation of mass, momentum and energy

$$\rho u = \text{Constant} \qquad \text{Mass} \quad (1)\ b$$

$$P + \rho u^2 = \text{Constant} \qquad \text{Momentum} \quad (1)\ c$$

$$\rho u \left(h + \frac{u^2}{2} \right) + q = I_a \qquad \text{Energy} \quad (1)\ c$$

Here ρ and u are mass density and velocity, P is the pressure. The absorbed laser intensity is I_a. q is the heat flux from the laser absorption region. h is specific enthalpy

Presently we shall consider classical conduction only. Thus, $q = -K_o T^{5/2} \frac{dT}{dx}$ where T is the electron temperature and $K_o = 20\left(\frac{2}{\pi}\right)^{3/2} \epsilon\, \delta_T \left(k / m_e^{1/2} e^4 Z \ln\Lambda\right)$

the usual spitzer conductivity formula[1].

In the energy equation enthalpy h can be expressed as

$h = (\gamma/\gamma-1)\frac{P}{\rho} = (\gamma/\gamma-1)\, C^2$, where P and ρ are pressure and mass density respectively. C is the isothermal sound speed. For an ideal monoatomic gas $\gamma = 5/3$.

There are two main velocities we must consider

1. Heat wave velocity, $v_H \sim I_a/\rho h$
2. Shock (driven by ablation) velocity $v_s \sim (P/\rho)^{1/2}$ where P and ρ are = pressure and mass density respectively.

We can classify different situations as under:

1. $v_s > v_H$: This situation is defined as subsonic deflagration. Here the shock front is ahead of the heat front.

2. $v_s = v_H$: This is known as Chapman-Jouget deflagration. Here the pressure and heat front move together. A situation usually found in chemical explosions or laser induced sparks in gases.

3. $v_s < v_H$: No pressure step is formed in this situation, as the heat wave takes over the acoustic disturbance.

ISOTHERMAL VS ADIABATIC FLOW:

In isothermal flow approximation, constant temperature in the corona is assumed. To keep the corona warm and compensate for the thermal losses due to plasma expansion, adequate thermal flux from the laser absorption location is required. The required heat flux[2] is given by ρC^3 , ρ is the density, at the low density side of the absorption site

and C sothermal sound speed. The isothermal expansion would be appropriate for high laser irradiances and low atomic mass targets. The heat capacity of the corona also has to be small to hold the approximation valid. When the laser intensity is low and target atomic mass is high (targets like gold, the heat capacity of the outer corona is high and the plasma is collisional. Under these conditions, adiabatic approximation is more approriate. The appropriate plasma flow velocity at the low density side of the absorption region is then given by $\sqrt{\gamma}\, C$ for an ideal monoatomic gas and c is the isothermal sound speed.

The zone between the ablation and critical surface is characterized by the electron thermal conduction Fig.1. At higher laser intensities the heat conduction is inhibited due to reasons not yet fully clear. However,. presently we shall not consider the inhibition.

For steady state:

$$\frac{\partial}{\partial x}\left[\dot{m}\left(\frac{\gamma}{\gamma-1}\right)c^2 + \frac{u^2}{2}\right] + q = 0 \qquad (2)$$

integrating the equation for $x < x_c$

$$\dot{m}\left[\frac{5}{2}c^2 + \frac{u^2}{2}\right] + q = Q \qquad (3)$$

constant Q represents the difference between the outward flux of kinetic energy plus enthalpy and the inward heat flux due to thermal conduction. To evaluate it, we look at the cold side of the ablation front Fig.1. Neglecting preheat ionization energy, energy invested in plasma production and target motion, and the velocity at the ablation front. Thus we find Q = 0.

$$\dot{m}\left[\frac{5}{2}c^2 + \frac{1}{2}u^2\right] - K_o T^{5/2}\frac{dT}{dx} = 0 \qquad - (4)$$

where

$$q = -K_o T^{5/2}\frac{dT}{dx}$$

Now, assuming that the conduction region containing a sonic point $(\rho_o ; u_o = c_o)$, with density ρ_o and flow velocity $c_o \equiv$ isothermal velocity of sound under steady state

$$\rho u = \rho_o u_o = \dot{m} \qquad --(5)$$

$$\rho c^2 + \rho u^2 = \rho_o c_o^2 + \rho_o c_o^2 = 2\rho_o c_o^2$$

$$\rho u (c^2 + u^2) = 2\rho_o c_o^2 u$$

$$c^2 + u^2 = 2 c_o u \qquad --(6)$$

Solution of equation 6 having velocity nearly zero at the ablation front is

$$u = c_o - (c_o^2 - c^2)^{1/2} ; \quad c \le c_o \qquad --(7)$$

Thus the flow has maximum temperature at the sonic point. If the corona is isothermal, the sonic point would also lie in the corona. This requirement can only become consistant if the localized absorption region is a boundary between the isothermal corona and the conduction zone. This situation is also consistant from the energy flow consideration (inward flow for ablation and outward flow for keeping the Corona warm, from the absorption location)

We can now write

$$I_{absorbed} = I_a = q_2 - q_1 \qquad ---(8)$$

where

$$q_2 = \rho_c c_o^3$$

$$q_1 = -K_o T^{5/2} \frac{dT}{dx}\Big|_{x_c - \delta x} = -3 m_o c_o^2 = -3\rho_c c_o^3 \qquad --(9)$$

or

$$I_a = 4 \rho_c c_o^3 \qquad ---(10)$$

Thus one quarter of the absorbed intensity is invested in keeping the corona warm and three quarter spent for ablation (via conduction) of the cold material

Mass ablation rate ($\dot{m}$), temperature(T_e) and ablation pressure (P_a) now can be written from the equation 10, for an isothermal expansion case.

$$\dot{m} = \rho_o c_o = (I_a \rho_c^2 / 4)^{1/3} \qquad ---(10)a$$

$$T_e = \left[\frac{A m_p}{K(z+1)}\right]\left(\frac{I_a}{4\rho_c}\right)^{2/3} \qquad ---(10)b$$

Since $c_o = \left[\frac{(z+1)KT}{A m_p}\right]^{1/2}$

and $$P = P_T + P_A = 2\rho_c c_o^2 = \left(\frac{2}{4^{2/3}}\right) I_a^{2/3} \rho_c^{1/3} \qquad --(10)c$$

For an adiabatic expansion, outward heat flux $q_2 = 0$. The sonic velocity at the critical surface ρ_c is $\sqrt{\gamma}\, c_o$ and mass ablation rate $\dot{m} = \sqrt{\gamma}\, \rho_c c_o$

$$I_a = \rho_c u \left[h + \frac{u^2}{2}\right] = q$$

$$= \rho_c c_o^3 \gamma^{1/2} \left[\frac{\gamma c_o^2}{(\gamma-1)} + \frac{\gamma}{2}\right] ; \quad \text{Since } h = \left(\frac{\gamma}{\gamma-1}\right) c_o^2$$

$$= 4.3 \rho_c c_o^3 \quad \text{for } \gamma = 5/3 \qquad ---(11)$$

Corresponding ablation pressure,

$$P = \rho_c c_o^2 + \gamma \rho_c c_o^2 = (1+\gamma)\rho_c c_o^2$$

$$= 2.66 \rho_c c_o^3 \qquad ---(12)$$

for $\gamma = 5/3$

Thus the scalings of ablation variables for an adiabatic case remain similar to those obtained for an isothermal case. However, the magnitudes vary a little.

NON LOCALIZED ABSORPTION:

As discussed earlier at low laser intensity, wavelength and larger pulse duration; the absorption dominantly takes place over an extended region in the sub-dense corona. Under the circumstances critical density ablation model becomes inapplicable. The maximum temperature point is now situated at a far away point in space from the critical density. The density at which the maximum temperature occurs, and also happens to be sonic point is given by[3,4]:

$$\rho_M \sim 2\rho_c \left(\frac{I_{inc}}{10^{14}}\right)^{1/4} (\lambda_{\mu m})^{5/4} \left(\tau_{L\,ns}\right)^{1/8} \bar{Z} \left(\frac{A}{2Z}\right)^{5/16} \qquad -(13)$$

I_{inc} = laser intensity in $10^{14}\,W/cm^2$, $\lambda_{\mu m}$ = laser wavelength, τ = pulse duration (ns) and $\bar{Z}$ = ave ion charge

mass ablation rate and pressure scale as following

$$P = 2\rho_M C_0^2 \simeq 7 \left(\frac{I_{inc}}{10^{14}}\right)^{3/4} (\lambda_{\mu m})^{-1/4} \left(\tau_{L\,ns}\right)^{-1/8} (\bar{Z})^{-1/8} \left(\frac{A}{2Z}\right)^{7/16} \text{ Mbars} \qquad -(14)$$

$$\mathring{m} = \rho_M C_0 \simeq 10^4 \left(\frac{I_{nc}}{10^{14}}\right)^{1/2} (\lambda_{\mu m})^{-1/2} \left(\tau_{L\,ns}\right)^{-1/4} (\bar{Z})^{-1/4} \left(\frac{A}{2Z}\right)^{7/8} \text{ g/sec cm}^2 \qquad -(15)$$

One can easily see that the dependence of the ablation parameters is not critical on the laser wavelength. This is because the absorption region is situated far away from the ablation surface.

Planar ablation is only an idealization. In fact, no laser-target experiment is truly planar. Plasma flow from the flat targets irradiated by finite laser spots, for example expands laterally. Flow becomes nearly spherical, when the plasma reaches a little beyond a distance equal to the laser spot radius R_o at the target surface. However, if the ablation to critical surface distance is much smaller than R_o or the laser pulse duration

τ_L is $\leq \frac{R_o}{C_s}$, where C_s is the appropriate sound speed then a planar theory may still be applicable. In general a spherical theory is more appropriate to describe an experiment.

When a flow diverges at a distance R_o from the target surface is considered[4,5] as described earlier, the laser absorption principally takes place in the region of one dimensional (1-D) flow, only a fraction ($\sim$ 30%) of the incident laser radiation is absorbed in the three dimensional (3 D) expansion region[5]. The density at the 1D - 3D transition region is given by

$$\rho_1 = (kT)^{3/4} \left(\frac{2}{5 C_A Z R_o}\right)^{1/2} \frac{Amp}{Z} \qquad -(16)$$

Here Amp and Z one ion mass and ion charge respectively. kT is the plasma temperature, R_o is laser spot radius, C_A is a constant $\left[C_A = 2.5 \times 10^{-55} \left(\frac{\lambda_L}{0.69}\right)^2 \text{c.g.s. units}\right]$ and λ_L is the laser wavelength is microns. The flow self regulates itself in the 1-D region such that the laser radiation is fully absorbed before reaching the critical density and reaches a steady state in a time $\sim R_o/C_s$ with density gradient $L_n \sim R_o$. Mass ablation rate ($\mathring{m}$) and pressure P are given by:

$$\mathring{m} = 5.3 \times 10^5 (\lambda_{\mu m})^{-4/9} \left(I_a/10^{13}\right)^{5/9} \left(\frac{Z R_o}{100\mu m}\right)^{-2/9} \text{ g/cm}^2\text{sec} \qquad -(17)$$

$$P = 1.8\, (\lambda_{\mu m})^{-2/9} \left(I_a/10^{13}\right)^{7/9} \left(\frac{Z R_o}{100\mu m}\right)^{-1/9} \text{ Mbars} \qquad -(18)$$

$A \simeq 2Z$ assumed with fully ionized plasma.

This model is applicable only till ρ_1, is less than ρ_c. As soon as $\rho_1 \rightarrow \rho_c$ the model turns into what was described a critical density absorption model earlier. The laser intensity at which this transition takes place is given by[5]

$$I \geq \left(\frac{\rho_c Z}{Amp}\right)^3 C_A R_o \left[\frac{5(Z+1)^3}{12\, Amp}\right]^{1/2} \qquad -(19)$$

EFFECT OF FLUX INHIBITION :

Classical heat flux is given by $q = \left| K T^{5/2} \frac{dT}{dx} \right|$ when the mean free path of the electrons becomes significant compared to the temperature scale length of the plasma the classical heat flux formula becomes invalid and flux is described by free streaming model and is given by

$$q\,(\text{free streaming}) = f\, n_e m_e \left(\frac{KT_e}{m_e}\right)^{3/2} \qquad -(20)$$
$$= 5\,\phi \rho c^3$$
$$f = 0.1\,\phi\, \frac{(Z+1)^{3/2}}{Z A^{1/2}} \qquad -(21)$$

n_e ; m_e and T_e are electron density mass and temperature respectively, Z is the charge of the plasma ion and A its atomic mass. Here flux limit ϕ has been expressed in terms of hydrodynamic variables.

We have seen that the maximum inward classical heat flux occurs at the critical surface and is equal to $3\rho_c c_0^3$. Thus we can write a condition for flux limited energy flow as

$$3\rho_c c_0^3 > 5\phi \rho_c c_0^3 \qquad -(22)$$
$$\text{or} \quad \phi < 0.6$$

In general it is assumed that the density, temperature and Mach number (M) of the flow (M = flow velocity/appropriate local sound velocity) do not show a jump at the location of laser energy deposition. However, if there is heat flux inhibition, there is every chance of a jump in these variables. The physical reason is the following. When flux is limited, the heat flux directed towards the dense matter drops very rapidly than the flux heating the subdense corona. Consequently mass ablation rate drops. As a lower mass flux passes through the critical surface, it is very strongly heated by the outward heat flux. The pressure does not change at the critical surface, thus a temperature and density jump are produced. One can look at the situation in the following way also. Energy equation (with limited

heat flow) becomes

$$\dot{m}\left(\frac{5}{2}c^2 + \frac{1}{2}u^2\right) - 5\phi\rho c^3 = 0 \qquad -(23)$$
$$\text{or} \quad M(5+M^2) - 10\phi = 0 \qquad -(24)$$

Here $M = u/c$ = Mach number of the flow.

Thus the Mach number is constant throughout the transport inhibition region and depend only on ϕ value. This means ρ, u and T must be constant in the space. This situation is unphysical and can be removed, if a density, temperature and Mach number jump is introduced at the critical (absorption) surface.

If the under dense corona ($\rho < \rho_2$, ρ_2 because of the jump) is assumed to be isothermal, the outward heat flux required is $\rho_2 c_2^3$, where c_2 is the isothermal sound speed in the corona. The outward heat flux may also become inhibited if $\rho_2 c_2^3 \geq 5\phi\rho_2 c_2^3$

Thus we note following situations:

1.	$\phi > 0.6$	No inhibition, flow behaves exactly like in the classical case $\dot{m}$, P remain the same.
2.	$0.2 < \phi < 0.6$	Inward flow is inhibited P and $\dot{m}$ become sensitive to ϕ value. Jump at the critical surface appear.
3.	$\phi < 0.2$	Inward as well as outward flow is inhibited. Isothermal condition will not be met, and expansion may be nearer to adiabatic case.

SCALING LAWS:

When the discontinuity is introduced due to flux inhibition, one can write

$$I_a = 4\rho_c c_2^3\, F(\rho_2, \phi) \qquad -(25)$$
$$F(\rho_2, \phi) = \rho_2/\rho_c \qquad -(26)$$

An emphirical relation, well satisfied in hydrodynamics is[2]

$$\rho_2/\rho_c = \phi/0.6 \qquad - (27)$$

$$F(\rho_2/\rho_c) = \begin{cases} \phi/0.6 & \phi < 0.6 \\ 1 & \phi \geq 0.6 \end{cases} \qquad - (28)$$

Now the scaling laws become:

$$T_2 = \left(\frac{A m_p}{(Z+1)k}\right)\left(I_a/4\rho_c\ F(\phi)\right)^{2/3} \qquad - (29)\ a$$

$$\mathring{m} = \rho_2 C_2 = \left(\frac{\phi}{0.6}\right)\left(I_a \rho_c^2/4F(\phi)\right)^{1/3} \qquad - (29)\ b$$

$$P = 2\rho_2 C_2^2 = 2\left(\frac{\phi}{0.6}\right)\left(I_a/4\ F(\phi)\right)^{2/3} \rho_c^{1/3} \qquad - (29)\ c$$

Thus inhibition $(\phi < 0.6)$ would produce higher coronal temperature, lower mass ablation rate and ablation pressure.

HYDRODYNAMIC EFFICIENCY:

One of the most important parameters in ablative implosion of a fusion target is hydrodynamic efficiency(η), defined as the ratio of kinetic energy of the accelerated target to the absorbed laser energy. We use a simple rocket model to illustrate the case. If the initial mass per unit area) of the target is m_0 and velocity at any moment t is $v(t)$ and its mass m(t). The rocket equation is

$$m(t)\frac{dv}{dt} = \text{Pressure} = P \qquad - (30)$$

Solution of the equation

$$v(t) = \frac{P}{\mathring{m}} \ln\left(\frac{m_0}{m(t)}\right) \qquad - (31)$$

for small mass ablation[6] hydrodynamic efficiency

$$\eta = \frac{\Delta M}{M_0} = \frac{m_0 - m(t)}{m_0} \qquad --- (32)$$

by defn; $\eta = \dfrac{m(t)\,v^2(t)}{2\,E_a} = \eta_0\left[\dfrac{x \ln^2 x}{1-x}\right]$; $x = \dfrac{m(t)}{m_0}$; $\eta_0 = \dfrac{P^2}{2 I_a \mathring{m}}$

Highest value of η is attained when $\dfrac{m(t)}{m_0} = x = 0.2$

Thus

$$\eta_{maximum} = 0.65\,\eta_0 \qquad ---- (33)$$

$$\eta_0 = \frac{P^2}{2 I_a \mathring{m}} = \frac{4\rho_2^2 C_0^4}{8\rho_2 C_0^3 \cdot \rho_2 C_0} = \frac{1}{2};\ \left(\phi \ \begin{matrix} < 0.6 \\ > 0.6 \end{matrix}\right)$$

Thus $\eta_{maximum} = 0.32$

Thus highest efficiency (with 80% of the initial mass ablated) is fixed.

However for an adiabatic corona there is no outward heat flux. Thus, the hydrodynamic efficiency is higher. Here the $\eta_{max} = 0.41$.

HOT ELECTRON DRIVEN ABLATION AT HIGH LASER INTENSITIES.

At high laser intensities and long wavelengths, hot electrons are generated near the critical density due to resonant absorption (or at quarter critical density due to $2\omega_{pe}$ decay or SRS). These electrons due to their long range penetrate and heat the dense ($> \rho_c$) part of the conduction zone and modify the temperature profile. Fig. . The sonic point in such a case has a density (ρ_s) not fixed at ρ_c (as in case critical density ablation) but is located at higher density ($\rho_s > \rho_c$). Here self regulation heating due to hot electrons can be considered. For hot electron driven ablation, simple models in planar geometry by Mima[7] and in spherical geometry by Kidder[8] have been worked out. In these models it is assumed that the hot electron range (λ_H) determines the sonic point density (ρ_s), the flow between the ablation front and ρ_c is steady state and isothermal. Applying s. regulation between the critical density (where hot electrons are produced) and the sonic point (determined by the hot electron range)

$$\int_0^{X_s} \frac{dx}{\lambda_H(x,t)} = 1 \qquad \text{--- (34)}$$

is estimated as

$$\rho_s = \left(1 + \frac{\lambda_0}{t\,C_s}\right)\rho_c \; ; \quad C_s \equiv \text{isothermal sound speed.} \qquad \text{--- (35)}$$

If the fractional loss due to hot ions is f, the energy balance

$$4\,\rho_s C_s^3 = (1-f)\,I_a \qquad \text{--- (36)}$$

$$\text{Pressure} \; ; \; P = (1-f_a)\,I_a/2C_s \; ; \quad P = 2\rho_s C_s^2$$

$$= \left(\frac{1}{\sqrt{2}}(1-f)\,I_{ab}\,\rho_s^{1/2}\right)^{2/3} \qquad \text{--- (37)}$$

using hot electron formula for electron range (λ_0) at the critical density

$$\lambda_0 = \frac{3.8\times10^{-3}}{(Z+1)\ln\Lambda}\,(kT_H)^2\,\lambda_{\mu m}^2 \qquad \text{--- (38)}$$

$$\frac{T_H}{1\,\text{kev}} \simeq 13\left(\frac{T_e}{1\,\text{kev}}\right)^{1/4}\left[\frac{I_L}{10^{15}}\right]^{0.4}\left[\frac{\lambda_L}{1.06\,\mu m}\right]^{0.8} \qquad \text{--- (39)}$$

Mass ablation rate ($\mathring{m}$) and ablation pressure scalings have been shown as

$$\mathring{m} = 9.6\times10^{5}\,t^{-2/3}\left[(1-f)\right]^{0.59} I_L^{0.85}\,\lambda^{1.04}\ \text{g/cm}^2\text{sec} \qquad \text{--- (4}$$

$$P = 93\,t^{-1/3}\left[(1-f)\right]^{0.7} I_L^{0.93}\,\lambda^{0.52}\ \text{Mbar} \qquad \text{--- (4}$$

The most serious objection of this model is isothermal assumption. At very high intensities the absorbed energy is given to a small fraction of hot electrons. Their temperature is typically several times greater than that of the background plasma.

In this talk we have discussed scaling laws for parameters like ablation pressure, mass ablation rate and coronal temperature for a planar as well as non ideal plasma flow which attains a three dimensional structure a little away from the target surface. We have also found out that shorter wavelengths are more suited for improved ablation pressure and mass ablation rates. Maximum hydrodynamic efficiency is however fixed and independent of the laser wavelength. But for a given intensity where optimum ablation is not achieved shorter laser wave lengths will provide a better hydrodynamic efficiency for a given laser intensity. At higher intensity and longer laser wavelength hot electrons are principal agents for energy transport and cause higher ablation density(ρ_s).

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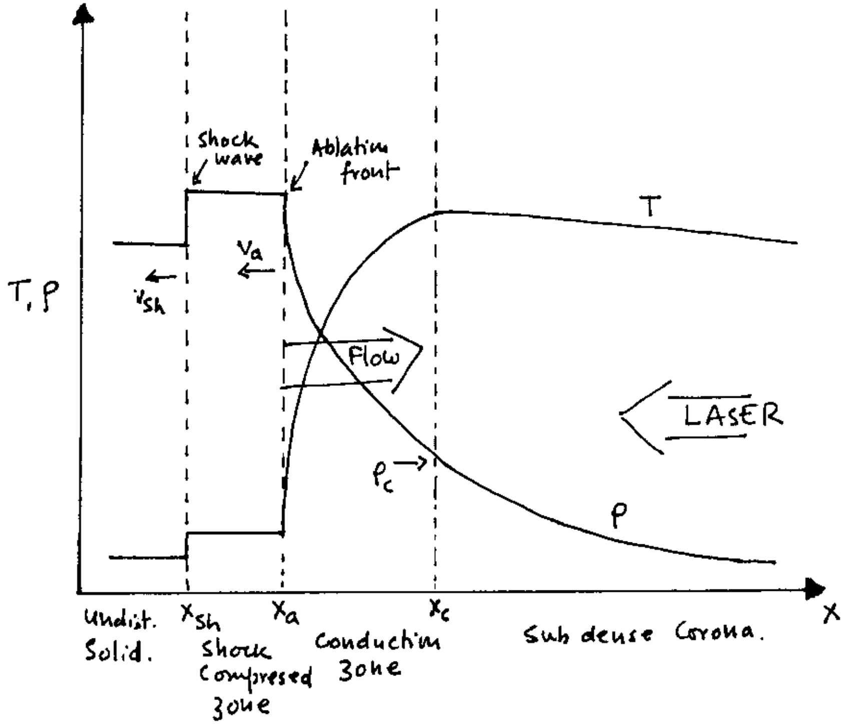

Density and Temperature profiles for a solid planar laser irradiated layer. Flow Consists of kinetic energy and enthalpy.

Fig 1

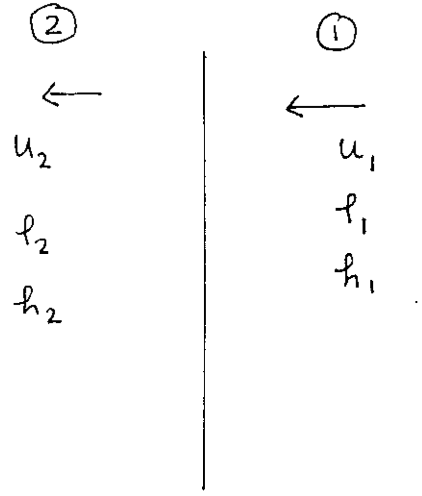

Fig 2

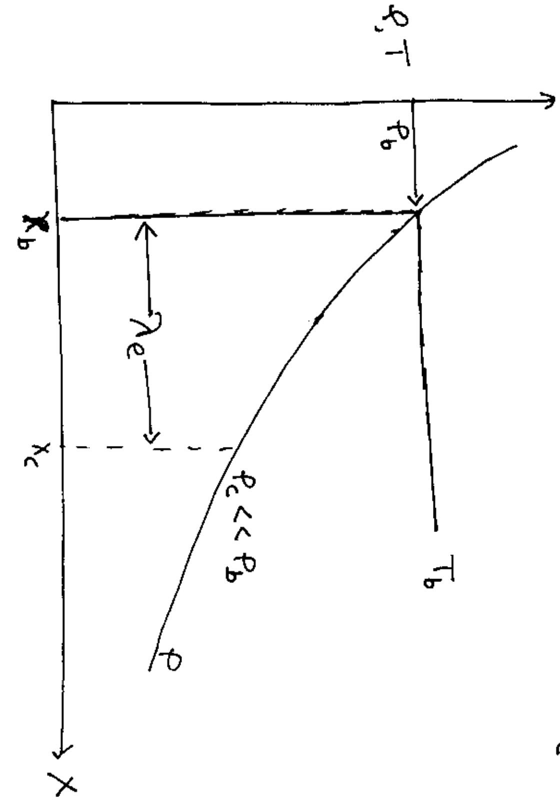

Fig 3

$$\lambda_e \sim \frac{(kT_e)^2 \lambda_{\mu m}^2}{(Z+1)\rho_n \Lambda}$$