

LA-UR- 97 - 4016

Approved for public release;
distribution is unlimited.

Title: Fast Ignitor Coupling Physics

CONF-97/082--

RECEIVED

FFR 0 2 1998

OSTI

Author(s): R. J. Mason, XPA
M. Tabak, LLNL

Submitted to: For presentation at the 11th Biennial
Nuclear Explosives Design Conference
'97 NEDPC

Lawrence Livermore National Laboratory
October 20-24, 1997

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

19980327 053

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy. The Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

DTIC QUALITY INSPECTED 3

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Fast Ignitor Coupling Physics (U)

R. J. Mason and M. Tabak*

Los Alamos National Laboratory, Los Alamos, NM 87545

*Lawrence Livermore National Laboratory, Livermore, CA 94550

The Fast Ignitor is an alternate approach to ICF in which short pulse lasers are used to initiate burn at the surface of the compressed DT fuel. The aim is to avoid the need for careful central focussing of final shocks, and possibly to lower substantially the energy requirements for ignition [1]. Ultimately, both goals may prove crucial to Science Based Stockpile Stewardship (SBSS). This will be the case should either emerging energetic needs, or funding difficulties render the presently planned radiative fusion approach to ignition with the NIF impractical. Ignition is a first step towards the achievement of substantial energy and neutron outputs for such Stewardship.

For success with the Fast Ignitor, the laser energy must be efficiently deposited into megavolt electrons (suprathermal), which must, in turn, couple to the background ions within an alpha particle range. To understand the electron fuel coupling, we have used ANTHEM plasma simulation code [2] to model the transport of hot electrons generated by an intense ($\geq 3 \times 10^{18} \text{ W/cm}^2$) short pulse 1.06 μm laser into plasma targets over a broad range of densities (0.35 to $10^4 \times n_{\text{crit}}$). Ponderomotive effects are included as a force on the cold background and hot emission electrons of the form, $F_{h,c} = -(\omega_{p,h,c}^2 / 2\omega^2) \nabla I$, in which I is the laser intensity and $\omega_p^2 = 4\pi e^2 n / m_0 \gamma$ with m_0 the electron rest mass. Our study will spell out the acceleration and transport mechanisms active in the Fast Ignitor environment.

We show that: 1) the intense (30 MG to 1.5 GG) magnetic fields arise in this interaction are due to the ponderomotive push on background electrons, and tardy electron shielding, and that 2) these fields can confine the heated electrons to the surface, possibly aiding fast ignition.

Figure 1 collects typical simulation results. Frame (a) shows axial cuts of the magnetic field for a $3.3 \times 10^{18} \text{ W/cm}^2$ glass laser drive producing 700 keV electrons with 40% absorption in an initial 50 times overdense plasma. It shows a peak field of 300 MG at 340 fs directed in consistency with a central stream of hot electrons into the plasma. Frame (b) shows concomitant B-field contours. In (c) we show the total ion charge density Zn_i and the electron division into hot n_h and cold n_c density components. Frame (e) is the hot emission electron flux nv_h , (f) gives the return flow nv_c , and (d) gives the total, $nv = nv_h + nv_c$. Clearly, the hot electrons are strongly focussed along the central axis of the beam through the null point in magnetic field.

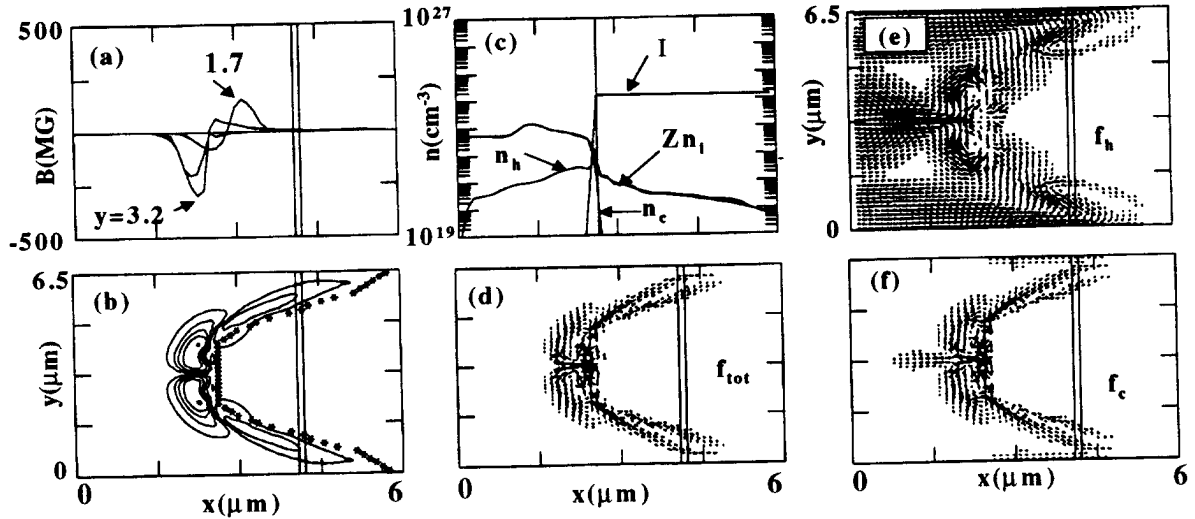


Figure 1. Magnetic fields, densities and electron flux under intense laser illumination.

ANTHEM indicates that the focussing effect grows more intense as both the background density and the laser intensity is increased. A resultant trapping of the hot electrons near the surface can lead to energy loss though fast ion surface emission. Such effects must be given careful consideration in capsule design for the Fast Ignitor. (U)

- [1] M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilks, J. Woodworth, E. M. Campbell, M. D. Perry, and R. J. Mason, *Phys. Plasmas* **1**, 1626 (1994).
- [2] R. J. Mason, *J. Comput. Phys.* **71**, 429 (1987).

Fast Ignitor Coupling Physics

Nuclear Explosives Design Physics Conference

**Lawrence Livermore National Laboratory
Livermore, CA**

October 20-24, 1997

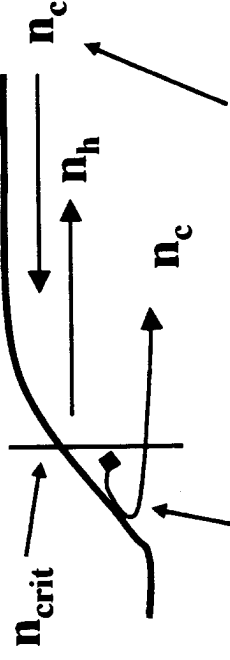


Applied Theoretical & Computational Physics Division
Plasma Physics Applications Group, XPA

Los Alamos

Full-particle implicit plasma simulation grew from the need to model ICF electron transport driven by CO₂ lasers

- Suprathermal electrons were driven by lasers into the surface of a pellet
- Resistive E-fields drew a cold return current
- Pressure driven E-fields held the hot electrons near in the high density regions and forced fast ion blow-off



We tried to use the E-fields established by Ohm's law in the background to govern hot particle transport

$$0 = -n_c e \vec{E} - v_{ci} n_c (\vec{v}_c - \vec{v}_i); \quad n_c v_c = -n_h v_h$$

- Later we realized that an E-field balancing the hot electron pressure was needed to hold the suprathermals in the corona

$$0 = -\nabla P_h - e n_h \vec{E}$$

- Adding these gave a momentum-like equation that with a finite E-field unless $n_e \rightarrow 0$; introduction of the electron inertial terms and Ampere's law avoided this singularity

The Implicit Moment codes avoid singularities in the velocities at low densities

- The electron velocities are obtained from the updated currents, rather than, say, an

$$\text{Ampere's law, e.g. } \vec{v}_e = -\frac{\dot{J}_e}{en_e} = \frac{-c}{4\pi en_e} \nabla \times \vec{B}$$

- That is, we use:

$$\frac{\partial n_e \vec{v}_e}{\partial t} = -\nabla \cdot \vec{P} - en_e (\vec{E} + \vec{v}_e \times \vec{B} / c) - v_{ei} n_e (\bar{v}_e - \vec{v}_i)$$



The new currents are combined with Maxwell's equations to produce the field predictions

We must solve:

$$\frac{\partial \vec{E}}{\partial t} = -4\pi e(Zn_i \vec{v}_i - n_e \vec{v}_e) + c \nabla \times \vec{B}$$

with

$$\frac{\partial \vec{B}}{\partial t} = -c \nabla \times \vec{E}$$



For plasma motion in the x-y plane this approach leads to a complex elliptic system for E_x , E_y and B_z

The implicit currents

$$\mathbf{j}_x^{(m+1)} = \mathbf{j}_x^{(m)} + n_x^{(m)} \frac{[\mathbf{E}^{(m+1)} \times \boldsymbol{\Omega}_x + (\mathbf{E}^{(m+1)} \cdot \boldsymbol{\Omega}_x) \boldsymbol{\Omega}_x]}{(1 + \Omega_x^2)}$$

Combine with Ampere's Law to yield the E- field components

$$E_x^{(m+1)} = \left(E_x^{(m)} - \beta E_y^{(m)} + \gamma \frac{\partial B_z^{(m+1)}}{\partial y} + \gamma \beta \frac{\partial B_z^{(m+1)}}{\partial x} \right) / (1 + \beta^2)$$

$$E_y^{(m+1)} = \left(E_y^{(m)} + \beta E_x^{(m)} - \gamma \frac{\partial B_z^{(m+1)}}{\partial x} + \gamma \beta \frac{\partial B_z^{(m+1)}}{\partial y} \right) / (1 + \beta^2).$$

Which combine with Faraday's Law to give the elliptic equation for B_z

$$B_z^{(m+1)} = B_z^{(m)} - c \Delta t \left[\frac{\partial E_y^{(m+1)}}{\partial x} - \frac{\partial E_x^{(m+1)}}{\partial y} \right]$$

Once the fields are known we can update the plasma components, and particularly the ions as particles

- If the electron moments -- n_e , \mathbf{j}_e , and the pressure tensor \mathbf{P}_e are simply updated from the fluid data, we have a hybrid code -- *probably with a small Δt , if \mathbf{P}_e is left explicit.*
- If electron particles are moved each cycle to update the moments, we have a full-particle implicit plasma code.



Features engaged for the Fast Ignitor

- Fluid “cold” background and “hot” emission electrons, fluid ions
- “Hots” emitted isotropically at critical and below over a skin depth
- Momentum equations advance relativistic momentum \mathbf{p} , $\mathbf{v} = \mathbf{p}/\gamma$
- Hot e^- drag against the background electrons - absorption at back bd.
- Specular boundaries top and bottom
- Grid-following light deposition algorithm with inverse-bremsstrahlung
- Hot e^- scatter against the ions -- introduces resistivity
- Flux-limited thermal conduction in the hot and cold electron fluids



In application to the Fast Ignitor we add ponderomotive terms to the electron momentum equations

- These are of the form $\mathbf{F}_{h,c} = -(\omega_{ph,c}^2/2\omega^2) \nabla I$, in which I is the laser intensity and $\omega_p^2 = 4\pi e^2 n/m_0 \gamma$ with m_0 the electron rest mass.
- They give rise to the predicted E-field:

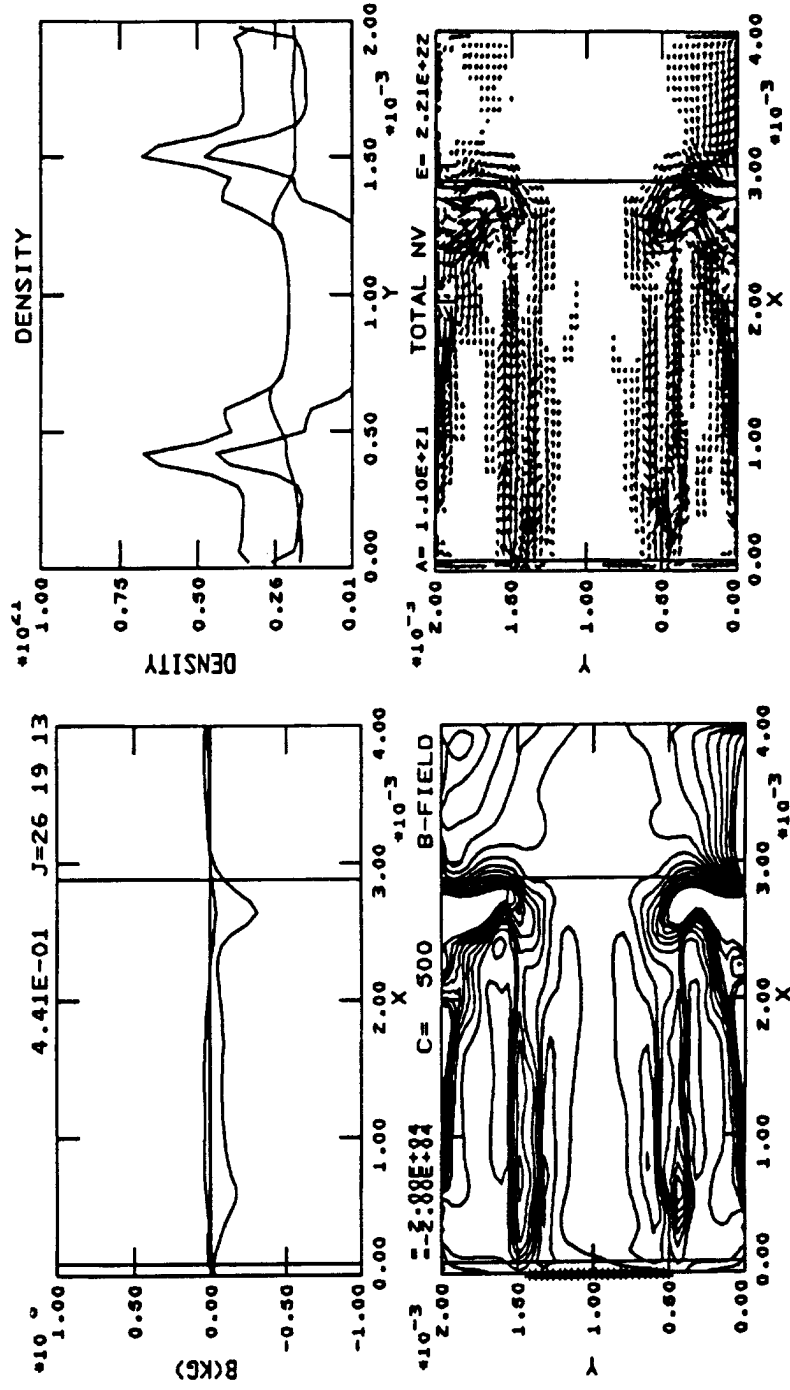
$$\mathbf{E}^{(m+1)} = \frac{\mathbf{E}^{(m)} - [4\pi e f^{(m)} - c \nabla \times \mathbf{B}^{(m+1)}] \Delta t + \left[\frac{-\nabla \cdot \mathbf{P}}{en} - \frac{v^{(m+1)} \times \mathbf{B}^{(m)}}{c} - \frac{4\pi e}{2mc\omega^2} \nabla I \right] (\omega_p \Delta t)^2}{1 + (\omega_p \Delta t)^2}$$

which for $\omega_p \Delta t \ll 1$ has a curl, yielding a B-field, i.e.,

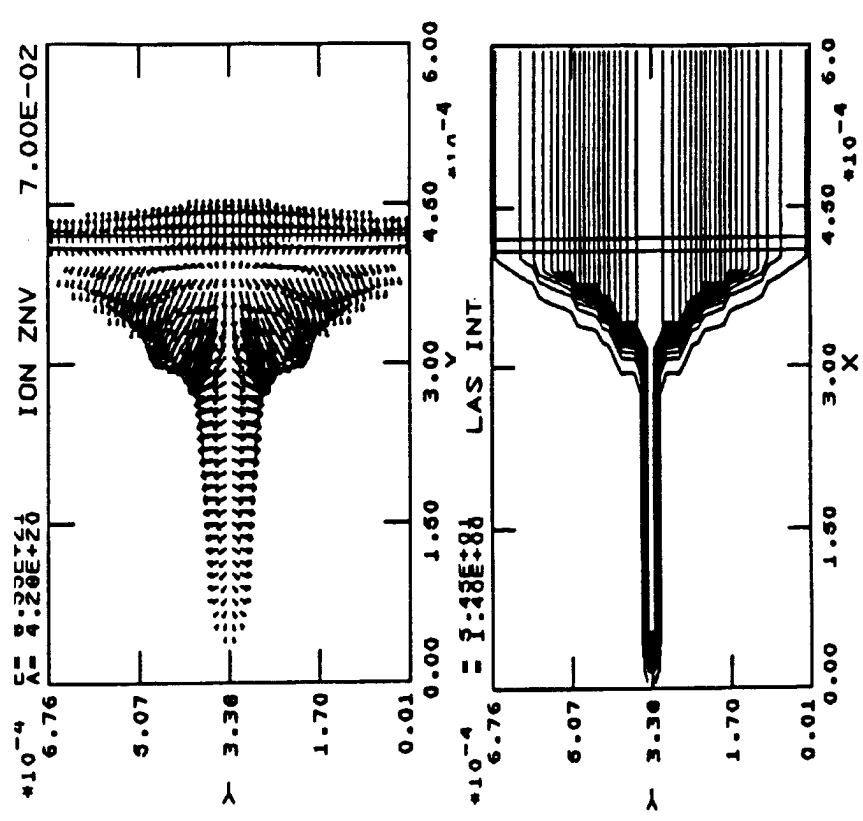
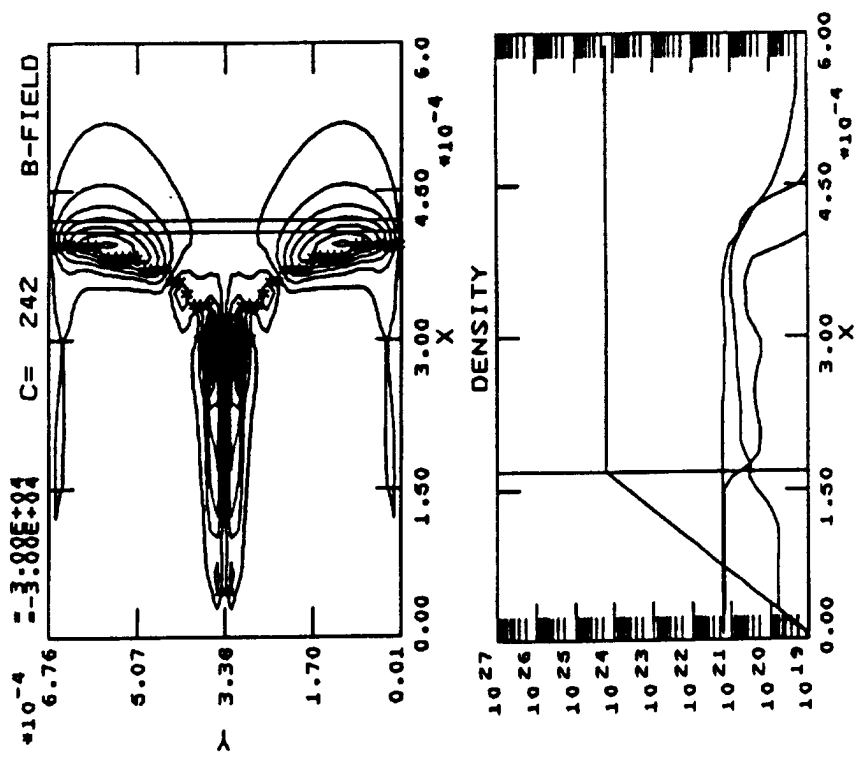
$$\mathbf{B}^{(m+1)} = \mathbf{B}^{(m)} - c \nabla \times \mathbf{E}^{(m+1)} \Delta t.$$



At 0.35 x n_{crit} with 40% anomalous absorption over 40 μm the laser creates a channel down to 0.2 n_{crit} and a ~10 MG B-field with e⁻ following the beam

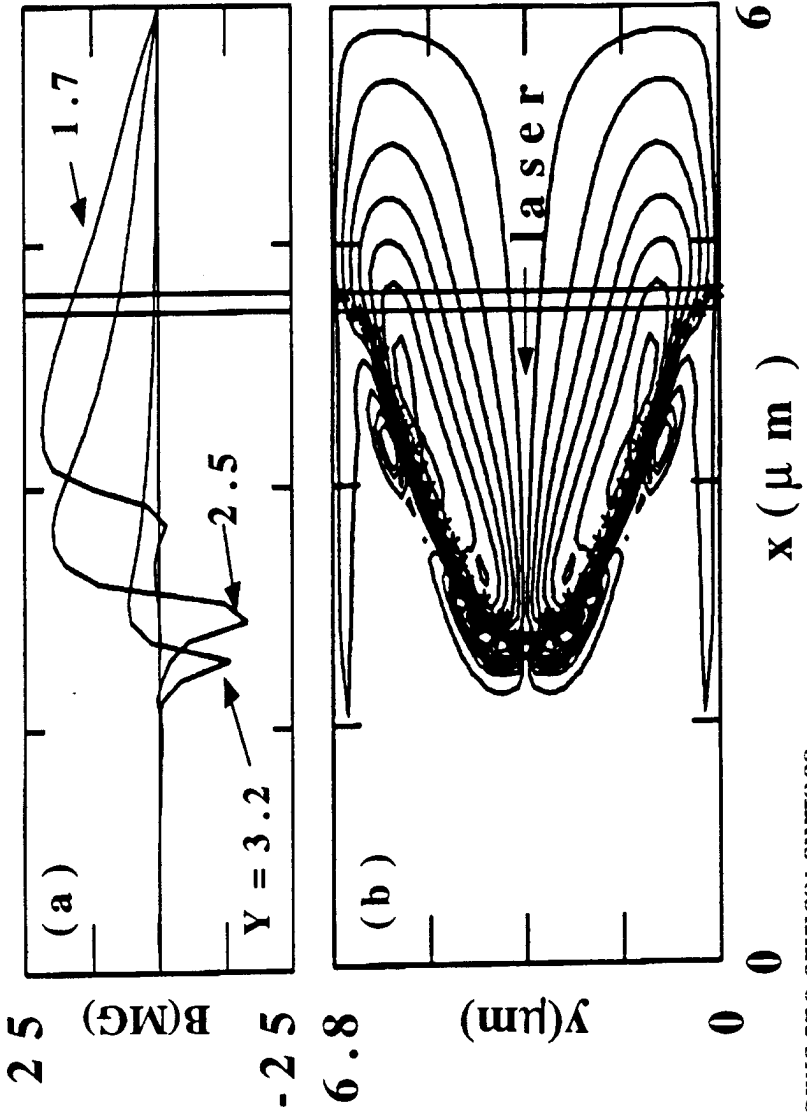


At $1.6 \times n_{\text{crit}}$ the 3.2×10^{18} W/cm² laser burns through the background by relativistic lowering of ω_p



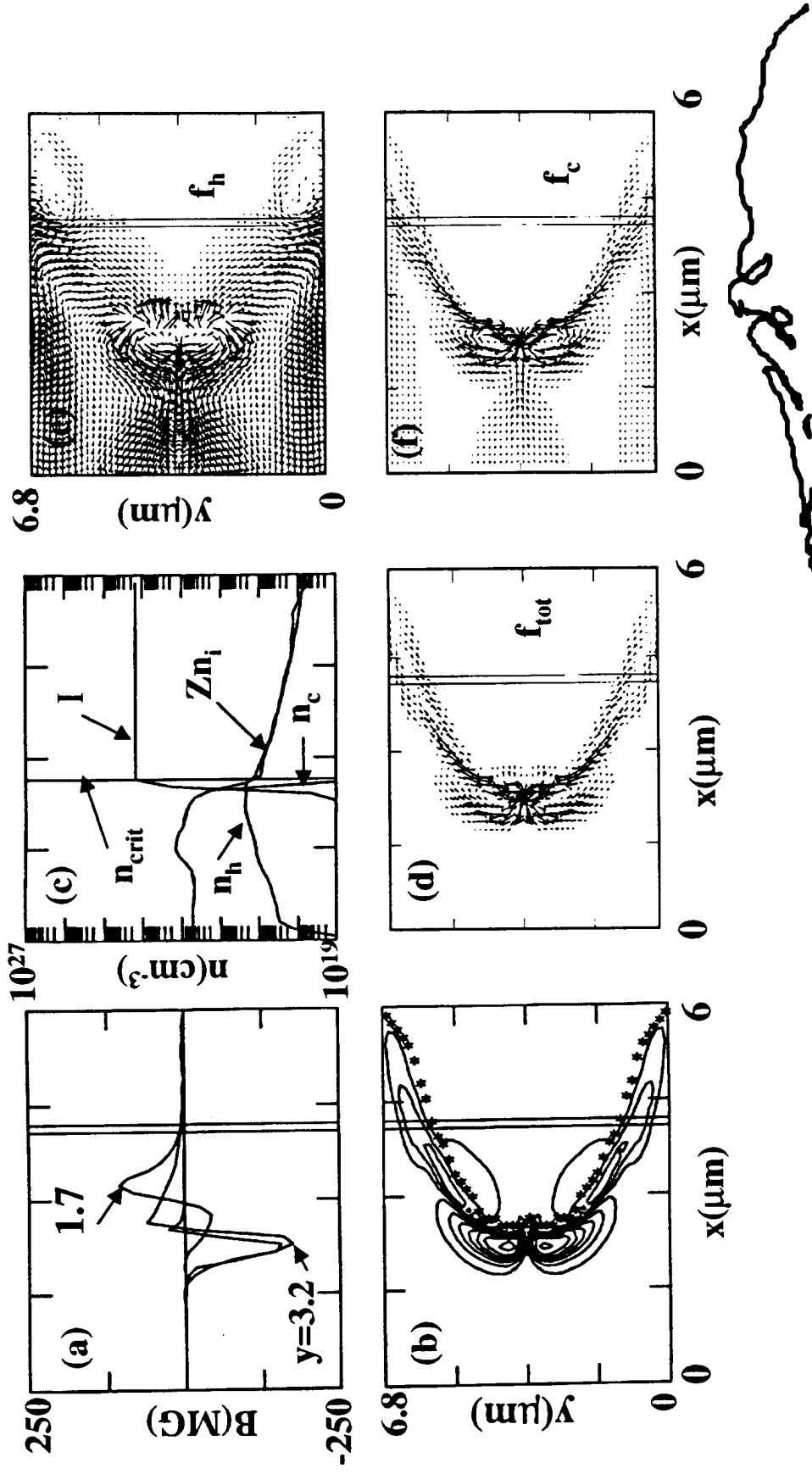
For a 4 x ncrit plasma driven at a net intensity of 5.6 x 10¹⁸ W/cm² we calculate a supercritical 16 MG B-field

- The slab accelerates at a velocity consistent with $nM_p u^2 = I/c$

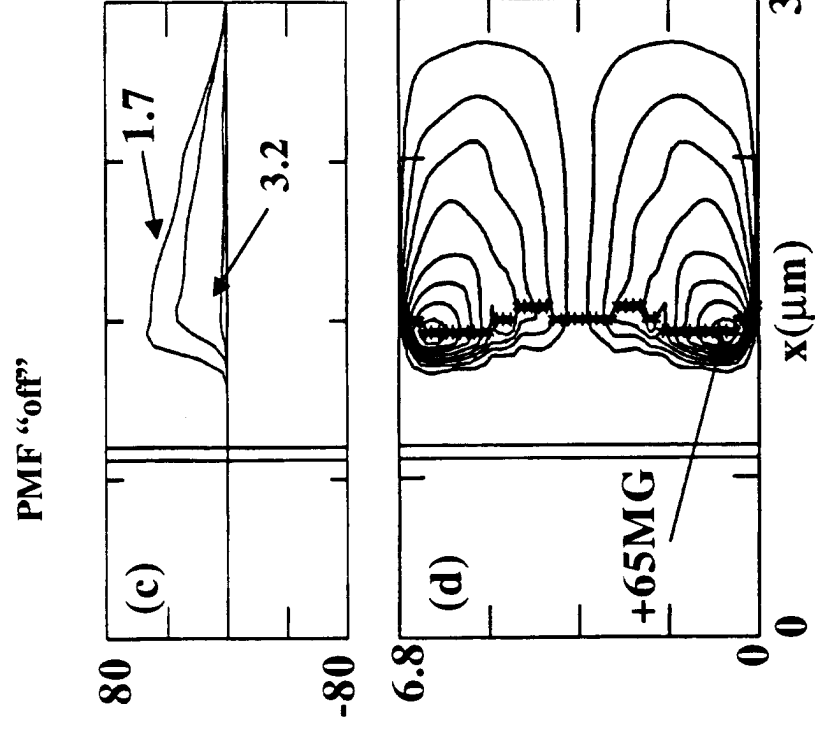
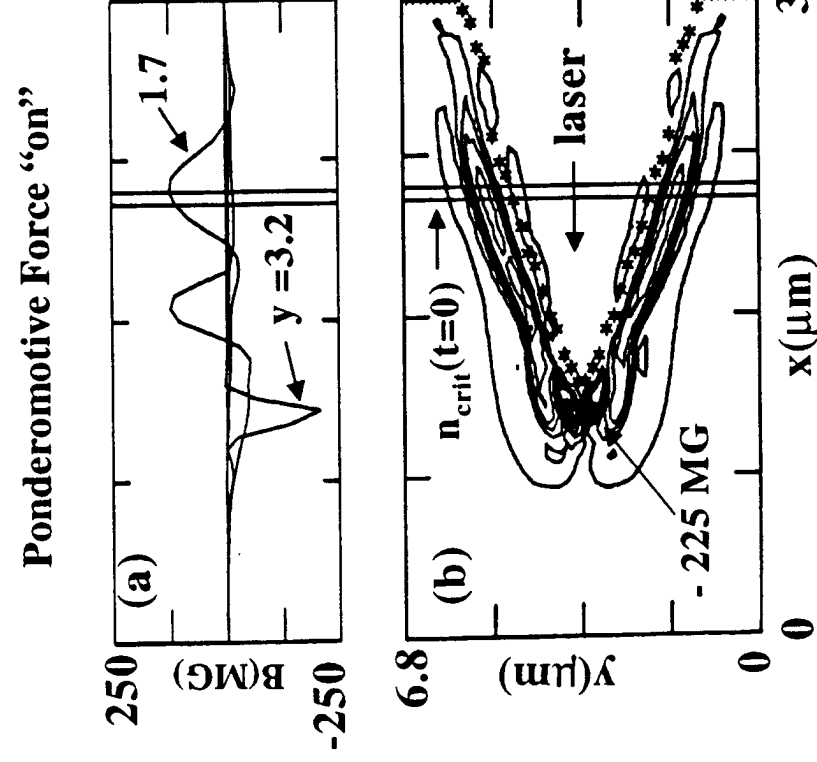


* marks the critical surface

The intense internal magnetic fields are consistent with a laser push driving the net electron flow axially into the target



The illumination of a $200 \times n_{\text{crit}}$ plasma with a 1.3×10^{19} W/cm² driver gives 250 MG internal B-fields, but only 65 MG thermoelectric (external) B-fields when the ponderomotive force is suppressed.



Observations and Conclusions

- **B-fields exceeding 250 MG have been calculated for $I > 10^{19} \text{W/cm}^2$ and sharp profiles with peak densities exceeding $200 n_{\text{crit}}$.**
- **Electron trapping near critical may derive from the PMF B-fields**
 - This could localize the electron coupling to ions and aid fast ignition.
- **Such trapping can give rise to fast ion blow-off.**
- **Intense propagation into $0.35 n_{\text{crit}}$ channels ejects ions laterally and yields a PMF-sourced 10 MG B-field at the channel edge, corresponding to hot electron flow in the laser direction.**
- **If refraction were added to ANTHEM, a central focusing of the light and dependent B-field are anticipated.**



M98002646



Report Number (14) LA-UR--97-4016
CONF-971082--

Publ. Date (11) 199710
Sponsor Code (18) DOE/DP, XF
JC Category (19) UC-700, DOE/ER

DOE