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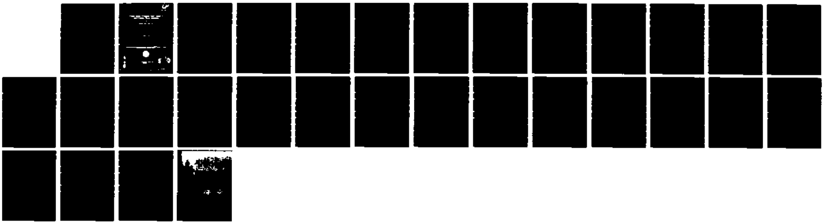

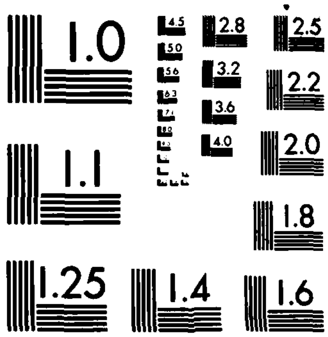

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Analytic models of the magnetic field evolution in laser-produced plasma expansions have been studied and applied to the NRL laser HANE (high altitude nuclear explosion) simulation experiment. Both one- and two-dimensional models have been investigated for laser plasma expansions with and without initial background magnetic fields. For the case with no initial background magnetic field, thermal source mechanisms have

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20. ABSTRACT (Continued)

been used to discuss the two-dimensional evolution and morphology of spontaneous self-generated magnetic fields. With an initial background magnetic field, one-dimensional models with discontinuous debris density profiles give unrealistically large magnetic field compressions, while predictions from two-dimensional models with smooth profiles are in reasonable agreement with initial NRL experimental observations.

CONTENTS

ANALYTIC MODELS OF MAGNETIC FIELD EVOLUTION IN LASER-PRODUCED PLASMA EXPANSIONS

I. INTRODUCTION

A high altitude nuclear explosion (HANE) can significantly perturb the natural ionosphere and magnetosphere by generating large-scale (tens to hundreds of kilometers), long-lived (several hours) ionization irregularities (striations). These irregularities can degrade radar and communication systems, e.g., through scintillation effects. As such, it is crucial to have a detailed understanding of the evolution of a HANE in order to achieve a reliable communications system capability in a nuclear environment. Several experiments have been conducted[1], both in space (barium cloud releases) and in the laboratory (laser-pellet explosions), in order to simulate various aspects of a HANE. Recently, renewed interest in laboratory laser-pellet HANE simulation experiments has been generated owing to detailed scaling studies.[1-3]

An important aspect of the early time (few seconds) evolution of a HANE is the manner by which the exploding debris plasma couples into the background air plasma. The nature of this early time coupling could seed or influence the evolution and structure of late time ionization irregularities. This coupling can either by collisional (particle-particle interactions) or collisionless (wave-particle interactions) depending on ambient densities and temperatures. Collisionless coupling proceeds via plasma microturbulence which in turn is driven by various plasma instabilities[4]. Recently, a set of "turn-on" conditions for collisionless coupling, in the context of the NRL laser plasma experiment, has been derived[5]. A key ingredient in determining whether or not the aforementioned plasma instabilities will be excited is the structure and magnitude of the local magnetic field in the debris-air coupling region. If the magnetic field compressions are too small several of the coupling instabilities will be inoperative. A detailed description of the early time magnetic field evolution and morphology is also important for discussing related topics such as electron heat transport, magnetic field driven interchange instabilities, and ion leakage mechanisms. Analytic models of the evolution of the magnetic fields can be used to validate HANE numerical simulations and also be compared with experimental results.

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In this report we study analytic models of the magnetic field evolution and compression in laser-produced plasma expansions. We treat both one- and two-dimensional models both with and without an initial background magnetic field. Many aspects of this problem have already been investigated[6-12]. However these studies have not been discussed or applied to recent NRL laser pellet experimental observations. The outline of this report is as follows. In Section II we present and discuss the general model equation for the evolution of the magnetic field in laser-produced plasma expansions. In Section III we study laser plasma expansions without an initial ambient background magnetic field and the expected magnitudes of spontaneous self-generated magnetic fields. The calculated self-generated magnetic fields are found to be in agreement with preliminary NRL experimental values. In Section IV we investigate, using both one- and two-dimensional models, laser plasma expansions into an ambient background magnetic field. The predicted field compressions are not inconsistent with those obtained using NRL experimental observations. We find that one-dimensional models using sharp debris density profiles give unrealistically large magnetic field compressions. We show that two dimensional models with diffuse profiles can explain several experimental observations. Finally in Section V we summarize our results.

II. BASIC EQUATIONS

For high β ($B^2/8\pi << Nk_BT$) plasmas, the equation for the evolution of the magnetic field $\underline{B}$ can be written[12-14]

$$\frac{\partial \underline{B}}{\partial t} = \nabla \times \underline{V} \times \underline{B} - \frac{c^2}{4\pi} \nabla \times \left[\underline{\eta} \cdot (\nabla \times \underline{B})\right] + \underline{S} \qquad (1)$$

where

$$\underline{S} = - \frac{ck_B}{eN_e} \nabla N_e \times \nabla T_e \qquad (2)$$

with $\underline{\eta}$ the resistivity tensor, $\underline{V}$ the fluid velocity, c the speed of light, k_B is Boltzmann's constant, and N_e and T_e are the electron temperature and density, respectively. Radiation pressure effects have been neglected in Eq. (2) since they can be shown to be small for the laser intensities used in the current NRL experiment. Equation (1) is simply Faraday's law with the electric field determined from the force balance equation for the electrons.

The generation of a magnetic field requires that the last term in Eq. (1), the source term $\underline{S}$, be nonzero. This requires that ∇N_e and ∇T_e be nonparallel.

By defining the dimensionless quantities $\check{t} = V_o t/L$, $\check{\nabla} = \nabla/V_o$, $\check{\underline{x}} = \underline{x}/L$, Eq. (1) can be written

$$\frac{\partial \underline{B}}{\partial \check{t}} = \check{\nabla} \times \check{V} \times \underline{B} - R_m^{-1} \check{\nabla}^2 \underline{B} \qquad (3)$$

where, for the moment, we have neglected $\underline{S}$ and defined V_o and L as a representative fluid velocity and a magnetic gradient scale length, respectively. Here R_m defines a magnetic Reynolds number $R_m = 4\pi\sigma L V_o/c^2$ with $\underline{\eta} \equiv \underline{I}\ \sigma^{-1}$ and $\underline{I}$ the unit tensor. For $R_m > 1$, magnetic field convection ($\check{\nabla} \times \underline{\check{V}} \times \underline{B}$ term) dominates over diffusion ($\check{\nabla}^2 \underline{B}$ term) whereas for $R_m < 1$ the opposite is true. An effective electron collision frequency ν^{eff} can be defined by $\sigma = N_e e^2/m_e \nu^{eff}$ where N_e and m_e are the electron density and mass, respectively. For $\nu^{eff} = \nu_{ei} = 3 \times 10^{-6}\ Z\ \ell n\ \Lambda\ N_e / T_e^{3/2}\ \sec^{-1}$, the classical Coulomb collision frequency, with Z the charge number and $\ell n\ \Lambda$ the Coulomb logarithm, we find $R_m \simeq 10^4$ L(cm) where we have taken $T_e \simeq 100$ eV and $V_o \simeq 4 \times 10^7$ cm/sec as representative NRL laser experimental parameters (B. Ripin, private communication). For L ~1 cm, $R_m \simeq 10^4$ dissipative effects are negligible. However, if the effective collision frequency in increased by other processes, e.g., plasma microturbulence, R_m will decrease and resistive effects will become more important. For example, for plasma turbulence resulting from the magnetized ion-ion instability[4] an effective collision frequency can be written

$$\nu_{ij}^{eff} = 0.15\ \omega_{Hi} \frac{\rho_i}{\rho} \left(\alpha_{ji}^{2/3} + 2^{-1/3}\ 3^{1/2}\ (\alpha_{ji}^{1/3} - \alpha_{ji}^{2/3})\right) \qquad (4)$$

where i and j refer to ion species i and j, $\omega_{Hi} = \omega_{pi}(1 + \omega_{pe}^2/\Omega_e^2)^{-1/2}$, ω_{pi}, ω_{pe} and electron plasma frequencies, ρ_i is the mass density of species i, ρ the total mass density and $\alpha_{ij} = N_j Z_j^2 m_i / N_i Z_i^2 m_j$. For aluminum (i) streaming through nitrogen (j), i.e, $N_i \simeq 10^{16}$ cm^{-3}, $N_j \simeq 10^{14}$ cm^{-3}, $Z_i = 10$, $Z_j = 3$ we find $R_m \simeq 10$ L(cm) ~ 10 for L ≃ 1 cm making resistive effects more important.

III. LASER PLASMA EXPANSION WITHOUT A BACKGROUND MAGNETIC FIELD

As shown in the previous section, spontaneous magnetic fields can be generated by nonparallel density and temperature gradients. These self-generated magnetic fields can be quite large[14] near the focal spot region. Since these spontaneous fields will be carried along with the expanding plasma they could influence greatly the electron and ion dynamics in the coupling shell. In addition, large-self fields also imply asymmetric departures from completely spherical expansion and reduced coupling of the laser engergy into the target.

According to Eq. (2), the magnitude and direction of the self generated magnetic field is determined by the geometrical configuration of the laser-plasma. A laser beam, which is cylindrically symmetric, will produce a plasma which expands in the direction of the normal to the target and is symmetric about its expansion direction. From symmetry considerations there can be no azimuthal density or temperature gradient. During the laser heating of the target, it is reasonable to assume that the largest contribution to the source term in Eq. (2) comes from a temperature gradient in the radial direction and a density gradient in the direction of the target normal due to expansion of the target plasma. Due to the finite radial extent of the laser beam a radial temperature gradient will exist near the edge of the focal spot. This combination of ∇T_e and ∇N_e will generate a magnetic field in the azimuthal direction in the form of a torus[12]. The self-generated field will be convected radially by the expanding plasma. This scenario has been confirmed by many previous laser-pellet experiments[14].

In order to approximate the self-generated magnetic fields in the NRL laser HANE experiment we assume a purely radial temperature gradient $\partial T_e/\partial r$ and a density gradient $\partial N_e/\partial z$ with r denoting distance perpendicular to the normal to the target plane and z representing distance in the axial direction perpendicular to the target plane. As a result Eq. (2) gives

$$S = (\partial B/\partial t)_{self} \approx (ck_B/eN_e)\,(\partial N_e/\partial z)\,(\partial T_e/\partial r) \qquad (5)$$

The radial temperature gradient is of the order $\partial T_e/\partial r \approx T_e/r_o$ where r_o is the radial extension of the laser heated plasma near the focal spot. We take the density gradient in the z-direction to be given by the debris ion expansion velocity V_o, i.e, $\partial \ln N_i/\partial z \approx \partial \ln N_e/\partial z \approx [V_o\tau_L + (\Delta V_o/V_o)R]^{-1}$ where τ_L is the duration of the laser pulse, ΔV_o is the thermal debris velocity spread, and R is the approximate position of the debris density maximum. Taking $(\partial B/\partial t)_{self} \approx B_{self}/\tau_L$ we have from (5)

$$B_{self} \approx 9 \times 10^7 \frac{T_e}{V_o r_o} \left[1 + (\Delta V_o/V_o)\ (R/V_o\tau_L)\right]^{-1} \text{ G} \qquad (6)$$

where T_e, V_o, r_o, τ_L are expressed in eV, cm/sec, cm, and sec, respectively. For $T_e \approx 100$ eV, $V_o \approx 4 \times 10^7$ cm/sec, $r_o \approx 1$cm, $\Delta V_o/V_o = 0.2$, $R = 0.5$ cm, $\tau_L = 4 \times 10^{-9}$ sec (B. Ripin private communication), Eq. (6) gives $B_{self} \approx 100$ G which is in agreement with experimentally measured values (S. Kacenjar, private communication).

To find the approximate time dependence of the self-generated magnetic field, we consider[12] the fluid variables N_e, T_e, V in Eq. (1) as consisting of zeroth order contribution plus a first order part, i.e., $N_e = N_{eo} + \Delta N_e$, $T_e = T_{eo} + \Delta T_e$, and $V = V_o + \Delta V$. The zeroth order parts N_{eo}, T_{eo}, and V_o describe a spherically symmetric expansion with the perturbations ΔN_e, ΔT_e, and ΔV representing a small departure from spherical symmetry giving rise to a source term $\underline{S}$ vanishes in the spherically symmetric case. In other words, we can linearize Eq. (1) and solve for $\partial \Delta B/\partial t$ using the zeroth order motion for $\underline{V}$ and $\underline{\eta}$ in the first two terms on the right hand side of Eq. (1). The perturbations ΔN_e and ΔT_e are retained in the source term $\underline{S}$.

The radius of the expanding laser plasma, r_s, is found from[12] the following

$$r_s(t) = R_o + \int_o^t V_s(t')\, dt' \qquad (7)$$

with R_o the initial radius. The velocity of the expanding plasma, in cylindrical coordinates, follows from the continuity equation

$$V_r = \frac{r}{r_s} V_s(t) \qquad (8a)$$

$$V_z = \frac{z}{r_s} V_s(t) \tag{8b}$$

The exploding plasma is assumed, in zeroth order, to have a homogeneous density N (t) in the course of its assumed adiabatic expansion so that

$$\frac{T}{T_o} = \left(\frac{N}{N_o}\right)^{\gamma-1} = \left(\frac{R_o}{r_s}\right)^{3(\gamma-1)} \tag{9}$$

Furthermore, we assume that the expansion decreases the plasma temperature so that the conductivity scales as

$$\sigma = \sigma_o \left(\frac{T}{T_o}\right)^{3/2} = \sigma_o \left(\frac{R_o}{r_s}\right)^{9(\gamma-1)/2} \tag{10}$$

where σ_o is the initial value and a Coulomb collisional conductivity[15] has been assumed. As a result, Eq. (1)-(2) for the azimuthal component ΔB_θ of the self-generated field, asuming cylindrical symmetry $\left(\frac{\partial}{\partial\theta} = 0\right)$ can be written

$$\frac{\partial B_\theta}{\partial t} = -\frac{\partial}{\partial z} (V_z B_\theta) - \frac{\partial}{\partial r} (V_r B_o) + D\left(\frac{1}{r}\frac{\partial}{\partial r} r \frac{\partial B_\theta}{\partial r} - \frac{B_\theta}{r^2} + \frac{\partial^2 B_\theta}{\partial z^2}\right)$$

$$+ S(r, z, t) \tag{11}$$

with $S = \frac{ck_B}{eN_e}\left(\frac{\partial N_e}{\partial r}\frac{\partial T_e}{\partial z} - \frac{\partial N_e}{\partial z}\frac{\partial T_e}{\partial r}\right)$

where, for clarity, we have dropped the Δ's from B_θ, V, N_e,and T_e and $D(t) = D_o(r_s/R_o)^{9(\gamma-1)2}$ with $D_o = c^2/4\pi\sigma_o$ We with to solve Eq. (11) as an initial value problem with B_θ (t=0) =0 and V_r, V_z given by Eq. (8).

For the expanding plasma cloud, we consider[12] the following debris density and temperature profiles which are smooth functions of position.

$$N_e = N_{eo} - \Delta N_e \exp(-r^2/r^2_s(t)) \tag{12a}$$

$$T_e = T_{eo} - (\Delta T_e/r_s) \int_o^z dz' \exp(-z'^2/r_s^2) \tag{12b}$$

From (12a) and (12b) we find

$$S(r, z, t) = (-2\, c\, k_B/e)(\Delta N_e/N_e)(r/r_s)(\Delta T_e/r_s^2)$$

$$x \exp\left[-(r^2 + z^2)/r_s^2\right] \tag{13}$$

Tidman (1975) has solved Eq. (11) using the profiles from (12) and finds, in scaled time units,

$$B_\theta(\breve{t}) = -8\pi\,(2\,e^2)^{-1/2}\,B_o\left(\frac{\Delta N_e}{N_e}\right)\left(\frac{\Delta T_e}{T_e}\right)\left(\frac{V_d}{V_o}\right)\breve{t}\,(1+\breve{t})^{-3} \tag{14}$$

where $B_o = k_B\,T_o\,\sigma_o/ec$, $V_d = D_o/R_o = c^2 / 4\pi\,\sigma_o\,R_o$, $r_s = R_o + V_o\,t$ (constant expansion velocity V_0), $\breve{t} = V_o\,t/R_o$ and $e = 2.71828$. Using parameters typical of the NRL laser experiment ($T_e \approx 100$ eV, $N_e \approx 10^{16}$ cm^{-3}, $V_o \approx 4 \times 10^7$ cm/sec), $B_\theta(\breve{t})$ is given by Fig. 1 for several ılues of $\Delta N_e / N_e$ and $\Delta T_e / T_e$. Both the magnitudes (several hundred and time dependence of B_θ are consistent with preliminary measurements ˙ved from the current NRL laser HANE experiment.

IV. LASER PLASMA EXPANSION WITH A BACKGROUND MAGNETIC FIELD

For realistic simulations of a HANE, a background magnetic field must be introduced into laser-pellet experiments. With a background magnetic field, magnetic field compression can now take place in addition to spontaneous magnetic field creation as disucssed in Section III. Magnetic field compression may be the first stage in the process leading to "pickup" of the background air ions. It is important to compute the spatial and temporal history of the magnetic field compression in order to determine where and when the peak compression is achieved.

A. One-dimensional models

We consider a one-dimensional model of laser-induced plasma expansions into a background magnetic field. The model consists of a debris plasma streaming with velocity $V_d\hat{\underline{x}}$ through a stationary background (air) plasma. Choosing to work in the debris frame of reference, the ion component of the expanding debris plasma is stationary with density n_D while the background plasma is assumed uniform with density n_B and having flow velocity $-V_d\hat{\underline{x}}$. The basic configuration is shown in Fig. 2. In the interaction region $-x_o < x < 0$, continuity and quasi neutrality are imposed where $x_o = V_D\,\tau_L$ with τ_L the duration of the laser pulse. These conditions determine the density $n_e = n_B + n_D$ and flow velocity $-V_e\,\hat{\underline{x}} = -(n_B/n_B + n_D)\,V_d\,\hat{\underline{x}}$ of the debris electrons. Initially, a constant background magnetic field $B_o\,\hat{\underline{z}}$ is taken to be normal to the flow but excluded from the interaction region as shown in Fig. 2. We wish to determine the field compression $B_z(x,t) / B_o$.

For the case where collisions are absent, the evolution of $B_z(x,t)$ was determined by Longmire[6] using magnetic flux conservation arguments and is illustrated in Fig.3. Here B_z jumps discontinuously from B_0 at $X = \varepsilon$ to $(V_d / V_e) B_o > B_o$ at $X = -\varepsilon$. The leading edge of the compression in the interation region is convected with velocity V_e.

Including collisional effects Eq. (1) gives for $B_z(x,t)$

$$\frac{\partial B_z}{\partial t} = \frac{-\partial}{\partial x}(V_x B_z) + \frac{\partial}{\partial x} V_x(x) L_c(x) \frac{\partial}{\partial x} B_z \tag{15}$$

where $L_c(x) = \nu(x) c^2/\omega_{pe}^2(x) V_x(x)$ with the effective collision frequency $\nu(x)$ being defined from $\sigma^{-1}(x) = \nu(x) m_e / N(x) c^2$. It should be noted that in the derivation of Eq. (1) and (2) the effects of electron inertia have been neglected. Eq. (15) has been solved for several special cases.[7,8,10]

As a simplified model we consider the case where the effective collision frequency is non zero only in the interation region, $-x_o < x < 0$. This effective collision frequency is defined as the sum of the classical Coulomb collision frequency plus an anomalous part due to plasma turbulence. Let

$$L_c(x) = \begin{cases} 0 & x > 0 \\ L_{co} & -x_o < x < 0 \\ 0 & x < -x_o \end{cases}$$

where L_{co} is constant. As a result the equation governing $B_z(x,t)$ for $-x_o < x < 0$ can be written

$$\frac{\partial B_z}{\partial t} - V_1 \frac{\partial B_z}{\partial x} - L_{co} V_1 \frac{\partial^2 B_z}{\partial x^2} = 0 \tag{16}$$

In the following dimensionless variables $\tilde{x} = x / L_{co}$, $\tilde{t} = |V_1| t / L_{co}$, and $\tilde{B} = B_z/B_o$ Eq. (16) can be written ($-x_o < x < 0$)

$$\frac{\partial B_z}{\partial t} - \frac{\partial B_z}{\partial x} - \frac{\partial^2 B_z}{\partial x^2} = 0 \tag{17}$$

where, for clarity, we have dropped the tildes. The initial and boundary conditions appropriate to Eq. (17) are: $\tilde{B}(x > 0.\ t = 0) = 1$, $\tilde{B}(-x_o <$

$x < 0,\ t = 0) = 0,\ \check{B}(x = \infty, t) = 1,\ B(x=0-\varepsilon, t) + \partial\check{B}/\partial x\ (x=0-\varepsilon, t) = 1.$

Eq. (17) together with these initial and boundary conditions can be solved to yield

$$B_z(-x_o < x < 0,\ t) = \frac{V_d}{V_e}\left(1 + (2\pi)^{-1} \exp(-x/2)\ \zeta(x.t)\right) \tag{18}$$

where

$$\zeta(x, t) = (1 - 2\ \partial / \partial x)\ \alpha(x, t)$$

and

$$\alpha(x, t) = \int_{-\infty}^{\infty} d u\ u\ (u^2 + \tfrac{1}{4})^{-2} \exp\left(-(u^2 + \tfrac{1}{4})t\right) \sin u x$$

$$= \pi (x - t) \exp(-|x|/2) + (\pi^{1/2}/2)$$

$$x \int_o^t d m \left(t\, m^{-3/2} - m^{-1/2}\right) \exp\left(\frac{-x^2}{4m} - \frac{m}{4}\right)$$

$$= \pi (x-t)\exp(-|x|/2) + \pi \operatorname{erfc}\left(\tfrac{1}{2} x\, t^{-1/2}\right) \sum_{n=o}^{\infty} \frac{x^{2n}(4n+t)}{2^{3n}(2n-1)!!n!}$$

$$+ \pi^{1/2}\exp(-x^2/4t) \sum_{n=1}^{\infty} \frac{x^{2n}(4n+t)}{2^{3n}(2n-1)!!n!} \sum_{k=o}^{n-1} (-2)^{k+1}(2k-1)!!\ \left(\frac{t}{2_x}\right)^{k+1/2}$$

Fig. 4 shows the evolution of $B_z(x,t)$ as given by Eq. (18). For times $\check{t} > 1$ collisions will smooth the discontiuous jump in B_z given the Longmire analysis[6].

B. Two-dimensional models

In the previous section, a one-dimensional model of an expanding laser plasma was assumed to have sharp discontinuous debris density profile in order to simplify analytical calculations. Unrealistically large magnetic field compressions were obtained[6] by assuming an infinitely steep density profile. In this section we show the effects of using a diffuse, smooth debris density profile by making a two-dimensional analysis[11] of a laser plasma expanding into a background magnetic field.

We consider a laser plasma expanding into a paraxial magnetic field $\underline{B} = B_o \hat{z} = B_o \cos\theta \, \hat{e}_r - B_o \sin\theta \, \hat{e}_\theta$ which is imbedded in a stationary background plasma and assume a spherical coordinate system (r, θ, ϕ) with the polar angle θ measured from the z-axis. Assuming spherical symmetry $(\partial/\partial\theta = \partial/\partial\phi = 0)$ expressions for B_r and B_θ from Eq. (1) can be written

$$\frac{\partial B_r}{\partial t} = (r \tan\theta)^{-1} V_r B_\theta + D \left(r^{-2} \frac{\partial}{\partial r} r^2 \frac{\partial B_r}{\partial r} - \frac{2B_r}{r^2} - \frac{2B_\theta \cot\theta}{r^2} \right) \tag{19}$$

$$\frac{\partial B_\theta}{\partial t} = - r^{-1} \frac{\partial}{\partial r} r V_r B_\theta + D \left(r^{-2} \frac{\partial}{\partial r} r^2 \frac{\partial B_\theta}{\partial r} - \frac{B_\theta}{r^2 \sin^2\theta} \right) \tag{20}$$

where we have neglected the self-generated magnetic fields in comparison with B_0 and noted the B_ϕ is negligible for very early times. On time scales short compared to the resistive time scale, the diffusive terms in (19) and (20) can be neglected and we are left with

$$\frac{\partial B_r}{\partial t} = (r \tan\theta)^{-1} V_r B_\theta \tag{21}$$

$$\frac{\partial B_\theta}{\partial t} = - r^{-1} \frac{\partial}{\partial r} r V_r B_\theta \tag{22}$$

We assume uniform expansion $V_r = V_0 r/r_0$, quasi-neutrality for the electrons, and a gaussian debris density profile $N_D(r,t=0) = N_0 \exp(-r^2/r_0^2)$ where $r_0 \simeq V_0 \tau_L$ with τ_L the duration of the laser pulse. Under these conditions, Eqs (21) and (22) can be solved[11] analytically for B_θ, B_r for short times δt such that the field is only slightly altered:

$$\delta B_\theta \simeq \frac{2 V_o B_\theta \delta t \, (N_o/N_B) \exp(-r^2/r_o^2)}{r_o \left[1 + (N_o/N_B) \exp(-r^2/r_o^2)\right]^2}$$

$$\left[\frac{r^2}{r_o^2} - 1 - \frac{N_o}{N_B}\right] \exp(-r^2/r_o^2) \tag{23}$$

$$\delta B_r = (r \tan\theta)^{-1} \left(\frac{N_o V_o}{N_B + N_o} \frac{r}{r_o} \right) B_\theta \delta t \tag{24}$$

where N_b is the background plasma density. The peak magnetic compression is achieved at $r = r_m$ where $\partial/\partial r (\delta B_\theta) = 0$ giving

$$(\delta B_o / B_o)_{max} \simeq (V_o \delta t / 2 r_o) \left[(r_m^2 / r_o^2) - 2 \right] \qquad (25)$$

with $r_m \simeq [f (N_o, N_B)]^{1/2} r_o$, $f(x,y) = \ln(x/y) - \ln g(x,y)$, $g(x,y) = (\ln (x / y) + 2) / (\ln (x/y) - 2)$. For example in $N_B \simeq 10^{14}$ cm^{-3} and $N_o \simeq 10^{16}$ cm^{-3} , we find $r_m \simeq 1.9 \, r_o$ indicating that peak magnetic field compression occurs ahead of the expanding laser-produced plasma cloud. Furthermore, the laser plasma cloud density at r_m is given by $N_o (r = r_m) \simeq 0.28 \, N_B$. A characteristic shell thickness, at early times, can be found using $\delta B_\theta \simeq \frac{1}{2} (\delta B_\theta)_{max}$, giving $t \simeq 0.42 \, r_o$. These analytically obtained features that (1) the maximum field compression occurs in front of the advancing shell and (2) the maximum field intensity in the compression region is proportional to the radial displacement of the shell are consistent with preliminary NRL laser experimental results (S. Kacenjar, private communication).

Finally, by consideration of the conservation of magnetic flux in two-dimensions, the field compression scaling as given by Eq. (23) and (24) can be shown to be reasonable. Consider an annulus of compressed magnetic field with inner and outer radii of r_1 and r_2, respectively. Magnetic flux conservation implies $B_0 r_2^2 = B_c (r_2^2 - r_1^2)$ where B_c/B_0 is the magnitude of the field compression. This gives $B_o / B_o \simeq r_2 / 2 \delta$, $\delta = r_2 - r_1$. For the NRL laser experiment $R_2 \simeq 3$cm, $\delta \simeq 1.3$cm , giving $B_c/B_o \simeq 1$–2 in agreement with observations (S. Kacenjar, private communication). In addition, the direct proportionality between B_c/B_0 and r_2 is not inconsistent with recent NRL experimental findings (S. Kacenjar, private communication).

V. SUMMARY

We have attempted to provide, in this preliminary report, simple analytic models for the magnetic field evolution in laser-induced plasma expansion in the context of the NRL laser plasma HANE simulation experiment. Both one- and two-dimensional models have been used for laser plasma expansions with and without initial background magnetic fields. For the case with no initial background magnetic field, we find reasonable agreement between analytic two-dimensional models and preliminary results from the NRL laser plasma experiment. It is shown that self-generated spontaneous magnetic fields are small in comparision to proposed ambient background fields. For the case of laser plasma expansion into a background magnetic field, one dimensional models with sharp, discontinuous profiles give unrealistically large magnetic field compressions while two-dimensional models incorporating smooth debris profiles give results are not inconsistent with current NRL experimental observations. Pr‹ iictions of magnetic field compressions are supported by simple conservation arguments.

Future work will include comparison of these analytic models with future experimental data and the use of these analytic models for validation of large numerical codes.

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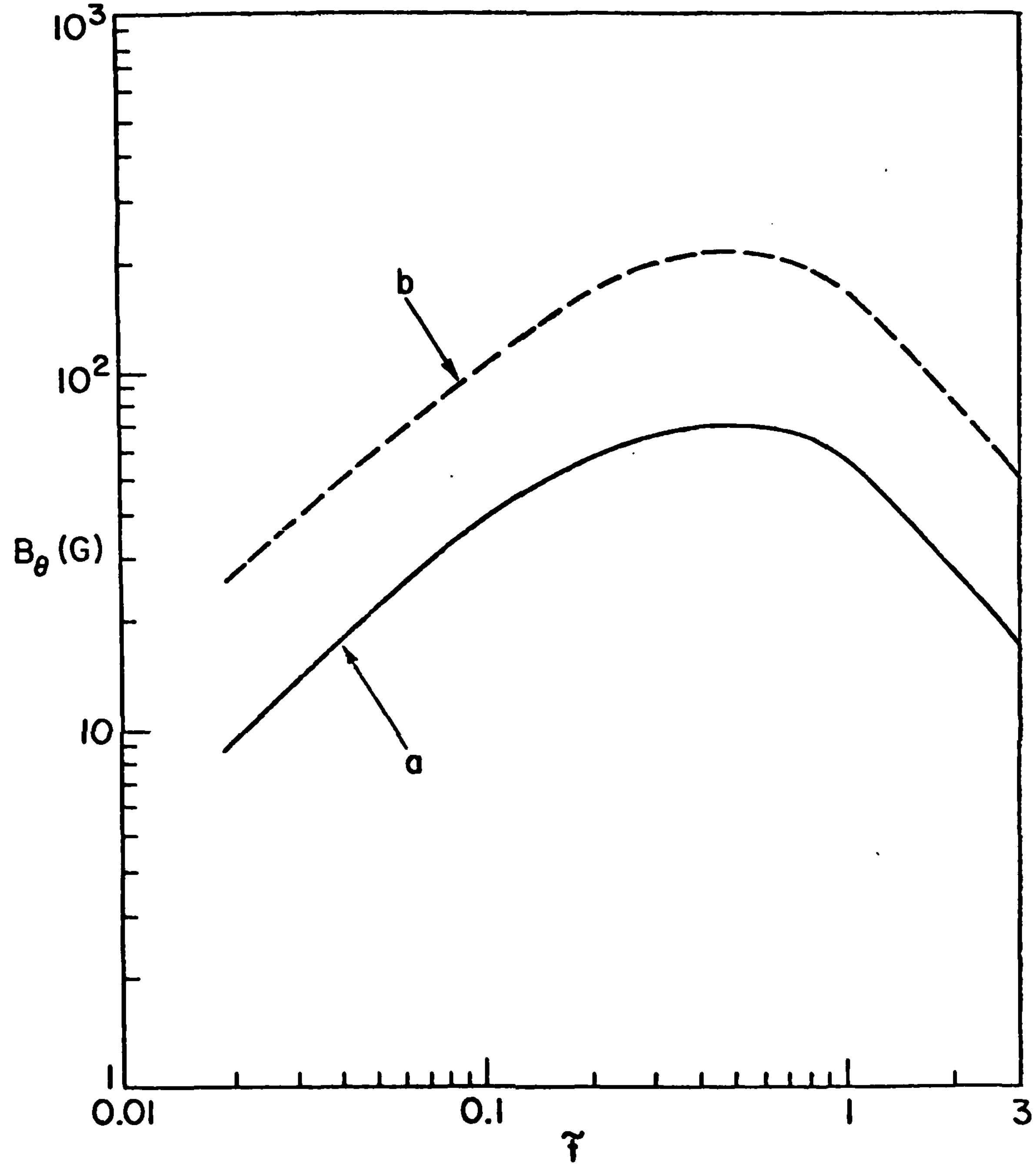
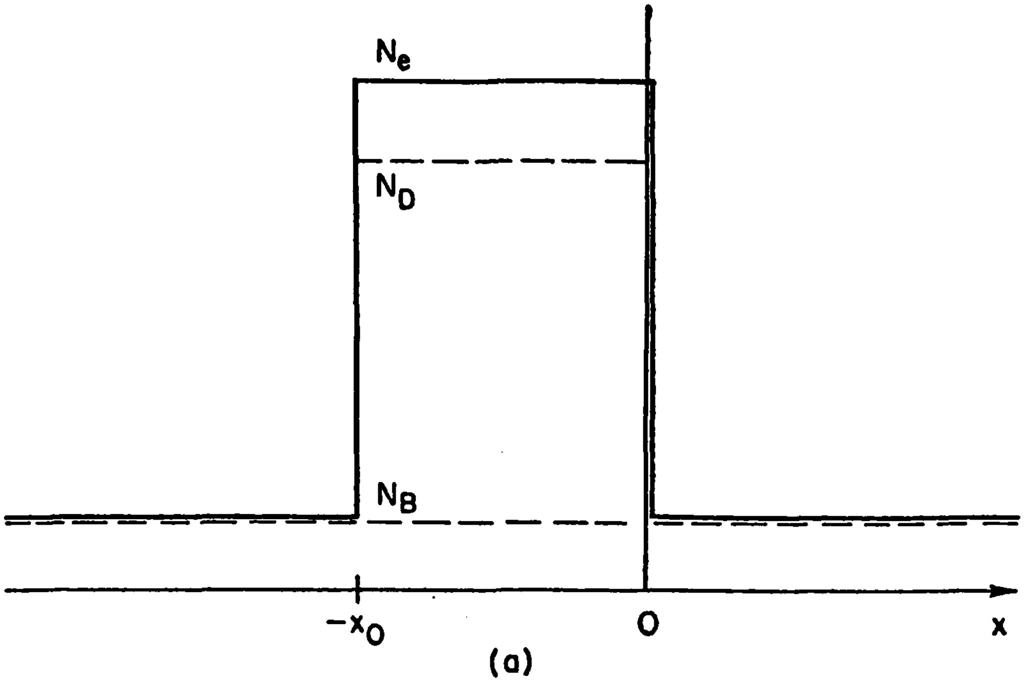


Fig. 1 Self-generated magnetic field B_θ produced by an asymmetic laser-plasma expansion vs. scaled time $t = V_o\tilde{t}/R_o$. Curve a corresponds to $\Delta N/N = \Delta T/T = 0.1$ while curve b corresponds to $\Delta N/N = \Delta T/T = 0.3$.



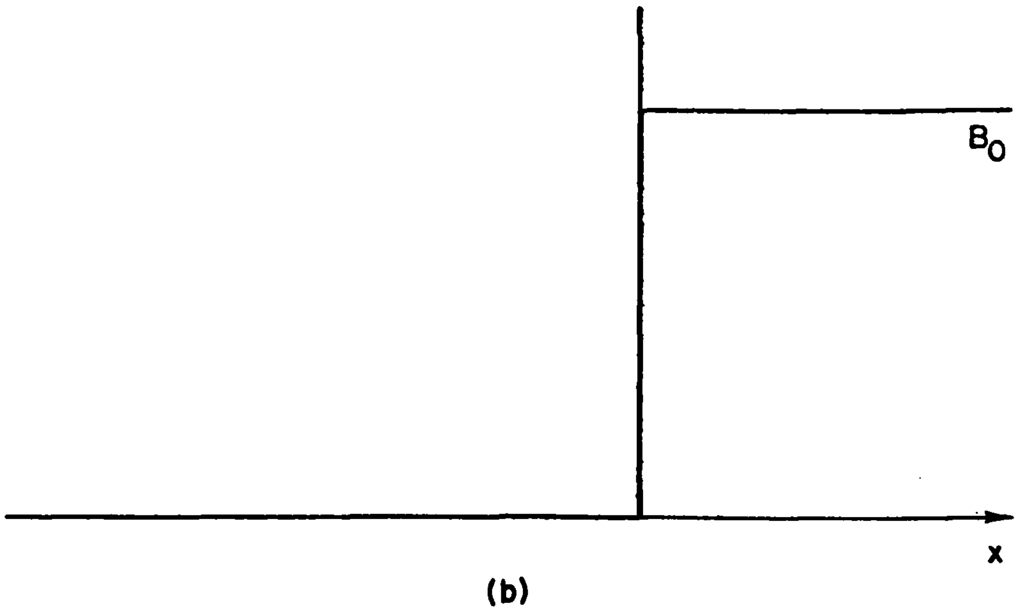


Fig. 2 Plot of (a) density of debris ions N_D, background ions N_B, and electrons $N_e = N_D + N_B$ as a function of x and (b) initial (t = 0) profile of background magnetic field. Here $x_o \cong V_D \tau_L$ with V_D the average debris velocity and τ_L the duration of the laser pulse.

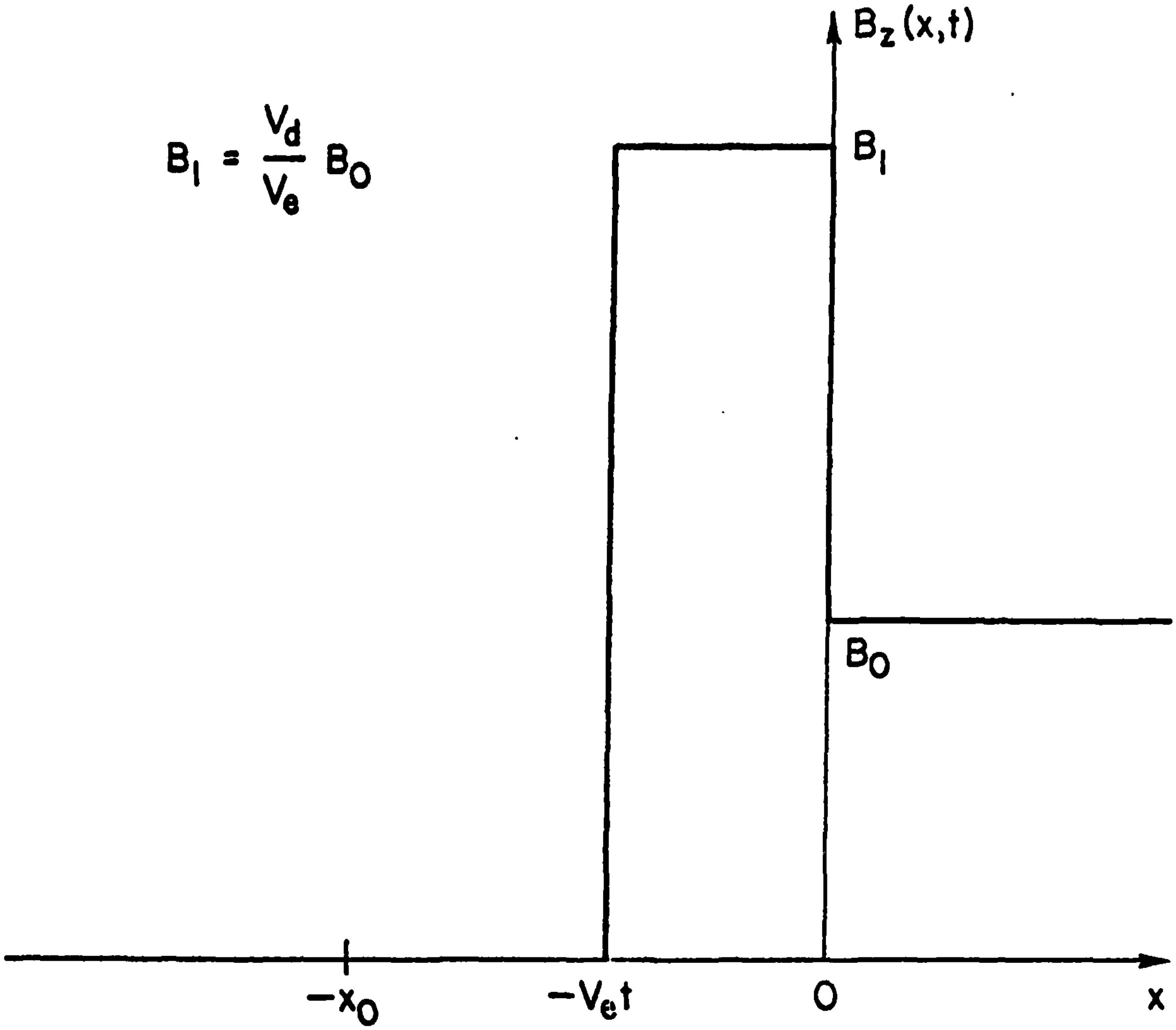


Fig. 3 Plot of $B_z(x,t)$ neglected resistance and inertia (Longmire solution).

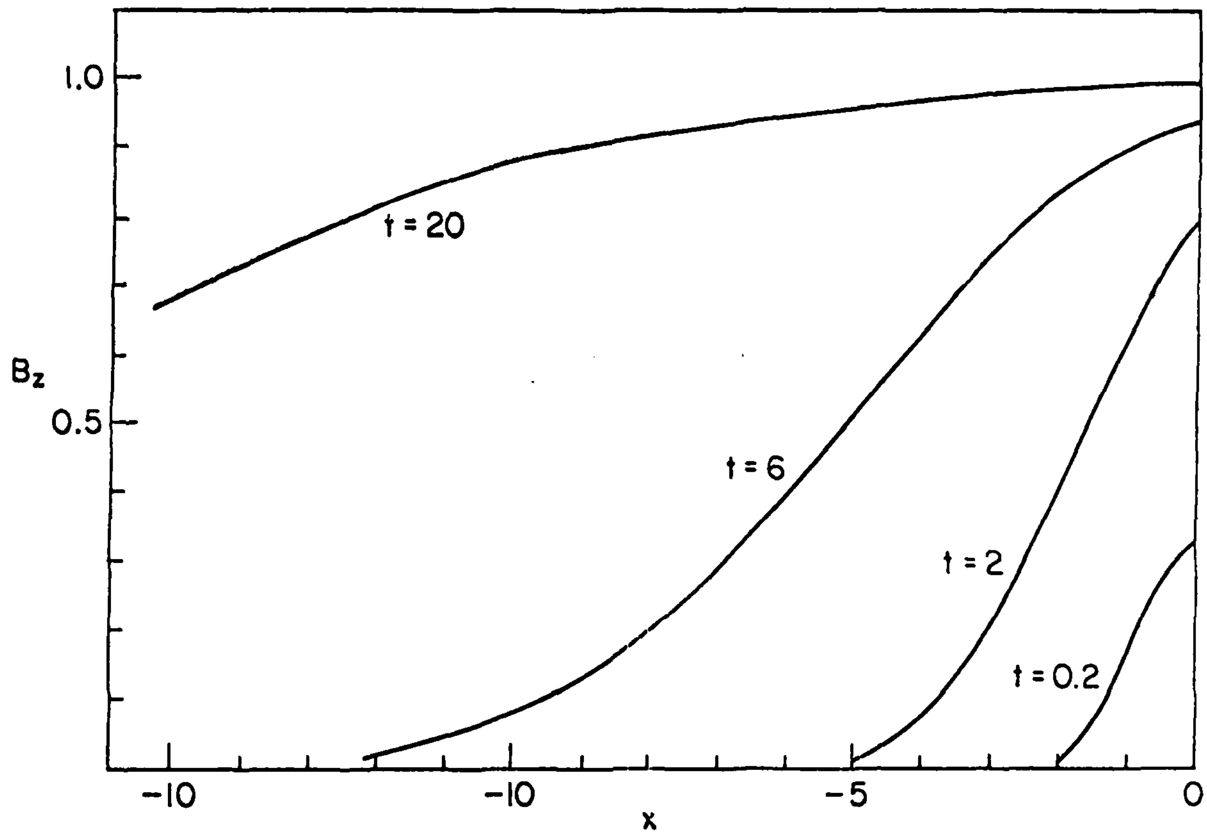


Fig. 4 Plot of $B_z(x,t)$ with constant resistivity for $- x_o < x < 0$. The quantities x, t, B_z are scaled by L_{co}, L_{co}/V_e, and $(V_D/V_e)B_o$, respectively.

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