COMPUTER SIMULATION OF LASER-DRIVEN IMPLOSION
OF DT-FILLED GLASS MICROBALLOONS

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Computer Simulation of Laser-Driven Implosion of DT-Filled Glass Microballoons

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Introduction

In the previous paper presented by E. Storm, et al, the Lawrence Livermore Laboratory experimental program on laser irradiation of deuterium-tritium filled glass microballoons was discussed. This paper focuses on the interpretation of those experiments as a whole with calculations of specific target irradiations used to demonstrate the present understanding of the physics involved.

The agreement between calculation and experiment is determined by many laboratory measurements. Figure 1 is a partial list of those measurements used for comparison. The optical energy balance is a good estimate of the energy absorbed by the target and the scattered light angular distribution is useful in determining the profile and positioning of the laser source, and possibly the presence (or absence) of magnetic

fields and inhibited electron transport. The x-ray spectrum is important in determining the electron conduction and distribution of laser-heated electrons, and as an estimate of the laser energy absorbed. A check on the absorbed energy is provided by the total energy emitted as x-rays. One of the most useful diagnostic tools is the x-ray photomicrograph which gives time-integrated information about local temperatures, and more important, a measure of the compression and the compressional point within the target system. The neutron production and alpha particle spectrum are important in verifying the compression (density) and DT ion temperatures of the fuel, and the density of the surrounding plasma from the exploding shell; also the question of the neutrons being produced by a genuine thermonuclear reaction may be answered.†

It is this set of measurements that is used to propose a model using the relevant physics, as is best understood for this class of targets; namely spherical glass shells of high aspect ratio (≈70:1) that are heated rapidly with a subsequent violent implosion/explosion.

The next section of this paper presents a general description of exploding pushers and the following sections discuss the physical processes (model) involved together with selected examples of measurement and calculation.

†For more information on this subject refer to presentation to follow by H. D. Shay entitled "Analysis of Laser-Fusion Experiments Determining the Ion Temperature of Burning DT Thermonuclear Fuel".
This type of spherical target, in contrast to other geometries, provides significant information about the laser light absorption model and presence of magnetic fields because of the highly curved nature of the absorption/conduction region.

Characteristics of Exploding Pushers

In an isentropic implosion, only the exterior of the shell is ablated, causing the interior portion of the shell to be accelerated slowly and resulting in its compression to higher and higher densities. However, in contrast, the exploding/imploding pusher is rapidly heated by the electrons which raises the pressure on the interior of the shell to about one megabar, thus causing this surface to be accelerated rapidly. In addition, the fuel is heated rapidly to about 0.1 eV by radiative preheat arising from reabsorption of bremsstrahlung, and recombination and line-radiation photons from the exterior plasma where electron temperatures are several hundred electron-volts. It should be noted that the thickness of the microballoons is comparable to the range of the photons, hence there is little shielding of the fuel from such effects. There is also preheat arising from superthermal electrons which are generated beyond the critical surface by absorptive instabilities and pass through the shell to deposit some of their energy in the fuel.

Figure 2 is a region-averaged pressure-density path of the DT fuel. At a time near the peak of the laser pulse, as
the interior surface of the shell is being accelerated, a moderately strong shock (less than 0.1 megabar) runs through the fuel heating it to a few tens of electron-volts. However, there has been little volume compression, and the density remains unchanged. The pressure continues to rise to about 1/2 megabar before the density begins to increase. Once the adiabat has been set, compression takes place with both the pressure and density increasing. For comparison, the Fermi-degenerate adiabat is shown for which near isentropic compressions should approximate. It can be seen from this picture that high density compressions cannot be obtained efficiently if there is a significant amount of preheat.

Another characteristic of exploding shells is provided by the electron and ion temperature and density of the fuel as a function of time. Figure 3 relates these three quantities to the time of the peak of the laser pulse. Recall that the fuel has already been heated to a few tens of eV and now the electron temperature is starting to rise above that of the ions; this is largely due to the conduction precursor from the initial shock and the hot electrons penetrating the glass shell at a time after the peak of the laser pulse. Finally, the ion temperature rises above that of the electrons and the fuel density begins to rise due to PdV work. However, the electrons do
not track the ions because of their large conductivity resulting in their being clamped in thermal equilibrium with the shell.

A third characteristic is the history of the glass shell. Figure 4 illustrates the peak density and shell thickness (defined as the width at $\rho = 1/3\rho_{\text{max}}$) relative to the peak of the laser pulse. At early times a shock runs through the shell, compressing it almost three-fold with a corresponding reduction in shell thickness. Then as the shock breaks through the interior surface, the shell rapidly expands and the density drops. At late times, when the shell stagnates against the fuel, there is again a small increase in the shell density. It is an interesting feature of exploding pushers that they appear to be relatively stable against hydrodynamic instabilities because of the increasing shell thickness and the nature of their acceleration.

Laser Light Propagation and Absorption Model

Figure 5 shows the physics used in the numerical simulation of the conversion of laser energy into electron energy. The light follows the laws of geometrical optics in the under-dense region of the plasma. A somewhat realistic laser beam profile and positioning is assumed and then traced through the plasma in a way that is dependent only on the local density gradient. As the individual rays approach the opaque region, they are partially reflected and traced back out through the
underdense plasma. At all points along the trajectory, there is some light absorption by classical inverse bremsstrahlung.

Additionally, there is an attempt at modeling resonant absorption and parametric absorption. Since the laser beam is linearly polarized as it is projected on a somewhat spherically symmetric absorption surface, there will be components of the electric field parallel to and perpendicular to this surface. Those components of the field in the plane of incidence (parallel) lead to increased absorption at the critical surface and as the angle of incidence increases (moving toward the perpendicular) the point of absorption moves away from the critical surface, reducing the absorption. The overall effect is a steepening of the density gradient and the angle of incidence to the critical surface for resonant absorption has a maximum that is dependent on the scale length of the density gradient. There are additional absorptive effects at near normal incidence due to parametric instabilities such as cratering at the critical surface, local ion fluctuations and plasma waves, etc. The numerical simulation technique is restricted to an axi-symmetric (two-dimensional) space and is thus not capable of treating the absorption of a polarized light source at an arbitrary angle to the critical surface. This absorption is modeled to be an average of the two extremes, parallel and perpendicular incidence. Additionally, the treatment of selfsteepening is not included.
because of numerical restrictions on the number and size of the Lagrangian zones, and the omission of the ponderomotive force. The resonance and parametric absorption is approximated by specifying a fraction of the laser energy (typically 25%) to be absorbed up to a certain angle of incidence (typically 35° - 40°) and complete reflection for larger angles; this is accomplished in the simulation by depositing the energy fraction at a surface near the critical surface (such as \( \rho = 0.5 \rho_c \)). This technique is based on the absorption work of Kruer and DeGroot.

No account is made for any stimulated backscatter or side-scatter as it is believed that these processes are not significant for the laser intensities of these experiments and that the density scale heights are so short.

Electron Heating and Transport Model

Figure 6 presents the electron conduction model. Electrons are heated by the classical absorption mentioned above and are distributed in an inverse bremsstrahlung spectrum. A fraction of the electrons are also heated by the anomalous absorption mechanism. It is the existence of resonance absorption and parametric instabilities that cause a significant number of electrons to be accelerated to large velocities by the generation of large electric fields near the critical surface. Hence, there is a strongly non-Maxwellian high-energy tail on the electron velocity distribution.
Normal electron transport within the plasma is assumed to take place with collisional transport coefficients using a multi-group, flux-limited diffusion approximation. However, recent experiments and calculations have demonstrated a need for a conduction inhibition mechanism. One such effect is due to electron-ion turbulence and/or the modified oscillating two-stream instability. This inhibition may become necessary when the electron temperature is several times that of the ions; the turbulence reduces the heat flow to the marginally stable drift velocity. It is not certain, at the present, that this form of conduction inhibition is playing an important role in the experiments. A more likely mechanism is the effect from self-generated magnetic fields. The model used here is confined to the term involving the gradients of the electron density and electron temperature. This produces an electric field whose curl is proportional to the development of the magnetic field. The effect is to produce local megagauss fields in the region of absorption which, in turn, prevent the electrons from carrying their energy inward to colder regions of the plasma.

Indeed, there are other magnetic field source terms (e.g., those arising from surface currents generated by non-axi-symmetric laser illumination and absorption) absent from the model. The effects of magnetic field diffusion may be important in the conduction inhibition model; i.e., classical and Bohm diffusion coefficients may be appropriate for different regions of absorption.
Comparison of Calculation with Experiment

The previous paper presented the overview of the glass microballoon experiments and correlated the different target parameters with the experimental observations. For the purposes of the calculations, they are most conveniently divided into three categories: two-beam, simultaneous irradiations; two-beam, delayed irradiations; and one-beam irradiations. All target and laser parameters were similar for all three cases; the microballoon diameter was about 85 μm with a wall thickness of approximately 0.5 μm and a DT gas density of 2 mg/cm³. Each beam of the laser delivered about 15 Joules in a 75 psec FWHM Gaussian, and for the second category of delayed beam experiments, one was delayed by 42 psec and later by 84 psec. Figure 7 is a schematic of the focusing and timing arrangement.

A constraint was placed on this series of calculations: all laser parameters, the absorption model, the electron conduction and inhibition model, and hydrodynamic physics were identical for all three target categories. The only exceptions allowed were the total incident light energy and laser beam focal position (spot size). Also, the target parameters (ball diameter, wall thickness, and DT gas pressure) were adjusted to those actually used in the experiments.
In addition to the relations between the experimental categories mentioned in the previous paper, the x-ray spectra show an interesting correlation. Figure 8 presents the typical spectra for all experiments; namely, a two-temperature distribution. The two-beam experiments have spectra whose intensity is approximately a factor of two greater than for the one-beam irradiations. This is to be expected since the incident energy was different by about a factor of 2 as was the absorbed energy. For the two-sided irradiations the x-ray spectra tend to be lower, for $h\nu > 10$ keV, for the 42 psec timing delay and lower yet for the 84 psec delay.

The simultaneous, two-beam experiment is perhaps the least sensitive of the three to variations in the physics assumptions. Figure 9 is the Lagrangian mesh of the imploded state showing a dominant intrusion of the glass shell from a position corresponding to the most intense portion of the laser beam. The majority of the neutron producing reactions occur in the fuel just ahead of this spike due to strong local PdV work. The shape of this jet is somewhat influenced by the inclusion of the magnetic field physics but does not affect the simulated measurements to a large degree, with one exception.

Figure 10 is the measured and calculated x-ray spectrum for which only the portion above $h\nu = 10$ keV is altered by the magnetic fields. It appears that the more uniform heating of
the sphere does not greatly inhibit the electron conduction except near the waist; this will be contrasted to the case of the one-sided implosion later.

The angular distribution of the scattered light fits the measurements quite well. This is shown in Figure 11 where it is seen to be symmetric about the waist of the target.

A very good agreement between experiment and calculation is obtained for the x-ray photomicrograph. Figure 12 is the microdensitometer scan of the data together with a profile of the contour along the axis of the laser beams. The corresponding computer generated representation is also shown along with the dimensions of the interesting features. Figure 13 is the computer enhanced photograph which is included to give a more realistic picture of the compressed region.

The delay of one beam relative to the other provides some insight into the role of the electron conduction model and the behavior of exploding pusher. Figure 14 is the experimental and calculated x-ray microscope pictures for the 42 psec delay experiment; this shows the compressed region to be displaced about 9 µm from the center of the target. Figure 15 is the corresponding experimental picture for the 84 psec delay irradiation showing an offset of 18 µm.

From these three data points an average velocity of the interface between the DT and glass can be estimated. Figure 16
is a plot of the compression offset from the center of the target against the relative beam delay. The average velocity is computed to be about 0.21 μm/psec, which agrees well with the calculated value.

A particularly interesting experiment to calculate is the one-sided irradiation of an 85 μm diameter ball with a 0.5 μm wall thickness. About 15 Joules in a 75 picosecond FWHM Gaussian laser pulse was focused on the target, with 3.5 ± 0.5 Joules being absorbed. Two calculations give considerably different results, depending primarily on the inclusion/exclusion of self-generated magnetic fields.

Figure 17 shows the angular distribution of scattered laser light. Experimental data points are shown for both the reflection in the plane of the laser polarization and perpendicular to it. The two lines are the calculations. It is clear that the inclusion of magnetic fields is proper, for any reasonable rearrangement of the laser profile/positioning cannot reproduce the measured distribution when magnetic fields are not used. This scattered distribution arises from the shape of the absorption/reflection surface which is strongly influenced by the magnetic field. Figure 18 shows the critical surface for the two cases at the time of peak laser intensity. Figure 19 is the iso-magnetic contours which are strongest near the outer edge of the ring portion of the laser beam; it is here that the
gradients of the density and electron temperature are the largest. Figure 20 is the corresponding electron temperature contours; the effect of the magnetic field is to keep the back of the ball from being heated by conduction. However, the conduction towards the laser axis is not as severely inhibited because of the smaller temperature gradients where the interior portion of the laser source is being absorbed.

Figure 21 is the Lagrangian mesh plots of the implosion's final state for the two calculations. There is comparatively little difference in the vicinity of the laser axis in contrast to that at the waist and behind the target.

Figure 22 is the x-ray spectrum from approximately 2.5 keV to 30 keV. The data points show a two-temperature characteristic corresponding to a 0.8 keV and a 7.9 keV Planckian spectrum. The calculations show that the magnetic field plays a small role in the "thermal" portion of the spectrum but is most significant in that portion generated by the superthermal electrons. Both calculations were run with the same coefficient ($\alpha = 4$) for the superthermal electron distribution function. As one is quick to note, the agreement between calculation and experiment is not good. A likely explanation for the discrepancy is that there is more inhibited electron conduction present than is used in the calculation. It has been suggested that there may be additional large magnetic fields present due to the nonaxial
symmetry of the experiment and/or a large effect arising from the resonant absorption process which is dependent on the incident electric field and plasma density gradient.

Finally, the numerical simulation of the x-ray photomicrograph is compared to the real one. Figure 23 is the beautiful, computer-enhanced, color-coded reproduction of the data. A more useful representation is the microdensitometer scan of the data for the region between 2.0 and 3.3 keV. This is shown in Figure 24 together with a trace drawn along the laser axis, and the corresponding simulated pictures from the magnetic field calculation. The interesting features are that the implosion appears symmetric about the laser axis and that the region of highest x-ray emission comes from the stagnated pusher. Indeed, the front of the shell has been translated a distance of about one ball diameter. The experimental point of compression is 43 µm behind the center and the calculated position is 38 µm.

Conclusions

One last comparison is the agreement for neutron production. Figure 25 tracks the number of neutrons produced from the four targets over approximately 3 orders of magnitude. It is clear that the computer simulation reproduces the trend although the calculations are slightly lower than the experimental results. This can be attributed, at least for the simultaneous
irradiation, to a coarseness in the Lagrangian mesh and/or inaccuracies in the positioning of the laser beam; different calculations have shown variations of a factor of 3 in the neutron yield not to be uncommon, with the other diagnostics remaining unchanged.

The agreement between theory and experiment is generally good; the most troublesome point being the fit to the experimental x-ray spectrum, especially for the region below 10 keV.

The agreement between experiment and calculation for the two-beam experiments is better than for the one-sided illuminations; the low energy portion of the x-ray spectrum agreeing to within a factor of 3. This is due to the more uniform heating of the glass shell, thus making the conduction and absorption models less sensitive to density and temperature gradients.

It has been demonstrated here that self-generated magnetic fields play an important role in determining the character of the implosion/explosion of the target. There may be, in fact, much stronger conduction inhibition arising from additional magnetic field source terms, different magnetic field diffusion coefficients, and/or inhibition from plasma fluctuations and instabilities.

There is also some indication that the absorption model (resonance absorption and parametric instabilities) may be insufficient without the inclusion of polarization effects and the selfsteepening of the density gradient.
ANALYSIS OF
GLASS MICROBALLOON
TARGET IRRADIATIONS

Figure 0
MEASUREMENTS USED FOR COMPARISON OF EXPERIMENT WITH CALCULATION

Optical energy balance
Scattered light angular distribution
X-ray spectrum for $2.5 < h\nu < 30$ keV
Integrated x-ray energy
X-ray photomicrograph
Neutron production (alpha particle spectrum)
COMPRESSION IS AFFECTED BY A LARGE FUEL PREHEAT

Figure 2
THE FUEL ELECTRON TEMPERATURE DOES NOT FOLLOW THE ION TEMPERATURE

Figure 3
THE EXPLODING SHELL'S THICKNESS CONTINUES TO GROW

Figure 4

--- Wall thickness (μm) ---

Density (gm/cm^3)

-150 -100 -50 0 50 100
Laser Light Propagation and Absorption Model

Geometric optics (ray tracing) through underdense region

Inverse bremsstrahlung along ray path

Resonance and parametric absorption simulation

No stimulated Raman or Brillouin scattering

Figure 5
ELECTRON HEATING AND TRANSPORT MODEL

Inverse Bremsstrahlung spectrum

Anomalous absorption (laser heated) spectrum

Collisional transport coefficients with multi-group, flux limited diffusion coefficients

Inhibited thermal conductivity when
\( \Theta_e/\Theta_i \gtrsim 10 \) (anomalous conductivity

Inhibited conductivity by self-generated magnetic fields

\[
\frac{dB}{dt} \sim \nabla \ln n_e \times \nabla \Theta_e
\]

Figure 6
ONE BEAM IS DELAYED RELATIVE TO THE OPPOSITE BEAM

\[ \sim 15 \text{ Joules} \ 75 \text{ psec FWHM per beam} \]

Figure 7
X-RAY SPECTRA ARE SIMILAR FOR ALL TWO-BEAM IRRADIATIONS

Figure 8
FINAL STATE OF SIMULTANEOUS IRRADIATION IS ASYMMETRIC
X-RAY SPECTRUM FOR SIMULTANEOUS BEAMS AGREES MODERATELY WELL

![Graph showing the relationship between intensity (keV/keV) and hv (keV) for x-ray spectra. The graph plots intensity on a logarithmic scale against hv, showing a decreasing trend.]
THE SCATTERED LIGHT IS SYMMETRIC FOR THE SIMULTANEOUS TWO-BEAM IRRADIATION

Figure 11
The simultaneous irradiation experiment has a symmetric compression.
COLOR COMPUTER ENHANCED X-RAY MICROSCOPE PICTURE

(Excluded from printing)
THE 42 PSEC DELAY EXPERIMENT SHIFTS THE COMPRESSION POINT 9 \( \mu m \)
THE 84 PSEC DELAY EXPERIMENT SHIFTS THE COMPRESSION POINT 18 μm

Figure 25
Average interface velocity can be calculated from delayed experiments.
THE SCATTERED LIGHT ANGULAR DISTRIBUTION IS AFFECTED BY MAGNETIC FIELDS

![Figure 17](image-url)

**Figure 17**
MAGNETIC FIELDS AFFECT CRITICAL SURFACE
MAGNETIC FIELDS ARE MOST INTENSE AT EDGE OF LASER BEAM
ELECTRON CONDUCTION IS INHIBITED BY MAGNETIC FIELDS

Figure 20
THE IMPLOSION FINAL STATE IS AT BACK OF THE TARGET
X-RAY SPECTRUM FOR ONE-BEAM IRRADIATION SHOWS EFFECTS OF MAGNETIC FIELDS

![Graph showing the effects of magnetic fields on the x-ray spectrum.](image)

- With magnetic fields
- Without magnetic fields
- Measured

Figure 22
COLOR COMPUTER ENHANCED X-RAY MICROSCOPE PICTURE

(Excluded from printing)
ONE-SIDED IRRADIATION HAS COMPRESSION POINT AT BACK OF TARGET

Figure 24
NEUTRON PRODUCTION AGREES WITH MOST CALCULATIONS

![Graph showing neutron production](image)

Figure 25
Calculation and experiment are generally in agreement.

Absorption/reflection model is good but may need a steeper density gradient.

Magnetic fields are generated.

Electron transport inhibition is incomplete.

Laser heated electrons do exist and affect implosion.

Figure 26