"SINGLE AND MULTI-BEAM LASER PELLET FUSION EXPERIMENTS"

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ABSTRACT

Absorption, reflection, and symmetry measurements have been made on spherical laser fusion targets for both single beam (highly non-symmetric), and four beam (more symmetric) irradiation, at incident laser energies of up to 250 joules. Optical, charged particle and x-ray measurement techniques are used to show the essentially symmetric behavior of the multi-beam irradiation. A measure of the effectiveness of lateral heat conductivity is obtained from a comparison of symmetric and non-symmetric irradiation results. Greater than 30% of the incident laser energy at an intensity of 10^{15} - 10^{16} W/cm² results in elevated plasma temperatures. The energy deposited in high energy photons is less than 10^{-3} of the absorbed energy. No distinct high energy ion component is observed and, in any case, less than a few percent of the absorbed energy resides in ions of energies >10 keV/nucleon.

Time resolved optical diagnostics have uncovered the presence of an "after pulse" emitted from the plasma at the laser frequency but following the trailing edge of the heating pulse.

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I. INTRODUCTION

Laser-pellet fusion requires high absorption of time-tailored laser pulses in an underdense region of the target density profile. Subsequent transport of this absorbed energy into the overdense regions of the target in a predictable manner, could then result in significant thermonuclear burn.

In this paper we discuss experimental studies of the absorption of laser radiation in spherical and cylindrical targets suitable for laser-pellet fusion. This work has been carried out at intensities up to 10^{16} watts/cm² on targets at a laser radiation wavelength of 1.06μ [1] in time tailorable pulsewidths of 200-500 picoseconds with four parallel beamlines each capable of delivering up to 200 joules.

The targets include 50μ to 200μ spheres of LiD, CH₂, CD₂, and C₃₆D₇₄, plus 400μ m cylinders of D₂ and CH₂. Both single beam and multi-beam experiments are described below. In all cases these studies are guided by detailed numerical modeling of the absorption physics and the dynamics of the dense plasma. [2,3]

Theoretical work carried out at the University bearing on these experimental results includes:

- (i) the effects of the refraction of laser energy incident on a non-homogeneous target,[4]
- (ii) resonant coupling of longitudinal fields and the generation of collisionless ion heating,[5,6]
- (iii) the saturation of stimulated Compton backscatter of incident laser radiation,[7]
- (iv) the stability and symmetry of imploding spheres and shells,[8]
- (v) the effect of non-linear radiation forces on the hydrodynamics of cold targets,[9]
- (vi) the dependence of radiation coupling efficiency on the frequency of radiation in both the weak and strong field collisional absorption limit.[10]

In section II we describe the single and multi-beam experiments. Careful measurements show an absorption efficiency above 30% in small spherical targets with a well behaved charged particle and temperature distribution. These observations can be explained by collisional and resonant absorption processes. Further, backscatter measurements show integrated reflectivity values of less than 10% on spherical targets with no peaked scattering at specific angles to the incident radiation, as would be indicated by some theoretical work on stimulated processes. A computational model of axi-symmetric irradiation of spherical targets is discussed and possibly accounts for refraction of the remainder of the incident radiation.

Section III includes a brief discussion of symmetry as observed from x-ray pinhole photographs. We conclude that the target behavior is very symmetric in the 4-beam irradiation case while the results of 2-beam irradiation allow us to make an estimate of the lateral thermal conductivity.

II. EXPERIMENTS

Laser System

The single and multiple beam experiments are all being conducted at the University of Rochester's high power laser irradiation facility described in ref.[1]. The parameters of this laser system are listed below (TABLE I).

TABLE I

Number of Beams	4
Output Aperture	11cm. ϕ
Total output area	380 cm ²
Pulsewidth	10 ⁻¹⁰ - 10 ⁻⁹ sec.(FWHM)
Pulse Tailoring	up to four pulses may be stacked together in arbitrary configuration.
Bandwidth	.3Å
Wavelength	1.06μm (.53 and .265μm possible by conversion in crystals)
Energy (Total)	>1000J (>.5nsec.) ~800J (~.15nsec.)
Beam Divergence	<.4mrad
Focusing Optics	f/2, 20cm, f.l. aspheric lenses
Focussed Power Density	10 ¹⁶ w/cm ²
Multibeam Focusing Configuration	planar (opposing beams)

Interaction Chamber

The chamber presently being used for the interaction experiments is shown schematically in Fig. 1. It is a 72cm. diameter stainless steel spherical chamber capable of operating in the range of 10⁻⁷ Torr. A number of particle and radiation diagnostics are simultaneously utilized to probe the laser produced plasma. These are listed below:

- i) Charged Particle Detection - A total of nine biased Faraday cups placed at various angles to the target are utilized to measure the number and velocity of the expanding ions. These are used in constructing a model of the expansion and deducing the absorbed energy.[11]

- ii) Time of Flight Mass Spectrometer - A dynamic mass spectrometer[12] is used to measure, simultaneously, the velocity distribution and charge to mass ratios of up to nine ion species.
- iii) X-ray Diagnostics - Three types of x-ray detectors are presently being used:
 - a) Ten solid state PIN diode soft x-ray detectors are used with various absorbers to deduce the plasma electron temperature.
 - b) Calibrated thermo-luminescent detectors[13] are used for measurement of the total x-ray energy and also an independent method of spectral distribution from foil transmission.
 - c) A pair of scintillator-photomultiplier detectors with lead shielding monitor the hard (100Kev) x-ray components.
 - d) X-ray pinhole photographs are obtained utilizing a 5X camera which produces six simultaneous views of the plasma x-ray emission with resolution of 10-15 μ m.
- iv) Neutron Flux - Two plastic scintillator-photomultiplier detectors located 15cm. and 100cm. from the targets are used for neutron time-of-flight measurements. A BF₃ counter set in paraffin is used for a total neutron counter. All detectors are calibrated with a Kaman Nuclear D-D source.
- v) Plasma Reflection and Emission - Both the angular dependence and the magnitude of the 1.06 μ m reflection from the plasma are monitored by means of photodiodes.[14] In addition, a high resolution (5psec.) streak camera is used to temporally resolve the time history of both the incident and reflected laser pulse. Measurements of the time dependence, spectral broadening and magnitude of the plasma emission at 2ω and $3\omega/2$ are also conducted using both broad band (cut-off filters) and narrow band (spectrometers) techniques.
- vi) Plasma Photography - Photographs in the fundamental radiation (ω) and its harmonics (2ω and $3\omega/2$) are obtained to measure the uniformity of the irradiation and to obtain information on the plasma density scale length. These photographs are taken both through the focusing optics at 90° to the plane of irradiation utilizing an auxiliary collecting lens and viewing system.

Targets

In the present set of experiments solid D₂, CH₂, C₃₆D₇₄, and (CD₂)_n have been used as target materials. The solid D₂ and CH₂ targets were in the form of 400 μ m diameter cylinders; the C₃₆D₇₄ and CD₂ targets were used in the form of solid spheres ranging in diameter from 80 μ m to 220 μ m.

Fig. 1 Schematic of experimental chamber showing (a) side view in the plane of irradiation and (b) top view.

The preparation and method of suspension of these targets is described in detail in Ref.[15]. A photograph of a typical target mounted on a thin glass needle is shown in Fig. (2).

Fig. 2 A 100 micron diameter solid spherical CD_2 target mounted on a 7 micron diameter glass whisker.

By utilizing a two axis viewing system, these targets could be located in space with a reproducibility of $10\mu\text{m}$. The position of the targets with respect to the focus of the laser beams was determined by means of an alignment cw Nd:YAG laser, made co-linear with, and having the same divergence as, the main laser beam. To confirm this fact, photographs of the focal spot of both the alignment laser and the high energy beam are taken by means of a microscope viewing system having a resolution of $5\mu\text{m}$. [16]

Single Beam Experiments

The cylindrical target experiments were undertaken to resolve the difference between the spherical target measurements [11] made at Rochester and the massive target measurements reported by the Limeil [17] group on D_2 targets. An apparent discrepancy existed in the reflectivity measurements which indicated a maximum of 10% for spherical targets of LiD and up to 50% on the D_2 targets at $1 \times 10^{15} \text{ W/cm}^2$.

The experiments were carried out with 1 beam illumination using a 20cm f/2 focusing lens. The pulse length for these experiments ranged between 500 and 700 picoseconds with an incident energy on the target of 25 to 150 Joules. The focal spot was measured to be 6×10^{-3} cm in diameter. An observed sensitivity of the reflectivity to target position was similar to that reported in ref. [18].

Fig. 3 Measured dependence of reflectivity on incident laser power density for 5×10^{-10} sec. (full width) laser pulses incident on solid 400 μ m diameter D₂ cylinders.

The dependence of reflectivity on incident intensity is shown in Figure (3). At intensities comparable to the Limeil experiments, very high reflectivities greater than 50% are observed; however, this high value falls as the intensity increases. At 5×10^{15} W/cm² the reflectivity is below 20% and continues to fall beyond that level. For comparison purposes measurements were made on CH₂ targets of the same geometry. For CH₂ the reflectivity is not as high at the low intensities; however, at high intensities the values are comparable.

The time dependent reflectivity for these targets was measured at ω , 2ω , and $3\omega/2$. A sample of the result is shown in Fig.(4). These measurements were made with a high speed streak camera and the data processed[19] to allow the amplitude to be linear with intensity. Each of the three traces includes a plot of the incident pulse for reference purposes only. Notice that at the fundamental the reflectivity peaks early, sometimes reaching values as high as 80% of the incident intensity. The reflectivity then decreases at the end of the pulse. The 2nd harmonic has a very different dependence rising later than the fundamental but then staying high up to the end of the pulse. The integrated values of the 2ω and $3\omega/2$ signals are each approximately 1% of the reflected fundamental signal. In contrast to the 2ω trace, the $3\omega/2$ time history follows the fundamental rather closely. These measurements indicate that the reflection may be a stimulated process turning off toward the end of the pulse. The second harmonic is clearly unrelated to this process since its time history in general anti-correlates with the fundamental. The $3\omega/2$ reflection tends to correlate with the fundamental.

Fig. 4 Time dependent reflectivity measurements. The incident laser pulse is displayed ahead of the reflection at the fundamental and its harmonics for reference. (a) Reflection of the fundamental ω . (b) Reflection at 2ω . (c) Reflection at $3\omega/2$. The time integrated reflectivity for this shot is 20% for the fundamental and 1% for ω and $3\omega/2$.

In addition to reflectivity measurements, the absorption of the incident laser radiation was determined from the expansion energy in the charged ions. Five charge collectors were used to determine the angular distribution of the expansion. Typical plumes were observed directed towards the incident laser beam. The dependence of absorption on incident laser intensity for the 400 μ diameter D_2 targets is shown in Fig. (5). The observed values of absorption of 30% agree well with the predicted absorption for inverse bremsstrahlung at the lower intensities. However, above 1×10^{15} W/cm² one expects the absorption to be intensity dependent [10] and this is not observed. The observation of a hard x-ray component with photon energies greater than 100 keV and a total energy content of less than 10^{-3} of the absorbed energy indicates that anomalous processes or resonant absorption are contributing to the interaction. The absorption in CH_2 targets of the same geometry is shown in Fig. (6). There were no significant differences observed between D_2 and CH_2 in this intensity range. Except at low intensities the sum of the absorption plus the reflectivity does not account for all the incident energy. It seems likely that the missing energy is in refracted light not collected by the lenses. Calculations of this refraction effect are discussed in Section III.

Fig. 5 Measured absorption for 5×10^{-10} sec. (full width) laser pulses incident on 400 μ diameter D_2 cylinders.

Fig. 6 Measured absorption for 5×10^{-10} sec. (full width) laser pulses incident on $400 \mu\text{m}$ diameter CH_2 targets.

D-D neutron yields between 5×10^3 and 4×10^4 neutron per shot were observed in the D_2 experiments. The scatter of these data makes the significance of neutron measurements at these intensities questionable.

After Pulse:

In most of the time resolved backscatter photographs, it was observed that the reflected pulse length at the fundamental exceeded the incident pulse by approximately 100 picoseconds. An examination of 40 shots give an average difference of 120 picoseconds with an RMS deviation of 60 picoseconds. The measuring technique was examined carefully to rule out any systematic error which might lead to this result. We believe that this is a real phenomenon possibly similar to after pulses observed in some low density plasmas.[21] A sample case of a clear afterpulse is shown in Fig. (7). The upper trace represents the time history of the incident pulse while the lower is the reflected pulse. The second peak in the reflected light comes after the fall in the incident intensity. The energy content of these after pulses can be as high as 2-3 joules. This is being studied theoretically in terms of energy

stored in electrostatic plasma waves.

Fig. 7. Times resolved reflection showing after pulse. Incident laser energy ~ 100 joules on $400\mu\text{m}$ diameter D_2 target.

Multi-beam Experiments:

Initial multibeam experiments have been carried out using four coplanar orthogonal beams. All beams are focussed with similar $f/2$ 20cm. focal length lens. The targets for these experiments were CD_2 spheres with diameters between 100-200 μ .

The primary objective of these studies is to explore the effects of asymmetry on the initial heating of the plasma and to compare the observations to the predictions of the one dimensional computer calculations.

Absorption measurements, similar to those described in the one beam case, have been carried out over a comparable intensity range. In this range the measured absorption is very close to the single

beam values of 30%, with 25% of the absorbed energy emitted in x-rays. The charge collector traces have been analyzed to produce energy distribution functions. Fig. (8) shows a comparison of a measured energy distribution function and that calculated from the 1D code for a comparable absorbed energy. The theoretical curve has been normalized to the point at 2keV.

In Fig. (8) the experimental energy distribution function is shown only to 14keV per average mass ion. In fact the charge collector current indicates ions with energies up to 15keV per nucleon or 30keV for deuterons and 180 keV for carbon ions. There is not an identifiable fast ion peak such as those reported in some laser plasma experiments. [26,27] A sample ion collector trace is shown in Fig. (9). Typically about 3% of the absorbed energy is contained in particles with velocities greater than 10^8 cm/sec.

Reflectivity has been measured to be 10%. In some cases, a significant portion of the beam (up to 50%) was found to be transmitted past the target. This may be due to changes in focusing or refraction of the laser light past the target. The question of refraction is addressed in Section III.

Symmetry

One of the primary goals of the multi-beam experiments is to ascertain the irradiation symmetry required to achieve a high compression. In the present set of experiments we attempted to measure both the incident laser radiation profile on the targets, and to determine by means of ion emission and x-ray pinhole photography the resultant ablation symmetry.

For this first set of experiments we chose the simplest (but least uniform) irradiation configuration. The four orthogonal beams are incident on the spherical targets in a single plane. The planes of polarization of opposing beams are orthogonal to minimize the transmission isolation problem. The best focus of all the beams is placed at the center of the target with an accuracy of $\pm 15\mu\text{m}$. The resulting irradiation is monitored by photographing the 2ω emission from the plasma in the direction perpendicular to all the beams and also along the direction of two of the beams.

The assumption made in interpreting these photographs is that the 2ω emission has its origin near the critical density region of the plasma and is thus a good indicator of the actual laser intensity distribution on the surface of the pellet. Some typical results of these measurements are shown in Fig. (10). It is obvious from such photographs that the laser intensity distribution on the surface of

Fig. 8 Comparison of theoretical and experimentally measured ion velocity distribution for the case of 20 joules absorbed in a 160 μm CD_2 target in a 2×10^{-10} sec. (full width pulse).

Fig. 9 Charge particle collector trace for the same conditions as Fig. 8. The collector is located 100cm from target.

the pellets is highly non-uniform consisting typically of four hot spots with a diameter of $70 \pm 20 \mu\text{m}$ equally spaced along the equator of the pellets.

Fig. 10 Photographs of 2ω emission from a spherical $200 \mu\text{m}$ diameter CD_2 target irradiated by a 2×10^{-10} sec wide, 200 joule laser pulse. (a) View orthogonal to direction of the four beams. (b) View along axis of one of the laser beams.

One of the indications of energy deposition uniformity (as opposed to irradiation uniformity) on the surface of the pellets is the emission symmetry of the blow-off plasma. The resulting high energy ions are sampled at nine different directions by means of Faraday cups. The energy and particle distribution produced in a typical four beam irradiation experiment is shown in Fig. (11a,b). This is to be compared to highly unsymmetric plasma expansions produced when a single beam is used for irradiating a spherical pellet, Fig. (11c).

Fig. 11 Comparison of angular dependence of total charged particle kinetic energy for multi-beam and single beam irradiation.
 (a) Charged particle energy distribution in the plane of irradiation for a four beam experiment. Target is $160\mu\text{m}$ CD_2 sphere, laser energy 150 joules delivered in 2×10^{-10} sec.
 (b) Same shot as (a) showing distribution of charged particle energy orthogonal to plane of irradiation.
 (c) Typical energy distribution for single beam experiment. Target is $160\mu\text{m}$ sphere of CD_2 , laser energy ~ 50 joules delivered in 2×10^{-10} sec.

A multi-frame, multi-pinhole x-ray camera is used to observe the target both in the plane and nearly normal to the plane of irradiation. The resolution of this device is 12 microns. Various thicknesses of Al and Be foil are used at the film plane.

Although irradiation of spherical CD_2 targets by four orthogonal coplanar beams is highly non-symmetric, lateral heat conduction smooths the x-ray emission profile to the point where even the intensity measured at the film is indistinguishable from that calculated using the same pulse conditions ($E_L \sim 50\text{--}200$ joules, $\tau \sim 200$ picoseconds) in spherical symmetry, Fig. (12).

For comparison we have carried out a number of 2-beam irradiation studies on the same targets using a coplanar, opposing beam configuration. In this case the x-ray image is non-symmetric and a measure of lateral heat conductivity.

Fig. 12 X-ray pinhole photographs showing (a) symmetric x-ray emission conditions in the case of 4 beam irradiation and (b) non-symmetric emission in the case of two opposing beams.

III. DISCUSSION

Energy Deposition Symmetry:

An examination of the time integrated x-ray pinhole photographs shows a symmetric bright emission ring surrounding the plasma (TLD and PIN diode arrays show the temperature of the ring to be 1.2keV). We interpret this ring to be the radiation from the thermal conduction front propagating inward towards the center of the plasma. This interpretation is consistent with the results from computer codes which contain rate dependent descriptions of the ionization state as well as the line and continuum radiation. A computed x-ray pinhole photograph, which is constructed with appropriate filtering, reproduces the photographs obtained experimentally.

The fact that there is a very good correlation between the predictions of a one-dimensional spherically symmetric computer code and plasmas produced by highly asymmetric illumination indicates that transverse thermal conduction is very effective. Using the estimate[22]

$$t = \ell^2 \langle z^2 \rangle n_e / 2.93 \times 10^{27} \langle z \rangle T_e^{5/2}$$

for the time required for thermal conduction to equilibrate temperature over a distance $\ell = (\pi \times 50 \mu)$, we find that $t = 150 \text{ psec.}$ at 1.5keV which is well within the time scales considered in these experiments.

We have performed a series of computational experiments to examine the effect of such experimentally observed high temperature coronas on the symmetry and stability of future experiments using more powerful lasers and leading to high compression of the plasma. One could envision a high temperature corona as being formed by a short, high intensity pulse at the leading edge of a pulse that is optimally tailored[23] to produce very high compressions. The numerical results, performed with a spherical harmonic perturbation code,[8] show clearly that the symmetrizing effect of lateral electron thermal conductivity on the high temperature corona prevents the growth of asymmetries impressed by non-uniform laser irradiation. It was observed that the minimum corona temperature for this effect was on the order of 0.1 keV. It should be noted, however, that the suppression of the growth of impressed asymmetries does not necessarily preclude the growth of the Rayleigh-Taylor type of instability. The growth rates associated with instability depend directly on the acceleration time history of the ablating surface and are independent of corona conditions.

Refraction:

In order to study the refraction of laser energy propagating in a non-homogenous plasma, we have developed a procedure referred to as the super photon method. This method, described in detail elsewhere,[4] incorporates the effects of beam distortion, finite propagation time and external focusing optics. Typical results from the super photon code can be seen in Figs. (13a) and (13b). For tutorial purposes, we have selected a D_2 plasma with a radius of 50μ at solid density surrounded by a corona of low density material which decreases from critical density to 0.1 critical in 50μ . The 90J laser pulse is Gaussian in time and space with a 100 psec rise time while the $f/2$ 20cm. focal length (ideal) focusing optics form a 100μ radius focal spot at the critical surface. Note that within the approximation of a spherically symmetric plasma and cylindrically symmetric laser pulse, the plasma still undergoes uniform 4π illumination. The ray paths are drawn in Fig. (13a) at 100psec. (pulse maximum) and Fig. (13b) shows the angular distribution of non-absorbed energy (only classical absorption is assumed here). These two figures clearly show the effects of refraction on rays which are not normally incident.

The superphoton code has been expanded to include the effects of resonant absorption.[24] Because of the fact that the fractional absorption of driver power in the steady state appears to be insensitive to the details of the damping of the resonant oscillations, it is possible to use a calculation with a vanishing effective damping rate.[25] We assume that all of the energy absorbed by this mechanism appears in the plasma as an increase of the temperature of a Maxwellian electron distribution. For a given laser wavelength, the fractional absorptivity depends on the angle to the normal at which a ray enters the plasma, the distance of closest approach of the ray to the critical surface and the scale length of the density gradient at critical.

As a numerical computation representative of the experimental situation discussed here, we consider a 100μ diameter solid sphere of CD_2 . The target is prepared for heating by a prepulse with a rectangular profile 200 psec. wide and containing 5J energy. After a 1.5 nsec delay, the scale length at critical is 30μ , the radius of the critical surface is 70μ , and the outer edge of the plasma is at 210μ . The 200 psec., 100J rectangular main pulse is focussed by an $f/2$ lens, 20cm. focal length with an ideal focus 25μ beyond the center of the plasma. In this case, 22J are absorbed classically and 17J are absorbed via resonant oscillation.

These computations suggest that a combination of classical and resonant absorption is sufficient to account for the experimental observation of a minimum of 30% absorbed energy. A change of focal position in the superphoton calculation, using a perfect focus, from

the center of the target to -50μ behind the target, for the same conditions reported above, shows an increase from no resonant absorption at center focus to 17% at -25μ and a decrease to 9% at -50μ . Because of the imperfect focus in the experiment, the computed absorptions from 22% (purely classical) to the peak 39% at -25μ , bracket the observed result.

Since the resonant absorption is so sensitive to the exact position of the target with respect to the focus of the laser beam, the observed large scatter in absorption efficiency under apparently identical irradiation conditions may be another indication of the presence of this type of absorption.

Fig. 13 (a) Path of refracted rays for a 90 joule laser pulse with a focal spot radius of $100\mu\text{m}$ incident on a spherical target having a $50\mu\text{m}$ overdense radius with $50\mu\text{m}$ underdense region.
(b) Angular dependence of non-absorbed energy for the same case.

SUMMARY

A series of experiments have been conducted to:

- (i) Measure the absorption and reflection of 1.06 μ m laser radiation with focused intensity ranging from 10^{15} - 10^{16} W/cm² incident on cylindrical D₂ and CH₂ targets, and spherical CD₂ targets.
- (ii) Measure the irradiation and energy deposition symmetry in four beam spherical target irradiation at laser intensities in the range of 10^{15} - 10^{16} W/cm².
- (iii) Verify predictions made by one-dimensional computer codes relating to absorption, refraction, and the x-ray emission distribution from spherical targets subjected to focused laser radiation in the range of 10^{15} - 10^{16} W/cm².

The results of these experiments may be summarized as follows:

- (i) Cylindrical D₂ and CH₂ targets with diameters greater than the laser focal spot exhibit absorption of at least 30% in the intensity range of 10^{15} - 10^{16} W/cm². This is greater than the absorption predicted by classical inverse bremsstrahlung implying the presence of non-collisional absorption in this intensity range, e.g., resonant absorption.
- (ii) Reflection from these targets peaks at a value around 50% at an intensity around 10^{15} W/cm² and then decreases with increasing intensity to a value around 10-20% at intensities close to 10^{16} W/cm².
- (iii) The highest reflection in the cylindrical target experiments appears to occur in the first 100 psec of the laser pulse approaching instantaneous values of 80%. The implication is that the high reflection is due to stimulated scattering which turns off during the pulse.
- (iv) An after pulse emission containing a few percent of the laser radiation energy has been observed in most of the cylindrical target experiments. This emission follows the laser pulse by about 120 psec., for incident laser. Intensities in the range of 10^{15} - 10^{16} W/cm² and pulse widths 5×10^{-10} sec (FW).
- (v) Four beam spherical target experiments on CD₂ exhibit the same absorption efficiency (30%) as the cylindrical target experiments. A large percentage of the laser radiation is refracted in some of the four beam target experiments, as predicted by computer code.
- (vi) Energy deposition on the surface of the spherical targets is measured to be considerably more symmetric than the incident laser irradiation. This is consistent with estimates of lateral thermal conductivity.

- (vii) The fraction of the target which is heated to high temperature in the spherical target experiments is consistent with one dimensional computer codes in which the laser energy is deposited near the critical density layer.
- (viii) In these experiments no distinct fast ion peaks are observed and the intensity of the hard x-ray component ($>100\text{keV}$) is typically 10^{-2} - 10^{-3} of the absorbed energy.

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