COMPARISON OF LASNEX CALCULATIONS WITH
EXPERIMENTAL RESULTS OF PARYLENE DISC IRRADIATIONS AT 1.06 \mu m

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Comparison of LASNEX Calculations with Experimental Results of Farylene Disc Irradiations at 1.06 μm

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ABSTRACT

Calculations are discussed using the 2D Lagrangian code LASNEX to simulate irradiation of Farylene discs. Using a representation of the experimental beam profile, geometric optics propagation, and an absorption model based on plasma simulations, the scattered light angular intensity distribution can be obtained. The use of a suprathermal electron heating spectrum and thermally generated magnetic fields with Braginskii transport coefficients leads to agreement with time-integrated x-ray spectra and x-ray spatial distributions. Details of the calculations and comparisons with other models are discussed.

Introduction

An accompanying report has presented a discussion of experiments performed to study laser light absorption, scattering and plasma transport processes using a 1.06 μm laser to irradiate Parylene discs in the intensity regime of $10^{15} - 10^{16}$ W/cm$^2$.

A schematic representation of the target/laser beam set-up is shown in Figure 1. The laser beam was focused via an f/1.1 lens onto a Parylene disc target 150 μm outside diameter and 10 μm thick. Pulses of 60 - 150 ps FWHM with energy 5-15 J were applied in nominal focal spot diameters of 50, 30, and 10 μm. The idealized intensity profiles used for the calculations are shown in the figure. For the 50 μm case, analysis was carried out both with a ring beam having 2:1 intensity ratio and with a smooth beam. The results discussed below are insensitive to this change in beam profile, except for a change in the angular distribution of scattered light.

In the present report, we discuss the implications of the experiment. The analysis is based primarily on numerical simulations of the plasma interaction processes using the code LASNEX, written by George Zimmerman. Direct comparison with measurements has proven useful for obtaining an understanding of the experiments, which unfortunately require unraveling of a variety of coupled absorption/transport processes, as indicated in Figure 2. We also present relevant results from plasma simulations, and some order of magnitude estimates to provide perspective.
Relevant Features of the Current LASNEX Model

LASNEX is an axisymmetric, Lagrangian fluid dynamics code. In Figure 3, the relevant features of the current model are highlighted. Laser light absorption is treated using a ray trace package written by D. S. Bailey, which treats refraction using a geometrical optics approximation. Absorption via inverse bremsstrahlung is computed along the entire ray trajectory.

A simple parametrization has been used to simulate absorption via collective processes. If a given ray has a turning point density greater than a density threshold, a fraction of its energy is absorbed at the ray’s turning point density, as indicated in Figure 3.

Electrons are treated using a Maxwellian thermal group together with multiple higher energy groups which can represent arbitrary suprathermal distributions. Both absorption and transport can produce electron distributions which differ significantly from a Maxwellian. Laser light absorption heats the electrons by promoting particles from the thermal group to the bins. Electrons heated by the absorption model dump all energy into the bins with the source function \( s_e(v) \) given by

\[
s_e(v) = \nu^2 \exp\left(-\nu^2/2\sigma^2_{th}\right)
\]  

(1)
where $v_{th}$ is the mean thermal velocity of all the electrons prior to heating ($v_{th}^2 = kT/m$) and $\alpha$ is a parameter which specifies the hardness of the generated spectrum. A value of $4 - 6$ produces heated electron spectra consistent with plasma simulations which account for self-consistent non-linear density gradient steepening.\(^6\)

The use of $\alpha$ should be considered as a computationally convenient way to vary the heated particle energies. More fundamentally, we will compare below the heated particle energies used in LASNEX to interpret the experiments with those generated by microscopic processes.

Electron conduction is modeled using flux-limited diffusion. The multigroup treatment allows for strongly varying mean-free-paths, and thus diffusion rates of electrons of differing energy.\(^7\) The energy flux transported by electrons of energy $E_e$ is constrained to be no greater than

$$F = 2 \times 10^{-7} r_{inhib} E_e^{3/2}$$

(2)

where $F$ is in W/cm\(^2\) and $E_e$ is in keV. In the usual flux-limited case, the value of $r_{inhib}$ is 1.0.

Thermoelectric magnetic field generation is included in the form $\mathbf{B} = \mathbf{V} \times \mathbf{E}$ where $n_e$ is the electron density and $T_e$ is the electron temperature.\(^8\) Magnetic field generation due to
Atomic alignment beam intensity variations, or due to resonance absorption, are not treated.

Thermal electron conduction transverse to the magnetic field direction (which is the z-direction in LANCEX) is modified using the transport coefficients of Prantskii. The electron heat conduction is strongly inhibited by the fields when \( \omega_{ce} \tau_{el} >> 1 \) with an effective flux reduction of

\[
\frac{\text{flux}}{\text{flux}_{in}} = \frac{\nu_e}{\nu_{e,\text{in}}} = \frac{1}{\text{MFP}} \frac{1}{\nu_e \tau_{el}}
\]

where \( \nu_e \) is the electron thermal velocity, \( L \) is the density scale height, \( \omega_{ce} \) the electron cyclotron frequency, \( \tau_{el} \) the electron-ion collision time, and \( \text{MFP} = \nu_e \tau_{el} \) the electron mean-free-path.

**Absorption and Scattering of the Laser Light**

It is quite easy to show that inverse bremsstrahlung absorption cannot account for the absorption fraction observed in the Parylene disc experiments, particularly for the 10^16 W/cm^2 shots. Here we will make a crude estimate of how much energy inverse bremsstrahlung could be expected to absorb. In order to absorb 30% of the incident energy at an incident intensity
\[ I_{\text{abs}} = 1 - \exp\left( -\frac{2\pi n \bar{v}_c}{\lambda_c} \right) \]  

where \( \lambda_c \) and \( n_e \) are the wave-number and number density of the incoming light, and \( v_c \) is the electron-ion collision frequency at the critical surface. Assuming a 1% of light, we obtain \( v_c = 1 \times 10^{11} \text{ cm/s} \) and \( I_{\text{abs}} = 0.99 \), nearly self-consistent with the originally assumed 30%. This estimate has ignored peam-moment-induced density gradient steepening and non-normal incidence which would reduce the effectiveness of inverse Bremsstrahlung. The plot of Figure 1 shows the absorbed fraction versus incident intensity. For this calculation, the scale height obtained in LASNEX, \( \lambda = 10^6 \text{ cm} \), has been used.

The terylene disc experiments, particularly at \( 10^{12} \text{ W/cm}^2 \), show
sufficiently higher absorption than inverse bremsstrahlung can provide.

Detailed calculations using LACHEX agree with the estimate presented above. Let the focal spot diameter, with peak intensity of $I \times 10^{12}$ W/cm², the total energy absorbed by inverse bremsstrahlung when $I_{\text{focal}} = 2 I_{\text{focal}}$ at $0.1^\circ$ incident. The experimental absorption is about twice as high, indicating that even at $I \times 10^{13}$ W/cm², supplementary absorption may be required. For the $100 \mathrm{mm}$ focal spot diameter, the situation worsens dramatically, with an $I_{\text{focal}}$ calculation showing only 0.5% absorbed out of 0.5% incident. The $10^\circ$ experiments, on the other hand, indicate $I_{\text{focal}}$ at ~4% of the incident light.

When the small parameter $I_{\text{focal}}$ is set to $I_{\text{focal}} = I_{\text{focal}}$ and the threshold fractional density is set between 0.1 and 0.2, the absorbed fraction of the incident laser light is essentially equal to $I_{\text{focal}}$, and the absorbed energies are consistent with experimentally observed values. The mean angle of incidence is at $20^\circ$, so nearly all the rays have $I_{\text{focal}} = 0.3 I_{\text{focal}}$. The absorption obtained is thus only weakly sensitive to the value chosen for $0^\circ$ threshold.

These values compare favorably with those computed in recent plasma simulations of laser-light absorption via parametric instabilities and resonance absorption. For example, Figure 1 shows the absorption efficiency versus angle of incidence as calculated.
in a series of similar simulations. The points are the
simulation results for s-polarized light (σ in the plane of
incidence), and the dashed line is an estimate assuming an equal-
ity of polarizations. This absorption efficiency ranges from
0% at normal incidence due to instability generation alone to
4% for another 1-cm source absorption at a rather steep angle
of incidence. These are simulations of a rather ideal model
of a plane wave, a plane sheet with no surface roughness, a thin
layer of the absorbing material, and the absorption not to be impaired by either critical
surface rippling or short wavelength instability. The
principal point is that calculations of light absorption via
reflectivity processes give values in reasonable agreement with
these experiments, as needed here to model realistic

Figures show some evidence that bulk air
reflectivity is being limited by the small mass and heat capacity
of the ensemble plasma, and this is a rather stiff constraint on
dense experiments with a short, rapidly rising pulse. For
eexample, in the 100-J experiment, we calculated that a
higher reflectivity would persist for only 10⁻² s. This is
consistent with one of the preliminary optical streak camera
measurements.

The results obtained using LACKEY to calculate the
angular dependence of scattered light are shown in Figure 7.
The reference calculations, using a spatially uniform
FrenkelKronig transport, and re-absorption flux limit, at a reasonable agreement with experimental results. This could be fortuitous, since the calculated shape varies with assumed ion profile.

X-Ray Spectrum, Suprathermal Electrons

The observed x-ray spectra for the 15 keV and 0.15 meV spot sizes are shown in Figure 7. The reference calculations, using $f_{\gamma} = 0.1$ and $f_{\beta} = 0$, show agreement with the experiment to within a factor of 2 over the entire spectrum. Note that the presence of suprathermal scattered electrons is strongly supported since the $f_{\beta} = 1$ calculations fall several orders of magnitude below the data at high energies.

The calculation of these spectra is non-trivial, since the most intense emission region for $\gamma = 10$ keV x-rays is around density $1.0 \text{ g/cm}^3$ while that for 1-2 keV x-rays is at density $0.1 \text{ g/cm}^3$. The time varying scale height, in suprathermal electron populations, and the spatial variation in transport inhibition make the connection between the electron populations in the critical density region and the time-integrated x-ray emission very indirect.

To some extent, a trade-off can be made between transport inhibition and suprathermal electron generation.
The transport of electrons is a function of energy. To make it easier to analyze the observed X-ray spectrum of the transport limit of the energy in the increased e- e- electron potential of the beam, one may observe the range of the transport. However, the allowable range tends to include extremely inhibiting thermal transport losses.

These "all-electron" losses, such as those in superfluid superconductors, for the reason that "very" is temperature in the thermal energy, while in the allowable range of possible views.

Note that calculations performed using the Friedel and loud prescription for the external instability give similar results. These calculations make the results. Thus, both methods have been tried in several cases, and the results are essentially identical with those using Braginskii transport coefficients.

Because of this interplay between absorption, electron heating, and transport, we do not claim high precision knowledge of heated electron distribution functions. But rather, the qualitative features of the electron heating are understood. At $I = 10^{16} \text{ W/m}^2$, the mean heated electron energy $\langle 0_h \rangle$ is $4$ keV in L JETFX and $5$ keV at $10^{15} \text{ W/m}^2$, $0_h \sim 10$ keV. These energies are in reasonable agreement with those computed in plasma simulations. For example, the heated electron temperature $\langle 0_h \rangle$
Due to resonance absorption can be estimated by wave breaking arguments to be

\[ e^{-} \frac{mc^{2}}{2} \left( 1 - \frac{\gamma - 1}{\gamma + 1} \right) \frac{1}{\gamma c} \frac{\hbar}{\hbar} \]

where \( v_o \) is the oscillatory velocity of an electron, \( l \) the scale length near critical and \( t \) the resonance function given in Ginzburg. Estimating \( t \approx 1 \) and using the self-consistent nonlinearly steepened density profile, \( W \approx 0.007 \left( \frac{\gamma c}{\hbar} \right) \text{ keV} \).

This gives 35 keV for \( I = 10^{16} \text{ W/cm}^2 \) and 12 keV for \( I = 10^{15} \text{ W/cm}^2 \). Again, the principal point is that plasma \( \chi \) relations of known processes give reasonable agreement.

X-Ray Spatial Distribution, Transport Inhibition

The x-ray microscope diagnostic shows that transport is significantly inhibited. In Figure 8 are shown film density traces parallel to and transverse to the laser beam propagation direction for an unfiltered channel with response from 0.3 to 2.0 keV. As discussed in Ref. 1, the x-ray microscope viewed the target edge-on, and the laser light plane of polarization was at 45° to the line between the target and the microscope.

The parallel direction shows the time-integrated emission across the density gradient. This turns out to be insensitive.
to conduction inhibition. In the direction transverse to the incident beam, a significant difference is observed between calculations with and without inhibition as shown in the figure. The calculations without magnetic field are clearly inconsistent with experiment. The agreement between the reference calculations and the experimental shots selected is the best observed, and is somewhat fortuitous. Other shots show deviation from axial symmetry and, particularly for 90 um cases, a somewhat narrower FWHM. Calculations with inhibition, for either magnetic fields or anomalous conduction are consistent with the experimental results, within the level of uncertainty introduced by possible beam spot size variations.

For the 40 um case, the reference LAMTEX calculated FWHM is 34 um, while the experimental values ranged from 55 um to 30 um with mean and standard deviation of 67, ± 9, um. For the 30 um case, the reference calculation FWHM is 24 um, while the experimental result is 37, ± 7 um.

**Ion Energy Distribution**

The data obtained from Faraday probe TCF measurements on the Parylene disc experiment show significant fractions of ion energy in a small group of fast ions. As shown in Figure 5, an
estimated 70% of the ion energy lies above $E/A > 1$ keV, for the
30 μm shots at intensities of $1-2 \times 10^{12}$ W/cm². Measurements
obtained using a magnetic spectrometer show a group of fast pro-
tons in the energy range of 100-150 keV.

Calculations with LASNEX indicate similar blow-off behavior.

The calculated ion distributions show 62% of the ion kinetic
energy above 50 keV for the 90 μm case. For the 90 μm case, the
reference calculation indicates 66% of the ion kinetic energy
above 50 keV. These numbers are in rough agreement with the data,
with the necessary proviso that uncertainties in both the experi-
ment and the analysis are large. These uncertainties arise from
experimental dynamic range problems, the unknown amount of re-
combination, which may depend upon the ion energy, and from the
single species, Lagrangian ion modeling in LASNEX.

Both transport inhibition and suprathermal electron populations
play a significant role in determining the amount of energy in
fast ions. In Figure 9 are summarized results showing the varia-
tion of hot ion production with modifications of transport
and suprathermal electron production.

The hot ions are produced by acceleration through the ambip-
olar potential (i.e., $\phi_h$) which builds up quickly as electrons
try to leave the target. Since the electron heat flow into the
target is inhibited, they can lose a large fraction of their energy
to this fast ion blow-off. A few simple estimates demonstrate
The electron heat flux carried into the target is

\[ \frac{\dot{E}_{\text{e}}}{\dot{E}_{\text{vac}}} \approx \frac{f_{\text{inh}}}{f_{\text{inh}}} \]

The energy flux carried off by hot ion expansion is

\[ \dot{E}_{\text{ion}} = \frac{5}{2} \frac{m_{\text{e}}}{m_{\text{e}}} \dot{E}_{\text{vac}} \]

where we have crudely estimated this on the basis of an isothermal expansion. The ratio of the heat the electron energy flux is then \( \approx 5 \sqrt{m_{\text{e}}/M} \dot{E}_{\text{inh}} \), where the rate of the electron energy flux is then \( \approx 5 \sqrt{m_{\text{e}}/M} \dot{E}_{\text{inh}} \). For the 30 μm spot example previously discussed, \( \dot{E}_{\text{inh}} = 1/90 \) for electrons of 10 keV or greater. Hence, our estimate gives ~ 2% of the absorbed energy being lost to fast ion expansion.

Conversely, this estimate is a bit higher than the calculations show (10%) because we have neglected the energy flux carried by lower energy electrons which are less inhibited and also neglected the energy flux by electrons through the holes in the magnetic field.

**Conclusions**

We have presented an analysis of laser irradiation of Farylene-dics. The most significant conclusions which can be drawn are the following:

1. We observe laser light absorption which is enhanced relative to expectations based on inverse bremsstrahlung, and which is consistent with plasma simulations.
2. The enhanced absorption is coupled with generation of suprathermal electrons.
3. Transport inhibition, such as would be produced by
thermoelectrically generated B fields, plays an
important part in determining plasma behavior.

With these hypotheses, we have been able to simulate
optical energy distribution and balance, x-ray spectral and
spatial emission, and ion energy distribution, with accuracy
sufficient to gain an understanding of detailed plasma processes.

Further improvement of the models will no doubt prove
necessary, as the parameter regime and the experimental diagnostic
capability expand.

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been contributed by P. Vershaw, C. Max, J. Ruckolla, and I.
Zimmerman. The contributions of the many experimentalists
whose work has been included here are appreciated.
REFERENCES/FOOTNOTE

1. H. A. Harr, L. N. Million, K. J. O'Sly, H. K. Kornblum and
   Y. C. Rupert, University of California Report, UCRL 77644


- Rotational symmetry around the Z-axis prevents direct
  simulation of jet effects, such as occur experimentally
  when, for example, the laser beam is not cylindrically
  symmetric, the absorption is azimuthally dependent, or
  the target axis is not collinear with the axis of the beam.

- L. S. Bailey, University of California Report UCRL 76881,

- Note that the LASEX version used for these calculations
  underestimates inverse bremsstrahlung absorption by computing
  the absorption coefficient using a mean temperature derived
  from a linear average over electron proof populations. On the
  other hand, self-steepening of the density gradient, which is
  not treated by LASEX, would tend to reduce inverse bremsstrahl-
  ung absorption.

- K. O. Stabrook, E. L. Yales, W. L. Kruer, Phys. Fluids 10,
  1111 (1973).

- The code does not explicitly treat kinetic Coulomb scattering.

- However, the current version approximates suprathermal scat-
11. We solve for the total number of electrons instead of just the thermal ones and estimate thermalization rates. This approximation is probably not significant for x-ray emission calculations, since the emission region is at relatively high density where most electrons are in the thermal state.

12. Some aspects of the magnetic field physics are not complete. The field generation terms do not include the suprathermal electron flux. The finite difference solution for the $E \cdot B$, thermal conduction term has not been used in the present work since the numerics are unsatisfactory. In addition, the suprathermal transport and collisionless drifts mutually perpendicular to both $\mathbf{B}$ and the driving force.


10. The form of $\Delta \mathbf{B}$ includes both the magnetic field inhibition and the collisional inhibition of the flux relative to the flux limit value. This split-up is merely for convenience in using flux limit arguments.


FIGURE CAPTIONS

Figure 1 Schematic representation of the target/beam geometry for the Parylene disc experiments.

Figure 2 Important competing plasma processes which must be understood to model the experiments.

Figure 3 Assumptions used with LAFLEX to model anomalous absorption and thermoelectric magnetic field generation and transport.

Figure 4 Estimated fractional absorption vs. incident intensity for inverse bremsstrahlung absorption. A scale height of 16 μm was assumed.

Figure 5 Absorption fraction vs. angle of incidence for light with its E-vector in the plane of incidence (points are results of 2-D relativistic particle simulation) and with an equal mix of polarizations (dashed line).

Figure 6 Comparison of calculated angular distributions of reflected and refracted light with experimental results for "90 μm" and "30 μm" cases.

Figure 7 Comparison of calculated x-ray spectra with experimental results. The μ = 1 calculations are shown dashed, and disagree by several orders of magnitude with the data at 50-100 keV.
Figure 8  Comparison of calculated and observed traces of x-ray images. The parallel direction scans represent the log of the x-ray emission intensity vs. position along the beam axis, with the beam incident from the left in the figure. The transverse scans were taken along the line perpendicular to the beam axis containing the point of greatest emission intensity. The calculations without magnetic fields or the relaxation inhibition (dashed lines) do not agree well with any of the images obtained experimentally.

Figure 9  Calculated experimental and calculated results for ion kinetic energy showing dependence of high energy tail on the amount of transport inhibition and the suprathermal electron populations.

Figure 10  Summary of major conclusions drawn from this work.
PARYLENE DISC EXPERIMENTS UTILIZE SIMPLE GEOMETRY TO OBSERVE PLASMA INTERACTIONS

Incident laser beam

Target

D = 90 μm, 30 μm, (10 μm)
6-9J
50-100 ps FWHM
1.06 μm
f1.1 lens

Idealizer beam intensity profiles

Figure 1

ANALYSIS OF THIS "SIMPLE" EXPERIMENT REQUIRES UNDERSTANDING OF MANY INTERLOCKING PHENOMENA

Figure 2
"REFERENCE" CALCULATIONS USE MODEL ASSUMPTIONS MOTIVATED BY IDEALIZED PLASMA SIMULATIONS AND THEORY

- Anomalous absorption (Krue, et al.)

\[
\text{Resonance absorption} \sim \begin{cases} 
 f_{\text{dump}} = 0.2 - 0.4 \\
 \rho_{\text{thresh}} / \rho_{\text{crit}} = 0.5 - 0.8 
\end{cases}
\]

\[n_e(v_e) \sim v_e^2 \exp \left(-v_e^2/2 \alpha v_{TH}^2\right)\]

\[\alpha \sim 4\]

- Thermoelectric magnetic fields (Braginskii or Bohm)

\[B \propto \nabla \ln n_e \times \nabla T_e\]

Transport inhibition

\[f_{\text{inhb}} \approx \frac{4v_{te}}{\omega_{ce} T_e L}\]

**Figure 3**

ESTIMATE SHOWS THAT CLASSICAL INVERSE BREMSTRAHLUNG DOES NOT ACCOUNT FOR OBSERVED FRACTIONAL ABSORPTION

**Figure 4**
TWO-D PLASMA SIMULATIONS OF LIGHT ABSORPTION

Estabrook, Valeo, Kruer PF, Sept.  

θ (degrees)

Figure 5

CALCULATED SCATTERED LIGHT DISTRIBUTION SHOWS
QUALITATIVE AGREEMENT WITH EXPERIMENT

WARNING: The calculated distribution depends quite sensitively on
assumed beam profile.

Ref. calc.
Exp.

Figure 6
X-RAY SPECTRUM IS ADEQUATELY SIMULATED ONLY WHEN SUPRATHERMAL ELECTRON GENERATION IS ASSUMED

Figure 7

X-RAY MICROSCOPE IMAGE IMPLIES THAT TRANSPORT INHIBITION EXISTS

Figure 8
ION ENERGY DISTRIBUTION DEPENDS UPON ELECTRON DISTRIBUTION AND TRANSPORT INHIBITION

Fraction ion energy above E/A = 10 keV

<table>
<thead>
<tr>
<th></th>
<th>&quot;90 µm&quot;</th>
<th>&quot;30 µm&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.</td>
<td>0.5 ± 0.2</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>Ref. calc.</td>
<td>0.22</td>
<td>0.66</td>
</tr>
<tr>
<td>No inhib.</td>
<td>0.03</td>
<td>0.15</td>
</tr>
<tr>
<td>$\alpha = 1$</td>
<td>0.06</td>
<td>0.29</td>
</tr>
</tbody>
</table>

* Assuming A/Z independent of E

SUCCESSFUL SIMULATION OF PARYLENE DISC EXPERIMENTS REQUIRES

- Anomalous absorption
- Suprathermal electron generation
- Transport inhibition

With these features, we can calculate

- Optical energy distribution and balance
- X-ray spectral emission
- X-ray spatial distribution
- Ion energy distribution