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TWO DIMENSIONAL ANALYTICAL CONSIDERATIONS OF LARGE MAGNETIC AND ELECTRIC FIELDS IN LASER PRODUCED PLASMAS

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Abstract

A simple model in two dimensions is developed and solved analytically taking into account the electric and magnetic fields in laser produced plasmas. The electric potential in this model is described by the non-linear differential equation

$$\frac{\partial^2\psi}{\partial x^2} + \psi \,\frac{\partial\psi}{\partial x}\Big/(1 - \psi) = 0 \quad ,$$

$\psi = e\phi/T$, where $e\phi$ is the electric potential energy and T is the temperature in energy units. The physical branch $\psi < 1$, defined by the electron density $n = n_0 \exp\psi$ boundary conditions $n(x = 0) = \text{const}$ and $n(x = +\infty) = 0$, introduces a typical electrostatic double layer. The stationary solution of this model is consistent for $-0.1 \lesssim \psi < 1$, with electron temperature in the KeV region and a ratio of the electric (E) to magnetic (B) fields of $[E/10^6 \text{ v/cm}]/[B/\text{MGauss}] \sim 1$.

Two Dimensional Analytical Considerations of Large Magnetic and Electric Fields in Laser Produced Plasmas

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1. INTRODUCTION

The rotating magnetized star model suggested by Biermann (1950) was applied by Stamper et al. (1971) to laser produced plasmas and large scale magnetic fields were predicted. The presence of megagauss magnetic fields have been since confirmed experimentally (Stamper et al., 1978; Raven et al., 1978; Briand et al., 1985) in laser produced plasmas. A large variety of theoretical models can produce these large magnetic fields (Max, 1982). In particular, large scale toroidal magnetic fields (see Fig. 1) can be generated if there is a nonzero angle between the local electron density (n) and temperature (T) gradients, i.e. the $\vec{\nabla}n \times \vec{\nabla}T$ mechanism (Stamper et al., 1971). Moreover, the same structure and magnitude for self-generated magnetic fields can be explained by hot electron ejection from the laser focal spot (Kolodner and Yablonovitch, 1979) or from the existence of an anisotropic electron pressure (Mora and Pellat, 1981). Furthermore, there are mechanisms which suggest large magnetic fields with small spatial scales, ranging from a few laser wavelengths to an electron mean free path. These small scale magnetic fields can be produced by the radiation pressure due to laser light absorption (resonance absorption; Stamper and Tidman, 1973; Stamper, 1975; Stamper, 1976). Similar structure of magnetic fields can be caused by thermal instability (Tidman and Shanny, 1974) or by Weibel instabilities (Ramani and Laval, 1978). All the models suggested above are causing magnetic fields in the megagauss range and have a significant effect on the physics of laser produced plasmas. In particular, the thermal transport inhibition, the lateral transport and the fast plasma blowoff can be related to the existence of these large magnetic fields (Forslund and Brackbill, 1982; Yates et al., 1982; Max et al., 1978).

Laser produced plasmas have in general very high values of $\beta \equiv 8\pi nT/B^2$, the thermal* to magnetic energy ratio, therefore the magnetic field does not dominate the hydrodynamics like in magnetic confined fusion devices. In particular the ion Larmor radius is large compared with the typical scale lengths such as the laser wavelength. Therefore in laser-plasma interaction it is crucial to understand the generation of electric fields in the plasma. It turns out that inhomogeneities in density and/or in temperatures have electric fields which can modify significantly the thermal conductivity and can affect the plasma behavior (Hora, 1985; Hora et al., 1984; Cicchitelli et al., 1984). Even without laser irradiation, the electric field strengths between the irradiated pellet corona of KeV temperature and the cold pellet interior, can exceed 10^6 V/cm, and therefore can drastically reduce the thermal transport (Lalousis and Hora, 1983).

A major breakthrough in understanding the electric fields in laser produced plasma was the introduction of a genuine two fluid code for electrons and ions coupled by the Poisson equation (Lalousis and Hora, 1983), so that the space charge quasi-neutrality is not assumed. The idea to use a fully general hydrodynamic code for electrons and ions require very extensive computer time. The time steps have to be much

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*The temperature is expressed in energy units, so that Boltzmann's constant is taken $K_B = 1$.

less than the shortest Langmuir oscillation time given by the plasma frequency for the highest occurring electron density (e.g. about 10^{-15} sec for a Nd laser produced plasma). By the use of this hydrocode it was shown that the interaction of high intensity light with an expanding plasma surface produces strong electric fields through the existence of electrical double layers (Hora et al., 1984).

Double layers, which consist of two thin adjacent regions of opposite excess charges, have been observed in a variety of laboratory plasmas (Hershkowitz, 1985; Sato et al., 1981; Stenzel et al., 1981; Towen and Lindberg, 1980; Levine and Crawford, 1980). These regions of positive and negative charges are, in general, separated by distances of the order of several Debye lengths and induce a large potential drop which can accelerate particles to high energies. The existence of the electric fields in plasma surfaces have been measured directly by electron beam probes (Mendel and Ohlsen, 1975) and indirectly from the non-linear force accelerated ions (Donaldson et al., 1979). A systematic experiment done at SOREQ (Eliezer and Ludmirsky, 1983; Ludmirsky et al., 1985) measured double layers in laser produced plasmas. These experiments show that the first part of a laser produced expanding plasma is positively charged followed by a negative plasma cloud within the temporal resolution of 1 nsec. This phenomenon was explained (Hora et al., 1984) by the generation of cavitons and the ponderomotive force action. The caviton structure in the plasma creates an inverted double layer in contrary to a freely expanding plasma which has first a negative and then a positive charge (Hora, 1975; Alfvén, 1981; 1984). The SOREQ experiments were calibrated in situ and therefore any regular double layer can precede the inverted double layer, only within a shorter time than the experimental resolution (1 nsec). The existence of strong electric fields via the generation of double layers can accelerate ions and electrons on one side of the plasma while stopping faster electrons moving inside the target on the other side of the plasma. In addition, double layers might strongly influence the plasma density profile, which in turn can influence the laser absorption process and transport phenomena. Moreover, these electric fields can play an important role in the formation and perpetuation of wave instabilities.

Large magnetic and electrostatic fields were confirmed experimentally in laser produced plasmas. Most of the two fluid models and numerical simulations are one dimensional due to the complexity and the time consuming computer codes. Moreover, the extension of the genuine two fluid code of Lalousis and Hora (1983) to two (or three) dimensions in order to incorporate the magnetic fields as well, seems to be a very difficult and complex task. Therefore any step towards such an achievement is important and in particular, modest analytical calculations in two dimensions might be useful. In this paper we discuss analytically a simple model in two dimensions which takes into account the existence of strong magnetic and electrostatic fields in laser produced plasmas. In chapter two the model is introduced and the stationary state is discussed. A new non-linear differential equation and its solution is derived. Chapter 3 concludes this paper with a short summary of the results and a discussion.

2. THE MODEL

The two dimensional geometry is defined in a plane x - y perpendicular to the direction of the magnetic field B, which is chosen to be in the z direction. In this case the magnetic field is only a function of x and y since $\vec{\nabla} \cdot \vec{B} = \frac{\partial B}{\partial Z} = 0$. Thus,

$$\vec{B} = B(x,y)\hat{Z} \quad , \tag{1}$$

where $\hat{Z}$ is a unit vector. We choose the laser irradiation in the x direction, (see Fig. 1), and assume an invariance under rotation about this "laser axis." In this case one can write the set of two fluid equations, one for the electron fluid and the second for the ion fluid, coupled by the Maxwell equations in the x - y plane. In particular, the electric field $\vec{E}$, the potential ϕ, the pressure gradient $\vec{\nabla}P$ and the temperature gradient $\vec{\nabla}T$ are functions of (x,y) only and can be described by

$$\vec{E}(x,y) = E_x \hat{x} + E_y \hat{y} = -\vec{\nabla}\phi(x,y) \tag{2}$$

$$\vec{\nabla}P(x,y) = \frac{\partial P}{\partial x}\hat{x} + \frac{\partial P}{\partial y}\hat{y} \tag{3}$$

where $\hat{x}$, and $\hat{y}$ are unit vectors in x and y direction. The thermal diffusion process leads to almost constant temperature in the subcritical density plasma in the laser direction where the thermal diffusivity is high (see e.g., Key, 1980). Therefore we assume

$$\vec{\nabla}T(y) = \frac{\partial T}{\partial y}\hat{y} \quad . \tag{4}$$

This geometry can be applied to laser produced plasmas by considering a series of x - y planes which are symmetric under rotations about the x axis (see Fig. 1).

The large magnetic fields (B $\sim$ 100 KGauss to 2 MGauss) which were measured in the corona of the laser produced plasmas have been inferred from Faraday-rotation diagnostics to have a toroidal structure like that described in Fig. 1 (Stamper et al., 1978; Raven et al., 1978). A simplified equation governing the development of these magnetic fields is

$$\frac{\partial \vec{B}}{\partial t} = -c \, \frac{\vec{\nabla} n \times \vec{\nabla} T}{en} + \vec{\nabla} \times (\vec{V} \times \vec{B}) \qquad (5)$$

where c is the speed of light, $\vec{V}$ is the electron flow velocity, e, n and T are the electron charge, number density and temperature pressure, respectively. Eq. (5) is an approximation to the complete magnetic field expression as obtained from the generalized Ohm's law (Braginskii, 1965) which takes also into account the resistive diffusion, the magnetic pressure and the thermal force.

We describe the stationary electron fluid by the following simple set of equations:

$$\vec{\nabla} \cdot (n\vec{V}) = 0 \qquad (6)$$

which describes the mass conservation,

$$en(\vec{E} + \frac{\vec{V}}{c} \times \vec{B}) + \vec{\nabla} P = 0 \quad , \qquad (7)$$

the momentum conservation equation, and

$$P = nT \quad , \tag{8}$$

the equation of state of an ideal gas. Moreover, we assume the Boltzmann distribution for the electrons

$$n = n_0 \exp(e\phi/T) \tag{9}$$

and a phenomenological electron temperature distribution

$$T(y) = T_0 \exp(-y/L_T) \quad . \tag{10}$$

The electric field component in the laser direction, E_x, which is the dominant component of the electric field, is assumed to have a similar x dependence as the magnetic field, namely

$$E_x(x,y) = \alpha(y)B(x,y) \quad . \tag{11}$$

In this model we actually are using the weaker relation

$$\frac{1}{E_x}\frac{\partial E_x}{\partial x} \simeq \frac{1}{B}\frac{\partial B}{\partial x} \tag{12}$$

rather than the more restrictive constraint given by eq. (11). Equations (6) - (12) describe the electron fluid.

The stationary ion fluid is described by the following equations:

$$\vec{\nabla} \cdot (n_b \vec{v}_i) = 0 \tag{13}$$

where n_b and $\vec{v}_i$ are the ion density (background) and velocity, respectively,

$$n_b M(\vec{v}_i \cdot \vec{\nabla})\vec{v}_i = n_b ze(\vec{E} + \frac{\vec{v}_i}{c} \times \vec{B}) - z\vec{\nabla}P_i \tag{14}$$

M and z are the ion mass and electric charge, respectively, while P_i is the ion pressure,

$$P_i = n_b T_i \quad . \tag{15}$$

Equations (13) - (15) describe the mass and the momentum conservations, and the equation of state for the ion fluid with a temperature T_i.

The two fluids, the electron and the ion, are coupled in their stationary state by the stationary Maxwell equations:

$$\vec{\nabla} \cdot \vec{E} = 4\pi e(n_b - n) \tag{16}$$

$$\vec{\nabla} \cdot \vec{B} = 0 \tag{17}$$

$$\vec{\nabla} \times \vec{E} = 0 \tag{18}$$

$$\vec{\nabla} \times \vec{B} = \frac{4\pi}{c^2} \vec{j} \tag{19}$$

where the current density $\vec{j}$ is given by the ion current $\vec{j}_i$ and the electron current $\vec{j}_e$,

$$\vec{j} = \vec{j}_i + \vec{j}_e = zen_b \vec{v}_i - en\vec{v} \quad . \tag{20}$$

We analyze now the stationary equations which describe the electron fluid. Using eqs. (4), (9) and (10) in the two dimensional geometry defined at the beginning of this section, one gets

$$\vec{\nabla} T = - \frac{T}{L_T} \hat{y} \tag{21}$$

$$\vec{\nabla} n = -en \frac{E_x}{T} \hat{x} + \frac{enE_y}{T} \left(\frac{\phi}{E_y L_T} - 1 \right) \hat{y} \quad . \tag{22}$$

These two relations together with the equation of state (5) yield the electron pressure gradient

$$\vec{\nabla}P = -enE_x \hat{x} + \left[\frac{nT}{L_T}\left(\frac{e\phi}{T} - 1\right) - enE_y\right]\hat{y} \quad . \tag{23}$$

Substituting this pressure gradient into the equation of motion (7) we get the electron fluid velocity,

$$V_x = \frac{(e\phi - T)c}{eL_T B} \quad , \qquad V_y = 0 \quad . \tag{24}$$

Using now the continuity equation (6) together with eqs. (22) and (24), the following relation is obtained

$$E_x = \left(1 - \frac{e\phi}{T}\right)\frac{T^2}{e^2\phi}\ \frac{1}{B}\frac{\partial B}{\partial x} \quad , \tag{25}$$

which can be rewritten by using eq. (11) or eq. (12),

$$E_x = \left(1 - \frac{e\phi}{T}\right)\frac{T^2}{e^2\phi}\ \frac{1}{E_x}\frac{\partial E_x}{\partial x} \quad . \tag{26}$$

Defining the dimensionless quantity ψ,

$$\psi \equiv \frac{e\phi}{T} \tag{27}$$

we derive from eq. (26) a non-linear differential equation which describes the electric potential in the plasma

$$\psi'' + \frac{\psi\psi'^2}{1 - \psi} = 0 \tag{28}$$

where

$$\psi' \equiv \frac{\partial\psi}{\partial x} = -\frac{eE_x}{T}$$

$$\psi'' \equiv \frac{\partial^2\psi}{\partial x^2} = -\frac{e}{T}\frac{\partial E_x}{\partial x} \quad . \tag{29}$$

Substituting $1 - \psi = Z$ eq. (28) reduces to $Z''/Z' = Z'/Z - Z'$ which can be immediately integrated, so that the x dependence (in the laser irradiance direction) of the potential $\psi(x,y)$ is derived,

$$\frac{x}{L_0} = Ei(1-\psi) + c(y) \quad \text{for} \quad \psi < 1 \tag{30}$$

$$\frac{x}{L_0} = E_1(\psi - 1) + \tilde{c}(y) \quad \text{for} \quad \psi > 1 \quad , \tag{31}$$

where $L_0 = L_0(y)$ is the scale length parameter, and the exponential integrals Ei and E_1 are defined by (Gautschi and Cahill, 1972)

$$Ei(Z) = \int_{-\infty}^{Z} \frac{e^t}{t}\, dt \qquad Z > 0 \tag{32}$$

$$E_1(Z) = \int_{Z}^{\infty} \frac{e^{-t}}{t}\, dt \tag{33}$$

3. RESULTS AND DISCUSSION

The x dependence of ψ, for $\psi < 1$ is plotted in Fig. 2. Since the electron density must have a (finite) constant value for $x \to 0$ and must vanish asymptotically for $x \to \infty$, we have to neglect our solution for $\psi > 1$, and to consider it nonphysical. The x-component of the electrostatic field (and of the magnetic field by using eq. (11)) is obtained from eq. (29) and (30),

$$\frac{eE_x}{T} = \frac{(1 - \psi)}{L_0} \exp(\psi - 1) \tag{34}$$

and this solution is given in Fig. 3. The y component of the electric field is also derived from eq. (30),

$$\frac{eE_y}{T} = \left(\frac{1}{L_T} - \frac{\partial}{\partial y}\right) \psi \quad . \tag{35}$$

The electron density n is given by eq. (9), and the ion density profile can be expressed in terms of the dimensionless potential ψ by using the Poisson eq. (16),

$$n = n_0 \exp\psi \tag{36}$$

$$n_b = \frac{n_0}{z}\left\{\exp\psi + \frac{\lambda_D^2}{L_0^2}\psi(1 - \psi)\exp(2\psi - 2) - \lambda_D^2\left(\frac{1}{L_T} - \frac{\partial}{\partial y}\right)^2\psi\right\} \tag{37}$$

where λ_D is the Debye length defined at a density n_0,

$$\lambda_D^2 = \frac{T}{4\pi n_0 e^2} \quad . \tag{38}$$

The last term in eq. (37), which is proportional to $\partial E_y/\partial y$ can be neglected for electric fields satisfying $E_y \ll E_x$ (or more precisely $\frac{\partial E_y}{\partial y} \ll \frac{\partial E_x}{\partial x}$). The structure of the electrical double layer charges is derived from eqs.

(36) and (37) and the result is plotted in Fig. 4 (we neglect the $\partial E_y/\partial y$ contribution). This model shows that the first part of a laser produced expanding plasma (towards the laser irradiation) is negatively charged followed by a positive plasma cloud. This "standard" double layer (Hora, 1975) is derived in our model mainly because we neglect the non-linear ponderomotive forces and the creation of caviton structures (Hora et al., 1984).

The electron fluid velocity is given by eq. (24). Using the solution for ψ and the relation (11), we get

$$V_x = -\alpha \frac{L_0}{L_T} \exp(1 - \psi) \quad . \tag{39}$$

From eq. (11), α can be numerically estimated from the experimental measurements of E_x and B, and in particular the following relation seems to be useful,

$$\alpha = 10^8 \left[\frac{\text{cm}}{\text{sec}}\right] \cdot \frac{(E_x/10^6 \ \text{V/cm})}{(B/\text{MGauss})} \tag{40}$$

so that for typical laser produced plasma experiments (Eliezer and Ludmirsky, 1983; Stamper et al., 1978; Raven et al., 1978) one has $\alpha \sim 10^8$ cm/sec.

The physical solution for the potential is derived in this model for $-\infty < \psi < 1$. However, the lower bound limit is determined from the assumption made by using the equation of motion (7). In this equation we neglected so far the term $(\vec{V} \cdot \vec{\nabla})\vec{V}$, therefore in order for our stationary solution to be consistent, one has to require that the $(\vec{v} \cdot \vec{\nabla})\vec{v}$ terms are small, namely,

$$\left|\frac{(\vec{v}\cdot\vec{\nabla})\vec{v}}{\frac{e}{m}v_x B}\right| = \frac{\alpha^2}{V_T^2}\frac{L_0}{L_T}\exp(1-\psi) \ll 1 \tag{41}$$

$$\left|\frac{(\vec{v}\cdot\vec{\nabla})\vec{v}}{\frac{eE_x}{m}}\right| = \frac{\alpha^2}{V_T^2}\left(\frac{L_0}{L_T}\right)^2 \exp(2-2\psi) \ll 1 \tag{42}$$

where m is the electron mass and

$$V_T^2 = \frac{T}{m} \simeq 4.2 \cdot 10^7\,(T/eV)^{\frac{1}{2}}\left[\frac{cm}{sec}\right] \quad . \tag{43}$$

For a density scale length L_0 of the same order as the temperature scale length L_T, $L_0 \approx L_T$, eq. (42) gives the stricter values for the lower limit of the ψ. In particular assuming $T \simeq 1000$ eV, $E_x \simeq 10^6$ v/cm and $B \simeq 1$ MGauss we obtain in our model a physical validity domain given by

$$-0.1 \lesssim \psi = \frac{e\phi}{T} < 1 \quad . \tag{44}$$

Analyzing now the last of the Maxwell equations, (19), we get

$$\frac{\partial B}{\partial y} = \frac{4\pi}{c^2}\,j_x \simeq \frac{4\pi}{c^2}\left(2.72\,en_0\alpha\,\frac{L_0}{L_T} - 2en_b v_{ix}\right) \tag{45}$$

$$\frac{\partial B}{\partial x} = \frac{1}{\alpha}\frac{\partial E_x}{\partial x} = -\frac{4\pi}{c^2}\,j_y = \frac{-T}{e\alpha L_0^2}\,\psi(1-\psi)\exp(2\psi-2) \quad . \tag{46}$$

The ion current in the y direction is much smaller than the dominant electron current in the x-direction. In particular

$$\frac{j_{i,y}}{j_e} = \frac{c^2}{\alpha^2}\left[\frac{(n_b - n)}{n_0}\right]\left[\frac{L_T}{2.72\,L_0}\right] \quad , \tag{47}$$

where the density fluctuations

$$\frac{\delta n}{n_0} \equiv \frac{n_b - n}{n_0} = \frac{\lambda_D^2}{L_0^2} \psi(1 - \psi) \exp(2\psi - 2) \lesssim 0.1 \left(\frac{\lambda_D}{L_0}\right)^2 \quad . \tag{48}$$

For $\lambda_D \sim 10^{-2}$ μ, $L_0 \sim 10$ μ and $\alpha \sim 10^8$ cm/sec, we get

$$\frac{\delta n}{n_0} \lesssim 10^{-7} \quad , \tag{49}$$

$$\frac{j_{i,y}}{j_e} \lesssim 10^{-2} \quad . \tag{50}$$

To summarize, we derive a simple model where the electric potential is described by the non-linear differential equation (28) with the solution given by eq. (30). The physical branch ($\psi < 1$) introduces a typical double layer with an electron cloud leading ahead of the ion cloud (see Fig. 4). This phenomenon is known to happen when there are not ponderomotive forces and caviton structures. The magnetic field, and the electric field in the x-direction, is maximum at $\psi = 0$ (see Fig. 3) where the electron density is about 1/3 its maximum value, in good agreement with experimental data.

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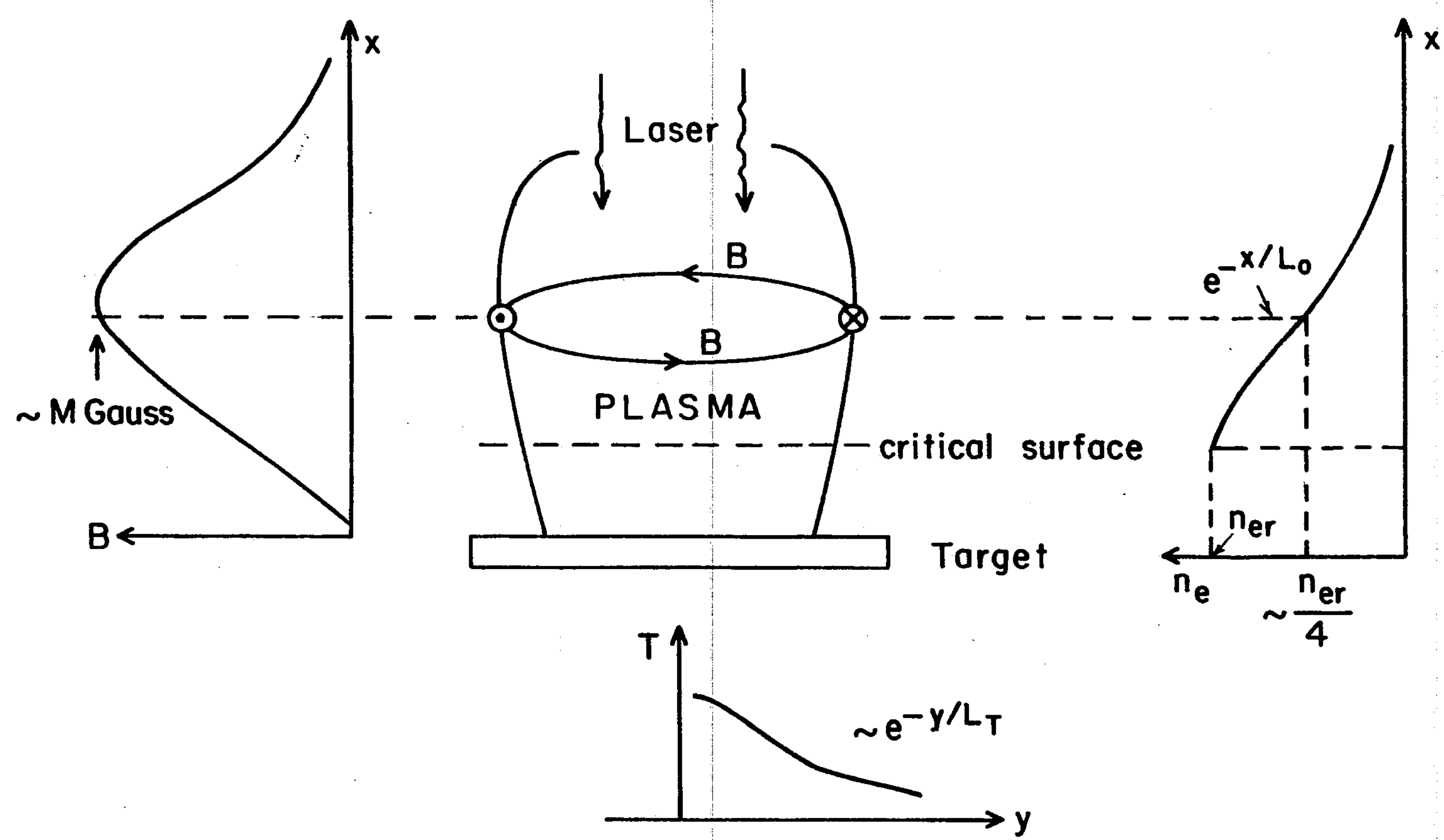
Figure Captions

Fig. 1: The description of the two dimensional geometry in x - y plane with typical density, temperature and magnetic field profiles.

Fig. 2: The dependence of the dimensionless potential ψ on the x coordinate (i.e., the laser irradiation direction).

Fig. 3: The main component of the electric field, E_x, and the magnetic field B described as a function of the potential ψ.

Fig. 4: The structure of the electrostatic double layer charges.


x
Laser
B
B
PLASMA
~ M Gauss
B
critical surface
Target
e^{-x/L_o}
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T
$\sim e^{-y/L_T}$
y

Fig. 1

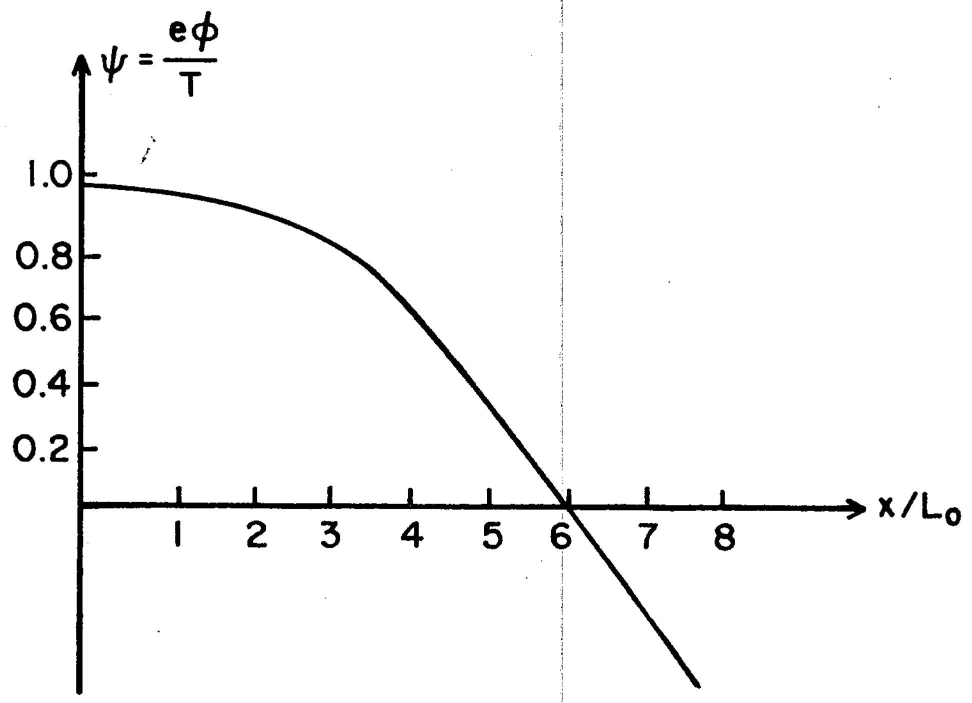


Fig. 2

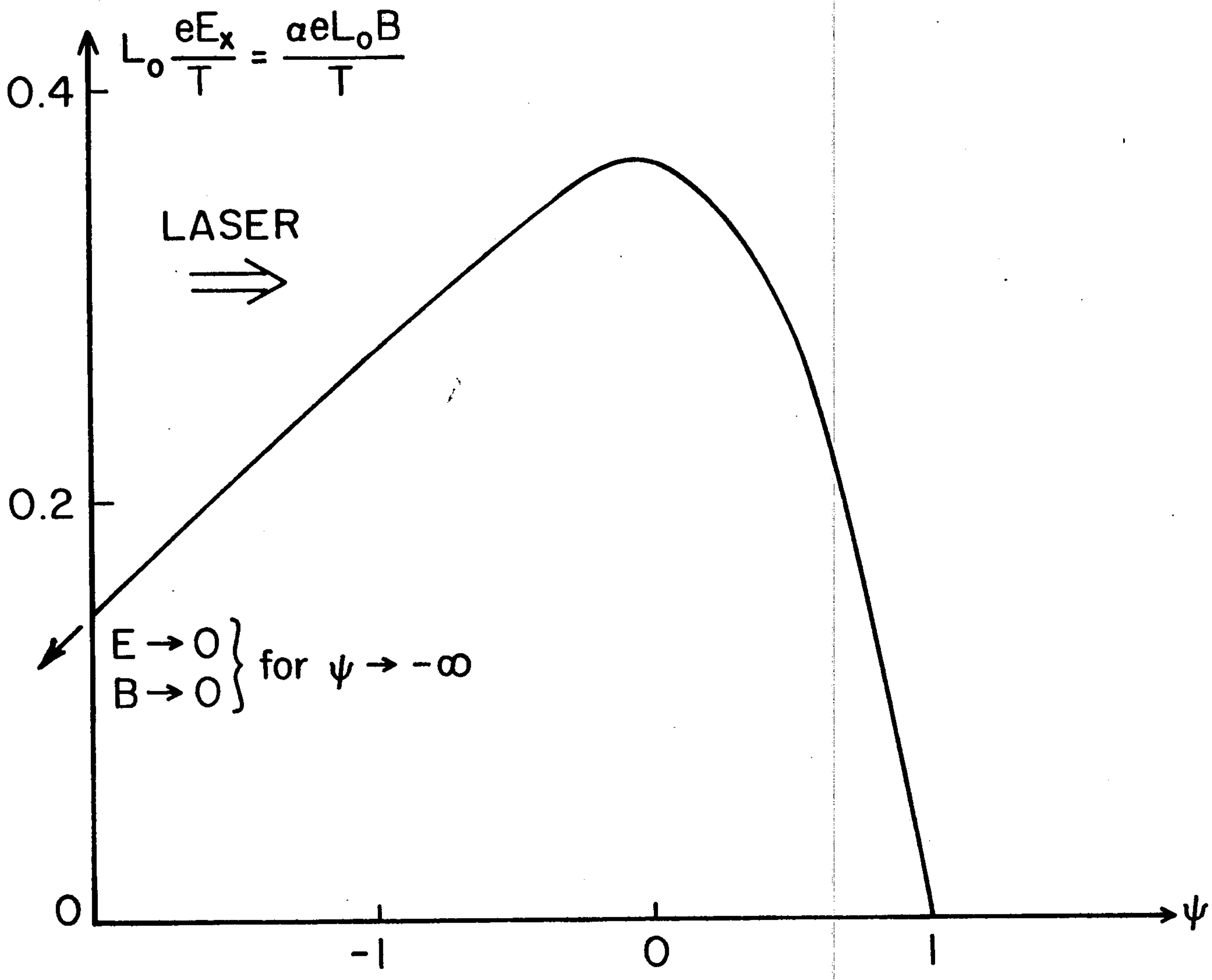
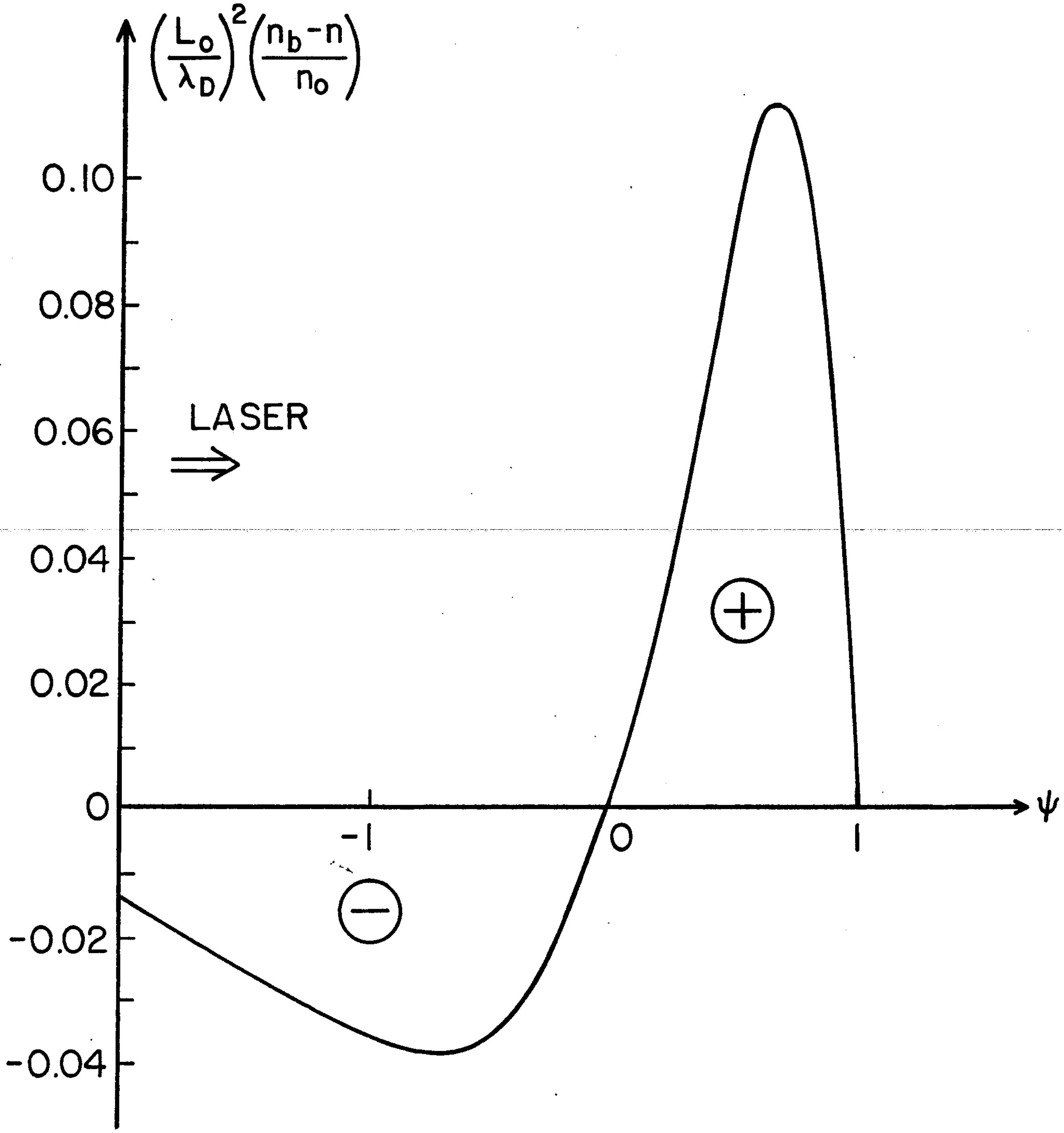

$L_o \frac{eE_x}{T} = \frac{\alpha e L_o B}{T}$
0.4
0.2
0
LASER
$E \to 0$, $B \to 0$ for $\psi \to -\infty$
-1
0
1
ψ

Fig. 3



$\left(\frac{L_o}{\lambda_D}\right)^2\left(\frac{n_b-n}{n_o}\right)$
0.10
0.08
0.06
0.04
0.02
0
-0.02
-0.04
LASER
-1
0
1
ψ

Fig. 4