3. Session 1
Interaction Experiments with Advanced Photon Sources (I)

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LLNL
SLAC/DESY Workshop on
Radiation Interaction with Matter
23-24 January, 1997

Interaction Experiments
with
Advanced Photon Sources

Richard More, LLNL
plus many collaborators

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Target Interaction Codes and Radiative Processes

Transparencies from presentation to JAERI KRE

LASNEX CODE GROUP:
G. Zimmerman, J. Harte,
D. Bailey, D. Kershaw,
and others

plus

D. Eder, W. Krueer, A. Osterheld
LASNEX — a versatile 2-D computer code with physical models for processes important to laser interaction and laser fusion

G. Zimmerman, J. Harte et al.
Laser interaction physics

- Plasma instabilities (Raman, Brillouin) where $\omega_L = 2\omega_p$
- Laser refraction by plasma
- Inverse bremsstrahlung
- Resonance absorption
  Absorption and reflection where $\omega_L = \omega_p$
Laser-matter interaction-LASNEX code

LASNEX calculation of laser absorption:

- 3-D ray-tracing calculates refraction by plasma
- Inverse bremsstrahlung absorption
- Resonance absorption is fit to plasma simulation results
  - Angle-dependent absorption
  - Production and spectrum of high-energy electrons
- Ponderomotive force from laser pressure
- One-dimensional electromagnetic wave package for short-pulse laser
Hydrodynamics:

- 2D expansion
- Ablation flow with heat conduction
- Shock front
- Equation of state $p(\rho, T), E(\rho, T)$
- Ionization state $Q(\rho, T)$
Laser-matter interaction-LASNEX code

LASNEX gives several choices for 2-D Hydrodynamics

• Quadrilateral Lagrange description for large distortions

• Second-order ALE and hand rezoning allow mesh straightening while maintaining accuracy; slide-lines allow flexible zoning and flow

• Partial pressures from all plasma components:
  — Magnetic \( J \times B \) force
  — Ponderomotive force of the laser light
  — Momentum deposition by photons and burn products

• QEOS in-line equation of state for thermal pressure
Thermal electron heat conduction

Substantial transport inhibition for long-pulse lasers

Conjectured explanations include
- Turbulence
- Large magnetic fields
- Non-Maxwellian electron distributions
Superthermal electrons ($E = 10-100$ keV)

- Production mechanism is not completely understood
- Electrons transport energy over large distances
Laser-matter interaction-LASNEX code

Superthermal electron transport in LASNEX

- Laser creates fast-electron spectrum
- Energy-loss in collisions with thermal electrons
- Fast electrons produce energetic x-rays
- Fast electrons change NLTE atomic populations
- Electron transport by multigroup diffusion
  - Relativistic corrections
  - Self-consistent electric field included
Thermal electron heat conduction

Conjectured explanations include

- Turbulence
- Large magnetic fields
- Non-Maxwellian electron distributions
Laser-matter interaction-LASNEX code

Thermal electron transport

- Electron heat conduction is calculated with flux-limited diffusion
- Finite-element option improves accuracy in distorted mesh
- Electron conduction is affected by
  - Magnetic fields
  - Partial ionization
  - Fermi degeneracy in dense matter
  - Collective effects
- One-dimensional nonlocal conduction in steep temperature gradients
Large electric and magnetic fields

Ambipolar electric fields

Magnetic field ~ $10^6$ gauss
Laser-matter interaction-LASNEX code

Magnetic fields are included in the fluid (MHD) approximation

- Externally imposed or generated in 2-D plasma
- Magnetohydrodynamics
- Hall effect and magnetic diffusion
- Nernst effect (tends to expel magnetic field)
- External circuit

Limitations on the geometry:
- 1-D has $B_0$ and $B_z$
- 2-D has $B_0$ only
Atomic ionization

- Transient (frozen) ionization
- Collisional-radiative with photo absorption
- Possibly non-Maxwellian thermal electrons
- LTE with ionization by compression of ion core
Laser plasma physics subroutines

DCA package is an in-line NLTE atomic kinetics model

DCA = Detailed configuration accounting rate equation code

- Data files or Inline hydrogenic model provide level energies and transition rates for user-selected levels
- Voigt line profiles
- Often used as post-processor for spectroscopic diagnostic of plasma conditions

Y. Lee, G. Zimmerman
Laser plasmas emit X-rays in several ranges of energy.
Laser-matter interaction-LASNEX code

Laser fusion codes simulate many diagnostics with a single model

- X-ray pictures show irradiation, heat flow and symmetry
- Broad-band x-ray spectra give temperature data
- Line spectra indicate temperature and density conditions
- Holographic interferograms and x-ray probes measure electron density
- Neutron images, neutron and charged-particle spectra, target activation measure nuclear reactions in the target
Fig. 24.20
Schematic of picosecond electron diffraction apparatus. A streak camera tube (deflection plates removed) is used to produce the electron pulse. The 25-keV electron pulse passes through the Al specimen and produces a diffraction pattern of the structure with a 20-ps exposure.
G. Mourou  
U. of Rochester

Temperature under Superheated Conditions (K)

1.2 1.4 1.6 1.8 2.0 x 1000

Absorbed Fluence to Achieve Melt (mJ/cm²)

Relative Delay (ps)

F_melt (equilibrium)

5 7 9 11 13 15

Fig. 24.31
Laser-induced melt metamorphosis for aluminum. The points mark the elapsed time for the diffraction rings to completely disappear. The vertical error bar represents the degree of uncertainty in defining the moment of complete melt. The region beneath the curve represents the conditions under which the Al is left in a superheated solid state.
Ultra Short Pulse Laser Interaction with Solid Targets

2nd US-Japan Workshop on Interactions of High Power Waves with Plasmas and Matter

December 16-18, 1996

R. More  R. Stewart
R. Walling  R. Shepherd
D. Price  B. Young
G. Guethlein  D. Gold
A. Osterheld  Z. Zinamon*
B. Wilson  B. White
W. Goldstein  F. Patterson

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Using ultra-short pulse laser, hot dense plasmas can be studied.

Good laser pulse quality, measured by absence of prepulse, gives precise control of plasma conditions.
USP Laser produces high temperature in a dense target plasma

Theory
At the LLNL USP laser we examine each aspect of the target interaction.
Why is absorption important?

• We plan a systematic campaign to generate hot plasma at
  — Known material density $\approx$ solid
  — Known high energy density $\approx 10^9$ Joule/gram

$\textbf{We require good absorption} \quad \gg \quad 1\%$

$\textbf{We must know the absorption in each specific target}$

• Absorption data gives us information about the hydrodynamic expansion of the target (motion during the heat pulse)

• Special phenomena are observed in certain materials

• 70% absorption occurs for p-polarized light at $60^\circ$ incidence. Does this give a useful increase of the effective laser power?
High energy-density matter on the USP laser

- During the early 90's we began with a simple optimism:
  - No prepulse
  - No hydrodynamic expansion
  - Easily produce high temperatures
  - An inexpensive laser

- By now we can be more precise
  - Prepulse is less than $10^{-8}$ of the $2\omega$ heat pulse
  - 100 A expansion at $10^{18}$ W/cm$^2$; 20 A for $10^{14}$ W/cm$^2$
  - Produce temperatures up to 1 keV, but with difficulty
  - A substantial investment in people, laser and diagnostics

- The qualified statements have less rhetorical power, but demonstrate progress in the science
Ultra-short pulse laser experiments

Laser absorption depends on intensity

Normal Incidence, 120 fsec Pulses

- Low prepulse
- Always irradiate fresh target material
- Measure pulse autocorrelation and spatial profile
- Measure incident, reflected and scattered energies

We understand the absorption by aluminum targets

LASNEX MODEL
- Gaussian beam profile
- Realistic time-history
- Maxwell equations with correct AC conductivity
- 2T EOS and conductivity
- Hydrodynamic expansion
- Nominal heat flow
Ultra-short pulse laser experiments

Angle-dependent absorption exceeds 60%

The theoretical calculation assumes a 50 Å surface expansion

D. Price, R. More et al.
Laser plasma physics subroutines

Multilayer code solves Maxwell equations for light incident on a specified planar density profile

\[
\rho(x) = \begin{cases} 
\rho_0 & x > L \\
\rho_0 e^{-\Delta x} & x < L
\end{cases}
\]

with \( \frac{\omega_p}{\omega} \propto \rho^{1/2} \), \( \omega_\tau \propto \rho^{-1} \)

Three inputs: \( L, r_1 = \frac{\omega_p}{\omega}, r_2 = \omega_\tau \)

- Solve Maxwell equations for s and p polarizations by matrix multiplications
- Results are independent of zoning
- Adjust input to match experiments
- Provision for additional intra-atomic absorption
Inverse Bremsstrahlung = AC conductivity

(for $\hbar \omega \ll kT$ and $E_f < kT$)

$$
\varepsilon = (n+ik)^2 = 1 + \frac{4\pi i \sigma(\omega)}{\omega}
$$

$$
\sigma = \frac{ne^2}{m} \left\langle \frac{\tau}{1 + i\omega \tau} \right\rangle
$$

$$
\bar{\tau} = (\langle \tau^{-1} \rangle)^{-1}
$$

$$
\varepsilon = 1 - \left(\frac{\omega_p}{\omega}\right)^2 \left\{ (\omega \bar{\tau})^2 F_2 - i (\omega \bar{\tau}) F_1 \right\}
$$

$$
F_1 \equiv B^2 \int_0^\infty \frac{u^3 e^{-u} \, du}{1 + B^2 (\omega \bar{\tau})^2 u^3}
$$

$$
F_2 \equiv B^3 \int_0^\infty \frac{u^{4.5} e^{-u} \, du}{1 + B^2 (\omega \bar{\tau})^2 u^3}
$$

Only 2 parameters occur:

$$
r_1 = \frac{\omega_p}{\omega} \propto (Z^* n_i)^{1/2}
$$

$$
r_2 = \omega \bar{\tau} \propto n_i^{-1}
$$
Three inputs: \( L, r_1 = \frac{\omega_p^0}{\omega}, r_2 = \omega \tau^0 \)

- Expect small scale length

\[ 1\text{Å} \leq L \leq 100\text{Å} \]

- For solid density aluminum, \( 3 \leq Z^* \leq 13; \)

\[ \text{expect } 5.1 \leq \frac{\omega_p^0}{\omega} \leq 10.6 \]

- \( \tau^0 = \) Collision time,

\[ \text{expect } 0.4 \leq \omega \tau^0 \]
The parameters which match the experiments vary in a plausible manner:

<table>
<thead>
<tr>
<th>I</th>
<th>L</th>
<th>ωp/ω</th>
<th>ωτ</th>
</tr>
</thead>
<tbody>
<tr>
<td>3·10^{14}</td>
<td>20 Å</td>
<td>5.1</td>
<td>0.4</td>
</tr>
<tr>
<td>1·10^{15}</td>
<td>20 Å</td>
<td>5.1</td>
<td>0.5</td>
</tr>
<tr>
<td>5·10^{15}</td>
<td>30 Å</td>
<td>5.8</td>
<td>0.6</td>
</tr>
<tr>
<td>1·10^{16}</td>
<td>50 Å</td>
<td>6.5</td>
<td>0.7</td>
</tr>
<tr>
<td>3·10^{17}</td>
<td>80 Å</td>
<td>7.2</td>
<td>0.75</td>
</tr>
</tbody>
</table>
Absorption depends on the target material

At high intensity, observe Universal Plasma Mirror reflection

Low Intensities:
- Conduction electron inverse bremsstrahlung
- Intra–atomic line absorption (interband transitions)

High Intensities:
- Free electron/ion inverse bremsstrahlung
- Novel mechanisms above about $10^{18}$ Watts/cm$^2$
How do transparent insulators absorb at high laser field?

Breakdown gives conduction electrons

- Multiphoton excitation
  \[ n \hbar \omega \approx \Delta E \]
- Impurities, color-centers, defects all give states in the energy-gap which can trap or release electrons

Conduction electrons absorb energy by inverse bremsstrahlung. Their absorption heats the solid.

There is avalanche ionization when the quiver energy is large enough.

This much is obvious, but what happens next?
**Al₂O₃ overlayer experiment measures absorption by oxide layer**

The oxide thickness L is varied

- \( \lambda = 400 \text{ nm} \)
- \( \theta = 15^\circ \)

The experiment shows 5 specific features which challenge the theory.

**Graph:**
- Absorption vs. Thickness L
  - \( A_s \approx A_p \)
  - Bump at 80%
  - 60-120 Å
  - \( I = 10^{13} \frac{W}{cm^2} \)

\( 10^4 \text{ Å} \)
Oxide overlayer data determines the optical properties of hot dense $\text{Al}_2\text{O}_3$

$$\theta = 15^\circ$$

Aluminum: $$\frac{\omega_p}{\omega} = 5.1 \quad \omega \tau = 11.0$$

$\text{Al}_2\text{O}_3$ (oxide): $$\varepsilon \approx 4.2 + 6.6 \lambda$$

![Graph showing absorption vs. thickness](image)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Absorption

Thickness (cm)

$I = 10^{13} \frac{W}{cm^2}$

Oxide:
$\varepsilon = 4.2 + 6.6 \lambda$

Aluminum:
$\frac{\omega_p}{\omega} = 5.1 \quad \omega \tau = 1.0$

$I = 2 \times 10^{13} \frac{W}{cm^2}$

Oxide:
$\varepsilon = 4.0 + 5.5 \lambda$

Aluminum:
$\frac{\omega_p}{\omega} = 5.1 \quad \omega \tau = 0.8$
I = 5 \times 10^{13} \frac{W}{cm^2}

Oxide:
\varepsilon = 3.5 + 8.0 \lambda

Aluminum:
\frac{\omega_p}{\omega} = 5.1 \quad \omega\tau = 0.7

I = 10^{14} \frac{W}{cm^2}

Oxide:
\varepsilon = 2.0 + 11.0 \lambda

Aluminum:
\frac{\omega_p}{\omega} = 5.1 \quad \omega\tau = 0.7
Oxide:
\( \varepsilon = -2 + 18j \)

Aluminum:
\( \frac{\omega_p}{\omega} = 5.1 \quad \omega \tau = 0.9 \)

Oxide:
\( \varepsilon = -12 + 35j \)

Aluminum:
\( \frac{\omega_p}{\omega} = 5.8 \quad \omega \tau = 1.2 \)
Ultra-short pulse laser experiments

Thin foil target – reflected and transmitted probes

Transmission can measure target ionization with the 100 fsec time resolution of the probe pulse

D. Price, R. More et al.
Ultra-short pulse laser experiments

Fourier interferometry can be used to measure expansion velocity

Characterize plasma with extraordinary space and time resolution

Apply to: test of hydrodynamics, x-ray laser design, and laser wakefield accelerator

R. Stewart, G. Guethlein, D. Gold et al.
Laser interaction physics subroutines

Our Maxwell equation subroutine predicts absorption and phase-shifts of probe pulses on laser-heated targets.

These predictions are consistent with experiment and enable us to interpret the data from two-pulse Fourier interferometry.
Ultra-short pulse laser experiments

Thin foil target — x-ray emission

Thin foil targets are heated to very high temperatures. They expand rapidly and cool at low density.

R. Shepherd, R. Stewart et al.
Ultra-short pulse laser experiments

Germanium L-shell spectrum from dense plasma

X-ray spectrometer with ultra-compact CCD read-out

B. Young, R. Shepard et al.