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Abstract

This paper presents the results of experiments in which a high-power laser was used to irradiate low density ($4 - 9 \text{ mg/cm}^3$) silica aerogel and agar foam targets. The laser-solid interaction and energy transport through the material were monitored with time-resolved imaging diagnostics, and the data show the production and propagation of an x-ray emission front in the plasma. The emission-front trajectory data are found to be in significant disagreement with detailed simulations, which predict a much more rapid heating of the cold material, and the data suggest that this discrepancy is not explainable by target inhomogeneities. Evidence suggests that energy transport into the cold material may be dominated by thermal conduction; however, no completely satisfactory explanation for the discrepancies is identified, and further experimental and theoretical research is necessary in order to resolve this important problem in laser-plasma interaction physics.

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I. Introduction

The interactions between high-power lasers and under-dense plasmas have received significant research attention in recent years [1-8]. In these experiments, the plasmas have generally been created by high-power laser irradiation of solid foil targets, and the experiments have been designed to produce and diagnose plasmas with electron densities which are below the critical density for light propagation at the laser wavelength, allowing plasma heating to proceed primarily by resistive inverse-bremsstrahlung.

The primary impetus for this research attention has been, and continues to be, the goals of the inertial confinement fusion (ICF) community. Larger implosion targets in both directly driven and indirectly driven geometries [9,10], necessary for efficient fusion yield at next-generation facilities [10], imply that the driving laser beams will create, and must then propagate through, large scale-length, under-dense plasmas ablated from implosion capsule surfaces in direct-drive experiments, or from hohlraum walls [11] in indirect-drive experiments. Further, recent target designs utilizing gas-filled hohlraums [12] would present similar difficulties. For these ICF-related applications, it is particularly important to understand and control parametric instabilities [13], which grow non-linearly in sub-critical plasmas and which therefore become increasingly significant in larger plasmas. These instabilities can scatter incident laser light and reduce laser-target energy coupling, or can produce non-thermal high-energy electrons which can pre-heat the implosion capsule, reducing compression and thus reducing fusion efficiency [9,10,13].

Several experimental approaches to under-dense laser-produced plasma research have been pursued, and these have generally used exploding-foil targets or low-density solid foam targets. A number of

experiments have examined scattered optical light from exploding-foil targets [1-6] in an attempt to understand parametric instabilities through their spectral signatures [13]. The plasmas have been formed and probed by a single laser beam or have been pre-formed and allowed to expand and rarefy before being probed. The exploding foil targets used in these experiments are relatively simple to manufacture and handle; however, the resulting transient plasmas are not well characterized, and hydrodynamics simulations must be relied on to predict time-dependent and spatially dependent plasma parameters such as temperature and density.

Several experimental studies have also been performed using low-density hydrocarbon-based foam targets [7,8]. Plasmas produced from these targets have not been investigated as extensively as those produced from exploding foils, primarily because of structure in the solid foams at the ~ 10 μm scale which complicates the interpretation of the experimental data [6,7]; however, the advantages of foam targets include relative ease of handling, well-characterized bulk material densities and potentially large dimensions. The foams are generally produced by a freeze-drying method, in which an aqueous solution of a carbohydrate polymer is rapidly frozen and the solvent is removed by a freeze-drying process. The final foam density is controlled by varying the initial carbohydrate concentration in the solution [14].

To summarize previous laser-produced plasma experiments with low-density foam targets, we note the following. Tanaka *et al.* [7] primarily studied parametric instabilities in $0.1 - 0.67 n_c$ ($n_e = 0.1n_c - 0.67n_c$) dextran ($\text{C}_6\text{H}_{10}\text{O}_5$) foams using $\lambda = 0.35$ μm , 1 ns laser irradiation at average intensities ranging from 5×10^{13} to 10^{15} W/cm^2 . They observed red-shifted back-scattered light near the laser frequency ω_0 , and observed a strong correlation between the back-scattered ω_0 signal, related to stimulated

Brillouin scattering (SBS), and the back-scattered $3\omega_0/2$ signal, related to the two-plasmon decay instability (TPD); they found that the back-scattered energy ratios ($E_{\text{back}}/E_{\text{laser}}$) of both signals remained constant for irradiances above $5 \times 10^{14} \text{ W/cm}^2$. They also reported a laser penetration depth, measured with a time-integrated soft x-ray pinhole camera, which was a factor of 2 - 3 less than predicted by simulations, and attributed the discrepancy to density inhomogeneities in the foam which were not included in the hydrodynamic ray-tracing simulations.

Figueroa *et al.* [8] measured the forward- and back-scattered Raman spectrum from 0.11 - 0.5 n_c dextran foams using $\lambda = 0.35 \text{ }\mu\text{m}$, 850 ps laser irradiation at an average intensity of $1.5 \times 10^{15} \text{ W/cm}^2$. They observed that the back-scattered spectrum was peaked between $\lambda = 0.47 \text{ }\mu\text{m}$ and $0.50 \text{ }\mu\text{m}$, corresponding to scattering from regions of the plasma where the electron density is 0.05 - 0.07 n_c , and observed that the spectral position of this peak did not vary with initial target density. The back-scattered energy ratio was measured to be 0.3% into the 5×10^{-3} steradian aperture of the focusing lens for foams with initial densities below 0.25 n_c , and 0.01% for foams with densities of 0.5 n_c . They also observed that the $\omega_0/2$ harmonic emission was detectable only for initial target densities greater than 0.25 n_c . In other experiments, Kodama *et al.* [15] used higher-density (over-dense) C_8D_8 foams for laser-induced shock-propagation studies, using x-ray streaked shadowgraphy to measure shock trajectories in 0.1 and 0.2 g/cm^3 foams, corresponding to 7.5 and 15 times n_c for the drive laser used. Finally, Afshar-rad *et al.* [16] irradiated 50 mg/cm^3 triacrylate ($\text{C}_{15}\text{H}_{20}\text{O}_6$) foams with soft x-rays from a Au burn-through foil at an intensity of $\sim 4 \times 10^{13} \text{ W/cm}^2$. The foam was back-lit and imaged in transmission, and changes in the material

opacity during irradiance were observed which indicated the production of a supersonic, soft x-ray driven ionization front.

While all the experiments noted above used hydrocarbon-based targets, few laser-produced plasma experiments have been performed with SiO₂ aerogel targets. These aerogels are similar to carbon-based foams [14], but are made by a different process based on super-critical drying of highly cross-linked inorganic gels [17]. The resulting aerogel material has much higher uniformity than freeze-dried, phase-separation foams, with ~ 300 Å structure, but is generally composed of metal-alkoxides such as SiO₂ rather than low-Z hydrocarbons typically used in under-dense plasma instability experiments [1-8]. However, their homogeneity makes them excellent target materials for investigations of laser heating and energy transport, where foams are suspect due to their large-scale structure [7].

In all the above foam experiments, relatively little emphasis has been placed on diagnosing heating and energy transport in under-dense plasmas. Broadly, the usual theoretical interpretation begins with the assumption that energy from a high-power laser is transformed primarily into heat in an under-dense target material, and that this energy transfer initially results from inverse-bremsstrahlung electron excitation caused by direct laser penetration [18-21]. When a high-power laser interacts with an under-dense material, the laser pulse initially ionizes a surface layer, creating a relatively cold plasma which is opaque to the laser light. This surface plasma is further heated and ionized until it is optically transparent, so that the remainder of the laser pulse can penetrate beyond the surface to heat and ionize deeper material. This process continues, and the resulting laser absorption wave moves deeper into the material, slowing as the accumulating depth of plasma

behind the front absorbs laser energy through continuing inverse bremsstrahlung heating so that the laser intensity at the front decreases.

Once a laser-energy deposition region becomes established, further heating of the cold material proceeds by diffusive thermal conduction [18,19,21]. In this case, electron thermal conduction and radiative re-emission from the deposition region transfer energy deeper into the material, producing a thermal heat wave which propagates into and ionizes the cold material, slowing as energy is spread over a larger volume and as temperature gradients relax.

The importance of the laser absorption wave relative to the thermal heat wave to material heating in a particular experiment will depend on the initial material density, material composition, and the laser intensity, and the general problem is complex. The laser absorption wave has been investigated theoretically (e.g. reference [20]), and previous experimental data on radiant energy deposition in under-dense foam targets have been attributed to direct laser penetration [7] or, analogously, to direct soft x-ray penetration [16]. However, the calculated and measured laser penetration depths in reference [7] were in disagreement, as noted above, and the discrepancy was attributed to density inhomogeneities in the foam targets.

In this paper, we report on a series of experiments performed at the Nova laser facility [22] at Lawrence Livermore National Laboratory (LLNL), in which we endeavored to quantitatively investigate laser energy transport and heating in under-dense plasmas created by high-power laser irradiation of low-density targets. In these experiments, we irradiated 8 mg/cm³ silica aerogel and 4 - 9 mg/cm³ agar foam targets with a single beam of the Nova laser at various peak irradiances between 4×10^{14} and 1.5×10^{16} W/cm², and monitored the resulting sub-critical plasmas with time-resolved diagnostics.

The primary purpose of these experiments was to observe the laser-induced heating of the material and the resulting energy transport into the cold material.

These experiments represent the first systematic time-resolved investigation of the interaction between a high-power laser and a sub-critical solid target material, and the first such research which focuses on highly uniform, non hydrocarbon-based aerogel targets. We compare the results of the experiments to detailed laser-plasma interaction and hydrodynamics simulations, and find significant disagreements between the calculated and measured laser energy penetration depths, similar to the discrepancies noted by Tanaka *et al.* [7]. However, the present data suggest that the discrepancies are not due to initial target material inhomogeneities. We find instead that the data can be modeled with a simple thermal conduction treatment, in which electron conduction from a shallow energy deposition region, rather than direct laser penetration, is responsible for the deposition and propagation of energy into the target material. While this interpretation of the results is useful and illuminating, it does not completely explain the discrepancies, and a full understanding of the experimental results has yet to be achieved.

This paper is organized as follows. In Section II, we describe the experimental diagnostics and the details of the experimental set-up. In Section III, we present the experimental data and describe how the data were reduced. In Section IV, we discuss the detailed laser-plasma interaction and hydrodynamics simulations we performed and compare the results to the experimental data. In Section V, we discuss the discrepancies between the data and the simulations, and discuss how some aspects of the data can be

better understood in terms of a thermal conduction model. Finally, in Section VI we summarize the results and conclusions of this research.

II. Nova Experiments

The present experiments were performed in the Two-Beam chamber of the Nova Laser Facility at LLNL and used a single beam to irradiate the targets. The beam provided up to 4200 J at $\lambda = 0.527 \mu\text{m}$ in a 1 ns pulse with a square temporal shape, and was focused with an $f/4.3$ lens. Some experiments also used a random phase plate (RPP), and this consisted of a transparent hexagonal phase array which yielded a larger laser focal spot with improved spatial uniformity [23-25]. The focal spot diameter without the RPP is $\approx 150 \mu\text{m}$ full-width at half-maximum intensity (FWHM), while the RPP produces an Airy-pattern focal spot with a first-minimum diameter of 1 mm and a FWHM of $440 \mu\text{m}$.

The laser energy on target was varied to maintain the following approximate peak (center of spot) irradiance conditions in the aerogel experiments: $4 \times 10^{14} \text{ W/cm}^2$ with the RPP; $1.5 \times 10^{15} \text{ W/cm}^2$ with and without the RPP; and $1.5 \times 10^{16} \text{ W/cm}^2$ without the RPP. All foam experiments used a RPP and maximum beam energy, providing a peak irradiance of approximately $1.5 \times 10^{15} \text{ W/cm}^2$. Peak irradiances were estimated based on unconverted (fundamental) laser beam energies measured on each shot, accounting for previously measured conversion efficiencies, and assuming $150 \mu\text{m}$ -FWHM Gaussian and 1 mm minimum-to-minimum Airy spatial intensity distributions for the un-smoothed and RPP-smoothed beam foci, respectively. Full-aperture optical spectrometers monitored back-scattered SBS along with specularly reflected light on several of the aerogel experiments at various irradiances, and in each case measured

less than 5% total back-scattered laser energy into the solid angle subtended by the focus lens.

The targets consisted of vertically oriented rectangular columns of SiO₂ aerogel ($\rho = 8 \text{ mg/cm}^3$, corresponding to a fully-ionized electron density of $2.4 \times 10^{21} \text{ cm}^{-3}$, or $0.6 n_c$ for the $0.527 \text{ }\mu\text{m}$ drive laser wavelength) or CH₂O agar foam ($\rho = 4$ and 9 mg/cm^3 , corresponding to fully-ionized electron densities of $1.3 \times 10^{21} \text{ cm}^{-3}$ and $2.9 \times 10^{21} \text{ cm}^{-3}$, respectively, or $0.32 n_c$ and $0.72 n_c$), approximately 1 mm wide and 1 - 2 mm deep (along the laser propagation axis) and approximately 5 - 10 mm tall. The aerogel targets were obtained by slicing 5 - 10 mm-long columns from a longer, molded strip, and are expected to have bulk densities which are uniform to better than several percent throughout the material; no skin effects are expected. The foam targets were individually laser-cut from large bricks of agar, and any skin effects in these targets would result solely from this machining process; the effects have not been quantified but are not expected to be significant.

Scanning electron micrographs of the target material surfaces are shown in Fig. 1. The structure of the 4 mg/cm^3 foam is fibrous, with $\sim 1 \text{ }\mu\text{m}$ fibers and $\sim 5 - 10 \text{ }\mu\text{m}$ voids, and web-like structures can be seen to connect some of the fibers; the structure of the 9 mg/cm^3 foam is very similar, the primary difference being an increase in the amount of web-like structure. The silica aerogel, in contrast, is very uniform, with some apparent structure consisting of $< 1000 \text{ }\text{\AA}$ cell walls and voids. At the $\sim 5000 \text{ }\text{\AA}$ scale (comparable to the Nova laser wavelength), the aerogel would thus be expected to be essentially homogeneous.

The diagnostic geometry for each experiment is shown in Fig. 2. The primary diagnostics consisted of the following: 1) GAX, a gated micro-channel plate imager. This instrument consisted of an array of sixteen $10 \text{ }\mu\text{m}$ -

diameter filtered pinholes in front of a micro-channel plate intensifier [26]. The cathode of the micro-channel plate consisted of four Au-coated transmission strips which were electrically pulsed at different times, yielding time resolution along the strips due to the 100 ps voltage duration and between the strips due to the variable delays. This instrument provided a two-dimensional spatial resolution of approximately 10 - 20 μm in 100 ps-duration frames. 2) SPHC, a streaked pinhole camera. The streak camera was a Kentech Instruments, Ltd., low-magnification model backed by an ITT F-4113 image intensifier and Kodak TMX-3200 film. The filtered pinhole was 10 μm in diameter and provided 10 - 20 μm spatial resolution at the target along the laser propagation axis, integrated over a 50 - 150 μm vertical width depending on the magnification used; slit-limited temporal resolution was generally 80 ps. 3) Keanetech, a streaked x-ray crystal spectrograph. This instrument consisted of a second Kentech streak camera coupled to a 10 cm convex-radius potassium hydrogen phthalate (KAP) crystal spectrograph. The spectrograph was configured to observe Si emission lines between 4 $\text{\AA}$ and 7 $\text{\AA}$. Time resolution was 80 ps, and the spectra were spatially integrated over the entire target region.

In each experiment, the laser was focused onto the front surface of the target at normal incidence. The laser spot was placed mid-way between the two sides, approximately 1 mm below the top surface of the column and 4 - 9 mm away from the bottom surface, which was glued to a plastic support rod. This arrangement, shown in Fig. 3, was chosen to minimize complications due to target edge effects and solid-density interactions with the glue and target supports.

III. Experimental Results

The primary experimental data we obtained consisted of two-dimensional gated x-ray images from the GAX diagnostic and one-dimensional streaked x-ray images from the SPHC diagnostic. All data were recorded on photographic film, and were digitized on a micro-densitometer for analysis. Relative intensity scales were obtained by converting film optical density to areal energy density through calibration wedges exposed onto each piece of film.

Typical data from the GAX diagnostic are shown in Fig. 4. In all three sets of two-dimensional images (a), (b) and (c), the laser is incident from the left, and the earliest time frame is on the left; later frames follow at 400 ps intervals relative to the first, though no absolute timing fiducial exists to establish a temporal reference. In the top four frames (a), an aerogel target was irradiated at an intensity of 4.1×10^{14} W/cm² using a RPP-smoothed beam, and the GAX pinholes were filtered with Be to transmit ($> 10\%$) x-rays with energies above 1.4 keV. In the middle four frames (b), an aerogel target was irradiated at an intensity of 1.3×10^{16} W/cm² using an un-smoothed beam, and the GAX pinholes were filtered with Be and Al to transmit x-rays with energies above 2 keV. Finally, in the bottom four frames (c), a 4 mg/cm³ foam target was irradiated at an intensity of 1.5×10^{15} W/cm² using a RPP-smoothed beam, and the GAX pinholes were filtered with Be to transmit x-rays with energies above 1.4 keV.

In each case, the data show the propagation of an x-ray emission wave induced by the incident laser beam. The filtering of the pinhole camera transmits x-rays with energies in the kilovolt range, and the observed wave front is therefore associated with the boundary between cold material and regions of the material heated to temperatures sufficient to allow significant

x-ray emission in this energy range. The x-ray energy range in these data corresponds primarily to Lyman-series line emission (prominent in the Keanetech x-ray spectra) in H-like and He-like silicon for aerogel targets, and to free-free and free-bound continuum emission in the lower-Z agar targets. Some weak x-ray emission was observed in front of the propagating front in the high-irradiance aerogel experiments, and is particularly evident in Fig. 4(b). Differential filtering of the GAX pinholes on other experiments indicated that this weak emission is primarily harder x-rays with energies > 7.5 keV, and is likely to be free-free and free-bound continuum radiation from plasma created by high-energy x-rays emitted near the incident surface and absorbed throughout the material.

The observed lateral (up-down) dimension of the emission region in the earliest frames (left side) of Fig. 4 correspond approximately to the laser focal spot dimensions, with the emission region in Fig. 4(b) being smaller because a smaller focal spot was used. Transport of energy in the axial direction (left to right) and in the lateral direction (up and down) is evident, and both lateral and axial transport velocities are larger when a smaller laser spot is used with high irradiance. The aerogel data show initial lateral transport velocities of up to 0.5 mm/ns early in the laser pulse at maximum irradiance, typically slowing to $\sim 0.1 - 0.2$ mm/ns for the remainder of the pulse. Detailed lateral energy transport trajectories were not obtained in these experiments, but axial transport trajectories were measured accurately with the SPHC.

Typical SPHC data are shown in Figs. 5 and 6. In Fig. 5, an aerogel target was irradiated at 1.3×10^{16} W/cm² with an un-smoothed beam. The plasma was imaged at approximately 23-times magnification onto the streak camera slit, and the axial position of the resulting x-ray emission wave was

continuously time-resolved. Fig. 6 shows similar data obtained from an aerogel target which was irradiated at 1.6×10^{15} W/cm² with an RPP-smoothed beam. The plasma was imaged at approximately 6-times magnification onto the streak camera slit.

In the high-irradiance data of Fig. 5, an initially rapid penetration of the x-ray emission wave front is observed (several mm/ns); the front gradually slows in time and shows no discontinuities when the drive laser turns off near $t = 1$ ns. Additionally, there is an early-time feature which is discernible in all the maximum-irradiance aerogel SPHC data but not in any of the lower-irradiance aerogel data (e.g. that of Fig. 6) or in the foam data. This feature shows an initially rapid penetration (50 - 100 μ m) which then slows, at which point a second feature (the main emission wave front) breaks away rapidly and itself gradually slows. The slow wave front continues to be weakly visible in the film data even after the main emission wave front has moved far ahead into the material, and differentially-filtered GAX data on other experiments showed this feature to be associated with bright high-energy (> 7.5 keV) x-ray emission. This feature is suggestive of the creation of a laser energy deposition region, and will be discussed in more detail in Section V.

Figs. 7, 8 and 9 show the compiled x-ray emission wave trajectory data from the aerogel and foam experiments, with time and distance in the target obtained from the known streak camera sweep speed and pinhole magnifications; the reproducibility of the data can be seen to be excellent. In each case, the front position at a particular time is defined as the 10% rising edge in intensity moving towards $z = 0$, and corresponds approximately to the emission front as would be visually discerned on film. The uncertainties introduced by the data reduction are estimated as ± 50 μ m in space and ± 40 ps in time. Fig. 7 shows the emission wave front trajectories from the low-

irradiance ($\sim 4 \times 10^{14} \text{ W/cm}^2$) and mid-irradiance ($\sim 1.5 \times 10^{15} \text{ W/cm}^2$) aerogel experiments, Fig. 8 shows the wave front trajectories from the high-irradiance ($\sim 1.5 \times 10^{16} \text{ W/cm}^2$) aerogel experiments, including the slow front behind the main emission front, and Fig. 9 shows the compiled trajectories from the foam experiments.

Several features in Fig. 7 are apparent; as the irradiance is increased, the initial penetration velocity increases, reaching 0.6 mm/ns at irradiances of $\sim 1.5 \times 10^{15} \text{ W/cm}^2$ with a RPP-smoothed beam, but in all cases the wave gradually slows to a nearly constant asymptotic velocity of $0.2 - 0.3 \text{ mm/ns}$ within 200 ps of the start of the laser pulse. This feature is independent of irradiance, and a continuous wave trajectory is maintained well after the laser turns off near $t = 1 \text{ ns}$.

In Fig. 8, the slow wave behind the main front is seen to move at a relatively constant velocity of $\approx 0.1 \text{ mm/ns}$; the slow front is observed to weaken in intensity near $t = 1 \text{ ns}$ but is still evident afterwards. The main emission front breaks away from the slow front after $100 - 200 \text{ ps}$, and moves rapidly into the material with an initial velocity of approximately 3 mm/ns ; this front then slows to a nearly constant asymptotic velocity of $0.2 - 0.3 \text{ mm/ns}$ after approximately 500 ps . As in the lower-irradiance data of Fig. 7, the wave trajectory is continuous near $t = 1 \text{ ns}$, and continues to gradually slow thereafter.

Finally, Fig. 9 shows the wave trajectories for the foam experiments. The lower density foams show a nearly constant propagation velocity of approximately 1 mm/ns , while the higher density foam shows a nearly constant propagation velocity of approximately 0.4 mm/ns ; again, no discontinuities are observed near $t = 1 \text{ ns}$. We emphasize that due to spectral filtering, the x-ray energies being observed in the foam experiments

correspond to continuum emission alone, while the emission observed in the higher-Z aerogel experiments is primarily line emission.

IV. Laser-Plasma Interaction and Hydrodynamics Simulations

To simulate the experimental results, we used a two-dimensional Lagrangian hydrodynamics code [27] with cylindrical r - z geometry. In the simulations, laser propagation in the plasma was treated in a three-dimensional ray approximation, using a two-dimensional moving grid to describe skew rays, and included filamentation effects [28]. We used the measured spatial intensity distribution [29] for the un-smoothed Nova best-focus, and a calculated Airy-pattern spatial intensity distribution for the RPP-smoothed beam focus.

In the simulations, rays deposit energy in the plasma primarily through inverse bremsstrahlung along the density gradient; additionally, some fraction of the incident energy (typically 25 - 50%) is deposited into high-energy (~ 100 keV) electrons near $n_e = 0.25 n_c$ in order to approximate anomalous absorption effects such as stimulated Raman scattering (SRS) [13]. In accordance with standard practice in laser-produced plasma thermal conduction modeling, electron transport was flux-limited with a flux-limiter factor of 0.01 - 0.03 [30-32]. We performed simulations for each set of experimental parameters for which data was obtained, these being the parameters resulting in the data curves of Figs. 7, 8 and 9.

The main results of the simulations were the temporal and spatial dependence of the deposited laser energy, mass density and electron temperature. In all cases examined, energy was deposited primarily by a laser absorption wave [20] which moved into the material and heated it to peak electron temperatures of at least several keV. Electron thermal conduction

was found to play a small role in the energy propagation into the material, and the results were relatively insensitive to the flux-limiter value we used. A typical spatial variation of electron temperature and mass density resulting from the simulations is shown in Fig. 10. There, a laser absorption wave has heated approximately one-third of the target depth to temperatures in excess of several keV after 0.3 ns; compression of the target material to ~ 1.4 times initial density is evident at the front position, with rarefaction evident behind the front.

In order to determine the plasma parameters which would result in maximum emissivity as observed by the SPHC diagnostic, the axial ($r = 0$) electron density and temperature curves for a typical aerogel experiment were used as input to a time-dependent spectral synthesis code, and the resulting Si Lyman-series spectrum was convolved with experimental filter response functions and spectrally integrated. We found that for the aerogel targets, the position along the temperature-density gradient where the electron temperature is 800 eV corresponds approximately to the 10% leading-edge x-ray emission position, as plotted in Figs. 7 - 9. This is consistent with time-resolved x-ray spectra obtained with the Keanetech diagnostic, which indicated electron temperatures, based on Lyman-series line emission ratios, of approximately 1 keV, regardless of laser irradiance and essentially independent of time due to spatial integration of the plasma emission; higher electron temperatures result in less line emission, so that peak electron temperatures behind the emission front could not be measured by Si line ratios. We therefore associate the position of the 800 eV temperature contour along the laser propagation axis ($r = 0$) with the x-ray emission front position as plotted in Figs. 7 - 9, for both the aerogel and the foam target materials.

The resulting plots of the 800 eV temperature front along the laser propagation axis at $r = 0$ are compared with the experimental data in Figs. 11 - 13. It is apparent from these plots that the simulation results are in very poor agreement with the experimental data, with the simulated laser-absorption wave velocities dramatically larger than the experimental x-ray emission front velocities in all cases examined. In addition, the simulation results are qualitatively different from the experimental data, particularly in the maximum-irradiance aerogel case, in that the simulations predict less curvature of the trajectories as a function of time, so that the simulated trajectories have larger initial speeds and slow much less with time than the experimental trajectories. Finally, no evidence of a second, slow wave-front (Figs. 5 and 8) is seen in the simulations.

The significant discrepancies between the present time-resolved experimental data and the simulation results are disturbing, and in qualitative agreement with the time-integrated measurements of Tanaka *et al.* [7]. While direct comparisons between the simulated temperature-front curves and the experimental x-ray emission-front curves are complicated by temperature gradients, spatial integration effects, uncertainties in the correlation between axial electron temperature and observed x-ray emissivity (particularly for the lower-Z agar target data), and by the three-dimensional nature of the hot plasma imaged in the experiments, it seems clear that such complications cannot explain the consistently large discrepancies we observe. Finally, additional simulations we performed, in which we varied parameters such as the flux-limiter factor, the supra-thermal electron energy, and the energy fraction absorbed into supra-thermal electrons, only succeeded in slowing the laser absorption wave velocity by a factor < 2 .

Several observations argue against an explanation based on initial density inhomogeneities in the target materials, as was proposed by Tanaka *et al.* [7]. First, while the observed discrepancies are evident in the agar data, which is of similar composition to the target materials used in previous experiments [7], the discrepancies are also evident in the aerogel data; as seen from Fig. 1, the scale of the inhomogeneities present in this material is several hundred angstroms, two to three orders of magnitude smaller than that of the agar foams. Second, the material in front of the x-ray emission front would be expected to be pre-heated and therefore partly homogenized by high-energy x-rays and electrons created by the laser-target interaction process, and such heating is evident experimentally at least in the maximum-irradiance aerogel data, as discussed in Section III. Third, several of the experiments used an additional beam of Nova to deliberately pre-heat the aerogel and agar targets by means of a thin Au-foil x-ray converter [33], yielding approximately 10^{12} W/cm² x-ray irradiance 1 - 8 ns prior to direct laser irradiation of the target by the second Nova beam. In all cases with x-ray pre-heating, no significant differences were observed in the x-ray emission front trajectories, and in fact several of the curves plotted in Figs. 8 and 9 (the solid-triangle high-irradiance aerogel curve of Fig. 8, the solid-diamond 4 mg/cm³ agar curve of Fig. 9, and the 9 mg/cm³ agar curve of Fig. 9) resulted from such x-ray pre-heated target experiments. Lastly and most significantly, essentially identical discrepancies were observed between simulation results and experimental data [34] obtained with CH-based gas-filled balloon targets using $\lambda = 0.527$ μ m irradiation and using gas densities approximately equivalent to the target densities used in the present experiments (Fig. 14).

It thus appears clear that an explanation for the discrepancies based on initial density inhomogeneities in the targets is untenable, and that a more

fundamental problem exists in our current ability to simulate laser heating and energy transport in under-dense materials. This outstanding problem is important for the fundamental understanding of laser-matter coupling, and has important implications for the interpretation of a large body of data involving relatively long-pulse (~ 1 ns) laser-solid interaction experiments, in which a laser creates and must then propagate through a long scale-length under-dense ablation plasma.

V. Discussion

As noted above, the simulations described in Section IV indicated that the dominant energy transport mechanism is the laser absorption wave. The interactions between a high-power laser and an under-dense plasma are complex and generally are not amenable to simple analytical analysis, but the experimental data provide several indications that this simulation result may be incorrect, and that the dominant energy transport mechanism may be electron thermal conduction instead.

First, as noted in Section III, the high-irradiance aerogel data from the SPHC shows a low-contrast, slow wave-front (Figs. 5 and 8) which is suggestive of the creation of a laser energy deposition region. This feature, which is not predicted by the simulations of Section IV, could be identified as the region where laser energy is deposited, by inverse-bremsstrahlung and by anomalous absorption mechanisms; the presence of anomalous absorption mechanisms would be consistent with the observation of strong high-energy x-ray emission from this region in differentially filtered GAX data, as noted in Section III. In this interpretation, laser energy is initially absorbed rapidly near the target surface, but further direct penetration of the laser beam is prevented; as the deposition region is heated, temperature gradients increase,

and a thermal conduction wave is launched into the target material. While the slow wave-front is observed only in the highest-irradiance aerogel data, it is possible that similar features are actually present in the other data, and are not visible because the deposition regions are too shallow to be resolved and because the high-energy x-ray emission is too weak to be observed. Such a supposition might explain the apparent off-sets of the SPHC curves in Figs. 7-8 from the origin, particularly evident in the mid-irradiance aerogel data of Fig. 7 and the 4 mg/cm³ agar data of Fig. 9.

Second, the SPHC data in all experiments show no significant slowing of the x-ray emission wave at the end of the 1 ns laser pulse, suggesting that the x-ray emission front is de-coupled from the laser pulse itself. In addition, the lateral transport velocities predicted by the simulations of Section IV are in reasonable agreement (~ 50% or better) with the limited lateral transport velocity data obtained from GAX two-dimensional images. Finally, the simulated lateral transport trajectories are in better qualitative agreement with the axial transport trajectories measured with the SPHC, in that gradual slowing is predicted.

Based on these observations, we constructed a simple "hot-plate" model of energy transport based on electron thermal conduction to examine the possibility that the results of this model might be in better agreement with the experimental data and might thus provide an indication of the source of the discrepancies between the data and the detailed simulations described in Section IV. This simple model relies on the same two-dimensional Lagrangian hydrodynamics code [27] used for the simulations of Section III, but was configured so that energy was deposited directly into thermal electrons at a constant rate for 1 ns in a specified cylindrical deposition region, 25 μ m deep, with a diameter chosen to approximately correspond to the laser

focal spot dimensions used in the experiments ($165\text{ }\mu\text{m}$ for the best focus and 1 mm for the RPP-smoothed beam focus). In this model, no laser is present, and energy transport is due primarily to electron thermal conduction (flux-limited, as in Section IV, with a standard flux-limiter factor of 0.03 [30-32]), radiative conduction being essentially negligible. As before, calculations were performed for each set of experimental parameters for which data was obtained, these being the parameters resulting in the data curves of Figs. 7, 8 and 9. In each case, the total amount of energy deposited into the cylindrical region was chosen to match the corresponding experimental value.

The plots of the 800 eV temperature front along the laser propagation axis at $r = 0$ resulting from this model are compared with the experimental data in Figs. 15 - 17. In these examples, hydrodynamics was frozen, but essentially identical results were obtained when hydrodynamics was included except in the highest-irradiance aerogel case, where the inclusion of hydrodynamics resulted in un-physical behavior due energy deposition zoning difficulties. Because the mechanism for the creation of a laser energy deposition region is not part of the model and because its thickness and temporal evolution likely vary between experiments, we shifted the origins of two of the curves (the mid-irradiance aerogel curve of Fig. 15 and the high-irradiance aerogel curve of Fig. 17) to better match the experimental curves. It is apparent that the agreement with the experimental data is in all cases significantly better than the agreement achieved with the detailed simulations described in Section IV. Agreement is clearly excellent with the mid-irradiance aerogel curve of Fig. 15, with both the mid-irradiance and high-irradiance aerogel curves of Fig. 16, and with the higher-density (9 mg/cm^3) foam curve of Fig. 17. Agreement with the low-irradiance aerogel curve of Fig. 15 and with the lower density (4 mg/cm^3) foam curve of Fig. 17

is not as good, however, and in these cases the model trajectories are in fact slower than the experimental data.

Based on these simple model results and on the experimental data, we postulate that in these experiments, and likely in those of Tanaka *et al.* [7] as well, laser energy is actually absorbed over a deposition depth which is small compared with the dimensions of the target, in contradiction with the predictions of detailed laser-plasma interaction and hydrodynamics simulations, and this supposition is supported by the observation of the slow wave-front evident in the highest-irradiance aerogel data of Figs. 5 and 9. Heating of the deposition region proceeds by inverse bremsstrahlung and by various anomalous absorption mechanisms; the latter produce high-energy x-rays which pre-heat the target material and result in the weak hard x-ray emission observed in the data of Fig. 4(b) (discussed in Section III) through scattering, absorption and re-emission. Deeper penetration of the laser pulse is prevented, and further energy transport into the material relies on the propagation of an electron-conduction thermal heat wave, which produces the strong x-ray emission directly observed in the experiments and slows primarily due to lateral transport of energy away from the laser propagation axis. The latter supposition is supported by the generally good agreement between the experimental x-ray emission-front trajectory data and the results of the simple thermal conduction modeling discussed above, with and without frozen hydrodynamics. Finally, the poorer agreement between the simple modeling results and some of the experimental data (the low-irradiance aerogel data of Fig. 15 and the low-density foam data of Fig. 17) could be attributed to the partial breakdown of this thermal-conduction scenario in the low-density and low-irradiance regime, where the laser absorption wave may indeed become the primary energy transport

mechanism. This explanation is supported by additional data obtained in gas-balloon experiments [34] using $\lambda = 0.351 \mu\text{m}$ laser irradiation in studies aimed at understanding laser propagation in gas-filled hohlraums, in which the x-ray emission front trajectories were found to be in more reasonable agreement with the results of detailed laser-plasma interaction and hydrodynamics simulations.

This explanation for the observed discrepancies, while appealing, is incomplete and relies on the supposition that laser energy is indeed deposited over a shallow depth, in contradiction with the predictions of simulations. We have no definite explanation for this possible contradiction, but we suggest that strong side-scattering due to density inhomogeneities created by the laser deposition process, stimulated Brillouin and/or Raman side-scattering of the laser [35], strong anomalous absorption (Raman and/or TPD) into high-energy electrons and ions [36] whose transport may be inhibited due to streaming instabilities, and critical-density formation due to unexpectedly high compression, perhaps due to ponderomotive pressure, could be responsible for slowing laser propagation in the plasma.

We emphasize, however, that the present detailed simulation predictions are clearly in significant disagreement with the experimental data, and we reiterate that the experimental data, particularly the x-ray pre-heated aerogel and agar data and the gas-filled balloon target data, suggest that this disagreement cannot be attributed to initial structure or density inhomogeneities in the targets. It appears that further theoretical and experimental research will be necessary before laser energy deposition and transport in under-dense plasmas is fully understood and can be accurately simulated with advanced codes.

VI. Summary

We have presented the results of experiments in which a high-power ($4 \times 10^{14} - 1.5 \times 10^{16} \text{ W/cm}^2$), 1 ns, $\lambda = 0.527 \text{ }\mu\text{m}$ laser was used to irradiate low density silica aerogel (SiO_2 , $\rho = 8 \text{ mg/cm}^3$) and agar foam (CH_2O $\rho = 4 - 9 \text{ mg/cm}^3$) targets. The laser-solid interaction and the resulting energy transport into the material were monitored with time-resolved and time-gated imaging diagnostics, and the data show the production and propagation of an x-ray emission front in the plasmas. The emission-front trajectory data were shown to be in significant disagreement with detailed laser-plasma interaction and hydrodynamics simulations, which predict a much more rapid heating of the cold material; this discrepancy becomes increasingly dramatic at higher irradiances, and is in qualitative agreement with the observations of previous experiments [7]. However, the present data suggest that this discrepancy is not explainable by initial target density inhomogeneities, as was previously attributed [7]. Instead, we find evidence in the experimental data which suggests that energy transport into the cold material may be dominated by electron thermal conduction from a relatively shallow laser energy deposition region, and we support this interpretation with the results of a simple "hot-plate" thermal-conduction model. We find that this interpretation can explain most of the features of the data, but does not address the mechanism by which laser energy might be absorbed over a shallow depth, in contradiction with detailed simulation results. We suggest that strong side-scattering, strong anomalous absorption, and/or compression above critical density could be responsible. We conclude that the details of laser energy deposition in under-dense plasma may be inadequately treated in detailed simulations, and that additional experimental and theoretical

research is needed in order to solve this outstanding problem in laser-plasma interaction physics.

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Figure Captions

Figure 1: Scanning electron microscope photographs of 4 mg/cm³ agar foam (a), 9 mg/cm³ agar foam (b), and 8 mg/cm³ silica aerogel (c) target materials.

Figure 2: Sketch of the diagnostic geometry for the experiments. The laser was incident from the right, and the diagnostics (described in the text) viewed the target from the positions shown; $\theta = 0^\circ$ is toward the focusing lens, $\phi = 0^\circ$ is out of the plane of the paper, and $\phi = 90^\circ$ is towards the bottom of the page.

Figure 3: Sketch of the target geometry. The laser was focused onto one face of a vertically oriented, rectangular column of aerogel or foam, approximately 1 mm below the top surface and 4 - 9 mm above the plastic support rod and glue. The primary x-ray imaging diagnostics then viewed the laser-solid interaction perpendicular to the laser propagation axis.

Figure 4: GAX gated x-ray imaging data showing an x-ray emission wave propagating through the target material, induced by a laser beam incident from the left. The top row (a) shows data from an aerogel target irradiated at 4.1×10^{14} W/cm² with a RPP-smoothed beam at four consecutive times separated by 400 ps each. The middle row (b) shows similar data from an aerogel target irradiated at 1.3×10^{16} W/cm² with an un-smoothed beam, and the bottom row (c) shows similar data from a 4 mg/cm³ foam target irradiated at 1.5×10^{15} W/cm² with a RPP-smoothed beam. The scale of all images is the same, given by the bar at the top of the figure, and dark corresponds to bright x-ray emission in these negative prints. The various straight lines and dark spots are caused by the edges of the gated micro-channel plate strips and by noise in the micro-channel plate.

Figure 5: SPHC streaked x-ray imaging data showing a continuous time record of the position of the x-ray emission front in an aerogel plasma irradiated at $1.3 \times 10^{16} \text{ W/cm}^2$. Time is increasing to the right, space into the target is up, and the laser is incident from the bottom of the figure. The wavy band near the center is a shadow of a fiber-optic cable, and is curved due to pinching effects in the streak camera caused by high exposure levels; the rectangular region is caused by hard x-rays passing through the cathode and directly exciting the phosphor screen. The time and space scales are given by the bars, and dark corresponds to bright x-ray emission in this negative print.

Figure 6: SPHC streaked x-ray imaging data showing a continuous time record of the position of the x-ray emission front in an aerogel plasma irradiated at $1.6 \times 10^{15} \text{ W/cm}^2$ with a RPP-smoothed beam. Time is increasing to the right, space into the target is up and the laser is incident from the bottom of the figure. The thin line is a time fiducial [37], and the rectangular region is caused by hard x-rays passing through the cathode and directly exciting the phosphor screen. The time and space scales are given by the bars, and dark corresponds to bright x-ray emission in this negative print.

Figure 7: Reduced SPHC streaked imaging data for the aerogel experiments at low- and mid- irradiance. The trajectories show the position of the x-ray emission front in the plasma versus time; the front position at a particular time is defined as the 10% rising edge in intensity moving towards $z = 0$. Scales were obtained from measured geometrical distances and camera magnification and from sweep rates quoted by the manufacturer. The trajectories are plotted for as long as they are visible in the data. The origin is uncertain due to the lack of absolute fiducials and due to alignment variations which obscured the beginning of the sweep on some

experiments; the uncertainty is estimated to be $\pm 50 \mu\text{m}$ in space and ± 40 ps in time. The experiments used RPP-smoothed beams unless noted in the legend.

Figure 8: Reduced SPHC streaked imaging data for the high-irradiance aerogel experiments. The trajectories show the position of the x-ray emission front in the plasma versus time (rapid front); the slow front is a low-contrast feature in the data which begins early in time (visible in Fig. 6) and slowly advances behind the main emission front. The uncertainty in the origin is estimated to be $\pm 50 \mu\text{m}$ in space and ± 40 ps in time. These experiments did not use RPP-smoothed beams.

Figure 9: Reduced SPHC streaked imaging data for the foam experiments. The uncertainty in the origin is estimated to be $\pm 50 \mu\text{m}$ in space and ± 40 ps in time. All experiments used RPP-smoothed beams.

Figure 10: Axial electron temperature (left vertical axis) and mass density (right vertical axis) vs. position z at time $t = 0.3$ ns from a detailed laser/plasma interaction and hydrodynamics simulation of the low-irradiance ($\sim 4 \times 10^{14} \text{ W/cm}^2$) aerogel experiment using a RPP-smoothed beam.

Figure 11: Reduced SPHC streaked imaging data for the low- and mid-irradiance aerogel experiments using RPP-smoothed beams (from Fig. 7), compared with the calculated position of the 800 eV temperature-front vs. time from detailed laser-plasma interaction and hydrodynamics simulations.

Figure 12: Reduced SPHC streaked imaging data for the mid- and high-irradiance aerogel experiments which did not use RPP-smoothed beams (from Figs. 7 and 8), compared with the calculated position of the 800 eV

temperature-front vs. time from detailed laser-plasma interaction and hydrodynamics simulations.

Figure 13: Reduced SPHC streaked imaging data for the foam experiments, which all used RPP-smoothed beams (from Fig. 9), compared with the calculated position of the 800 eV temperature-front vs. time from detailed laser-plasma interaction and hydrodynamics simulations.

Figure 14: Reduced SPHC streaked imaging data from a neopentane gas-filled balloon target, with a fully-ionized electron density of approximately 10^{21} cm⁻³, irradiated by a single RPP-smoothed, $\lambda = 0.527$ μ m laser pulse at approximately 5×10^{14} W/cm², compared to a calculated 800 eV temperature-front trajectory obtained from detailed simulations similar to those described in Section IV.

Figure 15: Reduced SPHC streaked imaging data for the low- and mid-irradiance aerogel experiments using RPP-smoothed beams (from Fig. 7), compared with the calculated position of the 800 eV temperature-front vs. time from electron conduction modeling. The origin of the mid-irradiance curve was shifted upwards by 80 μ m in order to overlay the experimental data.

Figure 16: Reduced SPHC streaked imaging data for the mid- and high-irradiance aerogel experiments which did not use RPP-smoothed beams (from Figs. 7 and 8), compared with the calculated position of the 800 eV temperature-front vs. time from electron conduction modeling. The origin of the high-irradiance curve was shifted upwards by 150 μ m and to the right by 250 ps in order to overlay the experimental data.

Figure 17: Reduced SPHC streaked imaging data for the foam experiments, which all used RPP-smoothed beams (from Fig. 9), compared with the

calculated position of the 800 eV temperature-front vs. time from electron conduction modeling.

(a)

Figure 7(a); J.A. Koch et al., Phys. Plasmas

(b)

Figure 1(b); J.A. Koch, et al., Phys. Plasmas

(c)

Figure 1(c); J.A. Koch et al., *Phys. Plasmas*

Figure 2: J.A. Koch et al., Phys. Plasmas

Figure 3: J.A. Koch et al., Phys. Plasmas

1 mm

(a)

(b)

(c)

time t

t + 400 ps

t + 800 ps

t + 1200 ps

Figure 4 : J.A. Koch et al., Phys. Plasmas

Figure 5: J.A. Koch et al., Phys. Plasmas

Figure 6: J.A. Koch et al., *Phys. Plasmas*

Figure 7: J.A. Koch et al., Phys. Plasmas

Figure 8: J.A. Koch et al., Phys. Plasmas

Figure 9: J.A. Koch et al., Phys. Plasmas

Figure 10: J.A. Koch et al., Phys. Plasmas

Figure 11: J.A. Koch et al., Phys. Plasmas

Figure 12: J.A. Koch et al., Phys. Plasmas

Figure 13: J.A. Koch et al., Phys. Plasmas

Figure 14: J.A. Koch et al., Phys. Plasmas

Figure 15: J.A. Koch et al., Phys. Plasmas

Figure 16: J.A. Koch et al., Phys. Plasmas

Figure 17: J.A. Koch et al., Phys. Plasmas